California’s Advanced Clean Cars Midterm Review

Summary Report for the Technical Analysis of the Light Duty Vehicle Standards
Executive Summary

In 2012, the California Air Resources Board (ARB or the Board) adopted the Advanced Clean Cars (ACC) program, a comprehensive set of standards for new vehicles in California through model year 2025. The components of the ACC program are the Low-Emission Vehicle III (LEV III) regulations that reduce criteria pollutants and greenhouse (GHG) emissions from light- and medium-duty vehicles for model years 2015 through 2025 and the zero-emission vehicle (ZEV) regulation, which acts as the focused technology-forcing piece of the ACC program by requiring manufacturers to produce increasing numbers of pure ZEVs (that is battery electric and fuel cell electric vehicles) and plug-in hybrid electric vehicles (PHEV) in the 2018 through 2025 model years.

When adopting these standards, the Board directed staff to conduct reviews specific to the California standards: the ZEV regulation, the 1 milligram per mile (mg/mi) particulate matter (PM) emission standard, and a general review of the format of the GHG standards, and to return with staff’s review no later than December 2016. This document and its associated appendices reflect the staff assessment in response to the Board. Table ES.1 displays summaries of the Board direction to staff from the adopted Board resolution. Additionally, the Board also committed to participating in a joint-agency review with the United States Environmental Protection Agency (U.S. EPA) and the National Highway Traffic Safety Administration (NHTSA) of the 2022 through 2025 model year GHG vehicle standards.

Table ES.1. Key Board Direction in 2012 Advanced Clean Cars Resolution

<table>
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Technology Progress since 2012

A significant part of the review focused on progress in technology since the original analysis and adoption of the standards in 2012. Advancements have already occurred in the vehicle and engine technologies being introduced by vehicle manufacturers to reduce GHG and criteria pollutant emissions including PM. ZEV technology has also seen significant development that, in many cases, is beyond what was envisioned just four years ago.

GHG Emission Control Technology Developments

- Manufacturers have successfully employed a variety of technologies that reduce GHG emissions and increase fuel efficiency many at a faster rate of deployment than was originally projected, notably, large penetration rates of advanced engine and transmissions across the industry in the last five years.
- Currently, manufacturers are over complying with the GHG requirements\(^1\) and are offering various vehicles on the road today that are already able to comply with the GHG standards for later model years. For example, of the more than 1,300 conventional vehicle model configurations available in 2016, 23 truck configurations,\(^2\) 23 sport utility vehicle (SUV) configurations,\(^3\) and 26 passenger car configurations\(^4\) meet 2020 or later GHG standards with a conventional gasoline powertrain. An additional 78 model variants comprised of hybrid electric vehicles (HEVs), PHEVs, and BEVs also meet the 2020 or later standards.

PM and Criteria Pollutant Emission Control Technology Developments

- In response largely to the ZEV regulation, manufacturers have been marketing passenger cars and SUVs meeting the 2025 LEV III criteria pollutant fleet average requirement of super ultra-low emissions vehicles (SULEV30) for over a decade. Sixteen manufacturers certified 74 vehicle models to the SULEV30 standards in 2016, including mainstream models like the Honda Civic, Chevrolet Impala, Nissan Altima, and Jeep Cherokee. The technology to meet this stringent requirement is well defined and manufacturers have significant lead time to incorporate it across their fleets.
- Testing data confirms that newer gasoline direct injection (GDI) vehicles have significantly lower PM emissions than earlier generation GDI vehicles and are readily capable today of meeting the upcoming 3 mg/mi standard with typical emission rates from 1.2-1.5 mg/mi.
- These significant advances in PM control from GDI engines position manufacturers well to make the final refinements in control towards the 1 mg/mi PM standard.

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\(^2\) Some variants of the F-150 meet the 2024 GHG standards while some variants of the Ram 1500 and the Chevrolet Silverado meet the 2021 GHG standards

\(^3\) Such as the Subaru Outback, the Nissan Rogue, and the Honda CR-V. Includes minivans and station wagons classified as trucks.

\(^4\) Such as the Mazda 6, the Hyundai Sonata, and the Honda Civic
ZEV Technology Developments

- Through August 2016, nearly 230,000 ZEVs and PHEVs have been registered in California, with an additional 62,000 in nine Section 177 states that have adopted California’s ZEV regulation. These contribute towards the more than half a million ZEVs and PHEVs in the U.S. and the expected 2 million ZEVs and PHEVs around the world by year’s end.
- Battery technology has improved and battery costs (as well as other component costs) have fallen dramatically (largely due to reduced material costs, manufacturing improvements, and higher manufacturing volumes), leading to an increase from 25 PHEV and BEV models offered today to manufacturer announcements of more than 70 unique models to be released over the next 5 model years.
- ZEV electric infrastructure in California and Section 177 ZEV states has grown with substantial investments in the past several years, and accelerated investments are expected as new infrastructure developments emerge. Over 17,000 Level 2 and 2,100 direct current fast charger (DCFC) connectors have been deployed across California and the nine Section 177 ZEV states.
- California’s current programs enabled by important legislation (most prominently Assembly Bill 8⁵) are launching the first major FCEV market and hydrogen fueling network in the U.S. Three FCEVs are currently for sale in California while 25 retail hydrogen refueling stations are open in California with an additional 20 stations already in development. Toyota and Honda have also announced partnerships with private companies for financial support of additional stations in California and the Northeast.

This summary report and its 13 appendices encompass ARB’s technical analysis for the midterm review of the adopted LEV III GHG and PM emission standards and ZEV requirements. The findings from this analysis support the following recommendations.

Findings and Recommendations:

2022 through 2025 model year GHG emission standards

*Continue California participation in the National Program by maintaining the “deemed to comply” provision allowing for compliance with the adopted U.S. EPA GHG standards for 2022 through 2025 model years.* The extensive multi-year joint-agency work summarized in the draft 2016 Technical Assessment Report (2016 TAR) showed clearly that the current national 2022 through 2025 model year GHG emission standards can be readily met at the same or lower cost than originally projected when the standards were adopted in 2012, predominantly with advanced gasoline engines and transmissions. The 2016 TAR analysis did not include several other new advanced vehicle technologies being introduced by vehicle manufacturers in the next few years that may provide significant benefits at similar or lower costs. Accordingly, after consideration of public comments received on the 2016 TAR, U.S. EPA released a Proposed Determination for public comment on November 30, 2016 that the national GHG standards currently in place for 2022-2025 model years remain appropriate under

⁵ Assembly Bill No. 8 (Perea, Statutes of 2013, Chapter 401)
the Clean Air Act and do not need to be amended. After considering additional public comments received on the Proposed Determination, U.S. EPA released a Final Determination on January 13, 2017 affirming that the national GHG standards for 2022-2025 model years would remain as adopted.

The updated national vehicle forecast shows that changes in vehicle fleet composition due to increased truck sales are now projected to result in a slightly higher 2025 model year fleet average CO₂ level. Similarly updated analysis for California, however, found that the originally projected California GHG benefits will still be achieved. An analysis specific to the California car/truck fleet mix projects the 2025 model year fleet average to be the same or lower than originally projected. Despite a similar trend as seen nationally in increased truck sales, the updated analysis projects the equivalent CO₂ fleet average in California will be between 153 and 167 grams per mile CO₂ compared to the original 2012 ARB projection of 166 grams CO₂ per mile, largely due to the actual share of passenger cars in the fleet mix being much higher than originally estimated. As such, the deemed-to-comply provision adopted by ARB to allow compliance with national GHG standards that preserved the GHG-reduction benefits of the California-specific GHG standards still puts California on track to achieve the projected GHG reductions from the 2025 model year fleet. Compliance with the current national GHG standards for model years 2022-2025 will result in equivalent or greater GHG benefits (at the same or lower cost to manufacturers) than originally projected for California and accordingly, consistent with the U.S. EPA Final Determination, changes to the stringency of the national or California GHG standards are not necessary or warranted.

These findings on the benefits to California are based on an analysis assuming the existing national GHG standards. If the stringency of the national GHG standards were substantially changed, despite the Final Determination by U.S. EPA based on a comprehensive record demonstrating that the existing standards should be maintained, these findings would likely be different. In that event, California could revisit whether it would have to conduct a new analysis to determine whether compliance with a new National Program would be an appropriate approach under California’s LEV III program to address California’s unique air quality challenges and its mandates to achieve aggressive GHG reductions to protect public health and the environment.

1 milligram per mile particulate matter emission standard

As previously reported to the Board in 2015, maintain the existing PM emission gravimetric measurement method for the 1 mg/mi standard. In responding to Board direction regarding examination of the tailpipe emission measurement capability at 1 mg/mi PM levels, staff reported to the Board in October 2015 that the gravimetric method for determining PM emissions is appropriate for measuring low PM emission levels and that the method will remain the approved procedure for determination of compliance with ARB’s LEV III PM emission standards. This decision was based on extensive emission testing and research of
laboratory methods conducted by ARB and published in the peer-reviewed literature.\(^6\) The agency’s research was conclusive with respect to the applicability of the gravimetric method, but also included several PM measurement alternatives such as counting particles and, while the work showed that none of the alternatives were equivalent to the current gravimetric method of determining PM mass, it revealed some potential benefits of several of the alternatives. Thus, the agency is committed to track further developments to ensure ARB’s measurement capabilities remain at the forefront of PM emission metrology and technology.

**Maintain the stringency and implementation schedule of the adopted 1 mg/mi PM emission standard applicable in 2025 model year.** To respond to the Board’s additional direction regarding reassessing stringency and implementation of the 1 mg/mi PM standard, additional emission testing and a review of vehicle PM emission control technology was conducted and is included in this report (Appendices J and K). This work determined that compliance with the 1 mg/mi emission standard by 2025 model year is feasible and that manufacturers are on track to meet this standard. The findings also support that the currently provided lead time is necessary to ensure manufacturers can incorporate broadly the knowledge gained from the in-use operation of newer, 3 mg/mi compliant, GDI systems into normally scheduled engine redesigns to optimize for PM control at little to no added cost. Test data and analysis shows that, although vehicle manufacturers have achieved significant PM emission reductions over the last engine redesign cycle, some are not yet controlling PM emissions well enough to consistently maintain the 1 mg/mi limit across all applicable operating conditions and over all vehicle models. In particular, further improvements are needed for gasoline direct injection (GDI) vehicles to meet a 1 mg/mi standard with a sufficient compliance margin, but manufacturers and suppliers appear to be on track to achieve control within the current lead time provided by the adopted regulation. Thus, earlier implementation than 2025 model year of the 1 mg/mi PM standard is not supported by this analysis as the reduced lead time would jeopardize the ability of manufacturers to ensure robust solutions that can be incorporated into scheduled engine redesigns and would likely lead to reliance on more costly, interim solutions such as gasoline particulate filters (GPF) to comply. On the other hand, the GPF is a viable solution, albeit at a higher cost, available to manufacturers now for meeting the most stringent 1 mg/mi PM limit.

**Develop more comprehensive PM emission standards to phase-in with the 1 mg/mi standard in 2025 model year to ensure manufacturers implement robust control strategies that result in low PM emissions in the real world.** The most recent set of emission test results suggests that additional regulatory requirements are needed to better ensure that when the 1 mg/mi Federal Test Procedure (FTP) standard is phased-in, it results in robust in-use PM control over a broader spectrum of driving conditions than encountered in the FTP. To this end, ARB plans to develop a more stringent US06 cycle PM emission standard, which would verify PM is well-controlled over more aggressive in-use driving conditions, as well as consider PM emission standards for other test cycles and ambient conditions as necessary to ensure in-use PM emissions are minimized.

California’s ZEV regulation

Strengthen the ZEV program for 2026 and subsequent model years to continue on the path towards meeting California’s 2030 and later climate change and air quality targets. Set new requirements to target credit provisions and regulatory structure adjustments in order to increase certainty on future vehicle volumes, technology improvement, and PHEV qualifications and other factors to maximize GHG and criteria pollutant reductions.

For the first time since the initial adoption of the regulation, the Board adopted increased ZEV credit requirements in 2012. This action, in concert with the development of strong comprehensive complementary policies to support infrastructure deployment and consumer awareness, led to the advancement of ZEV technology and growth in ZEV sales. Since the adoption of the 2018 through 2025 model year standards, manufacturers have been exceeding the annual requirements of the ZEV regulation and expanding the market nationwide by delivering ZEVs and PHEVs in states which have not adopted California’s ZEV regulation. Thus, committing now to a strong set of post-2025 requirements reinforces current progress and encourages manufacturers to continue advancements to electrify their fleets.

Modeling to meet the 2030 GHG targets established by SB 32 in the ARB Mobile Source Strategy report, released in May 2016, indicates approximately three million additional ZEVs and PHEVs will be needed in 2026 through 2030. To reach these volumes with any certainty, the new regulation will need modifications that provide a more direct connection to vehicle volumes and require vehicle characteristics that best ensure market success. For such significant revisions to the regulation to be successful, however, it would require greater market acceptance, more technology advancements, and lower technology costs than is known with certainty today. In PHEVs alone, the product offerings and architecture variations are increasing in diversity and it is too early to determine which combinations will be appealing to consumers while providing maximum GHG and criteria pollutant benefits. For BEVs, a step change is occurring with multiple offerings expected with 200+ miles of range at prices closer to mainstream conventional vehicles (even before state and federal incentives), with the first of these being launched within weeks of this report's release. Additionally, substantial changes to the regulatory structure will impact vehicle manufacturer product and compliance planning and necessitate sufficient lead time and stability to implement successfully while minimizing disruption to research, investment, and design cycles. Development of future new ZEV requirements needs to be done in concert with additional GHG (and potentially criteria pollutant) fleet-wide emission reduction requirements as was previously done in the 2012 ACC program. This coordinated approach ensures the regulations of multiple pollutants benefit from the synergistic effects and result in a single integrated policy to help meet California’s air quality and GHG goals. To this end, ARB intends to continue to collaborate on a technical basis with its federal partners such as the U.S. Department of Energy (DOE), U.S. EPA, and NHTSA to research, develop, and promote advancement of vehicle technologies including ZEV technologies necessary for California’s long term goals.

Maintain the current ZEV stringency for California through 2025 model year including the existing regulatory and credit structure. In 2012, the Board strengthened the ZEV regulation, nearly tripling the credit requirements for pure ZEVs in 2025 model year, and shifting
away from a stair-step approach (where requirements remained the same for three years at a time) to a simpler, linear annual increase in the requirements. Since then, the regulation has been achieving the goal of accelerating development of ZEV technology towards commercialization in California as demonstrated by the clear growth in the ZEV market, the introduction of more capable and longer range vehicles than originally projected, and earlier reduction in battery costs than anticipated. The 2012 Board action has resulted in over 215,000 ZEVs and PHEVs being placed in California over the last five years and an expansion from 25 models offered today to over 70 unique ZEV and PHEV models expected in the next five years. As a result of the vehicle technology advancements evident in the market, new minimum compliance scenarios were developed that project approximately 1.2 million cumulative sales of ZEVs and PHEVs by 2025 in California. While this revised compliance picture reflects a lower volume of vehicles than originally projected in 2012, the resultant improvements in ZEV and PHEV attributes, such as all-electric range and vehicle price, are expected to further broaden the appeal of these vehicles beyond the initial consumers and help achieve necessary future market expansion. Simply put, the market is seeing the introduction of better ZEVs. Outside of California, ZEV markets are expanding in the U.S. as well as globally, indicating that the industry is beginning a significant shift towards greater electrification.

Despite these successes, it is widely recognized that the ZEV and PHEV market is still in the early stages of development. While the market is rapidly changing with nine BEV and PHEV models already discontinued since their introduction, it is also unknown how many of the 70 announced models will succeed in the market. The current market has benefited from multiple purchase incentives that have substantially discounted ZEVs and PHEVs such that their prices are more aligned with those of conventional vehicles. But, between 2018 and 2025, these and other incentives are expected to phase out. While decreased reliance on incentives is essential for building a self-sustaining market, it is unclear what consumer response will be without purchase and other incentives (like high occupancy vehicle (HOV) lane access). Consumer awareness of ZEVs is still low and top motivations like saving money on fuel are less influential as gasoline prices remain low. Given the market uncertainties that still exist in these early years, regulatory stability of the 2018 through 2025 model year standards can help ensure a continued path of increasing, but achievable, ZEV volumes.

*Maintain the existing flexibilities, including as amended in 2014, for intermediate volume manufacturers (IVMs).* Regarding the ZEV requirements applicable to IVMs, this analysis found that a further reduction in the requirements is not warranted at this time. The Board adopted a number of flexibilities in the original rulemaking in 2012 and in an additional rulemaking in 2014 to help ease the transition of the IVMs into the more stringent requirements starting in model year 2018. While smaller than other manufacturers, to their credit, these manufacturers do have competitive products in the market and generally agree that there is a need to develop and introduce ZEV technologies to remain competitive into the future. All five current IVMs have clear and concrete plans to bring ZEVs to market in the next few years, with relevant announcements for two of the five as recently as November 2016. Additionally, as shown in the revised compliance scenario analysis, there are sufficient credits, both in their own banks and in the market, available for IVMs to help bridge any interim compliance gaps.

ES-7
Maintain the existing credit structure and use caps for PHEVs through the 2025 model year. PHEVs will continue to play a role in the electrification of transportation for long-term emission reduction targets. The adopted standards are consistent with ARB’s long-term modeling scenarios and already recognize PHEVs not only can help consumers and manufacturers transition to pure ZEVs but that they also can continue to be a significant share of the vehicle market. Based on in-use data from PHEVs, emission testing, and analysis of electric use conducted by ARB, PHEVs can generate significant benefits over conventional vehicles but do not generally result in GHG or criteria pollutant emission reductions equal to pure ZEVs. Given this and even more importantly, the technology-forcing goals of the ZEV regulation, the current regulation appropriately awards more credits to the longer range pure ZEV vehicles.

Further, as shown in the updated compliance scenarios, PHEVs are projected to make up more than 60 percent of all ZEVs and PHEVs on the road by 2025 even with the current use caps on PHEV credits. This indicates the current regulatory structure already provides sufficient flexibility as the ZEV market is developing to determine the role PHEVs will ultimately play. The new analysis does not support more flexibility for PHEVs at this time such as allowing manufacturers to comply with ZEV requirements with more PHEVs than currently allowed. And, while strong electric drive capability PHEVs with significant all-electric range and minimal engine starts are very encouraging, the analysis in this report finds that their benefits do not match or exceed those of pure ZEVs and, hence, PHEVs are appropriately credited less than pure ZEVs in the existing regulation. Furthermore, allowing for more credits per PHEV such that fewer total vehicles are needed to comply does not result in additional emission benefits or furtherance of the technology-forcing goals of the ZEV regulation.

Continue efforts by ARB and other stakeholders to accelerate and expand non-regulatory complementary policies that have been identified as successful in building market demand and removing remaining barriers to ZEV adoption. Irrespective of any regulatory action, appropriate complementary policies will need to be in place to support the expansion of the ZEV market as the market share will need, at a minimum, to approximately triple in the next nine years. ARB and other stakeholders will need to accelerate and expand non-regulatory and complementary actions that have been identified as successful to continue to enhance market demand for ZEVs and remove the remaining barriers to ZEV adoption. Examples of such policies include consumer rebates and tax credits, carpool lane access, availability of public charging infrastructure, parking incentives, and others.

ZEV regulation requirement for Section 177 ZEV states

Maintain the adopted flexibilities for the Section 177 ZEV states. Through Section 177 of the Clean Air Act, several states have previously adopted various California vehicle regulations to help achieve their air quality or GHG targets. In particular, nine states have adopted California’s ZEV regulation, collectively requiring that 25 percent to 30 percent of all new vehicles sold in the U.S. be subject to ZEV regulation requirements. California and its Section 177 ZEV state partners have embraced a strong collaboration for supporting ZEVs, entering into
a multi-state Memorandum of Understanding (MOU) in 2013 to help facilitate successful market development especially in the areas of non-regulatory complementary policies.

Recognizing the market development in the Section 177 ZEV states was not yet as far along as California’s, the Board adopted additional regulatory flexibilities and lead time to create a ramp into the 2018 and subsequent model year requirements for the states. Despite current lower sales in the Section 177 ZEV states, increased product offerings coming for the states, expiration of regulatory flexibilities that may have discouraged past sales efforts in the states, and more comprehensive complementary policies provide sufficient support for manufacturers to meet the increasingly stringent ZEV requirements in the Section 177 ZEV states. Additionally, credits both created in the Section 177 ZEV states and generated through the travel provision in the California market will help manufacturers who need more time to build a market for their vehicles between 2018 and 2025 model years.
Summary Report: California’s Mid-term Review of the Adopted LEV III GHG, PM, and ZEV Standards

Introduction

What is the Advanced Clean Cars program?

In 2012, the California Air Resources Board (ARB) adopted the Advanced Clean Cars (ACC) program, a comprehensive set of standards for new vehicles in California through model year 2025. This historic program, developed in coordination with the United States (U.S.) Environmental Protection Agency (EPA) and National Highway Traffic Safety Administration (NHTSA), combined the control of smog-causing (criteria) pollutants and greenhouse gas (GHG) emissions into a single coordinated set of requirements for model years 2015 through 2025 and assured the development of environmentally superior passenger cars and other vehicles that will continue to deliver the performance, utility, and safety vehicle owners have come to expect all while saving the consumer money through significant fuel savings. The components of the ACC program are the Low-Emission Vehicle III (LEV III) regulations that reduce criteria pollutants and GHG emissions from light- and medium-duty vehicles and the zero-emission vehicle (ZEV) regulation, which requires manufacturers to produce an increasing number of pure ZEVs (meaning battery electric and fuel cell electric vehicles) and plug-in hybrid electric vehicles (PHEV) in the 2018 through 2025 model years. When fully implemented, new vehicles are expected to emit 34 percent fewer GHG emissions and 75 percent fewer smog-forming emissions than today’s vehicles.

Vehicles and transportation fuels are the dominant sources of carbon emissions in California. ACC is an integral part of California’s ambitious long-term requirements to reduce the State’s impact on climate change and improve ambient air quality. The vehicle programs are a critical measure in the State Implementation Plan (SIP) for achieving national ambient air quality standards in the South Coast and San Joaquin Valley. They are also an integral part in ARB’s Scoping Plan to achieve the GHG reduction goals that were established through California legislation and Executive Orders. This year, GHG reduction targets in Executive Order B-30-15 were codified with the passage of Senate Bill (SB) 32 (Statutes 2016, Chapter 249, Pavley), which expanded the California Global Warming Solutions Act of 2006, by directing ARB to ensure that statewide GHG emissions are reduced to at least 40 percent below the 1990 level by 2030. Also in 2016 California enacted Assembly Bill (AB) 197 (Statutes 2016, Chapter 250, Garcia). AB 197, among other provisions, declares that continuing to reduce GHG emissions is critical for the protection of all areas of the state, but especially for the state’s most vulnerable

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8 Executive Orders S-3-05 (Schwarzenegger, 2005) and B-30-15 (Brown, 2015) establish long term GHG emission reductions of the state of 80% and 40% below 1990 levels by 2050 and 2030 (respectively).
communities, as those communities are affected first, and most frequently, by adverse impacts of climate change.

Although significant strides have been made toward improving California’s air quality, health-based state and federal ambient air quality standards continue to be exceeded in major regions throughout California. To achieve the 1997 8-hr ozone standard by the attainment date in 2023, oxides of nitrogen (NOx) emissions in the greater Los Angeles region must be reduced by an additional two thirds beyond reductions from all of the control measures in place today. Furthermore, to achieve the more stringent 75 parts per billion (ppb) 2008 8-hr ozone standard by 2031 will require an 80 percent reduction in NOx from 2012 levels. ARB is working with the local air quality management districts to prepare SIPs informed by ARB’s Mobile Source Strategy. The plans for attaining the most recently adopted 70 ppb ozone standard have not begun, but are expected to have to rely heavily on significant and on-going progress towards zero and near-zero mobile source emissions in California. The third generation “LEV III” regulations, adopted as part of the ACC program, build upon the requirements of the earlier LEV regulations and continue to reduce emissions from the light- and medium-duty fleet through the 2025 model year.

What is the midterm review (MTR), and how is California’s review different from the joint-agency national midterm evaluation?

The primary differences between state and federal actions are in the scope of the different reviews. While the national midterm evaluation was solely focused on a review of the federal GHG (and associated fuel economy) standards, ARB’s MTR is required to review California’s PM standard and ZEV regulation in addition to a review of the GHG standards. When adopting the current ACC program standards, the Board committed to participating in a joint-agency review with U.S. EPA and NHTSA of the 2022 through 2025 model year GHG tailpipe standards, first in a letter written the summer before the rulemaking, and later when adopting the ACC standards in its January 2012 Resolution. The Board also directed staff to conduct reviews specific to the California standards: the ZEV regulation, the 1 mg/mi particulate matter (PM) emission limit, and a general technical review relative to the format of the adopted GHG standards, the use of vehicle footprint as a key attribute, and reliance on the federal corporate average fuel economy or CAFE car/truck definitions. The Board also directed staff to return with its review no later than December 2016. Resolution 12-11 specified areas for staff to consider for its review as shown in Table 1 below.

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Table 1 - 2012 Advanced Clean Cars Resolution Direction

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<td>GHG</td>
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<td>PM</td>
<td>Re-examine the measurement methods, stringency, and timing of the adopted 2025 model year 1 mg/mi PM emission standard.</td>
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<td>ZEV</td>
<td>Monitor consumer acceptance of PHEVs and report on expected volumes in the ZEV program. Analyze in-use data for range extended battery electric vehicles (BEVx) and PHEVs, and propose appropriate modifications as needed. Conduct a study of the potential effects of adding an additional category of vehicles to the ZEV regulation for “BEV XX” vehicles that would be allowed greater use of an internal combustion engine than allowed for vehicles approved as “BEV X” vehicles in this action, where such BEX XX vehicles would only be applied to 25 percent of a manufacturer’s pure ZEV requirement.</td>
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In addition to the above Resolution direction, staff also monitored the evolution of the ZEV market and evaluated the effectiveness of the ZEV regulation as adopted in 2012, both in California and in the other states that have adopted California’s ZEV regulation. Staff received additional direction at the July 2016 Board Hearing to examine the ZEV credit banks, the treatment of credits for ZEVs and PHEVs within the regulation, and to explore ways to ensure that the market is growing in the appropriate timeframe to meet the long-term air quality and GHG emission reduction goals expressed in the regulation.\(^{12}\)

What was the review process of the ACC program?

**Extensive Consultation with Stakeholders**

Over the past four years, staff has held numerous and extensive consultation sessions and technical discussions with experts representing all of the major automakers and other leading technical stakeholder groups with an interest in the ACC standards on each of the three aspects of ARB’s midterm review. These discussions involved consideration of auto manufacturer market plans for technology development and examination of the most recent and relevant evidence concerning trends for technology and costs as noted in the 2016 TAR. In 2015, ARB

participated in systematic joint-agency (along with U.S. EPA and NHTSA) discussions with manufacturers regarding the evaluation of the GHG standards, which fed into the 2016 TAR described below. In 2016, ARB held separate discussions with most manufacturers to consider confidential business approaches for upcoming product and compliance plans for the ZEV and PM reviews.

*Extramural Research*

Research for generation of new knowledge is a key aspect of the agency analysis in support of this MTR. ARB has sponsored or co-sponsored six extramural research projects to support the mid-term review. Three projects have been completed to date. These projects, along with a short description are listed in Table 2 below.

**Table 2 - Advanced Clean Cars Midterm Review Extramural Research Projects**

<table>
<thead>
<tr>
<th>Research Contract Title</th>
<th>Author</th>
<th>Project Status</th>
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<tbody>
<tr>
<td>Technical Analysis of Vehicle Load-Reduction Potential for Advanced Clean Cars</td>
<td>Gregory Pannone, Control Tec (now Novation Analytics)</td>
<td>Complete</td>
</tr>
<tr>
<td>New Car Buyer’s Valuation of Zero-Emission Vehicles</td>
<td>Dr. Kenneth Kurani, University of California, Davis</td>
<td>Complete</td>
</tr>
<tr>
<td>Very low PM measurements for light-duty vehicles (E-99)</td>
<td>Dr. Heejung Jung, University of California, Riverside</td>
<td>Complete</td>
</tr>
<tr>
<td>The dynamics of plug-in electric vehicles in the secondary market and their implications for vehicle demand, durability, and emissions</td>
<td>Dr. Gil Tal, University of California, Davis</td>
<td>On-going</td>
</tr>
<tr>
<td>Examining Factors that Influence ZEV Sales in California</td>
<td>Dr. J.R. DeShazo, University of California, Los Angeles</td>
<td>On-going</td>
</tr>
<tr>
<td>Advanced Plug-In Electric Vehicle Usage and Charging Behavior</td>
<td>Dr. Tom Turrentine, University of California, Davis</td>
<td>On-going</td>
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Research findings from the “Technical Analysis of Vehicle Load-Reduction Potential for Advanced Clean Cars” and “New Car Buyer’s Valuation of Zero-Emission Vehicles” have been presented and published. These seminars are webcast and archived. Completion of the remaining projects is underway and ARB expects to make use of those findings in subsequent technical analyses, including those informing new post-2025 regulatory policies.

*Annual Board Informational Updates*

Beginning in October 2013, staff provided three annual informational updates on the ACC program to the Board, each emphasizing different aspects of staff’s review. Staff’s 2013 update focused on the general plan for the conduct of the midterm review, as well as various complementary policies and initiatives. The 2014 update related an in-depth examination of

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15 Access all archived research seminar webinars: [https://www.arb.ca.gov/research/seminars/seminars.htm](https://www.arb.ca.gov/research/seminars/seminars.htm)

16 Staff’s annual updates can be accessed at the following link: [https://www.arb.ca.gov/msprog/acc/acc-mtr.htm](https://www.arb.ca.gov/msprog/acc/acc-mtr.htm)
charging and fueling infrastructure needs, development of charging and fueling infrastructure networks in California, and provided detailed information about other on-going studies and research related to this MTR. In 2015, the first part of the PM review was presented to the Board on the topic of PM emission measurement feasibility and general laboratory practices. Additionally, staff presented information on consumer purchasing attitudes regarding ZEVs and PHEVs.

The Joint-Agency Draft 2016 Technical Assessment Report
The results of an extensive multi-year study are presented in the recently published 2016 Draft Technical Assessment Report: Midterm Evaluation of Light-Duty Vehicle Greenhouse Gas Emission Standards and Corporate Average Fuel Economy Standards for Model Years 2022-2025 (referred to as the 2016 TAR throughout this report). The 2016 TAR represents the culmination of new technology assessments, vehicle emission testing, and modeling work and updated analyses of the feasibility, costs and potential pathways to meeting the adopted national GHG standards for model years 2022 to 2025. In the development of the 2016 TAR, the three agencies drew from multiple sources of information ranging from stakeholders such as vehicle manufacturers and vehicle component suppliers to extensive in-house research at U.S. EPA’s National Vehicle and Fuel Emissions Laboratory. ARB staff provided an overview of the information presented in the 2016 TAR at the July Board Hearing.

Advanced Clean Cars Symposium: The Road Ahead
In September, 2016 ARB held a two-day technical ACC Symposium “The Road Ahead” in Diamond Bar, California at the South Coast Air Quality Management District headquarters. Over 100 participants and agency staff attended the symposium over the two days, and more participated via webcast. The first day featured presentations made by representatives from industry and academia on various groundbreaking trends in ZEV technologies, including the latest in battery technology, wireless charging, and ARB’s analysis of manufacturer provided plug-in electric vehicles (PEV) in use data and emissions testing of PHEVs. The second day covered engine and vehicle technologies that were not extensively used in the analysis for the 2016 TAR but are expected to be on production vehicles in the near term and could help meet the adopted GHG and PM standards.

California’s Final Report – The Midterm Review of the Adopted Standards
This report is a compilation of four years of staff work on each aspect of the midterm review. The thirteen appendices (labeled A through M) attached to this summary document will present the staff analyses:

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18 Agendas and presentations made at the September 26 and 27 Symposium are found here: https://www.arb.ca.gov/msprog/acc/acc-symposium.htm
A. Analysis of Zero Emission Vehicle Regulation Compliance Scenarios
Analysis of ZEV regulation compliance scenarios with updated inputs, ZEV calculator, and credit bank analysis.

B. Consumer Acceptance of Zero Emission Vehicles and Plug-in Hybrid Electric Vehicles
Analysis of California and Section 177 ZEV state ZEV and PHEV market development since the adoption of ACC, as well as a look at the potential for further market growth.

C. Zero Emission Vehicle and Plug-in Hybrid Electric Vehicle Technology Assessment
A review of the current status of ZEVs (both BEV and FCEV) and PHEV technology trends and summary of incremental vehicle costs.

D. Zero Emission Vehicle Infrastructure Status in California and Section 177 ZEV States
A review of the current status, station counts, technology trends, and costs of charging and hydrogen fueling infrastructure in California and Section 177 ZEV states.

E. Zero Emission Vehicle Complementary Policies in California and Section 177 ZEV States
A summary of complementary policies (apart from those covered under Appendix D) that are helping to spur the ZEV market in California and the Section 177 ZEV states.

F. Scenario Planning: Evaluating impact of varying plug-in hybrid electric vehicle (PHEV) assumptions on emissions
Analysis of sensitivities for increased electric vehicle miles traveled (eVMT), increased on-road PHEV numbers, and increased fuel economy on ARB’s latest long-term emissions reduction plans presented earlier in 2016 in the Mobile Source Strategy.

G. Plug-in Electric Vehicle In-Use and Charging Data Analysis
Analysis of manufacturer provided driving and charging data from eleven different PEV models.

H. Plug-in Hybrid Electric Vehicle Emissions Testing
Description and summary of testing completed in ARB’s Haagen-Smit Laboratory on blended PHEVs to analyze criteria pollutant emissions.

I. Alternative Credits for Zero Emission Vehicles and Plug-in Hybrid Electric Vehicles
In accordance with the Board’s 2012 resolution, a summary of various alternative ZEV regulation credit structures based on data from Appendix G.

J. Vehicle PM Emission Control Technology Assessment
Assessment of currently available PM emission control technologies, which could be employed on gasoline vehicles to meet the 1 mg/mi standard.
K. PM Emission Testing Results
Description and summary of results from testing at ARB’s Haagen-Smit Laboratory of vehicles with advanced gasoline GHG technologies and their ability to comply with the 1 mg/mi PM standard.

L. Emissions Impact Assessment for the 1 mg/mi standard
Background of the PM emission standard and updated emissions inventory analysis for implementing the 1 mg/mi PM standard earlier than in model year 2025.

M. California GHG technology trends
Analysis of trends in the California’s light-duty vehicle (LDV) fleet to assess the car/truck split and vehicle footprint effects since the adoption of the ACC regulations.

Greenhouse Gas Emission Standard Review

How have conventional vehicle technologies progressed since the adoption in 2012 of the GHG fleet average standards?

Since adoption of the GHG and fuel economy standards in 2012, manufacturers have employed a variety of technologies that reduce GHG emissions and increase fuel efficiency, many at a faster rate of deployment than was originally projected. According to U.S. EPA’s 2015 trends report (Trends Report), large changes in advanced engine and transmission penetration rates have taken place across the industry in the last five years, as shown in Figure 1. As expected, the penetration rate for individual technologies varies between manufacturers.

Figure 1 - Five Year Change in Light-Duty Vehicle Technology Penetration Share


What were the main findings of the 2016 TAR?

Independent and parallel analyses were conducted by U.S. EPA and NHTSA, with some input from ARB, thereby resulting in complementary conclusions and identifying multiple possible pathways to comply with the 2022 through 2025 model year GHG and fuel economy standards. In support of these analyses, information from multiple sources was used such as new vehicle certifications, full vehicle simulation modeling conducted by the agencies, extensive reviews of the published technical literature and technical conference information, vehicle manufacturer and supplier information and focused discussions, and the 2015 National Academy of Science report “Cost, Effectiveness and Deployment of Fuel Economy Technologies for Light-Duty Vehicles.”20 In general, the analyses confirm that the original estimates of the effectiveness of technologies in terms of efficiency and GHG performance examined in the 2012 Final Rulemaking (FRM) remain appropriate.

Technology Penetration

The agencies found the 2025 model year GHG standards can be met at approximately the same or lower cost, predominantly with advanced gasoline engines and transmissions. Light-weighting, improved aerodynamics, and better tires also provide additional GHG reductions. As shown in Table 3, compliance with the national standards is not expected to prompt automakers to rely on large quantities of ZEVs, PHEVs, or conventional hybrid electric vehicles (HEV). Increased use of such technologies would enable additional GHG emissions reductions but it would also increase projected vehicle costs.

<table>
<thead>
<tr>
<th>2025 Model Year Vehicle Technologies</th>
<th>U.S. EPA Analysis</th>
<th>NHTSA Analysis</th>
</tr>
</thead>
<tbody>
<tr>
<td>Turbocharged and Downsized Gasoline Engines</td>
<td>33%</td>
<td>54%</td>
</tr>
<tr>
<td>Higher Compression Ratio, Naturally Aspirated Gasoline Engines</td>
<td>44%</td>
<td>&lt;1%</td>
</tr>
<tr>
<td>8 speed and other Advanced Transmissions</td>
<td>90%</td>
<td>70%</td>
</tr>
<tr>
<td>Mass Reduction</td>
<td>7%</td>
<td>6%</td>
</tr>
<tr>
<td>Stop-Start</td>
<td>20%</td>
<td>38%</td>
</tr>
<tr>
<td>Mild Hybrid (48 Volt)</td>
<td>18%</td>
<td>14%</td>
</tr>
<tr>
<td>Full Hybrid</td>
<td>&lt;3%</td>
<td>14%</td>
</tr>
<tr>
<td>Plug-in Hybrid Electric Vehicle*</td>
<td>&lt;2%</td>
<td>&lt;1%</td>
</tr>
<tr>
<td>Battery Electric Vehicle*</td>
<td>&lt;3%</td>
<td>&lt;2%</td>
</tr>
</tbody>
</table>

* U.S. EPA’s modeling includes compliance with ZEV regulatory requirements in the reference fleet. Consequently, 3.5% of the fleet is projected to be an electric vehicle or a plug-in hybrid electric vehicle in the 2022 through 2025 model year timeframe due to the adoption of the ZEV regulations in California and Section 177 ZEV states. The NHTSA modeling does not include ZEV regulatory compliance in the reference fleet.

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Projected Vehicle Fleet Mix and Associated Emission Benefits

Additional key findings in the 2016 TAR relate to projected benefits and costs. The new analysis relies on updated assumptions of the mix of cars and trucks, which show that nationwide, people are purchasing more trucks and fewer cars than was projected in the 2012 Final Rule of the national program. The future projection of vehicle fleet mix is based on the U.S. Energy Information Administration’s 2015 Annual Energy Outlook (AEO) that factors in projected fuel prices with current trends and regulatory requirements. Because trucks are required to meet higher (less stringent) CO₂ standards than cars, the updated projected national fleet average for the 2025 model year is 175 grams per mile versus the original 163 grams per mile projection in the national standard. The corresponding projected fuel economy is 50.8 mpg nationally instead of 54.5 mpg. These updated projections assume that the stringency of the 2022 through 2025 model year GHG standards does not change.

Table 4 - 2025 Model Year Projected National Fleet Mix

<table>
<thead>
<tr>
<th>MY 2025 Fleet Mix</th>
<th>Original Projection</th>
<th>New Projection</th>
</tr>
</thead>
<tbody>
<tr>
<td>% Car</td>
<td>67%</td>
<td>52%</td>
</tr>
<tr>
<td>% Truck</td>
<td>33%</td>
<td>48%</td>
</tr>
<tr>
<td>Combined gCO₂e/mi</td>
<td>163</td>
<td>175</td>
</tr>
<tr>
<td>Combined mpg</td>
<td>54.5</td>
<td>50.8</td>
</tr>
</tbody>
</table>

Incremental Vehicle Costs and Payback Period

Finally, the 2016 TAR and the updated analysis used for the Final Determination project that the average incremental cost per vehicle to comply with the GHG standards in model year 2025 will be about the same or lower than the original projections used in the rulemaking. The payback period, however, has increased relative to the original estimate. This is because current and future fuel prices, as forecast by the 2015 and 2016 AEO, are lower now than what was projected back in 2012 during the original rulemaking. The revised longer estimate for the payback period is still well within the lifetime of the vehicle and operation of the vehicle beyond the payback period will result in additional consumer savings in the form of lower fueling costs.

Table 5 - 2025 Model Year Incremental Vehicle Costs and Payback Period

<table>
<thead>
<tr>
<th></th>
<th>Incremental Cost* per Vehicle in MY 2025</th>
<th>Payback Period</th>
</tr>
</thead>
<tbody>
<tr>
<td>2012 Rulemaking</td>
<td>$ 1,163</td>
<td>3.2 years</td>
</tr>
<tr>
<td>2016 TAR:</td>
<td></td>
<td></td>
</tr>
<tr>
<td>U.S. EPA Analysis</td>
<td>$ 910</td>
<td>5 years</td>
</tr>
<tr>
<td>NHTSA Analysis</td>
<td>$ 1,148</td>
<td>6 years</td>
</tr>
<tr>
<td>2016 Final Determination</td>
<td>$ 875</td>
<td>5 years</td>
</tr>
</tbody>
</table>

* All values adjusted to 2015$ per the United States Department of Labor Consumer Price Index inflation calculator. For reference, the 2012 rulemaking reported $1,070 (in 2010$) and the 2016 TAR reported $894 and $1,128 (in 2013$) for the U.S. EPA and NHTSA analysis, respectively.
What comments were submitted by stakeholders during the federal midterm evaluation?

On July 27, 2016, a “Notice of Availability of Midterm Evaluation Draft Technical Assessment Report for Model Year 2022–2025 Light-Duty Vehicle GHG Emissions and CAFE Standards” was published in the Federal Register, opening up a 60-day comment period during which interested parties were requested to submit comments to the agencies for consideration in the proposed determination of the standards. On September 26, 2016, the public comment period for the 2016 TAR closed. Since that time, ARB has worked with the federal agencies to review and address specific comments and generally agrees with the responses in U.S. EPA’s Proposed Determination that was released on November 30, 2016. Public comments for the Proposed Determination were due by December 30, 2016 and were subsequently considered by U.S. EPA before release of a Final Determination on January 13, 2017 that affirmed the existing GHG standards for 2022-2025 model years would remain as adopted. The technical comments are summarized below.

ARB received comments from the Alliance of Automobile Manufacturers, the Global Automakers as well as individual vehicle manufacturers, and component and material suppliers. Comments were also submitted by environmental organizations and fuel advocates.

The manufacturers’ comments are grouped into five categories; 1) numerous flaws in the modeling approaches used by the agencies result in over-estimation of the efficiencies of the technologies evaluated, which in turn leads to under estimation of compliance costs, 2) the agencies failed to adequately address consumer acceptance and employment impacts of the requirements, 3) harmonization of regulatory requirements for the GHG and fuel economy program is needed to assure a coherent and single national program, 4) the GHG and fuel economy credit structures should be streamlined and harmonized, and 5) the 2016 TAR fails to account for the impact on costs from the California ZEV program.

The environmental organizations either supported affirmation of the standards or urged an increase in stringency. They also raised concerns regarding the different modeling approaches used by the agencies. In general, these organizations commented that they felt U.S. EPA’s analysis was more appropriate than NHTSA’s approach, in part because U.S. EPA used more recent engine and transmission data in the modeling and a modeling methodology that kept vehicle performance neutral as technologies were added as well as because it included compliance with ARB’s ZEV regulation in the reference fleet.

The fuel advocates comments can be grouped into four main categories: 1) octane requirements for commercial fuel should be increased to enable the development and use of high efficiency internal combustion engines, with some advocating greater use of ethanol as a fuel additive, 2) flex-fuel credits should be restored, 3) the 2016 TAR fails to consider natural gas as a near-term, cost-effective approach to reducing carbon emissions, particularly for larger trucks. In addition, they argued renewable natural gas offers significant advantages over electrification in achieving life-cycle CO₂ benefits, and 4) the American Petroleum Association commented that credits and multipliers for “Advanced Technology Vehicles” should be
eliminated since they distort the marketplace and ignore the life-cycle emissions of these technologies.

One question of particular interest to California is whether the cost of compliance with the ZEV program should be attributed to the cost of compliance with the GHG regulations. As mentioned in the footnote for Table 3, U.S. EPA's modeling includes compliance with ZEV regulatory requirements in California and the Section 177 ZEV states in the reference fleet, while the NHTSA analysis does not. By including it in the reference fleet, the U.S. EPA analysis neither includes the GHG benefits from ZEVs to lower the fleet average closer to the final standards nor includes the costs from ZEVs required by the California regulation. Inclusion of compliance with the ZEV regulation is consistent with past practice by U.S. EPA and its “Guidelines for Preparing Economic Analyses”\(^\text{21}\) to consider compliance with all other relevant finalized vehicle regulations when assessing the impact of any one program. The ZEV regulation exists independently from the GHG regulations. Consequently, the costs of compliance with the ZEV regulations will not change regardless of the stringency or even the existence of the national GHG regulations. It is, therefore, not appropriate to attribute ZEV regulatory compliance costs to compliance with the national GHG program. California fully accounted for compliance costs in California with the increased ZEV requirements in the economic analysis that supported the 2012 ACC rulemaking. The program also included the costs of compliance for both the LEV III criteria pollutant regulations and the LEV III GHG regulations. Likewise, the states that subsequently adopted the ZEV regulation, as allowed by Section 177 of the Clean Air Act, followed the specific requirements of their individual state to legally adopt such requirements including any relevant economic and cost analysis.

Which other advanced gasoline technologies should ARB consider that were not evaluated in the 2016 TAR?

While the 2016 TAR and updated analysis in the Proposed Determination examined a range of technologies to reduce GHG emissions, some promising technologies under development by the manufacturers were not assessed due to their late stage of development. Among these technologies are variable compression ratio engines and skip-fire cylinder deactivation. These technologies were discussed at the recent ARB “Technology Symposium, Advanced Clean Cars: The Road Ahead,” held on September 27-28, 2016. ARB staff is tracking this and other technology for consideration in future clean vehicle policies.

Downsized, turbocharged gasoline direct injection engines play a prominent role in the 2016 TAR due to their significant efficiency gains over conventional non-turbocharged gasoline engines. However, the amount of boost that can be employed in a given engine design is generally limited to prevent pre-ignition under engine high load operation. While this can be mitigated through the use of cooled exhaust gas recirculation and direct injection, the governing factor in limiting boost is the fixed compression ratio inherent in conventional engine designs.

As a result, a compromise must be made between engine performance at low and high load operating conditions, limiting the efficiency gains offered by turbocharging.

One approach to maximizing efficiency gains from turbocharging is to vary the compression ratio. Nissan Motor Corporation has announced a new production ready 2.0 liter variable compression ratio turbocharged engine (VC-T). The VC-T engine can vary its compression ratio between 8:1 (for high power) to 14:1 (for efficiency), depending on engine speed and load demand. In addition, the VC-T runs on the Atkinson cycle at all times providing additional efficiency gains relative to the conventional Otto-cycle operation. The VC-T engine also uses both port fuel injection and direct injection to control emissions during cold-start (particularly PM emissions) and maximize power. Nissan cites a 30 percent efficiency improvement for the 2.0 liter VC-T over a non-turbocharged 3.5 liter V6.

Cylinder deactivation offers efficiency improvements by reducing engine pumping losses during low load operation. Current systems are typically limited to deactivated one half of the engine’s cylinders to address noise, vibration, and harshness (NVH) issues and provide up to an 8 percent improvement in engine efficiency. Tula Technology, Inc. has developed a more refined version of cylinder deactivation called Dynamic Skip Fire (DSF), whereby engine cylinders can be deactivated on a continuously variable basis. The decision to fire or skip a cylinder is made before each cylinder event allowing for an immediate response to driver torque demand. The system proactively manages the engine firing sequence, maintaining benchmark NVH characteristics. Other features of the DSF include eliminating catalyst refueling penalties by completely shutting off all cylinders during deceleration, and fast torque control which reduces or eliminates spark retard during transmission shifts. Testing on a 6.2 liter V8 engine has demonstrated a 17 percent reduction in CO₂ emissions.

Variable compression ratio engines and DSF cylinder deactivation are two examples of applications which show how the automobile industry is rapidly improving the efficiency of the internal combustion engine even beyond the technologies evaluated in the 2016 TAR. These recent developments, along with technologies evaluated in the 2016 TAR, are expected to provide automakers with an ever-increasing list of options for improving vehicle efficiency in a cost effective manner, while maintaining consumer appeal and vehicle performance.

Why does ARB think that the 2022 through 2025 model year GHG standards are appropriate?

The analysis in the 2016 TAR and updated in U.S. EPA’s Proposed Determination confirmed that the 2022 through 2025 model year GHG standards can be met predominantly with lower

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The analysis concludes that minimal usage of ZEV technology will be needed in the national fleet to meet the GHG standards in model year 2025, with less than 5 percent of LDVs taking the form of a BEV or PHEV, as shown in Table 3 above. Given the ZEV market share in California was already at 3 percent in 2015, manufacturers seem adequately positioned to achieve this level of nationwide electrification in another 10 years especially with manufacturer product plans to more than triple the number of ZEV models available in the next five years and with battery costs declining faster and earlier than previously anticipated.

It is also encouraging to note that historically, manufacturers have frequently outpaced projections by the agencies in terms of increasing the capability of a technology to meet the requirements, using additional technologies unforeseen in the original projections, and doing so at lower costs than expected. The automotive market is extremely competitive and manufacturers and suppliers have significant expertise in developing and deploying innovative solutions to meet regulatory standards. The 2016 TAR recognizes this is already happening with technologies like Atkinson cycle engines, 48 Volt mild hybrids, and continuously variable transmissions now projected to have a larger role than what was imagined just four years ago.

Accordingly, this analysis confirms that the current national 2022 through 2025 model year GHG standards can be readily met at the same or lower cost than originally projected and manufacturers will likely continue to make progress towards even more cost-effective solutions.

**What is the status of the treatment in the federal program of upstream emissions due to electricity and hydrogen generation for use in vehicles?**

Board direction to staff included continuing to collaborate with U.S. EPA and NHTSA in the development and midterm evaluation of the national standards to minimize the chance for a reduction in GHG benefits from the different regulatory treatment of upstream emissions in the California and Federal programs. At the time of that direction, the California GHG standards included provisions to assign GHG emissions to alternative fuel vehicles like BEVs, PHEVs, and FCEVs to account for any incremental increase in GHG emissions needed to produce the electricity or hydrogen relative to producing gasoline. The federal GHG standards similarly accounted for upstream emissions but a provision was being considered at the time to temporarily waive that requirement and the Board expressed concern that such an action would result in a slight decrease in the cumulative GHG benefits. The final federal standards did ultimately include a temporary exemption from that provision for all BEVs, PHEVs, and FCEVs through the 2021 model year and a more limited exemption through the 2025 model year for a maximum number of vehicles per manufacturer.
Based on the latest projections, a few manufacturers would be expected to exceed the maximum vehicle limits and be required to start accounting for upstream emissions before the 2025 model year. Thus, ARB will continue to work with the federal agencies to track and address this policy issue.

Meanwhile, a number of programs both specific to California and nationwide have evolved that are relevant to the assessment of upstream emissions for electricity generation and hydrogen fuel production. These include California’s Low Carbon Fuel Standard (LCFS), which requires a carbon intensity reduction in gasoline and diesel (which can be partly met with alternative fuel credits), and Renewables Portfolio Standard (RPS) which requires a renewable supply for electricity. Both of these rules directionally require reductions in GHG emissions associated with the production of vehicle fuels including electricity and hydrogen. Federally, the Clean Power Plan (CPP) adopted in 2015 could result in substantial reductions in GHG emissions from electricity generation nationwide yet there is significant uncertainty regarding the future of CPP given the current legal challenges. California, however, continues to vigorously defend the CPP and will continue to press U.S. EPA to fulfill its duties to control stationary source GHG emissions. Given these clean fuel programs have progressed beyond what ARB assumed in the 2012 rulemaking, it appears that upstream emissions for PHEVs, BEVs and FCEVs are being addressed.

Have consumer purchasing trends and California’s fleet mix shifted in vehicle footprint to larger and higher polluting vehicles or resulted in the reclassification of cars as trucks that would deviate from the projected fleet in staff’s original 2012 analysis?

The final question that the Board wished to examine concerning the LEV III GHG regulations was the question of a shift in California’s fleet mix to larger vehicles and the reclassification of cars as trucks that deviates from what was projected in the original rule and the impact on the expected benefits of these regulations. As discussed in the 2016 TAR, the current and projected future mix of new vehicle sales has shifted to more trucks and fewer cars than was originally projected in 2012 for the nationwide fleet. However, in terms of the California fleet, as discussed in Appendix M, the trends are similar but the overall result is different because of a larger fraction of car sales in California’s market.

With respect to footprint, the California and national fleets are showing a very slight increase in the sales weighted footprint of the combined fleet. However, it is not yet clear if the construct of the GHG standards are the determining factor influencing this trend. In its Trends Report, U.S. EPA looked at the average footprint for new cars and trucks sold nationwide for the 2008 through 2015 model years. That analysis, summarized in Table 6 below, shows the average footprint of a new car has increased by 0.8 square feet (approximately 1.8 percent) and the average footprint of a new truck has increased by 1.5 square feet (approximately 2.8 percent) within this time period.

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24 EPA 2015b
Table 6 - Average New Car and Truck Footprint for model years 2008 through 2015

<table>
<thead>
<tr>
<th>Model Year</th>
<th>Car Footprint (square feet)</th>
<th>Truck Footprint (square feet)</th>
</tr>
</thead>
<tbody>
<tr>
<td>2008</td>
<td>45.3</td>
<td>54.0</td>
</tr>
<tr>
<td>2009</td>
<td>45.1</td>
<td>54.0</td>
</tr>
<tr>
<td>2010</td>
<td>45.4</td>
<td>53.8</td>
</tr>
<tr>
<td>2011</td>
<td>46.0</td>
<td>54.4</td>
</tr>
<tr>
<td>2012</td>
<td>45.7</td>
<td>54.5</td>
</tr>
<tr>
<td>2013</td>
<td>45.9</td>
<td>54.7</td>
</tr>
<tr>
<td>2014</td>
<td>46.1</td>
<td>55.0</td>
</tr>
<tr>
<td>2015 (preliminary)</td>
<td>46.1</td>
<td>55.5</td>
</tr>
</tbody>
</table>


When combined with the increasing share of the market from truck sales, the slight increase in average footprint does result in an overall increased nationwide car/truck fleet average relative to what was originally projected. The largest influence appears to be a higher share of truck sales that generally have a larger footprint than cars rather than a significant increase in the average footprint within the car or truck segment itself. However, given the substantial lead time necessary to redesign base vehicle platforms including parameters that determine the footprint, it is probably too early to determine the impact of standards adopted only four years ago. Accordingly, the agencies will continue to monitor trends in the national and California-specific fleet and should there be an indication that the footprint based structure of the regulation is resulting in a loss of GHG reductions, ARB can consider options to fill the shortfall in future rulemakings.

On the question of reclassification of cars as trucks, there has been an increase in the share of trucks in new vehicle sales and the 2015 AEO projections noted earlier also predict a larger share of trucks in 2025 than originally projected. However, a shift to more trucks is not necessarily an indication of manufacturers making changes to reclassify vehicles that were formerly considered cars. U.S. EPA looked at national trends associated with the classification of small sport utility vehicles or SUVs (inertia weights of 4,000 pounds or less) as either cars or trucks between model years 2000 and 2015. SUVs of this size are classified as cars if they have 2-wheel drive and as trucks if they have 4-wheel drive and meet other design criteria. Based on the trends shown in Figure 2, it does not appear that a reclassification of small SUVs from cars to trucks is occurring at this time.
Observations to date largely confirm a change in consumer preference from sedans to crossover and small utility vehicles that are not related to a reclassification of an existing model from a car to a truck. For example, Toyota has indicated the RAV4 SUV is poised to displace the Camry sedan as the company’s top selling model in the U.S. resulting in increased truck sales not because Toyota is reclassifying a vehicle from a car to a truck but because consumers are choosing to buy a different vehicle. However, as noted with respect to vehicle footprint, it has only been four years since the GHG standards were adopted and vehicle redesigns that would be necessary to change a vehicle’s classification from car to truck can require significant lead time.

In the California fleet, preliminary data for the 2012 through 2014 model years are generally consistent with the trends observed nationwide although California has a significantly higher share of car sales than the nationwide fleet and the California vehicle footprints are slightly different for both the car and truck fleets. Similar to nationwide, the California car/truck mix is shifting towards higher truck sales but, unlike the national fleet where cars and trucks are expected to be about equal shares by 2025 in the 2015 AEO projections, cars are still expected to remain the larger share of the California fleet in 2025. Staff expects that further changes to car/truck sales mix and average footprint in the California fleet will likely be similar to trends happening nationwide as projected by the more recent 2016 AEO and has developed its
analysis by applying the same growth trends in the nationwide 2016 AEO to the California-specific fleet. The reader can refer to Appendix M for further details.

When considered in total, the newer and more accurate information regarding footprint and car/truck share in the California fleet does result in a different projection of GHG benefits than originally projected for ARB’s 2012 rulemaking. The original California projection included a conservative assumption that cars represented only 63 percent of the California market and that this fraction would essentially remain unchanged through model year 2025. For footprint, the original assumption was a constant 45.1 and 52.3 square feet for cars and trucks, respectively through 2025 model year. These assumptions resulted in a projected combined new car/truck fleet average of 166 grams per mile (g/mi) CO₂ in the 2025 model year in California. From actual sales data, it is now known that cars represented approximately 73 percent of the California fleet in 2012 and, despite a shift to more trucks since then, the car sales share is still above 69 percent today. It is also known that the actual footprint was about 1 percent higher and the truck footprint was about 5 percent higher than originally estimated.

The higher fraction of car sales results in lower (more stringent) emission targets for those years relative to the original assumptions, but the larger footprints mostly offset those reductions such that the overall emission targets remained essentially the same as the original 2012 projections for the 2012 through 2015 timeframe. Beyond the 2015 timeframe, however, the new projections based on the 2016 AEO generally show increased reductions (more stringent target standards) than originally projected primarily because the car share remains higher than originally thought. Accordingly, the combined new car/truck fleet average in California for 2025 is now projected to be between 153 and 167 g/mi CO₂ when using the AEO scenarios and footprint growth sensitivities analyzed by staff including the AEO reference, high fuel price, and low fuel price scenarios as illustrated in Figure 3 below. Only in the sensitivity case using the AEO reference, coupled with a continued footprint growth, does the combined new car/truck fleet average exceed what was estimated in the 2012 ARB rulemaking (167 vs. the original 166 g/mi CO₂).

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26 2016 TAR utilized data from the 2015 AEO report as the 2016 AEO report wasn’t published until Sept 2016
Particulate Matter Emission Standard Review

What are the LEV III particulate matter emission standards?

PM emissions from light- and medium-duty vehicles are regulated as part of the LEV program. Under LEV III, the PM emission standard for passenger cars, light-duty trucks, and medium-duty passenger vehicles was lowered from 10 mg/mi to 3 mg/mi starting with 2017 model year vehicles. The 3 mg/mi PM standard is phased-in incrementally with full implementation by model year 2021. LEV III lowers the PM standard even further to 1 mg/mi starting with 2025 model year vehicles and also phases-in incrementally, with full implementation attained by model year 2028. In the long term, the 1 mg/mi PM standard will be an effective backstop to retain the progress in PM emission reductions achieved by today’s gasoline car fleet in California and further reduce the health impacts associated with exposure to PM emissions. It will also help ensure the continued development of low-PM engine technology.

Mitigation of the impact of PM emissions on public health is of paramount concern to ARB. Consequently the Board directed staff to explore the feasibility of implementing this standard earlier than the scheduled 2025 model year implementation. This required a re-evaluation of
both the emission measurement feasibility and the technological feasibility of the 1 mg/mi PM standard based on the best available information available today.

*What emission reductions are expected from implementation of the 1 mg/mi PM standard?*

The relationship between PM exposure and health effects is well documented in that increased exposure leads to cardiopulmonary disease and several other adverse health outcomes. In general, lower PM standards will help reduce ambient PM2.5 emissions levels statewide, in the San Joaquin Valley (SJV), and near busy roadways. The implementation of the adopted 1 mg/mi standard is projected to reduce PM in 2035 by 0.33 tons per day (TPD) statewide and by 0.03 TPD in the San Joaquin Valley.

The black carbon fraction of PM emissions is a recognized short lived climate pollutant with a strong global warming potential (GWP), between 900 and 3200 times more powerful than CO₂, making even small reductions in black carbon directionally beneficial to meeting California’s GHG reduction goals. The climate change benefit in 2035 from the black carbon reduction associated with the 1 mg/mi standard is 70,000 and 270,000 metric tons CO₂-equivalent annually for 100-year and 20-year GWP, respectively, which is small but appreciable.

*Is the gravimetric PM mass measurement method appropriate for the 1 mg/mi standard?*

In October 2015, staff presented a technical review of the feasibility of low PM mass emission measurement to the Board.27,28 This review was conducted by ARB researchers, in collaboration with U.S. EPA, industry, and other stakeholders and was based on extensive studies, testing, and laboratory evaluation of PM emissions at 1 mg/mi and below.

As a result of these studies, staff concluded that the existing gravimetric method prescribed for the Federal Test Procedure (FTP) driving cycle and specified in the 40 Code of Federal Regulations, Parts 1065 and 1066 in conjunction with appropriate laboratory practices is sufficient for precise measurement of PM emissions at and below 1 mg/mi. These studies also revealed that, at very low PM emission levels, the correlation of PM mass to various alternative measurement metrics such as solid particle number emissions or black carbon emissions varied for different test cycles and engine technologies resulting in a determination that these methods were not equivalent to the gravimetric method in determining PM mass but still yielded useful information in understanding vehicle PM emissions.

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28 ARB 2015a.
Is technology available today that enables manufacturers to meet a 1 mg/mi PM standard?

While the core necessary technologies exist today, this new assessment suggests that additional refinement prior to vehicle portfolio-wide deployment is needed to ensure a robust solution to meet the standard. Advanced GDI technology, the fuel injection technology preferred by auto manufactures for its GHG benefit, coupled with appropriate in-cylinder improvements such as software or engine hardware modifications can be used to meet the 1 mg/mi PM standard. In-cylinder improvements are primarily aimed at reducing or eliminating fuel impingement on combustion chamber surfaces and other localized rich combustion areas that lead to incomplete combustion and high PM emissions. If cases exist where in-cylinder control is not sufficient or the manufacturer prioritizes other design considerations, aftertreatment devices such as gasoline particulate filters (GPFs) represent a viable alternative to meet the 1 mg/mi emission limit. These compliance options are explained further below.

Manufacturers can use a variety of software improvements to control PM emissions including optimized injection timing, precise fuel metering, and multiple injections per combustion event. These strategies, combined with engine hardware improvements, help to reduce fuel impingement on combustion chamber surfaces, the major contributor to PM emissions. This is particularly critical during cold start operation when the combustion chamber surfaces are cold and PM emissions are at their highest.

Improvements to engine hardware include improvements to the fuel injection system, combustion chamber design, and thermal management. Fuel injection system improvements include injector designs with shaped spray patterns to minimize or eliminate fuel impingement on combustion chamber surfaces, increased fuel system pressures to reduce fuel droplet size and improve atomization, and improved injector tip design to reduce coking, which can lead to increased PM formation as the system ages. Improvements to the combustion chamber and intake port designs include changes to the shape of the piston top to reduce fuel impingement, thermal management of the injector tip and piston top to facilitate rapid evaporation of liquid fuel, and intake port design to increase tumble and reduce wall wetting while improving the air/fuel mixture. Many of these changes require extensive engine hardware re-design.

Manufacturers can also employ aftertreatment changes to reduce PM emissions. Cold-start catalyst light-off strategies to rapidly heat up the catalyst and catalyst design can indirectly reduce PM emissions. Changes to the catalyst layout including the use of a more closely coupled catalyst to the exhaust manifold can reduce catalyst light-off time thereby limiting the duration of a catalyst light-off combustion strategy that temporarily increases engine-out PM emissions. PM emissions can also be directly controlled with a GPF. GPFs are placed in the exhaust to trap PM emitted by the engine regardless of vehicle operational mode. The GPF can be integrated into the existing emission control configuration as a catalyzed substrate that replaces a portion of the three-way catalyst system or as a separate non-catalyzed device that
is added downstream from the existing catalyst(s). GPFs have been reported to have low backpressures such that the adverse effect on GHG emissions is insignificant or minimal.²⁹ While the costs of adding a GPF may be higher than in-cylinder PM control solutions that can be incorporated during a scheduled re-design, they provide manufacturers with a robust alternative strategy for reducing PM emissions.

**Are vehicles capable of meeting the 2025 model year 1 mg/mi PM emission standard while complying with the stringent GHG and NMOG+NOx tailpipe standards?**

Effective PM emission control balances GHG, hydrocarbon (HC), and NOx emissions against PM reductions. This is particularly critical during cold-start emissions when up to 90 percent of criteria pollutant emissions occur. Some manufacturers have indicated that optimal fuel injection strategies for PM control during cold-start operation can significantly affect HC and NOx emissions. Accordingly, manufacturers must be careful when implementing new control strategies to maintain control of HC, NOx, and GHG emissions.

The test data and analysis presented in this report shows that vehicle manufacturers have achieved significant PM emission reductions over the last redesign cycle and are on track to meet the 1 mg/mi PM emission standard in the required timeframe even as they implement advanced technologies to reduce GHG, HC, and NOx emissions. A key aspect of this assessment is the ability of manufacturers to incorporate necessary in-cylinder ‘best-practices’ for PM control into scheduled engine updates or redesigns. As noted in Appendix K, recent testing of vehicles using engine technologies representative of likely future low GHG-emitting vehicles has shown considerable reductions in PM emissions in anticipation of the upcoming 3 mg/mi standard with most vehicles already emitting below 1.5 mg/mi. This is substantially lower than earlier generation GDI equipped engines and a direct result of the recent redesigns that most of the tested engines have had in anticipation of upcoming PM emission standards. As noted earlier, the ACC program was designed to ensure that manufacturers fully considered criteria pollutant requirements (including PM emissions) in concert with the increasingly stringent GHG standards as they developed GHG technologies for future vehicles but also factored in engineering and laboratory resource constraints that manufacturers face. These considerations resulted in the longer lead time provided for the phase-in of the 1 mg/mi PM emission standard.

**What are the results from ARB’s PM test program?**

ARB staff procured and tested commercially available vehicles that use low-GHG internal combustion engine technologies that are projected to be commonly used on light-duty vehicles between model years 2022 and 2025. These vehicles are described in Appendix K. Given the

https://www.arb.ca.gov/msprog/consumer_info/advanced_clean_cars/gasoline_direct_injection_particulate_control_e xperience_with_gasoline%20_particulate_filters_for_gasoline_vehicles_rasto_brezny.pdf
scheduled PM standard phase-in, none of the test vehicles were designed to meet the 1 mg/mi standard and none of the GDI equipped vehicles were yet certified to the 3 mg/mi standard (although the results indicate several were likely designed knowing that certification with the 3 mg/mi standard would be required in the next few years). The test program found that, although some vehicles emitted below the 1 mg/mi standard, the majority did not meet the standard with an adequate margin of compliance to account for variability and emission increases that can occur over the full useful life of a vehicle. The low-GHG internal combustion engine technologies that were tested mostly rely on in-cylinder controls that are likely solutions for compliance with the 3 mg/mi PM standard. Among the vehicles ARB tested to evaluate PM emissions include several that meet the stringent LEV II SULEV standards. These results show the potential of vehicles to simultaneously meet the future GHG and low criteria pollutant emission standards including PM standards.

According to staff’s analysis presented in Appendix J, there is still opportunity for further improvement of PM control relative to current GDI vehicles. Many of the vehicles ARB tested, presented in Appendix K, emit at levels that would readily comply with the 3 mg/mi PM emission standard with emissions from 1.2 – 1.4 mg/mi on the FTP cycle. This is consistent with manufacturers’ assertions that because of variability, uncertainty, and durability requirements for the full vehicle useful life of 150,000 miles, the target emission rate is about half the standard for vehicles certified to the 3 mg/mi PM standard. The data also indicate that controlling PM emissions to meet the 3 mg/mi standard does not necessarily lead to emission rates below 1 mg/mi and, for most vehicles, further work will be necessary to ensure compliance with a 1 mg/mi standard. Given the progress already seen with lower PM levels in anticipation of the 3 mg/mi standard, manufacturers should have sufficient time to incorporate further improvements in fuel system and engine design, controls, and calibration to reduce PM levels below the 1 mg/mi standard.

However, the test results shown in Table 7 below also revealed that some vehicles that exhibit good control of PM emissions on the FTP cycle have notably higher emissions on the US06 cycle, which is representative of high speed and acceleration driving conditions. As indicated by these test results, low FTP PM emissions do not necessarily correspond with low US06 emissions. This is of concern because the FTP and US06 standards are used by ARB to ensure robust in-use emission control over the spectrum of typical real-world driving conditions. Under the LEV III regulations, the FTP PM emission standard drops to 1 mg/mi in 2025, but the US06 standard remains at 6 mg/mi indefinitely. The test program results confirm that the current US06 standard may not ensure a sufficient level of emission control. Further, high emissions during the US06 cycle may relate to higher near-roadway emission levels and subsequent exposures, which can have a disproportionate impact on low income and sensitive populations who may reside, work, or spend significant time near busy roadways.
Staff also tested prototype gasoline particulate filters (GPFs) for controlling PM emissions on two newer GDI engines that had gone through a partial redesign cycle, but would not yet readily meet the 3 mg/mile standard. The emission reductions from GPF testing are shown in Table 8. On the FTP, an 88% reduction was observed for both vehicles and brought emissions to a level below 1 mg/mi. The effectiveness of the GPFs on the US06 was somewhat lower, reducing PM emissions by 72% and 54% respectively for the F-150 and Malibu. The results from both vehicles show that GPFs are an effective control technology to meet future 1 mg/mi PM standards, even for particularly challenging engines.
Should the 1 mg/mi PM emission standard be phased-in earlier based on the new analysis?

As discussed earlier, given manufacturers’ progress to date it is reasonable to expect that with a similar effort over the next design cycle(s), all future vehicles will be able to meet the 1 mg/mi FTP standards as projected in the 2012 LEV III ISOR.\textsuperscript{30} However, accelerating implementation of the 1 mg/mi PM standard would jeopardize the ability of the manufacturers to incorporate the next round of necessary PM refinements across their entire vehicle offerings and within scheduled engine design updates. Less time to engineer and innovate robust solutions would reduce the ability of manufacturers to validate their current round of PM improvements and determine if these improvements are sufficiently durable to ensure low emissions throughout the 150,000 mile useful life of LEV III vehicle standards.

While there are other technologies that are near production ready such as even more advanced injection control systems or GPFs that could be used prior to model year 2025 to meet the 1 mg/mi standard, such technologies would likely result in an increased cost to comply than originally projected and divert testing and development resources from manufacturers that are focused on achieving other required reductions in the same timeframe. Further, these new technologies are still evolving and additional time is needed to ensure they are ready for wide-scale deployment, have sufficient durability, and the implications of their use relative to other emission requirements such as on-board diagnostic systems is understood.

Because of the necessary time to incorporate robust solutions to further reduce PM, implementing the 1 mg/mi PM standards substantially sooner than model year 2025 would likely entail increased costs to manufacturers (through unscheduled redesigns or increased reliance on GPFs) and have limited additional emission benefit. For ambient air quality, the projected incremental PM benefit associated with earlier implementation of the 1 mg/mi standard would be 0.06 TPD statewide and 0.007 TPD in the SJV in 2035. Accordingly, staff is not recommending pursuit of a regulatory action at this time to require earlier implementation of the 1 mg/mi PM emission standard.

What is staff’s recommendation with respect to PM standards?

Staff’s updated analysis has confirmed that compliance with the 1 mg/mi FTP standard by 2025 is feasible and manufacturers are on track to meet the standard. And, as noted above, staff is not recommending earlier implementation of the 1 mg/mi standard. However, the same research and testing in support of this midterm review has revealed concerns regarding the robustness of PM control under broader in-use driving conditions than the FTP represents.

https://www.arb.ca.gov/regact/2012/leviilighg2012/levisor.pdf

ES-33
Accordingly, staff recommends pursuing a new regulatory update to ensure that, when the 1 mg/mi standard is phased-in, it results in robust PM control over the broad spectrum of driving conditions encountered in-use. Thus, staff recommends that the Board direct staff to: (a) pursue an increase in stringency of the US06 PM standard to ensure a similar level of PM emission control in conjunction with the 1 mg/mi FTP standard; and (b) to investigate adoption of additional standards and procedures applicable to other test cycles and ambient conditions that will ensure more comprehensive control of PM emissions under all operating conditions. These actions will also ensure that any future PM standards achieve meaningful and sustained in-use reductions.

ZEV Review

Are ZEVs and PHEVs still necessary for meeting California’s long term air quality and GHG goals?

The LDV sector accounts for nearly 30 percent of the state’s GHG emissions, making further reductions necessary in order to meet significant 2020, 2030, and 2050 GHG emission reduction targets in the future. In 2009, staff’s modeling found “… [pure] ZEVs will need to reach 100 percent of new vehicle sales between 2040 and 2050, with commercial markets for ZEVs launching in the 2015 to 2020 timeframe.” More recently, the ARB Mobile Sources Strategy report, released in May 2016, confirmed the essential role electrification will need to play in the LDV sector to meet California’s long term emission reduction goals. The updated VISION scenarios in the Mobile Source Strategy show that PHEVs can remain a permanent fraction of the market, providing more flexibility for manufacturers. However, as shown in Figure 4 the combined sales of pure ZEVs and PHEVs for light-duty vehicles will still need to achieve 100 percent by 2050. A recent American Lung Association analysis confirms the importance of a long-term, full electric transformation to reduce health based and social costs. The study estimates health based impacts in 2015 from passenger vehicles in California and the Section 177 ZEV states to be $24 billion, but that the cost could decline to $3 billion by 2050 under a scenario where sales of ZEVs and PHEVs reach 100 percent by 2050.

Do PHEVs provide equal or greater environmental benefit than BEVs?

Since 2014, manufacturers have used data from the U.S. Department of Energy (U.S. DOE) EV Project to support a position that PHEVs with substantial electric range could provide greater or equal environmental benefit than BEVs. This assertion along with the Board’s direction in 2012 led staff to assess how PHEVs are being used (in comparison to BEVs) and their overall emission impact.

A significant portion of PHEV miles can be attributed to grid powered energy (typically called a vehicle’s electric vehicle miles travelled or eVMT). This correlates well with the PHEV’s GHG emission benefit. However, eVMT does not provide a complete picture of how “ZEV-like” a PHEV is. One intrinsic benefit of a ZEV is its criteria pollutants emission reduction; zero engine starts mean ZEVs are an ideal solution to reducing criteria pollutant emissions. In this regard, staff analyzed two metrics to evaluate a PHEV’s criteria pollutant benefit using data provided by manufacturers: electric only trips (e-trips) and zero-emission vehicle miles traveled (zVMT). e-Trips are trips when the vehicle’s engine is not used at all (thus, an avoided engine start), whereas zVMT is the sum of miles from all e-Trips. Table 9, shown below is a summary of staff’s analyses; further details can be found in Appendix G.

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### Table 9 - Summary of eVMT and zVMT

<table>
<thead>
<tr>
<th>Type of Vehicle</th>
<th>VMT – Annual Miles</th>
<th>eVMT – Annual Miles (% of VMT)</th>
<th>zVMT - Annual Miles (% of VMT)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Toyota Prius (PHEV)</td>
<td>15,283</td>
<td>2,304 (15%)</td>
<td>589 (4%)</td>
</tr>
<tr>
<td>Honda Accord (PHEV)</td>
<td>15,221</td>
<td>3,246 (21%)</td>
<td>1,471 (10%)</td>
</tr>
<tr>
<td>Ford C-Max Energi (PHEV)</td>
<td>13,920</td>
<td>4,574 (33%)</td>
<td>2,525 (18%)</td>
</tr>
<tr>
<td>Ford Fusion Energi (PHEV)</td>
<td>15,076</td>
<td>4,776 (32%)</td>
<td>2,368 (16%)</td>
</tr>
<tr>
<td>Chevrolet Volt (PHEV)</td>
<td>12,403</td>
<td>8,924 (72%)</td>
<td>7,313 (59%)</td>
</tr>
<tr>
<td>BMW i3 (BEVx)</td>
<td>9,063</td>
<td>8,387 (93%)</td>
<td>N/A</td>
</tr>
<tr>
<td>BMW i3 (BEV)</td>
<td>7,916</td>
<td>7,916 (100%)</td>
<td>7,916 (100%)</td>
</tr>
<tr>
<td>Ford Focus Electric (BEV)</td>
<td>9,741</td>
<td>9,741 (100%)</td>
<td>9,741 (100%)</td>
</tr>
<tr>
<td>Honda Fit (BEV)</td>
<td>9,789</td>
<td>9,789 (100%)</td>
<td>9,789 (100%)</td>
</tr>
<tr>
<td>Nissan Leaf (BEV)</td>
<td>10,294</td>
<td>10,294 (100%)</td>
<td>10,294 (100%)</td>
</tr>
<tr>
<td>Tesla Model S (BEV)</td>
<td>13,494</td>
<td>13,494 (100%)</td>
<td>13,494 (100%)</td>
</tr>
</tbody>
</table>

Each average presented in Table 9 represents a set of drivers in a given time.\(^34\) However, driving data from the same vehicle model can vary widely dependent on when and under what driving conditions the data were collected. As an example, this can be seen when looking at data from the Chevrolet Volt. According to data from U.S. DOE’s EV Project, total Volt VMT is \(~12,400\) miles on average. Approximately 72% of these miles are driven electrically, and are referred to as the vehicle’s eVMT fraction. However, according to a 2016 General Motors press release based on a larger data sample of Volt drivers, Volts drive only 60% of their miles on grid-powered energy.\(^35\) This difference could be due to the fact that EV Project participants

\(^34\) Each manufacturer provided data set is fully described in Appendix G, Section II.  
were a limited set of very early adopters and were given no-cost Level 2 charging equipment for home installation.\textsuperscript{36}

Table 9 shows average eVMT and zVMT for each PEV analyzed in staff’s analysis. Averages, however, do not fully capture the model’s potential environmental benefit or impact. These factors (both eVMT and zVMT) are highly driver dependent and based on daily trip distance, daily trip count, and electric charging accessibility and region, just like all VMT for conventional or advanced technology cars. Shown below in Figure 5 and Figure 6, vehicles with similar electric ranges have varied eVMT and zVMT. Even among the BEVs with a 100 to 120 mile urban dynamometer drive schedule (UDDS) electric range, there is significant variance in total VMT, while Tesla’s Model S with well over 200 miles of range shows an even wider array of VMT across its single platform.

\begin{figure}[h]
\centering
\includegraphics[width=\textwidth]{figure5.png}
\caption{eVMT variation across PEVs}
\end{figure}

\textsuperscript{36} For a complete description of U.S. DOE of Energy EV Project and staff’s full analysis, see Appendix G.
Looking further into PHEVs criteria pollutant emission impacts, staff evaluated the cold start emissions of three blended PHEVs believed to be representative of currently available PHEVs and the results are presented in Appendix H.

For blended PHEVs, both grid energy and the internal combustion engine (ICE) can be used simultaneously to power the vehicle during charge-depleting (CD) operation. Generally this occurs when the vehicle power demand is higher than what the electric only propulsion system can provide and the vehicle starts the engine to combine the electric and ICE power to meet the vehicle demand. As a result, blended PHEV CD operation introduces a unique driving condition where the initial engine start of a trip occurs at a time where there is an immediate need for the engine to provide significant power and torque to help propel the vehicle. Such starts, referred to here as “high-power” cold-starts, can have different emission characteristics relative to the initial engine start of a conventional vehicle which typically occurs with the vehicle stopped, in park/neutral, and with a very low immediate torque demand. Figure 7 below shows a drive near ARB’s Haagen-Smit Laboratory where a blended PHEV was operated through various roadway conditions to understand the types of conditions that cause these high-power engine starts before the battery has been fully depleted.
The testing confirms that cold-start emissions can be significantly higher under high-power demand conditions relative to more traditional engine start conditions.\textsuperscript{37} Staff will conduct further testing and has begun discussions with the vehicle manufacturers to discuss emission control strategies and alternatives that may provide for more robust emission control in these conditions. It is also important to note that all of the vehicles tested are first generation PHEVs and most manufacturers are expected to introduce more capable second generation PHEVs in the near future. To the extent future blended PHEVs have stronger electric propulsion systems and longer electric range, those vehicles should be able to reduce the frequency of trips with an engine start including those with a high-power engine start. As one example, the Prius Prime is Toyota’s second generation PHEV and is designed to primarily operate as a non-blended PHEV, thereby potentially eliminating most high-power engine starts. However, as more manufacturers enter the PHEV market and PHEVs are introduced on larger and heavier vehicle platforms, blended PHEVs will likely continue to play a significant role and warrant continued evaluation to ensure in-use start emissions are controlled as robustly as possible.

Based on in-use data from PHEVs, emission testing, and analysis of electric use conducted by ARB, PHEVs can generate significant benefits over conventional vehicles but do not generally result in GHG or criteria pollutant emission reductions equal to pure ZEVs.

\textit{Could California meet its long term goals predominantly with PHEVs?}

ARB’s latest long-term scenario released in the Mobile Source Strategy (called the Cleaner Technologies and Fuels, or CTF, scenario) showed PHEVs could be a significant share of the

\textsuperscript{37} Appendix H describes staff’s in-house PHEV testing.
fleet (see Figure 4 above), and the light-duty vehicle sector would still be on track to meeting its share of emission reductions for the 2030 and 2050 GHG goals. This is due in part to aggressive assumptions in the vehicle sector including PHEVs achieving higher proportions of their miles on electricity, all gasoline vehicles having significant gains in fuel efficiency over time, increases in renewable energy usage, and slower growth in vehicle miles traveled (VMT) from all passenger vehicles. Allowing PHEVs to have a larger role in the future fleet helps to provide additional technology pathways toward meeting California’s long term goals. However, as explained in staff’s analysis of manufacturer-provided data and in-house testing, emission benefits from PHEVs are not only affected by vehicle range and architecture but are highly driver dependent, leading to significant uncertainty in future projections.

In order to assess the potential impacts of changes in PHEV parameters and higher PHEV sales fractions, staff developed several PHEV-focused VISION scenarios to assess how the presence of PHEVs in the LDV fleet may affect California’s ability to meet its statewide GHG and criteria pollutant emission targets in the future. When using the CTF scenario PHEV sales trajectories, higher and lower eVMT growth rates show a modest sensitivity of less than ±7.5 percent change in projected GHG emissions by 2050. When combined with higher PHEV sales trajectory, however, the projected impact from the eVMT sensitivity ranged from a 16 percent to 60 percent increase in GHG emissions showing a much greater sensitivity to how the PHEVs are used in the fleet. Similar trends are found for criteria pollutants, further explored in Appendix F.

This suggests that, though PHEVs can be a significant share of the future fleet, there are limitations that make it necessary to still pursue substantial BEV and FCEV volumes and that there is additional risk associated with PHEVs dependent on user behavior due to their flexible nature.
**How has ZEV technology progressed since 2012?**

Technology has progressed faster than staff anticipated during the development of the 2012 rulemaking. Manufacturers are announcing longer range, more capable BEVs and PHEVs on widely diverse platforms, and within segments with high overall sales (i.e., cross-overs, mid-size cars). The most expensive components are also developing quickly and improving in most ways: they are safer, cheaper, and more energy dense resulting in higher energy content battery packs. This has led to the announcement of 80 ZEV and PHEV offerings over the next five model years, shown below.

![Figure 9 - Expected ZEV and PHEV models by model year](image)

**BEVs and PHEVs**

In 2012, BEVs were expected to be primarily small vehicles, with no more than 100 miles test range capability. Given the Tesla Model S, even at the $66,000 or higher price point, is the highest selling ZEV (or PHEV) in 2016 MY thus far and is a full size sedan with a real-world range of over 200 miles, manufacturers are quickly responding to the demands in the market. Most notably, lower priced longer range BEVs reached dealer lots within weeks of this report’s release.38 These range improvements at lower prices come from various improvements, but predominantly from reduced battery costs and improved battery technology. Battery technology development is achieving higher energy density resulting in longer range from the same physical size battery pack.

In addition to improvements in the battery, manufacturers are announcing BEVs that will be equipped with higher powered fast charging39. This will help lessen charge times for the expected longer range BEVs. Additionally, the emerging car and ride sharing market, and

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development in connected and autonomous vehicles (CAV), provide a nexus with PEVs in future years as a way to reduce emissions.40

**FCEVs**

Since the 2012 ACC rulemaking, Hyundai introduced the Tucson FCEV, the first mass-produced FCEV made available for retail lease in California. Toyota followed with the purpose built Mirai, which is offered for lease or sale to consumers. Additionally, Honda has released the Clarity for lease.41 It is expected that two more manufacturers will release purpose built FCEVs over the next three model years.42,43 While current costs remain high, projections based on U.S. DOE cost modeling for FCEVs indicate future reductions. At annual production volumes of 100,000 FCEVs (as are expected with further roll out of hydrogen infrastructure throughout California), the fuel cell system could be near $6,000 for a 100 kW stack and balance of plant similar to those that have been incorporated into the sedans and crossover utility vehicles currently on the market.44 This marks the potential for roughly a 50 percent reduction in cost from today, based solely on economies of scale. Further cost reductions are expected due to technology development by the time annual production rates reach 100,000 FCEVs per year.

**Electric Motors and Power Electronics**

Applicable for all three of the technologies discussed above, manufacturers are looking ahead to improved electric motors and power electronics and reduced costs in attempts to meet the U.S. Drive targets. Manufacturers are bringing motor costs down by decreasing the total amount of rare earth metals used. General Motors, Honda, and BMW have all found ways to decrease rare earth metal usage in current products. In the case of General Motors, with the second generation Volt, rare earth metals were completely removed from one of their motor/generators in the powertrain system while still making the total powertrain more efficient and powerful for the customer.45

Manufacturers are also finding ways to better package power electronics to reduce part counts and complexity, and increase power density. On board chargers are increasing in total power capability and efficiency. Wide bandgap materials, like silicon carbide are currently being tested and developed by companies like Toyota with their hybrid Camry test fleet. Those materials will

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44 EPA 2016

enable even smaller, more efficient, and more power dense electronics on vehicles with lower cooling loads that will enable lower costs and longer ranges.\textsuperscript{46}

**Incremental Costs**

Battery costs have come down from what was assumed in the 2010 TAR and 2012 rulemaking. Comparing the 2010 TAR with the 2016 TAR assumptions, battery costs have been reduced between 20-35% depending on the application and size of battery pack, which can be seen comparing the 2011 BEV100 to the 2016 BEV75 in Table 10 below. However, staff is now expecting to see longer range BEVs on the road in future model years. This means that, compared to the 2012 ARB rulemaking which assumed a 100 mile electric range BEV (BEV100), incremental costs are slightly higher than would have been expected for high volume, fully learned out costs in MY2025 due to the expected increase in on board energy storage requirements (BEV200). Table 10 below compares the previous (2011) cost estimates to the updated 2016 TAR cost estimates.

**Table 10 - Incremental Costs (2025 ZEV compared to 2016 ICE vehicle, 2013\$)**

<table>
<thead>
<tr>
<th>2013 $</th>
<th>2011 ISOR (ACC Rulemaking)</th>
<th>2016 TAR (EPA, NHTSA, ARB) **</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>BEV100</td>
<td>PHEV40</td>
</tr>
<tr>
<td>Subcompact</td>
<td>$11,804</td>
<td>$11,182</td>
</tr>
<tr>
<td>MdC / SmMPV</td>
<td>$12,591</td>
<td>$12,037</td>
</tr>
<tr>
<td>Large Car</td>
<td>$14,566</td>
<td>$15,685</td>
</tr>
</tbody>
</table>

* ISOR Table 5.4 adjusted to 2013\$ with 1.09 CPI factor\textsuperscript{47}

** EPA OMEGA EV based on "label" range, ARB is UDDS. "Diff" = EPA BEV75 to ARB BEV100

Label vs. Test adjustment: 0.70

*** 15% weight reduction package

How has the overall ZEV and PHEV market developed in California and the Section 177 ZEV states since 2012?

Beginning in 2010, there was only one regulated manufacturer with a single product on the market: the Chevrolet Volt.\textsuperscript{48} Since that time, the market has grown to a total of 25 models offered by 14 manufacturers. With the exception of the GM “TBD” FCEV and the Mitsubishi Outlander PHEV\textsuperscript{49}, every model shown in the 2011 ZEV ISOR (released in preparation for the ACC rulemaking) has been released in the U.S. market. Seven additional models were released that were not anticipated prior to the 2012 ACC rulemaking.


\textsuperscript{48} The Tesla Roadster was available in very limited quantities. In 2010, Tesla was not regulated under the ZEV regulation.

\textsuperscript{49} The Mitsubishi Outlander is currently available outside of the U.S. but expected to launch in the U.S. in 2017.
California accounts for approximately 48 percent of cumulative ZEV and PHEV sales in the U.S. from 2011 to June 2016, with approximately 50 percent of total U.S. BEV sales and 47 percent of total U.S. PHEV sales. While the absolute number of ZEV and PHEV sales grew by approximately 5.2 percent from 2014 to 2015, the overall market share has remained at approximately 3 percent of statewide LDV sales for 2015 and the first half of 2016.

The Section 177 ZEV States have accounted for approximately 10 percent of cumulative ZEV and PHEV sales in the U.S. from 2011 to June 2016, 11 percent of cumulative U.S. ZEV sales and 18 percent of cumulative PHEV sales. Sales of ZEVs and PHEVs in the Section 177 ZEV states grew rapidly in the first three years, but remained flat at approximately 0.5 percent of total LDV vehicle sales from calendar year 2013 through 2015. During that same time period, ZEV sales increased slightly to 0.2 percent of Section 177 ZEV state LDV sales. By contrast, PHEV sales, which started around 0.3 percent in 2013, fell to around 0.2 percent of Section 177 ZEV state LDV sales in 2015. Despite these past trends, sales of ZEVs and PHEVs are up to 0.6 percent in the Section 177 ZEV states for the first half of 2016, the highest level ever.50

ZEV infrastructure in California and Section 177 ZEV states has grown with substantial investments in the past several years, and accelerated investments are expected as new infrastructure efforts emerge. Over 17,000 Level 2 and 2,100 direct current fast charger (DCFC) connectors have been deployed across California and the nine Section 177 ZEV states.51 Section 177 ZEV state infrastructure has outpaced vehicle deployment, with a higher connector per vehicle ratio than that found in California (refer to Appendix D for details). PEV infrastructure will continue to proliferate due to coordinated efforts through the ZEV Multi-State Task Force in the Section 177 ZEV states, and through California’s Public Utility Commission (CPUC) implementation of Senate Bill (SB) 350 (Statutes 2015, 44258.5 section, De Leon author). California’s current programs (most prominently legislation such as Assembly Bill 8, Statutes 2011, Section 41081, Perea author)) are enabling growth of the first major FCEV and hydrogen fueling markets in the U.S. Major policy and technical hurdles have been overcome in recent decades thanks to the coordinated efforts of State and industry partners. This substantial progress addresses issues of launching a new technology market. At the same time, stakeholders are also keenly aware of, and are addressing, new challenges in order to move FCEVs and hydrogen fueling into the mass-market.

Where does California and Section 177 ZEV states fit into a growing global ZEV market?

The global PEV market has increased steadily since 2011, reaching over 500,000 annual units in 2015, with many nations proposing increased regulatory pressure to reduce carbon emissions from vehicles. It is expected that the total global PEV market will surpass a cumulative 2 million

50 These sales data were calculated using “Dashboard Data”, fully described in Appendix B, Section VII
51 AFDC 2017. U.S. DOE Alternative Fuels Data Center, data as of 01/10/ 2017
http://www.afdc.energy.gov/fuels/electricity.html
vehicles by the end of this year (2016). However, as shown in Figure 10 this growth recently has been concentrated in regions outside of the U.S., though cost reductions from economies of scales occur regardless of location. In 2015, China had the highest PEV sales followed closely by Western Europe; California with the Section 177 ZEV states most recently ranks as the third largest PEV market, surpassing the volumes in Japan and Canada combined.

**Figure 10 - Global PEV Sales (2011 to 2015 calendar year)**

![Global PEV Sales Chart]

Why have sales in the U.S. stagnated in recent model years?

Fleet transformation to PHEVs and pure ZEVs requires not only auto manufacturers to develop and produce such vehicles, but also consumers to demand and ultimately purchase these products. Demand will be dependent on consumer awareness of the vehicles being offered as well as their characteristics – most notably vehicle price, available incentives, driving range, and infrastructure available for recharging/refueling – and how consumers value these attributes. In order for a consumer to purchase or lease a ZEV, they must first be aware that these vehicles are available in the market today. However, the results of independent studies all reveal a low level of ZEV awareness and confusion in California and the rest of the U.S. among the different ZEV technologies. In a 2016 UC Davis survey of new car buyers, over 34 percent of respondents across the U.S. could not name a single BEV available in the market. Similarly,

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54 Kurani 2016.
fewer than half of those polled in 2015 for an NREL study could name a PEV.\textsuperscript{55} Looking at other factors, according to Californians surveyed, PHEV and BEV<200 consumers (BEVs with less than 200 mile range) seem dissatisfied with the electric range of their vehicle. The most common changes PHEV and BEV<200 owners would make to their vehicles is to increase the electric range for a higher price (48 percent and 57 percent) and to give up performance (power/acceleration) for higher electric range (25 percent and 33 percent).\textsuperscript{56}

Additional factors, such as dealership availability and readiness or product diversity may also influence the rate at which market shares may grow. Although consumer choices for PHEVs and ZEVs are steadily increasing, they are still far outnumbered by a wide array of conventional technologies that may offer additional appealing characteristics such as lower prices, greater vehicle range, increased cargo and/or passenger capacity, and more attractive vehicle styling. Even for existing BEV drivers of all battery sizes, vehicle range ranked as their top concern during the shopping process, followed by vehicle price or availability of public charging infrastructure. While incentives and other policies may help consumers to overcome some of these concerns, others require further technological advances to satisfy customer requirements within acceptable price points.

However, eliminating barriers is not sufficient for growing a market as consumers also need to be persuaded to select a PHEV or ZEV. Among PEV drivers in California, Connecticut, and Massachusetts, saving money on fuel was the most common primary motivation for all PHEV and BEVx drivers as well as for BEV<200 drivers in California.\textsuperscript{57} These results are consistent with sentiments from non-PEV drivers in a 2015 UC Davis survey of new car buyers that fuel savings, as well as other factors, would be one of their motivations for purchasing a PHEV or ZEV. Therefore, current relatively low gasoline prices create a challenging landscape, especially if utilities are not offering supportive discounts for vehicle charging or consumers are not aware of or opting into these reduced electricity rates. As a result, some consumers may actually spend more money today to operate their PEVs than they would an HEV or ICE.

Finally, an illustrative analysis of dealer inventories of PEVs and comparable vehicles shows there to be disproportionately more PEVs available on dealer lots in California than in Section 177 ZEV states. Whether these inventories reflect sales rates in those areas or automakers producing limited quantities of first generation products cannot be distinguished by evaluating this data.\textsuperscript{58} Regardless, limited dealer inventories will reduce consumers' exposure to these vehicles and may contribute at least partially to the lower sales rates in the Section 177 ZEV States.

\textsuperscript{56} See Appendix B, Section VII for description of California’s CVRP Ownership Survey 2015 results.
\textsuperscript{57} See Appendix B, Section VII for description of California’s CVRP Consumer Survey 2015, Massachusetts 2016 MOR-EV Rebate Survey, and Connecticut’s 2016 CHEAPR Rebate survey results
\textsuperscript{58} See Appendix B, Section II for staff’s analysis of dealer availability, based on data collected from Edmonds.com
**Does staff believe sales will improve in the future?**

Historically, there has been no single factor that is solely correlated to increased PEV sales. Rather, continued activity and progress from all parties – government at all levels, industry, and advocacy organizations – on a range of measures will each play a role in supporting, cultivating and expanding consumer interest to enable further market growth of ZEVs and PHEVs.

PEV owners are satisfied with their vehicle as over 92 percent of respondents in California would probably or definitely recommend their specific PEV model. Virtually all of the BEV200+ consumers (99.9 percent) would probably or definitely recommend their vehicle, as would 96 percent of PHEV and 93 percent of short range BEV consumers. As vehicle technology has matured, PHEV and BEV consumers become more likely to definitely recommend their specific PEV model. For example, the percentage of Nissan Leaf owners that would definitely recommend their vehicle jumped from 44 percent for those who purchased in 2012 to 66 percent for those who purchased in 2014.56

Already over 10 percent of recent PEV buyers (or lessees) are repeat buyers. Given the large proportion of leases, many consumers will be returning to the market within two to three years and among all current PEV drivers, more than 90 percent would replace their current PEV with a ZEV or PHEV. These existing, satisfied PEV consumers also serve an important function in educating other consumers in the market. According to survey results of recent California rebate recipients59, another PEV driver is one of the most influential information sources for new buyers to choose a PHEV or BEV. So the greater the number of drivers coupled with other outreach initiatives, the faster consumer awareness will grow about these vehicles. When asked to design their next vehicle, 25-40 percent of new car buyers (almost exclusively conventional vehicle drivers) chose a PHEV, BEV, or FCEV.60 Although these results do not represent a market forecast, they do serve as a measure of market potential that could be realized with the necessary complementary actions to eliminate barriers. Notably, there is no clear evidence that future market growth would only come from previous hybrid electric vehicle (HEV) buyers. From 2015-2016, about 80 percent of the PEVs in California are being sold to consumers with no prior PEV ownership, and among this group only 8 percent are either replacing an HEV or have an HEV as another vehicle in their household.59

Consumers cite a variety of factors that prevent their selection of a ZEV or PHEV, that are expected to diminish with time. The majority of all new vehicles sold in the United States start at a base price of less than $25,000, though with additional option packages the average retail selling price of all vehicles in 2015 was $33,000.61 However, about half of the ZEVs and PHEVs sold in 2016 start at a base price over $35,000 before factoring in federal and state purchase incentives, while additional subsidies from auto manufacturers may reduce the price further still. Manufacturing developments and global economies of scale will facilitate cost reductions, while

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59 See Appendix B, Section VII for description of California’s CVRP Consumer survey data.

60 Kurani 2016.

continued government incentives can also help to offset the remaining incremental costs. Limited driving range, particularly of BEVs, as well as related infrastructure for charging or hydrogen refueling are also barriers to consumer adoption.\textsuperscript{59,60} As more auto manufacturers introduce additional options, though, in different vehicle segments with increasingly greater electrification, consumers will be more likely to have an option that meets their needs, and within their budgets. Governments at multiple levels as well as some auto manufacturers are also working to deploy more PEV and FCEV fueling infrastructure to support these vehicles.\textsuperscript{62} Concerns about long charging times are also anticipated to be resolved as auto manufacturers and suppliers have already announced advancements on charging speeds and energy storage that will soon be incorporated into product designs.\textsuperscript{63}

\textit{What challenges lie ahead for ZEV market growth to continue?}

While the market potential exists for increasing market shares of ZEVs and PHEVs, converting consumer interest into actual sales will still have challenges. The current market has benefited from a host of incentives which are set to expire eventually. These incentives have been effective in offsetting some of the incremental costs, and cost parity between ICEs and ZEVs or PHEVs for a self-sustaining market is not anticipated before 2025. The phase out of the largest of these incentives, the federal tax credit, will be staggered with the tax credit for FCEVs expiring on December 31, 2016 and the tax credit for PEVs phasing out for each manufacturer when it reaches 200,000 vehicles nationwide. Based on historic U.S. sales rates, at least four manufacturers would reach this threshold prior to 2025. Leading manufacturers General Motors and Nissan would reach first in 2022 followed by Ford and Tesla, though increasing sales of existing vehicles and introduction of new products would likely accelerate this timeline.\textsuperscript{64} In California, sufficient funding for the state purchase rebate remains an annual uncertainty and recent modifications by the legislature to limit which consumers and vehicles qualify for a rebate may affect market growth. Incentive programs in Section 177 ZEV States have also faced funding shortages at times, and required increased funding.\textsuperscript{65} Additionally, high-occupancy vehicle (HOV) lane access by single-occupancy ZEVs and PHEVs has been an effective incentive in many states; however, in California, current state law sunsets this access in 2019.

The high proportion of leased PEVs and FCEVs has accelerated the development of a secondary PEV market. Although analysis of used vehicle transactions and auction data shows limited net migration of PEVs between states, used vehicle prices of early model PEVs tended to be lower than HEVs but higher than ICEs.\textsuperscript{66} Among the small number of low or moderate income participants in California’s Enhanced Fleet Modernization Program purchasing PEVs, PHEVs and HEVs prices were similar, but an average of $7,000 more than the BEVs that were

\textsuperscript{62} See Appendix D for staff’s infrastructure assessment.
\textsuperscript{63} See Appendix C for staff’s technology assessment.
\textsuperscript{64} Calculated from historical sales trends discussed in Appendix B, Section III.A.2.c.
\textsuperscript{66} Based on analysis of Manheim Auction data. See Appendix B, Section VII for a complete description of Manheim Auction data.
purchased. For the broader market, though, lower PEV prices seem to be correlated to selling at faster rates, suggesting that used vehicle sellers are still developing optimal pricing strategies.67

**How have manufacturers complied with the ZEV regulation since the ACC 2012 rulemaking?**

Since the 2012 ACC rulemaking, manufacturers have been over-complying with the ZEV regulation requirements as illustrated in Figure 11 by producing more ZEVs and PHEVs than needed. Likely, this is in preparation for the higher requirements set by the Board for 2018 and subsequent model years. However, this production of vehicles, and subsequent banking of credits has created some controversy, not unlike past reviews of the ZEV regulation. This topic will be discussed further in the following sections.

**Figure 11 - Manufacturer Compliance Since 2012 Model Year (California and Section 177)**

![Figure 11 - Manufacturer Compliance Since 2012 Model Year](image)

**How have regulatory compliance scenarios changed as a result of the midterm review of the adopted standards?**

The latest analysis has taken into consideration technology advancements, manufacturer compliance trends, ZEV regulation credit banks, and future product announcements and resulted in updated minimum regulation compliance scenarios. Compliance scenarios are intended to explain the potential effect various flexibilities and developing technology has on the overall number of vehicles expected from the regulation. These scenarios are “minimum

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compliance scenarios”, which emphasizes the main goal of the ZEV regulation: to set a floor to ensure pure ZEV technology is being produced to help the technology reach commercialization. The question that these scenarios answer is how much could be expected (at a minimum) from the ZEV regulation in any given model year. These scenarios are not a market forecast of what actual total sales may be or will likely be in any given model year, but rather are regulatory compliance projections using the best available information at the time of this review.

Each new compliance scenario results in fewer vehicles than the expected compliance scenario prepared for the 2012 Board Hearing and a summary of staff's analysis can be found in Appendix A. Lower vehicle numbers are due mostly to longer electric range BEVs and PHEVs in every scenario, meaning each vehicle is earning more credit (in some cases twice as much) than originally projected. As pure ZEVs generally earn more credits per car than PHEVs, this change in assumptions directionally resulted in higher ZEV penetration, lower PHEV penetration, and lower overall ZEV and PHEV combined volumes in the new scenarios.

In the new minimum compliance scenarios, the analysis takes into consideration historical credits, a change from past compliance scenarios. To address the issue of credits more directly, credits exist in manufacturers’ credit banks due to vehicles being produced. Historically, the majority of manufacturers have carried a two to three year compliance margin from one year to the next. This factor is reflected in the updated compliance scenarios. A "credit balance" assumption was developed for each compliance scenario based on the number of credits manufacturers would leave in their banks relative to what would be needed for 2026 and subsequent model year compliance. Previously earned ZEV credits in excess of this assumed balance would be spread out evenly across the 2018 to 2025 model years to reduce the manufacturer's obligation for those years. The other assumptions made for each compliance scenario followed general themes related to the pace of technology development and market uptake. Below is a summary of each compliance scenario staff developed for this assessment.

<table>
<thead>
<tr>
<th>Scenario</th>
<th>Theme</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mid-Range ZEV-Technology Case</td>
<td>Continued advancement in ZEV technology leads to balance of new sales of improved capability ZEVs and moderate use of banked ZEV and GHG credits</td>
</tr>
<tr>
<td>Slow ZEV-Technology Case</td>
<td>Delayed advancement in ZEV technology leads to higher dependence on banked ZEV and GHG credits to support sales of only slightly improved ZEVs</td>
</tr>
<tr>
<td>High ZEV-Technology Case</td>
<td>Aggressive advancement in ZEV technology leads to larger increase in new sales of highly capable ZEVs as dominant mechanism for compliance</td>
</tr>
</tbody>
</table>

Results from the mid-range scenario for California and Section 177 ZEV states are shown in Figure 12 and Figure 13 below for the 2018 through 2025 model years only.
Through 2015 model year, 182,000 ZEVs and PHEVs have been registered in California, according to Department of Motor Vehicles’ registration data. Extrapolating for 2016 and 2017 model years, approximately 165,000 additional ZEVs and PHEVs are expected for the following two model years. Taking these pre-2018 vehicle numbers and adding them to staff’s mid-range
regulatory compliance scenario, nearly 1.2 million cumulative ZEVs and PHEVs can be expected by the 2025 model year.

*How will historical ZEV credit banks effect future compliance with the ZEV regulation?*

As an industry, manufacturers have been over complying with the ZEV regulation since the early years of the program. There are some manufacturers that have complied early and generated ZEV credits and some have bought credits to meet the requirements. In the early years, the Board awarded a large number of credits to jumpstart a very early technology market. To help manufacturers meet the requirements in the Section 177 ZEV states, the Board adopted the travel provision. These early credits provide insurance to the manufacturers for future requirements.

Starting in 2018 model year, the requirements have a steep ramp in the ZEV credit requirements. Also, during the 2012 rulemaking, staff addressed other concerns regarding credits by simplifying the overall credit structure. For example, the travel provision will no longer be applicable for BEVs, and credits generated per vehicle have been reduced.

Manufacturer credit banks will continue into the future, and in some cases, those banks will be representative of technology and market success. However, what is also certain is that there will be some market failures. Over the past four model years, products have already been released in the market, pulled back, revamped, and re-released due to market response to the technology.68 It could be argued, though, that credit banks provide space for manufacturers to innovate, and overall the market will benefit from improved products. As ARB re-evaluates the requirements for 2026 model year and beyond, the agency will consider credit structure revisions including taking into account the status of the credit banks at that time and regulatory provisions such as PHEV and BEV qualification criteria, credits per vehicle, credit lifetime, and credit usage limitations.

*Is electric vehicle miles traveled (eVMT) or zero-emission vehicle miles traveled (zVMT) an appropriate credit metric for the ZEV regulation?*

For 2018 and subsequent model years, PHEVs are credited on a linear scale (between 0.4 and 1.3 credits) based on the certified electric range on the urban dynamometer drive schedule (UDDS). One alternative factor suggested for consideration is electric vehicle miles traveled or eVMT. This is the portion of total vehicle miles that are attributed to electric power instead of gasoline, and therefore correlates with the GHG benefit of such a vehicle.

According to the analysis presented here, eVMT data is highly variable and dependent more on user behavior (driving, charging) than the vehicle itself (its inherent range or motor size).69

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69 See Appendix G for more information on staff’s analysis of manufacturer provided data from PEVs.
Though manufacturers have presented average eVMT numbers, data provided by the manufacturers to ARB show increasing overall VMT with unchanging eVMT each year for some models. According to early data received from General Motors\(^{70}\) during the EV Project, 72 percent of the Volt miles qualify as eVMT. However, according to more recent General Motors data sources,\(^ {71}\) the eVMT percentage for the Volt is actually closer to 60 percent. At this time, there is significant uncertainty as to how this percentage will increase or decrease with increasing infrastructure,\(^ {72}\) increased electric range for 2016 and subsequent Chevy Volts, fluctuating electricity and gasoline prices, or an expanding consumer base including customers who may not be as highly motivated to plug in as the earliest adopters.

Further, eVMT only has a strong correlation to a vehicle’s GHG emission benefit, but not to its criteria pollutant emission benefits. In the case of the Volt, according to manufacturer provided data, only 59 percent of a Volt’s miles would qualify as zero-emission VMT (zVMT), meaning the percent of total miles from trips without any engine operation (and the associated criteria pollutant emissions such as HCs and NOx). PHEVs with longer ranges and higher motor output power (Chevy Volt) do provide greater criteria pollutant benefits than blended-type PHEVs (Ford Fusion PHEV, Toyota Prius Plug-In). However, as illustrated in Figure 14, all PHEVs have lower zVMT than eVMT suggesting the criteria pollutant benefits relative to a BEV are not as great as the GHG benefits.

According to the analysis in Appendix I, it is not clear how changing to an eVMT (or zVMT) metric would better help California and the Section 177 ZEV states to meet long term criteria pollutant and GHG emission reduction goals than the current credit system. The current UDDS based system for 2018 and subsequent model years lines up well with an eVMT based system, especially when compared to a ~100 mile UDDS certified BEV.\(^ {73}\) And when compared to a zVMT based system, many PHEVs are likely currently over credited. The following Figure 14 shows a comparison of vehicles based on these various metrics.

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\(^{70}\) Data received from GM was from Volts in the EV Project. See Appendix G for more information.

\(^{71}\) Data based on in-use Volts from the most recent model years.

\(^{72}\) See Appendix D for more information on electric vehicle infrastructure roll out.

\(^{73}\) See Appendix I for staff’s full analysis on alternative credit structures.
Range determined over the UDDS cycle does credit what matters to the consumer: the vehicle’s electric range. In a 2015 survey of BEV and PHEV drivers, among those responding that they would likely replace their current vehicle with a PHEV, current PHEV drivers indicated an average desired all-electric range of 40-50 miles for their next PHEV while almost all current BEV drivers indicated a desired range of around 80 miles for their future PHEV. Other ARB and U.S. EPA GHG and criteria pollutant standards reward PHEVs for their environmental benefits while the technology-forcing ZEV regulation credits PHEVs based on an attribute that advances technology and supports consumer acceptance and market expansion: all-electric range.

**Should manufacturers be allowed to comply with more PHEVs for the 2018 through 2025 model years than already allowed in the regulation?**

No. It is often asserted that PHEVs can appeal to a broader population and serve as a transition to pure ZEV technology and, therefore, should be allowed to play a larger role in compliance with annual ZEV requirements. And as noted earlier, the updated VISION scenarios in the Mobile Source Strategy indicated approximately one-third of the total ZEVs could be PHEVs on a path to meeting 2050 targets. However, while the share of PHEVs can undoubtedly be larger than that, the sensitivity analyses presented in Appendix F demonstrate conclusively that there are both GHG and criteria pollutant consequences from a much higher share of PHEVs along with increased risk given the uncertainty in how consumers will use these vehicles. As shown in the new minimum compliance scenarios, PHEVs are projected to make up more than 60 percent of all ZEVs on the road by 2025 even with the current caps on PHEV credits. Further, banking and trading provisions already exist that would allow manufacturers with excess PHEV generated credits to bank them for future use or perhaps trade with other manufacturers that have not fully utilized their PHEV credit allowances. Combined, this provides sufficient flexibility in the current regulatory structure as the ZEV market is developing.

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**Figure 14 - Current Credit Scheme vs eVMT and zVMT**

The figure illustrates the comparison between current credits, eVMT (per veh), zVMT, and the percentage of vehicles that fall under each category. The data is presented for various models such as Toyota Prius (PHEV), Honda Accord (PHEV), Ford C-Max Energi (PHEV), Ford Fusion Energi (PHEV), Chevrolet Volt (PHEV), BMW i3 (BEV), Ford Focus Electric (BEV), Honda Fit (BEV), and Nissan Leaf (BEV) with ZEV credits ranging from 0% to 100%.
to determine the role PHEVs will ultimately play. Therefore, this new analysis does not support
the need for more flexibility for PHEVs at this time such as allowing manufacturers to comply
with more PHEVs than currently allowed.

What is the likelihood that the ZEV requirements adopted in 2012 can be met in the Section 177 ZEV states?

Sales of ZEVs and PHEVs in the Section 177 ZEV states lag behind California’s market. Many
stakeholders point to regulatory flexibilities, such as the travel provision and the existence of
banked credits, as part of the cause in holding back sales in the Section 177 ZEV states. These
could be factors resulting in lower sales; however, not all states are performing the same.
Oregon has a strong ZEV market, just behind California at 2 percent of LDV sales. The market
potential for ZEVs and PHEVs in the Section 177 ZEV states exists, and is slowly increasing
through a combination of government support, increased awareness, and expanded product
offerings. Much of the support for complementary policies in the Section 177 ZEV states has
developed within the past 3 years, after the adoption of the Multi-State ZEV Action Plan.

Recognizing the market development in the Section 177 ZEV states was not yet as far along as
California’s, the Board adopted additional regulatory flexibilities and lead time to create a ramp
into the 2018 and subsequent model year requirements for the states. These flexibilities include
reduced credit obligations in the Section 177 ZEV states, spread out over 6 model years, and
the ability to focus regionally on deliveries of PHEVs and ZEVs, rather than state by state.
Additionally, credits both created in the Section 177 ZEV states and generated through the
travel provision will help manufacturers who need more time to build a market for their vehicles
between 2018 and 2025 model years.

Do intermediate volume manufacturers need different treatment in the ZEV regulation?

In 2012, the Board adopted policies that required intermediate volume manufacturers (IVM) to
begin electrifying their fleet starting in 2018. These policies redefined many of the mid-sized
manufacturers (Daimler, BMW, Hyundai, Kia, and Volkswagen) as large volume manufacturers
(LVM), and allowed the remaining IVMs (Subaru, Volvo, JLR, Mitsubishi, Mazda, and Tesla) to
meet their 2018 through 2025 model year requirements exclusively with PHEVs. The Board
adopted additional flexibilities in 2014 for the remaining IVMs, ensuring these manufacturers
would remain defined as IVMs through 2025 model year, and granted more time to comply with

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74 Kurani 2016.
ZEV Action Plan” link
http://www.zevstates.us/about-us/, click on “Memorandum of Understanding” link
78 CCR Section 1962.1(d)(5)(E)3.a and b., and 1962.2(d)(5)(E)1.a.i. and ii.
79 See Appendix A for staff’s analysis of ZEV regulation compliance scenarios
their ZEV requirements. In Resolution 15-07, the Board directed staff to continue to evaluate
the issue of regulatory stringency during its midterm review process.80

Consultations were held with all but one IVM (Mazda) during the mid-term review process.81
Manufacturers confirmed various plans to full compliance with the regulation as adopted, and
are pursuing both PHEV and ZEV models, some recognizing it will be almost impossible to meet
their obligations exclusively with PHEVs. Many of the flexibilities adopted in prior rulemakings
adequately met many of the IVMs’ concerns. The following table lists the various flexibilities
already available to IVMs for the 2018 through 2025 model year ZEV requirements.

<table>
<thead>
<tr>
<th>Applicable Model Years</th>
<th>IVM Flexibility</th>
</tr>
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<tbody>
<tr>
<td>2018 and 2019</td>
<td>Allowed to meet full requirements with converted partial zero-emission vehicle (PZEV) and advanced technology PZEV (AT PZEV) credits</td>
</tr>
<tr>
<td>2018 and 2019</td>
<td>Additional “revenue test” to be able to qualify as IVM instead of LVM</td>
</tr>
<tr>
<td>2018 and subsequent model years</td>
<td>Can meet full requirement with PHEV credits</td>
</tr>
<tr>
<td>2018 and subsequent model years</td>
<td>Are allowed 3 model years to make up a credit deficit, and deficit can be fulfilled with PHEV credits</td>
</tr>
<tr>
<td>2018 through 2022 model years</td>
<td>Allowed to participate in “pooling” in Section 177 ZEV states</td>
</tr>
<tr>
<td>2018 and subsequent model years</td>
<td>If average sales grow above 20,000, are allowed 5 years to transition to LVM requirements</td>
</tr>
</tbody>
</table>

These flexibilities adopted by the Board addressed many concerns raised by the IVMs. More
importantly, these manufacturers do have competitive products in the market and generally
agree that they will need to develop and introduce ZEV technologies to ensure they remain
competitive into the future. All five current IVMs have clear and concrete plans to bring ZEVs to
market in the next few years, with relevant announcements for Mazda and Subaru made as
recently as November 2016.82 Additionally, as shown in the new compliance scenarios, there are sufficient credits, both in their own banks and in the market, available for IVMs to help
bridge any interim compliance gaps.

81 Mazda declined to meet with ARB staff regarding the review of the ZEV regulation.
Are the ZEV requirements in California, as adopted in 2012, appropriate for continuing to help develop the ZEV market?

Yes. The analysis reported here found that maintaining the adopted requirements for California through 2025 model year including the existing regulatory and credit structure is appropriate. In 2012, the Board successfully strengthened the ZEV regulation, nearly tripling the requirements for the 2018 through 2025 model years, and shifting away from stair-step requirements (where requirements remained the same for three years at a time) to annual increases in the requirements. Since then, the regulation has been achieving the goal of accelerating development of ZEV technology towards commercialization in California as demonstrated by the growth in the ZEV market, the introduction of more capable and longer range vehicles than originally projected, and earlier reduction in battery costs than anticipated. The 2012 Board action has resulted in over 215,000 ZEVs and PHEVs being placed in California over the last five model years. The transformation of the light-duty fleet has begun. Not only are manufacturers over-complying with the ZEV regulation in preparation for higher 2018 and subsequent model year requirements, manufacturers are delivering ZEVs and PHEVs in states which have not adopted California’s ZEV regulation, indicating that the industry is starting to shift towards greater electrification. Manufacturers are competing with each other for PEV consumers by continually refining the products they offer to suit consumer preferences. When asked, consumers have stated a desire for more electric range and more electric drive capability. Manufacturers have responded with more range and, instead of continuing to make vehicles with limited range and capability that barely meet ZEV regulation requirements, will be offering over 70 unique models over the next five model years, in almost every segment (vehicle size class) as illustrated in Figure 15.83

83 See Appendix C for staff’s analysis on future expected model offerings.
As a result of these vehicle technology advancements, the updated minimum compliance scenarios project approximately 1.2 million cumulative sales of ZEVs and PHEVs by 2025 in California. While this number might reflect a lower volume of vehicles needed for compliance than originally projected in 2012, the resultant improvements in ZEV and PHEV attributes, such as all-electric range and vehicle price, will be better vehicles expected to further broaden the appeal of these vehicles beyond the initial consumers and help achieve necessary future market expansion.

Despite the noted successes to date, the ZEV and PHEV market is in the early stages of development. The market is rapidly changing with nine BEV and PHEV models already discontinued since their introduction and it is also unknown how many of the 70 unique models will succeed in the market. The current market has benefited from multiple purchase incentives that have substantially discounted ZEVs and PHEVs such that their prices are more aligned with those of conventional vehicles. But, between 2018 and 2025, these and other incentives are expected to phase out. While decreased reliance on incentives is essential for building a self-sustaining market, it is unclear what consumer response will be without purchase and other incentives (like high occupancy vehicle (HOV) lane access). Consumer awareness of ZEVs is still low and top motivations like saving money on fuel are less influential as gasoline prices remain low. Given the market uncertainties that still exist in these early years, regulatory stability of the 2018 through 2025 model year standards can help ensure a continued path of increasing, but achievable, ZEV volumes.
Based on the midterm review, what ZEV regulatory changes does the new analysis suggest?

For the first time since the initial adoption of the ZEV regulation, the Board adopted increased ZEV credit requirements in 2012. This action, in concert with the development of strong comprehensive complementary policies to support infrastructure deployment and consumer awareness, led to the advancement of ZEV technology and growth in ZEV sales. Building on these strong trends, the new analysis supports a strengthening of the ZEV program for 2026 and subsequent model years to continue on the path towards meeting California's 2030 and later climate change and air quality targets. A rulemaking initiated by 2018 would target credit provisions, the current regulatory structure, and other changes to increase certainty on future vehicle volumes and reconsider PHEV qualifications\(^{84}\) and credits to ensure maximum GHG and criteria pollutant reductions are achieved. Development of future ZEV requirements would also need to be coordinated with new GHG (and potentially criteria pollutant\(^{85}\)) fleet-wide emission reduction requirements as was previously done in the 2012 ACC program where all three elements were simultaneously addressed. This comprehensive approach ensures the regulations are complementary and coordinated for the synergistic effects into a new vehicle policy to help meet California's air quality and GHG goals. To this end, ARB intends to continue to collaborate on a technical basis with its federal partners like the U.S. DOE to promote the advancement of ZEV technologies needed for ARB's long term goals and the U.S EPA and NHTSA to evaluate evolving conventional and electrified vehicle technologies to build on the existing GHG standards and pursue continued reductions in the national GHG standards for 2026 and subsequent model years.

Modeling to meet the 2030 GHG targets established by SB 32 in the ARB Mobile Sources Strategy report, released in May 2016, indicates approximately three million additional ZEVs and PHEVs will be needed in 2026 through 2030. To reach these volumes with any certainty, the new regulation will need modifications that provide a more direct connection to vehicle volumes and require vehicle characteristics that best ensure market success. For such significant revisions to the regulation to be successful, however, it would require greater market acceptance, more technology advancements, and lower technology costs than is known with certainty today. In PHEVs alone, the product offerings and architecture variations are increasing in diversity and it is too early to determine which combinations will be appealing to consumers while providing maximum GHG and criteria pollutant benefits. For BEVs, a step change is occurring with multiple offerings expected with 200+ miles of range at prices closer to mainstream conventional vehicles (even before state and federal incentives), with the first of these being launched within weeks of this report's release. Additionally, substantial changes to the regulatory structure will impact vehicle manufacturer product and compliance planning and

\(^{84}\) For example, California Senate Bill 859 recently revised the PHEV eligibility criteria for consumer rebates (CVRP) to a minimum of 20 miles of electric range rather than the 10 mile minimum range in ARB ZEV regulations necessary to qualify for ZEV credits.

\(^{85}\) Stronger LEV criteria pollutant fleet emission standards will also be considered as the state implements SIP strategies for the 2031 ambient air quality requirements, in addition to later attainment dates for the new ozone standards.
necessitate sufficient lead time and stability to implement successfully while minimizing disruption to research, investment, and design cycles.

Since the adoption of the 2018 through 2025 model year standards, manufacturers have been exceeding the annual requirements of the ZEV regulation and expanding the market nationwide by delivering ZEVs and PHEVs in states which have not adopted California’s ZEV regulation. Thus, committing now to a strong set of post-2025 requirements reinforces current progress and encourages manufacturers to further advances to electrify their fleets. Stronger post-2025 requirements will inherently influence the last model years before 2025 as manufacturers take actions to stay ahead of the requirements with some compliance margin. In the interim, ARB and interagency efforts should be made to help accelerate infrastructure deployment, increase consumer awareness, improve dealer knowledge, and preserve incentives. Staff will also continue to assess the development of the ZEV and PHEV market, battery and fuel cell technology, PEV and hydrogen infrastructure, the nexus with autonomous and car sharing transportation developments, the proliferation of complementary policies, and the overall environmental and economic impact of this emerging market.

What are some alternative regulatory and non-regulatory changes that the Board could consider prior to 2026 model year?

The analysis of the midterm review fully support the conclusion to focus on substantial new regulatory action for model year 2026 and beyond to increase certainty on future vehicle volumes while maintaining the existing requirements through 2025. As noted earlier, manufacturers are currently producing more vehicles than the regulation requires and, at least in part, it is because of the more stringent requirements starting in 2018 model year. In 2018, changes to the credit structure cause most vehicles to earn fewer credits per car as well as the overall requirement to increase in stringency every year from 2018 to 2025. Likewise, if the changes for 2026 result in increased stringency through structure and/or credit changes as intended, it is logical to assume that manufacturers would be similarly motivated to over-comply, or perhaps ‘early-comply’, in the years leading up to 2026 model year and result in increased vehicle volumes before 2026.

However, at the July 2016 hearing, the Board requested additional analysis by staff to address concerns around ZEV credits and increasing the number of ZEVs on the road prior to 2026 model year. The alternatives staff has considered include: a) increasing the ZEV requirement percentages for the final year of the current program (2025 model year); b) creating a credit usage restriction that may, for example, require a fraction of any model year’s compliance be from vehicles produced in that model year or by that manufacturer; c) increasing the cap on PHEV credits allowed, but requiring additional PHEVs to have increased electric range and electric drive capability; and d) increasing the ZEV requirements for the 2023-2025 model years with a focus on requiring additional pure ZEVs. Given the need to provide sufficient lead time following any formal rulemaking approval, the additional vehicles resulting from these alternatives could be minimal relative to production levels in anticipation of future requirements for 2026 model year and beyond. Furthermore, the flexibility provided by credits, even with
restrictions, would not necessarily require manufacturers to alter product plans to comply with increased requirements.

Non-regulatory actions will be just as critical as the ZEV regulation requirements in bolstering demand for ZEVs. Studies such as recent International Council on Clean Transportation (ICCT) research\(^{86}\) highlight historical correlations between existing ZEV sales and current regional market support actions (e.g., infrastructure, consumer campaigns, etc.). However, such relationships will continue to be dynamic and staff intends to evaluate changing market conditions to inform future decisions which may include contracts for external research to support this analysis.

Staff intends to continue to evaluate the market, including the effectiveness of complementary policies, over the next few years to help inform future regulatory proposals and to better quantify what is needed to support further development of the ZEV and PHEV market. The Low Carbon Transportation and Fuels Investments and Air Quality Improvement Program (AQIP) Funding Plan for fiscal year 2016-2017 discussed potential indicators for assessing a self-sustaining market in accordance with SB 1275. These indicators include: new ZEV and PHEV sales, battery and fuel cell technology advancements and costs, infrastructure development, product diversity, the used market for ZEV and PHEVs, consumer awareness, avoided health impacts, and consumer willingness to pay.\(^{87}\) Evaluation of these and other indicators, such as consumer purchase motivations, vehicle attributes, energy prices, and cumulative installed battery capacity, will help to assess the overall health and potential of the ZEV and PHEV markets in California and Section 177 ZEV States going forward.

**Summary**

The electrification of the light-duty fleet has begun. The ACC regulations, as adopted in 2012, continue to push manufacturers to produce more efficient and cleaner vehicles than ever before, and will continue to do so for years to come. Consistent with the draft 2016 TAR and Final Determination, updated analysis confirmed that the technology is available to readily meet, if not exceed, the current 2022 through 2025 model year national GHG emission standards at the same or lower cost than originally projected when the standards were adopted in 2012, predominantly with advanced gasoline engines and transmissions. Building on the staff’s 2015 report to the Board on the feasibility of measurement at low PM emission levels, additional emission testing and a review of vehicle PM emission control technology was conducted by staff and determined that compliance with the 1 mg/mi emission standard by 2025 model year is feasible and that manufacturers are on track to meet this standard.

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\(^{87}\) ARB 2016d. California Air Resources Board. Proposed Fiscal year 2016-17 Funding Plan for Low Carbon Transportation and Fuels Investments and the Air Quality Improvement Program. May 20, 2016. [https://www.arb.ca.gov/msprog/aqip/fundplan/proposed_fy16-17_fundingplan_full.pdf](https://www.arb.ca.gov/msprog/aqip/fundplan/proposed_fy16-17_fundingplan_full.pdf)
The ZEV regulation, significantly revised in 2012, continues to play a critical role in transitioning the vehicle fleet to achieve California’s long term air quality and GHG goals and has resulted in hundreds of thousands of ZEVs and PHEVs being placed in California over the last five years. Not only are manufacturers over-complying with the ZEV regulation in preparation for higher 2018 and subsequent model year requirements, manufacturers are delivering ZEVs and PHEVs in states which have not adopted California’s ZEV regulation.

As described in the Executive Summary above, and expanded upon throughout this report, the following recommendations have been prepared by staff for the Board’s consideration in the California Midterm Review.

2022 through 2025 model year GHG emission standards

- Continued participation in the National Program by maintaining the “deemed to comply” provision allowing for compliance with the adopted U.S. EPA GHG standards for 2022 through 2025 model years.

1 milligram per mile particulate matter emission standard

- As previously reported to the Board in 2015, maintain the existing PM measurement method for the 1 mg/mi standard.
- Maintain the stringency and implementation schedule of the adopted 1 mg/mi PM standard scheduled to begin in 2025 model year.
- Initiate regulatory action to develop and adopt additional PM standards to phase-in with the 1 mg/mi standard in 2025 model year to ensure manufacturers implement robust control strategies that result in low PM emissions in the real world.

California’s ZEV regulation

- Strengthen the ZEV program for 2026 and subsequent model years to continue on the path towards meeting California’s 2030 and later climate change and air quality targets.
- Maintain the adopted requirements for California through 2025 model year including the existing regulatory and credit structure.
- Maintain the existing ZEV requirements and flexibilities, including as amended in 2014, for IVMs.
- Maintain the existing ZEV regulation credit structure and caps for PHEVs through the 2025 model year.
- Maintain the ZEV regulation and flexibilities for the Section 177 ZEV states.
- Continue efforts by ARB and other stakeholders to accelerate and expand non-regulatory complementary policies that have been identified as successful in building market demand and removing remaining barriers to ZEV adoption.

Given the conclusion of the federal midterm evaluation process with the decision by U.S. EPA to maintain the adopted GHG standards in the Final Determination, ARB will remain engaged with U.S. EPA and NHTSA in support of continued participation in the National Program. Additionally, the agency will continue rigorous efforts to promote complementary policies that support the expanding ZEV market. Simultaneously, ARB will begin new multi-year technical
and market analysis to inform an expected rulemaking for the 2026 model year and beyond. In these efforts, ARB intends to build on its history of technical collaboration with federal agencies including U.S. DOE, U.S. EPA, and NHTSA in furthering the development and deployment of advanced vehicle technologies necessary for California’s GHG and clean air targets. ARB also recognizes the value of a continued national program for GHG standards and plans to continue to coordinate with EPA and NHTSA in the development of future standards.
# LIST OF ACRONYMS AND ABBREVIATIONS

<table>
<thead>
<tr>
<th>Acronym</th>
<th>Description</th>
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<tbody>
<tr>
<td>AEO</td>
<td>Annual Energy Outlook</td>
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<tr>
<td>ARB</td>
<td>California Air Resources Board</td>
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<tr>
<td>BEV</td>
<td>Battery electric vehicle</td>
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<tr>
<td>CAFE</td>
<td>Corporate Average Fuel Economy</td>
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<tr>
<td>CAV</td>
<td>Connected and autonomous vehicles</td>
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<tr>
<td>CCR</td>
<td>California Code of Regulations</td>
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<tr>
<td>CD</td>
<td>Charge-depleting</td>
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<tr>
<td>CO$_2$</td>
<td>Carbon dioxide</td>
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<tr>
<td>DSF</td>
<td>Dynamic Skip Fire</td>
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<tr>
<td>EGR</td>
<td>Exhaust gas recirculation</td>
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<tr>
<td>EIA</td>
<td>Energy Information Administration</td>
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<td>eVMT</td>
<td>Electric vehicle miles traveled</td>
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<td>FCEV</td>
<td>Fuel cell electric vehicle</td>
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<tr>
<td>FTP</td>
<td>Federal Test Procedure</td>
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<tr>
<td>GDI</td>
<td>Gasoline direct injection</td>
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<tr>
<td>GHG</td>
<td>Greenhouse gas</td>
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<tr>
<td>g/mi</td>
<td>Grams per mile</td>
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<td>GPF</td>
<td>Gasoline particulate filter</td>
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<td>HC</td>
<td>Hydrocarbons</td>
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<td>ISOR</td>
<td>Initial Statement of Reasons</td>
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<tr>
<td>IVM</td>
<td>Intermediate volume manufacturer</td>
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<tr>
<td>LDV</td>
<td>Light-duty vehicle</td>
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<tr>
<td>LEV</td>
<td>Low-emission vehicle</td>
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<tr>
<td>mg/mi</td>
<td>Milligrams per mile</td>
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<tr>
<td>mpg</td>
<td>Miles per gallon</td>
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<tr>
<td>MTR</td>
<td>Midterm review</td>
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<tr>
<td>MY</td>
<td>Model year</td>
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<tr>
<td>NHTSA</td>
<td>National Highway Traffic Safety Administration</td>
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<tr>
<td>NMOG</td>
<td>Non-methane organic gas</td>
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<tr>
<td>NOx</td>
<td>Oxides of nitrogen</td>
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<tr>
<td>NVH</td>
<td>Noise, vibration, and harshness</td>
</tr>
<tr>
<td>PEV</td>
<td>Plug-in electric vehicle</td>
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<tr>
<td>PFI</td>
<td>Port Fuel Injection</td>
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<tr>
<td>PHEV</td>
<td>Plug-in hybrid electric vehicle</td>
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<tr>
<td>PM</td>
<td>Particulate matter</td>
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<tr>
<td>ppb</td>
<td>Parts per billion</td>
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Section 177

**ZEV states:** States that adopt and enforce California’s ZEV regulations under Clean Air Act (CAA) Section 177

<table>
<thead>
<tr>
<th>Acronym</th>
<th>Description</th>
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<tbody>
<tr>
<td>SJV</td>
<td>San Joaquin Valley</td>
</tr>
<tr>
<td>SULEV</td>
<td>Super-ultra-low-emission vehicle</td>
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<tr>
<td>SUV</td>
<td>Sport utility vehicle</td>
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<tr>
<td>TAR</td>
<td>Technical Assessment Report</td>
</tr>
<tr>
<td>TPD</td>
<td>Tons per day</td>
</tr>
<tr>
<td>Abbreviation</td>
<td>Description</td>
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<td>--------------</td>
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<tr>
<td>TZEV</td>
<td>Transitional zero-emission vehicle</td>
</tr>
<tr>
<td>UDDS</td>
<td>Urban dynamometer drive schedule</td>
</tr>
<tr>
<td>ULEV</td>
<td>Ultra-low-emission vehicle</td>
</tr>
<tr>
<td>US06</td>
<td>A high-speed, high-acceleration, test procedure designed to measure off-cycle emissions</td>
</tr>
<tr>
<td>U.S. DOE</td>
<td>United States Department of Energy</td>
</tr>
<tr>
<td>U.S. EPA</td>
<td>United States Environmental Protection Agency</td>
</tr>
<tr>
<td>VC-T</td>
<td>Variable compression ratio turbocharged engine</td>
</tr>
<tr>
<td>VMT</td>
<td>Vehicle miles traveled</td>
</tr>
<tr>
<td>ZEV</td>
<td>Zero-emission vehicle</td>
</tr>
<tr>
<td>zVMT</td>
<td>Zero-emission vehicle miles traveled</td>
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REFERENCES


AFDC 2017. U.S. DOE Alternative Fuels Data Center, data as of 01/10/ 2017 http://www.afdc.energy.gov/fuels/electricity.html


https://www.arb.ca.gov/research/apr/past/12-332.pdf

http://blog.iseecars.com/2016/07/18/fastest-selling-used-cars/

http://www.mass.gov/eea/pr-2016/increased-funding-for-electric-vehicle-rebate-program.html


http://img03.en25.com/Web/NADAUCG/%7B49f71c70-31ef-4af9-870b-aeac4c6245bd%7D_201604_Atractive_Powertrains.pdf

https://www.arb.ca.gov/msprog/consumer_info/advanced_clean_cars/vct_engine_technology_yutaka_fujimoto.pdf


http://www.nrel.gov/docs/fy16osti/65279.pdf

http://www.arb.ca.gov/research/apr/past/13-313.pdf


Accessed January 11, 2017

Appendix A:
Analysis of Zero Emission Vehicle Regulation Compliance Scenarios:

Estimated minimum 1.2 million ZEVs and PHEVs by 2025

January 18, 2017
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I. Introduction
California’s zero emission vehicle (ZEV) regulation is a credit-based percentage requirement intended to balance new vehicle sales with the type of vehicle technology being produced. The regulation itself does not specify a total vehicle sales volume target. In the original Advanced Clean Cars (ACC) rulemaking, a potential compliance path was identified that manufacturers could pursue in the 2018 through 2025 model years for meeting ZEV regulation requirements. This compliance path estimated 1.4 million ZEVs (meaning battery electric vehicles, or BEV, and fuel cell electric vehicles, or FCEV) and plug-in hybrid electric vehicles (PHEV) on the road by 2025, making up approximately 15% of new vehicle sales in 2025 model year. Since the 2012 adoption of the ACC requirements, vehicle technology has advanced faster and developed more broadly than originally anticipated, and the assumptions used in the original rulemaking scenario no longer reflect vehicles expected in the 2018 through 2025 timeframe.

The ZEV midterm review (MTR) includes the detailed examination of all of the manufacturers subject to this regulation to assess the status of technology through their product plans. This proprietary information was used to develop revised compliance scenarios and a “ZEV Calculator” which are intended to explain the potential effect various flexibilities and developing technology has on the overall number of vehicles expected from the regulation. These scenarios are “minimum compliance scenarios”, which emphasizes the main function of the ZEV regulation: to set a floor to ensure pure ZEV technology is being produced to help the technology reach commercialization. The question that these scenarios answer is how much could be expected (at a minimum) from the ZEV regulation in any given model year.

Minimum compliance scenarios are typically used by ARB to determine the cost for manufacturers to meet regulatory requirements and are combined with projected emission benefits to determine the cost-effectiveness of the requirements. These scenarios are not a market forecast of what actual total sales may be or will likely be in any given model year, but rather are regulatory compliance projections using the best available information at the time of this review. The purpose of this appendix is to explain the inputs and process to develop these draft scenarios, as well as the ZEV Calculator tool, an Excel spreadsheet that can be used to compare various compliance scenarios simultaneously.

II. Summary
Staff developed three scenarios using the latest version of the ZEV calculator:1 a mid-range ZEV-technology case, a slow ZEV-technology advancement case, and a high ZEV-technology development case. Each of these cases uses a different set of assumptions briefly described in

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1 The ZEV calculator, an Excel tool, was first developed for the 2012 ZEV/ACC rulemaking to calculate minimum compliance with the 2018 through 2025 model year requirements. This appendix describes updated inputs used in an expanded ZEV calculator tool. The updated ZEV calculator is posted: https://arb.ca.gov/msprog/zevprog/zevcalculator/zevcalculator.htm
Table 1 that are consistent within each case, and pertain to overarching themes of technology readiness and pace of future development. In addition to considering future vehicle technology advancements and expected usage of regulatory flexibilities when developing these scenarios, the current ZEV credit banks were factored in, including near term expected credit generation and longer term expected credit usage. Details of the assumptions used for each scenario are provided in section IV.

Table 1 - Summary of Scenario Themes

<table>
<thead>
<tr>
<th>Scenario</th>
<th>Theme</th>
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<tbody>
<tr>
<td>Mid-Range ZEV Technology Advancement Case</td>
<td>Continued advancement in ZEV technology leads to balance of new sales of improved capability ZEVs and moderate use of banked ZEV and GHG credits</td>
</tr>
<tr>
<td>Slow ZEV Technology Advancement Case</td>
<td>Delayed advancement in ZEV technology leads to higher dependence on banked ZEV and GHG credits to support sales of only slightly improved ZEVs</td>
</tr>
<tr>
<td>High ZEV Technology Advancement Case</td>
<td>Aggressive advancement in ZEV technology leads to larger increase in new sales of highly capable ZEVs as dominant mechanism for compliance</td>
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Figure 1 below is a summary of the three cases and the minimum cumulative number of ZEVs and PHEVs expected from each scenario.

Figure 1 - California cumulative 2 scenario results (2010 through 2025 model year)

*For each scenario, it is assumed 347,000 ZEVs and PHEVs have been placed in California through 2017 model year. See Section III.B.2 and Section V.C (Table 8).

2 Throughout this report, PHEVs are assumed to be transitional zero-emission vehicles (TZEV) that meet the requirements in CCR 1962.2 (c), meaning all PHEV numbers shown throughout the report meet SULEV 30 exhaust emission certification, zero evaporative emissions, and have an extended warranty on the battery and emission system. Not all PHEVs currently sold are TZEVs and only TZEVs can be counted towards a manufacturer’s ZEV requirements. Accordingly, staff has excluded non-TZEVs from the PHEV calculations and analysis throughout this appendix.
The mid-range case yields a minimum 800,000 ZEVs and PHEVs cumulatively between 2018 and 2025 model year to meet the regulation. When added to the 182,000 ZEVs and PHEVs sold between 2011 and 2015 model year (based on data from the California Department of Motor Vehicles), and the additional 165,000 projected for 2016 and 2017 model years,\(^3\) approximately 1.2 million cumulative ZEVs, and PHEVs, can be expected by 2025 model year.

II.A 2012 “Expected Compliance Scenario”

In the initial statement of reasons (ISOR) for the 2012 Advanced Clean Car (ACC) rulemaking,\(^4\) a scenario was developed to help explain the effect of the proposal on the projected vehicle deliveries as a result of the amendments to the ZEV regulation in California. At that time, the main scenario in the staff report estimated 1.4 million cumulative ZEVs and PHEVs for the 2018 to 2025 model years. Figure 2 was presented in the original staff report.

![Figure 2 - California 2012 ZEV regulation compliance scenario](image)

When this scenario was developed for the 2012 rulemaking, the following assumptions were used:

- manufacturers would maximize the portion of the requirement that could be met with PHEVs
- manufacturers would minimize the number of pure ZEVs (BEVs, FCEVs) in any given year
- BEVs would be capable of 100 miles on the urban dynamometer drive schedule (UDDS) in the 2018 through 2025 model year timeframe

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\(^3\) See Section III.B.2 for details on the projection of 165,000 ZEVs and PHEVs for 2016 and 2017 model years.

• PHEVs would be comprised of a mix of blended (non-US06 test cycle capable) and non-blended (US06 test cycle capable) PHEVs with an electric range between 22 and 40 miles on the test cycle
• a growing number of manufacturers would be producing FCEVs with a 350 mile UDDS range through 2025

This original scenario did not take into account several regulatory flexibilities that were subsequently considered and adopted by the Board in the 2012 ACC rulemaking. Historical earned ZEV credits were also not considered in the scenario because most manufacturers, at the time of developing the ACC amendments, had modest levels of credits in their banks and limited numbers of announced products that they would be offering in the next few years.

Technology assumptions were also based on the best available information at that time. Neither manufacturers nor technology development projections supported the feasibility of 200 (or more) mile range BEVs in the near term, and only two PHEVs were on the market,5,6 with few others announced. Technology developed rapidly, and five years later, much more capable BEVs and PHEVs are available, and even more are scheduled for release within the next five model years.

III. Developing new minimum compliance scenarios

III.A Updating the ZEV Calculator

As part of the 2012 ACC rulemaking, staff developed a “ZEV Calculator”,7 which showed an industry wide minimum compliance scenario through 2025 for the ZEV regulation. Other analysis, which showed the impact of other regulatory flexibilities that were being considered for adoption, were also released, but until this point, one tool had not been released which combined all the flexibilities adopted into one calculator. In addition to regulatory flexibilities, the calculator has been updated so that a user can readily change assumptions regarding the use of flexibilities, banked credits, compliance strategy, and technology assumptions for the types of vehicles being produced. The output of the calculator remains the same: a minimum number of vehicles needed under each scenario to achieve annual compliance with the regulation on a fleet-wide basis. Staff used this enhanced ZEV Calculator when developing these new scenarios and, for convenience, the calculator has been pre-populated with the three scenarios presented in this document.

In developing the new minimum compliance scenarios presented in this report, a new analysis was conducted for compliance within the Section 177 ZEV states. In many cases, the analysis includes the same key assumptions for both California and Section 177 ZEV states. For example, manufacturers are assumed to produce and deliver for sale the same technology

PEVs (with the same range) in California and each of the Section 177 ZEV states. As will be discussed in detail below, the analysis takes into account the differences in the California and Section 177 ZEV state credit banks.

III.B Process
In developing the scenarios and ZEV Calculator, various assumptions in the ZEV Calculator used for the 2012 ACC rulemaking have been updated. The following section reviews the assumptions and inputs that were modified and how regulatory flexibilities were modeled to better represent the annual minimum (the “floor”) requirement through 2025 model year.

III.B.1 Annual Sales and Original Equipment Manufacturer (OEM) Market Shares
The annual sales assumptions affect every other output in the scenarios, since a manufacturer’s annual ZEV requirement is based on its total new vehicle sales. The scenario for the 2012 ACC rulemaking utilized ARB’s EMFAC 2010 projections of future California sales volumes to generate annual sales volume for each manufacturer. To calculate Section 177 ZEV state volumes, California volumes were multiplied by a factor of 2.0, a factor which was based on known sales data at the time. For the updated scenarios, new information exists both for total industry sales and for Section 177 ZEV state volumes. For total volumes, the updated scenarios are based on the U.S. Energy Information Administration’s Annual Energy Outlook (AEO) 2015 national sales projections. In accordance with the regulation, the revised analyses assume all manufacturers would use the previous year’s average method through 2025 model year to calculate their applicable sales volumes (and thus, their ZEV credit obligation).

According to IHS Automotive, in calendar year 2015, 12% of U.S. new vehicle sales were in California, and 16% were in the Section 177 ZEV states that have a ZEV requirement. Total annual sales projections for California and the Section 177 ZEV states were then calculated using these market shares and the AEO projections for nationwide volumes. In addition to data from IHS, calculated OEM specific market shares are based on publically available data posted with ZEV credit bank disclosure for California and the Section 177 ZEV states. Three of the nine states (Oregon, New York, and New Jersey) have easily accessible ZEV credit bank data. An average of these three market shares yields new representative OEM specific market shares for the Section 177 ZEV states. Because large volume and intermediate volume manufacturers (LVM and IVM, respectively) can comply with credit percentage requirements in different ways, the ZEV calculator allows for separate assumptions for the LVM market and the IVM market. Below is a list of manufacturers’ size classifications expected by 2018 model year.

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9 CCR 1962.2 (b)(1)(B), Calculating the Number of Vehicles to Which the Percentage ZEV Requirement is Applied.
10 IHS 2015. IHS Automotive. Polk new vehicle registrations for CYE2015
11 Staff confirmed the average of NY, NJ, and OR market shares closely align with actual OEM market shares in all nine states with confidential Polk vehicle registration data.
For the calculator, current market shares for each individual manufacturer (based on publicly available information) have been provided solely for informational purposes. These numbers have not been used directly in any of the assumptions other than determining the portion of total California and Section 177 ZEV state sales attributable to LVM and IVMs (to calculate their correspondingly different credit requirements). The individual manufacturer market shares provided in the calculator, however, represent that manufacturer’s market share of the LVM (or IVM, as applicable) market rather than its market share of total vehicles sales. For example, the total share of General Motors sales in CA is 9% on average for 2013 through 2015 model year. However, General Motors market share of the LVM market is 12%. The three new scenarios utilize confidential business information provided by individual vehicle manufacturers along with additional information to arrive at industry-wide generalizations of the technologies and paths expected to be used for minimum compliance. Accordingly, the scenario assumptions are not aligned with any individual manufacturer’s market share nor do they reflect manufacturer-specific future product plans or assumptions.

III.B.2 ZEV Credit Bank: Generating Credits
One aspect excluded from the model in past scenarios was the effect of banked ZEV credits on the overall number of vehicles that could be expected in any given year. During the development of the ACC rulemaking, historical credits were at relatively low levels and were expected to have an insignificant impact on compliance. Manufacturers have been over complying with ZEV regulations since the early years of the program. Typically, manufacturers have amassed credits banks under three conditions.

1) In early years, the Board awarded technology development with a larger number of credits per vehicle. For example, in the late 1990s and early 2000s, manufacturers could earn 40 credits per FCEV produced, and 10 credits per BEV produced when vehicles were basically non-existent and the Board wanted to jumpstart a very early technology market. Generally, these older
credits have already been used toward compliance or have been capped and, therefore, have limited use.

2) Manufacturers will purchase and trade credits to either diversify their credit bank, comply with current year requirements in the case of unforeseen technology failure, or prepare to meet future model year requirements.

3) Manufacturers are successful in producing vehicles, and sell more than the requirements call for in a given model year in response to growing consumer demand in an expanding market. Manufacturers choose to hold these credits rather than sell on the open market.

Since the 2012 ACC rulemaking, the ZEV market has grown significantly and manufacturers have started earning and banking credits while the requirements remain low. Compliance with 2015 model year ZEV regulation requirements is now complete for California and the Section 177 ZEV states, which is the basis for staff’s assumption on the total number of credits available in the credit bank. Some manufacturers carry a two to three model year credit compliance buffer, even after 2015 model year compliance.

In order to create a more accurate picture of credit balances into the 2018 model year, projections are included for 2016 and 2017 model year actual market sales to determine compliance and credit generation. To calculate the projected sales volumes for ZEVs and PHEVs in model years 2016 and 2017, historical sales numbers were used for ZEVs and PHEVs in California and Section 177 ZEV states for model years 2011 through 2015. A linear extrapolation of the historical sales data was then used to calculate projected sales of ZEVs and PHEVs in California and the Section 177 ZEV states. This data was also used to create a sales-weighted average per vehicle credit value of 3.29 for ZEVs and 1.98 for PHEVs in model year 2015. The average per vehicle credit values were used to convert the projected new vehicle sales numbers into the total projected number of credits generated for model year 2016 and 2017 ZEVs and PHEVs.

Each manufacturer’s total production volume for model years 2016 and 2017 was projected (to determine the ZEV credit obligation for each year). Since the 2008 ZEV regulatory amendments, Section 177 ZEV states have been required to publicly disclose manufacturers’ annual ZEV compliance data, including banked credits and total production volumes. However, as there is a lag in time for actual sales to complete (i.e., prior model year vehicles can be sold up to six months into the next calendar year), final accounting of actual sales and credits generated is not known until September of the following year (e.g., 2015 model year sales are not fully accounted for and documented until September of 2016). Accordingly, only

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13 See Appendix B, Section III.A.2.c. for total ZEV and PHEV sales volumes in California and Section 177 ZEV states.
14 For purposes of calculating average ZEV credit, a sales weighted average of BEVs, range extended battery electric vehicles (or BEVx) and FCEVs was computed.
15 California Exhaust Emission Standards and Test Procedures for 2018 and Subsequent ZEVs, section D.3.
ZEV and PHEV sales through 2015 model year are fully accounted for at this time and 2016 and 2017 sales must use projected sales numbers.

California posts ZEV compliance data including total bank balances, annual production volumes, and credit transfers, and has done so for model years 2009 through 2015. California’s ZEV compliance data was used to determine total production volumes for each regulated manufacturer in California for model years 2010 through 2015. Using Section 177 ZEV state model year 2014 compliance data, it was possible to determine each manufacturer’s annual light-duty production volume in each state. These production volumes were used to calculate the proportional value of each manufacturer’s light-duty sales (as compared to California sales). The proportional value was then applied to the manufacturer’s production volumes from the California ZEV compliance reports to estimate the yearly production volume for each regulated manufacturer in each of the Section 177 ZEV states for model years 2010 through 2015.

Through model year 2017, a manufacturer has the option to calculate the applicable production volume to which its ZEV credit percentages are applied by using either the current model year volume or a 3-year running average calculation (the average of the 4th, 5th, and 6th prior model year volumes). For simplification, staff assumed each manufacturer’s total sales volumes will grow over time, and as a result, the 3-year average calculation method would be more favorable to manufacturers as it will yield a lower applicable production volume and a lower annual ZEV credit requirement. The 3-year average method was used to calculate the total ZEV credit requirement for each manufacturer, in each state, for model year 2016 and 2017 compliance. The calculation of the total ZEV credit requirements also took into account various compliance flexibilities and regulatory requirements, such as the Section 177 ZEV state “Optional Compliance Path” and the carry forward provisions of previously earned ZEV credits.

One important provision to consider was the “travel provision” which has an effect on both California and Section 177 ZEV state ZEV credit banks. This provision allows manufacturers, through 2017 model year, to earn credits for BEVs and FCEVs placed in California or in a Section 177 ZEV state at a proportional value as if they were also placed in all the other states. This provision does not apply to PHEVs but does extend indefinitely beyond 2017 for FCEVs given the state of deployment of hydrogen refueling infrastructure. The applicable production volumes, calculated as explained above, were also used to calculate the proportional value for CA and the Section 177 ZEV states, in order to determine the number of credits that manufacturers could generate as a result of traveling credits. While not all previously earned ZEV credits eligible for travel have indeed been traveled as of this time, staff assumed for these scenarios that all manufacturers would choose to travel all credits earned in model year 2016.

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16 Section 177 ZEV states also make their ZEV credit banks publically available, though some require compliance with public records act guidelines.
17 CCR 1962.1(b)(1)(B)2. “Calculating the Number of Vehicles to Which the Percentage ZEV Requirement is Applied”
18 CCR 1962.1(d)(5)(E)3. “Optional Section 177 ZEV state Compliance Path”
19 CCR 1962.1(g)(6)(B) and (C) “Carry forward for 2009 – 2011 model year ZEV credits”
20 CCR 1962.1(d)(5)(E) 2. “Counting Specified ZEVs Placed in a Section 177 ZEV state and in California: Provisions for 2010 through 2017 Model Years”
and 2017. The total ZEV credit requirement was subtracted from the total number of credits earned after all manufacturers traveled their eligible credits to calculate the projected 2016 and 2017 model year ZEV and PHEV credit banks. This value was then added to the manufacturer's reported 2015 credit banks\(^{21}\) to determine the projected total number of banked credits after model year 2017 compliance.

As a result, all three scenarios essentially began with the assumptions that the industry, as a whole, would carry the following bank of ZEV credits into 2018 model year:

<table>
<thead>
<tr>
<th>Table 3 - Post-2017 Model Year ZEV Credit Bank Values</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>California</strong></td>
</tr>
<tr>
<td><strong>Industry Credits</strong></td>
</tr>
<tr>
<td>ZEV Credits</td>
</tr>
<tr>
<td>662,900</td>
</tr>
<tr>
<td>PHEV Credits</td>
</tr>
<tr>
<td>208,000</td>
</tr>
<tr>
<td><strong>IVM</strong></td>
</tr>
<tr>
<td>66,000</td>
</tr>
<tr>
<td>0</td>
</tr>
<tr>
<td><strong>Section 177 ZEV states</strong></td>
</tr>
<tr>
<td>ZEV Credits</td>
</tr>
<tr>
<td>776,600</td>
</tr>
<tr>
<td>15,500</td>
</tr>
<tr>
<td>PHEV Credits</td>
</tr>
<tr>
<td>45,000</td>
</tr>
<tr>
<td>0</td>
</tr>
</tbody>
</table>

Due to changes in the volume status definitions for manufacturers starting in model year 2018, many of the current IVMs will transition to LVM status. The projected number of credits that will be held by those manufacturers that will be IVMs in model year 2018 and beyond was estimated based on the projected industry credit total. First, 2015 ZEV compliance reports were used to determine the current percentage of total banked ZEV credits that are held by manufacturers expected to be IVMs in 2018 and beyond. This same percentage was then applied to the total projected industry credits to calculate the amount of banked credits that will be held by IVMs starting in 2018 model year.

III.B.3 Credit Usage
Manufacturers have emphasized that it is unrealistic to carry a “zero balance” in their ZEV credit bank going into a future model year. Manufacturers traditionally factor in compliance margins to ensure compliance given uncertainties in knowing ahead of time how well a particular vehicle model will sell. Therefore, a key assumption for each of the scenarios relates to how many credits OEMs would leave in their banks relative to what would be needed for 2026 and subsequent model year compliance. Given the adopted ZEV requirement is constant from 2025 model year on, the assumptions ranged between a compliance buffer representing as little as half a year’s compliance and as much as two years of compliance. This range is consistent with feedback from manufacturers who typically expressed targets of one to two years depending on their tolerance for risk. This is also consistent with historic compliance margins by vehicle manufacturers with emission regulations such as the GHG and criteria pollutant fleet average standards where industry is usually complying at a level equivalent to at least the next model year’s requirements if not beyond.

\(^{21}\) One manufacturer did not submit a complete report for model year 2015 compliance. Historical registration data was used to estimate the number of vehicles sold and approximately 22,000 credits were added to the California model year 2015 BEV bank balance.
For the new scenarios, any ZEV credits in excess of the targeted level for 2026 are spread out and used evenly across the 2018 through 2025 model years to reduce the manufacturer’s obligation for those years. For example, for the mid-range case, it was assumed that manufacturers (both IVMs and LVMs) would target a one year credit buffer (to be able to satisfy 100% of their 2026 model year requirements). Accordingly, all credits in excess of that needed volume were used evenly across all eight compliance years (2018-2025) to reduce the annual obligation. This resulted in LVMs selling vehicles to meet 80% of their obligation each year and using approximately 400,000 ZEV and TZEV credits to satisfy approximately 20% of the annual credit requirement in the 2018 through 2025 model years.

However, because one purpose of the scenarios is to determine the total number of vehicles that would be used to meet the 2018 to 2025 requirements, any credits used to meet a portion of the requirements must also be converted to the number of vehicles used to create those credits to get an accurate total vehicle count. In each scenario, the number of historical credits cumulatively used is translated back into the number of vehicles that would have had to be produced to originally generate those credits. This is done by dividing the number of historical credits used by the average credits per vehicle generated in the pre-2018 timeframe. These “vehicles” are then added into the cumulative number for each scenario to give a more accurate depiction of the true number of vehicles—produced during those years or prior to those years—used to meet the 2018-2025 requirements. For instance, if 50,000 extra ZEVs are produced prior to 2018 and the credits from those cars are then used to satisfy some of the credit obligation in 2018-2025, those 50,000 ZEVs are counted towards the cumulative number of vehicles required to meet the 2018-2025 requirements. These vehicle calculations were done for California only; the travel provision, as discussed previously, has helped generate credit banks in the Section 177 ZEV states prior to 2018 model year.

III.B.4 Credit Trading and Credit Purchases
Based on reported ZEV credit transaction activity, many manufacturers have participated in credit transfers, trades, and purchases. According to the 2015 model year ZEV credit bank, one manufacturer (Tesla) accounted for 85% of the credits (sold) to other manufacturers.\(^{22}\) As mentioned above, 2015 model year sales were used to forecast sales for 2016 and 2017 model year for purposes of creating a post-2017 bank, and all manufacturers producing ZEVs and PHEVs were considered in these forecasts. The output of each scenario is a minimum number of vehicles that could result from the entire industry, in minimum compliance with the regulation, in a given year. The scenarios equally represent a case where each manufacturer completely satisfies its own obligation or a case where “perfect” credit trading occurs, meaning individual manufacturers would generate, trade, buy, and sell credits as necessary for industry as a whole to exactly meet the annual requirements.

\(^{22}\) ARB 2016b.
III.B.5 OEM Technology Assumptions and Compliance

With recent product announcements about longer range BEVs in ever increasing numbers, many have speculated about the effect this could have on compliance with the ZEV mandate. Since 2012, OEMs have made significant progress in improving electric vehicle range, capability, and efficiency. Some manufacturers have focused on a specific ZEV technology while others have produced offerings in multiple technologies. This is a flexibility currently allowed by the regulation, but not necessarily modeled in past scenarios. All of these factors have been updated with the best available information in order to reflect these improvements in the new scenarios.

As previously mentioned, in Section II.B ARB’s expected compliance scenario developed for the 2012 ACC rulemaking assumed that all BEVs produced in compliance (through 2025 model year) would have a 100 mile test cycle range, all PHEVs would have 22-40 miles of test cycle range, and all FCEVs would have at least 350 miles of range (maxing out the number of credits that could be earned within the program). It was also assumed that all LVMs would make the maximum number of PHEVs allowed in any given year, and the minimum number of pure ZEVs. Additionally, it was assumed that all IVMs would produce only PHEVs to comply.

Using the most recent information for these updated scenarios, significantly more aggressive improvements in BEV and PHEV technology advancement are assumed. For example, the average BEV label (not test cycle) range for 2018 is projected to be approximately 150 miles in both the “Slower ZEV Tech” and “Mid-Range” cases. This assumption was determined from the sales-weighted label ranges of all non-premium BEV models in the California market for 2015 model year and factoring in expected short term improvements and announced product offerings. Several manufacturers have announced significantly increased driving ranges for their current BEV models beginning with the 2017 model year. Estimations of those increased ranges, based on such announcements, were then applied to vehicles that were available in 2015 model year, since those were known to be available for 2016 and 2017 model years. Additionally, for these new scenarios, the revised analysis considered an annual growth rate in electric range for both BEVs and PHEVs, rather than a constant or a discrete step change in average electric range. The assumptions for annual growth rate in range and for the average range in 2018 model year change for each of the three scenarios. FCEVs are still assumed to maximize credits (4 credits each, at 350 or more miles test cycle range) between 2018 and 2025 model year. The analysis does, however, include a modification of the projected market shares in the auto industry that would involve BEVs and/or FCEVs. All cases assumed some level of FCEV production, and the mid-range and high technology cases include the same number of FCEVs as in the latest projections reported in the ARB Assembly Bill 8 report.

24 Credits are awarded according to a vehicle’s UDDS range. Some stakeholders have commented that label range is easier to understand. The updated compliance calculator does use a “label” range as an input; however, the label range is converted into a UDDS test cycle range by dividing the label range by 0.7.
In general, OEMs have also coalesced (for the moment) on two distinct variants of PHEVs. To reflect this current trend, the ZEV Calculator allows for two separate PHEVs to be factored in (noted as PHEV A and PHEV B in the updated ZEV calculator) and the assumptions used for each PHEV vary across the three scenarios. In the regulation, a PHEV able to complete 10 miles in all electric mode (without an engine start) on the US06 test cycle earns an additional 0.2 credits based on the expectation that such a vehicle will be operated more like a ZEV and thus, credited using the same exact formula as ZEVs. As of today, only two PHEVs have been able to satisfy this requirement. Currently, the Chevrolet Volt and the Toyota Prius Prime are the only certified PHEVs able to earn this additional credit. Most other PHEVs on the market are blended, meaning the engine will come on independently as needed to meet higher driving demands before the battery is fully depleted, and they are unable to follow the US06 trace without starting and using the engine to supplement the electric powertrain. For these scenarios, the market shares of the industry were modified for each of the two types of PHEVs, as well as the assumed average range on each of these vehicles types.

Most manufacturers (LVM and IVM) have plans to produce a pure ZEV, with the majority focusing on longer than 100 mile range BEVs. This is evident from OEM press announcements, and confirmed directly by industry. Many have also announced plans to produce PHEVs at various ranges, with various all-electric power capabilities. Taking this into consideration suggests a slightly larger portion of the ZEV credit obligation would be met with production of pure ZEVs, rather than assuming all LVMs would fulfill as much of their requirement as possible with credits from PHEVs. Additionally, IVMs are on track to comply with a mix of BEVs and PHEVs, even though the regulation allows IVMs to comply fully with PHEVs. As pure ZEVs generally earn more credits per car than PHEVs, this change in assumptions directionally resulted in higher ZEV penetration, lower PHEV penetration, and lower overall ZEV and PHEV combined volumes in the new scenarios.

IV. Scenarios

IV.A Mid-Range ZEV Technology Advancement Case (Scenario 1)

In this new, central compliance scenario, there is continued advancement in ZEV technology, consistent with trends observed in the last few years, which would result in manufacturers selling an increasing number of ZEVs and PHEVs each year and utilizing flexibilities allowed within the regulation to reduce their ZEV obligation.

IV.A.1 Technology Assumptions:
This scenario includes a steady 5% annual growth in electric range for BEVs and both variants of blended and US06 capable PHEVs, starting from an all-electric range (AER), (label not test cycle) of 150, 20, and 40 miles, respectively. The range assumptions below show an industry wide average for BEVs and PHEVs in 2018 and 2025 model year.

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26 CCR 1962.2(c)(3)(A)1. “Allowance for US06 Capability”
27 Including the similar version with a shared architecture marketed as the Cadillac ELR
28 See Appendix C for future product offerings.
Table 4 - Mid-Range Scenario AER Label Average by Technology Type

<table>
<thead>
<tr>
<th>PEV type</th>
<th>model year 2018</th>
<th>model year 2025</th>
</tr>
</thead>
<tbody>
<tr>
<td>BEV</td>
<td>150 miles</td>
<td>211 miles</td>
</tr>
<tr>
<td>Non-US06 PHEV</td>
<td>20 miles</td>
<td>28 miles</td>
</tr>
<tr>
<td>US06 PHEV</td>
<td>40 miles</td>
<td>56 miles</td>
</tr>
</tbody>
</table>

Manufacturer technology diversity also plays into the number of vehicles that result in each of these scenarios. In the mid-range case, the manufacturers continue making the same types of vehicles and technologies (with higher ranges and more capability) they have been producing through 2016 model year. For example, manufacturers pursuing FCEVs in 2016 would continue to pursue producing FCEVs in 2018 and beyond. Those manufacturers working on US06 capable PHEVs would continue working on that technology in 2018 and beyond. However, competitive pressures, increased infrastructure availability, reduced battery prices, and positive market reception result in increases in vehicle capability and electric range over time. More manufacturers produce FCEVs as hydrogen infrastructure is built-out throughout California. The same trend is assumed for those manufacturers pursuing BEV and PHEV technology. More manufacturers (50% by 2025) offer longer range and US06 capable PHEVs. BEVs continue to be increasing in range through the 2025 timeframe. IVMs offer both BEVs and PHEVs, though no selection is made about which individual manufacturers would pursue one technology over the other or offer both. For IVMs, compliance was assumed to be met with a 50-50 split of non-US06 capable PHEVs and BEVs throughout the eight years of compliance with the standards.

IV.A.2 Regulation Assumptions:

By the end of December 2016, manufacturers are required to notify ARB of their intent to pursue the GHG-ZEV over compliance option, which allows manufacturers that over comply by at least 2 grams per mile with the federal GHG standard\(^\text{29}\) to use those credits, towards ZEV compliance through the 2021 model year. For this mid-range case, only a small portion of the LVM market (10%), consistent with product announcements in the time period, utilize this path. Another flexibility not previously considered in early scenarios is the cap on the usage of historical partial zero-emission vehicle (PZEV), advanced technology PZEV (AT PZEV), and neighborhood electric vehicle (NEV) credits.\(^\text{30}\) Analysis on the potential resulting bank of historical AT PZEV, PZEV, and NEV credits found that there were enough credits to fulfill approximately 75% of the allowed cap for these types of credits between 2018 and 2025. This assumption was held for all eight compliance years for the mid-range case.

As explained in Section II of this appendix, ZEV bank balances were examined. In this case, manufacturers maintain one model years’ worth of credit reserve in their banks (i.e., enough to

\(^{29}\) 40 CFR Part 86.1818-12

\(^{30}\) CCR 1962.2 (g)(6)(A) “Use of Discounted PZEV and AT PZEV Credits and NEV Credits”
fully comply with 2026 model year requirements\(^{31}\). Since the ZEV regulation requirements remain constant post 2025, manufacturers would have the same credit requirement in 2026 model year. Given the projected credit banks going into 2018, in any given compliance year, a LVM would meet (on average) 20% of its credit requirement with banked credits. Using the same one model year reserve assumption for IVMs, one of those smaller manufacturers would be able to meet almost 25% percent of its annual credit requirement with banked ZEV credits.\(^ {32}\)

**IV.A.3 Results**

**Figure 3 - Mid-Range Scenario Results (California)**

![Figure 3](image)

**Figure 4 - Mid-Range Scenario Results (California and Section 177 ZEV State Combined)**

![Figure 4](image)

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\(^{31}\) 2026 model year requirements are assumed to be the same credit percentage requirements as 2025 model year

\(^{32}\) See Section IV of this appendix for a detailed description of how banked credits have been accounted for in each scenario
The mid-range case results in approximately 8% of 2025 model year annual sales in California being ZEVs and PHEVs. By 2025, the mid-range case results in close to 900,000 ZEVs and PHEVs in California from minimum compliance with the regulation (solely for 2018 through 2025 model year requirements), with one million more cumulatively in the Section 177 ZEV states. Looking at combined Section 177 ZEV state and California sales, the mid-range scenario results in 7.5% of annual sales being ZEVs and PHEVs by 2025.

**IV.B Slow ZEV Technology Case (Scenario 2)**

For the second case, the scenario considers potential delays in technology advancement (i.e., battery costs remaining high, low demand, slow infrastructure development) leading to manufacturers spending more banked credits in order to comply with the regulation. The purpose of this scenario is to explore sensitivities showing high historical credit use over the 2018 through 2025 timeframe. \(^\text{34}\)

**IV.B.1 Technology Assumptions:**
This scenario includes a less aggressive 2.5% annual growth in range for BEVs and blended and non-blended PHEVs. In this case, BEVs and PHEVs have the same 2018 model year label range averages as for the mid-range case.

<table>
<thead>
<tr>
<th>PEV type</th>
<th>model year 2018</th>
<th>model year 2025</th>
</tr>
</thead>
<tbody>
<tr>
<td>BEV</td>
<td>150 miles</td>
<td>178 miles</td>
</tr>
<tr>
<td>Non-US06 PHEV</td>
<td>20 miles</td>
<td>24 miles</td>
</tr>
<tr>
<td>US06 PHEV</td>
<td>40 miles</td>
<td>48 miles</td>
</tr>
</tbody>
</table>

However, fewer manufacturers opt into putting as much technology on their vehicles, resulting in a greater number of manufacturers making non-US06 capable PHEVs, and all manufacturers by making both ZEV and PHEVs. Also, in this case, FCEVs remain at low (demonstration volume) levels. Due to lower AER and slower growth rate, this has the effect of fewer credits per vehicle, resulting in higher vehicle numbers needed to meet the requirements, especially in the earlier years of the regulation.

**IV.B.2 Regulation Assumptions:**
As stated above, manufacturers are more reliant upon regulatory flexibilities in meeting annual requirements. It is assumed that manufacturers representing 20% of the LVM market would need to take the GHG-ZEV over compliance provision, leaning more heavily on more of their

\(^\text{33}\) This number includes both vehicles newly produced and vehicles previously produced to generate credits that are then used to meet the regulatory obligation specifically in model years 2018 through 2025. See section V.C for analysis showing how these compliance scenarios can be used to calculate total cumulative vehicle numbers on the road in California by 2025.

\(^\text{34}\) Shulock 2016.
GHG fleet compliance in order to meet ZEV compliance. In terms of PZEV, AT PZEV, and NEV credits, 100% of the cap for both IVMs and LVMs for this set of historical credits would be met through 2025.

Finally, manufacturers use more of their ZEV credits, and only carry a credit bank at the end of 2025 representing one-quarter of their 2026 model year obligation.

IV.B.3 Results

Figure 5 - Slow-Technology Scenario Results (California)

Figure 6 - Slow-Technology Scenario Results (California and Section 177 ZEV State Combined)
The slow-technology case results in the fewest number of vehicles over the 2018 through 2025 time period that are the least technologically developed and consequently of lower consumer appeal, however due to higher historical credit use, it is assumed those vehicles would have to have been placed prior to 2018 model year (or in excess of the requirements) and are counted in the cumulative numbers show above, and discussed in further detail in Section V.A. While the lower range assumptions would lead to a need for more cars to meet the requirement, the scenario assumes these less capable PHEVs and BEVs, and lower production of FCEVs, result in a slower growth of ZEV sales. Additionally, this case results in a lower number of vehicles in the Section 177 ZEV states, because there are larger credit banks that are being spent. The slow technology case results in slightly more than 8% of 2025 model year annual sales in California being ZEVs and PHEVs. In the Section 177 ZEV states, PEVs resulting from the regulation would be 5% of annual sales in 2025.

IV.C High ZEV Technology Case (Scenario 3)
For a third scenario, the analysis explores the effect of aggressive advancement (even greater than currently announced) in all ZEV technology categories. In turn, this leads to longer range BEVs and PHEVs, and manufacturers not needing to utilize many of the flexibilities allowed by the regulation.

IV.C.1 Technology Assumptions:
An aggressive 7.5% annual growth in range for BEVs and US06 and non-US06 capable PHEVs is included in this scenario. In this case, the average 2018 model year BEV and PHEV label ranges are longer than previous scenarios. The table shows the averages assumed for the high technology case.

Table 6 - High Technology Scenario AER Label Average by Technology Type

<table>
<thead>
<tr>
<th>PEV type</th>
<th>model year 2018</th>
<th>model year 2025</th>
</tr>
</thead>
<tbody>
<tr>
<td>BEV</td>
<td>200 miles</td>
<td>300 miles</td>
</tr>
<tr>
<td>Non-US06 PHEV</td>
<td>25 miles</td>
<td>40 miles</td>
</tr>
<tr>
<td>US06 PHEV</td>
<td>45 miles</td>
<td>75 miles</td>
</tr>
</tbody>
</table>

A greater number of manufacturers are also assumed to be producing higher range US06 and non-US06 capable PHEVs, as well as FCEVs. Also, more manufacturers would comply fully with their annual ZEV requirement with BEVs only (vs. a mix of PHEVs and BEVs).

IV.C.2 Regulation Assumptions:
Like in the mid-range case, only a small portion of the LVM market (10%) takes the GHG-ZEV over compliance provision, and the same amount of the allowable cap (75%) would utilize historical PZEV, AT PZEV, and NEV credits. In this case, the manufacturers maintain enough credits in their bank at the end of 2025 to fully meet two additional model years’ requirements.
IV.C.3 Results

Figure 7 - High-Technology Scenario Results (California)

The high technology case results in a similar cumulative number of vehicles that result from the regulation as in the mid-range case. This is because technology assumptions have the greatest effect on the number of vehicles expected from each scenario, and similar technology assumptions are made in each case. The high technology case also results in fewer PHEVs, because more manufacturers are pursuing higher technology/longer range BEVs and FCEVs. By 2025, PHEVs and ZEVs represent 8.2% of annual California LDV sales, and cumulatively more than 850,000 vehicles between 2018 and 2025 model year. In the Section 177 ZEV states, due to FCEVs taking advantage of the travel provision and more credits being available, annual sales reach 5% by 2025, more than 600,000 cumulatively in all nine states.

Figure 8 - High-Technology Scenario Results (California and Section 177 ZEV State Combined)
Below is a summary of all assumptions (including assumptions made in the scenario developed for the 2012 ACC rulemaking) across all minimum compliance scenarios.

Table 7 - Summary of Compliance Scenario Assumptions

<table>
<thead>
<tr>
<th>Inputs</th>
<th>2012 ACC Rulemaking</th>
<th>Slower ZEV Tech</th>
<th>Mid-range</th>
<th>High ZEV Tech</th>
</tr>
</thead>
<tbody>
<tr>
<td>Annual growth in electric range</td>
<td>0%</td>
<td>2.5%</td>
<td>5.0%</td>
<td>7.5%</td>
</tr>
<tr>
<td>‘18-’25 model year BEV label range (mi)</td>
<td>70</td>
<td>150→180</td>
<td>150→210</td>
<td>200→300</td>
</tr>
<tr>
<td>‘18-’25 model year non-US06 PHEV label range (mi)</td>
<td>15 mile US06 or 28 mile non-US06</td>
<td>20→25</td>
<td>20→30</td>
<td>25→40</td>
</tr>
<tr>
<td>‘18-’25 model year US06 PHEV label range (mi)</td>
<td>40→50</td>
<td>40→55</td>
<td>45→75</td>
<td></td>
</tr>
<tr>
<td>GHG over-compliance</td>
<td>n/a</td>
<td>20% of LVMs</td>
<td>10% of LVMs</td>
<td>10% of LVMs</td>
</tr>
<tr>
<td>Credit Reserve (in ’26 model year)</td>
<td>n/a</td>
<td>25%</td>
<td>100%</td>
<td>200%</td>
</tr>
<tr>
<td>BEV only LVMs</td>
<td>n/a</td>
<td>0%</td>
<td>10%</td>
<td>10%</td>
</tr>
<tr>
<td>FCEV LVMs</td>
<td>17→40%</td>
<td>5%</td>
<td>35→45%</td>
<td>40→50%</td>
</tr>
<tr>
<td>US06 PHEV OEMs</td>
<td>n/a</td>
<td>35%</td>
<td>35→50%</td>
<td>50%</td>
</tr>
</tbody>
</table>

V. Summary of Results

New scenarios were developed reflecting updated or new information to analyze the impact of the regulatory requirements on the number and type of ZEVs reasonably expected for compliance in 2025. Three distinct scenarios were considered in order to explore model sensitivities. Each of the new scenarios result in fewer cumulative vehicles than the original compliance scenario used for the 2012 ACC rulemaking. This is due mostly to more capable
ZEVs projected for the market, which translated to longer range BEVs and PHEVs earning more credits (in some cases twice as much) than in the original compliance scenarios. However, the differences in the three new projected annual vehicle volumes are minimal, as shown below in Figure 9.

**Figure 9 - Annual Vehicle Volumes Projected by New Compliance Scenario Analysis**

The similarity between the projected annual number of vehicles expected based on each of the three new compliance scenarios suggests the regulatory flexibilities have a marginal effect relative to the effect of higher technology assumptions, which are vital in helping build the market. Manufacturers are responding to market demand by making more capable (and likely higher cost) BEVs and PHEVs. Below Figure 10 summarizes the results from each scenario by technology type.

**Figure 10 - Cumulative Vehicle Technology Type by Compliance Scenario (2018-2025)**
V.A “Bank Vehicles”: Accounting for Historical Credits

As noted above, these new scenarios represent the total number of vehicles that, for compliance, result from the updated analysis for the 2018 through 2025 model years presented in this report.

In the public process, an idea emerged that ZEV credits represent “paper cars” because presumably superfluous credits exist in the ZEV Bank (and are continuing to be awarded) that never came from actual vehicles. However, this idea is incorrect since every ZEV credit in the bank is the result of an actual vehicle being placed in California or the Section 177 ZEV states. In each of the new scenarios for analysis, the number of historical credits cumulatively used by the auto industry is translated back into the number of vehicles that would have had to be produced to originally generate those credits. This is done by dividing the number of historical credits used by the average credits per vehicle generated in the pre-2018 timeframe. These “vehicles” are then added into the cumulative number for each scenario to give an improved depiction of the number of vehicles—produced during those years or prior to those years—used to meet the 2018-2025 requirements. For example, if 50,000 extra ZEVs are produced prior to 2018 and the credits from those cars are then used to satisfy a credit obligation in 2018-2025, those 50,000 ZEVs are counted towards the cumulative number of vehicles required to meet the 2018-2025 requirements.

Below is the summary of the number of vehicles that would have had to have been produced in the pre-2018 timeframe, above and beyond the requirements, in order to generate sufficient additional credits used in each of the new three scenarios.

**Figure 11 - Historical Banked ZEVs and PHEVs by Compliance Scenario**

<table>
<thead>
<tr>
<th></th>
<th>Cumulative Historical Vehicles</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Bank ZEVs</strong></td>
<td></td>
</tr>
<tr>
<td>Mid Range</td>
<td>86,443</td>
</tr>
<tr>
<td>Slow Technology</td>
<td>134,804</td>
</tr>
<tr>
<td>High Technology</td>
<td>10,176</td>
</tr>
<tr>
<td><strong>Bank PHEVs</strong></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>39,524</td>
</tr>
<tr>
<td></td>
<td>67,347</td>
</tr>
<tr>
<td></td>
<td>-</td>
</tr>
</tbody>
</table>

V.B Longer range vehicles means more battery capacity

As stated previously, the purpose of the ZEV regulation is to help achieve commercialization and increasing the production volume of key technology components is an integral part of
achieving that goal. Most often, the total number of vehicles sold is considered a key metric for progress towards the regulation goal. However, as presented at the 2016 ACC Symposium, work by ARPA-E affirms that high volume battery manufacturing will be instrumental in getting costs and prices down, suggesting that other metrics may also be appropriate. Accordingly, this analysis considers the impacts to total battery volumes relative to the original 2012 assumptions. This was accomplished by assuming a battery pack capacity for each technology and range used in the three new scenarios, and multiplying that battery capacity by the volume of vehicles expected for those technologies and ranges. Battery capacity assumptions were developed in the same way for both BEVs and PHEVs, using the reported test cycle range from certification for available 2015 model year BEVs and PHEVs, and dividing that into the battery capacity of each of those models to identify each vehicle’s watt-hour per mile (Wh/mi) efficiency. A separate Wh/mi efficiency for BEVs and PHEVs was then calculated from the average of the 2015 model year BEVs and PHEVs, respectively. Each technology’s average efficiency was assumed to be the same for all model years or ranges across all compliance scenarios. That average efficiency was then used to calculate the required battery pack size to meet the required range identified for each technology by model year. Those required ranges were then used to calculate the total battery capacity by model year and the cumulative capacity across 2018 through 2025 model years of each scenario.

Figure 12 - Cumulative Battery Capacity (kWh) for Mid-Range and 2012 Compliance Scenarios (California)

Figure 12 shows that the updated compliance scenarios result in similar cumulative kWh of batteries produced by 2025, with annual accumulation of those kWh increasing above the

---


36 Tesla vehicles’ Wh/mi efficiencies were not calculated, because UDDS range numbers were not updated during the 2015 model year when Tesla added the 70kWh and 90kWh battery pack options.
original compliance scenario levels in the latter years. This is due to technology advancements, and more BEVs and PHEVs with greater battery capacity. These results help confirm that, despite a lower cumulative number of vehicles expected by 2025, significant progress is still being made within the current regulation towards achieving the broader goals of the ZEV regulation for advancing commercially viable technologies.

V.C How to use these compliance scenario results
The ZEV regulation intends to advance pure ZEV technology towards mainstream commercialization and ultimately transform the light duty vehicle market. One way it does this is by setting a regulatory minimum, or floor, to ensure an increasing number of vehicles are produced each year. As is shown below in Figure 13, manufacturers have over-complied with the regulatory requirements since the 2012 model year. And while this trend may continue, it is important to note that the updated compliance scenarios do not include any projection of vehicles above the regulatory minimum for 2018 through 2025 model years. Projections for 2016 and 2017 model year are based on partial year to date sales and DMV data and do, however, exceed the regulatory minimum, consistent with sales numbers for the past few years.

Figure 13 - Actual (and projected) annual compliance with 2012 through 2017 ZEV requirements

Through 2015 model year, 182,000 ZEVs and PHEVs have been registered in California according to Department of Motor Vehicles (DMV) data. According to projections derived from historical sales data\(^{37}\) and partial year to date sales information, approximately 165,000 additional ZEVs and PHEVs are expected for 2016 and 2017 model years. As explained above, the new scenarios take into account the number of vehicles produced above and beyond the requirements (in the 2016 and 2017 model years only) in order to more accurately project the

\(^{37}\) See Appendix B for more information on historical sales data.
credit banks available to manufacturers for the 2018 through 2025 years. And because the scenarios explicitly account for the number of vehicles used to generate credits that are subsequently used by manufacturers to meet part of their 2018 through 2025 requirements, these historical credits must be removed when summing 2018 through 2025 model year scenario results with the pre-2018 ZEV sales to avoid double-counting. Below is a summary table of these calculations for California for each scenario.

**Table 8 - Summary of Expected ZEVs and PHEVs by Compliance Scenario (California)**

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Mid-Range (Scenario 1)</td>
<td>182,000</td>
<td>165,000</td>
<td>953,000</td>
<td>(154,000)</td>
</tr>
<tr>
<td>Slow Tech (Scenario 2)</td>
<td>182,000</td>
<td>165,000</td>
<td>967,000</td>
<td>(230,000)</td>
</tr>
<tr>
<td>High Tech (Scenario 3)</td>
<td>182,000</td>
<td>165,000</td>
<td>867,000</td>
<td>(7,500)</td>
</tr>
</tbody>
</table>

The outcome is similar for the Section 177 ZEV states, as seen below.

**Table 9 Summary of Expected Vehicles by Compliance Scenario (Section 177 ZEV States)**

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Mid Range (Scenario 1)</td>
<td>48,000</td>
<td>34,000</td>
<td>1.1 million</td>
<td>(0)</td>
</tr>
<tr>
<td>Low Tech (Scenario 2)</td>
<td>48,000</td>
<td>34,000</td>
<td>720,000</td>
<td>(0)</td>
</tr>
<tr>
<td>High Tech (Scenario 3)</td>
<td>48,000</td>
<td>34,000</td>
<td>987,000</td>
<td>(0)</td>
</tr>
</tbody>
</table>

The total number of ZEV vehicles deployed in 2018 through 2025 would be the sum of these compliance numbers and any vehicles produced in over-compliance with the regulation requirements for the same years.

**VI. Conclusion**

The ZEV market has developed rapidly since the adoption of the ACC regulations in 2012. ZEV technology, especially for BEVs, has developed faster than anticipated and at declining costs resulting in longer range vehicles earlier than projected. Consumer feedback in support of longer range vehicles, competition, and the sales of current shorter range BEVs suggest that shorter range BEVs will have an increasingly more limited market than originally projected.
Based on this new data and knowledge, updates were made to the technical assumptions and inputs to develop new compliance scenario projections, as well as to develop an enhanced ZEV Calculator. The updated ZEV Calculator has been improved with newer data and added functionality which gives a more complete picture of compliance with the ZEV regulation through 2025. The updated minimum compliance scenarios reflect these changes, as well as regulatory flexibilities added in 2012 or later, and project approximately 1.2 million ZEVs and PHEVs on the road in California by 2025. Though these updated scenarios show a lower overall number of vehicles expected as compared to the scenarios developed for the 2012 ACC rulemaking, the vehicles will be more capable ZEVs and PHEVs that are critical to expand the market beyond early ZEV and PHEV consumers while continuing to drive increased battery volumes necessary to reduce ZEV costs.

Staff will continue to track technology progress to further refine the technology assumptions to better reflect trends in vehicle ranges, as well as electric powertrain developments. For future rulemakings, staff expects to utilize and continue to improve upon the ZEV calculator to develop further updated compliance scenarios.
VII. References


IHS 2015. IHS Automotive. Polk new vehicle registrations for CYE2015


Appendix B:
Consumer Acceptance of Zero Emission Vehicles and Plug-in Hybrid Electric Vehicles

January 18, 2017
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I. Key Findings

The zero emission vehicle (ZEV) regulation has been designed to accelerate commercialization of ZEV technology. While the ZEV regulation has been effective in generating product development and initial vehicle supplies, fleet transformation to near- or pure-ZEVs also requires consumers to demand and ultimately purchase these products. This appendix describes staff analysis using a variety of data sources on market trends, consumer acceptance, and the potential for market growth of plug-in hybrid electric vehicles (PHEV), battery electric vehicles (BEV), and fuel cell electric vehicles (FCEV) in California and states that have adopted California’s ZEV regulation under Section 177 of the Clean Air Act (Section 177 ZEV States) compared to other regions.

Since 2010, the market of ZEVs and PHEVs has developed from just a single vehicle model to 25 models offered by 14 manufacturers at the beginning of 2017. Although market shares have been relatively constant in recent years, as of June 2016, almost 450,000 ZEVs and PHEVs have been sold in the United States (U.S.), with California and Section 177 ZEV States accounting for about 60 percent of those sales. Although some models were initially only available for sale in states with a ZEV regulation, the market has also proliferated to other states in the U.S. and other countries, with a total of two million BEVs and PHEVs expected to be sold globally by the end of 2016. Compared to conventional hybrid electric vehicles (HEVs), BEVs and PHEVs have developed and diversified much more rapidly.

Regional variation in sales trends may be the result of uneven exposure to ZEVs and PHEVs at dealerships, which appears to be lower in Section S177 ZEV states, or through auto manufacturer advertising. Overall sales volumes are also affected by vehicle pricing, which can vary by state as a result of purchase incentives. The top 50 best-selling models of the 300 light-duty vehicle models offered in model year 2016 and almost 90% of all new vehicles sold during the first eight months of 2016 start at a base price of less than $35,000, with the largest volume of vehicles having a starting manufacturer suggested retail price (MSRP) between $20,000 and $24,999. In comparison, only when factoring in up to $10,000 worth of government incentives do ZEVs and PHEVs prices become competitive with conventional vehicle prices. Furthermore, dealers appear to be transacting ZEVs and PHEVs at prices close to starting MSRP, meaning that government incentives are resulting in effective prices paid by consumers substantially more discounted than those typically offered for conventional vehicles during the negotiation process.

1 See Section III.A for historic and current sales trends.
3 See Section III.A.3 for dealership availability analysis.
Multiple studies reveal a low but slowly increasing level of ZEV technology awareness and knowledge in California and throughout the U.S. and other studies show that increasing knowledge and exposure to these vehicles results in lasting, positive impressions. Among current ZEV and PHEV drivers, vehicle test drives served as influential information sources. Already over 10% of recent buyers (or lessees) are driving their second (or subsequent) ZEV or PHEV. The majority of households purchasing these vehicles have had no prior experience with any alternative fuel or hybrid technology. However, in general these households exhibit other characteristics conducive to ZEV and PHEV ownership, such as additional household vehicles, the ability to charge at home (or the ability to make changes to their residence that would allow for home-charging), and often the ability to charge at work.

During this initial stage of the market, many current ZEV and PHEV consumers were motivated to select their vehicle based on environmental benefits or a desire for the newest technology, though saving money overall or on fuel specifically is also a strong motivator. Purchase incentives and other complementary policies from assorted entities have also played an important role in supporting the emerging market by reducing the cost of purchasing or operating this new technology to the consumer. For example, workplace charging serves a dual role in supporting the market by providing consumers with assurances on charging away from home while also providing opportunities for increasing electric vehicle miles traveled.

However, until production costs fall sufficiently to more closely match with conventional vehicle prices, the future development of the market without continued incentives will be uncertain as purchase price remains a primary concern of potential consumers. Conversely, fuel cost savings have been a primary motivator for consumers to purchase a ZEV or PHEV, but continued relatively low gasoline prices in the near-term will reduce interest if vehicles do not provide counteracting appeal. Compounding this issue, some consumers may spend more to operate their plug-in electric vehicle (PEV, meaning any type of electrified vehicle with a plug) than they would a conventional vehicle if utilities are not offering (or consumers are not aware of) supportive electricity rates for vehicle charging.

Despite these challenges, additional growth in the ZEV and PHEV market is possible with continued action to increase product diversity, consumer awareness, and infrastructure deployment. More than 70 different ZEV and PHEV platforms are projected within the next five model years, though continued increases in overall market shares of ZEVs and PHEVs will require multiple successful models. The new vehicle market is highly competitive and diversified; even today's best-selling model of any technology does not account for more than four percent of total new light-duty vehicle sales in California or the U.S. Nonetheless, given the

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5 See Section III.C.1 for current ZEV consumer characteristics.
6 See Section III.C.2.d for discussion on the role of incentives and Appendix E for additional complementary policies discussion.
7 See Section III.C.1.e.iii for usage of EV rates and Section III.C.4.b for energy price impacts on operating costs.
8 See Section IV.A for future model availability.
9 See Section III.A.2.e for light-duty vehicle market shares.
large proportion of leases, many consumers will be returning to the market within two to three years and among all these current drivers, more than 90% report they would replace their current vehicle with another ZEV or PHEV and about half would be willing to pay additionally for greater all-electric range. While the majority of consumers would remain with their existing technology, there are slightly more consumers who would switch from a PHEV to BEV than the reverse, and the projected BEV offerings with greater all-electric range (often at lower price points) may further intensify this difference.\textsuperscript{10}

Finally, an emerging secondary market for ZEVs and PHEVs demonstrates demand for these vehicles, even in areas without regulatory requirements or purchase incentives. Combined with the new vehicle market, additional sales will continue to support development, production and supply of ZEV technologies that sustains employment and investments in California's automotive sector, while also spurring growth in battery manufacturing, infrastructure planning and construction, as well as electricity and renewable energy production. Such increases can also have spillover effects in other economic sectors.

\textsuperscript{10} See Section IV.B.1 for future purchase behavior of current ZEV and PHEV consumers.
II. Introduction and Background

Fleet transformation to near- or pure-zero emission vehicles (ZEV) requires not only auto manufacturers to develop and produce such vehicles, but also consumers to demand and ultimately purchase these products. Demand will be dependent on consumer awareness of the vehicles being offered as well as their characteristics – most notably vehicle price, available incentives, driving range, and the cost and convenience of recharging/refueling – and how consumers value these attributes. Additional factors, such as dealerships availability and product diversity may also influence the rate at which market shares may grow. This appendix describes consumer acceptance, sales trends, and pricing trends of plug-in hybrid electric vehicles (PHEV), battery electric vehicles (BEV), and fuel cell electric vehicles (FCEV) in California and states that have adopted California's ZEV regulation under Section 177 of the Clean Air Act (Section 177 ZEV States).  

The first part of the appendix describes the market landscape to date, which includes model offerings and regional availability, sales by region, vehicle availability on dealer lots, vehicle prices, awareness of ZEV (meaning BEV and FCEVs) and PHEV products among the general public, as well as attitudes and characteristics of existing PHEV and ZEV drivers. This discussion informs the following section of the appendix on the potential for market shares of these technologies to grow in the long term beyond current levels. Additionally, this appendix shows evolving consumer attitudes towards new vehicle technologies and provides indications of continued market growth based on future purchase behavior from both existing and prospective drivers. An emerging secondary market of PEVs also supports the possibility for developing a sustainable new vehicle market for electrified vehicles. Lastly, this appendix concludes with an overview of the broader economic implications for California that could result from increased ZEV and PHEV adoption to levels needed to comply with the ZEV regulation.

II.A. Data Sources

Staff analysis utilized an assortment of data sources. These include a combination of: freely available internet resources; subscription-based internet resources; licensed data from commercial vendors; data collected through state administered programs, including surveys to recipients of state vehicle rebate programs; ARB-sponsored research contracts; and assorted peer-reviewed publications and publicly available reports from external parties, such as media outlets, auto manufacturers, or other organizations. Some of these data sources are used for multiple analyses. Additional details on sources relied upon for original staff analyses are included in Section VII. A complete list of references is available in Section VI.

III. Recent Market Development and Current Status

Since its inception, the ZEV regulation has been designed to accelerate commercialization of ZEV technology. During the 1990s and early 2000, manufacturers produced and marketed a

\[\text{Footnote: Through Section 177 of the Clean Air Act, nine states have adopted California's ZEV regulation: Connecticut, Maine, Maryland, Massachusetts, New Jersey, New York, Oregon, Rhode Island, and Vermont. These nine states are commonly referred to as the Section 177 ZEV states.}\]
limited quantity of ZEVs, primarily distributed in California. The ZEV and PHEV market has developed considerably since the reemergence of commercially available vehicles with these technologies in late 2010. This section reviews staff’s current understanding of market trends, consumer awareness about ZEVs and PHEVs, and consumer acceptance and attitudes towards these vehicles. The first portion of this section summarizes historic and current sales trends with respect to model offerings, dealership availability, and vehicle pricing. As new products in the marketplace, with varying degrees of behavioral changes required for fueling these vehicles, the next portion of this section assesses consumer awareness and understanding of these vehicles. Next, this section discusses current PHEV and ZEV driver characteristics, as well as purchase motivations and barriers among both existing and prospective consumers alike. Finally, this section concludes with a review of current PHEV and ZEV driver experiences and attitudes towards their vehicles that may inform their future purchase behavior.

III.A. Historic and Current Sales Trends
This section focuses on the current wave of ZEV and PHEV sales, which began in 2010 with the introduction of the model year (MY) 2011 Chevrolet Volt, followed soon after by the MY2011 Nissan LEAF. The market of ZEVs and PHEVs has since developed to 25 models offered by 14 manufacturers at the beginning of 2017. In addition to ZEV and PHEV model availability, market shares, and sales volumes, it discusses regional differences between California, the Section 177 ZEV states and the rest of the United States, as well as provides comparisons between other technology types. Although market shares have been relatively constant in recent years, as of June 2016, almost 450,000 ZEVs and PHEVs have been sold in the U.S., with California and Section 177 ZEV States accounting for about 60 percent of those sales, roughly evenly divided between ZEVs and PHEVs in all regions. Although some models were initially only available for sale in states with a ZEV regulation, the market has also proliferated to other states in the U.S. and other countries. Compared to conventional HEVs, BEVs and PHEVs have developed and diversified much more rapidly and manufacturers have announced numerous future additional models that will continue to diversify consumer choices of PHEVs and ZEVs. Based on the current light-duty vehicle market structure, expanding ZEV and PHEV sales will likely require consumers to embrace multiple models.

To evaluate whether regional sales variation reflects differences in consumer access to vehicles, data on vehicle model inventories of PEVs and various comparable models from dealerships across major metropolitan areas were collected and analyzed. These data show a significant difference between PEVs and other conventional vehicles offered within the same city by the same manufacturer, with greater volumes of a comparable model available than the PEV. Differences in availability across cities show that some consumers could be less exposed to PEV technology when shopping for a new vehicle. While manufacturers do not seem to vary incentives offered at the dealership level across regions for the same vehicle models, they do seem to offer different incentives for different technology types.

Retail and transaction prices of ZEVs and PHEVs are also evaluated relative to the overall light-duty vehicle market to assess the extent to which past sales trends are the result of pricing strategies. The top 50 best-selling models of the 300 light-duty vehicle models offered in model year 2016 and almost 90% of all new vehicles sold during the first eight months of 2016 start at a base price of less than $35,000, with the largest volume of vehicles having a starting MSRP between $20,000 and $24,999. In comparison, only when factoring in up to $10,000 worth of government incentives do ZEVs and PHEVs prices become competitive with conventional vehicle prices. Furthermore, dealers appear to be transacting ZEVs and PHEVs at prices close to starting MSRP, meaning that government incentives are resulting in effective prices paid by consumers substantially more discounted than those typically offered for conventional vehicles during the negotiation process.

Understanding these trends helps to inform: 1) how the market has developed over time; 2) whether a sustainable market is developing; and 3) how the market may develop in the future.

III.A.1. Model Availability
Currently in the U.S., there are approximately 300 passenger car and light-duty truck models available, and the ZEV and PHEV market represents a small, but growing, number of this overall total number of vehicle models. The market has grown from one PHEV model in 2010 to 25 models of PHEVs, BEV, and FCEVs offered by 14 manufacturers at the beginning of 2017. The total number of ZEV and PHEV models available from each manufacturer in the U.S. by calendar year (CY) is shown in Figure 1. The ZEV portion includes BEVs and FCEVs, while the PHEV portion includes PHEV models that are TZEV-certified and also BEVx models.

Table 1 provides a more detailed listing of the available ZEV and PHEV models and also provides some perspective on manufacturers’ past success in launching new models. This table is an update to a table from the 2011 ZEV Regulation Initial Statement of Reasons(ISOR), which cataloged current and announced ZEV and PHEV models known at the time of the propose rulemaking. With the exception of the General Motors “TBD” FCEV and the Mitsubishi Outlander PHEV, every model has been released in the U.S. market. There have been ten additional models released that were not anticipated prior to the 2012 Advanced Clean Cars (ACC) rulemaking.

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13 WardsAuto data. See Section VII.E for further details.
14 PHEVs are classified in two categories: transitional zero emission vehicles (TZEV), which must meet super ultra-low-emission vehicle (SULEV) exhaust emission standards, provide an extended warranty on emission control systems, and have zero evaporative emissions in order to qualify for credits under California’s ZEV regulation, and non-TZEV PHEVs, which do not qualify to earn credits.
15 A BEVx is a vehicle powered predominantly by a zero emission energy storage device, able to drive the vehicle for more than 75 all-electric miles on the urban dynamometer driving schedule (UDDS), and also equipped with a backup auxiliary power unit (APU), which does not operate until the energy storage device is fully depleted and whose range does not exceed that of the all-electric mile range, and meeting super-ultra-low-emission vehicle (SULEV) standards.
17 The Mitsubishi Outlander is currently available in outside of the United States but expected to launch in the U.S. in 2017.
## Table 1 - Past and Current ZEV and PHEV Models

### Models Projected in the 2011 ZEV ISOR

<table>
<thead>
<tr>
<th>OEM</th>
<th>Model</th>
<th>Type</th>
<th>ISOR Projected</th>
<th>Actual Release/Initial Region</th>
<th>2017 Availability</th>
</tr>
</thead>
<tbody>
<tr>
<td>BMW</td>
<td>ActiveE</td>
<td>BEV</td>
<td>2011</td>
<td>2012, CA and S177</td>
<td>Discontinued</td>
</tr>
<tr>
<td></td>
<td>i3</td>
<td>BEV</td>
<td>2013</td>
<td>2014, All States</td>
<td>All States</td>
</tr>
<tr>
<td></td>
<td>i3 REx</td>
<td>BEVx</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>i8</td>
<td>PHEV</td>
<td>2014</td>
<td>2014, not TZEV</td>
<td>All States</td>
</tr>
<tr>
<td>FCA</td>
<td>500e</td>
<td>BEV</td>
<td>2013</td>
<td>2013, CA and OR</td>
<td>CA and OR</td>
</tr>
<tr>
<td>Ford</td>
<td>CMAX</td>
<td>PHEV</td>
<td>2012</td>
<td>2012, All States</td>
<td></td>
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<tr>
<td></td>
<td>Focus EV</td>
<td>BEV</td>
<td>2011</td>
<td>2012, All States</td>
<td></td>
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<tr>
<td></td>
<td>Transit Connect</td>
<td>BEV in prod</td>
<td>2011, CA and S177</td>
<td>Discontinued</td>
<td></td>
</tr>
<tr>
<td>GM</td>
<td>ELR</td>
<td>PHEV</td>
<td>unknown</td>
<td>2014, All States</td>
<td>Discontinued</td>
</tr>
<tr>
<td></td>
<td>Spark</td>
<td>BEV</td>
<td>2012</td>
<td>2013, CA and OR</td>
<td>Discontinued</td>
</tr>
<tr>
<td></td>
<td>Volt</td>
<td>PHEV</td>
<td>in prod</td>
<td>2010, All States</td>
<td>2nd gen, All States</td>
</tr>
<tr>
<td></td>
<td>TBD</td>
<td>FCEV</td>
<td>2015</td>
<td>n/a</td>
<td></td>
</tr>
<tr>
<td>Honda</td>
<td>Fit EV</td>
<td>BEV</td>
<td>2012</td>
<td>2012, CA and S177</td>
<td>Discontinued</td>
</tr>
<tr>
<td></td>
<td>TBD Accord</td>
<td>PHEV</td>
<td>2012</td>
<td>2013, CA and S177</td>
<td></td>
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<tr>
<td></td>
<td>Clarity</td>
<td>FCEV</td>
<td>in prod</td>
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<td>2nd gen, CA only</td>
</tr>
<tr>
<td>Hyundai</td>
<td>Tucson</td>
<td>FCEV</td>
<td>2015</td>
<td>2014, CA Only</td>
<td>CA Only</td>
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<td></td>
<td></td>
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<tr>
<td>Mercedes-Benz</td>
<td>TBD B-Class</td>
<td>BEV</td>
<td>2012</td>
<td>2014, CA and S177</td>
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</tr>
<tr>
<td></td>
<td>F-Cell</td>
<td>FCEV</td>
<td>in prod</td>
<td>2011, CA Only</td>
<td>Discontinued</td>
</tr>
<tr>
<td></td>
<td>smart fortwo ED</td>
<td>BEV</td>
<td>in prod</td>
<td>2011, All States</td>
<td>All States</td>
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<td></td>
<td></td>
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<tr>
<td>Hyundai</td>
<td>iMiEV</td>
<td>BEV</td>
<td>in prod</td>
<td>2011, All States</td>
<td>CA and S177</td>
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<tr>
<td></td>
<td>Outlander</td>
<td>PHEV</td>
<td>2013</td>
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<td>Expected 2017</td>
</tr>
<tr>
<td>Nissan</td>
<td>LEAF</td>
<td>BEV</td>
<td>in prod</td>
<td>2010, All States</td>
<td>All States</td>
</tr>
<tr>
<td>Tesla</td>
<td>Model S</td>
<td>BEV</td>
<td>2012</td>
<td>2012, All States</td>
<td>All States</td>
</tr>
<tr>
<td>Toyota</td>
<td>Prius Plug-in</td>
<td>PHEV</td>
<td>2012</td>
<td>2012, CA and S177</td>
<td>2nd gen, All States</td>
</tr>
<tr>
<td></td>
<td>Rav4 EV</td>
<td>BEV</td>
<td></td>
<td>2012, CA Only</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Scion iQ</td>
<td>BEV</td>
<td></td>
<td>2013, CA Only</td>
<td>Discontinued</td>
</tr>
<tr>
<td></td>
<td>TBD Mirai</td>
<td>FCEV</td>
<td>2015</td>
<td>2015, CA Only</td>
<td>CA Only</td>
</tr>
<tr>
<td>VW</td>
<td>e-up! e-Golf</td>
<td>BEV</td>
<td>2013</td>
<td>2014, CA and S177</td>
<td>All States</td>
</tr>
</tbody>
</table>

### Additional Models Not Projected

<table>
<thead>
<tr>
<th>OEM</th>
<th>Model</th>
<th>Type</th>
<th>2017 Availability</th>
</tr>
</thead>
<tbody>
<tr>
<td>FCA</td>
<td>Pacifica</td>
<td>PHEV</td>
<td>2017, All States</td>
</tr>
<tr>
<td>GM</td>
<td>Bolt</td>
<td>BEV</td>
<td>2016, CA and OR</td>
</tr>
<tr>
<td>Ford</td>
<td>Fusion</td>
<td>PHEV</td>
<td>2013, All States</td>
</tr>
<tr>
<td>Hyundai</td>
<td>Sonata</td>
<td>PHEV</td>
<td>2015, CA Only</td>
</tr>
<tr>
<td>Kia</td>
<td>Soul EV</td>
<td>BEV</td>
<td>2014, CA Only</td>
</tr>
<tr>
<td>Mercedes-Benz</td>
<td>C350e</td>
<td>PHEV</td>
<td>2016, CA and S177</td>
</tr>
<tr>
<td>Mercedes-Benz</td>
<td>S550e</td>
<td>PHEV</td>
<td>2015, CA and S177</td>
</tr>
<tr>
<td>Tesla</td>
<td>Model X</td>
<td>BEV</td>
<td>2016, All States</td>
</tr>
<tr>
<td>Volvo</td>
<td>XC90</td>
<td>PHEV</td>
<td>2015, All States</td>
</tr>
<tr>
<td>VW</td>
<td>A3 e-Tron</td>
<td>PHEV</td>
<td>2015, CA Only</td>
</tr>
</tbody>
</table>
Manufacturers have announced numerous future additional models that will continue to diversify consumer choices of PHEVs and ZEVs. Section IV.A of this appendix and Section I of Appendix C both provide a more detailed discussion of these future product offerings.

III.A.2. U.S. ZEV and PHEV Sales

Figure 2 shows annual U.S. sales of ZEVs and PHEVs for calendar year 2011 through June 2016. There have been 447,000 cumulative ZEV and PHEV sales (224,000 ZEV and 223,000 PHEV) in the U.S. from calendar year 2011 through June 2016. From calendar year 2011 to 2014, sales of ZEVs and PHEVs across the U.S. grew steadily, but flattened for 2015 and 2016. Relative to total light-duty vehicles (LDV) sales, ZEV and PHEV market shares from 2013 to 2016 have remained relatively constant. Currently, ZEV and PHEV sales comprise approximately 0.7% of U.S. LDV sales, with sales typically divided evenly between the two vehicle categories. Total U.S. ZEV and PHEV sales fell by 3% from calendar year 2014 to 2015, however this lag appears to be primarily due to PHEV sales, which fell by 13% from 2014 to 2015. By contrast, ZEV sales increased slightly from 2014 to 2015, by 6%. Total ZEV and PHEV sales have been higher by approximately 12% for the first half of calendar year 2016 relative to the same period in 2015; while PHEV sales increased more than 40%, ZEV sales declined by approximately 8%.

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18 For data source see sections VII.B Experian Automotive data and VII.E WardsAuto data.
19 As was previously discussed in model availability, the current wave of ZEV and PHEV sales actually began in calendar year 2010, however, this analysis beings with 2011 because the Dashboard data used in this analysis starts with sales from January 2011. DMV data show 2010 volumes to be minimal. See Sections VII.A and VII.C for additional details on data sources.
20 Dashboard data.
According to California DMV data of vehicles registered as of April 2016, non-TZEV PHEVs (PHEVs not certified to the TZEV standards) sold between 2011 and 2015 made up approximately 2% of total PEV and FCEV sales or 6% of the PHEV sales in California.\(^\text{22}\) While this is a relatively small percentage of the overall sales of new PEVs and FCEVs, more recent registrations suggest that this ratio has begun to shift. Non-TZEVs sold in California during the first four months of 2016 account for approximately 6% of the total PEV and FCEV sales and 12% of PHEV sales. Most of this shift results from the introduction of the BMW X5 PHEV, which accounts for more than 45% of the non-TZEV sales in California through April 2016. Other non-TZEV PHEVs include BMW’s i8 and 330e, as well as the Porsche Cayenne and Panamera S E-Hybrids. In general, these PHEVs have the requisite all-electric range necessary to qualify as TZEVs,\(^\text{23}\) however, they either do not meet the accompanying SULEV emissions requirements and/or do not provide a 15 year/150,000 mile extended warranty on the vehicle’s emission system. Although non-TZEVs do not earn ZEV regulation credits, additional modifications to these vehicles may allow them to qualify as TZEVs in future model years.

While ZEV and PHEV sales have not increased in the last two years, these trends are consistent with the overall passenger car segment, as most of the growth in light-duty vehicle sales stem from increases in light truck sales (which include pickup trucks, sport utility vehicles, crossover vehicles, and vans). Out of the 23 ZEV and TZEV models sold during the first half of 2016, 20 offerings fall within the passenger car segment. Between 2014 and 2015, passenger cars sales fell by 2.5%, while total U.S. light-duty truck\(^\text{24}\) sales increased by 12%. Over those same years, passenger car sales in California increased by 6%; however, light-duty truck sales were also very strong, growing by 19%. For the first half of calendar year 2016, passenger car sales

\(^{21}\) Dashboard data.  
\(^{22}\) Average sales of non-TZEVs from calendar year 2011 through April 2016.  
\(^{23}\) TZEVs must have a minimum 10 miles AER on UDDS.  
\(^{24}\) Trucks and truck based vehicles, such as SUVs, with a gross vehicle weight rating (GVWR) of less than 8,500 lbs.
sales decreased by 7% in the U.S. and also declined by 4% in California. Light-duty truck sales continued to grow, increasing by 1.3% and 13% during the first half of 2016 in the U.S. and California, respectively.

III.A.2.a. Comparison to HEV Market
The conventional hybrid electric vehicle market emerged during the early 2000s, with Toyota’s Prius leading the way, and often serves as an analog to the emerging PEV market. This comparison may seem appropriate given the fact that both markets seek to overcome the challenge of introducing consumers to electrified vehicle platforms, however, there have been significant differences in sales trends and vehicle availability between the two markets. To better understand market trends for PEVs, staff compared the current PEV market with the early years of the HEV market. Figure 3 shows the number of HEV models available in the U.S. from each manufacturer from calendar year 2000 to 2015. By 2015, there were 11 manufacturers offering a total of 47 different HEV models with the number of HEVs appearing to have stabilized in recent years.

Figure 3 - HEV model diversity by manufacturer CY2000-2015

Figure 4 uses a combination ZEV and PHEV model counts discussed in section III.A.1 and AFDC data for HEV model counts to provide a direct comparison of the number of models available in the early years of the ZEV and PHEV market to the similar market phase of the HEV market. The HEV market started with two manufacturers each offering a single product, and over the first seven years of model availability grew to offer a total of seven models. Over the same period of time, the ZEV and PHEV market grew to offer a total of 26 ZEV and TZEV models, with an additional seven PHEV models that are not TZEV certified. The HEV market, by contrast, did not offer 26 models until more than ten years after its introduction. Additionally, the

25 For data source see section VII.J AFDC HEV sales data.
26 The analysis for this HEV market comparison was done on a calendar year basis, and 26 models were offered for sale within calendar year 2016.
HEV market has never shown the same level of manufacturer diversity as the majority of the available HEV models were marketed primarily by three manufacturers: General Motors, Honda, and Toyota. Therefore, while the HEV market trajectory may illustrate one path for an electrified platform to be introduced into the market, it is not a direct comparison for the PEV market, which has developed and diversified much more rapidly.

Figure 4 - Early market model diversity by technology type

Figure 5 shows annual U.S. HEV sales volumes (left y-axis) and market share (right y-axis) by manufacturer. Figure 6 compares ZEV and PHEV sales to HEV sales data over the first six years of the respective technologies being available. These two graphs further illustrate the fact that HEV sales have been (and continue to be) dominated by only a few manufacturers, while ZEV and PHEV sales have only grown more diverse over time. Figure 5 shows Toyota producing approximately 68% of all new HEV sales in the US and accounting for 1.6% of total U.S. LDV sales in 2015. By comparison, Tesla had the largest percentage of ZEV or PHEV sales in the U.S. for calendar year 2015 at 21%, which only accounted for 0.13% of total U.S. LDV sales.

Both vehicle markets showed similar sales trends over the first five years of model availability, with ZEV and PHEV sales reaching around 0.6% and HEV sales reaching 0.5% of total U.S. LDV sales. The HEV sales data shows a significant jump in sales between years five and six, where sales jumped from 0.5% to 1.24%, a large portion of this increase resulting from a single manufacturer. As discussed in section 0, ZEV and PHEV sales dropped by 3% between years five and six, or from 2014 to 2015. While ZEV and PHEV sales have been higher for the first half of 2016, the ZEV and PHEV market seem unlikely to sharply increase in 2016 as the HEV market did between 2004 and 2005, however several new model introductions or redesigns have the possibility of dramatically increasing sales in 2017.

27 The HEV model counts did not distinguish between non-PZEV certified HEVs that do not qualify for credits under the ZEV regulation through MY 2017 and those HEVs that do qualify for credits; therefore it was necessary to include non-TZEV certified PHEVs in this part of this analysis.
III.A.2.b. Comparison of CA/S177/U.S. Sales Trends
California has the largest PEV (and FCEV) market in terms of volume and market share in the U.S. In addition to a long history of the ZEV regulation, California and the nine Section 177 ZEV states have adopted several complementary policies to support the ZEV and PHEV market. Some manufacturers have also been distributing these vehicles outside of states where they

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Figure 5 - HEV annual U.S. sales volumes by manufacturer CY2000-2015

Figure 6 - Comparison of ZEV and PHEV sales to HEV sales in early years of U.S. market

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28 AFDC HEV sales data.
29 For ZEV and PHEV sales data source see Section VII.B Experian Automotive data; for HEV sales data source see Section VII.A AFDC HEV sales data.
would earn regulatory compliance credits (Rest of the U.S.); sales trends in these states provide insights into consumer acceptance of ZEV and PHEV technologies in the absence of potential regulatory market distortions. Evaluating sales trends in all three regions can also help assess progress towards achieving economies of scale that can contribute to vehicle cost reductions. This section uses Dashboard data to evaluate differences in sales trends between the three geographic regions: California, the Section 177 ZEV states, and the Rest of the U.S., which includes the remaining 40 states and the District of Columbia.

Figure 7 directly compares sales between the three U.S. regions. California comprised approximately 12% of total U.S. new LDV sales from 2013 through June 2016, while the Section 177 ZEV states accounted for approximately 17% of sales and the Rest of U.S. region accounting for the remaining 71%. While both ZEV and PHEV sales declined in the Rest of U.S. region from 2014 to 2015, sales of ZEVs have remained fairly constant across every region and have actually increased in California and the Section 177 ZEV states. The reduction in total U.S. ZEV and PHEV sales from 2014 to 2015 resulted from the drop in sales of PHEVs in every region, with the largest drop of 22% occurring in the Rest of U.S.

Figure 7 - ZEV and PHEV sales by region CY2011 through June 2016

Total U.S. ZEV and PHEV sales for the first half of 2016 increased 12% compared to the first half of 2015 (11% California, 2% Rest of U.S., and 51% in the Section 177 ZEV states). This increase in ZEV and PHEV sales is consistent with that of the overall LDV market which grew by 2.8% in California and 2.1% in the entire U.S. for the first half of 2016 over the same time period for 2015. Taking a closer look at this national increase, sales of PHEVs grew in every region over this time span (24% California, 55% Rest of U.S., and 96% in the Section 177 ZEV

30 Dashboard data.
31 Dashboard data.
32 Dashboard data.
states). While sales of ZEVs have increased in California (2%) and the Section 177 ZEV states (9%), sales have fallen in the Rest of U.S. by 25%.

However, within each time period, Figure 8 shows sales about evenly split between PHEVs and ZEVs across all of the regions, with California and the Rest of U.S. region showing a slight bias toward ZEVs. For Section 177 ZEV states, these technology splits vary depending on the region analyzed: Oregon’s sales tend to align more with California, whereas the Northeast Section 177 ZEV states tend to favor PHEVs.

Figure 8 - ZEV/PHEV sales splits by region CY2011 through June 2016

In California, there have been 216,000 cumulative ZEV and PHEV sales (111,000 ZEV and 105,000 PHEV) from the beginning of calendar year 2011 through June 2016. California accounts for approximately 48% of cumulative ZEV and PHEV sales in the U.S. during this time period, with approximately 50% of total U.S. BEV sales and 47% of total U.S. PHEV sales.

Figure 9 shows that ZEV and PHEV sales grew steadily from calendar year 2011 through 2014, but appear to have stagnated recently. While ZEV and PHEV sales grew by approximately 5.2% from 2014 to 2015, the overall market share has remained at approximately 3% of California LDV sales for 2015 and the first half of 2016. Taking a closer look at the different vehicle technologies, ZEV sales have grown 18% and now account for approximately 1.6% California’s LDV sales, whereas PHEV sales declined 7% between 2014 and 2015, and now account for approximately 1.4% of California LDV sales, down from a high of 1.6% in 2014.

33 Dashboard data.
The Section 177 ZEV states have accounted for approximately 13% (58,000) of cumulative ZEV and PHEV sales in the U.S. from 2011 to June 2016, 11% (21,300) of cumulative U.S. ZEV sales and 18% (36,500) of cumulative PHEV sales. As shown in Figure 10, sales of ZEVs and PHEVs in the Section 177 ZEV states grew rapidly in the first three years, but remained flat at approximately 0.5% of total LDV vehicle sales in those states from calendar year 2013 through 2015. During that same time period, ZEV sales increased slightly to 0.2% of Section 177 ZEV state LDV sales. By contrast, PHEV sales, which started around 0.3% in 2013, fell to around 0.2% of Section 177 ZEV state LDV sales in 2015. Despite these past trends, sales of ZEVs and PHEVs are up to 0.6% in the Section 177 ZEV states for the first half of 2016, the highest levels to date for that region.

The Rest of U.S. region comprised 39% (172,000) of the total cumulative ZEV and PHEV sales in the U.S. from 2011 through June 2016, 41% (91,600) of cumulative ZEV sales and 36% (81,000) of cumulative PHEV sales. Sales in the Rest of U.S. region peaked in 2014 with 26,700 ZEVs and 19,000 PHEVs, which represents a total of 0.4% of the LDV sales for that region. However, these sales fell by 15% from 2014 to 2015, and for the first half of 2016 accounted for approximately 0.3% of regional LDV sales, with sales fairly evenly split between the two technologies.

34 Dashboard data.
III.A.2.c. Total Annual Volumes
This section looks at new ZEV and PHEV registrations from Experian Automotive data to better understand how individual vehicle model sales are driving the overall market and to provide a better picture of which vehicles contributed most of the 3% decrease in U.S. ZEV and PHEV sales between calendar year 2014 and 2015. Figure 11 and Figure 12 show California registrations from calendar year 2011 through 2015 (the last complete year of sales data by model available); California's ZEV sales totaled approximately 33,000 and PHEV sales totaled 25,000 in 2015. The three best-selling ZEV models in California (e.g. Tesla Model S, Nissan LEAF, and Fiat 500e) combined made up just over 66% of the total ZEV sales in calendar year 2015. The best-selling PHEV models, which were the Chevrolet Volt, the Ford Fusion and the BMW i3 REX, combined made up 70% of PHEV sales. With the exception of the FIAT 500e, California's top-selling PEV models are all distributed in other states as well and models that are only distributed to California are low volume.

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Dashboard data.
The Section 177 ZEV state ZEV and PHEV sales by model are shown in Figure 13 and Figure 14, respectively. For calendar year 2015, these nine states had combined ZEV and PHEV sales of approximately 11,500 (5,900 ZEVs and 5,600 PHEVs). Combined sales for the top three selling ZEV models in this region, the Model S, the Nissan LEAF, and the Chevrolet Spark, was 74%. The Volt, Fusion, and C-Max are the three best-selling PHEVs, accounting for a combined 72% of PHEV sales in calendar year 2015 in that region.

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36 Experian Automotive data.
37 Experian Automotive data.
For calendar year 2015, combined ZEV and PHEV sales in the Rest of U.S. region totaled just over 35,000 vehicles. The three best-selling ZEV models for this region were the Nissan LEAF, the Tesla Model S and the BMW i3, which comprised 95% of all ZEV sales. Similar to the Section 177 ZEV States region, the Volt, Fusion, and C-Max are the three top-selling models, which likewise accounted for around 75% of the PHEV sales in the Rest of U.S. region.

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38 Experian Automotive data.
39 Experian Automotive data.
Table 2 summarizes the three best-selling ZEV and PHEV sales from each region for calendar year 2015. This table additionally includes each model’s regional market share within its given technology type (ZEV or PHEV) and the market share for the combined ZEV and PHEV market. This table data highlights that there are approximately five models (Tesla Model S, Nissan LEAF, Chevrolet Volt, Ford Fusion Energi, and Ford C-Max Energi) which currently constitute the majority of ZEV and PHEV sales in the U.S. Only Nissan sells the majority of its volume outside of states with a ZEV regulation and except for Tesla, the market shares of the remaining auto manufacturers has generally become more concentrated in California or Section 177 ZEV States over time. Given the previous discussion in Section III.A.2.a showing more diversity in the ZEV and PHEV market then during a similar stage of the HEV market, additional product options may increase the likelihood of meeting consumer preferences and requirements that can facilitate greater adoption of these new vehicle technologies.

<table>
<thead>
<tr>
<th>Region</th>
<th>Technology Type</th>
<th>Make</th>
<th>Model</th>
<th>Regional Market Share by ZEV Type</th>
<th>Regional Market Share of Total ZEV and PHEV Sales</th>
</tr>
</thead>
<tbody>
<tr>
<td>California</td>
<td>ZEV</td>
<td>TESLA</td>
<td>MODEL S</td>
<td>31%</td>
<td>17%</td>
</tr>
<tr>
<td></td>
<td>ZEV</td>
<td>NISSAN</td>
<td>LEAF</td>
<td>19%</td>
<td>11%</td>
</tr>
<tr>
<td></td>
<td>ZEV</td>
<td>FIAT</td>
<td>500E</td>
<td>17%</td>
<td>10%</td>
</tr>
<tr>
<td></td>
<td>PHEV</td>
<td>CHEVROLET</td>
<td>VOLT</td>
<td>34%</td>
<td>15%</td>
</tr>
<tr>
<td></td>
<td>PHEV</td>
<td>FORD</td>
<td>FUSION</td>
<td>20%</td>
<td>9%</td>
</tr>
<tr>
<td></td>
<td>PHEV</td>
<td>BMW</td>
<td>I3 REX</td>
<td>16%</td>
<td>7%</td>
</tr>
<tr>
<td>Section 177 ZEV States</td>
<td>ZEV</td>
<td>TESLA</td>
<td>MODEL S</td>
<td>51%</td>
<td>26%</td>
</tr>
<tr>
<td></td>
<td>ZEV</td>
<td>NISSAN</td>
<td>LEAF</td>
<td>15%</td>
<td>8%</td>
</tr>
<tr>
<td></td>
<td>ZEV</td>
<td>VOLKSWAGEN</td>
<td>E-GOLF</td>
<td>8%</td>
<td>4%</td>
</tr>
<tr>
<td></td>
<td>PHEV</td>
<td>FORD</td>
<td>FUSION</td>
<td>28%</td>
<td>14%</td>
</tr>
<tr>
<td></td>
<td>PHEV</td>
<td>FORD</td>
<td>C-MAX</td>
<td>23%</td>
<td>11%</td>
</tr>
<tr>
<td></td>
<td>PHEV</td>
<td>CHEVROLET</td>
<td>VOLT</td>
<td>21%</td>
<td>10%</td>
</tr>
<tr>
<td>Rest of the U.S.</td>
<td>ZEV</td>
<td>NISSAN</td>
<td>LEAF</td>
<td>49%</td>
<td>32%</td>
</tr>
<tr>
<td></td>
<td>ZEV</td>
<td>TESLA</td>
<td>MODEL S</td>
<td>41%</td>
<td>26%</td>
</tr>
<tr>
<td></td>
<td>ZEV</td>
<td>BMW</td>
<td>I3</td>
<td>5%</td>
<td>4%</td>
</tr>
<tr>
<td></td>
<td>PHEV</td>
<td>CHEVROLET</td>
<td>VOLT</td>
<td>38%</td>
<td>13%</td>
</tr>
<tr>
<td></td>
<td>PHEV</td>
<td>FORD</td>
<td>FUSION</td>
<td>20%</td>
<td>7%</td>
</tr>
<tr>
<td></td>
<td>PHEV</td>
<td>FORD</td>
<td>C-MAX</td>
<td>20%</td>
<td>7%</td>
</tr>
</tbody>
</table>

As shown in Figure 12 and Figure 14 the sharp decline in PHEV sales in California and the Section 177 ZEV States described in section III.A.2.b resulted primarily from two vehicles being discontinued in 2015: the Toyota Prius and the Honda Accord. The Prius Plug-in was the best-selling PHEV in both California and the Section 177 ZEV states in calendar year 2014. Sales of all the other PHEV models in both California and the Section 177 ZEV states were fairly flat from 2014 to 2015. Based on Figure 11 and Figure 13, the ZEV models that decreased in sales from 2014 to 2015 are either vehicles that have been on the market for a while, such as the

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40 Experian Automotive data.
Nissan LEAF and the Smart ForTwo Electric, or were discontinued in 2015, such as the RAV4 EV.

III.A.2.d. ZEV and PHEV Market Share of OEM Total LDV Sales

Figure 15 shows ZEV and TZEV market shares based on each OEM’s individual California LDV sales volumes for calendar year 2014 and 2015. In California, overall ZEV and PHEV sales (including TZEV and non-TZEV certified PHEVs) were approximately 3% the total LDV market during this time period. However, the ZEV and PHEV market share for each OEM is more variable. Year-over-year market shares fell for each of the six largest manufacturers (FCA, Ford, GM, Honda, Nissan, and Toyota); only in the case of GM did total ZEV and PHEV market shares decline because of an increase in overall sales volumes. In contrast, PEV market shares increased for the next four manufacturers despite the increase in overall sales. These trends may be a function of the fact that the larger manufacturers introduced products in 2012 and 2013, and by 2015 were transitioning to their next generation products. For example, General Motors announced the new Volt at the Detroit Auto Show in January 2015 and released it later that year as a 2016 MY vehicle. Toyota also announced plans to discontinue the Prius Plug-in in May 2015 and will be releasing the Prius Prime PHEV by the end of 2016. Meanwhile, the four smaller manufacturers released their ZEV and PHEV products in this timeframe, and as a

Figure 15 - ZEV and PHEV market share of manufacturer total sales in California CY2014 and CY2015

41 Dashboard data.
42 Hyundai is not included in Figure 15 because the Experian Automotive data used to create this graph did not include sales data for the Hyundai Tucson FCV.
45 http://www.toyota.com/priusprime/
46 ZEV and TZEV sales based on Experian Automotive data, total manufacturer sales volumes based on CNCDA Quarterly Report.
result 2014 reflects only a partial year of sales. For example, the Kia Soul EV was announced in early 2014 as a 2015 MY vehicle\textsuperscript{47} and BMW released the i3 in early 2014.

Additionally, although ZEV and PHEV market shares for some of the largest manufacturers may be below those of the smaller manufacturers, when factoring in their total California market shares shown in Figure 16, their total volumes of ZEVs and PHEVs may still be greater. While market shares are relevant for regulatory compliance, total volumes of ZEVs and PHEVs are also important for increasing consumer exposure to these products and generating scale economies for cost reductions.

\textbf{Figure 16 - Manufacturer market shares in California for CY2015}\textsuperscript{48}

\begin{center}
\begin{tikzpicture}
\begin{scope}
\pie<1-5>{Toyota=21,Honda=13,Ford=10,GM=10,Nissan=9,FCA=8,Volkswagen=5,\ldots}
\end{scope}
\end{tikzpicture}
\end{center}

\textbf{III.A.2.e. Building ZEV and PHEV Market Shares in the Context of the Entire Light-Duty Vehicle Market}

This section provides additional context for how individual vehicles and vehicle segments contribute to the overall California and U.S. LDV market for calendar year 2015 to illustrate which segments provide the greatest opportunities for ZEV and PHEV models. Additionally, current \textit{model} shares show that no single model accounts for more than 4\% of the total market, which indicates that an expanded and sizeable ZEV and PHEV market requires consumers to embrace multiple models.

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\textsuperscript{48} CNCDA 2016.
California market shares for each vehicle segment are shown in Figure 17. More than half of new light-duty vehicles sold are passenger cars body styles (darker colors) as opposed to light trucks (lighter colors). The two largest segments – subcompact and standard midsize passenger cars – contribute more than one-third of sales and are also the segments in which many ZEVs and PHEVs are currently offered (and more are expected in the future). Within the light truck category, compact SUVs (often built on unibody chassis similar to passenger cars and may also be included in a manufacturer’s passenger car fleet for performance standard averages) comprise the largest segment and is the segment in which many future PHEV and ZEV offerings are expected.

For context, Figure 18 shows the five best-selling individual vehicle models within each segment in California. The five best-selling vehicles overall are all passenger cars and comprise just over 17 percent of all new light-duty vehicles sold. At about 10,000 units, Tesla’s Model S was the best-selling ZEV or PHEV in California in calendar year 2015 and the third best-selling model in the Luxury and Sports segment (the only ZEV or PHEV model to rise to be within the top five in its class). However, relative to the roughly two million light-duty vehicles sold in the state in

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50 See Section IV.A for discussion on future model availability.
51 CNCDA Quarterly Reports. See Section VII.K for further data source details.
2015, the Model S represents a total market share of 0.5% (around the 50th percentile among all of the segment leaders).

Figure 18 - Market shares of top 5 models within each Segment in California CY 2015 52

As the California sales data do not include all available models, Figure 19 uses U.S. vehicle sales data from WardsAuto to calculate the overall market share for each of the 300 models offered for sale in 2015. 53 Similar to the California market, only the top-selling vehicle, the Ford F-Series (which includes a large assortment of variants) exceeds four percent of the market, and even the fifth best-selling model, the Toyota Corolla, comprises only two percent of total sales. In California, the top three best-selling vehicle models in calendar year 2015 were all passenger cars (i.e. Honda Civic, Honda Accord, and Toyota Prius). By contrast, the top three best-selling vehicle models in the U.S. were all light-duty trucks (i.e. Ford F-Series, Chevrolet Silverado, and Ram 1500). Within both markets the top three vehicles combined total approximately 11% of the total LDV market.

Of the 300 models, the top 10 percent of models account for about 50 percent of all light-duty vehicle sales in the U.S. with each of these models exceeding 1 percent overall market share. The remaining half of the market is comprised of the remaining 90 percent of models, many of which are relatively low volume. More than half of all models have 0.25 percent market share or less; however, even models with 0.1 percent market share in the U.S. represent 16,000 units.

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52 CNCDA Quarterly Reports.
53 Exotic models such as very high-end luxury or performance vehicles were excluded, e.g. Rolls Royce, Ferrari, etc.
While current market shares for individual ZEV and PHEV models are relatively low, they are similar to those of many of their conventional technology counterparts.

**Figure 19 - Market share of 300 conventional, PHEV, and ZEV models in U.S. CY2015**

III.A.2.f. Global Sales Volumes of PEVs
Combining the U.S. PEV sales volumes from the previous sections with global PEV sales volumes, the global PEV market has increased steadily since 2011, reaching over 500,000 units in 2015. However, as shown in Figure 20, recently this growth has been concentrated in regions outside of the U.S., though cost reductions from economies of scales occur regardless of location. In 2015, China had the highest PEV sales followed closely by Western Europe; California with the Section 177 ZEV States most recently ranks as the third largest PEV market, surpassing the volumes in Japan and Canada combined. It is expected that the total global PEV market will surpass a cumulative 2 million vehicles by the end of 2016.

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54 WardsAuto data.
56 Carrington 2016.
III.A.3. Dealership Vehicle Availability

One question posed by stakeholders is whether low numbers of PEVs on dealer lots across the Section 177 ZEV states helps to explain their sales rates relative to California's. Vehicle availability at dealerships can help explain what potential consumer might encounter in terms of how many choices are available when purchasing a vehicle. In contrast to model availability discussed in Section III.A.1, this analysis evaluates select PEVs (as well as comparable vehicle models) available on dealer lots, over a period of time, across specific cities. Even if a manufacturers distributes certain models for sale in a particular city or state, physical vehicles may not be available on dealer lots for customers to see and test drive.58

One 2016 study asserted that more PEV models are available in California compared with the rest of the U.S. and all automakers could improve their availability of PEVs and the number of models available at dealership, especially outside of California.59 Staff recognizes one of the highest selling PEVs in the Section 177 ZEV states is the Tesla Model S, which is not sold at any dealership, but through online orders and sales. However, all manufacturers with a current pure-ZEV obligation offer vehicles for sale through a traditional network of dealers.

Inventory data was collected from all dealerships within each city once a week via Edmunds.com. The following major metropolitan cities were chosen to be representative of the larger state: Boston, New York City, Albany, Baltimore, Los Angeles, Portland (OR), and

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57 DOE 2016b and Experian Automotive data.
58 See Section III.B.5 for more information on the effectiveness of test drives on PEV purchase decisions.
Table 3 - PEV models and comparable vehicles by manufacturer

<table>
<thead>
<tr>
<th>Manufacturer</th>
<th>PEV model</th>
<th>Comparable vehicle model</th>
<th>Comparable sales model</th>
<th>Best-selling passenger car</th>
</tr>
</thead>
<tbody>
<tr>
<td>BMW</td>
<td>i3</td>
<td>i3 REx</td>
<td>M235</td>
<td>328</td>
</tr>
<tr>
<td>GM</td>
<td>Volt</td>
<td>Cruze*</td>
<td>Corvette</td>
<td>Cruze</td>
</tr>
<tr>
<td>Ford</td>
<td>Fusion Energi</td>
<td>Fusion Hybrid</td>
<td>Focus ST</td>
<td>Fusion</td>
</tr>
<tr>
<td></td>
<td>C-MAX Energi</td>
<td>C-MAX Hybrid</td>
<td>Focus ST</td>
<td>Fusion</td>
</tr>
<tr>
<td>Nissan</td>
<td>LEAF</td>
<td>Versa</td>
<td>Juke</td>
<td>Altima</td>
</tr>
</tbody>
</table>

* The Chevrolet Cruze is both the best-selling and comparable vehicle model to the Volt.

Table 4 - Average daily number of vehicles on dealership lots from October 2015 to May 2016 (with number of dealership carrying each vehicle)

<table>
<thead>
<tr>
<th>City</th>
<th>PEV Model</th>
<th>PEVs available (dealerships)</th>
<th>Comparable vehicles available (dealerships)</th>
<th>Comparable sales models available (dealerships)</th>
<th>Best-selling PC models available (dealerships)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Boston</td>
<td>i3</td>
<td>13 (4)</td>
<td>38 (5)</td>
<td>32 (5)</td>
<td>201 (5)</td>
</tr>
<tr>
<td></td>
<td>Volt</td>
<td>33 (14)</td>
<td>28 (16)</td>
<td>29 (14)</td>
<td>28 (16)</td>
</tr>
<tr>
<td></td>
<td>Fusion Energi</td>
<td>32 (16)</td>
<td>50 (21)</td>
<td>14 (18)</td>
<td>328 (24)</td>
</tr>
<tr>
<td></td>
<td>C-Max Energi</td>
<td>17 (15)</td>
<td>46 (23)</td>
<td>14 (18)</td>
<td>328 (24)</td>
</tr>
<tr>
<td></td>
<td>Leaf</td>
<td>22 (15)</td>
<td>62 (14)</td>
<td>81 (15)</td>
<td>582 (15)</td>
</tr>
<tr>
<td>New York City</td>
<td>i3</td>
<td>6 (6)</td>
<td>43 (14)</td>
<td>69 (17)</td>
<td>464 (17)</td>
</tr>
<tr>
<td></td>
<td>Volt</td>
<td>29 (30)</td>
<td>69 (31)</td>
<td>81 (33)</td>
<td>69 (31)</td>
</tr>
<tr>
<td></td>
<td>Fusion Energi</td>
<td>196 (28)</td>
<td>67 (28)</td>
<td>20 (25)</td>
<td>1005 (33)</td>
</tr>
<tr>
<td></td>
<td>C-Max Energi</td>
<td>55 (26)</td>
<td>14 (16)</td>
<td>20 (25)</td>
<td>1005 (33)</td>
</tr>
<tr>
<td></td>
<td>Leaf</td>
<td>6 (9)</td>
<td>134 (34)</td>
<td>101 (37)</td>
<td>2652 (38)</td>
</tr>
<tr>
<td>Albany</td>
<td>i3</td>
<td>0</td>
<td>1 (2)</td>
<td>6 (2)</td>
<td>59 (2)</td>
</tr>
<tr>
<td></td>
<td>Volt</td>
<td>3 (3)</td>
<td>10 (3)</td>
<td>7 (3)</td>
<td>10 (3)</td>
</tr>
<tr>
<td></td>
<td>Fusion Energi</td>
<td>7 (5)</td>
<td>25 (8)</td>
<td>4 (5)</td>
<td>105 (9)</td>
</tr>
<tr>
<td></td>
<td>C-Max Energi</td>
<td>4 (5)</td>
<td>4 (4)</td>
<td>4 (5)</td>
<td>105 (9)</td>
</tr>
<tr>
<td></td>
<td>Leaf</td>
<td>3 (3)</td>
<td>27 (4)</td>
<td>21 (4)</td>
<td>227 (4)</td>
</tr>
<tr>
<td>Baltimore</td>
<td>i3</td>
<td>5 (4)</td>
<td>17 (5)</td>
<td>30 (6)</td>
<td>138 (6)</td>
</tr>
<tr>
<td></td>
<td>Volt</td>
<td>15 (14)</td>
<td>57 (16)</td>
<td>51 (15)</td>
<td>57 (16)</td>
</tr>
<tr>
<td></td>
<td>Fusion Energi</td>
<td>52 (13)</td>
<td>76 (16)</td>
<td>27 (15)</td>
<td>337 (16)</td>
</tr>
<tr>
<td></td>
<td>C-Max Energi</td>
<td>32 (12)</td>
<td>29 (16)</td>
<td>27 (15)</td>
<td>337 (16)</td>
</tr>
<tr>
<td></td>
<td>Leaf</td>
<td>18 (10)</td>
<td>163 (13)</td>
<td>43 (13)</td>
<td>520 (13)</td>
</tr>
<tr>
<td>Los Angeles</td>
<td>i3</td>
<td>41 (14)</td>
<td>101 (14)</td>
<td>94 (14)</td>
<td>603 (14)</td>
</tr>
<tr>
<td></td>
<td>Volt</td>
<td>186 (17)</td>
<td>61 (17)</td>
<td>87 (17)</td>
<td>61 (17)</td>
</tr>
<tr>
<td></td>
<td>Fusion Energi</td>
<td>491 (18)</td>
<td>174 (19)</td>
<td>71 (19)</td>
<td>580 (19)</td>
</tr>
<tr>
<td></td>
<td>C-Max Energi</td>
<td>96 (18)</td>
<td>140 (18)</td>
<td>71 (19)</td>
<td>580 (19)</td>
</tr>
<tr>
<td></td>
<td>Leaf</td>
<td>83 (16)</td>
<td>720 (16)</td>
<td>87 (16)</td>
<td>1346 (16)</td>
</tr>
<tr>
<td>Portland</td>
<td>i3</td>
<td>5 (2)</td>
<td>22 (2)</td>
<td>17 (2)</td>
<td>65 (2)</td>
</tr>
<tr>
<td></td>
<td>Volt</td>
<td>24 (10)</td>
<td>17 (9)</td>
<td>25 (9)</td>
<td>17 (9)</td>
</tr>
<tr>
<td></td>
<td>Fusion Energi</td>
<td>90 (8)</td>
<td>43 (13)</td>
<td>14 (10)</td>
<td>108 (15)</td>
</tr>
<tr>
<td></td>
<td>C-Max Energi</td>
<td>42 (9)</td>
<td>37 (11)</td>
<td>14 (10)</td>
<td>108 (15)</td>
</tr>
<tr>
<td></td>
<td>Leaf</td>
<td>70 (6)</td>
<td>77 (6)</td>
<td>20 (6)</td>
<td>159 (6)</td>
</tr>
<tr>
<td>Seattle</td>
<td>i3</td>
<td>23 (3)</td>
<td>34 (3)</td>
<td>38 (3)</td>
<td>108 (3)</td>
</tr>
<tr>
<td></td>
<td>Volt</td>
<td>10 (12)</td>
<td>19 (14)</td>
<td>26 (15)</td>
<td>19 (14)</td>
</tr>
<tr>
<td></td>
<td>Fusion Energi</td>
<td>105 (12)</td>
<td>61 (14)</td>
<td>31 (15)</td>
<td>234 (15)</td>
</tr>
<tr>
<td></td>
<td>C-Max Energi</td>
<td>38 (12)</td>
<td>88 (15)</td>
<td>31 (15)</td>
<td>234 (15)</td>
</tr>
<tr>
<td></td>
<td>Leaf</td>
<td>74 (7)</td>
<td>31 (7)</td>
<td>26 (7)</td>
<td>183 (7)</td>
</tr>
</tbody>
</table>

B - 26
Seattle. Note that Washington is not a Section 177 ZEV state, but was included as a comparable city in order to analyze the potential effect of the ZEV regulation. Staff also analyzed some non-PEV models to provide context for the way in which a given manufacturer/dealer stocks vehicles. For each PEV chosen, a comparable vehicle (in terms of segment class), a vehicle with similar sales volumes, and the best U.S selling passenger car for that manufacturer was studied, shown in Table 3. Table 4 summarizes the average number of vehicles available in each city and vehicle type, as well as the number of dealerships carrying each model in (parentheses). These numbers were then averaged over the six month period, resulting in an average daily "snapshot".

Analyzing these data on inventories among dealerships that offer PEVs compared to comparable vehicle models, there is a difference between cities and manufacturers. In Los Angeles, all dealerships carry the PEV and comparable vehicles. Baltimore, Portland and Seattle dealers have PEVs available at most dealerships across all manufacturers. Boston BMW, GM and Nissan dealers carry PEVs at their dealerships, but Ford dealers offer limited PEVs and only at some dealerships. In New York City, only the GM and Ford dealers have similar dealership availability between the PEV model and other comparable vehicles. Nissan and BMW dealers do not carry as many the PEVs on their lots, which may translate to low sales.

III.A.3.a. PEV Availability
Using data from Table 4 on average daily PEV availability, Figure 21 shows the average number of PEVs available at dealership lots for each city. This figure illustrates the significant difference in availability between Los Angeles and all other cities for these select PEVs.

Figure 21 - Average daily number of PEVs available at dealerships by city
According to these data, it does appear that PEVs are less available in pure volume in Section 177 ZEV state cities than in Los Angeles, California. However vehicle volumes have not been normalized for new vehicle sales within each of the cities. For reference, New York City, Boston and Baltimore have similar PEV market shares per capita, but New York has more models available on dealer lots, especially the Ford products.

III.A.3.b. PEV and Comparable Vehicle Availability
To help further explain PEV availability at the dealership, staff analyzed availability for comparable vehicles for each model. For each city and PEV, staff developed a “target fleet” to compare the number of vehicles across cities. This “target fleet” consists of the PEV of interest, all the comparable models, and the best-selling vehicle. Staff looked at each PEV (presented in subsequent figures), but for simplicity, have provided an example first with the Ford Fusion Energi (PHEV).

Figure 22 shows the relationship between the Ford Fusion Energi and its comparable vehicles (Ford Fusion Hybrid, Focus ST and Fusion) and how this relationship differs between cities. In Los Angeles, PEVs comprise a larger percentage of the "target fleet," though Portland and Seattle exhibit similarly higher percentages of PEVs that are greater than those in the northeast states.

---

Figure 23 - Percent breakdown between PEV and conventional vehicle model availability

Relative Difference Between Comparable Vehicles
BMW i3

Relative Difference Between Comparable Vehicles
Ford C-MAX Energi

Relative Difference Between Comparable Vehicles
GM Volt

Relative Difference Between Comparable Vehicles
Nissan Leaf
Figure 23 shows the remaining four PEVs and their comparable vehicles. Note for BMW, the dealership lots in Portland and Oregon have relatively more BMW i3 and i3 REX models when compared to other cities. Even though the Chevrolet Volt is available in all 50 states across the U.S., there are significantly greater numbers available on dealer lots in California, though Boston and Portland are close behind. For the Nissan Leaf, California dealers offer similar vehicle inventory volumes as Portland and Seattle, however Portland and Seattle Leaf sales make up a larger portion of sales for this “target fleet”.

It is difficult to fully analyze dealer availability without knowing city sales numbers to accurately compare market size with dealer inventory. However, these data show a significant difference between PEVs and other conventional vehicles offered within the same city by the same manufacturer. For example, BMW offers the M235 in much higher volumes (and relative percent) compared to the i3 or the i3x. However, for BMW this trend is the same for all the cities analyzed. GM, however, offers the Volt (which is the highest selling PHEV in the U.S.) as a much larger proportion of overall sales in each city. Differences in availability across cities show that some consumers could be less exposed to PEV technology when shopping for a new vehicle.

The Union of Concerned Scientists also conducted their own study investigating this topic. They concluded that most drivers would have difficulty locating an electric vehicle at a dealership outside of California. Many more models are offered for sale in California, 24 in CY2015 compared to 14 in any other state and over half the sales of the most popular electric vehicles occurred in California. Focusing on availability on the dealer lots from January to June 2015, they found stark differences in dealer availability on the lots with Baltimore having only 10% of the vehicles available in Oakland after adjusting for relative car ownership.

III.A.4. New Vehicle Manufacturer Suggested Retail Prices of ZEVs and PHEVs
As discussed in Appendix C, incremental vehicle costs of ZEVs and PHEVs are anticipated to remain well above the cost of conventional vehicle technology in the near term. These higher costs are likely to be passed onto consumers and reflected in part or in whole in the price of new vehicles. Under the dealer franchise business model, consumers do not necessarily pay the price that is suggested by the auto manufacturer, as dealers have flexibility to negotiate prices and may also have incentives offered by the manufacturer that can be passed onto customers. For example, in 2015, the average MSRP of a midsize car was $27,000 but the average transaction price was just below $24,000. Nonetheless, the manufacturer suggested retail price (MSRP) generally reflects auto manufacturer pricing expectations and serves as a benchmark for consumers and lenders on a vehicle’s value.

61 Reichmuth and Anair 2016.
Pricing data for the nearly 300 models\textsuperscript{63} offered in MY2016 were assembled from a combination of Wards data, auto manufacturer websites, and other third-party auto buying guides. A vehicle model may have a wide variety of MSRP\textquoteright s given that they often come with optional, higher priced engine configurations, accessories, and amenities. The base prices analyzed here reflect the starting MSRP and destination fee for each model, with ZEVs and PHEVs itemized separately. Only when factoring in up to $10,000 worth of government incentives do ZEVs and PHEVs prices become competitive with conventional vehicle prices. However, average starting prices for BEVs with ranges of less than 200-miles are $3,000 less than PHEVs without any government incentives. Meanwhile, at the dealership level, PHEVs appear to receive greater incentives from manufacturers than BEVs, though not well-beyond those offered on conventional vehicles. These two pricing factors combined may account for the relatively constant and even market share split between the two technologies.

Staff used January to August 2016 U.S. sales volumes for each of these models to estimate a sales-weighted base price distribution. As shown as shaded bars in Figure 24, the majority of all new vehicles sold start at a base price of less than $25,000 and vehicles are most frequently

Figure 24 - Sales volume and number of models by base price Jan-Aug 2016\textsuperscript{64}

\textsuperscript{63} Exotic models such as very high-end luxury or performance vehicles were excluded, e.g. Rolls Royce, Ferrari, etc.

\textsuperscript{64} WardsAuto data and manufacturer websites.
sold with starting prices ranging from $20,000-$24,999. The top 50 best-selling models and almost 90% of all new vehicles sold start at a base price of less than $35,000. The colored points denote the number of different models of each powertrain type that are offered in each price category. The number of models offered in each price category roughly follows the distribution of U.S. sales in each category, with the $20,000-$24,999 price range also offering the greatest number of model choices. However, the higher average volume per model for this popular price range also suggests that the number of models is not solely responsible for the higher sales volumes, as this category also includes some of the market's best-selling models.

To focus more closely on the trends of ZEVs and PHEVs, Figure 25 shows these powertrains in isolation. The figure illustrates that the lower bound sales price for ZEVs with significant sales volumes is lower than that for PHEVs, falling in the $25,000-$29,999 range. However there are also substantial volumes in the upper price ranges, making the sales more distributed across price categories, even though the model offerings are more concentrated at the lower price ranges. The lower bound for PHEVs falls in the $30,000-$34,999 range, which is about $10,000 more than the mode for ICEs (previous shown in Figure 24), and the vast majority of PHEVs sold are in this price range. Although 30 percent more ZEVs were sold during this period than PHEVs, it is not clear whether a greater number or diversity of PHEV models across price ranges would increase overall PHEV market shares even if they were offered at lower price points.

Current government purchase incentives can reduce the price of a new ZEV or PHEV to be more similar to new ICEs. While federal tax credits depend on individual consumers' tax situations and state incentives vary in amount and eligibility, Figure 26 illustrates sales volume and model counts for ZEV and PHEV prices adjusted to include federal and California state incentives. When accounting for these incentives, there are now ZEVs available in the two lowest price categories. Only when factoring in up to $10,000 worth of government incentives does the ZEV and PHEV price distribution become similar to the overall (mostly ICE) market, though the median price occurs in the $25,000-$29,999 range which is higher than the median price for ICEs. Some of this price increase may result from these vehicles having more features included as standard equipment similar vehicles with conventional powertrains might include as optional. Nonetheless, these price differences are relatively consistent with the higher technology costs for the different technologies that are discussed in Appendix C.

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65 Federal tax credit for purchases are claimed directly by the consumer on federal income tax returns and are not refundable in the case of the credit value exceeding an individual's tax liability, however tax credits are claimed by the title holder for leases. Federal tax credit varies based on battery size.

66 California state incentives assumed to be $2500 for all BEVs and $1500 for all PHEVs and do not include the additional rebates for low and moderate income households. Other state rebate incentives are of similar amounts. See Appendix E for more details. Some local government agencies also offer additional purchase incentives.
Figure 25 - ZEV and PHEV sales volume and number of models by base price Jan-Aug 2016

**ZEV (including BEVx)**
- Sales - ZEV
- Models - ZEV

**PHEV**
- Sales - TZEV PHEV
- Models - TZEV PHEV
Comparing the two columns in Table 5 shows that federal tax incentives and California-specific rebates reduce the base price of BEVs, PHEVs, and FCEVs by around $10,000, $7,000, and $13,000, respectively. Even after these price reductions, ICE base prices are lower than the sales-weighted average prices of all ZEVs and PHEVs. The average base price of passenger car ICES is around $25,000, while the average base price for ICE light trucks is just under $30,000.

BEV prices have a bimodal distribution, which represents two distinct price groups of BEVs: higher-priced BEVs (BEV200+) and the remaining BEVs (BEV<200). The average price for BEV<200 vehicles (around $23,000) is only competitive against the average price of passenger ICES ($25,000) after both the federal and state purchase incentives. Even after omitting the higher priced performance PHEVs that are not TZEV-eligible, PHEVs are offered at higher prices than BEV<200s with or without incentives.

### Table 5 - U.S. sales-weighted MSRP with and without purchase incentives

<table>
<thead>
<tr>
<th>Technology Type</th>
<th>Sales-weighted Average MSRP</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Without purchase incentives</td>
</tr>
<tr>
<td>All BEVs</td>
<td>$53,500</td>
</tr>
<tr>
<td>BEV&lt;200</td>
<td>$33,300</td>
</tr>
<tr>
<td>All PHEVs</td>
<td>$43,000</td>
</tr>
<tr>
<td>TZEV-certified PHEVs</td>
<td>$36,300</td>
</tr>
<tr>
<td>FCEVs</td>
<td>$58,700</td>
</tr>
<tr>
<td>All ICES</td>
<td>$27,600</td>
</tr>
<tr>
<td>Passenger Cars</td>
<td>$24,600</td>
</tr>
<tr>
<td>Light Trucks</td>
<td>$29,500</td>
</tr>
</tbody>
</table>
III.A.4.a. New vehicle transaction prices of PEVs

Rarely do consumers pay the exact MSRP with franchised dealers. While both MSRP and transaction prices have be increasing with time for the industry as a whole, in 2011 the actual transaction price was 93% of the MSRP and by 2015 had fallen to 91%. This reduction has been fueled in part by consumer cash incentives offered by auto manufacturers. At a vehicle segment level, the change in the ratios has been more pronounced, with small and compact cars that were previously in the mid-90% falling to be on par with the industry average in 2015. Meanwhile, midsize car segment started at the industry average in 2011 and has since fallen to 88%.  

Analyzing the purchase price of MY2015 PEVs currently registered in California Department of Motor Vehicle (DMV) records in April 2016 shows that on average, the transaction price of PEVs ranges from 98% for BEVs
to 103% for PHEVs of starting MSRP. Note that the DMV information does not always include MSRP for additional options or upgrades to the base model. For example, while it is possible to differentiate between the two trim levels of a Ford Fusion Energi PHEV, it is not possible to differentiate between the base Titanium version and the “fully-loaded” version, which would add an additional $6,700 to the MSRP. To the extent that consumers are opting for any additional features that would increase MSRP, the transaction price ratio would decline, which would reflect discounts provided by the dealer and/or manufacturer. Additionally, federal or state incentives can also reduce the ultimate price paid by the consumer, effectively further lowering this ratio, even though the dealer would transact at closer to MSRP. Assuming the same incentive values used for Figure 26, Figure 27 shows how the incentives lower the adjusted transaction price-MSRP ratio to 65% for BEVs and 84% for PHEVs. These results suggest that dealers and manufacturers are providing similar levels of discounts for ZEVs and PHEVs as they typically do for conventional vehicles, however the additional incentives provided by government is resulting in even lower costs for consumers.

To explore additional pricing trends, staff analyzed the Experian Automotive dataset to compare differences in prices of new leased and purchased PEVs from 2011 to 2015 for the 10 states that report purchase price data. As the Experian Automotive dataset does not provide purchase prices for California, the median transaction price of MY 2015 vehicles found in the California DMV registration data and the Experian Automotive data were compared to ensure comparability (see Table 6). The comparison suggests that California vehicle prices is generally somewhat higher, which can either reflect differences in the trim levels or options purchased and/or the availability of additional state incentives that can offset this higher price.

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67 NADA 2016b.
68 Excludes Tesla vehicles where are not sold under a dealer franchise business model. By default, the transaction price to MSRP ratio will always be 1.
69 There are ten states in the Experian Automotive data that are listed as providing purchase price data: Colorado, Kentucky, North Carolina, North Dakota, New Mexico, Ohio, Oklahoma, Texas, Virginia, and West Virginia.
Figure 27 - Ratio of California MY 2015 PEV transaction prices (assuming federal and state incentives) compared to MSRP\(^{70}\)

Table 6 - California DMV vs Experian Automotive MY2015 transaction prices

<table>
<thead>
<tr>
<th></th>
<th>Median CA DMV Price ($)</th>
<th>Median Experian Automotive Price ($)</th>
<th>Difference ($)</th>
</tr>
</thead>
<tbody>
<tr>
<td>BMW i3</td>
<td>42,100</td>
<td>40,070</td>
<td>2,030</td>
</tr>
<tr>
<td>Chevrolet Volt</td>
<td>34,300</td>
<td>33,350</td>
<td>950</td>
</tr>
<tr>
<td>Ford CMAX Energi</td>
<td>33,100</td>
<td>33,100</td>
<td>0</td>
</tr>
<tr>
<td>Ford Fusion Energi</td>
<td>37,300</td>
<td>33,598</td>
<td>3,702</td>
</tr>
<tr>
<td>Nissan LEAF</td>
<td>28,900</td>
<td>25,123</td>
<td>3,777</td>
</tr>
<tr>
<td>Tesla Model S</td>
<td>95,300</td>
<td>96,200</td>
<td>-900</td>
</tr>
<tr>
<td>Toyota Prius Plug-in</td>
<td>30,700</td>
<td>30,596</td>
<td>104</td>
</tr>
</tbody>
</table>

For new vehicles in the ten states that reported prices, staff ran a regression of price on whether a vehicle is leased and additional control variables, including vehicle model, purchaser race and income, dealership location, and the month and year of the transaction.\(^{71}\) The results from the

\(^{70}\) CA DMV data.
\(^{71}\) Specifically, the regression takes the form of:

\[
\text{Price}_{it} = \beta_0 + \beta_1 \text{Lease}_i + \gamma X_{it} + \epsilon_{it}
\]

Where subscript \(i\) denotes a specific vehicle and \(t\) denotes a specific month and year the vehicle was transacted. Price is the reported purchase price, Lease is an indicator for whether the vehicle was leased of purchased. \(X\) is a set of control variables including race indicators, income, the state the dealer was located in, and the year and month of
regression indicate that when controlling for some demographic, geographic, and time variables, that a leased PEV has a purchase price that is $7,400 lower than that of a purchased PEV. This difference is statistically significant at the 1% level. Additionally, the coefficients on the year and month of purchase control variables indicate how the average purchase price on PEVs, after controlling for model, lease status, dealer location, race, and income, suggest a downward trend in the purchase price over time. This downward trend could be a factor of both decreases in MSRP over time or a decrease in overall transaction prices through manufacturer discounts. Four models have lowered their starting MSRP from initial release to 2015, and accordingly the distribution of transaction prices for these models has also fallen. The regression also suggests that on average, wealthier individuals pay more for vehicles.

III.A.4.b. Dealer incentive data analysis
To evaluate whether price differences may result from differential incentives offered by auto manufacturers for dealers to promote with consumers, staff collected data from AutoNews\textsuperscript{72} for cash incentives offered between February 2016 and August 2016 for the same regions and vehicle models included in the dealership vehicle availability analysis described in Section III.A.3. The data suggest manufacturers offer similar incentives for the same technology type across regions. However, manufacturers offer different incentives for the different technology types.

Figure 28 shows the average incentives offered by technology type and region. Overall, BEVs appear to receive lower incentives than the other technologies, while PHEVs receive the highest level of incentives. The BEVs in the data (BMW i3, Ford Focus Electric, and Nissan LEAF) had $0 cash incentive for the majority of the sample period, while the PHEVs (Chevrolet Volt, Ford CMAX Energi, and Ford Fusion Energi) and HEV models have larger cash incentives than comparable ICEs produced by those manufacturers. One potential explanation for this difference is that government incentives tend to be higher for BEVs than PHEVs, which reduces the need for manufacturers to provide equivalent incentives. Additionally, as previously discussed, MSRP<sub>s</sub> for PHEVs are higher on average than those of BEV<sub>s</sub>&lt;200<sub>s</sub>, which may result in a greater need to offer additional incentives at the dealership level.

\textsuperscript{72} See Section VII.F for data description of AutoNews data.
III.B. **Consumer Awareness and Knowledge of ZEVs and PHEVs**

In order for consumers to purchase or lease a ZEV or PHEVs, they must first be aware that these vehicles are available in the market today. The National Research Council's Report, "Overcoming Barriers to Deployment of Plug-in Electric Vehicles," finds that lack of knowledge about both PEV benefits and offerings poses a barrier to mainstream adoption.\(^{74}\) Additionally, advertising expenditures in 2015 for select PEV models is highly variable across regions and manufacturers.\(^{75}\) This section summarizes ARB-sponsored research by UCD along with independent surveys and reports from Morpace, the National Renewable Energy Lab (NREL), Consumer Federation of America (CFA), Public Policy Institute of California (PPIC), and others that examine awareness and knowledge of ZEVs and PHEVs among new car buyers and general consumers in California and the rest of the U.S.

The results of these independent studies all reveal confusion and low levels of ZEV and PHEV awareness about the different PEV and FCEV technologies. For example, fewer than half of the respondents from two surveys – one by UCD and the other by NREL – were able to name a specific PEV model and even fewer a BEV. Results from the PACE survey similarly reveal a low level of awareness of basic facts regarding PEVs and FCEVs. For instance, fewer than half

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\(^{73}\) AutoNews data.


\(^{75}\) NESCAUM 2016.
of the respondents reported knowing that BEVs do not have a gasoline engine; only two-fifths reported knowing that PHEVs could be refueled at any gasoline station, and only a third reported knowing that FCEVs are refueled at hydrogen fueling stations. In addition, UCD, NREL and CFA studies have determined that those who are more knowledgeable about PEVs are more interested in acquiring one compared with those who are less knowledgeable. Furthermore, results from CFA surveys indicate that consumers are becoming more interested in acquiring PEVs, although the NREL surveys did not observe this increase. This section also discusses reports that analyze the effects of behind the wheel experience on attitudes towards PEVs. Results reveal that exposure to PEVs through ride and drive events or car-sharing programs seem to result in lasting, positive impressions and serve to be one of the most influential information sources for helping consumers decide on a PEV. Second to a vehicle test drive, another PEV driver is the other most influential information source for new buyers to choose a PHEV or BEV.

III.B.1. UC Davis 2015 Survey of New Car Buyers’ ZEV Valuation
This ARB-funded research project, completed in April 2016,76 collected information on the decision-making process and factors influencing the choices of new light-duty vehicle purchasers in California, focusing on the barriers and motivations for purchasing near-zero and zero emission vehicles. The study was designed to: measure consumer awareness, knowledge, experience and valuation of ZEVs and PHEVs; analyze consumer decision making regarding ZEV and PHEV purchase decisions; and compare consumers in California with consumers in other states, especially Section 177 ZEV States.

The vast majority (95% in California and 96% in overall sample) of the vehicles owned by survey respondents are fueled by gasoline. While many respondents claim to be “familiar enough with [ZEVs and PHEVs] to make a decision about whether one would be right for their household,” their familiarity was not gained from actual experience driving PHEVs, BEVs, FCEVs, or even HEVs (see Figure 29). Measured on a scale from -3 (none at all) to 3 (extensive driving experience), and excluding those who scored themselves as unsure or declined to answer, the mean scores for California respondents are all negative (HEVs, -1.14; BEVs, -1.97; PHEVs, -2.10; and FCEVs, -2.28) and the 75th quartile score for PHEVs, BEVs, and FCEVs varies from -1.77 (BEVs) to -2.73 (FCEVs). In short, within the realistic accuracy of the survey, more than three-fourths of this sample of California new car buyers had no driving experience with PHEV, BEVs or FCEVs. This result holds for respondents from the other states as well. It is also worth noting that despite an additional ten years in the market, survey respondents are also indicating limited familiarity with HEVs.

Figure 29 - Self-reported driving experience by drivetrain type

Note: A score of -3 represents no experience at all, 3 represents extensive driving experience. Excludes unsure or declined to state.

The measures of prior consideration show new car buyers in California were more likely than those in the other study states to have already purchased, shopped for, or at least gathered information on PEVs and FCEVs. Yet even in California, new car-buyers’ valuations of ZEVs and PHEVs were largely unformed. As shown in Figure 30, almost half (49%) of this sample of California new car buyers was aware of ZEV and PHEV purchase incentives from the federal government, while only one-third reported they were aware that California offers ZEV and PHEV purchase incentives. California's percentages were the highest in any state in the study and well above the average across all states (44% federal and 18% state). Respondent awareness of incentives offered by other entities, (e.g., cities, utilities, or manufacturers), is comparable to or lower than their awareness of state government incentives. Despite marketing of PEVs and deployment of PEV charging infrastructure since 2010, as well as federal, state, and local incentive programs for PEV purchase and use, 77% of respondents representing new car-buying households in California have yet to seriously consider a PEV for their household; 92% have yet to ask themselves the same question about FCEVs.

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78 At the time the survey was administrated, over 85,000 rebates had been awarded to PEV and ZEV drivers through California’s Clean Vehicle Rebate Project beginning in 2010, totaling over $180 million in incentives, https://cleanvehiclerebate.org/eng/rebate-statistics. See Appendix E for additional incentives available in California and Section 177 ZEV States.
More than five years after PEV marketing started in California, two-thirds of respondents—who as new car buyers have searched for information about cars, been on new car lots, and purchased a vehicle during this period—could not name a BEV for sale in the U.S., as shown in Figure 31. Of those in California who could name a BEV for sale, 95% named one of only two of the earliest BEVs commercially available: a Nissan LEAF and a Tesla Model S. Lack of understanding of the differences between BEVs, PHEVs, and HEVs is a likely explanation for why respondents named PHEVs when asked for makes and models of BEVs. Fewer respondents from other states were able to name a BEV model than those from California, although in Oregon, Maryland, Massachusetts, and Delaware a slightly higher fraction of respondents were able to name a PEV model than those from California.

The conclusion that most California new car-buyers have yet to even consider ZEVs or PHEVs was reinforced by the interviews conducted in California, Oregon and Washington, in which it was clear that most respondents formulated their first ZEV and PHEV valuations in the process of completing their survey and interview. Overall, awareness of HEVs, PEVs, and FCEVs was so low that it is reasonable to assume most new car buyers’ assessments prior to completion of the survey were based largely on ignorance. But without more effective dissemination of information about the availability and the technology of ZEVs and PHEVs, most California new car buyers will not have an opportunity to form a positive valuation.

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III.B.2. Morpace Powertrain Acceptance and Consumer Engagement Surveys

ARB licensed the use of the complete respondent data for the 2015 administration of the syndicated Powertrain Acceptance and Consumer Engagement (PACE) survey conducted by Morpace to better understand new vehicle owners nationwide to assess their awareness and perception of alternative powertrain technologies as well as their household characteristics and other attitudes.

According to the 2015 PACE Survey, consumer knowledge and awareness of alternative fuel technologies is low. Respondents indicated that 45% “own/have owned or know very well” a BEV, which is similar to the 44% for PHEVs. However, direct questions about knowledge of technologies indicated very low rates of understanding. Only 2% of respondents claimed they knew of all the facts presented for both BEVs and separately for PHEVs. Only 53% indicated they were aware that BEVs used only an electric motor. Even fewer (50%) indicated knowing there are zero exhaust emissions associated and fewer (45%) knew there is no gasoline engine in a BEV (see Figure 32). For PHEVs, only 45% of respondents reported knowing that PHEVs use both an electric and a gasoline engine (see Figure 33). Respondents seemed to be the least aware of basic facts regarding FCEVs, with less than a third reporting they knew those vehicles only emit water (see Figure 34). Evaluating based on regions, respondents in California or Section 177 ZEV states were not uniformly more informed about any technology than respondents in the rest of U.S.

Note: Darker bars represent states or regions with a ZEV regulation.

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Figure 32 - 2015 PACE Survey respondent BEV technology awareness

- Uses only an electric motor: 53%
- Battery stores electricity to drive motor: 52%
- Zero exhaust emissions: 50%
- No gasoline engine: 45%
- 75-250 miles of pure electric driving on a full charge: 35%
- It is recommended that BEV owners install a 240V charging station at home for convenience: 34%
- BEVs fully charge in 4-6 hrs. with a 240V charger and special equipment, or 6-12 hrs. on 120V: 31%
- Can achieve equivalent of more than 100 "MPG", though no gasoline is ever used: 30%
- Batteries are recycled at the end of vehicle life: 28%
- 240V/120V chargers are becoming more common in parking lots/public spaces: 23%
- HOV (high occupancy vehicle) lane approved in certain states: 14%
- None of the above: 9%

81 2015 PACE Survey. See Section VII.I for further details on this survey.
A gasoline engine and battery electric motor work together to propel the vehicle

The Plug-in Hybrid gasoline engine can be filled at any gas station

For maximum fuel efficiency, the battery should be plugged-in between trips

Gasoline engine shuts down when not needed, restarts automatically when needed

Lower tailpipe CO2 emissions due to reduced fuel consumption

Larger battery than Hybrid allows longer "all-electric" operation when Hybrids, reducing use of gas engine

All-electric range; 15-50 miles on battery alone. If the battery is not charged, vehicle will drive like typical Hybrid vehicle

Can achieve 100MPG. If driven short distances within all-electric range (charged between trips), it's possible to use only electric power

Full charge requires 2-4 hrs. with 240V and special equipment, a common household outlet (120V) is 2-3 times longer

Batteries are recycled at the end of vehicle life

240V/120V chargers are becoming more common in parking lots and other public spaces

HOV (high occupancy vehicle) lane approved in certain states

None of the above

---

82 2015 PACE Survey.
According to the 2015 PACE survey results, there is some evidence that overall awareness is improving slowly over time. Respondents showed small percentage improvements relative to (a separate set of respondents to) the 2014 PACE Survey in the fraction that indicated “know something about what it does” or “Own/have owned or know very well” for all technologies, largely as a result of gains in the portion of respondents owning or knowing very well (see Figure 35).

83 2015 PACE Survey.
Consumer perceptions play a significant role in forming consumer purchase decisions, though sometimes these perceptions may be based upon incorrect information. Figure 36 compares respondent perceptions of BEVs, PHEVs, and FCEVs along the same list of vehicle features. Participants rated BEVs more positively for environmental benefits, fuel economy, cost to refuel or charge vehicle, and newest technology. In contrast, more view BEVs negatively than positively on all other attributes, but especially for driving range, time required to refuel or charge, towing/hauling capacity, and acceleration/passing capability, and dependability and reliability. Although some of these perceptions may reflect today's BEV characteristics, for example currently only one BEV offers any towing capability and driving range of most BEVs is less than 100 miles per charge, others are more subjective and may be based on incorrect or outdated information. Respondents rated the same features more positively for PHEVs as they did for BEVs. The PHEV attributes viewed most negatively are time required to refuel or charge, driving range, convenience of refueling or charging, acceleration/passing capability, and towing/hauling capacity. While these relative ratings are similar for both types of PEVs, both the positive and negative ratings are generally lower in magnitude, suggesting that consumers are more ambivalent towards PHEVs than BEVs. Perceptions of FCEVs differ more dramatically from those of PEVs. The attribute with the strongest positive association for FCEVs is the fact that it is the newest technology, which may in turn result in the strongest negative associations being purchase price and ability to find qualified mechanics for servings. Although positive perceptions outweigh negative ones for environmental benefits and fuel economy, these are similar in magnitude to the perceptions of PHEVs, which were lower than those of BEVs.

84 PACE Surveys.
### Figure 36 - 2015 PACE Survey respondent perceptions of BEVs, PHEVs, and FCEVs

<table>
<thead>
<tr>
<th>Feature</th>
<th>BEVs</th>
<th>PHEVs</th>
<th>FCEVs</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fuel economy</td>
<td>-8% 19%</td>
<td>-7% 14%</td>
<td>8% 13%</td>
</tr>
<tr>
<td>Purchase/lease price</td>
<td>-14% 6%</td>
<td>-11% 7%</td>
<td>-26% 8%</td>
</tr>
<tr>
<td>Cost to refuel or charge vehicle</td>
<td>-12% 15%</td>
<td>-9% 12%</td>
<td>-16% 10%</td>
</tr>
<tr>
<td>Acceleration/passing capacity</td>
<td>-28% 6%</td>
<td>-12% 7%</td>
<td>-14% 6%</td>
</tr>
<tr>
<td>Dependability and reliability</td>
<td>-22% 7%</td>
<td>-11% 7%</td>
<td>-18% 6%</td>
</tr>
<tr>
<td>Ability to find qualified mechanics to service vehicle</td>
<td>-15% 6%</td>
<td>-10% 7%</td>
<td>-28% 7%</td>
</tr>
<tr>
<td>Towing/hauling capacity</td>
<td>-29% 6%</td>
<td>-12% 6%</td>
<td>-13% 7%</td>
</tr>
<tr>
<td>Resale value</td>
<td>-15% 7%</td>
<td>-11% 9%</td>
<td>-17% 7%</td>
</tr>
<tr>
<td>Insurance cost</td>
<td>-14% 9%</td>
<td>-8% 8%</td>
<td>-19% 9%</td>
</tr>
<tr>
<td>Overall value</td>
<td>-15% 7%</td>
<td>-10% 9%</td>
<td>-21% 8%</td>
</tr>
<tr>
<td>Safety</td>
<td>-14% 10%</td>
<td>-9% 9%</td>
<td>-17% 8%</td>
</tr>
<tr>
<td>Long-term maintenance costs</td>
<td>-16% 11%</td>
<td>-11% 8%</td>
<td>-19% 9%</td>
</tr>
<tr>
<td>Convenience of refueling or charging vehicle</td>
<td>-18% 7%</td>
<td>-12% 8%</td>
<td>-22% 7%</td>
</tr>
<tr>
<td>Peace of mind</td>
<td>-17% 8%</td>
<td>-11% 7%</td>
<td>-20% 7%</td>
</tr>
<tr>
<td>Time required to refuel or charge vehicle</td>
<td>-29% 8%</td>
<td>-17% 8%</td>
<td>-13% 7%</td>
</tr>
<tr>
<td>Driving range</td>
<td>-31% 7%</td>
<td>-13% 8%</td>
<td>-11% 10%</td>
</tr>
<tr>
<td>Environmental benefits</td>
<td>-7% 23%</td>
<td>-6% 13%</td>
<td>-8% 16%</td>
</tr>
<tr>
<td>Image</td>
<td>-14% 10%</td>
<td>-11% 10%</td>
<td>-13% 9%</td>
</tr>
<tr>
<td>Newest technology</td>
<td>-9% 12%</td>
<td>-7% 11%</td>
<td>-9% 26%</td>
</tr>
</tbody>
</table>

- **Negative Association**
- **Positive Association**

---

85 2015 PACE Survey.
Respondents indicated some interest in making their next vehicle either a ZEV or PHEV, which appears to be correlated with both their current vehicle segment and their familiarity with the technology type. Figure 37 plots familiarity (defined as reporting own(ed)/know very well what it does) against purchase interest (defined as probably or definitely interested in purchasing) for each vehicle technology based on the respondents' current vehicle type. In general, the points all fall along the diagonal, demonstrating strong correlation. Luxury vehicle owners (open markers) appear to have the greatest familiarity and interest in all three ZEV technologies. Among the non-luxury vehicle owners, familiarity and interest in FCEVs was lower than for PEVs, potentially a reflection of the current limited FCEV offerings.

Figure 37 - Relationship between technology familiarity and interest by ZEV technology type

However, this relationship may not hold at the regional level. Statistical tests ($X^2$ statistic) comparing California to Section 177 ZEV states to the rest of U.S. reveal differences in interest between regions, but no difference in levels of understanding of PEV and FCEV technologies.

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86 2015 PACE Survey.
As shown in Figure 38, purchase interest in BEVs among California respondents is 18 percentage points greater than for the rest of the U.S. while interest is ten percentage points greater in Section 177 ZEV states. In both regions, interest in BEVs is slightly greater than for PHEVs. Purchase interest in FCEVs revealed the same trend across regions but with slightly less interest in California in spite of the fact that there retail hydrogen refueling infrastructure is only available in California at this time.

Figure 38 - CA and SectionS177 ZEV state interest in ZEV technology for next vehicle relative to rest of U.S.  

III.B.3. NREL CARAVAN Surveys
A National Renewable Energy Lab (NREL) report investigated consumer attitudes toward PEVs.  The report was based on a February 2015 CARAVAN survey conducted by the Opinion Research Corporation, which sampled 1,015 households selected to be representative of the U.S. The survey has a margin of error of ± 3% at the 95% confidence level. Overall, almost half (48%) of respondents were able to name a specific PEV model, with the most commonly named models being the Chevrolet Volt (20%), the Toyota Prius Plug-in (18%), the Tesla Model S (14%), and the Nissan Leaf (10%). By far the most exposure respondents had with PEVs was seeing one in parking lots (49%), followed by sitting in a PEV (16%), driving a PEV (5%), and having a neighbor with a PEV (5%). Only 18% of respondents were aware of PEV charging infrastructure at their work or other locations they frequented, with only 10% of respondents passing these locations regularly.

87 2015 PACE Survey.
Table 7 - Summary of NREL CARAVAN Survey findings about consumer awareness

<table>
<thead>
<tr>
<th>Awareness/Exposure Metric</th>
<th>Percent of Respondents</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Model Availability Awareness:</strong></td>
<td></td>
</tr>
<tr>
<td>Ability to name a specific PEV model</td>
<td>48%</td>
</tr>
<tr>
<td><strong>Infrastructure Awareness:</strong></td>
<td></td>
</tr>
<tr>
<td>Not aware of any charging stations at work or near stores</td>
<td>79%</td>
</tr>
<tr>
<td><strong>PEV Exposure:</strong></td>
<td></td>
</tr>
<tr>
<td>Driving a PEV</td>
<td>5%</td>
</tr>
<tr>
<td>Sitting in a PEV</td>
<td>16%</td>
</tr>
<tr>
<td>Neighbor with PEV</td>
<td>5%</td>
</tr>
<tr>
<td>Seen one in parking lots</td>
<td>49%</td>
</tr>
</tbody>
</table>

**III.B.4. Consumer Federation of America Surveys**

The Consumer Federation of America commissioned the Opinion Research Corporation to conduct national surveys on consumer attitudes towards PEVs. The surveys were administered in August of 2015\(^89\) and 2016\(^90\) via landline and cell phone with 1,009 and 1,007 adult Americans completing the survey, respectively. The margin of error reported was ± 3%. Results indicate that interest in acquiring a PEV has increased between 2015 and 2016, rising from 31% to 36%. Results from the 2015 survey show that most Americans (54%) have a positive view of EVs. Both surveys revealed that the more consumers know about PEVs, the more positive their attitudes towards them and the more likely they are to consider acquiring one. However, only 6% reported knowing a great deal and 21% reported knowing a fair amount about PEVs in 2015. Results from the 2015 survey reveal that older respondents and males with higher education levels and higher incomes reported knowing more about PEVs and were more likely to express an intention to purchase. In contrast, results from the 2016 survey indicate young adults are the most interested in PEVs, with 50% of 18-34 year olds saying they would consider buying a PEV. In 2016, over half (55%) of survey respondents who reported knowing a great deal about PEVs were interested in buying one, while only 22% of those who reported no knowledge of PEVs also expressed interested in buying one.

**III.B.5. Effect of behind the wheel experience and more information**

When non-PEV consumers are exposed to PEVs evidence suggests they become more interested in acquiring them. The impact of exposure to PEVs through participation in ride and drive events and carsharing programs has been shown to have a positive effect on attitudes.

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towards PEVs and increase interest in PEV adoption.\textsuperscript{91,92,93} Additionally, the effect of educating consumers on fuel costs of different vehicle technologies using their own commuting patterns has also been shown to improve opinions of PEVs and interest in acquiring a PEV.\textsuperscript{94} However, it should be noted that drivers who attend ride and drive events and participate in carsharing may not be representative of the “average” consumer.

The Plug-in Electric Vehicle Collaborative (PEVC) held six ride and drive events coupled with surveys before and after the test drive and a follow up survey 3-6 months after the test drive.\textsuperscript{95} These events were held throughout California between August and November 2015. The pre- and post-drive surveys were completed by a total of 365 (pre) and 350 (post) respondents, while 53 participated in the follow-up survey. Analysis of the survey responses indicates that 76\% of participants were more likely to consider acquiring a PEV after test driving one, with participants slightly preferring a BEV (40\%) over a PHEV (36\%). The follow-up survey determined that an average of 15\% of the ride and drive participants had purchased or leased a PEV 3-6 months after the ride and drive event. A further 14\% of all participants are still planning to acquire a PEV. On average, 55\% and 38\% of participants reported that the test drive was very important and somewhat important part of their decision to consider purchasing or leasing a PEV.

Similarly to PEVC’s ride and drive surveys, the Metropolitan Transportation Commission (MTC) held ride and drive events coupled with surveys in the San Francisco Bay Area between May and October 2014.\textsuperscript{96} A total of 1,483 and 1,386 participants completed the pre- and post-drive surveys with 266 completing the follow-up survey at least two months after the event. A total of 79\% of participants reported that test driving a PEV improved their overall opinion of electric vehicles. Results from MTC’s ride and drive surveys show that immediately after the test drive respondents rated all of the eight dimensions comparing PEVs to conventional gasoline vehicles higher, with statistical significance, than before the test drive. The PEV dimensions that most improved between the pre- and post-survey were driving performance/handling (39\% vs 57\%), appearance (31\% vs 48\%), and overall quality (48\% vs 63\%). Participation in the ride and drive events also resulted in statistically significant reductions in the impact of tested potential barriers to owning a PEV that. These barriers tested included cost of purchase, limited driving range, difficulty finding a charging station on the road, concerns about the vehicle running out of

\textsuperscript{95} McLarney and Sarles 2014.
\textsuperscript{96} McLarney and Sarles 2014.
electricity on the road, time it takes to recharge vehicle, and difficulty charging a vehicle at home. Furthermore, 68% of survey participants reported being more likely to purchase a PEV after test driving one. The follow-up survey indicates that 11% of all ride and drive participants purchased or leased a PEV following their attendance at the event with the vast majority stating their test drive at the event positively impacted their decision to acquire a PEV. It is worth noting that not all of the positive impacts on perceptions of PEVs persisted months after the ride and drive event. For example, the percentage of participants that rated the PEV range as somewhat worse or much worse than a conventional gasoline vehicle went from 50% immediately after the test drive to 78% a few months after.

Carsharing is another avenue to expose consumers to PEV technologies. One study that investigated the effect of PEV carsharing on subsequent ownership found this exposure positively influenced customer perceptions and increased propensity to acquire a PEV, especially among younger people and women.\textsuperscript{97} Control and experimental groups consisting of a total of 3,662 carsharing members were surveyed between November, 2014 and February 2015 throughout the U.S. The control group was comprised of carsharing members who had not used the PEVs available to them, while the experimental group consisted of those that had used PEVs. However, 60% of all members of the experimental group had previous experience with a PEV either as a driver or passenger. Members of the control group indicated they would have liked to have used the PEVs through their carsharing program, but had not due to these vehicles not being available for reservations, either because others were using them, they were not in locations convenient to the users, or users did not know what these vehicles look like. Overall, over 40% of the experimental group reported that their desire to own a PEV was greater or much greater now as a result of their exposure through carsharing. Members of the experimental group were more likely to recommend driving and buying these vehicles over the control group. These differences were found to be statistically significant. Furthermore, members that used PEVs more often had a better opinion of ZEVs as well as a greater desire to own them. When asked what type of vehicle they expect to acquire next, 5% and 12% and of the experimental group reported they would acquire a PHEV or BEV, respectively. In contrast, 3% and 9% of the control group indicated they would acquire a PHEV or BEV as their next vehicle. Notably, those in the experimental group reported an increase of 3% and 9% for those who would acquire a PHEV or BEV and a 24% decrease of those that would acquire a gasoline vehicle next compared to before they participated in a carsharing program.

In addition to experience behind the wheel, simply giving consumers more information on PEVs also increases their interest in acquiring one. A study analyzed the effect of providing information on fuel costs of different vehicle technologies for specific commuting patterns on attitudes regarding PEVs.\textsuperscript{98} The EV Explorer\textsuperscript{99} is an informational, map-based on-line tool that allows users to compare fuel costs for different vehicles based on their own commuting

\begin{footnotesize}
\begin{itemize}
\item \textsuperscript{97} Shaheen, et al. 2015.
\item \textsuperscript{98} Sanguinetti, et al. 2016.
\item \textsuperscript{99} University of California, Davis. “EV Explorer” http://gis.its.ucdavis.edu/evexplorer/.
\end{itemize}
\end{footnotesize}
patterns, local fuel prices, and charging opportunities. A total of 108 participants were asked questions before and after utilizing the EV Explorer tool. Participants reported a significantly greater intention to acquire a PEV after using EV Explorer.

These findings are consistent with survey results of current PEV drivers in California who reported on information sources that are most influential in their purchase decisions. Figure 39 shows that vehicle test drives rank among the highest influential information source for all PEV types, and as the most influential for BEV200+ drivers. Other PEV drivers and third-party reviews also ranked high as influential information sources. Although the survey does not ask directly about where test drives occur, these results support outreach efforts like ride and drive events featuring other "real life" PEV drivers as effective marketing mechanisms. Extended test drives or pre-purchase rental programs may also help to further develop the PEV market.

**Figure 39 - Ranking scores by PEV type on most influential information sources in California**

![Figure 39 - Ranking scores by PEV type on most influential information sources in California](image)

**III.C. Current ZEV consumer purchase behavior**
New car buyers have a wide array of models from which to choose, only a small fraction of which are currently available with ZEV technology. Understanding the purchase motivations of past and recent buyers will be important for developing strategies to accelerate the market. To date, consumers have been varied in the degree to which financial, environmental, or performance attributes have influenced their choices, however the majority of households purchasing these vehicles have had no prior experience with any alternative fuel or hybrid

\[100\text{ CVRP results, Jun2015-Sept2016. See Section VII.G.1 for further details on CVRP survey.}\]
technology. Favorable characteristics, such as their access to charging and other household vehicles, as well as a variety of incentives further help to enable PEV ownership. Workplace charging also serves a dual role in supporting the market by providing consumers with assurances on charging away from home while also providing opportunities for increasing electric vehicle miles traveled. Finally, as a new technology, dealerships or retail stores serve significant roles in providing education to customers; however, the newness and constantly evolving marketplace creates challenges in keeping sales representatives up to date. This section describes staff's findings related to current PEV\textsuperscript{101} consumer purchase behavior and experiences in both California and Section 177 ZEV states.

\textbf{III.C.1. ZEV Purchaser Characteristics}

This section largely draws upon survey results administered to recipients of California's, Connecticut's, and Massachusetts' state incentive programs\textsuperscript{102} to describe who is currently driving ZEVs and PHEVs, the characteristics of their households, and the circumstances under which these vehicles were acquired. A few higher level aggregate data sources provide a more complete picture of the overall market, though with less granularity. Combined, these two approaches produce insights into what factors both enable and motivate the choice of a PEV, which in turn informs how the market may be developing and how consumers may respond to market changes in the future as well as how to appeal to a broader customer base.

\textbf{III.C.1.a. Purchase or Leased Vehicles}

Leasing provides consumers with an opportunity to experience electric-drive technology with relatively less commitment and generally lower monthly payments than outright purchase (and financing) of a PEV. The nature of leasing means that fleet turnover will be accelerated as most lease terms last 24 to 36 months, rather than the typical ownership period of five to seven years for the purchase of a new vehicle. However, with pre-paid mileages usually ranging from 10,000 to 15,000 annual miles, consumers with high travel demand may opt for purchases over leases.

The CVRP application data show different purchase and lease rates among the different PEV technologies and over time. Overall, the majority of BEV<200s and BEVxs have been leased (83% each), while half (50%) of the PHEVs have been purchased, and the majority of BEV200+s (83%) have been purchased.\textsuperscript{103} However, as shown in Figure 40, the trend over time among all PEV technologies has been an increase in the share of leases. For instance, only 30% of BEV<200s were leased in 2011, while the fraction jumped to 94% in the first four months of 2016. Similarly, 33% of PHEVs were leased in 2012 increasing to 76% in 2016.

\textsuperscript{101} Currently, there are only around 500 FCEVs in California and fewer than 100 survey responses. Therefore, FCEV demographics were not included in this section.

\textsuperscript{102} See Section 0 for descriptions of the California Clean Vehicle Rebate Project (CVRP) surveys, the Connecticut Hydrogen and Electric Automobile Purchase Rebate (CHEAPR), and the Massachusetts Offers Rebates for Electric Vehicles (MOR-EV).

\textsuperscript{103} Note that Tesla initially did not offer vehicles for lease, which may contribute to their high purchase rates.
Eligibility for California’s vehicle rebate requires applicants to lease their vehicles for at least 30 months, and therefore these survey results exclude any lessees who may have leased their vehicles for a shorter time period. As a result, the lease indicator in the Experian Automotive data shows a slightly higher fraction of lessees of all PEV types for transactions from 2011 to 2015 in California. Table 8 shows the lease fraction for California, the Section 177 ZEV states and the rest of U.S. Although the relative ranking of PEV types that are most frequently leases is consistent across the three regions, California’s market shows a higher fraction of leases for all categories.

Table 8 - Percent of leases within each region for each PEV type for 2011-2015 registrations

<table>
<thead>
<tr>
<th>PEV Type</th>
<th>CA</th>
<th>Section 177 ZEV States</th>
<th>Rest of U.S.</th>
</tr>
</thead>
<tbody>
<tr>
<td>PHEV</td>
<td>51%</td>
<td>46%</td>
<td>48%</td>
</tr>
<tr>
<td>BEVx</td>
<td>82%</td>
<td>54%</td>
<td>58%</td>
</tr>
<tr>
<td>BEV&lt;200</td>
<td>86%</td>
<td>66%</td>
<td>64%</td>
</tr>
<tr>
<td>BEV200+</td>
<td>16%</td>
<td>6%</td>
<td>12%</td>
</tr>
</tbody>
</table>

Note: Column widths are proportional to number of rebates granted for each PEV type and purchase year.

---

Figure 40 - Percent of CVRP rebated vehicles purchased and leased through April 2016

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104 CVRP Rebate data.
105 Experian Automotive data.
III.C.1.b. Number of Household Vehicles

The majority of 2015 and 2016 CVRP recipient respondents have more than one vehicle in the household. As shown in Figure 41 respondents in single-vehicle households are more likely to have a PHEV than the other types of PEVs, however the vast majority of PHEV drivers have at least one other household vehicle.

Figure 41 - Number of household vehicles by PEV type in California\textsuperscript{106}

Note: Column widths are proportional to the number of respondents in each PEV category.

California’s Ownership survey respondents represent a cross-section of the cumulative PEV drivers with over six months of experience with their vehicles and acquired their vehicles prior to 2015. As shown in Figure 42, less than 13% of these respondents belong to a single-vehicle household. Overall, only a slightly higher percentage of PHEV households are single vehicle households (13%) compared with BEV<200 households (9%). Despite potential range or infrastructure limitations, nine percent is a non-trivial fraction of single-vehicle households who drive BEV<200. A similar percentage of BEV200+ households only have one vehicle (11%) compared to PHEV households. These trends are fairly similar across different PEV models, and the percentage has slightly increased with purchase year.

\textsuperscript{106} CVRP results, Jun2015-Sept2016.
ILL.C.1.c. Replacing or Adding Vehicles
Given the high lease rates discussed in Section III.C.1.a, whether vehicles are acquired as a replacement vehicle or additional to a household's fleet can influence vehicle usage and future purchase behavior. Leased vehicles that are added without a new driver to the household may have a lower likelihood of being replaced (immediately) upon expiration of the lease while replacement vehicles may have a greater likelihood of resulting in repeated leases. The majority of all CVRP, CHEAPR\textsuperscript{108} and MOR-EV\textsuperscript{109} recipients shown in Figure 43 replaced a vehicle with the rebated PEV. In CA, PHEVs, BEVx, and BEV200+ replaced household vehicles at similar rates (70 - 74\%). Similarly in Massachusetts, PHEVs, BEV200+ and BEVx were acquired as replacement vehicles at roughly the same rates (76 - 80\%). In California and Massachusetts BEV<200s replaced a vehicle 63\% of the time. In Connecticut, PHEVs were replacement vehicles in 85\% of instances compared with 58\% for BEV<200s.

\textsuperscript{107} Ownership results. See Section VII.G.4 for details about California's ownership survey.
\textsuperscript{108} See Section VII.G.2 for details about Connecticut's CHEAPR incentive program survey.
\textsuperscript{109} See Section VII.G.3 for details about Massachusetts' MOR-EV inventive program survey.
Figure 43 - Fraction of PEV rebated that were a replacement or additional vehicle based on CVRP, MOR-EV, and CHEAPR Surveys\textsuperscript{110,111,112}

Note: Column widths for each state are proportional to the number of respondents in each PEV category.

Figure 44 - Reasons for vehicle purchase/lease now in California\textsuperscript{113}

Note: Single, taller bars reflect reasons exclusive to each transaction type. Bars will sum to more than 1 given respondents were permitted to select more than one reason.

Reasons for replacing or adding a vehicle can be further analyzed when looking at California buyers, as shown in Figure 44. For both replacing and adding households in the 2015-2016 timeframe, government or employer incentives are most commonly cited as motivating the timing of their recent transaction, suggesting that consumers may be concerned about the

\textsuperscript{110} CVRP results, Oct 2013-Nov 2015.
\textsuperscript{111} MOR-EV results.
\textsuperscript{112} CHEAPR results.
\textsuperscript{113} CVRP results, Jun2015-Sept2016.
longevity of existing incentives such as tax credits or rebates. Additionally, both types of households frequently noted spending too much on fuel. Appealing prices or low interest/lease rates were more often cited for adding households than replacing households, rather than changes in consumer tastes or needs. Pricing strategies thus do help to expand the market. About half of the replacement transactions were out of "necessity" such as vehicles becoming too old or unreliable, leases expiring, or being damaged in accidents.

III.C.1.d. Prior ownership of alternative fuel vehicles
Approximately 80% of respondents to the 2015-2016 CVRP survey report that their household is purchasing or leasing their first PEV. Despite notions that consumers will need to ease their way into greater degrees of vehicle electrification, these results suggest that many drivers are willing to take the plunge into full electrification without any transition.

As shown in Figure 45, those acquiring BEV<200s are the group with the highest proportion of respondents new to PEVs; this also represents the PEV type with the largest number of respondents and greatest market share. Those acquiring PHEV, BEVx, and BEV200+ are all more likely to have had some prior PEV experience, though mostly having only one previous PEV. In the case of PHEVs, the launch of the redesigned Chevrolet Volt during this survey period likely temporarily magnifies the number of experienced PEV drivers, though still nearly 70% of Chevrolet Volt respondents reported this to be their first PEV. Furthermore, among those new to PEVs, only 17% are transitioning from HEVs, either reporting that their PEV replaces an HEV or that another vehicle in their household is an HEV.

Figure 45 - Number of prior PEVs purchased or leased by PEV type in California

![Figure 45 - Number of prior PEVs purchased or leased by PEV type in California](image)

Note: Column widths are proportional to the number of respondents in each PEV category.

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Nationally, the National Automobile Dealers Association (NADA) analyzed vehicle disposal data including new and used vehicle retail transactions from over 7,500 automotive franchises in the United States and Canada originating from J.D. Power’s Power Information Network® (PIN).\textsuperscript{115} As shown in Figure 46, results reveal that 85% of consumers who purchased BEVs between 2013 and 2015 disposed of a gasoline powered vehicle followed by an HEV (8%). Similarly, 77% of PHEV consumers replaced a gasoline vehicle followed by 18% replacing an HEV over these three years. An average of 3.5% of BEV consumers replaced another BEV, with another 0.7% of BEV consumers replacing a PHEV; PHEV consumers had similar replacement levels. Although all these percentages have been relatively stable over the three years studied, the percentage of PHEV consumers that have replaced a PHEV has increased from 1.8% in 2013 to 6.4% in 2015 which seems to have offset the decline in PHEV consumers replacing an HEV. In contrast, no consumers have replaced a BEV with an HEV and only 0.1% have replaced a PHEV with a conventional hybrid.

\textbf{Figure 46 - Replaced technology type for BEV and PHEV purchases CY2013-2015\textsuperscript{116}}

\begin{figure}[h]
\centering
\includegraphics[width=\textwidth]{Figure46.png}
\caption{Replaced technology type for BEV and PHEV purchases CY2013-2015}
\end{figure}

\textbf{III.C.1.e. Charging Locations}

Given that PEV recharging/refueling may be different from conventional vehicles, understanding where current PEV drivers are able to charge their vehicles and the cost of this charging provides more insights into who is buying PEVs and why. Additionally, infrastructure availability is useful for gauging how the market is penetrating to different consumer groups and the benefits of policies that facilitate infrastructure deployment that can help to expand the market.

\begin{itemize}
\item \textsuperscript{115} NADA 2016a. National Automobile Dealers Association. April 2016. \textit{Alternative Powertrains: Analysis of Recent Market Trends & Value Retention}. \url{http://img03.en25.com/Web/NADAAUCG/%7B49f71c70-31ef-4af9-870b-aec4c6245bd%7D_201604_AltPowertrains.pdf}.
\item \textsuperscript{116} NADA 2016a.
\end{itemize}
**III.C.1.e.i. Home charging**
The ability to charge at home is one of the advantages of PEV ownership. Correlated to home parking, over 90% of recent PEV consumers in California can and do charge at home. The larger the battery pack, the more often the household is using faster charging speeds (240V, level 2) at home, as shown in Figure 47 (light and dark blue). The majority of PHEV, BEVx, and BEV<200 respondents are relying on slower charging speeds (120V, level 1), of whom only about one-third do not believe faster charging to be necessary to meet their needs. However, the remaining respondents indicate costs, complexity, or authority as renters or members of homeowners associations as reasons for not installing level 2 charging and may benefit from public policy to address these issues. In contrast, the overwhelming majority of current BEV200+ drivers are able to charge at home at level 2 speeds. Assuming home will be the predominant location for charging in the future, these results may foreshadow future needs for PEV drivers to increase their home charging speeds as more larger battery vehicles are introduced that accommodate longer daily drive cycles (or allowing less frequent charging, especially in multi-PEV households).

*Figure 47 - Type of home charging by PEV type in California*

![Figure 47 - Type of home charging by PEV type in California](image)

Note: Column widths are proportional to the number of respondents in each PEV category.

This higher charging speed will likely result in some additional cost for some future purchasers of longer range PEVs. Among those using outlets, 80% of respondents reported not needing any upgrades at all to be able to charge at home. As shown in Figure 48, installing level 1 or 2 outlets is typically less expensive than installing a full charging station (electric vehicle service equipment or EVSE) due to the lower material cost. Regardless of the type of upgrade, though, residential charging infrastructure has been added at a median cost of less than $1000; with

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outlets being installed at a median cost of $600 and EVSEs procured and installed at a median cost of $900.

Figure 48 - Distribution of infrastructure costs for residential charging in California 2015-2016.118

Note: Bars of each color sum to 1.

III.C.1.e.ii. Workplace charging
Workplaces can serve as "second showrooms" for employees to learn about new vehicle technologies from their colleagues and a number of employers have joined initiatives such as the U.S. DOE’s Workplace Charging Challenge to provide their employees with opportunities to charge their vehicles while at work. In addition to assisting with workforce retention, workplace charging can increase the electric vehicle miles traveled (eVMT) of PEVs, especially for those consumers whose commute distances exceed the all-electric range of their vehicles. When workplace charging is available for free, this can serve as an incentive for employees. However, even when only paid charging is offered, the availability of infrastructure can still enable PEV adoption for those who are not able to charge at home, or provide the necessary comfort or flexibility for using a PEV for more than just commuting purposes. In the future, workplace charging may also be important for vehicle grid integration and balancing electrical loads that incorporate a greater share of renewable energy sources.

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California PEV consumers tended to have more access to workplace charging (39-49% depending on PEV type) compared to Massachusetts consumers (28-36%), especially the BEV<200 (47% vs 34%) and BEVx (49% vs 30%) drivers. The number of respondents not working/working from home was fairly similar among both states across PEV types except for for BEV200+ consumers (19% CA vs 26% MA).

Figure 49 - Workplace charging availability for CVRP and MOR-EV Survey respondents\textsuperscript{119,120}

![Figure 49 - Workplace charging availability for CVRP and MOR-EV Survey respondents](image)

Note: Column widths for each state are proportional to the number of respondents in each PEV category.

The majority of PEV drivers in California who have access to workplace charging (about one-quarter of the entire sample) are able to charge for free, which contributes to lowering total vehicle ownership costs and is consistent with other survey results showing free charging more generally to be an important incentive. Additional to battery size, frequency of workplace charging usage also seems to be correlated to whether access is free or paid. When workplace charging is provided for free, usage is much more frequent than when drivers must pay (though specific costs are not collected) as shown in Figure 50 and Figure 51.

This finding would support the use of pricing to manage charging congestion at workplaces and elsewhere. Although future increases in battery sizes may suggest a reduced need for infrastructure away from home, still roughly 40 percent of BEV200+ drivers reported using workplace charging at least once a month even when paid. So while charger types, configurations, pricing and ratios will continue to evolve, the need for workplace charging infrastructure will likely remain, especially for drivers without access to home charging, and existing infrastructure investments will continue to serve PEV drivers in the future.

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\textsuperscript{119} CVRP results, Oct 2013-Jun 2016.
\textsuperscript{120} MOR-EV results.
Figure 50 - Workplace charging frequency in California when free\textsuperscript{121}

Note: Column widths are proportional to the number of respondents in each PEV category.

Figure 51 - Workplace charging frequency in California when paid\textsuperscript{122}

Note: Column widths are proportional to the number of respondents in each PEV category.

\textsuperscript{121} CVRP results, Jun2015-Sept2016.
\textsuperscript{122} CVRP results, Jun2015-Sept2016.
IL.C.1.e.iii. **Residential electricity rates for PEV charging**

While electric-drive technology is inherently more energy efficient than internal combustion engines, operating cost savings will not be realized for PEVs if electricity prices are too high. While some employers, retailers, municipalities, and auto manufacturers offer free charging at various locations, home remains the predominant location for vehicle charging. In California, electric utilities have been somewhat more progressive in offering reduced electricity prices for PEV charging during off-peak hours. These EV time-of-use (TOU) rates can potentially encourage PEV adoption by allowing PEV drivers to charge their vehicles at certain times when electricity rates are lower. As a result, some consumers may still have lower PEV operating costs than those driving conventional vehicles even during times of low fuel prices. Gauging the share of drivers aware of these charging discounts helps utilities and their regulators to improve their outreach. Additionally, if a significant portion of drivers are aware of the EV rates but are not electing to use them, this could suggest modifications to the rate structures may be needed to support further PEV market growth.

More than 60% of California respondents use or plan to use an EV electricity price rate for charging at home. However, in Massachusetts more than 89% of consumers do not use or do not plan to use EV rates and this likely reflects that Northeast utilities are only beginning to offer charging discounts. Vehicles with larger battery packs have the potential to benefit more from adopting a special utility rate for charging their PEV at home as they have the ability to consume the most electricity at discounted rates (and offset higher rates for other household consumption). However, actual electricity consumption will depend on (electric) vehicle miles traveled, which in turn determines the financial benefit of adopting an EV or TOU rate. As a result, opting into a reduced rate for EV charging is only somewhat correlated to battery size. In Massachusetts, more PHEV consumers use or plan to use EV rates than BEV<200 consumers (11% vs 4%) while in California similar proportions of PHEVs and BEV<200 drivers use EV rates for charging at home (62% vs 63%). Interestingly, although Ford C-MAX and Fusion Energi PHEVs have the same battery capacity, Fusion drivers in California have opted into EV rates in larger numbers, suggesting other influencing factors.
As shown in Figure 53, about one-fifth of recent California consumers were aware of an EV rate offered by their utility but have elected to remain with their existing residential rate, presumably because this rate would not provide financial benefits based on their household's electricity consumption patterns. About another fifth of respondents are unaware of any EV rate. Although in some cases, consumers with municipal utilities may not have EV rates available to them, the vast majority of respondents have their electricity provided by one of the three investor-owned utilities (IOU) that do offer EV (or TOU) rates.

Note: Column widths for each state are proportional to the number of respondents in each PEV category.

Figure 53 - Share of adoption/awareness of reduced utility rates for PEV charging by PEV type in California\textsuperscript{125}

Note: Column widths are proportional to the number of respondents in each PEV category.

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\textsuperscript{123} CVRP results, Oct 2013-Jun 2016.
\textsuperscript{124} MOR-EV results.
\textsuperscript{125} CVRP results, Jun2015-Sept2016.
Figure 54 shows adoption/awareness levels across utilities in California to be more variable. Similar fractions are unsure of whether they are charging using any discounted rates, but there are larger differences in the other categories. Within the segments aware of EV rates, opt-in rates are higher within IOUs; while territories like San Diego Gas and Electric (SDG&E) have the highest proportion of BEV200+ respondents that may be skewing these results, the vehicle market shares in Southern California Edison (SCE) and Los Angeles Department of Water and Power (LADWP) are similar, suggesting that the rates themselves (or their various conditions, such as separate meter requirements or TOU parameters) account for the differences.126

![Figure 54 - Share of adoption/awareness of reduced utility rates for PEV charging by utility in California](image)

Note: Column widths are proportional to the number of respondents in each utility.

III.C.1.f. Residence
The ability and motivation for most current PEV drivers to charge at home, as discussed in the previous section, may be related to the attributes of their residence. Specifically, consumers who own their own homes have greater autonomy to make modifications to allow for home charging; the type of residence will also affect access to electricity at vehicle parking locations; and the presence of photovoltaic solar panels (which itself is likely correlated to home ownership) may affect motivations to charge at home from an environmental or financial perspective. At this stage of the market, the majority of PEV consumers appear to be those for whom home charging is easiest. Broadening the market to other segments, such as renters of multi-unit dwellings will likely require additional policy interventions to provide more opportunities for these consumers to charge, either with additional infrastructure deployment or agreements with local charging station hosts to allow nearby residents to charge overnight. However, increases in vehicle range, faster onboard vehicle charging speeds, and the

126 See Appendix E for discussion of residential electricity prices in California.
proliferation of DC fast charging stations can also facilitate adoption among those who do not have access to home charging if vehicle charging becomes more similar to gasoline refueling.  

**III.C.1.f.i. Rent/own**

Home ownership increases the probability that a consumer would have the authority to install or upgrade electrical equipment that would allow for or improve home PEV charging. This authority is not automatic as some home ownership associations may have restrictions on renovations that would be visible from outside the property. However, interior upgrades would likely not be prohibited, and in all cases, ownership increases the probability that the consumer will remain at that location in the mid- or long-term, so any investments to the residence will be less likely to be stranded. To date, a large majority of PEV consumers own their own residence, with minimal variation between the different PEV types or regions, as shown in Figure 55. These trends may be correlated to residence type as well as household income levels.

**Figure 55 - Percentage of respondents that rent or own their residence based on CVRP, MOR-EV, and CHEAPR Surveys**  

Note: Column widths for each state are proportional to the number of respondents in each PEV category.

**III.C.1.f.ii. Residence type and home parking**

PEVs offer the possibility of convenient charging when charging is available at home. The availability of home charging is highest when consumers have off-street parking available at their residence, which in turn is correlated to their type of residence. Most PEV consumers tend to live in detached single family homes, as shown in Figure 56. It is worth noting a few PEV models that were more prevalent among those that lived in an apartment/condo or attached housing. In Connecticut, both Ford Enegi models and the BMW i3 were acquired slightly more by apartment/condo residents, suggesting that the additional gasoline powertrain provides needed flexibility. In Massachusetts, the Fusion Energi, BMW i3 REx, Smart Fortwo, and VW e-
Figure 56 - PEV driver residence types based on CVRP, MOR-EV, and CHEAPR Surveys\textsuperscript{132,133,134}

Note: Column widths for each state are proportional to the number of respondents in each PEV category.

Golf are among those found living in attached houses and apartments/condos. In California, the Toyota Prius Plug-in, Fiat 500e, Ford C-MAX Energi, and Nissan Leaf were more likely to be acquired by those living in attached houses and apartments/condos.

Combining the residence type of current PEV consumers with the parking location at home in California and Massachusetts, Figure 57 shows the majority live in detached houses but the distribution between parking in a garage and the driveway is similar. Surprisingly, the share of those parking in driveways exceeds 30% in both states. California PEV consumers living in attached houses and apartments or condominiums were more likely to have a garage to park their vehicle in than those in Massachusetts (74% and 60% vs 48% and 53%). Carports were also much more likely to be present in California than Massachusetts PEV residences. A similar

Figure 57 - PEV driver home parking type and residence type based on CVRP and MOR-EV Surveys\textsuperscript{135,136}

Note: Column widths for each state are proportional to the number of respondents in each residence type.

\textsuperscript{132} CVRP results, Oct 2013-Jun 2016.
\textsuperscript{133} MOR-EV results.
\textsuperscript{134} CHEAPR results.
\textsuperscript{135} CVRP results, Oct 2013-Nov 2015.
\textsuperscript{136} MOR-EV results.
proportion of respondents in both states live in multi-unit dwellings where they may not have dedicated parking for their PEV, such as in a parking lot or on the street, though a small fraction of both BEV and PHEVs consumers are seemingly able to manage; at this stage of the market, PHEVs do not seem to be favored by those living in apartments or condos more so than BEVs.

**III.C.1.f.iii. Solar panels at your residence**

The presence of solar panels that produce electricity at a residence informs both the emissions impact of PEV usage as well as the potential charging behavior of these consumers. While households that are motivated by environmental reasons to purchase a PEV may similarly be motivated to install solar panels, the presence of these panels may have also motivated their purchases as PEV operating costs could be lower if solar panels are already present at the residence. Alternatively, the extent to which a PEV purchase motivates the installation of solar panels demonstrates the co-benefits of PEV market expansion for emission reductions in the electricity sector.

As shown in Figure 58, higher percentages of California PEV consumers have installed (25-35%) and planned to install (48-58%) solar panels in their home within the next year compared to those from Massachusetts (17-23% and 18-27%). Similar shares of PHEV and BEV<200 consumers in California had solar panels installed at their home (~25%), whereas more BEV<200 than PHEV consumers did in Massachusetts (23 vs 18%). California BEV200+ consumers were the most likely (35%) to have solar panels installed across all vehicle technologies in these two states. In contrast, a higher percentage of BEV<200 (23%) consumers had solar panels installed than BEV200+ (19%) consumers in Massachusetts.

**Figure 58 - Solar panels at residence of PEV drivers based on CVRP and MOR-EV Surveys**

![Figure 58 - Solar panels at residence of PEV drivers based on CVRP and MOR-EV Surveys](image)

Note: Column widths for each state are proportional to the number of respondents in each PEV category.

**III.C.1.g. Comparison to current conventional new car buyers**

At around 80%, the lease rates of PEVs are considerably higher than occur in the overall new vehicle market where leases comprised about 23% of new vehicle transaction at the end of

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138 MOR-EV results.
2010 and have climbed to about 33% by the end of 2015.\textsuperscript{139} PEV households also tend to have more household vehicles than the more general new car buying population, where about one-third of households have only one vehicle\textsuperscript{140} compared to the roughly 10% of single-vehicle PEV households.

Based on the UCD New Car Buyers Study, three-fourths of respondents in states sampled (73%) report they own their home, 26% rent, and approximately 1% lease or have some other arrangement. The PEV respondents to surveys in California, Connecticut, and Massachusetts show higher levels of home ownership than in the broader new vehicle market. Potentially related to these home ownership levels, at least 80% of PEV households live in a detached house, compared to the approximately 70% among overall households in California and Section 177 states (see Figure 59).

Finally, Figure 60 shows that about 70% of new car-buying Californians and only 45% of Massachusetts consumers park at least one vehicle in a garage or attached carport at their residence. However, among PEV drivers in these two states, the share of parking in a garage or carport is similar around 60%. It is possible that garage parking is more important for PEV ownership in New England than it may be in more temperate California. Alternatively, California PEV drivers may be able to be more reliant on workplace or public infrastructure that reduces the need for charging at home and the associated garage parking.

\textbf{Figure 59 - Residence type among new car buyers by state}\textsuperscript{141}

\begin{figure}
\centering
\includegraphics[width=\textwidth]{figure59}
\end{figure}

\begin{itemize}
\item \textsuperscript{140} 2015 PACE Survey.
\item \textsuperscript{141} Kurani, et al. 2016.
\end{itemize}
III.C.2. ZEV Purchase Motivations
Understanding existing drivers’ motivations for choosing a PEV is important for developing effective outreach materials and campaigns to build upon existing market shares. Consistent with surveys of new car buyers describing their motivations for (hypothetically) choosing a ZEV and PHEV, survey results of actual PEV drivers show that motivations can be varied, ranging from financial or environmental benefits to vehicle performance. Additionally, given the current subsidies and incentives devoted to encouraging PEV and FCEV adoption, measuring their role in the purchase decision will inform how their future sunset might affect market development. Infrastructure, particularly at home, also plays an important role in enabling a PEV purchase, though as PEVs increase their vehicle range, infrastructure on the way to destinations will become increasingly important to consumers.

III.C.2.a. Conventional new car buyer motivations for ZEVs and PHEVs
Returning to the ARB-funded research project on new car buyers, positive or negative consumer valuation was expressed by survey respondents’ stated preferences for a plausible next new vehicle. During the design game, respondents were asked to design a plausible next new vehicle for purchase assuming varying costs for different vehicle technologies, with and without certain incentives. ZEV valuation was determined by the vehicle drivetrain type selected by respondents during the survey’s vehicle design game. Vehicle drivetrain types included: internal combustion engine (ICE), HEV, BEV, PHEV, or FCEV. Once (partially) informed about ZEV and PHEV technologies, a substantial share (38%) of survey respondents valued them positively.

Within this overall context of generally low levels of prior experience or consideration of PEVs and FCEVs, 38% of the California sample had a sufficiently positive valuation to design a PHEV.

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(21%), BEV (11%), or FCEV (6%) as their next new vehicle, as shown in Figure 61. The California sample was more likely than respondents from most other study states to design their next new vehicle to be a PEV or FCEV. Household factors associated with positive valuation of ZEVs and PHEVs by respondents include:

- Prior consideration of PEVs or FCEVs—to the extent they have searched for related information or visited a vehicle dealership;
- Higher familiarity with all drivetrain types;
- Greater experience driving HEVs, PEVs, or FCEVs;
- Access to home charging/fueling infrastructure;
- Favorable assessments of the comparative safety and reliability of PEVs compared to ICE vehicles;
- Concern that air pollution is both a regional threat and a personal risk.

Figure 61 - Design game results of vehicle technology valuations by state\textsuperscript{144}

Motivations for designing PEVs or FCEVs were assessed on a scale from 0 = not at all important to 5 = very important. Respondents were presented with a list of 17 possible

\textsuperscript{144} Kurani, et al. 2016.
motivations derived from prior research. However, respondents were restricted to spend a maximum of 30 points summed across all 17 items. Because not all respondents spent the maximum number of points, an “average” score for any individual item is the total number of points spent by all respondents, divided by the number of respondents, and divided again by the number of items. The resulting mean motivation score for the California sample is 1.38. Any item scoring higher than this is interpreted as having a “high” score. The highest scoring motivations for positive valuation are listed in Table 9 as well as the percent of respondents assigning the maximum five points to each of these motivations.

The highest-rated self-reported motivations for positive valuation of PEVs or FCEVs were a mix of private and pro-social factors including: fuel cost savings, interest in new technology, home charging convenience, and reducing climate change, air pollution, oil imports, and payments to oil producers. Saving money (in this case, restricted to fuel cost savings) is not often at the top of the list of ZEV motivations in academic papers, policy discussions, and market analyses. However, 41 percent of respondents who design a ZEV give the maximum number of possible points to saving money on fuel costs (and two-thirds assign two or more points)—possibly revealing a “partial rationality” that apportions costs to different categories and treats them separately from and possibly even differently than vehicle purchase costs.

Table 9 - Highest-scoring motivations of new car buyers for designing a PEV or FCEV

<table>
<thead>
<tr>
<th>Motivations for Designing a PEV or FCEV</th>
<th>Mean</th>
<th>% 5 pts.</th>
</tr>
</thead>
<tbody>
<tr>
<td>To save money on gasoline or diesel fuel</td>
<td>2.91</td>
<td>41.0</td>
</tr>
<tr>
<td>I’m interested in the new technology</td>
<td>2.39</td>
<td>29.8</td>
</tr>
<tr>
<td>It will reduce the effect on climate change of my driving</td>
<td>1.87</td>
<td>23.0</td>
</tr>
<tr>
<td>It will reduce the effect on air quality of my driving</td>
<td>1.84</td>
<td>20.5</td>
</tr>
<tr>
<td>It will reduce the amount of oil imported to the United States</td>
<td>1.55</td>
<td>16.7</td>
</tr>
<tr>
<td>I’ll pay less money to oil companies or foreign oil producing nations</td>
<td>1.52</td>
<td>17.0</td>
</tr>
<tr>
<td>It will be fun to drive</td>
<td>1.49</td>
<td>14.6</td>
</tr>
<tr>
<td>It will be safer than gasoline or diesel vehicles</td>
<td>1.47</td>
<td>15.6</td>
</tr>
</tbody>
</table>

Mean Motivation Score 1.38

Households who have the infrastructure to charge or fuel at home and those with higher familiarity with all drivetrain types and greater experience driving HEVs, PEVs, or FCVs were more likely to have a higher ZEV or PHEV valuation. Similarly, households with more favorable assessments of the comparative safety and reliability of PEVs, and the driving range per charge/fueling and charging, and fueling times of ZEVs were more likely to design such vehicles. Households who are more concerned that air pollution represents both a regional threat and a personal risk are also more likely to design ZEVs. Households who have already considered purchasing a ZEV—to the extent they have searched for information, visited a vehicle dealership, or may drive one already—have higher valuations of ZEVs.

Based on their vehicle designs, most respondents appeared uninterested in PEVs or FCEVs (at least at this point in time). Motivations against designing such vehicles were assessed by a process similar to that used to identify motivations for designing them. The global mean score for all motivations against ZEVs was 0.96. California respondents’ highest-scoring self-reported motivations against designing a PEV or FCEV as their next new car are listed in Table 10, sorted from high to low by their mean score. The top self-reported reasons for negative valuation of PEV or FCEV were: limited access to vehicle charging facilities; vehicle purchase price; vehicle range; and lack of familiarity with vehicle technologies. Many of the respondents’ highly rated motivations against designing a ZEV are connected to the newness of the vehicles. Arguably other motivations against, such as the high initial purchase price and distance per charge or fueling, may also belong to what the researchers characterize as “teething problems of new technology.” This is not to dismiss the on-the-ground importance of these concerns, but to note that consumers’ concerns may be ameliorated with each new generation of technology, with continued market growth and infrastructure deployment, and with continued accumulation of experience and information by consumers.

### Table 10 - Highest-scoring motivations of new car buyers against designing a PEV or FCEV\(^{146}\)

<table>
<thead>
<tr>
<th>Motivations Against Designing a PEV or FCEV</th>
<th>Mean</th>
<th>% 5 pts.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Limited number of places to charge or fuel away from home</td>
<td>2.52</td>
<td>37.0</td>
</tr>
<tr>
<td>Cost of vehicle purchase</td>
<td>2.08</td>
<td>30.2</td>
</tr>
<tr>
<td>Distance on a battery charge or tank of natural gas is too limited</td>
<td>1.82</td>
<td>24.9</td>
</tr>
<tr>
<td>I’m unfamiliar with the vehicle technologies</td>
<td>1.73</td>
<td>23.0</td>
</tr>
<tr>
<td>Concern about electricity, e.g. blackouts and overall supply</td>
<td>1.48</td>
<td>17.8</td>
</tr>
<tr>
<td>Can’t charge vehicle with electricity or fuel with hydrogen at home</td>
<td>1.46</td>
<td>20.7</td>
</tr>
<tr>
<td>Concern about time needed to charge or fuel vehicle</td>
<td>1.39</td>
<td>16.3</td>
</tr>
<tr>
<td>Cost of maintenance and upkeep</td>
<td>1.23</td>
<td>15.0</td>
</tr>
<tr>
<td>Concerns about batteries</td>
<td>1.01</td>
<td>10.7</td>
</tr>
<tr>
<td>Cost to charge or fuel</td>
<td>0.99</td>
<td>10.4</td>
</tr>
<tr>
<td>I’m waiting for technology to become more reliable</td>
<td>0.97</td>
<td>10.4</td>
</tr>
</tbody>
</table>

**Mean motivation score** 0.96

Following-up with some survey respondents during in-person interviews in California, Oregon, and Washington, the long list of motivations to not design a PEV or FCEV, that is, the list of concerns that most respondents have about these vehicles, is itself a barrier. Many people simply have too many questions, certainly too many for financial purchase incentives alone to overcome. The misunderstandings and lack of knowledge of PHEVs, BEVs, and FCEVs and the inability to accurately distinguish between these technologies may be the most important finding of the interviews. Interviews revealed that the PHEV design concepts of charge-depleting and charge-sustaining operation as well as all-electric vs. assist (blended) modes caused considerable confusion. Much of the confusion crosses from HEVs to PHEVs to BEVs: interviewees spoke of choosing “assist” PHEV designs rather than “all-electric” PHEV designs.

because they were afraid of being stranded when the PHEV battery was discharged. (When in actuality, at such a moment, the ICE in a PHEV would continue to power the vehicle.) Some respondents still wrongly believe that HEVs have to be plugged in.

While most of those who do not design a PEV or FCEV may be motivated by multiple concerns, fewer seem outright resistant. When asked about whether they have already considered PEVs or FCEVs, only 15% of the CA sample replied they have not and would not consider buying a PEV, 25% an FCEV, and 12% neither a PEV nor FCEV.

Similarly, a UCLA new car buyer survey, conducted in 2014, is being analyzed as part of the ARB-sponsored UCLA ZEV Sales Factors study to identify potential consumer segments for PEVs. The study’s analysis of stated preference data of 1,261 potential new-car buyers estimates respondents’ valuation of vehicles of different drivetrain types (but with otherwise comparable attributes). Although there is a portion of respondents who have negative valuations and a low likelihood of selecting a PEV as a future vehicle purchase, other segments have a more positive valuation of PEVs, particularly those who have environmentalist and early adopter tendencies and who live in single-family homes. Additionally, another larger segment who do not live in single-family homes and who live near HOV lanes have a positive valuation of PHEVs, but not BEVs.

Building on the UCLA survey work, the study is also exploring PEV incentive policy design variations in order to estimate how vehicle technology preferences – combined with consumer income and incentive levels – could impact incentive program outcomes such as cost-effectiveness, allocative equity and total program cost. The UCLA study’s simulation of rebate program designs indicates that the CVRP policy in force in 2015, (offering $1,500 for PHEVs and $2,500 for BEVs), was effective, increasing the virtual market share of PEVs by about 7% over a reference scenario without CVRP incentives.

III.C.2.b. Initial Interest in PEVs among current PEV drivers

At this phase of the market, the majority of consumers began their shopping process already very interested or exclusively interested in a PEV, and a relatively small minority began without knowing about these vehicles or having no interest. Only between 2-4% of California consumers across all models reported no interest in an EV prior to purchasing one, whereas 0-10% and 0-12% of Massachusetts and Connecticut consumers had no initial interest (see Figure 62). Although PHEVs do not have the range or infrastructure limitations of BEVs that might allow them to appeal to a broader population at this time, there is not an appreciable difference in the initial interest (or lack of interest) between the different PEV technologies.
Overall, although general interest is similar across the states, purchasers in Connecticut and Massachusetts were less resolved (as measured by only interested in an EV) on their PEV purchase. Over two-thirds of all California, Massachusetts, and Connecticut state rebate recipients were only interested or very interested in a PEV when they shopped for their PEV. California had the highest “only interested in EVs” respondents compared with Massachusetts and Connecticut (>37% vs 33%, and 27%). Among those in California interested only in PEVs, more than half were only interested in the specific model they selected; this was true even for those with no prior PEV ownership, i.e. not replacing a vehicle whose lease was expiring. However, not surprisingly, commitment to PEVs at the start of the shopping process is strongest among those with three or more prior PEVs.

Related to initial interest is the type of information that was sought prior to a PEV selection. Recent California PEV drivers were asked to rate the ease of finding information on PEV-related topics on the internet during their shopping process. As shown in Figure 63, over one-third of respondents rated finding information about home electricity rates somewhat or very difficult to find. Residential electricity rates are highly variable, even within the same utility territory, and despite some utilities providing generic, on-line cost calculators, these do not necessarily incorporate individualized usage history and actual subscribed rates to provide more accurate customized estimates.

A large proportion of respondents did not look for information on the internet about safety or warranties. Although they maybe have sought this information from dealer representatives rather than searched on-line, these relatively higher proportions suggest less consideration of these factors in their PEV decision. Similarly high proportions did not seek information to compare PEVs to non-PEVs, which likewise supports the finding that many respondents began their shopping process intent on a PEV.

\[147\] CVRP results, Oct 2013-Nov 2015.
\[148\] MOR-EV results.
\[149\] CHEAPR results.
III.C.2.c. Primary PEV Purchase Motivations
Existing consumers of PEVs at this stage of the market can be roughly categorized as motivated by three major factors: environmental benefits, savings, and technology. These results are consistent with sentiments of conventional new car buyers discussed in Section III.C.2.a on their potential motivations for purchasing a ZEV or PHEV. As shown in Figure 64, the top three motivations reported by CVRP survey respondents for acquiring a PEV were saving money on fuel, reducing environmental impacts, and HOV lane access. Before the introduction of the “saving money overall” response in the CVRP survey version of 2015, the percentage reporting that saving money on fuel was their top motivation reached a high of 44% and 41% for those who acquired their PHEV or BEV<200 in 2014. The combined fraction of PHEV and BEV<200 respondents most motivated by saving money on fuel or overall (available only in 2015 and 2016) was similar to those reporting that saving money on fuel was their top motivation in 2014. It could be that as fuel prices have decreased, PHEV and BEV<200 consumers have become less motivated to save money on fuel (through their vehicle purchases), although these trends are confounded by modifications to the survey response options.

California PHEV, BEV<200, and BEV200+ consumers have become more motivated to reduce their environmental impacts over time, which may be correlated to declining fuel prices and

additional consumers not selecting a PEV for savings motivations. Purchase motivations based on HOV lane access peaked across PHEV, BEVx, and BEV200+ California PEV consumers in 2015. PHEV respondents were the most motivated by HOV lane access among those who acquired their vehicle in 2015. This finding coincides with reaching the limit of single-occupant HOV lane access decals for PHEVs and BEVx in late 2015. In contrast, there was a slight increase in the fraction of BEV<200 respondents being motivated by HOV lane access in early 2016.

As shown in Figure 64 and Figure 65, the most common motivations for acquiring a PEV among all three states were to save money on fuel and reducing environmental impacts. Overall, BEV<200 consumers across the three states were slightly more interested in reducing their environmental impacts than PHEV owners were. California's BEV<200 consumers were more interested in saving money on fuel than on reducing their environmental impacts (33% vs 25%) in contrast with consumers in Massachusetts (27% vs 38%) and Connecticut (35% vs 38%), suggesting that California's BEV<200 market has begun to expand to more mainstream

Figure 64 - PEV purchase motivations over time in California\(^{151}\)

Note: Column widths are proportional to number of rebates granted for each PEV type and purchase year. Lighter shading indicates response option was not present for all survey administrations.

\(^{151}\) CVRP results, Oct2016-Sept2016.
consumers. Nonetheless, reducing environmental impacts has also been an important factor for drivers across PEV types. And even for those who select another primary factor, reducing environmental impacts is still an important factor in their decision, just not the most important.

Finally, there appears to be an emerging group concentrated within the BEV200+ category but also in other PEV types who have a desire to have the newest technology, and arguably are motivated by more typical factors that influence a conventional vehicle purchase such as

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152 MOR-EV results.
153 CHEAPR results.
performance and styling, comfort, etc. Although the BEV200+ category currently includes only Tesla premium models and may be correlated to Tesla’s brand image, this does suggest the potential for PEVs to be attractive to a different consumer base provided that the vehicle can also provide satisfactory attributes. While BEV200+ consumers in California were most motivated by reducing environmental impacts, those in Massachusetts were most motivated by vehicle performance, which may foreshadow future consumer response to longer-range BEVs. As additional vehicle offerings become available in this PEV category at lower price points, this result will need to be re-evaluated.

### III.C.2.d. Role of Incentives

In a nascent market, incentives can play an important role in offsetting incremental costs while government incentives also offer legitimacy to new product types. As previously discussed in Section III.C.1.c both replacement and additional PEV transactions in California were partially spurred by incentives offered by government and/or auto manufacturers. Figure 66 suggests that one-time monetary incentives related to the initial purchase appear to be more important to a purchase decision than ongoing incentives accrued through vehicle usage and operation. As only those Californians who received a state vehicle rebate are invited to complete the survey, the sample is slightly skewed and the importance of the state vehicle rebate may be overstated. However, the importance of the state rebate is similar to that of the federal tax credit, which

**Figure 66 - Importance of various financial incentives in PEV decision in California**

![Figure 66](image_url)

<table>
<thead>
<tr>
<th>Incentive Type</th>
<th>Proportion</th>
</tr>
</thead>
<tbody>
<tr>
<td>State vehicle rebate</td>
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</tr>
<tr>
<td>Federal tax incentives</td>
<td>0.75</td>
</tr>
<tr>
<td>Mfr/dealer incentives</td>
<td>0.50</td>
</tr>
<tr>
<td>Parking incentives</td>
<td>0.25</td>
</tr>
<tr>
<td>EV electricity rates</td>
<td>0.00</td>
</tr>
<tr>
<td>Free charging</td>
<td>0.00</td>
</tr>
<tr>
<td>Carshare/rental</td>
<td>0.00</td>
</tr>
</tbody>
</table>

academic studies estimate as driving over 30% of PEV sales nationwide.\textsuperscript{155} Although the amount of the federal tax credit may be three to five times the amount of the state rebate, studies\textsuperscript{156} have shown that upfront payment incentives appear to be more effective than deferred payments like tax credits, which may counteract the strict difference in dollar benefits. Indeed, it may be the combination of all of these incentives that motivates a consumer, where the whole is greater than the sum of each of the individual incentives.

Nonetheless, when asked about their purchase decision in the absence of a state vehicle rebate, overall less than 40% would have purchased their exact same vehicle anyway. Generally, PHEV consumers are more likely to have bought or leased their vehicle without the state rebate compared to BEV<200 consumers. This could be a reflection of the state rebates typically being smaller for PHEVs than BEVs (while federal tax credits can be equivalent). These distributions are consistent with when survey respondents in California, Connecticut, and Massachusetts are asked more generally whether or not they would have purchased their PEV without a state rebate, as shown in Figure 67. However, it is also important to note that all other incentives are assumed to remain available and should any of those be eliminated, the role of the state rebate would likely shift.

Figure 67 - Role of state rebate in PEV selection based on CVRP, MOR-EV and CHEAPR Surveys\textsuperscript{157,158,159}

Note: Column widths for each state are proportional to the number of respondents in each PEV category.

While some respondents may be overstating the impact of the rebates given a desire to appease the survey administrators (who are also the rebate administrators), the variation in responses between the PEV types suggests that there may still be relative differences in effectiveness of a state rebate in the context of other available incentives. For example, those motivated by environmental reasons may be less sensitive to a purchase incentive than those.

\textsuperscript{157} CVRP results, Oct 2013-Nov 2015.
\textsuperscript{158} MOR-EV results.
\textsuperscript{159} CHEAPR results.
who were most interested in saving money on fuel. A follow-up question in the California survey on likely actions in the absence of a state rebate supports the general notion that this incentive is helping to increase the size of the PEV market. Figure 68 shows that in California without a rebate, over half of the BEV<200 respondents report that they either would not have made any purchase or would have purchased a new or used non-PEV instead. Although the portion of PHEV, BEVx and BEV200+ respondents who would not be part of the market is smaller than that of BEV<200s, the rebate is nonetheless still expanding the market for these PEV types as well.

The UCLA ZEV Sales Factors Study is exploring the relationship between HOV lane access and PEV purchases. Using registration data for 2010-2013 and Caltrans data on HOV lane miles, the research team is examining the relationship between HOV lane miles (within a 30 mile radius of a census tract). Preliminary results indicate that HOV lane proximity is correlated with PEV sales in the area, suggesting that some PEV purchases are motivated by single-occupancy access to HOV lanes. The researchers estimated that incremental PEV sales of two, four and 10 PEVs per census tract are attributable to access to 20, 40 or 140 miles of nearby HOV lanes, respectively. These results are consistent with survey results of California PEV drivers’ attitudes about this incentive.

As discussed in Section III.C.2.c, about 15% of California respondents reported their primary motivation for selecting a PEV was to gain access to the HOV lane without the requisite number

Figure 68 - Transaction type without California state vehicle rebate

![Transaction type without California state vehicle rebate](image)

Note: Column widths are proportional to the number of respondents in each PEV category.

of passengers, as is currently allowed through legislation until January 1, 2019. Although seemingly less important than the vehicle rebate or federal tax credit, the ratings of this non-monetary incentive are of similar importance to that of manufacturer and dealer incentives, and Figure 69 shows the importance of HOV lane access to be inversely proportion to battery size, which is consistent with the fractions shown previously in Figure 64 indicating that HOV lane access was their primary motivation for purchasing a PEV. As might be expected, these rankings are correlated to the frequency respondents use this incentive, with PHEV drivers overall using the HOV lane access incentive the most. These results may reflect the range limitation of similarly priced BEV<200s and the greater travel demand of PHEV drivers that make HOV access more beneficial. However, they also suggest that PHEV sales to date have been more influenced by the HOV access incentive and the expiration of this incentive will likely affect the future mix of PEV sales.

Figure 69 - Importance of HOV lane access to purchase decision in California

<table>
<thead>
<tr>
<th>Proportion</th>
<th>Not at all important</th>
<th>Slightly important</th>
<th>Moderately important</th>
<th>Very important</th>
<th>Extremely important</th>
</tr>
</thead>
<tbody>
<tr>
<td>PHEV</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>BEV&lt;200</td>
<td></td>
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<td></td>
<td></td>
<td></td>
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<td>BEV&lt;200</td>
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<td></td>
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<tr>
<td>BEV200+</td>
<td></td>
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</tbody>
</table>

Note: Column widths are proportional to the number of respondents in each PEV category.

III.C.2.e. Role of infrastructure in purchase decision
Concerns about infrastructure, particularly away from home, is often noted by new car buyers as a barrier, though current PEV drivers mostly have access to charging at home and to a lesser degree at their workplaces (see Section III.C.1.e) and additional infrastructure continues to be deployed (see Appendix D). Consistent with the UCD New Car Buyers Study, the ability to charge at home appears to be universally important.

As shown in Figure 70, the relative importance of infrastructure at home, work, near shopping/friends/family/transit, and on the way to other destinations between PHEV, BEVx, and BEV<200 drivers are quite similar, with work being the second most important location and the remaining two locations about equal to each other. For the decision to purchase PHEVs and BEVxs, the flexibility to use gasoline results in less dependence on charging near or on the way to other, non-work or home destinations. The availability of workplace charging was most important for BEV<200 drivers in their purchase decision, least important for BEV200+ drivers, and of intermediate importance for PHEV and BEVx drivers. However, as shown previously in Figure 50 and Figure 51, PHEV drivers reported charging at work most frequently and BEV200+ drivers reported the least frequent workplace charging. This finding highlights the dual role that

Figure 70 - Importance of charging at different locations in California PEV purchase decisions

Note: Column widths are proportional to number of respondents in each PEV category.

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workplace charging serves to support the PEV market – one to promote adoption by providing consumers with assurances on locations away from home to charge and a second that increases vehicle miles traveled powered by grid electricity, reducing environmental impacts and displacing petroleum consumption.

Additionally, in the 2015 Ownership survey, PHEV drivers were more likely than BEV drivers (of all battery sizes) to disagree with the statement "there are enough places to charge my PEV." Interestingly, BEV200+ drivers appear to be distinct in their ranking of charging on the way to destinations as being nearly as important as home charging, and are slightly more satisfied with the coverage of the charging network. Whether these sentiments are specific to Tesla's Supercharger network or transferrable to other BEV200+’s will be evaluated as more BEV200+’s enter the market. Nonetheless, the introduction of ever longer range BEVs will increase the reliance on these "layover" charging stations (presumably with faster charging) to broaden the market.

III.C.2.f. Other Studies
A survey of 3,236 early PEV consumers throughout the U.S. that participated in the EV Project asked about motivations for purchasing or leasing a PEV. The highest-ranking response was “[P]EVs are energy efficient and cheaper in the long run than gasoline vehicles”, followed closely by “[P]EVs are environmentally friendly and reduce greenhouse gas emissions.” The lowest-scoring motivation was related to HOV lane access, perhaps because HOV lanes are not available throughout the U.S.

For comparison with the California, Massachusetts and a Connecticut survey results, a study of Norwegian PEV owners reported that consumers were generally satisfied with their vehicles. Less than 1% and 2% of these consumers stated they would not buy their BEV or PHEV again. The three most frequent reasons given by PEV owners who said they would buy a PEV again were economy of use, environmental performance, and future-proof technology. In addition, BEV owners who will purchase another BEV also said free usage of toll roads would be a motivation. This incentive is not available to PHEV owners in Norway.

III.C.3. Role of dealers
All auto manufacturers with a current ZEV obligation use a dealer franchise business model to retail their vehicles. Less than 10% of PEV consumers in California or Massachusetts report that a sales representative tried to discourage a PEV purchase. This holds true across

165 Tesla Motors, which currently does not have a ZEV requirement, sells direct to customers through retail stores.
167 MOR-EV results.
168 There may have been more consumers who were convinced not to select a PEV and are therefore omitted from the survey population. 10% is thus a minimum estimate.
time, PEV types, models, and whether at a traditional dealership or at a retail store. Among these consumers, the most common reasons provided by sales representatives was the incremental price of the PEV (sometimes in relation to fuel savings), the vehicle range relative to driving needs, and a lack of inventory or long wait time for product delivery. Nevertheless, dealers serve as the point of contact for consumers and understanding the dealership experience of existing customers may help to explain current sales trends or help to improve future market growth.

As dealers serve important intermediary roles between automakers and consumers, gauging their knowledge on various PEV topics can help to improve dealer-oriented outreach materials and the customer experience in the showroom. Based on the California results shown in Figure 71, dealer representatives are most knowledgeable about topics related to the vehicles themselves and less knowledgeable about charging aspects. Potentially this is a reflection of the complexity and variability within each topic. Vehicle-related topics such as performance will be limited to perhaps a few trim levels, while financial incentives are generally fixed for each vehicle model, so this type of information can be confined to fact sheets or other easily referenced documents.

Figure 71 - Dealer knowledge of PEV topics in California\textsuperscript{169}

In contrast, residential electricity rates are much more complicated and can differ for drivers of the same PEV based on utility, usage, metering options, and whether they have solar panels installed at their home, which means there is no single “one-size-fits-all” answer that can be provided by all dealer sales representatives. Similarly, public charging locations that will be relevant to a potential PEV driver will vary based on their individual travel patterns and dwell

\textsuperscript{169} CVRP results, Jun2015-Sept2016.
times. With continued investments from both public and private entities, training dealer salespeople to know where upwards of 4,200 public charging stations are located is impractical, though promoting infrastructure websites or smartphone apps, such as U.S. DOE’s Alternative Fuels Data Center portal, to dealer representatives may be a more effective method of ensure consumers are provided with the latest information.

In addition to improving training or outreach materials to educate sales representatives, dealerships could also adjust the services they provide intended to create or assist new PEV drivers as there appears to be a mismatch between those that are received and those that respondents report to be valuable. Figure 72 shows that more often than not, California respondents are not offered services that they think would have been valuable. The areas in dark or light blue represent the total portion of respondents who value a particular service, with those in the dark blue area also receiving this service (Fulfilled). Whether or not received, assistance with applying for CVRP (Rebate submission help) is the service that is most valued, followed by assistance applying for an HOV sticker, and then a PEV specialist to answer questions about the vehicle or additional services. However, the most often reported service that would be valuable that was not provided (light blue area) is an extended test drive or pre-

Figure 72 - Comparison of offered and valuable dealer services in California

Note: Unnecessary indicates a service was offered that a respondent did not rate as valuable. Fulfilled indicates a service was offered that a respondent did rate as valuable. Unfulfilled indicates a respondent rated a service as valuable but was not offered it. The remainder, not shown, reflects respondents who did not rate the service as valuable nor was it offered to them.

purchase rental. As not all dealers may be able to offer this service, there may be a role for other entities to develop these programs. Those actually receiving services are represented by the two upper dark blue and yellow areas, with those receiving a service they deemed not valuable shown in yellow (Unnecessary). Assistance setting up vehicle smartphone apps appears to be the service deemed unnecessary most often, though many other respondents found this service to be helpful, which likely reflects variation in customer needs rather than suggests that dealers should discontinue certain services. Overall, one- to two- fifths of respondents believe they would have benefited from a dealer service that was not offered to them (Unfulfilled).

III.C.4. Purchase Barriers
As discussed previously in Section III.C.2.a, self-reported reasons for negative valuations of ZEVs and PHEVs among new car buyers include limited access to vehicle charging facilities, vehicle purchase price, vehicle range, and lack of familiarity with vehicle technologies which mirror initial concerns during the shopping process of existing PEV drivers. While incentives and other policies may help consumers to overcome some of these concerns, others require further technological advances to satisfy customer requirements within acceptable price points.

III.C.4.a. Initial Concerns about Choosing BEVs
In California's CVRP Consumer survey, BEV and PHEV drivers alike are asked to rank their top three concerns about BEVs during the shopping process. As shown in Figure 73, all PEV drivers express concern about BEV vehicle ranges which uniformly had the highest ranking score regardless of the PEV type ultimately selected. For current BEV drivers, this question was posed as reasons they were concerned about choosing a BEV, though these concerns were somehow alleviated or not so overwhelming as to prevent them from ultimately selecting a BEV. Not surprisingly, those with a BEV200+ were not as concerned about range as <BEV200 drivers. For current PHEV (and BEVx) drivers, this question was posed as reasons that they decided against a BEV; with the highest score of all the PEVs for vehicle range, the range offered by BEVs is presumably insufficient to meet the travel needs of current PHEV drivers. Both of these results suggest that as longer range BEVs are introduced into the market, this will ease concerns over BEV adoption, potentially transforming some existing PHEV drivers into BEV drivers, as well as appealing to a broader customer base. These findings on existing PEV drivers are consistent with the opinion of the general public, 56% of whom state they would need a minimum electric range of 300 miles in order to consider a BEV.172

171 To facilitate comparisons between the different PEV types, ranking scores were computed to factor in both the number of respondents including a concern in their top three list as well as its position within this list. Ranking scores are calculated by assigning a score to each ranking, summing the scores for each factor, and then dividing by the total number of rankings. For instance, the number of PHEV respondents ranking vehicle price #1 is multiplied by 3, #2 by 2, and #3 by 1; these are then summed and this total is divided by the total number of PHEV respondent rankings.

172 Singer 2016.
Although the results shown here suggest that high electricity costs were not major concerns to most respondents, those results did show limited public charging infrastructure to be a possible barrier. Combining this with the results shown previously in Figure 63 where over one-quarter of respondents found it somewhat or very difficult to find information about "Locations, use and payment of charging away from home" would suggest the need for improving or centralizing the on-line presence of public charging locations and details, especially as more infrastructure is deployed in the future. Although experienced PEV drivers may have knowledge of and access to numerous websites, smartphone apps, and even in-vehicle navigation systems to locate nearby charging stations, market development may be hindered if prospective buyers have difficulty accessing information that can alleviate perceptions of limited public infrastructure.

Vehicle pricing will also be important to growing the market. The only current BEV200+ offerings are classified as luxury vehicles, and these drivers rank high prices as almost concerning as vehicle range. Even though non-luxury BEVs are more moderately priced, vehicle prices are often still one of the top three concerns among PHEV and BEV<200 respondents. However, as discussed previously in Section III.A.4 and III.C.2.d, an assortment of incentives offered by governments, automakers, and dealers are able to partially address this concern.

Rounding out the top three concerns over a lack of public charging infrastructure. Despite continual investments from a variety of providers, the perception, if not reality, is that

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opportunities to charge away from home are too limited. Even for longer range BEV200+ drivers whose battery capacity may cover most daily driving needs, the current charging network seems insufficient. This finding would support further expansion of the public charging network.

Interestingly, attributes associated with new technology, such as continuing developments, uncertainty about battery life, safety records, or repair costs, are not as concerning to respondents of current PEV drivers. Likewise the logistics and cost of charging at home did not appear to be barriers to these respondents. Potentially at this stage of the market, many PEV drivers could be categorized as “early adopters” interested in new technology whose lifestyles are easily compatible with PEV ownership.

III.C.4.b. Effects of Energy Prices on PEV Operating Costs
Fuel savings have been one of the main selling points for PEVs and a potentially large contributor to reducing the total cost of ownership for these vehicles. Especially during periods of high fuel prices, PEVs provide consumers with an opportunity to decouple from the volatility of global oil markets. For the FY2016-2017 Funding Plan for Low Carbon Transportation and Fuels Investments and the Air Quality Improvement Program, ARB staff explored the potential relationship between fuel prices and demand for state vehicle rebates in California. While BEV rebate applications increased for ZEVs in 2015 despite lower gasoline prices, monthly PHEV rebate applications were generally lower than those for the prior year, though staff was not able to establish a direct relationship.

Preliminary results of the UCLA ZEV Sales Factors Study suggest that PEV purchases are positively associated with the price of gasoline. Evaluating California registration data for new and used plug-in electric and hybrid electric vehicles purchased from December 2010 through October 2015 and gasoline price data from Gas Buddy, a county-scale analysis found that a $1 increase in gasoline price (from $3 to $4), is associated with a more than 200 percent increase in average monthly PEV sales, but stopped short of attributing any causal impact to gasoline price changes. The analysis also indicates that the association between gas prices and PEV sales is stronger in the less wealthy inland areas of the state.

However, while electricity prices may be more stable and predictable over time, they can be highly variable across and even within regions.174 Consumers considering whether to purchase a PEV have multiple cost calculators available, either from utilities, government agencies, automakers, and others. Depending on the consumer’s vehicle choices and residential electricity rates, though, a PEV is not universally the lowest operating cost option.

Figure 74 shows how varying energy prices in different states compare relative to the operating costs of certain vehicle choices. The lines in the figure represent the breakeven points where the operating costs for the vehicles labeled in the corresponding color would be equivalent for

174 See Appendix E for discussion of residential electricity prices in California.
Figure 74 - Comparison of PEV average operating costs across select states in CY2015\textsuperscript{175}

Points above a line means cheaper to use gasoline than electricity

Points below a line means cheaper to use electricity than gasoline

Notes: Solid lines show PHEV operating costs using either gasoline or electricity. Dashed lines show BEV operating costs compared to specified ICE or HEV. Dark blue squares indicate states with ZEV regulations.

Either energy source, i.e. the cost of driving a PEV one mile using electricity would be the same as driving the same vehicle (if PHEV) or comparable vehicle (if BEV) using gasoline. The solid lines represent PHEVs where the operating costs are based on the vehicle efficiencies of the same vehicle using either fuel. The dashed lines represent BEVs, where the operating costs are based on the electricity efficiency (Wh/mi) of the BEV and the gasoline efficiency (miles per gallon) of an ICE or HEV. The efficiency of BEVs is less variable than that of ICEs so the main reason for the variation between these lines is due to the different fuel economies of the comparison vehicles.

The points plotted on this chart show the average 2015 prices of gasoline and electricity for various states, the dark blue points representing California and Section 177 ZEV States, and the light orange points representing other states with high PEV market shares. When gasoline prices are high and electricity prices are low, the lower right-hand quadrant of this chart, consumers will save money driving with electricity rather than gasoline. In contrast, when gasoline prices are low and electricity prices are high, the upper left-hand quadrant of this chart, operating a vehicle with gasoline will be less expensive than using electricity. The distance of the points from the lines reflect the sensitivity of consumers in each state to fluctuating energy prices.

prices. In California or Oregon, gasoline prices can fall, moving the point towards the center of the graph, however so long as electricity prices remain stable, or through time-of-use or discounted PEV charging rates, consumer savings are relatively assured. In contrast, many northeast states have relatively high electricity prices that place them above some of the breakeven lines, where choosing a PEV would not necessarily result in fuel savings unless they have access to discounted PEV charging rates or free charging at work or elsewhere. For many of these other states, being so close to the breakeven lines makes them more sensitive to falling gasoline prices. For PHEVs, this figure also illustrates a market challenge if the same vehicle would not result in fuel savings from not charging. As discussed in Appendix G, the charging behavior of PHEV drivers is highly variable and may in part be determined by energy prices.

**III.C.5. Current ZEV and PHEV Consumer Attitudes**

Understanding current ZEV consumers’ attitudes towards their PEVs is important for assessing how different vehicle models may or may not be succeeding in the market. These first-hand experiences will shape their future purchase decisions and inform how the market may develop in the future. This section explores results from the California Ownership Survey as well as other independent surveys, which show that the majority of current PEV owners and lessees are satisfied by their experiences with the technology. While many existing PEV drivers could be considered early adopters, there are still improvements they would like to see in their next PEV, such as increased range, faster charging, and ability to charge wirelessly, and auto manufacturers incorporating these features into future products may be able appeal to a broader consumer base.

**III.C.5.a. PEV Ownership Survey Results**

As described in Section VII.G.4, the Ownership Survey sampled a random subset of PEV consumers stratified across time starting with early (2011) and ending with more recent (2014) PEV consumers in California, for a total of 6,500 completed responses. Overall, 98% of respondents still had the PEV for which they received the state rebate and the few who no longer have their PEV generally purchased their PEV prior to 2013. Almost all of those who no longer had the PEV for which they received the state rebate reported having a different PEV instead, and less than 0.2% of respondents indicated not having any PEV. Not surprisingly, respondents of older PEV model years are more likely to no longer have the rebated PEV, but rather a different PEV. For example, 8% of the 2011 model year BEV<200 owners had a different PEV when completing the survey. Of those who no longer had their rebated PEV, 13 had their leases expired, 45 sold/traded it in or ended lease early, 10 had their vehicle damaged/stolen and 15 had other reasons.

**III.C.5.a.i. Recommending a PEV**

PEV owners were satisfied with their vehicle as over 92% of respondents would probably or definitely recommend their specific PEV model. Virtually all of the BEV200+ consumers would probably or definitely recommend their vehicle, as would 96% of PHEV and 93% of BEV<200 consumers. Given that many prospective PEV drivers rely on the opinion of existing PEV drivers, these high levels of recommendation are important for continued market growth. As shown in Figure 75, as the market has matured, both PHEV and BEV consumers have become
more likely to definitely recommend their specific PEV model, which may be correlated to the continued improvements auto manufacturers have made to vehicles between full redesigns.

This increasing trend is especially encouraging as more recent purchasers are less likely to be considered "early adopters" and potentially more typical of conventional vehicle buyers. Relatedly, the percentage of respondents who would not recommend their PEV to someone they know looking for a new car is lower for more recent purchasers. However, even those who did not like their vehicle would still recommend a different PEV to someone they know looking for a new car. A follow-up question was asked of the 265 respondents who would probably and definitely not recommend their PEV specific model: of these, only 21% and 32% probably or definitely would not recommend a different PEV model than the one they owned, which represents about 1% of the overall survey population.

Figure 75 - Percent of California PEV drivers who would recommend their vehicle

III.C.5.a.ii. Improving PEVs
All respondents were asked either “how would you change your PEV” (for current PEV drivers) or “what changes would have allowed you to consider keeping your PEV or acquiring another?” (for prior PEV drivers) These questions allowed respondents to check multiple answers among this list: 1) give up power/acceleration for greater electric range, 2) give up electric range for

Note: Column widths are proportional to number of respondents for each PEV type and purchase year.

176 Ownership results.
greater power/acceleration, 3) give up electric range for lower price, 4) increase electric range for higher price, 5) increase vehicle size for higher price, 6) increase charging speed for higher price, 7) ability to charge wirelessly for higher price, 8) I wouldn’t change anything about my PEV, and 9) other.

Although some drivers are content with their vehicles as-is, many PHEV and BEV<200 consumers seem dissatisfied with the all-electric range of their vehicle. Figure 76 shows all PEV drivers, including some BEV200+ drivers, would be willing to pay for additional range, either in the form of a higher vehicle price or by giving up power or acceleration. Conversely, few respondents were willing to sacrifice range for improving performance or reducing purchase price. Additionally, the most common “other” response was to increase the range without increasing the price. The next most common changes PEV owners would make to their vehicles are to increase charging speed and have the ability to charge wirelessly for a higher price. These findings suggest that future offerings that offer these features or improved attributes will increase the likelihood of existing PEV drivers purchasing another PEV or recommending PEVs to other consumers.

Figure 76 - California PEV drivers desired vehicle changes

III.C.5.a.iii. Minimum all-electric range for replacement PHEV
Respondents who indicated a PHEV as their replacement vehicle were subsequently asked the minimum all-electric range they would require. Responses were capped at 100 miles given known PHEV market offerings at the time when the survey was administered. Consistent with

177 Ownership results.
the desire for increased range, Figure 77 shows the distribution of ranges for a replacement PHEV based on the respondent's current PEV model. Current PHEV owners reported wanting their replacement PHEV to have a median between 40-50 miles of all-electric range, and the median desired range for replacement PHEVs far exceeds the all-electric range of their existing model. In contrast, current BEV drivers want even more all-electric range in a replacement PHEV than current PHEV drivers. In fact, the median range desired by almost all BEV<200 respondents was 100 miles, or the maximum allowed response, suggesting that they are not willing to sacrifice the all-electric range provided by their BEV but wanting the added flexibility/utility of the additional range provided through gasoline. Whether additional BEV model offerings with greater all-electric range at lower price points would alter these selections remains a topic for future research.

Figure 77 - Minimum desired all-electric range for replacement PHEV of current PEV drivers in California

Note: Circles indicate mean range desired, horizontal line indicates median range (median is at 100 if not shown).

III.C.5.b. Other surveys of PEV consumers
Independent surveys from UCD and Consumer Reports further support that PEV consumers are satisfied with their purchases.

A 2015 survey of current PEV owners in California was conducted via internet by researchers at UCD. Results reveal that PEV owners are loyal to the technology as evidenced by their repeated purchase/lease of PEVs. The percentage of respondents that reported having two PEVs in their household at the time of the survey increased steadily as a function of newest PEV model year acquired, going from about 7% to 12% for those who purchased a MY2012 compared to MY2015 PEV. Furthermore, the percentage of respondents that reported

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178 Ownership results.
previously owning/leasing a PEV in addition to their current one also increased as a function of PEV model year acquired, reaching 13% for MY2015 PEVs. In other words, 23% of those who have a MY2015 PEV are repeat PEV owner/lessees.

The 2015 Annual Auto Survey conducted by Consumer Reports determined PEVs were the top three ranked vehicles based on owner satisfaction for use as commuter vehicles.\textsuperscript{180} In total, over 230,000 responses were obtained from Consumer Reports subscribers who owned vehicles less than three years old. The top three vehicles rated were the Tesla Model S, Chevrolet Volt, and Nissan Leaf among all types of vehicles, including conventional gasoline vehicles and HEVs.

IV. Long-term Consumer Acceptance Potential
While future market shares of ZEVs and PHEVs are unknown, product offerings, technological advancements consumer attitudes, and economic conditions are certain to change. Although the longevity of existing incentives or future energy prices remain uncertain, the potential exists for consumer acceptance to increase well beyond today's levels. The diversity and improvements of future products are likely to appeal to a broader consumer base especially when combined with continuing complementary policies such as outreach and awareness campaigns (see Appendix E) and infrastructure deployment (see Appendix D). By model year 2021, more than 70 unique models are anticipated to be available by all auto manufacturers combined. These vehicles will be offered at a variety of generally lower price points and many will also provide over 200 miles of all-electric driving range, addressing two of the main attributes that current consumers often perceive as barriers to considering a ZEV. The emergence of a secondary market of ZEVs and PHEVs also provides greater opportunities for consumers to experience these kinds of vehicles. Added to these new consumers are the existing, satisfied drivers who are likely to purchase or lease subsequent vehicles, as well as continue to inform others of the benefits of electrified driving.

IV.A. Future model availability
In section III.A.1, Table 1 lists historic ZEV and PHEV model availability and also the 25 models (15 ZEV and 10 TZEV) currently available at the beginning of 2017. As discussed in Appendix C, the number of new ZEV and PHEV models is expected to grow rapidly to 80 total vehicle offerings available for the 2021 model year. With that model growth, the vehicle offerings are expected to become more diverse in terms of the vehicle segment, size classification, and all-electric range options. Greater diversity of available ZEV and PHEV models are more likely to meet the demands of a greater number of consumers with more varied requirements. The vehicles listed in Table 11 are new, additional models expected to be released in the coming year alone.

Table 11 - Expected ZEV and PHEV Models to be Released in 2017

<table>
<thead>
<tr>
<th>ZEV Type</th>
<th>OEM</th>
<th>Model</th>
<th>Vehicle Segment</th>
</tr>
</thead>
<tbody>
<tr>
<td>BEV</td>
<td>Daimler</td>
<td>Smart ForFour Electric</td>
<td>PC</td>
</tr>
<tr>
<td></td>
<td>Hyundai</td>
<td>Ioniq BEV</td>
<td>PC</td>
</tr>
<tr>
<td></td>
<td>Tesla</td>
<td>Model 3</td>
<td>PC</td>
</tr>
<tr>
<td>TZEV</td>
<td>Daimler</td>
<td>Mercedes-Benz GLC350e</td>
<td>LDT</td>
</tr>
<tr>
<td></td>
<td>Hyundai</td>
<td>Ioniq PHEV</td>
<td>PC</td>
</tr>
<tr>
<td></td>
<td>Kia</td>
<td>Optima PHEV</td>
<td>PC</td>
</tr>
<tr>
<td></td>
<td>Mitsubishi</td>
<td>Outlander PHEV</td>
<td>LDT</td>
</tr>
<tr>
<td></td>
<td>Volvo</td>
<td>V90 PHEV</td>
<td>PC</td>
</tr>
<tr>
<td></td>
<td>Volvo</td>
<td>S90 PHEV</td>
<td>PC</td>
</tr>
</tbody>
</table>

In addition to these upcoming new vehicles, manufacturers have made announcements regarding a number of current models that will either be refreshed or receive a battery upgrade in the next year. These include the refreshed MY2017 Smart ForTwo,\(^\text{181}\) as well as the MY2017 Ford Focus EV and BMW i3, both of which will have a projected all-electric EPA label range of approximately 100 miles.\(^\text{182,183}\) By 2017 every transitioning LVM that will be subject to LVM status starting in 2018 will be offering at least one ZEV and one PHEV model, and by 2019 every manufacturer will be producing at least one ZEV or PHEV model regardless of volume status.

Table 12 provides an overview of the ZEV and PHEV models by expected EPA size classification and the technology type that are expected to be available by MY2021, showing a total of 80 ZEV and TZEV vehicle offerings across almost every EPA size classification and vehicle technology. This chart is similar to the Current and Future ZEV/TZEV Models by Model Year figure in Section II.B.4 of Appendix C. This analysis relies on publicly available news articles about expected future models and is consistent with information provided by manufacturers during meetings with ARB staff. Notable within this table is the introduction of the new the fuel-cell plug-in electric vehicle (FCPEV) technology type. With the planned launch of the GLC F-Cell,\(^\text{184}\) Mercedes-Benz will combine the long driving range and short fueling time of a FCEV with the convenience of vehicle charging at home to enable shorter electric trips like a PHEV.


Table 12 - ZEV and TZEV Model offerings available by MY2021

<table>
<thead>
<tr>
<th>EPA Size Classification</th>
<th>BEV</th>
<th>BEVx</th>
<th>FCEV</th>
<th>FCPEV</th>
<th>PHEV</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pickup</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Minivan</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>1</td>
</tr>
<tr>
<td>Standard SUV</td>
<td>2</td>
<td></td>
<td></td>
<td></td>
<td>7</td>
</tr>
<tr>
<td>Small SUV</td>
<td>9</td>
<td>1</td>
<td>1</td>
<td>11</td>
<td></td>
</tr>
<tr>
<td>Large Car</td>
<td>2</td>
<td></td>
<td></td>
<td></td>
<td>2</td>
</tr>
<tr>
<td>Mid-Size Car</td>
<td>7</td>
<td>2</td>
<td></td>
<td></td>
<td>13</td>
</tr>
<tr>
<td>Compact Car</td>
<td>2</td>
<td></td>
<td></td>
<td></td>
<td>7</td>
</tr>
<tr>
<td>Subcompact Car</td>
<td>3</td>
<td>1</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Two-Seater</td>
<td>1</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Unknown Size Passenger Car</td>
<td>5</td>
<td>1</td>
<td>1</td>
<td>2</td>
<td></td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td>31</td>
<td>1</td>
<td>4</td>
<td>1</td>
<td>43</td>
</tr>
</tbody>
</table>

In addition, a number of auto manufacturers have announced widespread electrification of their portfolios to support their own corporate sustainability goals to reduce the environmental impacts of their products. For example, the Ford Motor Company has publically announced that it is investing $4.5 billion to develop electric vehicles, which will allow them to bring 13 electrified vehicles to market by 2020, including a small SUV BEV with 300 miles of all-electric range. In addition, they have committed to have some amount of electification, including ZEVs, PHEVs, and HEVs, in at least 40% of their product offerings in that same timeframe. Daimler recently unveiled its EQ concept at the Paris Auto Show, which will serve as the basis for a family of BEVs, and has also announced plans to invest $1 billion into battery technology to power those vehicles. Volvo has similarly announced plans to electrify their entire range of vehicles. Volkswagen group has announced plans to electrify vehicles across their entire family of product offerings. Volkswagen expects battery-powered vehicles to account for approximately 25% of new vehicle sales by 2025, and at the Paris Auto Show unveiled the IQ concept.

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which utilizes their new MEB platform, a modular vehicle platform for a range of electric vehicles. At the 2015 LA Auto Show, Audi of America President, Scott Keogh, announced that 25% of vehicles sold by Audi in the U.S. will be electrified vehicles by 2025.\textsuperscript{192} In addition to the unveiling of the Mission E at the end of 2015, a range-topping long-range performance BEV, Porsche announced plans to invest 700 million euros into their production facilities to accommodate the production of electric vehicle components.\textsuperscript{193} The future of the ZEV and PHEV market is rapidly evolving, and with a range of new companies releasing vehicles in the next few years, consumers will have increasingly more vehicle choices to continue transforming the light-duty fleet and commercializing ZEV technology.

\textbf{IV.B. Future consumer purchase behavior}

Additional ZEV and PHEV model availability and diversity address the supply-side of the market. Consumers will also need to demand these products at increasing rates for the ZEV and PHEV markets to grow. This section describes the segments from which additional sales can be derived. Although awareness and interest in ZEV technologies is increasing, additional sales are not guaranteed and collective action from government and industry will be needed to support this growing market.

\textbf{IV.B.1. Current ZEV and PHEV drivers}

Current ZEV and PHEV drivers are one of the most certain segments of the market to purchase ZEVs and PHEVs in the future. As previously discussed in Section III.C, this consumer base is already familiar with the technology; likely to already have access to supporting infrastructure; has demonstrated an interested in new technology; likely to have leased their vehicle and thus needing a replacement within a few years; and is largely satisfied with the vehicle technologies. Multiple studies suggest that over 80% of current PEV drivers are likely to be repeat buyers.

California's 2015 Ownership Survey asked over 6,000 current PEV drivers the technology type they would select if needing to replace their vehicle suddenly. Respondents tended to select the specific vehicle technology they currently have, as shown in Figure 78. This is especially true for BEV200+ owners as 86% of them reported they would acquire another BEV to replace their current one, though it should be noted that this percentage has decreased from 92% for those who purchased or leased their vehicle in 2012 to 79% for those who did in 2014. In contrast, the percentage of BEV<200 respondents who would replace their vehicle with another BEV has increased starting from 62% for those who acquired their vehicle in 2012 to 70% for those who did in 2014. A similar increase was observed in PHEV respondents who would replace their vehicle with another PHEV from 60% to 68% over the same purchase years. These increases suggest improving experiences for newer model year vehicles. Overall, slightly more PHEV

owners would change to a BEV than BEV<200 owners would change to a PHEV (21% vs 18%). Interest in FCEVs seems greater among PHEV drivers, which may be a result of having greater travel demand needs that are better suited for longer-range FCEVs or a correlation to Toyota’s PHEV and FCEV offerings.

Figure 78 - Technology type of replacement vehicle based on current PEV type in California

Note: Column widths are proportional to number of respondents for each PEV type and purchase year.

Nationally, over 3,000 of the EV Project participants were surveyed in June 2013 by Idaho National Lab researchers. Results reveal that the overwhelming majority (96%) of participants of the EV Project would also replace their PEV with another PEV. Specifically, 81% of Leaf owners would replace their Leaf with another BEV and 15% would replace it with a PHEV. Similarly, 70% of Volt owners would replace their Volt with another PHEV, while 27% would replace it with a BEV.

Ford commissioned a survey of 10,000 PEV owners through Plug Insights. The results of this survey indicate that 92% of BEV owners and 94% of PHEV owners plan to acquire another PEV in the future. Similar to other studies, more BEV owners plan to acquire another BEV, while more PHEV drivers plan to switch to a BEV. The survey also found that 73% of PHEV owners...

194 Ownership results.
195 See Appendix G for EV Project description.
196 INL 2015.
who have a second vehicle that is powered by gasoline plan to replace it with either a PHEV or a BEV.

Finally, the 2015 PACE survey sampled 136 PHEV drivers, 138 BEV drivers, and 154 HEV drivers. Asked about their future purchase interest, summarized in Figure 79, almost 90% of BEV drivers stated they would most likely purchase another BEV and only a small fraction would purchase a PHEV. In contrast, more PHEV owners reported they will consider a BEV than a PHEV for their next vehicle (46% vs 40%). Less than 10% of BEV or PHEV drivers would consider an ICE or HEV, and had less interest in FCEVs than the overall sample. HEV drivers expressed the greatest interest in FCEVs though largely were interested in remaining with HEV technology.

**Figure 79 - 2015 PACE Survey respondent likely drivetrain technology of next vehicle**

![Figure 79 - 2015 PACE Survey respondent likely drivetrain technology of next vehicle](image)

**IV.B.2. Conventional new car buyers**

Reliance on existing ZEV and PHEV drivers to purchase additional vehicles will not be sufficient to create the market growth that is necessary. Reaching long-term goals will require a more widespread consumer base to adopt these technologies, meaning current consumers without ZEVs or PHEVs will need to convert one or more of their household vehicles prior to 2025. Stated interest or intentions to purchase a ZEV or PHEV in the future is not a precise or definitive predictor of future sales as consumer tastes and needs – as well as product offerings – are continually changing. However, interest can be nurtured into consideration or intention with dedicated effort and expressions of interest gauge the potential demand for products should they be delivered for an acceptable price and with the requisite features. This section describes various studies that assessed interest among predominantly conventional vehicle buyers in California and Section 177 ZEV states in potentially purchasing a ZEV or PHEV.

198 2015 PACE Survey.
IV.B.2.a. UC Davis 2015 Survey of New Car Buyers' ZEV Valuation
Section III.B.1 explains ARB's contracted study with UC Davis on new car buyers' valuation of ZEV and PHEV technologies. ZEV and PHEV valuation is assessed in a design game, which corresponds most closely to present reality, showing how new car buyers value ZEV technology, its attributes, and whether they would be willing to pay for such technology. In the final game, respondents were presented a scenario in which BEVs were not available in full-size body styles, though federal, state, and local incentives were offered. In this scenario, 38% of CA respondents designed their next new vehicle to be a PHEV (21%), BEV (11%), or FCEV (6%). Comparable totals in the other states surveyed range from a low of 24% (New Jersey) to a high of 38% (Oregon) of respondents who design their next vehicle to be a ZEV or PHEV.

Extrapolating to a population level estimate, this subset of the sample of new car-buying households in CA represents nearly 1.5 million similar households in CA and 3.3 million similar households for all of the survey regions combined. These estimates were calculated by combining data from several sources and estimating the total number of households that are represented by UC Davis survey respondents who designed a ZEV or PHEV in the final design game. These calculations are summarized in Table 13. The result is that over three million households across the states studied—who already spend the income, wealth, or credit needed to buy new cars—sufficiently value the idea of a ZEV or PHEV to design one as their household’s next new vehicle.

Table 13 - Population estimates of new car buying households with positive PEV or FCEV valuations

<table>
<thead>
<tr>
<th>State/Region</th>
<th>Total Number of Households¹</th>
<th>Share of Households with Vehicle available¹</th>
<th>Percent of Households that Buy New Vehicles²</th>
<th>Percent of Respondents that Designed a PEV or FCEV</th>
<th>Population Estimate (x1,000)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Oregon</td>
<td>1,522,988</td>
<td>92%</td>
<td>33%</td>
<td>38.7%</td>
<td>181</td>
</tr>
<tr>
<td>California</td>
<td>12,617,280</td>
<td>92%</td>
<td>33%</td>
<td>38.1%</td>
<td>1,476</td>
</tr>
<tr>
<td>Washington</td>
<td>2,645,396</td>
<td>93%</td>
<td>33%</td>
<td>35.9%</td>
<td>295</td>
</tr>
<tr>
<td>Maryland</td>
<td>2,155,983</td>
<td>91%</td>
<td>33%</td>
<td>31.4%</td>
<td>204</td>
</tr>
<tr>
<td>Delaware</td>
<td>339,046</td>
<td>94%</td>
<td>33%</td>
<td>28.0%</td>
<td>30</td>
</tr>
<tr>
<td>New York</td>
<td>7,255,528</td>
<td>70%</td>
<td>33%</td>
<td>27.9%</td>
<td>474</td>
</tr>
<tr>
<td>Massachusetts</td>
<td>2,538,485</td>
<td>87%</td>
<td>33%</td>
<td>27.7%</td>
<td>205</td>
</tr>
<tr>
<td>New Jersey</td>
<td>3,188,498</td>
<td>88%</td>
<td>33%</td>
<td>23.7%</td>
<td>222</td>
</tr>
<tr>
<td>NESCAUM</td>
<td>16,078,204</td>
<td>81%</td>
<td>33%</td>
<td>26.6%</td>
<td>1,151</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td><strong>3,337</strong></td>
<td></td>
<td></td>
<td></td>
<td><strong>3,337</strong></td>
</tr>
</tbody>
</table>

1. US Census [http://www.census.gov/quickfacts/table/HSG010214/00](http://www.census.gov/quickfacts/table/HSG010214/00) and American Community Survey. Figures are as of July 1, 2014.
2. Based on a survey in November 2014 by UCD of all car-owning households in California the subset estimated to meet the definition of new car buyers used in this study.
3. Total does not double count Massachusetts, New York, and New Jersey as part of NESCAUM.

IV.B.2.b. Union of Concerned Scientists Survey

The Union of Concerned Scientists surveyed 1,200 drivers to assess their perception of PEV policy and potential barriers to PEV adoption. The survey was conducted online from April 1 - April 8, 2016. Respondents were selected from drivers over 18 years of age who live in California, Connecticut, Maine, Massachusetts, New Hampshire, Rhode Island, Vermont, New Jersey, New York, or Pennsylvania. Additionally, participants had to either have off-street parking with access to an electrical outlet or a plug-in electric charger at home; did not need a vehicle for towing and hauling; and had a maximum vehicle capacity requirement of five passengers. The results of the survey revealed that 35% of the participants in the Northeast states would consider a PEV for their next vehicle purchase or lease and 55% of participants expressed interest in PEV technology. Comparatively, 54% of consumers in California would consider a PEV for their next purchase or lease and 65% of consumers are interested in EV technology.

The study highlighted areas which influenced consumers’ perception of EVs. For both regions, the top attributes of a PEV among those who would consider a PEV for their next vehicle

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²⁰⁰ Kurani, et al. 2016. The second through fourth columns estimate the number of households that meet the definition of “households who acquire new vehicles,” that is: respondent households that had —at the time of the survey— acquired a new vehicle since January 2008. The fourth column —Buy new vehicles, %— is an estimate based on data for California only, thus the estimates for all other states and regions assume this percentage in other states is similar. Taking the product across each row produces the Population Estimate in the sixth column.

purchase were: lower purchase prices, being able to drive 200 miles on a fully charged battery, and more charging infrastructure in parking lots and shopping centers. Survey respondents in the Northeast states indicated the low number of charging stations seen while traveling as one of the major concerns of owning an EV. California respondents noted a desired 200 mile travel range as the top concern. Respondents in both CA and the Northeast states cited providing a tax credit or rebate for the purchase or lease of plug-in electric vehicles, incentives for businesses to install charging stations, and a more streamlined process for installing charging stations at multi-dwelling housing units, as their top three areas of public policy that need improvement.

IV.B.2.c. Public Policy Institute of California Surveys
The Public Policy Institute of California’s surveys on “Californians & the Environment” conducted in 2015 and 2016 included some questions on PEVs. In contrast to the UCD study which was an internet-based survey that only surveyed new car buyers, the PPIC surveys were conducted entirely on landline telephones and cellphones and were based on a representative sample of California adults. A total of 1,702 and 1,704 California residents completed the survey in July 2015 and 2016, respectively. A ±3.5% margin of error was reported. Results reveal that nearly half of the respondents (48% and 47%) in 2015 and 2016 have seriously considered getting a PEV as their next vehicle. In addition, younger Californians were more likely to report they have seriously considered getting a PEV (55%) than Californians age 55 and older (34%). The overall percentages are significantly higher than those from other surveys (20-24% based on NREL study and 31-36% based on CFA) perhaps because of the California-only sample, which could be argued has a more mature PEV market. However, the UCD study also reported a lower percentage of California new car buyer participants willing to design a ZEV or PHEV (38%) compared to the fraction of PPIC survey respondents willing to consider a PEV. Furthermore, a greater percentage of PPIC survey respondents reported they already had a PEV in 2016 (8%) than in 2015 (5%), which are both generally higher than PEV fleet or market shares during those years. These differences could be due to the difference in sampling methodologies or question framing.

IV.B.2.d. Other Surveys
Two additional surveys are broader in nature, but do include some measures of future purchase intentions from mostly current ICE or HEV drivers US-wide. The 2015 NREL Caravan Survey discussed in Section III.B.3 reported that compared to traditional gasoline vehicles, 52% of respondents stated PHEVs were just as good or better while 45% of respondents said the same for BEVs. 24% of respondents would consider a PHEV for their next vehicle and 20% would consider a BEV, though a smaller percentage reported they expect to purchase or lease a PHEV (2%) or a BEV (2%). Consideration was higher for both PEV types when respondents were aware of PEV charging stations, were able to name a specific model, or planning a new


B - 105
vehicle (as opposed to used) as their next purchase. Additionally, 51% of respondents reported they were willing to pay some incremental costs for PEVs: 14% would be willing to pay over $9,000 and 17% would be willing to pay $4,000-5,000, and 20% not willing to pay more than $4,000. \(^{204}\) The NREL CARAVAN survey was repeated with 1,008 respondents in February 2016. \(^{205}\) Preliminary results indicate little movement in PEV attitudes between 2015 and 2016. While the fraction of respondents that expected to consider a PEV as their next vehicle was similar between both years, the percent that expected to purchase a PEV increased from 2% in 2015 to 3-4% in 2016.

Morpace’s 2014 and 2015 PACE Surveys shows similar national trends, shown in Figure 80, with the addition of gauging interest in FCEVs. In general, interest levels are higher than the fraction of respondents categorized as “true intenders” based on their responses to other questions. Compared to the 2014 PACE Survey, interest in FCEVs and BEVs rose while PHEV interest remained constant. Between these two surveys, the fraction of true intenders remained similar for ZEVs but fell by four percentage points for PHEVs. However, in the 2015 results, the sum of true intenders of ZEVs and PHEVs total 10%.

Figure 80 - 2014 and 2015 PACE Survey respondent interest in ZEVs or PHEVs as next vehicle purchase \(^{206}\)

**IV.B.3. Future Incentives**

As discussed in section III.C.2.d and Appendix E, the current ZEV and PHEV market has benefited from a host of incentives and complementary policies that have contributed to sales trends observed to date. However, the continuation of some of these incentives into the future is uncertain.

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\(^{204}\) Singer 2016.


\(^{206}\) 2014 and 2015 PACE Surveys.
The federal tax credit is one of the most important incentives offered to consumers for purchasing their PEV. This credit has been especially effective for lessees as it is factored into the vehicle price used for calculating lease payments, which avoids any delay in claiming the credit until filing federal tax returns as well as ensures even those consumers without a large tax liability benefit from the full value of the tax credit. Also described in Appendix E, the Qualified Plug-in Electric Drive Motor Vehicle Tax Credit varies by the capacity of the vehicle's battery pack, awarding a $2,500 credit for vehicles with a five kilowatt-hours (kWh) battery and an additional $417 credit per kWh up to a maximum of $7,500. The tax credit begins phasing out for each manufacturer when its nationwide sales of qualified PEVs reach 200,000 vehicles. Based on historic sales rates, staff estimates at least four manufacturers would reach this threshold prior to 2025. Leading manufacturers General Motors and Nissan would reach this threshold first in 2022 followed by Ford and Tesla, though increasing sales of existing vehicles and introduction of new products would likely accelerate this timeline. The $8,000 federal tax credit for FCEVs will expire on December 31, 2016. Neither tax credit is being discussed in Congress for an extension.

In California, sufficient funding for the state purchase rebate remains a perennial uncertainty. Recent modifications to program eligibility requirements by the state legislature may reduce the occurrence of waiting lists but current incentive funding collected through AB8 will sunset in 2023. Incentive programs in Section 177 ZEV States described in Appendix E have also faced funding shortages at times and may not necessarily keep pace with future demand.

Additionally, high-occupancy vehicle (HOV) lane access by single-occupancy ZEVs and PHEVs has been an effective incentive in five states, including California. As discussed in Section III.C.2.c, access to HOV lanes has been one of the frequently cited primary motivations for acquiring a PEV, especially PHEVs. Current California state law granting access for these vehicles sunsets on January 1, 2019, though federal law allows for provisions to be extended to 2025.

As sales of ZEVs and PHEVs grow, local government or employer incentives, whether directly related to vehicle purchase or more indirectly through free or discounted parking and/or charging can also play a role in supporting and developing the market. How these individual entities may modify these incentives will further change the future landscape for new car buyers. However, the extent to which any phase-out of incentives creates challenges for forthcoming products will depend on the rate at which incremental technology costs decrease and vehicle attributes improve that increase consumers’ willingness to pay for ZEVs and PHEVs.

**IV.C. The Secondary ZEV Market**

A used PEV market is quickly emerging as the higher lease rates for PEVs are resulting in a large influx of vehicles entering this market. For context on the overall secondary market, according to California New Car Dealers Association Quarterly Reports, between 2012 and March 2016, there have been over three million used vehicles of model years 2009 and newer...
(e.g., similar to the model years of used PEVs) sold in California of all technology types or about half the number of all new vehicles sold during this time. Typically, only about one-third of California and U.S. households purchase or lease a new vehicle at least every 5 years. According to Edmunds, the second quarter of 2016 saw the highest average prices in the used vehicle market ever ($19,367), which they attributed to a high fraction (58%) of the used vehicles sold in franchises being less than three years old and a heavier light truck mix that tends to retain higher values. Despite these recent higher prices, over the last three years the resale values of used vehicles have been decreasing due to the increased preference for leasing, which continues adding newer used vehicles into the secondary market. Edmunds reported that the average residual value among all vehicle classes less than three years old sold in the second quarter of 2016 was 64%, down from a high of 70% in 2012.

This section explores what is currently known about the secondary ZEV market, beginning with ARB-sponsored research. This on-going study has estimated the size of the secondary PEV market in California to be about 10,000 vehicles or 5-8% of all PEVs on the road. About half of used PEV households surveyed have only purchased used vehicles in the past. Surprisingly, 12% of used PEV owners surveyed had no other vehicle in their household besides their single used PEV. The majority (86%) of used PEV owners were satisfied with PEV technology and would either repeat their purchase or opt for a new PEV instead. However, the average household income of used PEV owners was found to be fairly high ($173,400). With time, though, the growing secondary PEV market has the potential to enable more households to purchase and benefit from driving PEVs.

A staff analysis of Experian Automotive data is also included in this section followed by discussion of external reports focused on the secondary PEV market. Not only do the majority of PEVs sold as new vehicles in California tend to stay in state as used vehicles, but California is also a net importer of used PEVs. Growing pains associated with developing a market for this new technology are evident with low average residual values. However, there are signs that demand for used ZEVs has been increasing, which indicate a possible sustainable used ZEV market. For example, used PEVs on average are not lingering on the market and used models such as the Tesla Model S have lower depreciation than other gasoline-powered vehicles in the same vehicle segment.

207 CNCDA Quarterly Reports.
208 Tal and Nicholas 2016b.
210 The National Automobile Dealers Association (NADA) found that in the first eight months of 2016 the lease share of new vehicles reached 31%, compared to just 24% three years earlier.
211 Tal and Nicholas 2016b.
IV.C.1. UC Davis Secondary PEV Market Research Project

Because the PEV secondary market is still so new, there are few research studies that have analyzed its health. ARB is sponsoring a UCD research project titled “The Dynamics of Plug-in Electric Vehicles in the Secondary Market and their Implications for Vehicle Demand, Durability, and Emissions.”\textsuperscript{212} Researchers are employing surveys and analyzing used vehicle transaction data to evaluate the impact of factors such as battery life, energy prices, infrastructure availability, attributes and prices of vehicle offerings, and economic conditions, on the demand and prices of used PEVs and on their usage. The project is also evaluating whether the secondary market is expanding access to PEVs to a wider array of consumers than the new PEV market. Both parts of this project are currently ongoing and are expected to be finalized in 2017. Preliminary results from this project are discussed in the next two subsections.

IV.C.1.a. Secondary PEV Owner Survey

The goal of surveying used PEV buyers was to identify the socioeconomic characteristics and purchase motivations of used PEV buyers, and to understand how these vehicles are being driven and charged. Of the over 14,000 potential used PEV owners/lessees in California identified through the DMV database, 4,700 were randomly selected to receive survey invitation letters. About 28% of those who started the survey indicated that they did not have a used PEV. Scaling the potential used PEV population based on this percentage yields about 10,000 actual used PEV owners/lessees in California. A total of 602 self-identified used PEV owners/lessees completed an internet-based survey May-June 2016.\textsuperscript{213} Results from a survey of new PEV owners that was conducted by the same research team was used for comparison. Analysis of the self-reported purchase price, excluding the 121 responses from Tesla owners, shows that used PEV prices were correlated positively with the original purchase price and negatively with vehicle age and mileage. Used PHEVs maintained an average retention value (resale value relative to new MSRP) that is 10 percentage points higher than used BEVs. Additionally, used PEVs with a high occupancy vehicle (HOV) lane access sticker sold for $1,430 more than used PEVs without the sticker. Most of these used PEVs were purchased after 2-3 years of usage by the original owner. The self-reported median odometer reading of the used PEVs at the time of purchase was 21,500 miles (mean 23,400 miles). For a further discussion of estimated annual miles driven and charging behavior of used PEV survey respondents see Appendix G.

Nearly half of the respondents (49%) have only previously purchased used vehicles for their household. In addition to one used PEV, most respondents also have one (39%) or two (41%) ICE vehicles in their household. Yet, 12% of the used PEV respondents belong to a single PEV household, another 4% are from a two-PEV household, and a further 4% have two PEVs plus at least one ICE vehicle. Used PEV buyers tend to be interested in acquiring a PEV at the start of their shopping process: 28% of respondents reported they were only interested in the specific

\textsuperscript{212} See Section VII.L for more details on ARB-contracted research. 
\textsuperscript{213} Tal and Nicholas 2016b.
make and model they ended up purchasing, 33% were only interested in PEVs, and 24% were very interested in a PEV.

The survey also revealed that 86% of used PEV owners are satisfied with PEV technology. Over three quarters (77%) of the respondents would repeat their purchase if they had to do it again, while 9% would opt for a new PEV instead of a used one. In contrast, only 3% of respondents reported they would not purchase another PEV. When asked about the condition of their used PEV battery at the time of purchase, a little over a quarter of the respondents reported that it had 100% of original capacity, 45% reported it had 90-99% of its original capacity, and 13% reported it had 80-89% of its original capacity. About 13% did not know the condition of their battery at the time of purchase.

Used PEV-owning households have relatively high incomes compared to conventional vehicle consumers, though lower incomes than new PEV-owning households. The mean household income reported by used PEV owners is $173,400 (median of $150,000) versus a mean of $227,000 (median of $200,000) as reported by new PEV owners in a 2015 survey. The exceptions are the owners of used Toyota Prius Plug-in, the Ford Focus Electric, and the Toyota RAV4 EV which have more similar household incomes compared to new owners of these PEV models. UCD researchers explained this could be due to the low availability of the Ford Focus Electric and Toyota RAV4 EV and the high demand for used PEVs with HOV access stickers. For comparison, UCD researchers note that the average household income from the 2012 California Household Travel Survey was $89,800 for households with older vehicles versus $119,400 for households with new vehicles.

IV.C.1.b. Used Vehicle Transaction Data Analysis
Manheim data analyzed to date by UCD researchers is included in this section to understand the demand of used PEVs in California. Manheim is a wholesale vehicle auction company with 62 exchanges in North America whose primary buyers are vehicle dealerships. The preliminary data analyzed consists of all transactions in the United States from January 2014 through July 2015 excluding Alaska, Hawaii, and Pennsylvania. Each transaction record contains vehicle information (vehicle identification number (VIN), vehicle make, model, and model year), odometer reading, transaction price, and auction origin and destination states. The Manheim data analyzed includes transactions of all PEVs (n=9,685) in the U.S., and 50% of HEVs and “comparable” ICEs transactions in California, and 10% of HEVs and “comparable” ICEs transactions in the rest of the U.S. A total of 63,923 HEV transactions are included in the data analyzed. The “comparable” ICEs (n=250,914) were limited to the Ford Focus, Honda Civic, Nissan Sentra, and Toyota Corolla. It should be noted that Manheim exchanges do not include Tesla vehicles.

Auctioned Nissan Leafs account for nearly two-thirds of all used PEV transactions in this dataset with the remaining being an assortment of non-LEAF BEVs and PHEVs. Of vehicles

214 Personal communication with Dr. David Rapson, October 3, 2016.
terminating in California, the average auction price of used PEVs was about $1,000 less than the average auction price of used HEVs but over $4,000 higher than that of used comparable ICEs vehicles during this period. Auctioned Nissan Leaf vehicles terminating in California during this time were cheaper than those terminating elsewhere in the United States, with an average price in California about $600 lower than in all other states. In contrast, the non-Leaf PEVs auctioned in California received higher average prices by about $1,000 to $3,000 than those in other states. The average auction price of HEVs fell between the average price of Leaf and Non-Leaf PEVs, with similar prices in other states. For comparison, there was limited regional variation in the average auction price of comparable ICE vehicles. However, the age of the vehicles may play a role since the average model year of all PEVs auctioned is two years newer (2012.3) than the average of HEVs (2010.2) and three years newer than that of comparable ICE vehicles (2009.0). The effect of vehicle age on auction prices is still being explored. In addition, the effect of mileage on auction prices is also being investigated.

Preliminary results suggest that over three-fourths of all vehicles auctioned by Manheim in California remain within the state, with 76% of PEVs, 84% of HEVs and 88% of comparable ICEs. California had a similar net inflow of PEVs and comparable ICE vehicles, suggesting similar demand for these vehicle technologies. In contrast, California experienced a net outflow of HEVs through the Manheim exchanges between 2014 and the first half of 2015, indicating there was greater demand for these vehicles in other states during this period, potentially due to California consumers shifting from HEVs to PEVs.

**IV.C.2. Migration of Used PEVs and Comparable Vehicles**

The Experian Automotive data\textsuperscript{215} provides another approach for ARB staff to evaluate the migration of used PEVs, which contains the vehicle identification number (VIN) for all PEV transactions—new and used—for the entire country. A total of almost 38,000 used PEVs were identified based on a unique VIN occurring in the data two or more times between 2011 and 2015.\textsuperscript{216} About 60% of these used PEVs were PHEVs, of which another two-thirds were Chevrolet Volts. Of the 40% used PEVs that are BEVs, almost 80% of these are Nissan Leafs. As the first entrants to the PEV market, Volts and Leafs comprise about 70% of the entire used PEV market and these two models will strongly influence current trends.

As shown in Table 14, the majority of used vehicles, regardless of technology, generally stay within their originating region which supports continued promotion of PEVs within regions. About the same fraction of PEVs remain in California according to both the Experian Automotive and Manheim results. Of the PEVs originating in California, a greater share was transferred to Other States than other gasoline-only technology types, suggesting that there is higher demand for (or limited supply of) used PEVs in these states. Likewise, for PEVs originating in Section 177 ZEV states, a sizeable share was transferred to Other States and at a greater rate than gasoline-only vehicles are transferred.

\textsuperscript{215} For data description, see Section VII.B on Experian Automotive data.
\textsuperscript{216} Note that this method also includes owners who move from one state to another and must re-register the same vehicle; these vehicles will appear as a used vehicle transaction even though vehicle ownership has not transferred.
Table 14 - Origin and destination regions for used vehicles in CY2011-2015\(^\text{217}\)

<table>
<thead>
<tr>
<th>Origin</th>
<th>Destination</th>
<th>PEVs</th>
<th>ICEs/HEVs</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>California</td>
<td>S177 ZEV States</td>
<td>Other States</td>
</tr>
<tr>
<td>California</td>
<td>10,850</td>
<td>417</td>
<td>3,077</td>
</tr>
<tr>
<td>S177 ZEV</td>
<td>436</td>
<td>2,149</td>
<td>2,117</td>
</tr>
<tr>
<td>Other States</td>
<td>1,347</td>
<td>1,709</td>
<td>15,691</td>
</tr>
</tbody>
</table>

Note: Percentages of each vehicle technology type by origin are shown in parentheses.

Regardless of ZEV regulatory status, the presence of incentives for both new and used vehicles may distort typical migration patterns for used vehicles as states with new PEV purchase incentives may have lower demand for used PEVs, while states with used PEV purchase incentives may attract a disproportionate share of used vehicles. Table 15 details the states offering new and/or used PEV purchase incentives between CY2013 and 2015. In some states, incentives may only be offered for a particular type of PEV however all would reduce the initial purchase price of the vehicle. Note as well that all states offering used PEV incentives also offer new PEV incentives.

Table 15 - States offering new and used PEV purchase incentives in CY2013, 2014, or 2015

<table>
<thead>
<tr>
<th>New PEV Purchase Incentive States</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>ZEV states:</strong> California, Connecticut, Maryland, Massachusetts, New Jersey, Vermont</td>
</tr>
<tr>
<td><strong>Non-ZEV states:</strong> Colorado, District of Columbia, Georgia, Illinois, Louisiana, Pennsylvania, South Carolina, Tennessee, Texas, Utah, Washington, West Virginia</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Used PEV Purchase Incentive States</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>ZEV states:</strong> California, New Jersey</td>
</tr>
<tr>
<td><strong>Non-ZEV states:</strong> Colorado</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>State without PEV Purchase Incentives</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>ZEV states:</strong> Maine, New York, Oregon, Rhode Island</td>
</tr>
<tr>
<td><strong>Non-ZEV states:</strong> Alabama, Alaska, Arizona, Arkansas, Delaware, Florida, Idaho, Indiana, Iowa, Kansas, Kentucky, Michigan, Minnesota, Mississippi, Missouri, Montana, Nebraska, Nevada, New Hampshire, New Mexico, North Carolina, North Dakota, Ohio, Oklahoma, South Dakota, Virginia, Wisconsin, Wyoming</td>
</tr>
</tbody>
</table>

Note: Purchase incentives include state tax credit, rebate (sometimes in conjunction with scrappage requirement), or sales tax exemption.

Based on used vehicle transactions occurring between January 1, 2013 and December 31, 2015, Table 16 further distinguishes the flow of vehicles between the states based on their ZEV regulation status and availability of purchase incentives. In California, the net outflow of PEVs is largely driven by the export of BEVs, however, these vehicles are only a fraction of the total used PEVs originating from the state. California is different from the two other states offering both new and used PEV incentives, which show a small net inflow of all types of vehicles,

\(^{217}\) Experian Automotive data.
potentially reflecting the counteracting forces of the two incentive types. While a net outflow might be expected from states with incentives on only new PEV purchases, this is observed only in states with a ZEV regulation. States without a ZEV regulation, but offering new PEV incentives, show a net inflow of both types of PEVs. Likewise, among states without any purchase incentives, those states without a ZEV regulation have a net inflow of PEVs that is of the opposite direction of the flow of conventional vehicles. Overall, the net effects are small relative to the population of used vehicles, however there appears to be the emergence of demand in a secondary market reflected by the net inflow of used PEVs to states without ZEV regulations and/or purchase incentives.

Table 16 - Flow of vehicles by PEV type and state incentive categories in CY2013-2015

<table>
<thead>
<tr>
<th>Flow</th>
<th>California</th>
<th>New PEV Purchase Incentives</th>
<th>New and Used PEV Purchase Incentives</th>
<th>States Without PEV Purchase Incentives</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>S177 States</td>
<td>Non-S177 States</td>
<td>S177 States</td>
</tr>
<tr>
<td>BEV</td>
<td>In</td>
<td>823</td>
<td>282</td>
<td>2,031</td>
</tr>
<tr>
<td></td>
<td>Out</td>
<td>-2,714</td>
<td>-265</td>
<td>-1,248</td>
</tr>
<tr>
<td></td>
<td>Net</td>
<td>-1,891</td>
<td>17</td>
<td>783</td>
</tr>
<tr>
<td>PHEV</td>
<td>In</td>
<td>927</td>
<td>1,012</td>
<td>2,280</td>
</tr>
<tr>
<td></td>
<td>Out</td>
<td>-706</td>
<td>-1,174</td>
<td>-2,097</td>
</tr>
<tr>
<td></td>
<td>Net</td>
<td>221</td>
<td>-162</td>
<td>183</td>
</tr>
<tr>
<td>All PEV</td>
<td>In</td>
<td>1,750</td>
<td>1,294</td>
<td>4,311</td>
</tr>
<tr>
<td></td>
<td>Out</td>
<td>-3,420</td>
<td>-1,439</td>
<td>-3,345</td>
</tr>
<tr>
<td></td>
<td>Net</td>
<td>-1,670</td>
<td>-145</td>
<td>966</td>
</tr>
<tr>
<td>ICE/HEV</td>
<td>In</td>
<td>922</td>
<td>6,113</td>
<td>1,236</td>
</tr>
<tr>
<td></td>
<td>Out</td>
<td>-1,826</td>
<td>-1,751</td>
<td>-3,354</td>
</tr>
<tr>
<td></td>
<td>Net</td>
<td>-904</td>
<td>4,362</td>
<td>-2,118</td>
</tr>
</tbody>
</table>

Note: Green shading means net imports and red means net exports.

Whether there is any significance to the presence of a ZEV regulation or incentives to these migration patterns is unclear, as these states are not entirely contiguous. To explore whether used PEV migration is driven by geographic factors, the states were categorized into regions according to Table 17.

---

218 Experian Automotive data.
Table 17 - State categorization of regions

<table>
<thead>
<tr>
<th>CA</th>
<th>Mountain</th>
<th>Southwest</th>
</tr>
</thead>
<tbody>
<tr>
<td>California</td>
<td>Colorado</td>
<td>Arizona</td>
</tr>
<tr>
<td>CA</td>
<td>Idaho</td>
<td>New Mexico</td>
</tr>
<tr>
<td>Pacific</td>
<td>Montana</td>
<td>Oklahoma</td>
</tr>
<tr>
<td>Oregon</td>
<td>Nevada</td>
<td>Texas</td>
</tr>
<tr>
<td>OR</td>
<td>Utah</td>
<td></td>
</tr>
<tr>
<td>Washington</td>
<td>Wyoming</td>
<td></td>
</tr>
<tr>
<td>WA</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Hawaii</td>
<td></td>
<td></td>
</tr>
<tr>
<td>HI</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Alaska</td>
<td></td>
<td></td>
</tr>
<tr>
<td>AK</td>
<td></td>
<td></td>
</tr>
<tr>
<td>North Central</td>
<td></td>
<td>Southeast</td>
</tr>
<tr>
<td>Illinois</td>
<td>Connecticut</td>
<td>Alabama</td>
</tr>
<tr>
<td>IL</td>
<td>Delaware</td>
<td>Arkansas</td>
</tr>
<tr>
<td>Indiana</td>
<td>District of Columbia</td>
<td>Florida</td>
</tr>
<tr>
<td>IN</td>
<td>Maine</td>
<td>Georgia</td>
</tr>
<tr>
<td>Iowa</td>
<td>Maryland</td>
<td>Kentucky</td>
</tr>
<tr>
<td>IA</td>
<td>Massachusetts</td>
<td>Louisiana</td>
</tr>
<tr>
<td>Kansas</td>
<td>New Hampshire</td>
<td>Mississippi</td>
</tr>
<tr>
<td>KS</td>
<td>New Jersey</td>
<td>North Carolina</td>
</tr>
<tr>
<td>Michigan</td>
<td>New York</td>
<td>South Carolina</td>
</tr>
<tr>
<td>MI</td>
<td>Pennsylvania</td>
<td></td>
</tr>
<tr>
<td>Minnesota</td>
<td>Rhode Island</td>
<td></td>
</tr>
<tr>
<td>MN</td>
<td>Vermont</td>
<td>Virginia</td>
</tr>
<tr>
<td>Missouri</td>
<td></td>
<td>West Virginia</td>
</tr>
<tr>
<td>MO</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Nebraska</td>
<td></td>
<td></td>
</tr>
<tr>
<td>NE</td>
<td></td>
<td></td>
</tr>
<tr>
<td>North Dakota</td>
<td></td>
<td></td>
</tr>
<tr>
<td>ND</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Ohio</td>
<td></td>
<td></td>
</tr>
<tr>
<td>OH</td>
<td></td>
<td></td>
</tr>
<tr>
<td>South Dakota</td>
<td></td>
<td></td>
</tr>
<tr>
<td>SD</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Wisconsin</td>
<td></td>
<td></td>
</tr>
<tr>
<td>WI</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Generally at least half of all used BEVs and PHEVs remain in their originating region. Despite some BEV models being available exclusively in California and/or Oregon, these models comprise less than 4% of California's exports. The Nissan Leaf, which is distributed nationally, comprised the bulk of California's BEV exports as well as the majority of imports to the Northeast region. Although vehicles might be expected to migrate between nearby regions, Table 18 shows that the largest portion of BEVs originating in California are imported into the Southeast region. In contrast, Table 19 shows that PHEVs are imported into the Southeast region at only about a tenth of the rate. Two factors likely contribute to this pattern: 1) the overall supply of "native" used BEVs in the Southeast region is less than half that of "native" used PHEVs; 2) at the same time, Georgia offers HOV lane access for single-occupancy BEVs only and recently discontinued state purchase incentives on new BEVs. This finding suggests that complementary policies that apply to used vehicles (including usage-based incentives) will also be important for retaining the emission benefits generated by PEV adoption.
Table 18 - Origin and destination region of used BEVs in CY2011-2015

<table>
<thead>
<tr>
<th>Origin Region</th>
<th>Destination Region</th>
<th>CA</th>
<th>South-west</th>
<th>Mountain</th>
<th>North Central</th>
<th>Pacific</th>
<th>North Atlantic</th>
<th>South-east</th>
<th>Grand Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>CA</td>
<td></td>
<td>4,413</td>
<td>364</td>
<td>366</td>
<td>312</td>
<td>475</td>
<td>249</td>
<td>966</td>
<td>7,148</td>
</tr>
<tr>
<td>Southwest</td>
<td></td>
<td>292</td>
<td>562</td>
<td>68</td>
<td>67</td>
<td>61</td>
<td>40</td>
<td>140</td>
<td>1,230</td>
</tr>
<tr>
<td>Mountain</td>
<td></td>
<td>120</td>
<td>59</td>
<td>288</td>
<td>15</td>
<td>40</td>
<td>4</td>
<td>8</td>
<td>534</td>
</tr>
<tr>
<td>N. Central</td>
<td></td>
<td>72</td>
<td>51</td>
<td>26</td>
<td>494</td>
<td>10</td>
<td>36</td>
<td>92</td>
<td>781</td>
</tr>
<tr>
<td>Pacific</td>
<td></td>
<td>151</td>
<td>55</td>
<td>121</td>
<td>21</td>
<td>2,002</td>
<td>10</td>
<td>21</td>
<td>2,381</td>
</tr>
<tr>
<td>N. Atlantic</td>
<td></td>
<td>114</td>
<td>24</td>
<td>17</td>
<td>70</td>
<td>14</td>
<td>399</td>
<td>170</td>
<td>808</td>
</tr>
<tr>
<td>Southeast</td>
<td></td>
<td>100</td>
<td>87</td>
<td>31</td>
<td>135</td>
<td>18</td>
<td>143</td>
<td>1,113</td>
<td>1,627</td>
</tr>
<tr>
<td><strong>Grand Total</strong></td>
<td></td>
<td>5,265</td>
<td>1,202</td>
<td>917</td>
<td>1,114</td>
<td>2,620</td>
<td>881</td>
<td>2,510</td>
<td>14,506</td>
</tr>
</tbody>
</table>

Table 19 - Origin and destination region of used PHEVs and BEVxs in CY2011-2015

<table>
<thead>
<tr>
<th>Origin Region</th>
<th>Destination Region</th>
<th>CA</th>
<th>South-west</th>
<th>Mountain</th>
<th>North Central</th>
<th>Pacific</th>
<th>North Atlantic</th>
<th>South-east</th>
<th>Grand Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>CA</td>
<td></td>
<td>6,434</td>
<td>149</td>
<td>152</td>
<td>154</td>
<td>192</td>
<td>53</td>
<td>62</td>
<td>7,196</td>
</tr>
<tr>
<td>Southwest</td>
<td></td>
<td>88</td>
<td>827</td>
<td>41</td>
<td>71</td>
<td>25</td>
<td>31</td>
<td>64</td>
<td>1,147</td>
</tr>
<tr>
<td>Mountain</td>
<td></td>
<td>47</td>
<td>49</td>
<td>410</td>
<td>65</td>
<td>31</td>
<td>23</td>
<td>60</td>
<td>685</td>
</tr>
<tr>
<td>N. Central</td>
<td></td>
<td>352</td>
<td>201</td>
<td>134</td>
<td>3,363</td>
<td>71</td>
<td>467</td>
<td>565</td>
<td>5,153</td>
</tr>
<tr>
<td>Pacific</td>
<td></td>
<td>71</td>
<td>17</td>
<td>22</td>
<td>22</td>
<td>992</td>
<td>3</td>
<td>15</td>
<td>1,142</td>
</tr>
<tr>
<td>N. Atlantic</td>
<td></td>
<td>263</td>
<td>94</td>
<td>77</td>
<td>790</td>
<td>52</td>
<td>2,178</td>
<td>646</td>
<td>4,100</td>
</tr>
<tr>
<td>Southeast</td>
<td></td>
<td>113</td>
<td>131</td>
<td>37</td>
<td>328</td>
<td>31</td>
<td>797</td>
<td>2,424</td>
<td>3,861</td>
</tr>
<tr>
<td><strong>Grand Total</strong></td>
<td></td>
<td>7,368</td>
<td>1,468</td>
<td>873</td>
<td>4,793</td>
<td>1,394</td>
<td>3,552</td>
<td>3,836</td>
<td>23,284</td>
</tr>
</tbody>
</table>

IV.C.3. Enhanced Fleet Modernization Program (EFMP) and Plus-Up Pilot Program

Another source of used vehicle pricing data comes from California's Enhanced Fleet Modernization Program (EFMP) and Plus-Up Pilot Program that incentivizes households to replace scrap older, higher-polluting vehicles. Pricing and financing terms for replacement vehicles are collected from program participants, which provide early data on trends of ZEV and PHEV resale values compared to other technologies. In the first fifteen months of the EFMP and EFMP Plus-Up pilot program (July 1, 2015 through September 30, 2016), 1,411 vehicles were replaced in the South Coast and San Joaquin Valley air districts. Over 80 percent of the

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219 Experian Automotive data.
220 Experian Automotive data.
221 See Section VII.H for more details on EFMP.
vehicles replacements are categorized as used vehicles.\footnote{222} Table 20 shows the breakdown of purchase price and financing by replacement vehicle technology type for the subset of used vehicles. The most common replacement vehicle technology by far was conventional hybrid (40\%), with an average purchase price of almost $20,000. The average price of a PHEV was similar to that of HEVs, which is about $3500 more than a conventional vehicle. BEV average purchase prices (mostly Nissan LEAFs) are about $4,000 lower than conventional vehicles and $7,500 lower than PHEVs or HEVs.

Table 20 - Used vehicle price and financing of EFMP replacement vehicles (July 1, 2015 through September 30, 2016)

<table>
<thead>
<tr>
<th>Vehicle Technology</th>
<th>Max EFMP Incentive</th>
<th>Count</th>
<th>Purchase Price</th>
<th>Loans</th>
<th>Average Interest Rate (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td>Average</td>
<td>Standard Deviation</td>
<td>Count</td>
</tr>
<tr>
<td>BEV</td>
<td>$9,500</td>
<td>197 (17%)</td>
<td>$12,685</td>
<td>$3,374</td>
<td>99</td>
</tr>
<tr>
<td>Conventional</td>
<td>$4,000</td>
<td>177 (15%)</td>
<td>$16,735</td>
<td>$4,152</td>
<td>167</td>
</tr>
<tr>
<td>Hybrid</td>
<td>$7,000</td>
<td>455 (40%)</td>
<td>$19,870</td>
<td>$4,168</td>
<td>421</td>
</tr>
<tr>
<td>Minivan</td>
<td>$4,000</td>
<td>10 (1%)</td>
<td>$20,092</td>
<td>$4,157</td>
<td>10</td>
</tr>
<tr>
<td>PHEV</td>
<td>$9,500</td>
<td>309 (27%)</td>
<td>$20,099</td>
<td>$3,260</td>
<td>264</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td></td>
<td>1148</td>
<td>$\text{Average} = \text{Total Average Purchase Price} / \text{Total Count}</td>
<td>$\text{Standard Deviation} = \sqrt{\frac{\text{Total Count} \times \text{Total Standard Deviation of Purchase Price}^2 - \text{Total Count} \times \text{Total Average Purchase Price}^2}{\text{Total Count} - 1}}</td>
<td>961</td>
</tr>
</tbody>
</table>

IV.C.4. Other Analyses

Analysis of over two million used vehicle model year 2013-2015 transactions between January and May, 2016 by iSeeCars.com revealed that the fastest-selling used vehicles among all technologies were BEVs.\footnote{223} Used BEVs stayed in the market an average of 29.2 days in 2016, a decrease of 8 days compared to the same period in 2015. Between 2015 and 2016, used BEVs decreased in price the most an average of 15.2\% or $3,830. Used conventional hybrids were the second fastest selling vehicle technology, remaining on the market an average of 38.2 days, which is a decrease of 5 days compared with 2015. The average decrease in price between 2016 and 2015 for used HEVs was 3.7\% or $889. Used PHEVs were the third fastest selling vehicle technology, staying in the market an average of 40.7 days, a decrease of 2 days compared to 2015. The average decrease in price year-over-year for used PHEVs was 5.1\% or $1,214. Used gasoline vehicles remained on the market the longest, averaging 42.5 days. The average price of used gasoline vehicles decreased by 1.0\% or $242 between the two years.

More specifically, iSeeCars.com found the Toyota Prius Plug-in, Nissan Leaf, and Tesla Model S to be the three fastest selling used vehicle models among all used vehicles regardless of technology. The Toyota Prius Plug-in was the fastest selling vehicle with an average of 19.7 days on the market, which is over two times faster than the average light-duty vehicle. During

\footnote{222} Used vehicles are defined based on having odometer readings greater than 5,000 miles and whose model year is at least one year greater than the purchase year.

the same time period in 2015, the used Prius Plug-in remained on the market double the time, an average of 38.1 days. This halving of the number of days on the market for the used Prius Plug-in was attributed by iSeeCars.com to the high demand and limited supply of HOV carpool lane stickers since the maximum number of PHEVs allowed to get a sticker was reached in late 2015 coupled with a 17% drop in average price between 2015 and 2016 ($22,945 versus $19,057). The Nissan Leaf was the second-fastest selling used vehicle on the market in 2016 going from 38.7 days in 2015 to 24.3 days in 2016. The price paid for the Leaf dropped by $2,219 between 2015 and 2016. iSeeCars.com explains that the high demand for the used Leaf likely came from its low average price of $12,533, which makes it one of the most affordable used vehicles on the market overall. The Tesla Model S was the third-fastest selling vehicle in the study spending an average of 26.1 days on the market, likely due to its relatively high demand and limited supply and 17% price decrease from 2015 to 2016.

While ICEs typically depreciate 45% to 50% in three years, some suggest BEVs, except for the Tesla Model S, depreciate 60% to 75% in the same time period. In contrast, the Model S depreciates about 40% in its first three years, which is more similar to conventional vehicles. Possible factors given by Nerdwallet that affect depreciation values include worry about battery degradation over time, new model introductions with longer driving ranges and other features, unknown battery replacement costs, the impact of federal and state incentives for new ZEVs, and the preference towards the newest features of early adopters.

Analysis of used vehicle transaction data between 2012 and August 2016 previously published by Autolist reveals that the Tesla Model S has the slowest depreciation rate in its vehicle segment, even when compared to leading gasoline-powered vehicles. For example, a Model S with 50,000 miles typically depreciates 28% of its original value while comparable large luxury gasoline vehicles, such as the Mercedes-Benz S-Class, Porsche Panamera and BMW 7 Series, with the same mileage depreciate about 40%. In contrast, other PEVs tend to depreciate at a faster rate than their gasoline-powered competition. For vehicles with 50,000 miles, the comparable gasoline vehicles, such as the Toyota Corolla, Honda Civic, Toyota Prius (hybrid), and Ford Focus, depreciate about 25%, while the Chevrolet Volt and Nissan Leaf depreciate about 43% and 59% of their original value.

In 2015, the National Automobile Dealers Association (NADA) calculated the retention values of used PEVs using a three-month (March-May 2015) average of NADA’s average trade-in value divided by the vehicle’s MSRP. The published retention values do not include any include any federal, state or dealer incentives. Overall, results reveal that used PEVs overall have a

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lower retention value compared to gasoline-powered vehicles. As shown in Table 21, the retention of one year old PEVs ranges from 83.1% for the Tesla Model S to 34.9% for the Mitsubishi i-MiEV. For comparison, NADA notes that the one year old retention averages for gasoline powered luxury large, mid-size and compact vehicle segments falls between 70.1% and 62.7%. Therefore, the Model S and the Porsche Panamera S-E maintain higher retention values than the average of the large luxury vehicle segment. Because the top two PEVs with lowest depreciation value are luxury vehicles, the Model S and Porsche Panamera S-E, NADA suggests their strong retention values are predicated on demand for owning a vehicle with cachet and exclusivity. The Model S continued to maintain a higher retention value among two and three year old models (71.1% and 57.2%) compared with the average of the luxury large segment (57.8% and 49.5%). The two PEV models that consistently have the highest depreciation are the i-MiEV and the Nissan Leaf. The three year old retention values of mainstream PEVs ranges from 47.6% to 20.6%, while that of comparable gasoline powered vehicles is greater than 46.2%. NADA explains the low retention value of PEVs through range

Table 21 - PEV retention value percentages by model year calculated in 2015\(^{227}\)

<table>
<thead>
<tr>
<th>PEV</th>
<th>Model Year 2014 Retention %</th>
<th>Model Year 2013 Retention %</th>
<th>Model Year 2012 Retention %</th>
<th>ARB-calculated Model Year 2012 Retention % using after-incentive MSRP</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tesla Model S</td>
<td>83.1</td>
<td>71.1</td>
<td>57.2</td>
<td>64.5</td>
</tr>
<tr>
<td>Porsche Panamera S-E</td>
<td>78.4</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Toyota RAV EV</td>
<td>71.3</td>
<td>55.8</td>
<td>47.6</td>
<td>59.3</td>
</tr>
<tr>
<td>Honda Accord Plug-in</td>
<td>69.8</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Toyota Prius Plug-in</td>
<td>68.8</td>
<td>53.6</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Ford Fusion Energi</td>
<td>62.7</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>BMW i3</td>
<td>61.4</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Cadillac ELR</td>
<td>57.5</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Chevrolet Volt</td>
<td>56.1</td>
<td>35.8</td>
<td>31.3</td>
<td>40.4</td>
</tr>
<tr>
<td>Ford C-Max Energi</td>
<td>53.7</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Fiat 500e</td>
<td>50.1</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Chevrolet Spark EV</td>
<td>47.2</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Mercedes-Benz B-Class</td>
<td>47.1</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Ford Focus Electric</td>
<td>46.5</td>
<td>34.9</td>
<td>31.8</td>
<td>42.4</td>
</tr>
<tr>
<td>Smart Fortwo Electric</td>
<td>45.8</td>
<td>38.2</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Nissan Leaf</td>
<td>43.5</td>
<td>36.5</td>
<td>25.3</td>
<td>34.8</td>
</tr>
<tr>
<td>Mitsubishi i-MiEV</td>
<td>34.9</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Average Comparable ICE</strong></td>
<td><strong>63-70</strong></td>
<td><strong>54-58</strong></td>
<td><strong>46-50</strong></td>
<td><strong>NA</strong></td>
</tr>
</tbody>
</table>

\(^{227}\) NADA, 2015a. Incentives assumed include $7500 federal tax credit and $2500 state rebate for BEVs and $1500 state rebate for Chevrolet Volt
and technology concerns, as well as stiff competition from highly efficient and lower cost gasoline powered vehicles. However, adjusting MY2012 MSRPd to reflect federal and state incentives that would have been available for these vehicles when new and recalculating the retention values shows PEVs to be more similar to conventional vehicles. Reducing MSRPd by up to $10,000 increases retention scores by about 10 percentage points. Low retention values are thus partially a reflection of government purchase incentives.

V. Economic Impacts of ZEVs and Advanced Technology Vehicles
California’s ZEV market exhibits signs of growth throughout the supply chain of the automotive industry. As discussed in SectionIII.A.2, new ZEV sales in California were nearly seven times higher in 2015 than in 2011, which far exceeds the growth rate of the new light-duty vehicle market for the same period. Increased ZEV sales continue to help California meet statewide environmental and economic goals by improving public health, safety, and general consumer welfare. The development, production and supply of ZEV technologies also sustain employment and investments in California’s automotive sector, while spurring growth in battery manufacturing, infrastructure planning and construction, as well as electricity and renewable energy production. Research has shown that a faster penetration rate of ZEVs in California increases wages across various industries in the state, particularly for lower- and middle-income households that earn under $40,000 a year. The same research also found that the spillover effects associated with ZEV adoption increase jobs in nearly all economic sectors, implying that accelerated ZEV adoption creates more opportunities in occupations with higher wages.

California’s ZEV market growth coincides with the state’s general economic recovery, making it difficult to isolate the contribution of ZEV adoption to job growth in the state. Still, as organizations such as CALSTART and the Advanced Energy Economy Institute (AEEI) have emphasized, growth in the broader clean technology industry has expanded the network of manufacturers, suppliers, and producers of advanced energy and fuels. The AEEI describes advanced energy as encompassing technologies, services and energy sources that are clean and secure in the long-run, including “energy efficiency, demand response, energy storage, natural gas electric generation, solar, wind, hydro, nuclear, electric vehicles, biofuels and smart grid.” Results from AEEI’s 2016 California Advanced Energy Employment Survey showed that jobs related to advanced energy grew by 18% in 2015, six times faster than the growth of statewide employment across all industries. AEEI estimates that there are currently 142,000

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228 Total CA LDV Sales are obtained from the CNCDA Quarterly Reports and Dashboard data.
229 This section mostly focuses on the direct impacts of adopting advanced technology vehicles; there are additional indirect and induced economic benefits at the state and national level that are not discussed here. One of these benefits is improvements in energy security. Given that passenger vehicles account for around 70% of transportation oil consumed nationally, the electrification of light-duty vehicles in California and in the U.S. is expected to reduce the country’s reliance on foreign petroleum imports.
jobs in advanced energy production and 19,000 jobs in advanced grid technologies. Looking forward, the AEEI expects California’s advanced energy jobs to grow by 8% in 2016, and CALSTART projects that the state’s ZEV manufacturing industry will employ more than 25,000 workers by 2020. These job-growth estimates are consistent with California’s long-term plans for widespread electrification of the state’s transportation system. This section discusses the employment and investment benefits associated with developing the ZEV and advanced technology vehicle market in California.

V.A. Automotive Sector’s Recovery
The latest employment levels shown in Figure 81 for California’s broader motor vehicle manufacturing industry are approaching pre-recession levels, while jobs in motor vehicle body, engine, and parts manufacturing have also been recovering in recent years. These observations are consistent with trends in the automotive industry at the national level, which show employment numbers for motor vehicle and parts manufacturers, suppliers, and dealers are returning to levels observed before the 2008 recession.

Figure 81 - California’s automotive employment by industry

![Figure 81 - California’s automotive employment by industry](image)


California maintains a unique position as a driver of innovation and environmental regulations, fostering growth of light- and heavy-duty ZEV manufacturers in the state and in the nation. While a number of companies are considering ZEV manufacturing prospects in California, Tesla Motors, a prominent electric vehicle manufacturer, intends to grow its 9,000-employee workforce in the state to more than 15,000 before 2018.\(^{235}\) Still, as shown in Figure 81, motor vehicle manufacturing accounts for a relatively small share (approaching 9,000 jobs) of California’s larger automotive sector’s employment base. Parts dealers and automotive repair and maintenance workers make up an overwhelming majority of jobs in the sector, accounting for around 189,000 and 113,000 jobs, respectively, in 2015. Parts wholesalers also account for a sizable share of jobs in the auto sector, showing steady employment numbers over the past decade (in the mid 30,000’s). A recent report by Next 10 shows that clean technology investments in California have increased considerably after 2013, particularly for transportation-related projects.\(^{236}\) California accounted for around two-thirds of all clean technology investments made in the U.S. in 2015. This statistic is unsurprising considering California’s share of all venture capital investments in the country exceeded two-thirds in 2015. However, as noted by the Next 10 report, venture capital investments are just one of the diversified financing instruments that are being used in the clean technology space. Other funding resources include private and public grants, loans, and equity. While national clean technology investments increased by $14.5 billion (5%) between 2014 and 2015, they grew by $9.8 billion (35%) in California over the same period. Clean technologies for transportation applications received the largest share of venture capitalist investments in 2015, both nationally (47%) and in California (60%).

V.B. ZEV and Advanced Technology Vehicle Jobs

Growing public- and private-sector interests for deploying new vehicle technologies, and the increasing stringencies of vehicle emission standards, are contributing to ZEV and PHEV sales in California. These sales may grow existing auto sector jobs and create opportunities for new businesses and innovations in related industries. New ZEV-related manufacturing jobs are expected to stem directly from vehicle, parts, and battery manufacturers, but businesses that enable ZEV and PHEV adoption (such as alternative fuel producers and suppliers, charging infrastructure providers; vehicle and grid software developers; utility providers; etc.) will also likely see considerable gains in employment. While the production and operation of ZEVs and PHEVs will stimulate economic growth, in the long-run there may also be job losses in industries

\(^{235}\) CALSTART 2016 report on the clean transportation technology industry (CTTI) tracks more than 300 California companies that are transforming the state’s economy through advances in clean energy technology, manufacturing, distribution, and related services. Daily Kanban obtained information from Tesla Motor’s CAEATFA (California Alternative Energy and Advanced Transportation Financing Authority) application, showing that production activities for Tesla’s Model 3 will increase employment in California by 5,600 jobs. They also found that Tesla plans to build manufacturing sites in California for supplying component materials that are currently provided by non-California suppliers. (Niedermeyer 2016. Edward Niedermeyer. October 4, 2016. Daily Kanban. “10 True Facts from Tesla’s Model 3 CAEATFA Application.” http://dailykanban.com/2016/10/10-true-facts-teslas-model-3-caeatfa-application/)

with occupations closely tied to the manufacturing, supplying, and servicing of conventional vehicles. Jobs related to the oil and gas industry (extraction, transportation, refining, etc.) may also decrease as petroleum use is reduced due to a suite of transportation and fuel standard measures. In view of these counteracting economic effects, studies have sought to estimate the net impact of ZEV and PHEV adoption on jobs, accounting for how much these vehicles both accelerate and slow job growth across different economic sectors.

Using various methodologies and assumptions, studies have provided estimates of the net job growth stimulated by further deployment of ZEVs and PHEVs through 2030. The following tables adapted from an International Economic Development Council report summarize the estimates provided by some reports on the net job impacts of adopting advanced technology vehicles more broadly, in California and in the United States. The outlined studies indicate that the number of jobs created by adopting advanced technology vehicles would more than offset the job losses. Although the scenarios and assumptions behind each study vary, their results suggest that harmonized fuel economy and GHG standards will generate considerable employment benefits by 2030, ranging from 38,000 to 236,000 net jobs in California and 129,185 to 1.9 million net jobs in the U.S. As a leader in ZEV adoption, California accounts for a sizable share of the net job gains estimated for the nation. Note that forecasts are sensitive to assumptions about future policy adoption, technology development, investor confidence, infrastructure deployments, and other factors.

Among reports that have estimated job growth impacts of advanced technology vehicles in California, a 2012 UC Berkeley study on plug-in electric vehicle deployment and a 2011 Next 10 study are notable. The UC Berkeley study used the Berkeley Energy and Resources (BEAR) model to forecast economic impacts of three policy scenarios of varying levels of PEV deployment. The baseline conditions for the modeling exercise assumed that California continues with current State PEV deployment commitments and post-1990 Federal fuel economy standards. Two scenarios were then analyzed where PEV deployment increases by 15.4% and 45%, respectively, in addition to the baseline by 2030. The resulting net jobs estimated under these assumptions ranged between 50,000 and 100,000 across all sectors in 2030.

The Next 10 study estimated net job impacts for 2025 by assessing a range of fuel economy standard stringencies. One of the analyzed policy scenarios assumed that California’s emission standards and 2016 Low Carbon Fuel standards would remain the same through 2025. The estimated net jobs under this scenario were around 38,000 by 2025, which is in a comparable


238 Roland-Holst 2012.

range to the 50,000 net jobs estimated for 2030 by the UC Berkeley study under similar assumptions. However, Next 10 also analyzes the impacts of the following increases in Federal economy standards: (1) Fuel economy standards increased by 4% annually between 2017-2025 (37 mpg federal average; 46 mpg new vehicle standard); (2) Fuel economy standards increased by 6% annually between 2017-2025 (43 mpg California fleet average; 54 mpg new vehicle standard); (3) Fuel economy standards increased by 6% annually between 2017-2025 (52 mpg California fleet average; 54 mpg new vehicle standard) and assumes that the standard pushes development of new state-of-the-art vehicle technology. These different scenarios yield (1) 158,000 jobs; (2) 205,000; and (3) 236,000 by 2025.

Table 22 - Net job growth estimates for California from adopting advanced technology vehicles

<table>
<thead>
<tr>
<th>Source</th>
<th>Estimate Year</th>
<th>Net Jobs in California(#)</th>
</tr>
</thead>
<tbody>
<tr>
<td>UC Berkeley (2012)</td>
<td>2030</td>
<td>50,000 - 100,000</td>
</tr>
<tr>
<td>Next 10 (2011)</td>
<td>2025</td>
<td>Resulting from CA standards: 38,000 Resulting from Federal standards: 158,000 – 236,000</td>
</tr>
</tbody>
</table>

At the national level, four studies that estimated the net job impacts of adopting advanced vehicle technologies are summarized in Table 23. Due to the wide range in scale and scope of scenarios analyzed, the net job impacts estimated across these studies ranged from 11,000 in 2020 to 1.9 million in 2030. The UC Berkeley (2009) study evaluated three adoption scenarios with varying gas prices and PEV subsidies. The base case assumed low gas prices that gradually increased to $4 per gallon by 2030. A second scenario considered high gas prices above $5.50 per gallon. Finally, the third scenario assumed that the private sector absorbs costs associated with consumer adoption (operator-subsidized). In this scenario, a subsidy of 3 cents per mile is used in addition to existing $7,500 federal tax credit. In 2030, these three scenarios resulted in 130,000; 315,000; and 350,000 national jobs across all sectors, respectively.

<table>
<thead>
<tr>
<th>Source</th>
<th>Estimate Year</th>
<th>Net Jobs in the United States (#) All Sectors</th>
</tr>
</thead>
<tbody>
<tr>
<td>UC Berkeley (2009)</td>
<td>2030</td>
<td>130,000 - 350,000</td>
</tr>
<tr>
<td>Blue Green Alliance/ACEEE (2012)</td>
<td>2030</td>
<td>570,000</td>
</tr>
<tr>
<td>Electrification Coalition (2010)</td>
<td>2030</td>
<td>Total: 1.9 million</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Manufacturing: 560,000</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Motor vehicle parts: 106,000</td>
</tr>
<tr>
<td></td>
<td></td>
<td>EV electric &amp; electronic parts suppliers: 112,000</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Travel &amp; tourism: 276,000</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Professional services: 73,000</td>
</tr>
<tr>
<td>National Resources Defense Council (2010)</td>
<td>2020</td>
<td>11,000 - 32,000</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Estimates include employment changes in the supply chain of manufacturing sector and indirectly impacted non-manufacturing jobs</td>
</tr>
</tbody>
</table>

The Blue Green Alliance/ACEEE (2012)\(^{241}\) also published a study showing that different federal fuel economy and GHG standard would yield around 570,000 net jobs across all sectors in 2030. The study used ACEE’s Dynamic Energy Efficiency Policy Evaluation Routine (DEEPER) model to evaluate impact of August 2012 Federal standards. Assumptions were made about the incremental cost of new vehicles; financing costs to consumers; changes in energy demand; fuel savings and reallocations; administrative costs to government.

The largest job impact estimates for advanced technology vehicle adoption were made by Electrification Coalition.\(^{242}\) For 2030, this report estimated that 1.9 million net jobs across various sectors would be gained as a result of a wide range of adoption scenarios and policies recommended by the Electrification Coalition in the 2009 Electrification Roadmap. The University of Maryland’s Inforum LIFT economic forecasting model was used to assess the impacts of the following specific policies: increasing ZEV and PHEV purchases; deploying charging infrastructure and upgrading utility IT to support electrified transportation; accelerating


domestic electric vehicle battery production and purchase; and supporting auto manufacturers to equip and prepare auto production plants for manufacturing electric vehicles. An important assumption made by this study was that 75% of passenger VMT would be electric by 2040. Table 23 details the various sectors where the estimated net job impacts would be distributed.

Focusing more on near-term 2020 impacts, the National Resources Defense Council examined the economic impacts of policies that encourage domestic production and improved vehicle economy. The study analyzed three main scenarios that assumed 25%, 50%, and 75% of total technology value are produced domestically, corresponding to Low, Medium, and High retention of total job benefits. Considering the appeal of non-PEVs when oil dependence decreases, and accounting for non-US jobs that may be created with PEV adoption, the study estimated that net job impacts would range from a low of 11,000 to a high of 32,000 by 2020.

The number of vehicles sold in California affects demand for workers in the auto sector’s supply chain. This relationship holds with ZEV and PHEV sales as well, which have slowly grown over the past seven years. One factor in the growth of ZEVs and PHEVs hinges on consumer valuations of fuel savings relative to the cost of purchasing a vehicle. Although gas prices have been low since the 2014 drop in global crude oil prices, long-term projections indicate they will increase steadily through 2040. Meanwhile, over the next few decades, the incremental price difference between a ZEV or PHEV compared to a conventional vehicle is expected to decrease as manufacturers leverage research, scale economies, technology improvements, and other innovations in their production processes. Assuming that actual vehicle sales align with the vehicle projections of the minimum compliance scenario, employment for all auto dealers would increase, while creating jobs in the rest of the supply chain (motor vehicle and battery manufacturers; parts dealers, suppliers, and wholesalers; auto repair and maintenance workers; etc.). To the extent that new, ZEV-related jobs created from increasing ZEV and PHEV manufacturing and sales may offset job losses from traditional ICE vehicle production and sales, the increasing ZEV and PHEV market share requirements could result in a significant net positive impact on employment in the auto sector and related industries. Future work will quantify the demand and the supply-side effects of production input prices, labor capacity, and other factors to estimate the net job impact of increasing market shares for ZEV and PHEV sales.

V.C. ZEV and Advanced Technology Vehicle Investments
California’s automotive industry maintains strong ties with the state’s engineering and technology firms. This link is particularly important for ZEV and PHEV adoption and infrastructure deployment, as production relies heavily on advancements in battery, fuel cell, and grid technologies. Large multinational technology companies as well as existing auto

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244 AEO’s 2015 reference-case projections indicate that motor gasoline prices will approach $4/gallon in 2040. The reference case is modeled after the 2014 global oil market.

245 See Appendix C for additional cost estimates.
manufacturers have demonstrated growing interests in developing autonomous vehicle technologies and advanced safety features that are well-suited for electric vehicle systems and platforms. More broadly, the conglomeration of high-tech software and hardware firms in California has spurred innovations in engine, battery, and vehicle parts research, development and production. Tesla Motors, for example, is planning to advance its battery packs, electric motors, and gearbox technologies along with other R&D efforts at its headquarters in Palo Alto.\textsuperscript{246} Engineering and manufacturing firms based in California are also able to share or license their new products to other companies, which may lead to new developments in other related sectors. For example, the development of hydrogen infrastructure is supported by firms like Quantum Technologies that produces hydrogen tanks and dispensers and FasTech that performs hydrogen station testing and commissioning. Table 24, adapted from CALSTART’s report on California’s Clean Transportation Technology Industry, highlights some of the private sector’s investment plans and commitments that can support further development of ZEV and PHEV technologies or infrastructure.

Table 24 - California-based private sector investment plans and commitments

<table>
<thead>
<tr>
<th>Company</th>
<th>Plans and Investments</th>
</tr>
</thead>
<tbody>
<tr>
<td>AeroVironment</td>
<td>- Manufacturer of EVSE and power cycling and test systems for electrification equipment.</td>
</tr>
<tr>
<td></td>
<td>- Operate and manage a network connected</td>
</tr>
<tr>
<td></td>
<td>- Participant in Nissan’s No Charge to Charge program.</td>
</tr>
<tr>
<td>ChargePoint</td>
<td>- Working with BMW and Volkswagen to expand EV charging network to connect east and west coasts while ensuring there are sufficient charging corridors within both coasts</td>
</tr>
<tr>
<td>eMotorWerks</td>
<td>- Manufacturer of smart charging devices for home use</td>
</tr>
<tr>
<td>Faraday Future</td>
<td>- Plans to manufacture electric cars</td>
</tr>
<tr>
<td>Google</td>
<td>- Significant investments in autonomous vehicles</td>
</tr>
<tr>
<td></td>
<td>- Potential partner with existing OEM</td>
</tr>
<tr>
<td>Greenlots</td>
<td>- Solutions for payment, network management, and installation and support of EV charging networks</td>
</tr>
<tr>
<td></td>
<td>- Partnership with Kia for KIA Chargeup</td>
</tr>
<tr>
<td>Karma Automotive</td>
<td>- Electric car development plans</td>
</tr>
<tr>
<td></td>
<td>- Employee investments (100 engineers)</td>
</tr>
<tr>
<td>Lucid Motors (formerly Atieva)</td>
<td>- Electric car development plans</td>
</tr>
<tr>
<td></td>
<td>- Produced all-electric prototype van (Edna)</td>
</tr>
<tr>
<td>Polyplus</td>
<td>- Leader in advanced battery technology development</td>
</tr>
<tr>
<td></td>
<td>- Developed and patented the protected lithium electrode (PLE)</td>
</tr>
</tbody>
</table>

\textsuperscript{246} Niedermeyer 2016.
- Plans to increase 9,000-employee workforce in the California to more than 15,000 before 2018
- Plans to build manufacturing sites in California for supplying component materials that are currently provided by non-California suppliers

Public sector investments have also played a critical role in enabling the development, production, and adoption of advanced vehicle technology in California. FirstElement Fuel plans to build at least 19 hydrogen filling stations in California with assistance from over $30 million in grants as well as additional loans from Honda and Toyota. HyGen and Stratos Fuel have received over $6 million and $2 million, respectively, in grant awards to support the construction and operation of four more hydrogen stations in California.

Additionally, U.S. DOE’s Vehicle Technologies Office is a leader in funding battery-related research and development, investing over $1 billion since 1992, to address challenges of ZEV technologies. These challenges include battery development and manufacturing costs, technology barriers for electric drivetrains, and broader issues with the public’s awareness of ZEVs. Reducing the cost of batteries and improving their efficiency are paramount factors in improving the affordability of ZEVs and PHEVs. U.S. DOE’s research support has also played an important role in lowering the costs of transportation fuel cells by 50% reduction since 2007 and DOE recently stated its plans to invest $30 million to help fuel cell and hydrogen technologies continue growing. Other notable public sector financing resources for growing the ZEV and PHEV markets include grants and subsidies from the American Recovery and Reinvestment Act, as well as financing and tax incentive programs availed by the California Alternative Energy and Advanced Transportation Financing Authority.

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VI. References


http://www.ppic.org/content/pubs/survey/S_715MBS.pdf.

http://www.ppic.org/content/pubs/survey/S_716MBS.pdf.


http://tsrc.berkeley.edu/sites/default/files/ZEV%20Whitepaper_FINAL_0.pdf.


VII. Data Source Descriptions
Staff analysis utilized an assortment of data sources. Each data source is described briefly below. Some data sources are used for multiple analyses. Only sources relied upon for original staff analysis are discussed in this section.

VII.A. Alliance of Automobile Manufacturers ZEV Sales Dashboard ("Dashboard data")
This data, referred to as "Dashboard data" in this document, was recorded manually from the Alliance of Automobile Manufacturers’ publically available website ZEVFacts.com. This site contains information for consumers on ZEV technology, background on the ZEV regulation, and a ZEV sales dashboard. The dashboard displays statewide cumulative and monthly ZEV sales figures for every state in the U.S. starting from January 2011 through the present. Most recent sales data is typically two months behind the current calendar month (i.e. Sales data for June is updated at the end of August). Data for the ZEV sales dashboard is populated using information from a third party vendor that tracks new vehicle registrations across the US.

Dashboard data is aggregated by BEV, FCEV and PHEV technologies. The PHEV sales data includes sales of both TZEV and non-TZEV certified PHEVs as well as range-extended battery electric vehicles (BEVx). The dashboard omits sales of the Honda Fit EV, Honda FCX Clarity, and the BMW ActiveE, all of which were marketed in limited quantities prior to MY 2014 and all of which have since been discontinued. In addition to monthly sales figures, the dashboard displays light-duty vehicle (LDV) market share for each vehicle technology from calendar year 2013 through the present, which was used to approximate total statewide monthly LDV sales figure for each state.

VII.B. Experian Vehicle and Consumer Demographic data ("Experian Automotive data")
ARB licensed data from Experian Information Solutions, Inc., referred to as "Experian Automotive data" in this document, related to new and used vehicle registrations of BEVs, FCEVs, and PHEVs as well as "comparable" gasoline-only HEVs and ICE vehicles. The data set includes a total of 1 million observations for vehicles transacted from January 2011 through December 2015. Each observation provides details on vehicle characteristics, including vehicle identification number (VIN), purchase characteristics, and owner demographics. Some observations also include purchase price information, though generally only for registrations in states that have not adopted the ZEV regulation. Almost all BEV, FCEV, and PHEV registrations – both new and used – in the U.S. are included, regardless of vehicle seller. A random sampling of new and used comparable ICEs and HEVs drawn from California, Section 177 ZEV states, and states providing purchase price information comprise the remainder of the observations.

VII.C. California Department of Motor Vehicles Registration data ("DMV data")
California's Department of Motor Vehicles (DMV) provides ARB with periodic updates of BEV, FCEV, and PHEV registrations in California, referred to as "DMV data" in this document. These updates reflect the on-road statewide vehicle populations of each of the models. As opposed to

249 http://www.zevfacts.com/sales-dashboard.html
250 Most recent sales data is typically two months behind the current calendar month (i.e. Sales data for June is updated at the end of August).
cumulative new vehicles sales, these populations account for vehicle migrations and scrappage that may occur over time, though migration and scrappage is fairly minimal for recently purchased vehicles. DMV data were used to determine survey samples and provide additional detail on vehicle counts when other data sources were incomplete.

As vehicle license fees are based on a vehicle's value, registration records also include vehicle purchase prices, which represent the transaction price for new vehicles when a vehicle has not been transferred. Registration records also include the original base list price of the vehicle series, which is interpreted as the starting manufacturer suggested retail price of a vehicle model.

**VII.D. Dealer Inventory data from Edmunds.com (“Edmunds.com Inventory data”)**

Data accessed through an application programming interface (API) on dealer inventory was collected once a week from Edmunds.com over a period of six months from October 15, 2015 through May 25, 2016. Parameters collected included vehicle specifications, dealer information, and inventory, including unique VIN. Inventory data was queried within a 30-mile radius of the seven U.S. cities shown in Table 25. Almost all of the cities are located in California or a Section 177 ZEV State and were selected based on their populations according to the 2010 U.S. Census. For comparison, inventory data was also collected from Seattle because while not a Section 177 ZEV State, Washington has had strong ZEV and PHEV sales and inventory may be transferred from neighboring Oregon.

The most centrally located ZIP code was chosen for each city. New Jersey was excluded from the analysis because the largest city by population, Newark, falls within the 30 mile search radius of New York City, the largest city in New York State. Staff chose the city of Albany to help explore whether there are regional differences within a given state.

<table>
<thead>
<tr>
<th>City</th>
<th>State</th>
<th>ZIP code (radius=30 miles)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 Los Angeles</td>
<td>CA</td>
<td>91423</td>
</tr>
<tr>
<td>2 Boston</td>
<td>MA</td>
<td>02118</td>
</tr>
<tr>
<td>3 Baltimore</td>
<td>MD</td>
<td>21201</td>
</tr>
<tr>
<td>4 New York</td>
<td>NY</td>
<td>10019</td>
</tr>
<tr>
<td>5 Albany</td>
<td>NY</td>
<td>12206</td>
</tr>
<tr>
<td>6 Portland</td>
<td>OR</td>
<td>97212</td>
</tr>
<tr>
<td>7 Seattle</td>
<td>WA</td>
<td>98102</td>
</tr>
</tbody>
</table>

Inventories the vehicles listed in Table 26 were collected. PEVs with national distribution as well as three kinds of comparison vehicles: “Comparable Vehicle,” represents the vehicle within a manufacturer's vehicle lineup that most closely approximates the PEV model in terms of body size and style, or identical models with differing drivetrains whenever possible.; “Comparable Sales Volume” vehicles were chosen with similar national sales volumes to the PEV model; and "Best Selling Passenger Car" represents the passenger car within a manufacturer's portfolio with the highest national sales volume in 2015. In some cases, the same vehicle may represent multiple comparison vehicles.
Table 26 - Vehicle Models Used for Dealer Inventory Queries

<table>
<thead>
<tr>
<th>Manufacturer</th>
<th>PEV Model</th>
<th>Comparable Vehicle</th>
<th>Comparable Sales Volumes</th>
<th>Best Selling Passenger Car</th>
</tr>
</thead>
<tbody>
<tr>
<td>BMW</td>
<td>i3</td>
<td>i3x</td>
<td>M235</td>
<td>328</td>
</tr>
<tr>
<td>Ford</td>
<td>Fusion Energi</td>
<td>Fusion Hybrid</td>
<td>Focus ST</td>
<td>Fusion</td>
</tr>
<tr>
<td>Ford</td>
<td>C-MAX Energi</td>
<td>C-MAX Hybrid</td>
<td>Focus ST</td>
<td>Fusion</td>
</tr>
<tr>
<td>GM/Chevrolet</td>
<td>Volt</td>
<td>Cruze</td>
<td>Corvette</td>
<td>Cruze</td>
</tr>
<tr>
<td>Nissan</td>
<td>LEAF</td>
<td>Versa</td>
<td>Juke</td>
<td>Altima</td>
</tr>
</tbody>
</table>

While the data is extensive, it is possible that every dealer (and subsequent vehicle inventories), may not be included on the website. Although the data collected may not contain every vehicle in the dealership inventory, the data analyzed is a good representation of dealership availability for the regions.

**VII.E. Ward's Automotive Data Center ("WardsAuto data")**
Ward's Automotive maintains a paid subscriber-only section on their website, [www.wardsauto.com](http://www.wardsauto.com) that includes access to copyrighted, downloadable datasheets on a wide array of vehicles-related statistics, such as vehicle model year offerings, including specifications such as size class and manufacturer suggested retail prices, as well as manufacturer-reported nationwide monthly or annual sales of vehicle models. Data originating from these datasheets are referred to as "WardsAuto data" and form the basis for estimating sales volumes by varying manufacturer suggested retail price categories in the United States.

**VII.F. Automotive News Data Center ("AutoNews data")**
Automotive News maintains a paid subscriber-only data center through their website, [www.autonews.com](http://www.autonews.com), that includes a searchable database on incentives offered by auto manufacturers (via dealers) for specific vehicle makes and models over time. The data include cash rebate amounts on purchases, discounted financing terms for borrowers, and other available discounts (e.g. military personnel or recent college graduate discounts). This data, referred to as "AutoNews data" in this document, was recorded manually on a monthly basis from February to August 2016 based on searches for the ZIP codes listed in Table 25 of both ZEV and non-ZEV vehicle models offered by BMW, GM, Ford, Nissan, and Toyota shown in Table 27; although data for all auto manufacturers are available, these five manufacturers were queried based on distributing PHEVs and ZEVs nationwide, or having a best-selling vehicle.
Table 27 - Vehicles included in new vehicle dealer incentive analysis

<table>
<thead>
<tr>
<th>Manufacturer</th>
<th>Model</th>
<th>Technology Type</th>
<th>Number of MY and Trim Level Combinations</th>
</tr>
</thead>
<tbody>
<tr>
<td>BMW</td>
<td>2 Series</td>
<td>ICE</td>
<td>2</td>
</tr>
<tr>
<td>BMW</td>
<td>228i</td>
<td>ICE</td>
<td>1</td>
</tr>
<tr>
<td>BMW</td>
<td>320i</td>
<td>ICE</td>
<td>4</td>
</tr>
<tr>
<td>BMW</td>
<td>328d</td>
<td>ICE</td>
<td>4</td>
</tr>
<tr>
<td>BMW</td>
<td>328i</td>
<td>ICE</td>
<td>4</td>
</tr>
<tr>
<td>BMW</td>
<td>330e</td>
<td>ICE</td>
<td>2</td>
</tr>
<tr>
<td>BMW</td>
<td>330i</td>
<td>ICE</td>
<td>1</td>
</tr>
<tr>
<td>BMW</td>
<td>335i</td>
<td>ICE</td>
<td>3</td>
</tr>
<tr>
<td>BMW</td>
<td>340i</td>
<td>ICE</td>
<td>2</td>
</tr>
<tr>
<td>BMW</td>
<td>i3</td>
<td>BEV (and BEVx)</td>
<td>3</td>
</tr>
<tr>
<td>BMW</td>
<td>M2</td>
<td>ICE</td>
<td>1</td>
</tr>
<tr>
<td>BMW</td>
<td>M235i</td>
<td>ICE</td>
<td>2</td>
</tr>
<tr>
<td>BMW</td>
<td>M3</td>
<td>ICE</td>
<td>1</td>
</tr>
<tr>
<td>Ford</td>
<td>C-Max Energi</td>
<td>PHEV</td>
<td>2</td>
</tr>
<tr>
<td>Ford</td>
<td>C-Max Hybrid</td>
<td>HEV</td>
<td>2</td>
</tr>
<tr>
<td>Ford</td>
<td>F-150</td>
<td>ICE</td>
<td>106</td>
</tr>
<tr>
<td>Ford</td>
<td>Fiesta</td>
<td>ICE</td>
<td>1</td>
</tr>
<tr>
<td>Ford</td>
<td>Focus</td>
<td>ICE</td>
<td>26</td>
</tr>
<tr>
<td>Ford</td>
<td>Focus Electric</td>
<td>BEV</td>
<td>2</td>
</tr>
<tr>
<td>Ford</td>
<td>Fusion Energi</td>
<td>PHEV</td>
<td>5</td>
</tr>
<tr>
<td>Ford</td>
<td>Fusion Hybrid</td>
<td>HEV</td>
<td>10</td>
</tr>
<tr>
<td>Ford</td>
<td>Fusion</td>
<td>ICE</td>
<td>23</td>
</tr>
<tr>
<td>GM</td>
<td>Corvette</td>
<td>ICE</td>
<td>7</td>
</tr>
<tr>
<td>GM</td>
<td>Cruze</td>
<td>ICE</td>
<td>16</td>
</tr>
<tr>
<td>GM</td>
<td>Cruze Diesel</td>
<td>Diesel</td>
<td>1</td>
</tr>
<tr>
<td>GM</td>
<td>Equinox</td>
<td>ICE</td>
<td>2</td>
</tr>
<tr>
<td>GM</td>
<td>Volt</td>
<td>PHEV</td>
<td>5</td>
</tr>
<tr>
<td>Nissan</td>
<td>Altima</td>
<td>ICE</td>
<td>18</td>
</tr>
<tr>
<td>Nissan</td>
<td>Juke</td>
<td>ICE</td>
<td>6</td>
</tr>
<tr>
<td>Nissan</td>
<td>LEAF</td>
<td>BEV</td>
<td>7</td>
</tr>
<tr>
<td>Nissan</td>
<td>Maxima</td>
<td>ICE</td>
<td>1</td>
</tr>
<tr>
<td>Nissan</td>
<td>Versa</td>
<td>ICE</td>
<td>15</td>
</tr>
<tr>
<td>Toyota</td>
<td>Camry</td>
<td>ICE</td>
<td>3</td>
</tr>
<tr>
<td>Toyota</td>
<td>Camry Hybrid</td>
<td>HEV</td>
<td>3</td>
</tr>
</tbody>
</table>
VII.G. Clean Vehicle Rebate Programs and Surveys

California, Massachusetts, and Connecticut all offer rebates for new vehicle purchases of PHEVs and ZEVs. Program eligibility varies by state, though the Center for Sustainable Energy (CSE) administers all three programs. Basic information on all of California’s Clean Vehicle Rebate Project (CVRP) recipients, such as date of purchase, rebated vehicle including VIN, recipient’s utility, and lease information is referred to as "CVRP rebate data." Rebate statistics are also available publicly through the Rebate Statistics Dashboard at:

- California: https://cleanvehiclerebate.org/eng/rebate-statistics
- Massachusetts: https://mor-ev.org/program-statistics

Each of these states has also been surveying their rebate recipients about their purchase motivations, purchase experience, and household characteristics. Based on current market shares of PHEVs and ZEVs, data sources of general new car buyers include only a limited number of actual drivers of these vehicles, making data sources focused specifically on these technologies more valuable. Table 28 summarizes the response rates for each PEV type.

Table 28 - Summary of CA, MA, CT rebate program survey responses

<table>
<thead>
<tr>
<th>Vehicle Technology</th>
<th>CA CVRP Recipients</th>
<th>CA CVRP Survey Responses</th>
<th>CA Response Rate</th>
<th>MA MOR-EV Recipients</th>
<th>MA MOR-EV Survey Responses</th>
<th>MA MOR-EV Response Rate</th>
<th>CT CHEAPR Recipients</th>
<th>CT CHEAPR Survey Responses</th>
<th>CT Response Rate</th>
</tr>
</thead>
<tbody>
<tr>
<td>PHEV</td>
<td>51,452</td>
<td>9,792</td>
<td>19.0%</td>
<td>963</td>
<td>313</td>
<td>32.5%</td>
<td>422</td>
<td>196</td>
<td>46.4%</td>
</tr>
<tr>
<td>BEVx</td>
<td>1,755</td>
<td>514</td>
<td>29.3%</td>
<td>-</td>
<td>30</td>
<td>-</td>
<td>75</td>
<td>18</td>
<td>24.0%</td>
</tr>
<tr>
<td>BEV&lt;200</td>
<td>52,062</td>
<td>10,997</td>
<td>21.1%</td>
<td>804(^{252})</td>
<td>345(^{253})</td>
<td>42.9%(^{254})</td>
<td>161</td>
<td>112</td>
<td>69.6%</td>
</tr>
<tr>
<td>BEV200+</td>
<td>18,015</td>
<td>3,847</td>
<td>21.4%</td>
<td>703</td>
<td>193</td>
<td>27.5%</td>
<td>N/A</td>
<td>N/A</td>
<td>N/A</td>
</tr>
<tr>
<td>All</td>
<td>123,284</td>
<td>25,150</td>
<td>20.4%</td>
<td>2,470</td>
<td>851</td>
<td>34.5%</td>
<td>658</td>
<td>326</td>
<td>49.5%</td>
</tr>
</tbody>
</table>

Additionally, a cross-section of California rebate recipients was surveyed in April-May 2015 to learn about their PEV experience and attitudes to date. When analyzing these survey results, the vehicle technology categories were broken down into: PHEV, BEVx, BEV<200 (BEVs with less than 200 mile electric range), and BEV200+ (BEVs with more than 200 mile electric range). Details from these four surveys are discussed below.

\(^{251}\) Additional details on these complementary policies can be found in Appendix E

\(^{252}\) This number includes BEVx rebate recipients

\(^{253}\) To be consistent with MOR-EV program guidelines, this number includes BEVx survey respondents

\(^{254}\) This number includes BEVx in the response rate
VII.G.1.  **California Clean Vehicle Consumer Survey ("CVRP results")**

For the duration of California’s CVRP program, rebate recipients have been invited to complete a voluntary, on-line survey about their PEV purchase. Early rebate recipients were invited to complete the survey following at least a six month ownership period, but beginning in 2014 rebate recipients were invited on a rolling basis as their rebate applications are received/approved, which generally occurs shortly after the vehicle has been purchased. Over time, the survey questionnaire has been revised periodically, though some questions have remained unchanged. Thus, some results presented are based on different sample periods and sample numbers, as noted. The results reported in this document are referred to as "CVRP results." Total responses cover invitations distributed to participants who purchased their vehicles between April 2010 and mid-June 2016. Although a limited number of FCEV drivers have been receiving rebates since the beginning of the CVRP, the survey was not designed to capture their purchase motivations and experiences until July 2016; to date, total responses from FCEV drivers are not sufficient for analysis.

Due to the small sample size for some PEV models, “other” categories were made by combining models that had fewer than 150 responses. The “Other BEV” category consists of BMW 1 Series Active E (n=12), CODA (n=5), Th!nk City (n=6), Tesla Roadster (n=20), Honda Fit EV (n=112), and Mitsubishi i-MiEV (n=48). The “Other PHEV” category comprises Audi A3 e-tron (n=86), Cadillac ELR (n=94), Honda Accord Plug-In (n=90), Hyundai Sonata Plug-in (n=69), Mercedes-Benz S-Class 550e (n=8), and Volvo XC90 T8 (n=15).

**Figure 82 - CVRP: Rebate PEV**

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255 A complete description of California’s CVRP is included in Appendix E.
VII.G.2. Connecticut Hydrogen and Electric Automobile Purchase Rebate ("CHEAPR results")
For the duration of the CHEAPR program, rebate recipients have been invited to complete a voluntary, on-line survey about their clean vehicle purchase.

PEV models with fewer than 10 total responses were combined to form the “Other” category, which includes the PHEVs: Audi A3 e-tron (n=3), Hyundai Sonata Plug-in Hybrid (n=5), and Toyota Prius Plug-in Hybrid (n=9); and BEVs: Ford Focus Electric (n=7), Kia Soul EV (n=1), Mercedes-Benz B-Class (n=4), and Smart Fortwo (n=4).

Figure 83 - CHEAPER: rebated PEV type

VII.G.3. Massachusetts Offers Rebates for Electric Vehicles ("MOR-EV results")
For the duration of the MOR-EV program, rebate recipients have been invited to complete a voluntary, on-line survey about their clean vehicle purchase.

Some models were combined to form the “Other” category if the total responses per model were fewer than 10. The Other PHEVs include BMW i8 (n=6), BMW X5 xDrive40e (n=2), Cadillac ELR (n=8), Porsche Cayenne S E-Hybrid (n=1), and Toyota Prius Plug-in (n=9). The Other BEVs include Honda Fit EV (n=2) and Mitsubishi i-MiEV (n=3).

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256 Full description of the CHEAPR program found in Appendix E.
257 Full description of the MOR-EV program found in Appendix E.
VII.G.4. **California PEV Ownership Survey ("Ownership results")**
The PEV Ownership Survey was administered between April and May 2015 by CSE on behalf of ARB. A total stratified random sample of 20,000 non-fleet CVRP recipients was invited to participate via email. All PEV owners invited had their vehicle registered with the California DMV as of October 2014. The goal of the survey was to understand the attitudes of individual owners or lessees of PEV consumers who had their vehicle for more than 6 months to ensure that they had sufficient time and experience with their vehicles to inform their responses. The sample chosen was stratified across counties and model years beginning with PEV purchased in 2011 to approximate the California population of PEVs. The overall response rate was 33% and the distribution of respondents’ initial PEV types is shown in Figure 85. Note that a small
number of respondents no longer had the vehicle for which they received a rebate but this did not disqualify them from completing the survey. Overall, 46% of respondents originally had a PHEV followed by 38% with a BEV<200 and 15% with a BEV200+ and the overwhelming majority of all respondents bought or leased a PEV in 2013 or 2014. See Table 29 for a complete breakdown of respondents by PEV model and purchase year.

Table 29 - Ownership survey respondents by PEV model and purchase year

<table>
<thead>
<tr>
<th>PEV</th>
<th>2011</th>
<th>2012</th>
<th>2013</th>
<th>2014</th>
<th>All</th>
</tr>
</thead>
<tbody>
<tr>
<td>Chevrolet Volt</td>
<td>0</td>
<td>243</td>
<td>595</td>
<td>365</td>
<td>1,203</td>
</tr>
<tr>
<td>Ford C-MAX Energi</td>
<td>0</td>
<td>11</td>
<td>186</td>
<td>125</td>
<td>322</td>
</tr>
<tr>
<td>Ford Fusion Energi</td>
<td>0</td>
<td>0</td>
<td>151</td>
<td>188</td>
<td>339</td>
</tr>
<tr>
<td>Toyota Prius Plug-in</td>
<td>0</td>
<td>288</td>
<td>269</td>
<td>526</td>
<td>1,083</td>
</tr>
<tr>
<td>Other PHEV</td>
<td>0</td>
<td>0</td>
<td>23</td>
<td>30</td>
<td>53</td>
</tr>
<tr>
<td>BMW i3 REx</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>49</td>
<td>49</td>
</tr>
<tr>
<td>Chevrolet Spark</td>
<td>0</td>
<td>0</td>
<td>51</td>
<td>76</td>
<td>127</td>
</tr>
<tr>
<td>Fiat 500e</td>
<td>0</td>
<td>0</td>
<td>139</td>
<td>321</td>
<td>460</td>
</tr>
<tr>
<td>Ford Focus Electric</td>
<td>0</td>
<td>29</td>
<td>57</td>
<td>73</td>
<td>159</td>
</tr>
<tr>
<td>Honda Fit EV</td>
<td>0</td>
<td>8</td>
<td>38</td>
<td>26</td>
<td>72</td>
</tr>
<tr>
<td>Nissan Leaf</td>
<td>73</td>
<td>165</td>
<td>460</td>
<td>523</td>
<td>1,221</td>
</tr>
<tr>
<td>Smart Electric Fortwo</td>
<td>0</td>
<td>0</td>
<td>44</td>
<td>63</td>
<td>107</td>
</tr>
<tr>
<td>Toyota RAV4 EV</td>
<td>0</td>
<td>19</td>
<td>143</td>
<td>106</td>
<td>268</td>
</tr>
<tr>
<td>Other BEV&lt;200</td>
<td>1</td>
<td>7</td>
<td>12</td>
<td>54</td>
<td>74</td>
</tr>
<tr>
<td>Tesla Model S</td>
<td>0</td>
<td>88</td>
<td>604</td>
<td>282</td>
<td>974</td>
</tr>
<tr>
<td>All</td>
<td>74</td>
<td>858</td>
<td>2,772</td>
<td>2,807</td>
<td>6,511</td>
</tr>
</tbody>
</table>

Note: shading represents PEV technology: yellow = PHEV, orange = BEVx, red = BEV<200, and dark red = BEV200+.

VII.H. Enhanced Fleet Modernization Program and Plus-Up Pilot Program

The Enhanced Fleet Modernization Program (EFMP) and Plus-Up pilot program, currently implemented in the South Coast and San Joaquin Valley air districts, started in July of 2015. The program provides incentives to low income residents living in or near disadvantaged communities to scrap their older, higher-polluting vehicles and replace them with fuel-efficient conventional or advanced technology cars. The incentive amounts depend on each applicant’s household income and choice of replacement vehicle. The price, mileage, and loan terms for the replacement vehicles used for analyzing the price of PEVs in the secondary market in these air districts come from the vehicle sales contracts, which the vehicle dealers submit to the districts directly.

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258 See https://www.arb.ca.gov/msprog/agip/ldv_pilots/efmp_plus_up_faq.pdf for program details.
VII.I. Powertrain Acceptance & Consumer Engagement survey ("PACE Survey")

Morpace first administered their Powertrain Acceptance & Consumer Engagement (PACE) survey in 2009 and has repeated this syndicated survey annually starting in 2013. ARB has licensed the use of the complete respondent data for the 2013, 2014, and 2015 administrations. The 2015 PACE survey was administered between October 29 through December 1, 2015 to an online panel of new vehicle owners nationwide to assess their awareness and perception of alternative powertrain technologies as well as their household characteristics and other attitudes. The survey includes a total of 2,138 new car buyers, of which 136 drive PHEVs, 138 drive BEVs, and 154 drive HEVs.

The sample was weighted to be representative of vehicle segment/class distributions. 54% of respondents were male, 83% Caucasian, 79% married, 87% reside in single family house, 88% own their home, and over 70% had a college degree. The median age of respondents was 40 years old with a median annual income was $90,000 and a median household size of three. The weighted sample size of the study along with the sample sizes for each of the vehicle segments and by powertrain is shown in Table 30.

Table 30 – Morpace 2015 PACE Study Sample Sizes

<table>
<thead>
<tr>
<th>Segment</th>
<th>Sample Size</th>
</tr>
</thead>
<tbody>
<tr>
<td>Traditional Engines</td>
<td>1710</td>
</tr>
<tr>
<td>Mainstream Car</td>
<td>502</td>
</tr>
<tr>
<td>Luxury Car</td>
<td>286</td>
</tr>
<tr>
<td>Mainstream CUV/SUV</td>
<td>444</td>
</tr>
<tr>
<td>Luxury CUV/SUV</td>
<td>183</td>
</tr>
<tr>
<td>Pickup Truck</td>
<td>191</td>
</tr>
<tr>
<td>Minivan</td>
<td>104</td>
</tr>
<tr>
<td>Alternative Powertrains</td>
<td>428</td>
</tr>
<tr>
<td>Hybrid Electric Vehicle (HEV)</td>
<td>154</td>
</tr>
<tr>
<td>Plug-in Hybrid Electric Vehicle (PHEV)</td>
<td>136</td>
</tr>
<tr>
<td>Battery Electric Vehicle (BEV)</td>
<td>138</td>
</tr>
<tr>
<td><strong>Total Sample</strong></td>
<td><strong>2138</strong></td>
</tr>
</tbody>
</table>

VII.J. Alternative Fuels Data Center ("AFDC HEV sales data")

The U.S. Department of Energy’s Alternative Fuels Data Center (AFDC) website provides analysis of U.S. alternative fuel vehicle sales. Data used by AFDC for analysis is gathered from public sources and available for download. Specifically, ARB staff downloaded HEV sales data, accessed at the AFDC website,\(^{259}\) and referred to as "AFDC HEV sales data" in this document, which consists of HEV sales numbers from calendar year 1999 through 2015 for the US. This data serves as the basis for the number of HEV model offerings during this time period.

VII.K. CNCDA’s California Auto Outlook Report ("CNCDA Quarterly Reports")
The California New Car Dealer Association (CNCDA) posts quarterly California Auto Outlook reports available through their website. These reports provide data on individual manufacturer’s California vehicle sales trends. Data on manufacturer’s 2012 through 2015 annual new vehicle sales was gathered manually from this report. This data, referred to as "CNCDA Quarterly Reports," was used to determine statewide manufacturer market shares as well as estimates of vehicle segment shares and overall statewide market shares of best-selling vehicle models.

VII.L. ARB-contracted research
ARB’s Research Division funds a number of extramural research projects on air pollution and climate change as part of the Board’s Annual Research Plan. Research projects must first be approved by the board-appointed Research Screening Committee (RSC), comprised of eleven scientists and engineers from academia, government, or industry, before funding is awarded by the Board. Final reports are also reviewed and approved by the RSC before they are published following project completion on the projects' webpages. Three recent research contracts are relevant to assessing the PHEV and ZEV markets discussed in this appendix include:

- "New Car Buyer's Valuation of Zero-Emission Vehicles," Contract 12-332, University of California, Davis (UCD) (with additional funding from the Northeast States for Coordinated Air Use Management or NESCAUM), https://www.arb.ca.gov/research/single-project.php?row_id=65166, referred to in this document as "UCD New Car Buyers Study"


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260 http://www.cncda.org/Auto_Outlook.asp
California's Advanced Clean Cars Midterm Review

Appendix C: Zero Emission Vehicle and Plug-in Hybrid Electric Vehicle Technology Assessment

January 18, 2017
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I. Introduction and Vehicle Summary

When developing the Advanced Clean Cars (ACC) rulemaking in 2011 for 2018 and subsequent model years, Air Resources Board (ARB or the Board) staff had limited knowledge of how the market would develop. Details of future vehicles including upcoming Ford and BMW products were slim and based mostly from press releases at the time. Since the adoption of the ACC regulations, zero emission vehicle (ZEV, which includes battery electric vehicles, or BEV, and fuel cell electric vehicles, or FCEV) and plug-in hybrid electric vehicle (PHEV) technology has progressed quickly. This has led to introductions (and announcements) of vehicles with longer ranges and more efficient and capable drivetrains far earlier than expected.

The 2010 Joint Agency Draft Technical Assessment Report (2010 TAR) projected ZEV technology and costs, using the Argonne National Labs (ANL) Battery Pack and Costing tool (BaTPaC), and were considered at the time to be aggressive assumptions, even for the 2025 model year. However, indications from other sources and updated work from the 2016 Joint Agency Draft Technical Assessment Report (2016 TAR) shows that those 2010 projections were somewhat conservative. With batteries being a large share of the cost of PHEVs and BEVs, those cost reductions are enabling longer range and more capable versions of those vehicles, earlier than was originally projected. Updated information on FCEV costs was also included in the 2016 TAR; however, FCEVs were not included in the greenhouse gas fleet modeling due to limited sales and higher incremental costs in that timeframe.

Despite impressive cost reductions in batteries, ZEVs and PHEVs are projected to have significant cost premiums relative to future conventional internal combustion engine (ICE) technology. The 2016 TAR projects an incremental cost of $6,500 to $14,200 for PHEV40 and BEV200s over an equivalent ICE vehicle in the 2025 model year. While these incremental costs compare similarly to those projected by the 2010 TAR, they represent updated ZEV technology packages. Given market offerings and battery cost reductions, the PHEV20 and BEV150 packages modeled in the 2010 TAR were updated to PHEV40 and BEV200 packages for the 2016 TAR resulting in an increase in battery content (and associated cost even with the reduced battery prices). For the non-battery components of the PHEV and BEV packages, the costs in the 2016 TAR are largely identical to what was assumed in the 2010 TAR and originally derived from a teardown study of a 2010 Ford Fusion Hybrid conducted by FEV Group (FEV).

---

3 PHEV40 means a 40 mile all electric range (label) PHEV (non-blended)
4 BEV200 means a 200 mile all electric range (label) BEV
5 PHEV20 means a 20 mile all electric range (label) PHEV (blended)
6 BEV150 means a 150 mile all electric range (label) BEV
under contract with the United States Environmental Protection Agency (U.S. EPA). To update these component costs to be reflective of technology improvements since 2010, ARB has a teardown contract currently underway on recently introduced PHEVs and BEVs.

This appendix provides an assessment of the progress of BEV, PHEV, and FCEV technology since the 2012 adoption of the ACC regulations. Section II presents staff’s assessment of plug-in electric vehicle (PEV) technologies, which includes BEVs and PHEVs, and components related to these vehicles. Section III includes staff’s assessment of FCEV technology.

I. A. Past and Current Zero Emission Vehicle Models
The ZEV market has seen a significant increase in available models since the Nissan Leaf and Chevrolet Volt 2010 market introductions. Currently, the market has increased from one to 25 unique vehicle offerings as of January 2017. Table 1 in Appendix B shows the past and currently available ZEVs and PHEVs.

BEV technology has progressed quickly since the market introduction of the Nissan Leaf in 2010. The Leaf has increased in range by 45% since its first model year. The Tesla Model S has received several increases in range and the addition of a second motor for an all-wheel drive (AWD) version since its market introduction in 2012. The most recent iteration of the Model S is rated at 315 miles of label range. Tesla's Model X came to market at the end of 2015 with AWD, seating for seven passengers, and towing capability. BMW i3 now has an option for a bigger battery pack with even more range. General Motors released its Chevrolet Bolt EV on the market at the end of 2016, with 238 miles label range. Several other manufacturers have announced longer range mass market BEVs, with notable examples including the next generation Nissan Leaf, the Tesla Model 3, and a small Ford sport utility vehicle (SUV).

PHEV technology also continues to evolve as manufacturers introduce different architectures and all electric capabilities as they respond to feedback from consumers indicating they want more electric range from the technology. General Motors' second generation Chevrolet Volt was released in late 2015 with 53 miles EPA label all electric range (AER); an improvement of 15 miles of range over the previous generation. The Volt represents best-in-class technology in terms of range for a PHEV and has been well received by many automotive critics. Vehicle manufacturers have also started to implement PHEV technology on platforms beyond the small and mid-size passenger car segments. Chrysler plans to offer the Pacifica 8-passenger mini-

---

7 One model from a manufacturer subject to the ZEV regulation in 2010
9 See Appendix B, Section VII for a description of the CVRP Ownership Survey results
10 EPA label range represents the approximate number of miles that can be travelled in combined city and highway driving, and is based on the UDDS cycle plus several others that represent higher speeds and accelerations as well as colder and hotter weather conditions. To determine PEV range, the vehicle completes a 2-cycle (UDDS) and multiplies the value by 0.7. Values in this document will be EPA label range, unless otherwise noted.
van with a 16kWh battery pack by the end of this year.\textsuperscript{12} Volvo currently offers its XC90 7-passenger SUV with an AWD drivetrain and 13 miles label equivalent AER (EAER).\textsuperscript{13} Several other manufacturers have also announced plans to offer PHEV options in many of their current and future models.

At the time of the ACC rulemaking in 2012, there were no light-duty mass-produced fuel cell vehicles available on the market. That has changed with introduction of the Hyundai Tucson Fuel Cell in 2015 model year. It was subsequently followed by the releases of the Toyota Mirai and Honda Clarity Fuel Cell.\textsuperscript{14} As noted in Appendix D, more than 25 retail hydrogen fueling stations are now open and increases in FCEV deployment are expected over the next several years.

**I.A.1. Future Vehicles**

Figure 1 below shows the aggregate number of expected ZEV and PHEV models through the 2021 model year, based on information provided by the manufacturers to ARB as well as public announcements. The figure shows significant growth from 24 vehicle offerings in model year 2016 to approximately 80 vehicle offerings expected by 2021.

![Figure 1 - Aggregate TZEV and ZEV Models by Model Year](image)

Additional expansion of vehicle model offerings is also expected after 2021, but less certainty is known as manufacturers have not yet solidified plans for those years. However, several manufacturers have announced longer term, broad reaching electrification plans that will affect model years 2022 to 2025, and beyond. Audi, at the 2015 Los Angeles International Auto Show,


announced that it is committed to achieving 25% of U.S. sales from electric vehicles by 2025.\textsuperscript{15} Audi will likely need to develop several more electrified models across its product line to reach such sales goals. In December of 2015, Ford announced that it would be investing $4.5 billion into electrified vehicle solutions.\textsuperscript{16} Part of that plan involves adding 13 new electrified vehicle nameplates by 2020, which amounts to more than 40% of the company’s global nameplates. Volvo also announced that it has a target to sell one million electrified cars by 2025 which will utilize Volvo’s two new modular architectures.\textsuperscript{17} While Volvo’s specific model plans have not been announced, its 2025 target will likely require many more electrified models than what is available today.

Similar announcements have also come from Daimler, Honda, VW, and the Hyundai Motor Group. In June of 2016, Daimler announced that it would be investing seven billion euros in ‘green’ technology over the following two years.\textsuperscript{18} Daimler subsequently announced the creation of an all new Mercedes-Benz sub-brand “EQ”, which will be dedicated to bringing all-electric vehicles to market.\textsuperscript{19} Honda’s CEO announced in February of 2016 that the company will strive to have two-thirds of the overall sales come from electrified vehicles by 2030.\textsuperscript{20} VW announced a new group strategy name “TOGETHER – Strategy 2025” that includes a major electrification initiative with more than 30 new electric vehicles (including Audi) by 2025 and annual sales between two and three million units.\textsuperscript{21} The Hyundai Motor Group in April of 2016 announced a new electrification plan that includes 26 new models by 2020. In reference to the announcement, the senior vice president of Hyundai Motor Group’s Eco Technology Center said “This is the basement that we will build upon.”\textsuperscript{22}


II. PEV Technology Status and Progress

There have been several advancements in PEV technology that were not originally projected by staff for the 2012 ACC rulemaking (and development of the Federal GHG standards). The 2010 TAR modeled the longest range BEV with up to 150 miles of range (on the EPA fuel economy label) because, at the time, BEVs with 200 miles or more of range were expected to be too expensive relative to a conventional vehicle to be feasible. Additionally, staff assumed in its 2011 ZEV regulation compliance scenario that all BEVs produced in compliance (from 2018 through 2025 model year) would have a 100 mile test cycle range\(^{23}\) (approximately 70 mile ‘label range’), all PHEVs would have 22-40 miles of test cycle range (~14-30 mile label range), and all FCEVs would have at least 350 miles of test cycle range (maxing out the number of credits that could be earned within the program).\(^{24}\) Since then, multiple manufacturers have announced 200 mile (or more) label range BEVs and multiple PHEVs at various ranges, likely due to decreased batteries costs and increased vehicle efficiency, further discussed in this section.

II. A. Industry Targets for PEVs

The U.S. Department of Energy (U.S. DOE) and U.S. Driving Research and Innovation for Vehicle efficiency and Energy sustainability (U.S. DRIVE) have both set goals for key PHEV, BEV, and FCEV components which they see as critical milestones to advance the ZEV market.

In order to identify and address some of the challenges faced by the future ZEV market, the U.S. DOE created the Electric Vehicle (EV) Everywhere Grand Challenge, announced by President Obama in 2012. The effort identified several key areas that “can enable the purchase cost combined with the operating cost of an all-electric vehicle with a 280-mile range to be comparable to that of an internal combustion engine vehicle of similar size after five years of ownership.”\(^{25}\) To reach that goal, several targets were established as shown in Table 1.\(^{26}\)

\(^{23}\) Test cycle range means all electric range on the urban dynamometer drive schedule (UDDS).


Table 1 - U.S. DOE EV Everywhere Grand Challenge 2022 Targets

<table>
<thead>
<tr>
<th></th>
<th>Battery</th>
<th>Electric Drive System</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Cost</strong></td>
<td>$125/kWh</td>
<td>$8/kW</td>
</tr>
<tr>
<td><strong>Energy Density</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Volumetric</td>
<td>400 Wh/L</td>
<td>-</td>
</tr>
<tr>
<td>Gravimetric</td>
<td>250 Wh/kg</td>
<td>-</td>
</tr>
<tr>
<td><strong>Power Density</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Volumetric</td>
<td>-</td>
<td>4 kW/L</td>
</tr>
<tr>
<td>Gravimetric</td>
<td>2 kW/kg</td>
<td>1.4 kW/kg</td>
</tr>
<tr>
<td><strong>Efficiency</strong></td>
<td>-</td>
<td>94%</td>
</tr>
</tbody>
</table>

Recently, the U.S. DOE has begun discussions of draft targets that reach beyond these 2022 targets. While there are minimal details available on the assumptions and methodology of the new targets as they are not yet finalized, U.S. DOE representatives have publicly presented on an aspirational draft target of $80/kWh by approximately 2030 to make BEVs more price competitive with internal combustion engines.\(^{27}\) Of note, these targets are not projections of battery costs in a specific timeframe but rather cost targets that U.S. DOE has calculated that would need to be achieved for increased price competitiveness of BEVs relative to internal combustion engine vehicles. The agency expects to continue to engage with U.S. DOE as it further updates targets that have helped prioritize and guide innovation in battery and electric drive technology.

U.S. Driving Research and Innovation for Vehicle efficiency and Energy (DRIVE)\(^{28}\) has also put forth industry targets that align with the EV Everywhere targets. However, these additional targets were established specifically for conventional hybrid electric vehicles (HEV), as ancillary components (interconnects, fuses, etc.) account for a larger percentage of the total system cost, mass, and volume. For BEVs and PHEVs where those ancillary components are a much smaller part of total electrification system, the goals were focused on the components that make up the largest share of the costs. The targets, which were also shown in the 2016 TAR\(^{29}\) and in Table 2 below, are useful as benchmarks to assess industry’s progress on individual components.

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\(^{28}\) A private/public partnership managed by the U.S. Council for Automotive Research (USCAR) of which the U.S. DOE is a member

\(^{29}\) EPA 2016.
Table 2 - U.S. DRIVE 2015 and 2020 Targets for Electrified Components

<table>
<thead>
<tr>
<th></th>
<th>U.S. DRIVE Target (Lab Year)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>2015</td>
</tr>
<tr>
<td>Electric Motor</td>
<td>1.3 kW/kg</td>
</tr>
<tr>
<td></td>
<td>$7/kW</td>
</tr>
<tr>
<td>Power Electronics</td>
<td>12 kW/kg</td>
</tr>
<tr>
<td></td>
<td>$5/kW</td>
</tr>
<tr>
<td>Motor and Electronics</td>
<td>1.2 kW/kg</td>
</tr>
<tr>
<td>Combined</td>
<td>$12/kW</td>
</tr>
<tr>
<td>3 kW DC/DC Converter</td>
<td>1.0 kW/kg</td>
</tr>
<tr>
<td></td>
<td>$60/kW</td>
</tr>
</tbody>
</table>

II. B. PEV Technology Trends
ZEV technology continues to change rapidly as the industry responds to evolving market pressures, consumer demands, and California, U.S., and other global regulatory requirements. Some manufacturers are only now beginning to release first generation ZEV products while others are starting to place their second and third generation vehicles in the market. Those vehicles utilize various technologies that continue to change. This portion of the ZEV technology assessment will focus on batteries, electric motors, on-board chargers (OBC), power electronics, and materials that make advancements in those systems possible. There have also been several broader trends in ZEV technology taking place within the industry: battery packs with increased, energy capacity, vehicle with more electric range, and expanding ZEV technology onto various vehicle segments. All of those things are leading to a wider range of models that offer customers more utility.

II.B.1. 2016 Technical Assessment Report PEV Findings
The 2016 TAR identified several new trends and reaffirmed several others that were part of the 2012 federal Final Rulemaking (FRM). The first trend noted is that the current BEV market appears to have bifurcated into two segments. The first is a non-luxury segment with prices targeting mass-market segment offerings and an average 85 mile label AER, with significant range increases to beyond 200 miles expected in the next few years. The second is a luxury segment already offering well over a 200 mile label AER. Staff expects both segments to continue to pursue range increases until the manufacturer determines it has found the

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30 The goals were established for the 2015 and 2020 lab years (which are intended to approximate five years before the component would be ready for commercialization and wide-scale mass production).
appropriate combination of range and price that appeals to the largest segment of consumers. Staff expects some manufacturers will likely offer various battery pack sizes on each model, much like Tesla currently does for its Model S and Mitsubishi does for its i-MiEV (in Japan only).

The projection for the amount of range that the furthest BEVs travel on a single charge has changed. The BEV150 category was replaced with BEV200s for the fleet analysis. While PHEV with increased AER were considered to replace PHEV40s (2010 TAR assumption) in the analysis, ultimately, the 2016 TAR analysis modeled PHEV40s due to industry trends and lack of evidence average PHEV range would increase.

There has been an increase in the 20 mile EAER PHEV offerings for the 2015 and 2016 model year in the luxury and performance oriented segments. Additionally, second generation PHEVs that are now coming to market are offering more AER due in part to customer demands for a more all-electric driving experience.

Electric motor sizing for both BEVs and PHEVs were revised to better reflect what industry is doing. Manufacturers have been able to realize more accelerative performance out of lower power electric motors than what the 2010 TAR modeled. Electric motors were originally assumed to require similar nominal power as an ICE to achieve the same performance. Due to the electric motors ability to make full torque off of idle, the model was revised to use electric motors with lower nominal power ratings and still achieve equivalent vehicle performance.

Reductions in battery costs were realized due to several changes in inputs to the BatPaC model along with other changes to how BEVs and PHEVs were modeled. Version 3.0 of the BatPaC model was released late in 2015 with lowering of raw material input costs, adjustment of cathode technologies, and several other changes. Changes to the vehicle modeling itself included increased state of charge (SOC) windows for BEVs and PHEV40s, increased driveline efficiency, and higher applied aerodynamic drag reductions among other things. Those changes resulted in smaller and lower cost battery packs due to the reduced energy required to achieve the same range, and a lower cost per kilowatt-hour (kWh).

Current and publicly announced near term PEV models span platforms from subcompact cars to large cars, and small sport utility vehicles (SUV) to minivans confirming the technology is available for a large portion of the market segments. Manufacturers are also using both shared and dedicated platforms for their PEV offerings indicating there is not yet a clearly defined superior approach. In some cases, use of a global platform allows commonality across models and international markets for increased volumes while in other cases, a dedicated platform allows for a higher level of optimization for the PEV technology.

Even with the advancements, PHEV and BEV models were still not projected to play a significant role in the fleet in the 2016 TAR analysis. In that analysis, less than 6 percent of the 2025 fleet is expected to be comprised of ZEV or PHEV vehicles and the majority of those vehicles were included in the reference fleet as necessary to meet the ZEV regulation in California (and the Section 177 ZEV states) rather than projected as needed by the U.S. EPA's OMEGA model to meet the 2018 through 2025 model year greenhouse gas standards.
Other findings noted in the 2016 TAR included acknowledgement that passenger cabin heating and cooling needs as well as battery thermal management systems can have a significant impact on BEV and PHEV energy efficiency and range. Some vehicles, such as the Nissan Leaf, have switched to a heat-pump based heating, ventilation and air conditioning (HVAC) system in place of the more commonplace resistive heating used on PEVs. This method can be more efficient in energy management while satisfying cabin temperature needs. Some manufacturers have also implemented features such as temperature preconditioning of the cabin or battery while the vehicle is still plugged in and more targeted cabin heating systems employing items like heated steering wheels and heated seats to meet driver demands for comfort without expending as much energy to heat the entire cabin.

Direct current fast charging (DCFC) is increasing in availability and popularity, and can support charging at much higher rates than Level 2 (up to 150 kW in some cases, subject to the capability of the vehicle being charged). As range increases for PEVs, DCFC needs are growing fast and may affect usage of Level 2 electric vehicle supply equipment (EVSE); however, there is no universal standard for the DCFC connectors. Those connectors fall into three categories, Society of Automotive Engineers (SAE) International Combo Connector, CHAdeMO and Tesla superchargers.

II.B.2. Battery Pack Energy Capacity Increases
Battery pack capacities have increased in both BEVs and PHEVs, and will likely continue to do so based on manufacturer announcements. Several manufacturers have announced updates of existing BEVs that will include higher energy capacity battery packs. BEV and PHEV battery pack growth by model year is graphically represented in Figure 2 and Figure 3, respectively.

II.B.2.i. Examples of Current and Future BEVs with Increased Battery Pack Energy Capacity
- The 2011 Nissan Leaf was introduced with a 24kWh battery pack. For 2016 model year, Nissan replaced it with a 30kWh battery pack utilizing the same exterior dimensions in some of the trim level variants of the vehicle.
- The Chevrolet Spark EV currently has a battery pack with 19kWh of capacity. The Bolt EV, which is expected to replace the Spark EV, will have 60kWh of energy capacity when it goes on sale at the end of 2016.
- The Tesla Model S battery pack energy capacity options have steadily grown in size since the introduction of the vehicle in 2012. The smaller 60 kWh option grew to 70 kWh in 2015, and then a 75 kWh option was added for 2016. The largest of the initial battery pack offerings (the 85kWh version) also grew to 90kWh in 2015, and a 100kWh version

33 More information on DCFC and other infrastructure developments can be found in Appendix D.
was announced on August 23, 2016 which customers have already started taking deliveries of\textsuperscript{36}.
- The 2017 model year BMW i3 will see an increase in its battery pack size from 22 kWh (nominal) to 33 kWh (nominal)\textsuperscript{37}.
- Ford is expected to update the 2017 model year Focus BEV to be capable of at least a 100 mile label range, an upgrade from the 74 mile label range in the first generation product\textsuperscript{38}.
- An executive from the Volkswagen Group stated that its e-Golf will receive a battery pack update from 24.2 kWh to 35.8 kWh for the 2017 model year\textsuperscript{39}.

Figure 2 - BEV Battery Pack Growth by Model Year\textsuperscript{40}

\textit{II.B.2.ii. Examples of Current and Future PHEVs with Increased Battery Pack Energy Capacity}
- Chevrolet increased the size of the battery pack from 16 kWh in its first generation Volt to 18.4 kWh for the second generation of the vehicle\textsuperscript{41}.

\textsuperscript{40} For vehicles that have been certified by EPA. Incorrect information obtained from \url{http://www.fueleconomy.gov/feg/download.shtml} and supplemented by manufacturer
- The soon to be released Prius Prime has a battery pack with an energy capacity that is twice that of the older 2012 through 2015 model year Prius Plug-In Hybrid; 8.8kWh for the Prime and 4.4kWh for the older Prius Plug-In Hybrid. 42
- The 2017 model year Porsche Panamera 4 E-Hybrid will have a 14.1kWh battery pack43 up from 9.4kWh44 of the previous model year.

Figure 3 - PHEV Battery Pack Growth by Model Year

II.B.3. Vehicle All Electric Range Increases
Vehicle AER has been steadily increasing since the 2012 ACC rulemaking due to the aforementioned battery pack capacity increases, along with efficiency improvements made to drivetrains and associated components. The first generation Chevrolet Volt is one example of range improvements absent a battery change, as its AER increased from 35 miles to 38 miles without any reported change in nominal battery energy capacity. 45 The Nissan Leaf (BEV) was introduced for the 2011 model year with 73 miles label AER, which increased to 75 miles in 2013 model year, and to 84 for 2014 model year with no changes to the battery pack nominal energy capacity. For the 2016 model year, the Leaf with the 30kWh battery pack received another increase to 107 mile label AER.46 Tesla’s Model S has received updates since its introduction for the 2012 model year resulting in increases in range. Other than the increases in

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battery pack energy capacity, the Model S has seen range increases resulting from a dual motor AWD drivetrain option amongst other undisclosed efficiency updates. The single motor 90kWh Model S variant was certified by U.S. EPA with 263 miles of range, while the dual motor variant with the same (listed) battery pack capacity was certified at a range of 286 miles; an increase of roughly 8.7%.

The U.S. DOE developed a chart, shown in Figure 4 which compares the median range of ZEVs for 2016 model year. Since this figure was released, the maximum range number has changed slightly for the 'All-Electric Vehicles', because Tesla announced its Model S P100D package for 2016 model year that is certified at 315 miles label AER, a significant increase from other Model S vehicle packages.

Figure 4 - U.S. DOE Chart Comparing PEVs and Conventional Vehicle Ranges for 2016 Model Year

II.B.4. Increased Platform and AWD Capability

Industry is also expanding its PEV product offerings into vehicle size, type, and range segments previously unoccupied by any BEV or PHEV. As mentioned previously Volvo introduced its 14 mile EAER XC90 T8 7 passenger AWD PHEV SUV in 2016 model year. Volvo will begin offering that same AWD drivetrain in its S90 large luxury sedan for the 2017 model year with the

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wagon version, the V90, to follow in late 2017 calendar year.\textsuperscript{49,50} Mercedes-Benz introduced the GLE550e 4matic 12 mile label AER PHEV AWD SUV in 2016 model year. BMW brought a PHEV AWD SUV to market for the 2016MY with its X5 xDrive40e, but it is not currently eligible for transitional ZEV (TZEV) credits because the engine is not certified to the required Low Emission Vehicle (LEV) III super-low-emission vehicle (SULEV) 30 emission standard.\textsuperscript{51} In January 2017, Chrysler started delivering its 8-passenger Pacifica Hybrid, the first PHEV to be released in the mini-van segment.\textsuperscript{52} The Pacifica Hybrid has an EPA certified all-electric label range of 33 miles and qualifies as a TZEV.

Figure 5 shows the number of available and expected ZEV and PHEV (TZEV only) models through 2021. To begin, staff compiled an extensive list of all the currently available models and all of the future models that are expected to be released using publically available news articles. While staff looked at all articles that mentioned the release of potential future vehicles, ultimately this analysis focused on only those vehicles featured in articles that referenced information from an official OEM spokesperson or press release. This analysis was additionally informed in part by confidential meetings with OEMs. In developing this list, staff assumed that each vehicle model would be offered for at least six model years. The figure indicates that the product offerings are expected in broader market segments than currently available and that further increases in range are expected.

Staff was interested in determining model year of the vehicle, likely EPA size classification, and total AER for all future available vehicles. Where this information was not available, an effort was made to compare the vehicle to the current offerings in a manufacturer’s lineup or to current best-selling ZEV or PHEV models, typically by using release year referenced to mean model year. In cases where the article projected a release “late” in a calendar year, the next calendar year was chosen as model year. For example, the Chevrolet Bolt EV was released in late calendar year 2016 as a model year 2017 vehicle. Staff utilized the EPA Size Classification\textsuperscript{53} for vehicle size as this is information is available as a reference for all current EPA certified vehicles and is a publically available metric. In most cases the stated vehicle range was assumed to be the EPA label range.

\textsuperscript{51} PHEVs are classified in two categories: transitional zero-emission vehicles (TZEV), which must meet super ultra-low-emission vehicle (SULEV) exhaust emission standards, provide an extended warranty on emission control systems, and have zero evaporative emissions in order to qualify for credits under California’s ZEV regulation, and non-TZEV PHEVs, which do not qualify to earn credits.
The chart in Figure 5 shows all of the 2018 through 2021 model year vehicles staff expects to be available to consumers based on vehicle technology type (e.g. BEV, BEVx, TZEV, and FCEV), EPA size class, and projected vehicle range. The chart focuses on ZEVs and PHEVs that are TZEV certified and are therefore qualified to be used toward ZEV compliance. The chart is color coordinated based on vehicle technology. In cases where a given model will be available with more than one vehicle range, as is the case with two of the currently available BEV models, a vehicle icon will appear as slightly translucent. The icons are sized relative to the key located on the left side of the chart that indicates the number of models expected in that segment, range, and technology type. In order to reduce the size of the chart, the “Small Car” size classification includes all vehicles that are expected to be classified as a Two-Seater, Minicompact, Subcompact or Compact. Additionally, the Mid-Size Car classification includes several models that are expected to fall within the passenger car segment but publicly available details are insufficient to determine the EPA Size Class.
## 2018-2021 MY Unique ZEVs by Size, Type, and Range

**Figure 5**

### Electric Range (EPA Label)

<table>
<thead>
<tr>
<th>Electric Range (EPA Label)</th>
<th>10-20</th>
<th>20-30</th>
<th>30-40</th>
<th>40-100</th>
<th>100-150</th>
<th>150-200</th>
<th>200-250</th>
<th>250-300</th>
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<tr>
<td>Small Car*</td>
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</tr>
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<td></td>
<td></td>
<td></td>
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<td></td>
<td></td>
</tr>
</tbody>
</table>

### EPA Size Class

- **Pickup Truck**
- **Minivan**
- **Standard SUV**
- **Small SUV**
- **Large Car**
- **Mid-Size Car**
- **Small Car**

**KEY**

1. **= TZEV Model**
2. **= BEV Model**
3. **= BEVx Model**
4. **= FCEV Model**

*Small Car combines models designated: Two-Seater, Minicompact, Subcompact, and Compact
II.B.5. Current State of PEV Specific Technology

Understanding both battery and non-battery technology is critical to understanding the current status of PEVs and where the technology may be headed. Key technologies include battery cells and packs, battery management systems, drive motors, inverters, on-board chargers (OBC), direct current to direct current (DC-DC) converters, PEV specific HVAC components, and high voltage wiring and interconnects. While batteries account for the greatest portion of vehicle cost, non-battery components are essential to the operation of the vehicles.

II.B.5.i. PHEV and BEV Cross-Over

In trying to understand economies of scale and applicability of advancements in individual technologies, it is important to note where PHEVs and BEVs use the same and/or different components. While PHEV and BEV powertrains use similar components, layouts can be quite different. BEV electric machines tend to have a single speed gear reduction gear box centralized between a vehicle’s axles. PHEV electric machines usually reside somewhere in the powertrain system, generally with the ICE and its transmission. These basic differences in layout can have an effect on the types and designs of motors, transaxles, battery cells, and power electronics that are used in each technology. Additionally, PHEVs typically have lower power OBC to support lower energy capacity battery packs.

II.B.5.ii. Powertrain Layout and Transaxle Configurations

Many of the differences between BEVs and PHEVs exist in their respective transaxle architecture. All the BEVs on the market use single speed gear reduction transmissions to transmit the electric machine power to the wheels. The designs tend to be relatively simple and compact compared to PHEVs or even more conventional powertrain technologies. BEVs, at the moment, locate the combined electric motor and gearbox at either the front or rear axle. In the case of the dual-motor Tesla Model S, it uses an electric motor and gearbox combination at both the front and rear axles.

PHEVs, in contrast, come in a variety of different formats and configurations. In the case of the systems from Ford, General Motors, Toyota, and Chrysler, they have two electric motors that are packaged in a transaxle assembly designed for a front-wheel drive vehicle (FWD). Other systems being utilized include electric motors located between the engine and transmission (P1 or P2 location in Figure 6), at the axle (P4), or a combination of these locations. A simplified diagram of the typical locations of electric motors in HEVs can be seen in Figure 6.
Figure 6 - Electric Motor Positions in HEVs\textsuperscript{54}

Shown in Figure 7\textsuperscript{55} and Figure 8\textsuperscript{56} are the Chevrolet Bolt EV powertrain and the second generation Chevrolet Volt electric powertrain to highlight some of the differences. The Bolt EV, like every currently available BEV, uses an electric motor attached to a single speed gearbox. The Volt, has two electric motors coupled with two planetary gear sets and two clutches in a unit that attaches to the vehicle’s ICE. There is additional complexity in the Volt powertrain compared to that of the Bolt EV, both from a mechanical perspective and a controls perspective.

\textbf{Figure 8 - Chevrolet Bolt EV Electric Powertrain} \hspace{0.2cm} \textbf{Figure 7 - Chevrolet Volt (Gen 2) Electric Powertrain}


Two other examples of BEV and PHEV powertrain architecture and layout include the Tesla Model S and Volvo XC90 T8, shown in Figure 9 and Figure 10, respectively. The Tesla Model S rear drive unit includes an electric motor coupled to a single speed gear reduction transaxle packaged with a drive motor inverter assembly. The Volvo XC90 T8 has a FWD 8-speed transmission mated to the gasoline engine and equipped with a crank integrated starter generator (CISG), and an electric rear drive unit in the P4 position that couples a motor, single speed gearbox, and power and control electronics in a single package.

Figure 9 - Tesla Model S Rear Drive Unit Assembly

Drive unit is located between the rear wheels

II.B.5.iii. Electric Machines
In most cases, both BEVs and PHEVs use permanent magnet electric machines. Induction based electric machines are used in some BEVs, most notably current Tesla models, but rarely in other current installations. The one exception is the upcoming Cadillac CT6 PHEV. It will have one induction electric machine and one permanent magnet machine in its rear-wheel drive (RWD) electric vehicle transmission (EVT).\textsuperscript{59}

While most electric machines in BEVs and PHEVs are of the permanent magnet variety, they generally differ in design for many reasons. BEV electric machines are responsible for providing all of the motive power for the vehicle. PHEV systems can be split into two different groups: blended and non-blended. Blended PHEVs do not have an electric drive powertrain that is capable of meeting all of the motive power requirements of the vehicle on electric power only. Non-blended PHEVs, like the Chevrolet Volt, are capable of driving on electric power over the entire range of driving conditions. Non-blended PHEVs require electric machine(s) that are capable of delivering power levels roughly equal to that of the ICE.

With current power densities of electric machines and the size of single gear reduction transaxles, BEV electric machines can be relatively powerful. PHEVs are generally more limited by the space constraints available in a vehicle that also has a gasoline engine and conventional transmission. This leads to differences in sizing and power densities of the motors. Additionally, cooling electric machines in a PHEV when they are packaged in a transaxle that is connected to an ICE can be more complicated due to the heat produced by the ICE.


II.B.5.iv. Battery cells
The battery cells for PHEVs and BEVs also require different things. Due to the power requirements compared to the battery pack size, BEVs require high specific energy from a battery while PHEVs require a balance of energy and power. In almost every case, PHEVs use different battery cells than BEVs. Not only are the physical cell designs and energy capacities different, the variation of lithium-ion chemistry for each vehicle technology is different. Only two manufacturers have used the same battery on their BEV and PHEV: Mitsubishi Outlander PHEV (not available in the U.S.) and i-MiEV, and Honda Accord PHEV and Fit EV. Some OEMs have said they are planning to use the same cell in the future if battery manufacturers are able to meet specific targets; however such solutions appear to be less common as they represent additional compromise on the optimization of the cell to one or both of the applications.

II.B.5.v. Battery Packs
The different energy requirements for BEVs and PHEVs with cost and packaging limitations dictate different battery pack configurations, physical dimensions, and energy contents for the two technologies. There are some common components, like the battery management system, safety disconnects, power wiring, and potentially thermal management systems that could be shared between the two types of vehicles. However, the battery packs between the two vehicle technologies will be different in many ways including the battery cells and the count and configuration of the battery cells due to the electric topology.

II.B.5.vi. Inverters
The power requirements for PHEVs – particularly blended PHEVs - and BEVs will require different drive motor inverters due to the differences in electric power capability of the drivetrains. Designs may be able to be scaled up in power, but the inverters will likely not be the same component.

II.B.5.vii. On-Board Chargers
PHEVs and BEVs have different battery pack energy capacities and very often do not use OBCs with the same power level. Similar to inverters, the device may be able to be scaled up in power, but it will not be the same part. Potentially, smaller OBCs could be operated in parallel to provide more power, as Tesla has done in the past. This could allow an identical lower power level PHEV OBC component to be used in a BEV to provide the power level needed but necessarily results in a less optimized solution.

Since 2010, manufacturers have coalesced around lithium-ion batteries in virtually every ZEV application with a few notable exceptions. The Toyota Mirai currently uses a nickel metal hydride (NiMH) battery pack very similar to Toyota’s Camry Hybrid. However, the fourth generation Prius now offers lithium ion batteries in all but the least expensive trim variant. The

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Prius has generally led the way in terms of hybrid technology development of Toyota’s hybrid systems. Toyota engineers have more recently indicated that its lithium-ion technology has reached cost equivalency with its NiMH technology, but with more energy density allowing them to pack more energy into a battery pack at a similar cost.\(^\text{62}\)

### II.B.6.i. Lithium-ion Battery Overview
Lithium-ion batteries are not manufactured in one format. There are currently four different physical battery cell formats that lithium-ion batteries are packaged in; cylindrical, prismatic, pouch, and button formats. For the purposes of this assessment, button cells will not be included, because they are not used in any implementation as an energy storage mechanism for PEV drivetrains. A diagram of a cylindrical cell is shown in Figure 11. Typically, cylindrical cells come in the ‘18650’ format. ‘18650’ cells are an industry adopted cell standard that has the nominal dimensions of 18mm in diameter and 65.0mm in length (for reference, a conventional AA size alkaline battery is typically 14mm in diameter by 50mm in length). Consumer electronics, particularly laptops and battery operated power tools, have made the ‘18650’ battery cell the most widely produced lithium-ion battery format. The demand has driven development, optimization, and volume cost reductions for those cells, which has helped the ‘18650’ cells in Tesla’s Model S and Model X vehicles achieve some of the highest energy density and specific energy measurements on the market.

![Figure 11 - Cylindrical lithium-ion battery](image)

Prismatic battery cells have been designated as such due to their rectangular prismatic shape as see in Figure 12. Prismatic cells have been used in cell phones and some low profile laptops, but also have seen implementations in HEVs, PHEVs, and BEVs. The most notable example is the Toyota Prius, which uses prismatic cells in both NiMH and Lithium-ion variants. Other vehicles that also use prismatic lithium-ion battery cells include the Fiat 500e and the

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\(^{62}\) Tajitsu, 2016, Naomi Tajitsu, Norihiko Shirouzu. Reuters Technology News. “Warming to lithium-ion, Toyota charges up its battery options” 30 October 2016

discontinued Honda Fit EV. The prismatic container is designed in such a way that it manages the natural swelling of the components of the cell during charging and discharging. Pressure build-up due to gassing of the components that may occur during cycling of the cell is usually managed through a vent of some kind. While prismatic cells are generally considered to be the safest cell containment design, they give up both specific energy capacity and energy density to cylindrical and pouch cells.

**Figure 12 - Cross Section of a Prismatic Cell**

Pouch cells can be described just like their name indicates. The contents of the cell are sealed within a foil pouch. The pouch is designed to handle the swelling of the components and outgassing, but its external dimensions will change in doing so. This creates additional challenges for packaging considerations when designing battery modules and packs. Nissan Leafs with the 24kWh battery pack use pouch cells packaged as modules that contain four pouch cells. An image of the module is shown in Figure 13. General Motors chose a slightly different design path with its Chevrolet Volt. LG Chem designed and manufactured pouch cells that are more exposed within the pack than the Leaf’s enclosed modules. But, that design allows for higher packing density and can better accommodate the liquid cooling design General Motors implemented in the Volt’s battery pack. An example of an exposed pouch cell that is used in the Kia Soul EV can be seen in Figure 14.

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Lithium-ion batteries consist of the following main components: A cathode, an anode, current collectors, a separator, electrolyte, and case of some kind to contain those components. Figure 15 shows how those components comprise a lithium-ion battery cell. It is important to highlight the individual components, because increases in energy or power density often are not from equal improvements in each component. Improvements from technology advancements most often occur within an individual component and result in corresponding changes made to the other components to appropriately handle that change. The equation to determine the theoretical specific energy of a battery can be seen in Equation 1 where $C_A$ is the theoretical capacity of the anode, $C_C$ is the theoretical capacity of the cathode, and $Q_M$ is the specific mass of all the other components. The same equation can be used to calculate energy density if the variables are input in terms of mAh cm$^{-3}$ instead of mAh g$^{-1}$.

**Figure 15 - Idealized Lithium Ion Battery**

![Lithium Ion Battery Diagram](image)

**Equation 1 - Total Cell Gravimetric Energy Density**

\[
\text{Total cell (mAh g}^{-1}) = \frac{1}{(1/C_A) + (1/C_c) + (1/Q_M)}
\]

\[
= \frac{C_A C_c Q_M}{C_A Q_M + C_c Q_M + C_A C_c}
\]

Equation 1 highlights the need for advancements in all three areas in order for energy density and specific energy to increase at a rate similar to increases in both energy capacity metrics of the individual components. If one component sees several large increases and the other two portions do not, those large increases become less and less effective at increasing the total cell energy density or the specific energy of the battery cell.

Lithium ion encompasses several different technologies and variations that use lithium ions as the transport mechanism for electrons. Figure 15 also shows how a lithium-ion battery works. Ions shuttle between the cathode and anode during charging and discharging. Upon discharge, the oxidation of the anode occurs (loss of electrons), and the cathode is reduced (gains electrons). The reverse of those phenomena take place during charging.

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II.B.6.ii. Current State of Cathodes and Anodes

Lithium ion battery chemistries with nominal voltages of 3.5V or more are used in the majority of the ZEV products. Cathode variations that are currently being used in the majority of BEV and PHEV applications at those nominal voltages include manganese oxide spinel (LMO), nickel cobalt aluminum (NCA), nickel manganese cobalt (NMC), and NMC-LMO blends. It should be noted that the different cathode chemistries themselves have many variations based on the relative amounts of individual elements within each variations.

Nissan and its battery production company, AESC, chose LMO technology for the battery cells in its Leaf.\(^69\) AESC has made changes to the battery chemistry since the vehicle’s introductory 2011 model year, but there have been no reported significant changes in cathode formulation that would change energy density through the 2015 model year. For 2016 model year, Nissan announced a larger, 30kWh battery pack that includes changes to the battery chemistry for increased cell energy density.\(^70\) The Chevrolet Volt in its introductory model year used a LMO dominant/NMC cathode blend.\(^71\) The second generation Volt (2016 model year) kept with a NMC-LMO blend, but had changes made to its cathode formulation, including increased NMC content and a reduction in LMO material.\(^72\)

Industry input to the update of the ANL BatPaC model used in the 2016 TAR has shown that the industry is moving towards higher nickel content NMC for high energy capacity cells.\(^73\) The model was updated to replace the NMC441 cathode option with NMC622 as it is more representative of where the market is going. The 2017 model year Chevrolet Bolt EV will have battery cells that General Motors refers to as 'Nickel-rich' lithium further confirming that manufacturers are moving towards higher nickel content NMC cell.\(^74\) Confidential business information gathered during meetings with OEMs on ZEV technology also confirmed that the cathode material replacement was appropriate for BatPaC, particularly for the near term. Additionally, the model was updated to include a user selectable NMC-LMO blend ratio which better represents the options available to OEMs. Battery cells with varying NMC-LMO blend cathodes are being used in many PHEV and HEV applications in vehicles like the future Chevrolet Volt\(^75\) and Ford Energi products.\(^76\)

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\(^{69}\) AESC, 2016.


For most applications, with the exception of LTO based battery cells that require a specially coated graphite anode, conventional graphite anodes are the industry standard for cost, specific energy, and energy density reasons. However, graphite anodes in most lithium ion battery applications are getting very close to their theoretical energy capacity of 372 mAh/g. Some applications are already reporting values close to 350 mAh/g. Changes in anode chemistry will likely be required to gain any more energy density and specific energy from the anode. One OEM has publically stated that they are already introducing silicon into the anode of their battery cells to improve energy density. Elon Musk, during a conference call, stated “…We’re shifting the cell chemistry for the upgraded pack to partially use silicon in the anode. This is just sort of a baby step in the direction of using silicon in the anode. We’re still primarily using synthetic graphite, but over time we’ll be using increasing amounts of silicon in the anode.”

II.B.6.iii. Current State of Battery Pack Configurations
Manufacturers must decide on battery pack topologies, specifically in terms of the number of cells connected in parallel and series. This can be dependent upon a number of factors. Understanding what manufacturers chose to do is critical to knowing what the power demands of the drivetrain will place on individual battery cells, and the voltage range that the battery pack will operate within. Equipment that will operate on the high voltage bus must interface with that voltage, which will have an effect on the cost of that equipment. Increasing the voltage on packs could require voltage isolation specifications of existing equipment to be upgraded to handle the higher voltage. Current standards for CHAdeMO and SAE J1772 CCS DCFC equipment limits operating voltages to 500V or less. Any battery pack with an operating voltage higher than that would not be able to use any existing CHAdeMO or SAE CCS fast charging infrastructure without additional equipment on-board the vehicle. To date, many manufacturers have chosen to design battery packs for their PEVs with nominal pack voltages ranging between 300 and 400V.

Battery packs from several of the OEMs are currently configured with 96 cells in series. Known vehicles using that configuration include the Nissan Leaf, Chevrolet Volt and Spark EV, Kia Soul EV, BMW i3, at least one version of the Tesla Model S, and the forthcoming Bolt EV and Chrysler Pacifica Hybrid. The number of parallel strings of cells range from one to five excluding the battery packs from Tesla which use large quantities of ‘18650’ cells in parallel to realize the larger pack capacities. Other PHEVs outside of the Chevrolet Volt and soon to be

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82 Liu, 2016.
released Chrysler Pacifica Hybrid\textsuperscript{84} are using fewer cells in series for their battery packs. The Ford C-Max and Fusion Energi packs both utilize battery packs with 84 cells in series. The Ford Focus Electric and the BMW i3 are both receiving larger battery packs for MY17. The BMW i3 battery pack configuration is receiving new, higher capacity cells, but the configuration of the pack will stay the same.


Battery thermal management systems are critical for keeping a battery within its operating temperature range to ensure temperature based battery cell degradation and performance are minimized. The type of system that is used on a vehicle has implications on cost and performance. The efficiency of the system has additional effects on the power required to run such a system, which affects how much additional battery capacity must be allocated just for thermal management. Additionally, thermal management system performance can play a role in how fast a vehicle’s battery can be charged, because many lithium-ion chemistries can generate relatively large amounts of heat during high charge load events.

There are two basic types of battery pack thermal management currently in use on vehicles. The first is the passive variety which the Nissan Leaf employs. Nissan chose not to integrate any sort of active thermal management system on the Leaf, and relies on airflow underneath the battery pack, use by the driver, and ambient temperatures to control battery cell temperature.

The second is active systems that can utilize air, liquid, or refrigerant mediums for cooling and heating. Currently available vehicles and the type of battery thermal management each employs are shown in Table 3. Most active air thermal management systems operate in a similar manner; they use a fan to push or pull cabin air through the battery pack. On the other hand, liquid based cooling systems can vary in design. Some systems can function in multiple ways by using different liquid transfer circuits to heat or cool the battery in different ways. Both generations of the Chevrolet Volt use a liquid cooling system that incorporate metal plates between cells which have an ethylene glycol solution that flows through them. The Chrysler Pacifica PHEV that is expected to be released at the end of 2016 uses various devices in the coolant pathway: “To keep the pouch cells at a steady operating temperature, batteries can be heated with glycol/water via a heat exchanger from the engine’s cooling system, or a 7-kW heater located in the engine thermal system also can warm the batteries. For cooling, a refrigerant-based a/c chiller system is used. “These heating and cooling techniques mean the battery pack has full-function capability in all climates,” said Clark.\textsuperscript{85}

Table 3 lists the BEV and PHEV (only those that are TZEV certified) models currently on the market, or that will be in the near future, and their respective battery thermal management system type. The majority of models available on the market currently use active liquid type systems. Sustained high temperature is one of the primary drivers of degradation in lithium-ion battery cells, and it seems that many manufacturers are choosing to use liquid thermal management systems to mitigate those effects amongst many other possible reasons. \(^{88}\)

<table>
<thead>
<tr>
<th>Manufacturer</th>
<th>Model</th>
<th>Battery Thermal Management Type</th>
</tr>
</thead>
<tbody>
<tr>
<td>Audi</td>
<td>A3 e-Tron</td>
<td>Liquid</td>
</tr>
<tr>
<td>BMW</td>
<td>i3 and i3 REX</td>
<td>Refrigerant</td>
</tr>
<tr>
<td>Cadillac</td>
<td>ELR</td>
<td>Liquid</td>
</tr>
<tr>
<td>Chevrolet</td>
<td>Volt</td>
<td>Liquid</td>
</tr>
<tr>
<td>Chevrolet</td>
<td>Spark EV</td>
<td>Liquid</td>
</tr>
<tr>
<td>Chevrolet</td>
<td>Bolt EV</td>
<td>Liquid</td>
</tr>
<tr>
<td>Chrysler</td>
<td>Pacifica Hybrid</td>
<td>Liquid</td>
</tr>
<tr>
<td>Fiat</td>
<td>500e</td>
<td>Liquid</td>
</tr>
<tr>
<td>Ford</td>
<td>Focus Electric</td>
<td>Liquid</td>
</tr>
<tr>
<td>Ford</td>
<td>C-Max and Fusion Energi</td>
<td>Air</td>
</tr>
<tr>
<td>Hyundai</td>
<td>Sonata Plug-In Hybrid</td>
<td>Air</td>
</tr>
<tr>
<td>Kia</td>
<td>Soul EV</td>
<td>Air</td>
</tr>
<tr>
<td>Mercedes-Benz</td>
<td>B-Class Electric Drive</td>
<td>Liquid</td>
</tr>
<tr>
<td>Mercedes-Benz</td>
<td>S550e</td>
<td>Liquid</td>
</tr>
<tr>
<td>Mitsubishi</td>
<td>i-Miev</td>
<td>Air</td>
</tr>
<tr>
<td>Nissan</td>
<td>Leaf</td>
<td>Passive</td>
</tr>
<tr>
<td>Smart</td>
<td>Fortwo electric drive</td>
<td>Liquid</td>
</tr>
<tr>
<td>Tesla</td>
<td>Model S and Model X</td>
<td>Liquid</td>
</tr>
<tr>
<td>Toyota</td>
<td>Prius Prime</td>
<td>Air</td>
</tr>
<tr>
<td>Volvo</td>
<td>XC90 T8</td>
<td>Liquid</td>
</tr>
<tr>
<td>VW</td>
<td>e-Golf</td>
<td>Air</td>
</tr>
</tbody>
</table>

\(^{87}\) INL, 2016.  
II.B.7. Expected Developments in Energy Storage Technology

Information learned through meetings with OEMs on their upcoming ZEV technology showed that part of the pathway to higher energy density cells will include higher nickel content cells with graphite anodes, and better management of thermal and SOC dependent aging affects. Some OEMs are working with battery manufacturers to implement cells with some silicon added to the graphite anode. There is also potential to begin to see some additional non-conventional lithium-ion based cells in consumer products and PEVs in the near term. OEMs are taking the learnings from the introduction of their first generation battery packs to greatly improve their next generation products.

II.B.7.i. Battery Cell Expected Developments

As was stated previously, the replacement of NMC441 cathodes with NMC622 material in ANL’s BatPAC model as used for the 2016 TAR is more aligned with where battery manufacturers are headed. Several OEMs confirmed that the change was appropriate during meetings with ARB, and may be implemented in near term vehicles. In a presentation at the 2016 Advanced Clean Cars Symposium, Sue Babinec, a senior commercialization adviser for the U.S. DOE Advanced Research Projects Agency – Energy (ARPA-E) gave a presentation which displayed the Chinese EV Market Roadmap from Yano Research Institute Ltd. for battery technology. For the year 2020, the roadmap identified NCA and NMC811 cathodes with a composite silicon/graphite anode and a high voltage capable electrolyte (=>4.35V).89

Tesla appears to be staying with Panasonic’s NCA technology and cylindrical cells. Both Tesla’s Chief Technology Officer (CTO) J.B. Straubel and Chief Executive Officer (CEO), Elon Musk have stated that the Gigafactory in Nevada will produce cells in the ‘2170’ format (21mm in diameter and 70.0mm long) for Tesla’s upcoming Model 3 BEV.90 Total Battery Consulting has based its Tesla battery analysis on the larger format and projects a 4.9Ah cell to be used in the Model 3 when it comes to market.91 This is an increase from the 3.4Ah ‘18650’ format cells that are currently used in the Model S and Model X.

A near term potential improvement in batteries may come via silicon. Pure silicon anodes have tremendous potential in terms of theoretical specific energy. The fully lithiated phase of silicon at room temperature shows a maximum capacity of 3579 mAh/g compared to the 372 mAh/g for graphite. The lithiated silicon undergoes massive volume expansion of up to 280%.92 Such a volume change would quickly cause mechanical damage to the anode’s solid electrolyte interphase (SEI) and to its connection with current collector. Despite the volume expansion

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issue, battery manufacturers are finding ways to integrate silicon into graphite anodes in small but increasing amounts to increase energy density.

As noted earlier, Tesla has reportedly started using battery cells that have some silicon in the anode. During meetings with other manufacturers, some stated that adding silicon to the graphite in the anode provided a pathway to increasing energy density, but it was unclear whether those cells would be in products before 2021.

More energy dense battery cells are also becoming available as a result of many undisclosed changes to cell chemistry and makeup. The 2017 model year BMW i3 and i3 REX are receiving a more energy dense battery pack made possible by new Samsung SDI cells that increased from 60Ah to 94Ah in energy resulting in longer range vehicles for customers. The physical dimensions of the battery remain the same which allows for much simpler implementation of the new battery in the same vehicle design. The second generation Chevrolet Volt is also using higher energy content cells in its battery pack compared to the first generation vehicle. The individual cells grew from 15.5Ah to 26Ah which allowed General Motors to cut down on the total number of cells by one third, and still grow the total battery pack energy capacity from 16.5kWh to 18.4kWh. The additional energy capacity is one the primary reasons the new Volt’s AER increase. With no change in the number of cells or electrical topology, the 2016 model year Nissan Leaf pack increase relates directly to the same percentage increase in cell size; a 25% increase in battery cell capacity which translates to an increase from 32.5Ah on the 24kWh pack to more than 40.5Ah in the new 30kWh pack. During meetings with OEMs about their forthcoming ZEV technology, some indicated that they would be using increased capacity cells as they became available with their PHEV products.

II.B.7.ii. Expected Battery Pack Developments

OEMs are moving towards higher cell count modules to reduce material usage and improve packing efficiency. The 2016 model year Nissan Leaf’s 30kWh battery pack received a few internal design changes, one of which increased the number of cells per module from four to eight. Nissan showed a prototype 60kWh battery pack for the Leaf at the 2015 Tokyo Auto show. The pack was said to have 288 cells with what looked like 16 discrete modules. If the pack is any indication of what a 60kWh Leaf pack may look like then the number of cells per module for the new pack will likely increase beyond the eight per module in the current 30kWh Leaf pack. The higher number of cells in a module can potentially reduce costs and as seen in the Leaf, help to increase the energy density of the battery pack.

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93 BMW, 2016a.
97 Nissan, 2016.
The Chevrolet Bolt EV and Volt are two other examples of the trend to increase the number of cells per module. The Bolt EV has two different module sizes. One with three parallel cells arranged with ten groups in series for a total of 30 cells, and another with three parallel cells with eight groups in series for a total of 24 cells in the module. The first generation Volt had nine modules with either 18 or 36 cells per module. The second generation Volt has fewer modules, but its smallest module size is up to 24 cells, and the larger module down to 32 cells.

Chrysler had its Pacific Hybrid battery pack on display at the 2016 Advanced Automotive Battery Conference in Detroit, Mi. The pack looked to have 6 distinct similar modules and claimed to have a configuration of 96 cells in series.

II.B.7.ii.1. Higher Voltage Packs

Porsche displayed its Mission E concept BEV at the International Auto Show in Frankfurt, Germany on September 15th of last year, 2015. The concept was said to have an 800-volt battery system that Porsche claimed “offers multiple advantages: shorter charging times and lower weight, because lighter, smaller gauge copper cables are sufficient for energy transport.” The Mission E was then greenlighted for production by the end of the decade on December of 2015 with Porsche specifically calling out the 800-Volt energy storage system again on the vehicle. At the 2016 Advanced Automotive Battery Conference (AABC), Porsche development engineer, Dr. Christian Jung, gave a presentation entitled “The Future of EVs and Fast Charging at 800V”. The presentation showed that Porsche is moving along with developing the 800-Volt hardware – most of which Porsche stated was already capable of the higher voltage - to support a battery pack that operates around that voltage. Their 800-Volt pack was stated to have lost 40kg of mass from a 400-Volt version due to reductions in copper and cabling. The presentation also made the case that higher voltage technology is the enabling piece for DCFC at rates over 200kW. The production version of the Porsche Mission E may be the introduction of a technology that will allow for DCFC up to 350kW and the faster battery charge times that come with it.

II.B.7.ii.2. Battery Pack Thermal Management

OEMs are also redesigning battery thermal management systems and cell packaging. Rather than use the slim liquid cooling plates that sit between cells, the new Bolt EV battery pack uses what General Motors calls ‘Conductive Solid Fins’. The conductive fins are connected to a liquid thermal management system where the heating, cooling, and pumping mechanisms reside outside of the battery pack. While the conductive fins may be slightly less effective at removing or adding heat to the individual cells, the design takes advantage of the greater thermal capacitance of the Chevy Bolt EV’s entire battery pack compared to that from the Chevy Spark

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EV. The Chevy Bolt EV’s battery pack thermal management methodology allows the entire battery pack to be simpler and easier to assemble than it would have been otherwise.\textsuperscript{102,103}

Another example of modifications to thermal management systems comes from Tesla which further indicates an area that other OEMs may be concentrating on for ZEV and PHEV models in the near term. On August 23, 2016, Tesla announced the introduction of the P100D version of its Model S. The new battery pack has been stated to have redesigned cell modules to increase the packing density which includes changes to the thermal management system. The previous highest energy pack from Tesla was its 90kWh version. Elon Musk, in reference to the design changes that enabled the increase in total pack energy stated “The cell is the same, but the module and pack architecture is changed significantly in order to achieve adequate cooling of the cells in a more energy dense pack and to make sure we don’t have cell to cell combustion propagation.”\textsuperscript{104} Those improvements in thermal management can help batteries to last longer, work more consistently and efficiently, and improve vehicle safety. As a result of the cell and pack level technological developments, manufacturers are increasing the density of their battery packs on both a volume and mass basis.

The second generation Chevrolet Volt battery increased its volumetric energy density from 118Wh/l to 119Wh/l and its mass based energy density from 87Wh/kg to 101Wh/kg.\textsuperscript{105} The Chevrolet Bolt EV also realized large improvements over the Spark EV. The Bolt EV’s battery pack has a volumetric energy density of 210 Wh/L versus 137Wh/L for the Spark EV, and mass based energy density of 138Wh/kg versus 88Wh/kg for the Spark EV.\textsuperscript{106,107,108} The Chrysler Pacifica Hybrid pack shown at AABC 2016 was stated to have a volumetric energy density of 113Wh/L and 100Wh/kg which is roughly the same as the second generation Volt pack. These recent developments coupled with the other aforementioned advancements in this section likely indicate the direction and scale of improvements that other OEMs will take with their future near-term products.

II.B.8. Potential Long-Term Developments in Energy Storage Technology

Battery technology developments over the longer term are much less certain. There is an enormous amount of ongoing research to develop a better battery. While there are lots of promising advancements happening in research labs around the world every day, there is unlikely to be a ‘silver bullet’ that will suddenly meet the U.S. DOE EV Everywhere goals for

\textsuperscript{103} Smith, 2016.
\textsuperscript{105} GM, 2016c.
\textsuperscript{106} Liu, 2016.
energy storage technology. Several OEMs indicated to staff that the pathway towards a better battery will include nickel-rich NMC cathodes (like NMC622 or NMC811) coupled with graphite anodes that contain increasing amounts of silicon. That pathway will likely be combined with improvements in other internal cell components like binders and electrolyte formulations to enable higher energy and power densities.

The U.S. DOE Vehicle Technology Office (DOE VTO) Advanced Battery Research and Demonstration Program is focusing funding for the 2016-2020 time period on silicon anode technology with high-voltage cathodes to achieve those 2022 DOE goals. The DOE believes that there is a clear pathway towards meeting the 2022 goals which includes higher voltages cathodes, intermetallic anodes, and expanded work on lower cost materials, electrode, and cell manufacturing. For beyond 2022, the DOE VTO will continue to focus on Li-metal and solid state battery research.\textsuperscript{109} A few other potential longer term technologies include lithium sulfur (Li-S) based chemistries, lithium-air (LiO\textsubscript{2}), redox flow, and multivalent intercalation chemistries.

Solid state batteries, which are generally lithium-ion based, replace the electrolyte and separator in a battery cell with a solid material. That material is usually a type of polymer or ceramic. Solid state cells potentially can work with a variety of different anodes and cathodes and have several potential technical advantages. An example of an idealized conventional battery and all-solid state battery can be seen in Figure 16. Current lithium-ion battery cells use electrolytes that are flammable under extreme conditions. By replacing that electrolyte with a solid material that is not flammable, the cell can then withstand extreme abuse. Seeo, a battery startup that was purchased by Robert Bosch General MotorsB (Bosch) in August of 2015 displayed some of the abuse testing on their solid state Li-metal - LFP cells at the 2016 Advanced Automotive Battery Conference (AABC) in Detroit, Michigan. The cells exhibited no smoke or flames under crush, penetration, short circuit, thermal shock, over-discharge, or overcharge testing. The cells also showed thermal stability up to 180 degrees Celsius.\textsuperscript{110}

Another potential advantage of a solid state design is the possibility for bi-polar stacking. Instead of having separate, discrete cells that must be connected in series via bus bars, the cells themselves are layered on top of each other with the cathode of one cell set atop the anode of another cell. Bipolar designs have the potential to minimize IR losses between adjacent cells in a bipolar cell stack. There is a large amount of potential to minimize packaging materials and total volume with a bipolar solid state cell stack. And, with the potential high levels of safety inherent to the solid state cells, they could be packaged in crush zones on a vehicle. The packaging opportunities could give manufacturers more flexibility with vehicle designs to increase passenger and cargo utility.

Solid state technologies are not without significant barriers. One of those includes the much greater resistance to ion mobility of the solid state electrolyte. As a result, current solid state cells exhibit very low specific power and power density relative to conventional lithium-ion batteries. Often times, a solid-state battery requires a higher operating temperature to be able to charge or discharge at any reasonable rate, which makes it impractical for electrified vehicle applications where a battery heater would have to run constantly.

Several companies are currently developing solid state battery cell technology targeting commercialization as soon as possible. Some of those companies have been purchased by larger corporations. Sakti3, a startup spun out of the University of Michigan was acquired by Dyson in October of 2015 for $90 million. As was mentioned earlier, Seeo was purchased by Bosch last year. There are many other companies working on solid state technology, some of which include Solid Power, 24-M, Ilika, PolyPlus, and Toyota.

At the 2016 AABC, Dr. Juergen Gross of Robert Bosch General MotorsbH (Bosch) gave a presentation entitled “Drivers and Technologies for Li-Metal Solid-State Batteries.” The presentation, in part, covered Seeo’s battery technology that Bosch now owns. Cycle life testing

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of the Li metal – LFP cells showed impressive results. However, no details were given on the specific energy and power, or the energy and power densities. But, according to the presentation, Bosch believes that they will have a solid state cell ready for series production after 2020 to meet the needs of the market.113

Yuki Kato of Toyota Motor Europe NV/SA also presented at the 2016 AABC on Toyota's development of its solid state technology. Yuki Kato and other team members recently published their work in Nature Energy entitled "High-power all-solid-state batteries using sulfide superionic conductors".114 The test cell displayed very little internal resistance, especially at 100 °C, and the ability to operate at extremely high current densities. The paper claims stable cycling of the cell at up to 18C. In the presentation given at the AABC, charts displayed discharge curves with current densities well beyond that. Toyota appears to have made major headway towards surpassing one of the major barriers for solid-state batteries.

24M has designed what the company calls a semi-solid lithium-ion battery. The company set out to simplify the internal structure of a lithium-ion battery to make is faster and cheaper to produce. The semisolid electrodes require no drying and the company claims it takes one-fifth of the time for conventional lithium-ion to go from components to cell. 24M's technology has the potential to significantly reduce the cost of producing battery cells.

As part of ARPA-E's BEEST program, 24M received funding to develop their technology. ARPA-E's Project Impact Sheet identified the cell as having two thick (450µm) electrodes; the anode is graphite and the cathode is LFP. The project, which lasted from September 2010 to February 2014, concluded "with the successful delivery of a 17Wh cell that... cycled at a high efficiency (more than 85% roundtrip), and showed reasonable cycle life (more than 1000 cycles) with limited capacity loss. 24M has designed the cell to operate at a continuous charge/discharge rate of C/4, and have also shown good performance in grid duty cycles with sustained power pulses of up to 2C."115 24M was awarded another round of funding by the U.S. DOE in October 2014 to further develop its manufacturing processes. The project concluded with 24M delivering cells on a process that operated with a 96% yield beating its target of 85%.

24M entered into a MoU with NEC Energy Solutions, Inc. (NEC ES) in October of 2015 to supply the semisolid lithium-ion cells for the NEC ES integrated storage systems. In October of this year, 2016, 24M delivered an initial batch of production-sized cells to NEC ES for testing and validation. If things continue as expected, 24M will begin delivering production cells to NEC ES sometime next year (2017)116. 24M has also received more funding to further develop its

113 Gross, 2016.
technology. USABC with the U.S. DOE awarded 24M with $7 million over 36 months in June of this year (2016) to demonstrate that its approach to cell design and manufacturing can meet the USABC 2020 battery targets for EV applications.\textsuperscript{117}

Lithium metal anodes are another area that has significant potential to improve batteries. Unfortunately, lithium metal anodes like to form dendrites (tree-like structures made of lithium metal in this case) that quickly reduce the battery’s ability to store energy. Solid state batteries potentially could help with dendrite formation by mechanically restricting the ability of the dendrite to form. The PolyPlus Battery Company in a partnership with SCHOTT North America was awarded grant funding from ARPA-E to “develop thin electrodes made of lithium foil protected by a flexible Li-ion conductive glass separator sheet... The approach is based on PolyPlus’ proprietary Li-metal/glass electrode technology, and takes full advantage of commercially scalable glass sheet manufacturing techniques to produce a highly conductive separator that prevents the formation and propagation of dendrites in a lithium metal battery cell.”\textsuperscript{118} Finding ways to restrict dendrite growth in lithium metal anodes is one the barriers to viable batteries utilizing the technology.

SolidEnergy Systems Corp. was also represented at the 2016 AABC in a presentation given by Mei Cai of General Motors Global R&D Center. The presentation reiterated the need for advanced materials to meet the 2020 USABC goals for commercialization. Lithium metal anodes have high specific capacity (3860 mAh/g) compared to graphite (LiC\textsubscript{6} – 339 mAh/g) and silicon (Li\textsubscript{1.75}Si – 1860 mAh/g). Solid Power’s third generation cells with an ultra-thin lithium metal anode is listed as having a specific capacity 400-500Wh/kg and an energy density of 1200Wh/L. The current development example is constructed with an ultra thin lithium "anode-free", a ceramic anode-lyte, a polymer anode-lyte, a thin cathode-lyte separator, and a cathode (also part of the cathode-lyte) of more traditional LCO, NCM, or NCA material. General Motors is currently in the process of testing that development cell which had about 225 cycles on it at the time of the presentation with some noticeable capacity fade (about 75% of the original capacity)\textsuperscript{119}. Batteries utilizing Solid Energy's technology are apparently entering into consumer electronics as this report is being written. Solid Energy will be attempting to bring smart phone batteries into the market in 2017 and electric car batteries as early as 2018.\textsuperscript{120}

A team consisting of 24M, Sepion Technologies, Berkeley Lab, and Carnegie Mellon University received $3.5 million as in funding from the U.S. DOE ARPA-E to develop "novel membranes and lithium-metal anodes for the next generation of high-energy-density, low-cost batteries".

The funding is part of the U.S. DOE ARPA-E Integration of Novel Ion-Conducting Solids (IONICS) program that looks to accelerate solid state technology.\footnote{121}

LiS battery technology is another area that is undergoing large amounts of research in hopes of developing a commercially viable product for EV applications. LiS batteries hold the promise of low cost and high specific energy. However, LiS suffers from the loss of sulfur during cycling which quickly degrades the cell. Oxis Energy, Sony, PolyPlus, Sion Power, Ilika, and Johnson Matthey are a few of the companies involved with LiS research and development.

Oxis Energy has joined a coalition of European manufacturers and research institutes on the Advanced Lithium Sulfur battery for EVs (ALISE) collaborative effort. ALISE’s objective is to achieve a stable 500Wh/kg Li-S cell by 2019.\footnote{122} Oxis Energy has evaluation samples of its Long Life and Ultra Light cells available.\footnote{123,124} The company recently put out a press release claiming to have tested a development cell at over 400Wh/kg of specific energy capacity and to have cells currently being deployed for vehicle demonstration and development testing.\footnote{125}

PolyPlus Battery Company was awarded a U.S. DOE ARPA-E 36 month grant to develop low-cost, high-performance lithium-sulfur batteries in February of 2013. The company also received another U.S. DOE Advanced Manufacturing Office (AMO) grant to work with Corning Inc. and Johnson Controls Inc. to develop its Protected Lithium Electrode battery technology and manufacturing for use with Li-S, Li-Water, and Li-Air batteries. PolyPlus’ PLE technology in combination with aqueous electrolytes potentially enables an energy dense and stable Li-S battery with long cycle life. In December of 2014, PolyPlus released a statement that it had constructed a 500Wh/kg primary Li-Air battery pack that was verified by scientists at the U.S. Army CERDEC.\footnote{126} The U.S. DOE AMO funding for the production project concluded at the end of August of 2015.\footnote{127} Polyplus’ semi-automated pilot production line is currently being used to build and validate PolyPlus’ technologies.

Advanced battery technologies beyond currently available lithium-ion could help to drive the light-duty market towards higher levels of electrification. With batteries being the dominate cost

of PHEV and BEV powertrains, it is imperative that those costs continue to come down. Advanced battery technologies have the potential to allow for batteries that exceed the U.S. DOE goals, and bring electrified vehicles to market that are equal in cost to their conventional ICE counterparts.

II.B.9. Well-to-Wheel (WTW) and Cradle-to-Grave (C2G) Emissions

Direct emissions from vehicle operations can be estimated and directly measured in testing (e.g., exhaust, fuel system evaporation). However, a broader evaluation of the environmental impacts of PEVs can be conducted through a “well-to-wheel” (WTW) emissions analysis, where emissions are estimated in fuel production and delivery processes, in addition to the vehicle operation. An even broader evaluation can add lifecycle stages, including vehicle manufacturing and vehicle retirement, commonly called “cradle-to-grave” (C2G) evaluations.

Both of these types of analysis typically involve estimating marginal emission factors (e.g. gCO₂e/mile) for varying vehicle powertrain types to compare them side-by-side. For example, an analysis could compare the WTW emission factors of a conventional combustion vehicle to an electric vehicle with today’s technology. Many WTW and C2G studies also forecast how the emission factors will change with varying fuel and vehicle performance improvements over time (e.g., fuel economy improvements, renewable fuel content).

ARB conducts on-going WTW analyses as part of the Vision program,¹²⁸ and also studied it as part of the ACC rulemaking in 2012. The Vision work includes understanding emission forecasts specific to California under current policies, mobile and stationary emission inventories, and future strategies. For the ACC rulemaking environmental impact analysis, WTW emission factors were used, in addition to vehicle manufacturing emissions. The criteria emission factors for fuel production stages account for the unique, strict stationary facility emission controls in place locally to meet national air quality standards (e.g. refineries).

Probably the most widely used and cited WTW analysis tool for light-duty vehicles is ANL’s Greenhouse Gases, Regulated Emissions, and Energy Use in Transportation (GREET) model.¹²⁹ It is used for national policy development, academic research, and many independent studies. It is most robust for greenhouse gas emissions, but the criteria emission factors are national averages and do not account for local controls in varying states. ANL also studies C2G emission impacts and has recently published a study for light-duty vehicles.¹³⁰,¹³¹

ARB is familiar with additional research studies and plans to review them as part of future rulemaking efforts. This includes work by the Union of Concerned Scientists,\textsuperscript{132} Carnegie Mellon University,\textsuperscript{133} and UC Davis.\textsuperscript{134} Results can vary widely based on whether the studies consider future year emission factors (vs. current year only), battery life assumptions (e.g. whether a battery is replaced during the life of the vehicle), and whether a BEV fully offsets the annual driving of a conventional car.

Nearly all WTW analyses show that ZEVs and PHEVs have lower emissions, but the fuel production emissions vary widely based on geographic location, which affects utility territories and their fuel production mix, biofuel blending with gasoline, etc. In California, where electric grid and hydrogen policies are in place to require a renewable fuel mix, WTW emissions are substantially lower for BEVs and PHEVs. When evaluating C2G emissions, batteries are more energy intensive to manufacture, so manufacturing emissions tend to be higher (but are compensated by vehicle operation emission benefits). As battery sizes increase in BEVs for driving range, vehicle manufacturing emissions per BEV also rise. Shorter range vehicles, with smaller battery packs and more frequent charging, would reduce this impact but have more limited consumer appeal. An example of the most recent light-duty vehicle WTW greenhouse gas emission analysis from the U.S. DOE is shown below in Figure 17.\textsuperscript{135}


II.B.10. Battery Recycling and Reuse

Lithium-ion batteries for electric vehicles are currently expensive and represent a sizeable physical system in a vehicle (volume and mass). As a result, it is natural to consider battery recycling (to minimize waste) or battery second use (B2U) where a vehicle battery is repurposed for other uses after reaching its useful life in the car (typically defined when the battery usable energy capacity has declined to 70-75% of its original value). Currently, the value of materials in lithium-ion batteries may not be high enough to incentivize battery disassembly for recycling to recover them for secondary markets. This may change in the future as disassembly techniques evolve. A recent study by Argonne National Laboratory explores the potential for automotive battery recycling, describing a working system to reduce processing costs. To improve the economics of recycling, the study recommends enhancing separation technology to recover battery cells, developing greater recycling process flexibility, and where possible, standardizing battery materials and designs.\(^{136}\)

Using vehicle battery packs (or modules from packs) for second use has a large potential. There are many public and private parties studying B2U and the potential business opportunities. The business case for a vehicle B2U depends on the value of the competitive product, which would be new batteries specifically designed for stationary purposes. Varying use profiles and applications are being considered. This includes back-up power for buildings (e.g. warehouses, cell phone towers, etc.) or energy storage for buildings and/or the grid to supplement renewable energy. Preliminary analysis shows cost margins may be small, but there is strong potential for this to grow. Minimizing costs for removing the batteries from vehicles and repurposing them will be important. This includes identifying quick and low cost means to test the used battery’s varying cells for performance and life to determine if some cells need to be repaired or replaced. Vehicle manufacturers have already begun to take steps in this direction by designing the battery pack to be able to have separately replaced modules or portions of the pack instead of the entire pack as early PEVs required.

There are many research and pilot projects being conducted around the world on B2U. In California, the U.S. DOE’s National Renewable Energy Laboratory (NREL) and California Energy Commission (Energy Commission) have partnered with the Center for Sustainable Energy (CSE) and University of California San Diego. Automakers are experimenting with this, including announced projects by General Motors and Nissan using Volt and Leaf batteries. BMW has been leading a study in California with the Public Utilities Commission (PUC), Integrated System Operator (ISO), and local partners.

II.B.11. Non-Battery Components
Non-battery components refer to anything that is not contained within the battery pack. This includes propulsion components and power electronics. Components outside of the battery pack have seen many developments since the analysis was done for the 2012 FRM. Drive motors have become smaller and more power dense, particularly in terms of volumetric power density. Inverters, OBCs, and DC-DC converters are also becoming smaller and more power dense. Substantial improvements in the design and packaging have occurred as manufacturers release second generation vehicles or expand their PEV offerings.

II.B.11.i. Propulsion Components
Propulsion components for PEVs have various synonymous names including e-machines, electric machines, traction motors, motor/generators, or electric motors. For the purposes of this discussion, they will be referred to as electric motors or generators depending on contextual implementation of that motor or generator in a drivetrain, or jointly as electric machines.

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Given their usage to date in PEVs, the focus in this assessment is mainly on permanent-magnet and induction type electric machines. Permanent-magnet electric machines are sometimes referred to as brushless direct-current (DC) motors, but both permanent-magnet and induction electric machines are powered by alternating-current (AC) on production PEVs. On-board battery packs produce DC power, so that must be converted to AC power via an on-board inverter.

The 2016 TAR provides an explanation of the two electric machine types: "In the duty cycles typical of PEV applications, permanent-magnet motors have certain advantages in energy efficiency due in part to the presence of integral permanent magnets to generate part of the magnetic field necessary for operation. However, these magnets add to manufacturing cost, particularly when they contain rare earth elements. In contrast, induction motors use copper windings to generate all of the magnetic field and can be manufactured without rare earth elements. Although the windings are significantly less costly than magnets, generation of the field in the windings is subject to additional I2R losses that are not present in permanent magnet motors. In some conditions, this causes induction motors to be slightly less energy efficient than permanent-magnet motors\(^{140,141}\), although the choice between the two types of motor ultimately depends on the specific application."


Table 4 - Electric Machine Type for MY16 and Known Expected MY17 ZEVs and TZEVs

<table>
<thead>
<tr>
<th>Manufacturer</th>
<th>Model</th>
<th>Electric Machine Type (Motor A/B)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Audi</td>
<td>A3 e-Tron</td>
<td>PM</td>
</tr>
<tr>
<td>BMW</td>
<td>i3 and i3 REX</td>
<td>PM+Reluctance</td>
</tr>
<tr>
<td>Cadillac</td>
<td>ELR</td>
<td>PM/PM</td>
</tr>
<tr>
<td>Chevrolet</td>
<td>Volt</td>
<td>PM/PM</td>
</tr>
<tr>
<td>Chevrolet</td>
<td>Spark EV</td>
<td>PM</td>
</tr>
<tr>
<td>Chevrolet</td>
<td>Bolt EV</td>
<td>PM</td>
</tr>
<tr>
<td>Fiat</td>
<td>500e</td>
<td>Induction</td>
</tr>
<tr>
<td>Ford</td>
<td>Focus Electric</td>
<td>PM</td>
</tr>
<tr>
<td>Ford</td>
<td>C-Max &amp; Fusion Energi</td>
<td>PM/PM</td>
</tr>
<tr>
<td>Hyundai</td>
<td>Sonata Plug-In Hybrid</td>
<td>PM</td>
</tr>
<tr>
<td>Kia</td>
<td>Soul EV</td>
<td>PM</td>
</tr>
<tr>
<td>Mercedes-Benz</td>
<td>B-Class Electric Drive</td>
<td>Induction</td>
</tr>
<tr>
<td>Mercedes-Benz</td>
<td>S550e</td>
<td>PM</td>
</tr>
<tr>
<td>Mitsubishi</td>
<td>i-Miev</td>
<td>PM</td>
</tr>
<tr>
<td>Nissan</td>
<td>Leaf</td>
<td>PM</td>
</tr>
<tr>
<td>Smart</td>
<td>Fortwo electric drive</td>
<td>PM</td>
</tr>
<tr>
<td>Tesla</td>
<td>Model S &amp; Model X</td>
<td>Induction</td>
</tr>
<tr>
<td>Toyota</td>
<td>Prius Prime</td>
<td>PM/PM</td>
</tr>
<tr>
<td>Volvo</td>
<td>XC90 T8</td>
<td>PM/PM</td>
</tr>
<tr>
<td>VW</td>
<td>e-Golf</td>
<td>PM</td>
</tr>
</tbody>
</table>

Table 4 shows that most manufacturers are choosing permanent magnet motors for their vehicle applications. The only ZEV or PHEV other than the Tesla Model X and S, and the Mercedes-Benz B-Class Electric Drive (which uses a Tesla designed drivetrain) to use an induction electric machine is the Fiat 500e. One interesting vehicle to note is the BMW i3. It uses "a proprietary hybrid synchronous motor designed to exploit both permanent magnets and the reluctance effect."144

While permanent magnet electric machines generally hold an efficiency advantage over their induction counterparts, the permanent magnet electric machines require magnets. Very often, those magnets are of the rare earth variety; they contain light and heavy rare earth metals. There has been some instability in rare earth pricing in the past which impacts the cost to manufacture permanent magnet electric machines. Figure 18 shows what happened to

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142 Table uses data obtained from EPA online certification database (https://www3.epa.gov/otaq/cert.htm)
Neodymium and Dysprosium prices when it was reported that China threatened to stop international supply of the two materials.\textsuperscript{145}

\textbf{Figure 18 - Price History for Neodymium and Dysprosium Rare Earth Materials}\textsuperscript{146}

![Price History for Neodymium and Dysprosium Rare Earth Materials](image)

Rare earth magnets have come down in cost since China's reported supply threats, but those magnets are still understood to represent a significant portion of the costs of permanent magnet electric machines. Several manufacturers have taken steps to address the cost and cost instability issues. General Motors made a lot of changes to the second generation Chevrolet Volt powertrain to reduce rare earth metal usage in both of the drive motors. Those changes "resulted in a reduced-dysprosium-type grain boundary diffusion magnet technology for the Gen-2 Volt's Motor B: rare-earth content dropped from 282 g (10 oz) to 40 g (1.4 oz). Motor A is rare-earth-free. It uses a General Motors proprietary ferrite multi-barrier magnet technology, developed from the ferrite magnets commonly used in high end industrial and automotive (starter motor) applications. The two new motors together reduce total rare-earth content from 3.2 kg (7 lb) on the first generation system to 1.2 kg (2.6 lb)."\textsuperscript{147} Nissan also took steps to reduce rare earth metal usage in its Leaf powertrain. For model year 2013, as part of the Leaf's powertrain redesign, Nissan was able to reduce heavy rare metals by 40%.\textsuperscript{148}

Honda Motor Company, Ltd. announced in July of 2016 that, in a partnership with Daido Steel, it had designed an electric machine that can utilize Daido Steel's new Neodymium magnets which are made without any heavy rare-earth metals: "Daido Electronics Co., Ltd., a wholly owned subsidiary of Daido Steel, has been mass-producing neodymium magnets using the hot deformation method, which is different from the typical sintering production method for neodymium magnets...the two companies achieved, for the first time in the world, a practical application of a neodymium magnet which contains absolutely no heavy rare earth yet has high heat resistance and high magnetic performance suitable for use in the drive motor of hybrid vehicles." The first use of this technology will be in Honda's Freed hybrid electric vehicle which

\textsuperscript{145} Widmer, 2015.
\textsuperscript{146} Widmer, 2015.
\textsuperscript{147} Brooke, 2014.
is only available in select Asian markets. However, Daido Steel also announced in August of 2016 that it "has decided to build a neodymium magnet factory in the U.S. to meet growing demand from automakers there for motors used in hybrid and electric vehicles" indicating that vehicles in the U.S. market will likely begin utilizing its magnets.

As was stated earlier, the BMW i3 utilizes a hybrid electric machine that looks like a permanent magnet motor but also utilizes reluctance effects to improve its efficiency and power density. With this approach, it is believed that BMW was able to design the motor to use less rare earth material than a conventional permanent magnet motor. It is estimated that the motor uses 1kg of magnets to produce 250Nm of torque and 125kW vs. the 2kg of magnets the Nissan Leaf’s electric machine requires to produce 280Nm of torque and 80kW.

Power density and efficiency of electric machines has also been trending upward in second generation products. One example of this can be seen in the improvements General Motors made between its Spark EV and Bolt EV designs. Both vehicles utilize permanent magnet motors, but the Bolt EV drivetrain is better in most ways. Peak power density has improved by over 55% and efficiency has improved as the motor can deliver 9% more maximum power with 7% less AC phase current. The Volt also saw electric machine improvements from its first generation to second generation versions. "Gen 2 system motor volume was reduced by 20% vs. Gen 1 and motor mass was reduced by 40%.”

Current electric machines are also achieving the U.S. DRIVE targets far earlier than expected. While the cost of the motors has not been publically disclosed, both the BMW i3 and Chevrolet Bolt EV already meet the U.S. Drive targets for gravimetric power density of an electric machine by "lab year" 2020 (approximately 2025 for commercial availability). The BMW i3’s motor has a maximum output of 125kW in a 50kg package that equates to 2.5kW/kg. The Chevrolet Bolt EV has achieved 150kW of peak power in a package that has a mass of 76Kg for a gravimetric power density of 1.97 kW/kg. Those improvements have resulted in both vehicles achieving very good acceleration performance numbers. BMW reports that its i3 (60Ah) BEV can do 0-60MPH in 7.0 seconds and General Motors states that the Bolt EV will do it in less than 7 seconds.

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151 Widmer, 2015.
152 Liu, 2016.
154 BMW, 2016b. BMW USA, “BMW i3,” [Accessed 1 November 2016]
**II.B.11.ii. Power Electronics**

Power electronics encompass all non-battery components that are not electric machines. Power electronics are critical to the proper functional operation of an electrified vehicle. Inverters convert DC power produced by the traction battery to the AC power required by a vehicle’s electric machine(s). Most also operate as a rectifier (converting AC power to DC power) in order to capture the energy produced by the electric machine during regeneration events to put that energy back in the vehicle’s battery. On-board chargers take external AC power and convert it to DC to charge the battery. DC-DC converters take the high-voltage that a vehicle’s traction battery operates at and drops it down to 12 volts, or other DC voltages, for the various other vehicle accessories and systems.

**II.B.11.ii.1. Inverters**

Modern inverters are quite efficient at converting AC power to DC power with most achieving efficiencies above 90 percent over a wide range of operating conditions. Currently, inverters use insulated-gate bipolar transistors (IGBT) or metal-oxide-semiconductor field effect transistors (MOSFET) to achieve those efficiencies. High powered inverters also generate a lot of heat which generally requires liquid cooling to keep operating temperatures in check. PHEVs compound the temperature problem, as the packaging constraints usually require the inverter to be placed underneath the hood with the internal combustion engine.

Manufacturers are already finding new and better ways to package inverters and other power electronics. The first generation Chevrolet Volt integrated most of the power electronics into a module that General Motors refers to as the Traction Power Inverter Module (TPIM). The second generation Volt had many improvements made to the TPIM. Total simultaneous power capability of the new TPIM was reduced from 221kVA to 180kVA, but power density improved by 43% (kVA/Kg). Volume of the module improved from 13.1L to 10.4L and mass was also reduced by over 43% from 14.6Kg to 8.3Kg. Some of the improvements to the revised TPIM can be attributed to the integration of the TPIM with the transaxle housing. This enabled the replacement of the six large 3-phase AC motor power cables with less expensive and lower mass rigid buss bars. Another source of the improvements comes from Delphi’s Viper double sided cooled IGBT system. The novel design package was presented by Delphi at EVS26 in 2012. Delphi stated that "The new packages provide low electrical and thermal impedances, can be tested individually, and also provide the capability for double sided cooling. Due to their unique design, these packages enable higher and more uniform current densities. Combined with matching coefficient of thermal expansion, this design provides for a highly reliable component that can also be easily manufactured using standard low-cost, high volume manufacturing processes."  

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Another example of advancements made to power electronics modules can be seen in the improvements made by Toyota from the third to fourth generation Prius. While the Prius is a conventional hybrid, it is likely that the improvements made to the conventional hybrid will also be implemented in the model year 2017 Prius Prime PHEV; the Prime has the same motor/generator powertrain as the conventional Prius except with the addition of a one way clutch to use both motors to provide motive power. Toyota reduced the volume of what they call the power control unit (PCU) from 12.6L to 8.2L; a reduction of about 35%. The volume reduction was in due in some part to a similar advancement utilized by the second generation Chevrolet Volt TPIM, smaller IGBTs enabled by double sided cooling. Toyota was also able to reduce losses from the IGBTs by about 20%. Increasing the efficiency of inverters can allow manufacturers to reduce battery pack energy capacities which reduce costs of the vehicle, or increase range for the same capacity battery pack. The volume and mass reductions also increase overall vehicle efficiency and provide for better packaging opportunities.

II.B.11.ii.2. On-Board Chargers
OBCs have also increased in efficiency and power capability since the 2012 ACC rulemaking. Nissan debuted the Leaf with a 3.6kW OBC but added an upgrade to a 6.6kW OBC by the 2013 model year. Chevrolet introduced the Spark EV with a 3.3kW OBC but will equip the Bolt EV with a 7.2kW OBC. The BMW i3 came with a 7.2kW OBC in its introductory model year but is receiving an updated charger next year that can take up to 32A, and in markets where 3-phase AC power can be supplied, the new OBC can accept up to 11kW of power. The Tesla Model S in 2012 came standard with a 10kW charger. Tesla has offered an option to customers for a 20kW system which utilized two of the 10kW OBCs (using 80amps at 240V). Tesla introduced a new 48A (11.5kW) OBC with the Model X and then made that OBC standard on the Model S in 2016 when the vehicle received a facelift. An optional 72A OBC was made available sometime after the Model X was introduced and on the Model S after the facelift. The 72A OBC appears to be a single unit, exceeding the original 40A unit in power capability by 80%.

PHEVs are also receiving more powerful OBCs. General Motors brought the first generation Chevrolet Volt to market with an OBC that was capable of 3.3kW. The OBC was updated on the second generation Volt to charge the battery at 3.6kW. Porsche has also increased the power capability of the OBCs on its PHEV products. The company added an optional 7.2kW OBC on its Cayenne E-Hybrid and made the same option available on the forthcoming Panamera 4 E-
Hybrid in addition to the originally offered 3.6kW units. The higher powered units give customers the opportunity to charge their vehicles in less time for a similar capacity battery pack or to allow for inclusion of larger capacity packs without increasing charging time.

Physical volume of OBCs has also trended downward. The Chevrolet Bolt OBC at 12.3L is smaller in volume than the Chevrolet Spark EV OBC at 13.0L. This decrease in volume happened despite the fact that the Bolt EV OBC can handle more than twice the power; 7.2kW vs. 3.3kW. Mass is up on the Bolt EV OBC, 12.0Kg vs. 9.3Kg, but the gravimetric energy density is up by 69%. The Spark EV OBC has a power density of 354 W/Kg while the Bolt EV has a power density of 600 W/kg. Increasing the power density of OBCs gives the manufacturer more flexibility to place and package it on the vehicle, potentially giving the customer more space or other benefits.

Efficiencies of OBCs are increasing as well. While changes in efficiency may not result in differences on the range of the vehicle, they do affect the wall to wheel efficiency of the vehicle and the “miles per gallon gasoline equivalent” rating that is reported on the label. Idaho National Lab’s Advanced Vehicle Testing group has tested several chargers on vehicles under various input power conditions. Table 5 shows the results of that testing on the various vehicles. General Motors has reported that the OBC on the 2016 Volt is 93% efficient using level 1 charging, and 95% efficient when using level 2. INL did not have its own testing results for the 2016 Volt, but General Motors’ results would make the new Volt OBC more efficient than anything that INL has tested and reported results for.

Table 5 - INL OBC Testing Results of Several Vehicles

<table>
<thead>
<tr>
<th>Make</th>
<th>Model</th>
<th>MY</th>
<th>L1 Max Power (kW)/ Eff (%)</th>
<th>L2 208V Max Power(kW)/ Eff (%)</th>
<th>L2 240V Max Power (kW)/ Eff (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Chevrolet</td>
<td>Volt</td>
<td>2012</td>
<td>1.38 / (86.6)</td>
<td>3.14 / (88.5)</td>
<td>-</td>
</tr>
<tr>
<td>Nissan</td>
<td>Leaf</td>
<td>2012</td>
<td>1.38 / (86.4)</td>
<td>3.71 / (88.7)</td>
<td>-</td>
</tr>
<tr>
<td>BMW</td>
<td>i3</td>
<td>2014</td>
<td>1.33 / (89.6)</td>
<td>6.47 / (93.4)</td>
<td>7.22 / (93.8)</td>
</tr>
<tr>
<td>Nissan</td>
<td>Leaf</td>
<td>2015</td>
<td>1.38 / (78.4)</td>
<td>6.16 / (90.5)</td>
<td>-</td>
</tr>
<tr>
<td>Mercedes</td>
<td>B-Class</td>
<td>2015</td>
<td>1.38 / (84.7)</td>
<td>-</td>
<td>7.10 / (91.4)</td>
</tr>
</tbody>
</table>

II.B.12. Non-Battery Components Expected Developments

Components outside of battery packs have also been moving along at an impressive pace. Electric machines will continue to get more powerful and power dense, while improving drive efficiency and lowering costs. Manufacturers are, and will be, installing higher power OBCs on vehicles to enable faster battery recharge times. New wide bandgap SiC material technology is currently coming to market and will enable more efficient and power dense power electronics with the potential for lowering cost.

166 Korzeniewski, 2016
167 Liu, 2016
II.B.12.i. Propulsion Components Expected Developments
Suppliers and OEMs continue to make progress towards the U.S. DOE EV Everywhere targets. In the case of electric machines, many have already reached the U.S. Drive 2020 lab year goals for power density on production vehicles. Electric motors in vehicles like the BMW i3 and the Chevrolet Bolt EV have already achieved specific power ratings well above the U.S. DOE targets. The challenge will be in hitting the specific power targets at the cost targets. Most OEMs are using permanent magnet electric machines despite their need to use expensive magnets. But, several OEMs have already shown products with large reductions in rare earth metal usage. This appears to be the trend into the near future due to the efficiency advantages of permanent magnet electric machines over their inductive counterparts. Higher efficiency electric machines require smaller overall batteries and are very attractive given the high cost of batteries. Those lower costs will help to bring vehicle prices down relative to conventional ICE vehicles.

During meetings with OEMs, several indicated that they are working with suppliers to continue to remove rare earth metals from their electric machines. The motivation to do so is centered on reducing cost and risk of cost fluctuations. Collaborative efforts like the previously mentioned work between Honda and Daido Steel will likely take place between other OEMs and suppliers. Daido Steel’s new U.S. neodymium magnet factory is expected to come online in 2019 and should help to provide the market with more magnetic components for future electric machines.

OEMs are, for the most part, keeping electric machine development in house. However, there are some suppliers that have already brought, or will bring, electrified propulsion products to market. YASA Motors offers a line of electric machines based on axial flux technology. YASA’s electric machines exhibit very high power densities; as high as 10kW/kg in some cases with peak efficiency of up to 96%.170 The specific power is well above the U.S. DOE targets but the cost of YASA’s products has not been publically disclosed.

Electrified axle assemblies have the ability to enable all-wheel drive (AWD) on PHEVs without any mechanical connection between the electrified transaxle and the ICE drivetrain. Volvo has already implemented the GKN eAxle in the XC90 T8, and will have the same electric AWD on its forthcoming S90 and V90 T8 models. Suppliers are beginning to come to market with fully integrated electrified transaxle solutions as well. GKN, Xtrac, and ZF all have forthcoming products. GKN announced its e-Twinster electrified axle based on the Twinster unit currently used in the Ford Focus RS that is capable of torque vectoring (the ability to direct torque to either side of the vehicle that helps enhance a vehicle’s driving dynamics).171 The eDrive Twinster is rated at 60 kW and 240 Nm with a maximum speed of 13,000 rpm.172 YASA Motors has partnered with Xtrac to create the P1227 Integrated Lightweight Electric Vehicle transmission line (ILEV). The configurable gearboxes can be used in various configurations


such as an integrated electrified axle solution similar to GKN’s. The ILEV, when used in place of a differential, can be configured with two YASA motors to provide up to 3,900 Nm of torque and 320 kW at the wheels in a 95 kg package for a specific power of 3.37 kW/kg, not including power electronics.\textsuperscript{173} ZF announced its electric axle drive at the beginning of 2016 and stated that it will go into volume production in 2018. The ZF unit uses an induction motor to produce up to 150 kW and 380 Nm in torque which can result in up to 3,500 Nm of torque at the axle. It is a fully integrated design which includes the power electronics with a total mass of 113 kg and a specific power of 1.32 kW/kg which is very close to the U.S. DOE EV Everywhere goal for a combined motor and power electronics package.\textsuperscript{174}

Another development that is likely to find its way into blended power-split PHEVs is the use of a one way clutch on the electric machines that are usually designated to generate electric power from the ICE rather than power the wheels. Both the 2017MY Prius Prime and Chrysler Pacifica Hybrid PHEVs are using such a device. “For the first time in a Toyota hybrid, the system uses a “dual motor drive.”… a new one-way clutch engages both the generator (MG1) and electric drive motor (MG2) for drive force, the first time MG1 has been used for that purpose.”\textsuperscript{175} The Chrysler Pacifica Hybrid does the same thing to expand that power capability of the electrified portion of the powertrain.\textsuperscript{176} The vehicles can then provide customers with a more electric experience on a power-split system without increasing costs significantly.

\textbf{II.B.12.ii. Power Electronics Expected Developments}

Manufacturers are continuing to make progress towards the U.S. Drive and EV Everywhere goals for not just propulsion components, but power electronics as well. Double sided cooling of IGBTs and related components that debuted in both the newest versions of the Chevrolet Volt and Toyota Prius likely represent where the industry is headed when it comes to inverter packaging and design in the very near future. Hitachi has shown that for the same chip size, an increase of up to 30\% in current was possible with double sided vs. singled sided cooling.\textsuperscript{177} Some of the OEMs that staff met with indicated that the DOE target for motor and power electronics should be achievable for the combination of motor and inverter. The developments allow for smaller designs and more efficient thermal management which can lower costs and provide for more flexible packaging of those components on a vehicle.

Some other interesting developments were shown at DOE’s 2016 Annual Merit Review. General Motors presented on a U.S. DOE co-funded project to develop a next generation inverter capable of 55kW of peak power and 30kW of continuous power. The project identified the DOE

\begin{itemize}
  \item \textsuperscript{175} GCC, 2016b. Green Car Congress, “Prius Prime PHEV pricing to start at $27,100; on sale later this year,” 7 October 2016. \url{http://www.greencarcongress.com/2016/10/20161007-prius.html}, [Accessed 14 October 2016]
\end{itemize}
targets of $3.30/kW at a volume of 100,000 units with a power density of 13.4 kW/l, specific power of 14.1 kW/kg and efficiency of over 94% for 10-100% speed at 20% rated torque. The prototype device met the U.S. Drive 2020 power density target and is expected to meet the cost target when the design is scaled up to higher power levels. To meet automotive reliability requirements and bring a scaled up device into production, the substrate attachment process would need further refinement.\textsuperscript{178}

Vehicle OBCs will also continue to improve and increase in power. The updated BMW i3 (94Ah) will have an OBC that can utilize 3 phase AC electricity to extend its peak power capability to 11kW.\textsuperscript{179} The Chrysler Pacifica Hybrid will have a unit capable of 6.6kW.\textsuperscript{180} Several OEMs showed staff confidential plans that involved increasing on-board charger capability that went hand in hand with range increases as new products come to market, or are going through a refresh. These improvements lead to the potential for consumers to recharge their vehicles in less time with supporting infrastructure.

In order to meet the DOE EV Everywhere performance and cost targets for power electronics, several entities have been developing wide bandgap materials to replace silicon (Si) in switching electronics. Wide bandgap refers to the amount of "energy required for an electron to jump from the top of the valence band to the bottom of the conduction band within the semiconductor. Materials which require energies typically larger than one or two electronvolts (eV) are referred to as wide bandgap materials."\textsuperscript{181} Two materials, Silicon Carbide (SiC) and Gallium Nitride (GaN) show great promise for RF power and switching applications. GaN lends itself better to higher frequency applications due to its higher electron mobility and electron saturation velocity. SiC has lower electron mobility and saturation velocity than GaN, but its thermal conductivity is much higher, lending itself to be better in high power density applications.\textsuperscript{182}

Several DOE research and development projects have been ongoing to prove that wideband technology is viable. One such project was awarded to Cree, Inc. and began in December of 2014. Cree has subsequently spun off its Power and RF division into a new company, Wolfspeed, which Infineon has agreed to purchase.\textsuperscript{183,184} The project has set out to develop

\textsuperscript{179} BMW, 2016c.
Automotive Electronics Council (AEC) Q101 -001-006\textsuperscript{185} qualified 900V SiC MOSFETs that could then be incorporated into a 88kW automotive inverter with the goal of meeting or exceeding the DOE targets on cost and performance. The MOSFETs have been proven and sampled, and the project is currently working on implementing the MOSFETs in an inverter for PEVs to benchmark and compare to existing technologies. A modeling tool was used to predict inverter losses across the EPA 2-cycle tests. The model assumed a Ford Focus EV with a 90kW internal permanent magnet motor coupled with either a C-Max 90kW Si IGBT inverter or the Wolfspeed 88kW SiC inverter. Results of the modeling showed that SiC reduced inverter losses by 67\% across the combined EPA drive cycle compared to the Si inverter.\textsuperscript{186} Cost is still somewhat of an issue due to low yields on relatively small wafer fabs, but as wafer sizes and yields increase, cost of the technology should come down.\textsuperscript{187}

Another U.S. DOE funded research project was awarded to Delta Electronics to develop a GaN-based bidirectional 6.6kW OBC for PEVs. The program goals for the OBC included a design that would operate at 95\% efficiency, provide a 30\% to 50\% improvement in power density over other benchmark designs (0.45 to 0.75 kW/L), and be capable of a switching frequency range of 0.3-1MHz. The project, so far, has shown a prototype part that achieved a total system efficiency of over 96\% from 280 to 420V to the battery. The project is expected to finish in FY17 after which Delta is looking to create a commercialization plan to bring such a product to market, but it is unclear as to when that may happen.\textsuperscript{188} Toyota has started on-road testing of SiC technology in a fleet of hybrid Camrys and a fuel cell bus.\textsuperscript{189} SiC based power electronics have allowed Toyota to significantly reduce the volume of the PCU on its vehicles. Toyota displayed the result of those prototype design efforts in 2014 which can be seen in Figure 19. The goal of the project is to gather data on performance of the SiC equipped boost converter and drive motor inverter to further the development of the technology and bring it to market as soon as possible.


During staff's meetings with OEMs, several OEMs indicated that SiC appeared to be a viable technology for MY2020 and later vehicles. Some of the delay in market introduction is due to current cost constraints of the material that stem from low yields during material creation. The likely initial applications for SiC technology will be traction drive inverters. OEMs also indicated that they did not see GaN as being cost viable until closer to 2025CY where the technology will most likely be used in devices like OBCs where higher frequency switching capability is more important than power capability.

II.B.13. Other Expected Developments

There are currently three DCFC standards available in the U.S. for customer use. Two of the three, SAE J1772 Combo Connector System (SAE CCS) and CHAdeMO standards, are essentially limited to 50kW of power delivery to the vehicle. The third, Tesla’s proprietary standard and connector, is capable of delivering up to 145kW of charging power on its Supercharger network which it created to “to remove a barrier to the broader adoption of electric vehicles...” At this point in time, Tesla indicates that it only allows its vehicles to charge at a rate of 120kW. However, there has been quite a lot of movement towards developing higher powered fast charging standards. Those higher power standards have implications for equipment on a vehicle, as the battery pack and supporting hardware must be able to support those higher power charging rates.

The CHAdeMO Association announced in June of 2016 that it plans to release an amendment to its standard that will enable charging rates of up to 150kW. The higher charge rate
amendment specifically states that the plug will remain the same, allowing current vehicles that utilize CHAdeMO DCFC to use the new 150kW capable infrastructure installations. The press release also stated that the CHAdeMO Association was in the process of conducting a 350kW (1000V x 350A) technical study in anticipation of future market demand.\textsuperscript{193}

The Charging Interface Initiative Association (CharIN) was formed in 2015 in part to develop the Combined Charging Standard (CCS) which the SAE Combo connector is part of. CharIN is working with an impressive set of members including automakers, infrastructure suppliers, and service providers to set standards for 150kW in the near term and up to 350kW in the not too distant future. At the 2015 Electronics in Vehicles (ELIV) conference in Germany, the CharIN group displayed charging equipment and vehicles capable of charging at 150kW.\textsuperscript{194}

In July of 2016, the Obama Administration announced several federal and private sector actions to accelerate EV adoption in the U.S. One of those actions included conducting a study to explore the feasibility of 350kW charging for EVs. The U.S. DOE in partnership with industry members, NREL, and other stakeholders will research the vehicle, battery, infrastructure, and economic implications of 350kW DCFC.\textsuperscript{195} The charging equipment appears to be feasible, as ITT Cannon recently announced that they will be introducing next-gen DCFC equipment at eCarTec 2016 which has been tested to 400A at 1000V (400kW). The design includes a liquid-cooled connector and cable that enables high current throughput in a manageable size cable.\textsuperscript{196} However, batteries may not quite be ready for the demands that charging at 350kW would place on them. Porsche, with its 800V battery system technology is poised to best take advantage of the higher charging rate, but in a presentation at the 2016 AABC, Dr. Christian Jung showed that the fastest the vehicle can charge at is 225kW due to limitations of the battery cells themselves.\textsuperscript{197} It is unclear whether there is time to adjust cell parameters for the vehicle by its market introduction to allow the vehicle to charge at rates faster than 225kW. As battery technology continues to develop, charge acceptance is set to increase which will allow future battery packs to take advantage of charging power rates closer to the 350kW target. Consumers will be able to charge at faster rates and minimize down time from refueling using the high powered infrastructure.

DCFC technology is not the only charging sector undergoing accelerated development. Barney Carlson from INL gave a presentation at ARB's 2016 Advanced Clean Cars Symposium entitled "Wireless Charging for Electric Vehicles: INL's Testing Supports Code & Standards Development". INL is currently testing and developing wireless charging equipment to develop


\textsuperscript{195} Nakada, 2014.


SAE’s wireless charging standard SAE TIR J2954.\(^{198}\) The technical information report (TIR) calls out two different power levels identified and the press release adds two more potential power levels for future revisions of the work in progress (WIP) standard. Those power levels can be seen in Table 6. Wireless power transfer (WPT) equipment will begin rollouts on commercial vehicles starting with the 2017MY Mercedes-Benz S550e PHEV. The system on the S550e will use Qualcomm’s Halo technology to wirelessly transfer power at up to 3.6kW with an efficiency of 90% relative to a conductive system of the same power level.\(^{199}\) Several OEMs indicated that they would begin to roll-out WPT systems on vehicles between the 2018 and 2020MY. WPT systems may have strong potential for autonomous vehicle charging that could have significant impacts on BEV and PHEV markets in the future.

### Table 6- SAE TIR J2954 and Future Potential Power Levels

<table>
<thead>
<tr>
<th>Power Level Name</th>
<th>Power (kW)</th>
<th>Standard</th>
</tr>
</thead>
<tbody>
<tr>
<td>WPT 1</td>
<td>3.7</td>
<td>TIR J2954</td>
</tr>
<tr>
<td>WPT 2</td>
<td>7.7</td>
<td>TIR J2954</td>
</tr>
<tr>
<td>WPT 3</td>
<td>11</td>
<td>Future Revision of J2954</td>
</tr>
<tr>
<td>WPT 4</td>
<td>22</td>
<td>Future Revision of J2954</td>
</tr>
</tbody>
</table>

A few OEMs have announced plans for dedicated or flexible vehicle platforms that are designed with electrification in mind from the outset. The flexible platform allows for better integration of batteries, motors, and power electronics without requiring the vehicle model to be dedicated to the powertrain. Volvo has designed two such flexible platforms, Scalable Platform Architecture (SPA) and Compact Modular Architecture (CMA). SPA is currently in use with the XC90 and will underpin the soon to be released S90 and V90 vehicles, allowing them to simply incorporate the AWD T8 PHEV engine package from the XC90. The smaller platform, CMA, will be used in a similar manner on smaller vehicles. CMA is expected to debut in 2017 and will have a PHEV engine option (T5) that can be offered in any vehicle riding on the CMA platform.\(^{200}\)

Dedicated electrified platforms may debut in the near term. Currently, Tesla is the only manufacturer that offers a dedicated pure BEV electrified platform that is used for more than one vehicle model. Volkswagen has announced a flexible, EV only platform, that the company calls its Modular Electric Drive kit (MEB). The MEB platform will play a major role in bringing the over 30 pure-electric vehicles to market by 2025 as laid out in VW’s Strategy 2025 plan.\(^{201}\) The platform will allow VW to do away with the costs and complexities of converting an ICE based platform to utilize a BEV powertrain. Additionally, it will allow for engineers and designers to take

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\(^{201}\) VW 2016
advantage of the opportunities presented with the more compact drive motors used by BEVs and lack of need for emissions equipment.

II.B.14. Potential Long-Term Developments in Non-Battery Components
Developments to non-battery components to the medium and long term are more difficult to assess. Based on information gathered from meetings with OEMs, the focus will be on reducing costs. That is likely to include continued focus on removing rare-earth metals from electric machines and any associated componentry. OEMs and suppliers will continue to push towards more specific power and power dense electric machines to meet the U.S. DOE EV Everywhere targets. Doing so will result in smaller, lighter, more powerful electric machines which will enable more capable vehicles in a wider variety of platforms and implementations.

Power electronics are expected to see a continued push towards more efficient, lower cost designs. SiC based systems will likely see continued development to further improve efficiency and that will meet the U.S. DOE EV Everywhere goals. GaN materials may become viable closer to 2025 which will allow smaller and even more efficient OBCs. Some OEMs indicated that their PHEVs will come with progressively higher powered OBCs. GaN will be important in making sure that OBCs do not grow in size proportional to their power capability increase. The potential for high levels of efficiency with GaN could help to lower well to wheel emissions, decrease charge times, and decrease the cost to refill the battery because a higher portion of the power would be transferred from the wall to the vehicle’s battery pack rather than lost through inefficiencies.

II.B.15. Potential Long-Term Developments in Charging Technology
Longer term will likely see the proliferation of 350kW DCFC if initial rollouts of the infrastructure take place successfully. As was discussed in II.B.13, Porsche has reported that it doesn’t expect its Mission E vehicle to be fully capable of 350kW charging with the battery technology that is slated to be on the vehicle when it debuts on the market. As battery technology improves to allow higher charging rates, vehicles will be able to accept increasing amounts of charging power closer to the 350kW rate. It is also likely that vehicles will have to move to higher voltage battery packs, like the Porsche 800V design. Charging cord wire diameter, and mass, is directly proportional to its current carrying ability. Without a major advance in cable cooling or material technology, reasonably sized charge cables will be limited to about 350A in current capability. Levels beyond 350A would result in the cable being too heavy and bulky for people to use. CHAdeMO, in the announcement about its amendment for 150kW, called out a potential future 350kW standard from them as 350A at 1000V.202 The higher charging rates will allow customers to refill BEVs much more quickly, allowing for extended range trips with refill times that are more similar to conventional ICE vehicles.

If the initial rollout of wireless charging on vehicles proves successful, the market will likely see a proliferation of the technology across many models. If the SAE TIR J2954 standard is any indication, power levels of the systems on future vehicles will increase. OEMs that disclosed product plans which included wireless charging showed that they expect to increase wireless

202 CAE 2016.
power capability on the vehicles as the technology becomes available. Additionally, OEMs are installing increasing levels of autonomous vehicle capability on more and more models. That technology coupled with wireless charging has the potential to allow vehicles to manage their own charging without human intervention.

II.B.16. Connected and Autonomous Vehicles (CAV) and Car Sharing
Passenger vehicle technology and travel activity are undergoing a much wider transformation beyond electric drive powertrains. On the engineering front, technology for smart sensors and cloud networking are allowing vehicles to be connected to one another and infrastructure, as well as provide automated driving functionality. Although these are not inherently linked, most industry leaders are creating connected and autonomous vehicles (CAV), and are rushing to market with the innovations due to competition and the interest to provide enhanced safety and convenience services for consumers. These transformations are emerging in the market today, but will become much more widespread in the period after 2025.

In addition to CAV technology innovations, the use profile of passenger vehicles is being transformed as well. As the sharing economy emerged in recent years, vehicle business models began with car sharing (e.g. ZipCar or Car2Go), but now also include ride sharing (e.g. Lyft or Uber). Both of these emerging business models have the potential to dramatically change vehicle ownership models, and use of cars. Some industry leaders and independent experts are beginning to find a nexus between all three of these transformations, and are looking for a way to leverage each other – autonomous, shared, and electric (ASE) – although they do not have to be combined. General Motors’ partnership with Lyft to create a CAV on the Bolt EV platform is just one example.\(^\text{203}\)

Staff have been studying these trends and are starting to identify research and policy actions that could influence the vehicles’ environmental impact. These policy actions bridge across a number of programs at ARB, including vehicle regulations, regional planning, infrastructure development, research, and more. ARB is identifying which actions should be implemented soon to influence business models, compared to research and analysis that should be conducted over a number of years to understand the scale of the environmental and energy impacts. The development of these actions is being coordinated with the California DMV, which has authority over CAV safety rules, Caltrans, the Governor’s Office of Planning and Research (OPR), CPUC, U.S. EPA, U.S. DOT, and other agencies.

Changes to the vehicle emission regulations to potentially incentivize shared platforms and/or CAVs will need time to evaluate. Recent research has been showing that shared vehicle programs can reduce individual car ownership and encourage advanced vehicle purchases\(^\text{204}\), but has cautioned that the impact on total vehicle miles traveled (VMT), and therefore energy


usage, could vary widely from large reductions to large increases. Figure 20 below highlights this potential range of energy consumption from varying elements in this transformation.

**Figure 20 - Estimated ranges of operational energy impacts of vehicle automation through different mechanisms**

![Figure 20](image)

Given the uncertainty in CAV impacts on the environment, vehicle regulation changes should not be made in the near term, but rigorous research, analysis, and pilots should be launched to quickly gain further understanding. As an example, connected vehicle functionality has the potential to increase vehicle efficiency, as demonstrated by federal funded research at UC Riverside, but achieving real emission reductions depend on how many vehicles are connected on roadways, whether smart city infrastructure is in place, and whether the vehicles are in urban vs. rural areas. Specifically, connected vehicles could sail through smart intersections with communications to smart streetlights, improving traffic flow. In addition to operational uncertainty, many autonomous vehicle functions are being introduced into the market regardless of vehicle regulations, responding to competition to provide enhanced safety functions for drivers. ARB regulatory teams intend to study these CAV opportunities carefully, but will need further data and evidence of their widespread environmental benefits before adopting rule changes.

Other ARB policy actions should progress more quickly. Research contracts should be established to study ASE innovations in varying forms. ARB’s partnerships with the state’s air

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206 Wadud 2016.

districts and MPOs should be enhanced to help coordinate regional pilot studies, smart city infrastructure, and VMT impact data collection. Opportunities to place electric vehicles in these services and programs should be aggressively supported, which will include strategic consideration of electric charging infrastructure and consumer awareness. The emergence of connected and autonomous, as well as shared platforms is already occurring, but how rapidly they expand into electric drive platforms, and how rapidly the vehicle functions are used in practice, depends on government actions (federal, state, regional, and local). ARB intends to take a leading role to guide this activity.

II. C. PEV Costs
As the PEV market has taken hold in the past five years, and sales have steadily grown, manufacturing has expanded for EVs and major components, bringing production scale and learnings, both resulting in cost reductions. Manufacturing investments are growing rapidly as suppliers and automakers prepare for EV markets around the world.

Many battery manufactures have brought innovation to the market, and a few have been successful enough to expand in production and contract scale to drive costs down. LG Chem and Panasonic are both making large investments as customer contracts are growing. The most unique production investment is Panasonic’s partnership with Tesla in the Gigafactory, being completed in Reno, Nevada. The facility, once completed, will produce more batteries than all other global lithium-ion production in 2013. Automakers are also beginning to make large investments in battery manufacturing as technology has evolved. Daimler and Volkswagen have both announced plans to produce packs in partnership with cell suppliers, similar to what Tesla is doing with Panasonic. Nissan was one of the first to do this with their AESC partnership, creating manufacturing hubs in Japan, the UK, and Tennessee.

II.C.1. Battery Costs
In addition to large advancements in lithium ion battery performance over the past few years, cell and pack costs have also seen dramatic improvements. In the 2012 ACC rulemaking, ARB leveraged battery cost projections from the 2010 TAR which relied heavily on an earlier version of Argonne National Laboratory’s BatPaC model. Updated cost projections from Argonne’s BatPaC model, in addition to recent public statements from battery and vehicle manufacturers, show costs are declining at a faster rate that assumed in the 2012 rulemaking. Table 7 below is an excerpted table from the ACC ZEV ISOR that showed the battery pack cost assumptions for select years. For reference, the range designation for the BEV100 and PHEV20 represents all electric range on the UDDS cycle.

Table 7 - Incremental battery pack (and system) costs used in 2012 ACC rulemaking (2009)\textsuperscript{210}  

<table>
<thead>
<tr>
<th>System per-vehicle costs ($)\textsuperscript{a}</th>
<th>2012</th>
<th>2015</th>
<th>2020</th>
<th>2025</th>
</tr>
</thead>
<tbody>
<tr>
<td>PHEV20 battery pack</td>
<td>8,078</td>
<td>6,462</td>
<td>3,309</td>
<td>2,647</td>
</tr>
<tr>
<td>BEV100 battery pack</td>
<td>21,367</td>
<td>17,094</td>
<td>8,752</td>
<td>7,002</td>
</tr>
<tr>
<td>FCV fuel cell system</td>
<td>18,908</td>
<td>10,208</td>
<td>5,220</td>
<td>4,756</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>System per-unit costs ($/kWh)</th>
<th>2012</th>
<th>2015</th>
<th>2020</th>
<th>2025</th>
</tr>
</thead>
<tbody>
<tr>
<td>PHEV20 battery pack ($/kWh)</td>
<td>1053</td>
<td>842</td>
<td>431</td>
<td>345</td>
</tr>
<tr>
<td>BEV100 battery pack ($/kWh)</td>
<td>605</td>
<td>484</td>
<td>248</td>
<td>198</td>
</tr>
<tr>
<td>FCV fuel cell system ($/kWh)</td>
<td>163</td>
<td>88</td>
<td>45</td>
<td>41</td>
</tr>
</tbody>
</table>

\textsuperscript{a}Based on midsize car / small multipurpose vehicle class, as compared to a 2008 baseline; Figures 3 and 4, in Section 2.2.3, show the system costs graphically.

A compilation of varying recent battery pack cost projections is shown in Figure 21 published in a prominent 2015 Nature study.\textsuperscript{211} The graphic shows the wide variation in current costs, highlighting how market leaders have a significant cost advantage today. However, the costs begin to converge in 2025 between $200-300/kWh. Many automakers are settling on a few battery manufacturers whose costs have declined recently, although multi-year contracts for initial electric vehicles have locked a few automakers into higher costs until the contracts expire. ARB has added the recent 2016 TAR cost assumption for the BEV200 onto the graph for comparison ($140/kWh at the pack level for a standard size car). As ARB met with manufacturers for the mid-term review, most confirmed aggressive cost projections in the range of $150-200/kWh were reasonable.

\textsuperscript{210} ARB, 2011a.
Sue Babinec, a senior commercialization advisor for the U.S. DOE ARPA-E gave a presentation on energy storage technology at the 2016 Advanced Clean Cars Symposium: The Road Ahead. The presentation discussed costs and looked more closely at the 2015 Nature study. While the time based approach of the Nature study is helpful in looking at where the industry is at, an alternative to projecting prices comes by looking at manufacturing volume based effects at a single plant. By aggregating current battery manufacturers and their volumes, one can better extrapolate higher volume prices. The presentation showed that a 35GWh plant could achieve a price of $190/kWh and a 7GWh plant could achieve a price of $235/kWh. The work done by ARPA-E comes at the price and cost issue from a slightly different perspective, and affirms that high volume battery manufacturing will be instrumental in getting costs and prices down.\textsuperscript{213}

At the 2016 AABC, Dr. Menahem Anderman gave a plenary keynote presentation discussing where Total Battery Consulting, Inc. (TBC) sees the electrified vehicle market going. The team analyzed a 37Ah PHEV NMC (523) metal can cell price at 10 million cells per year. The analysis showed a price of $195/kWh for calendar year 2018 which also included an 8.0% warranty and profit markup. TBC also analyzed a cell similar to what will be used in the Chevrolet Bolt EV. A NMC622 56Ah pouch cell in calendar year 2018 at a production volume at 24 million cells per year came out to $145/kWh. That price included an 8.0% warranty and profit markup and what TBC referred to as “aggressive assumptions”. Dr. Anderman also stated that negotiated contract pricing is dropping faster than costs, and that improvement in manufacturing yields and volume

\textsuperscript{212} Nykvist, 2015.
\textsuperscript{213} Babinec, 2016.
expansion support lower costs. TBC’s analysis, while only showing cell costs, supports the lower costs projected by the 2016 TAR.\textsuperscript{214}

In the 2016 TAR for direct manufacturing costs, U.S. EPA leveraged the ANL BatPaC model to create supply curves for their vehicle cost analysis. The changes in battery cost projections since the 2012 FRM for U.S. EPA’s modeling stems from using ANL’s most recent BatPaC Version 3 and changes to vehicle component sizing (e.g. usable battery capacity, motor power, energy efficiency, etc) that have resulted in reductions to gross battery capacity and power requirements.\textsuperscript{215} Citing a specific excerpt from the 2016 TAR, “Since the FRM, EV battery pack cost projections have fallen by an average of 24-27% (13-19% per kWh), as a result of better pack topology and cell sizing, reductions in pack capacity and power to energy (P/E) ratio, and other factors. PHEV battery pack costs were lower by 9-12% (2-3% per kWh), for similar reasons.” Figure 22 and Figure 23 below show the full battery pack costs for varying vehicle size classifications from the analysis in the 2016 TAR. The pack costs account for a varying size battery depending on the vehicle load requirements. For the same driving range, a larger pack is required to support the energy demands of larger vehicles.

**Figure 22 - BEV200 Battery Pack Costs, 2013\textsuperscript{216}**

\begin{figure}[h]
\centering
\includegraphics[width=\textwidth]{bev200_batterypackcosts.png}
\end{figure}

\textsuperscript{214} Anderman, 2016.
\textsuperscript{215} EPA, 2016a. pages 5-346 to 5-347
\textsuperscript{216} EPA, 2016a.
ARB will continue to study battery technology into the foreseeable future as the technology develops. ARB will also continue to collaborate with the U.S. DOE on its understanding of battery technology and the state of the industry. As new battery cost and performance targets become available from the U.S. DOE and other entities, ARB will utilize those targets in total cost of ownership and vehicle costing models to identify where cost parity of PEVs with conventional ICE technologies may develop.

II.C.2. Non-Battery Costs
Information on non-battery costs learned from meetings with manufacturers indicates that some of those manufacturers may achieve all of the DOE EV Everywhere non-component battery costs targets before 2022. However, that response was not consistent across all manufacturers and current and projected future costs were not disclosed to staff during those meetings. The 2016 TAR developed the projected non-battery costs by relying heavily on the original FEV contracted tear down of a 2010 Ford Fusion Hybrid that was used in the 2012 FRM. The 2016 TAR’s discussion of costs derived using tear-down studies can be found in section 5.3.2.1.1 of the document.

The proliferation of PEV technology since the FEV Ford Fusion Hybrid tear-down study was completed highlights an opportunity to update the non-battery component costs. ARB has contracted with Ricardo to conduct tear down studies of several newer components to update these cost assumptions. Staff will use the results of those tear downs to update non-battery costs when they become available.

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217 EPA, 2016a.
II.C.3. Rolled Up PEV Costs
Table 8 below compares the previous (2011 ARB ACC ISOR) cost estimates to the updated 2016 TAR (joint agency). While battery costs have been updated to reflect the recent reductions, a nuance in comparing these analyses is that staff now expects to see longer range BEVs relative to what was originally assumed. This means that, compared to the 2012 ARB rulemaking, the newer incremental vehicle costs include a much larger battery pack (BEV200 today vs. a BEV100 from 2011). As a result of decreased battery costs but increased battery packs, the updated incremental vehicle costs for expected vehicles (BEV200) are about the same as they originally were estimated for the lower capability vehicles (BEV100). The incremental price varies from approximately $12,000 to $17,000 for a BEV200.

However, the two platforms most directly comparable show the scale of the battery cost reductions. The BEV75 from the 2016 TAR can be compared to the BEV100 in the 2011 ACC ISOR because ARB’s original BEV100 was based on test cycle range and equates to approximately a BEV70 for EPA label range as is used in U.S. EPA’s analysis. Comparing these two platforms shows vehicle incremental costs for a shorter-range BEV have declined between 22-36% depending on vehicle size in the 2025 model year.

Table 8 - Incremental Vehicle Costs (2025 ZEV compared to 2016 ICE vehicle, 2013)

<table>
<thead>
<tr>
<th></th>
<th>2013</th>
<th>2011 ISOR (ACC Rulemaking)</th>
<th>2016 TAR (EPA, NHTSA, ARB) **</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>BEV100</td>
<td>PHEV40</td>
</tr>
<tr>
<td>Subcompact</td>
<td></td>
<td>$11,804</td>
<td>$11,182</td>
</tr>
<tr>
<td>MdC / SmMPV</td>
<td></td>
<td>$12,591</td>
<td>$12,037</td>
</tr>
<tr>
<td>Large Car</td>
<td></td>
<td>$14,566</td>
<td>$15,685</td>
</tr>
</tbody>
</table>

* ISOR Table 5.4 adjusted to 2013$ with 1.09 CPI factor
** EPA OMEGA EV based on "label" range, ARB is UDDS. "Diff" = EPA BEV75 to ARB BEV100 Label vs. Test adjustment: 0.70
*** 15% weight reduction package

III. FCEV Technology Status and Trends
The current status of FCEV technology can be illustrated by a comparison between the recent 2014 status reported in the 2016 draft TAR, the historic 2010 TAR reported values, and the future 2020 and ultimate U.S. DOE targets. These targets are based on cost of ownership parity with hybrid drive technology and achievement of U.S. DOE target costs of hydrogen at the pump.

The relative progress of key FCEV technology groups are summarized in Table 9. Several technologies are midway from 2010 to the ultimate targets including, fuel cell (FC) system efficiency, FC system costs, FC durability, and hydrogen storage costs. As the FCEV technology

\[218\] ARB, 2011a.
technologies have improved, commercially available vehicles have been introduced. As both the number of available models and sales expand, it is expected that the technology will continue to improve toward the U.S. DOE targets.

Table 9 - Technology Status and U.S. DOE Targets for Automotive Fuel Cell and Onboard Hydrogen Storage Systems

<table>
<thead>
<tr>
<th></th>
<th>2010 TAR</th>
<th>2014 Status</th>
<th>2020 DOE Target</th>
<th>Ultimate DOE Target</th>
</tr>
</thead>
<tbody>
<tr>
<td>System Efficiency</td>
<td>53-59%</td>
<td>60%</td>
<td>65%</td>
<td>70%</td>
</tr>
<tr>
<td>System Cost</td>
<td>$61/kW ($51/kW)*</td>
<td>$55/kW ($43/kW)*</td>
<td>$40/kW</td>
<td>$30/kW</td>
</tr>
<tr>
<td>Fuel Cell System Durability</td>
<td>2,500 hrs.</td>
<td>3,900 hrs.</td>
<td>5,000 hrs.</td>
<td>5,000 hrs.</td>
</tr>
<tr>
<td>Vehicle Range</td>
<td>254 miles</td>
<td>312 miles **</td>
<td></td>
<td></td>
</tr>
<tr>
<td>H2 Storage Costs</td>
<td>$20/kWh</td>
<td>$17/kWh ($13/kWh)***</td>
<td>$10/kWh</td>
<td>$8/kWh</td>
</tr>
</tbody>
</table>

* 2010 TAR values include the then-current 2009 reported status and the 2010 update in parentheses. The 2014 Status includes the reported current cost status and a potential reduced cost based on available or near-term technologies in parentheses.

** Based on U.S. EPA rating for the 2015 Toyota Mirai. The U.S. EPA rating for the 2017 Honda Clarity was recently certified at 366 miles.

*** 2015 AMR reports a current cost status of $17/kWh, but the potential for reduction to $13/kWh in very short term with application of technologies within DOE’s funded programs.

III. A. Available FCEV Models:
Currently, three manufacturers (Hyundai, Toyota and Honda) offer FCEV models for sale or lease (see Figure 24). An additional two models have been announced for future release expanding the breadth of vehicle types to include a four-door sedan, a two-wheel drive SUV, and an all-wheel drive SUV. The available and announced FCEV models are summarized in Table 10 below.

A demonstration all-wheel drive, four-door pickup truck FCEV has been announced by General Motors that will be provided to the U.S. Army for testing in a year’s time (see Figure 25). The fuel cell features that the military has indicated are desirable include reliability, instant high torque at any vehicle speed, silent stationary operation, reduced thermal and acoustic signatures (reduced detection), field electricity generation, and fresh water production.

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219 EPA, 2016a.
220 Honda 2016a.
Figure 24 - FCEV Models Available in California now – Toyota, Hyundai, Honda

Figure 25 - General Motors Demonstration Military All-wheel Drive Four-door Pickup Truck

\(^{224}\) ibid
Most large vehicle manufacturers have ongoing fuel cell research and pre-production development programs. Manufacturers that are not yet committing to formal production programs point to the lack of fueling infrastructure as the primary reason for a delay in product development. Manufacturers currently offering FCEVs have indicated that they are prioritizing vehicles for areas with multiple hydrogen fueling stations. In the meantime, manufacturers are making agreements with other auto manufacturers or technology providers on fuel cell related research and development. The main goal is to spread risk and costs of complex technology development. Automotive partnerships include GM and Honda, Toyota and BMW, and Daimler, Ford and Nissan.

Toyota partnered with BMW in 2013 to supply BMW with a drivetrain and hydrogen storage technology, which includes the fuel cell stack and system, the hydrogen tank, motor, and battery. The goal is for BMW to produce a commercial vehicle by 2020 and for Toyota to raise production volumes to achieve lower costs.²²⁵ A few days later, Daimler, Nissan, and Ford announced a partnership to jointly invest in FC technology development with an explicit goal of quickly reducing costs by sharing investment capital and leveraging economies of scale.²²⁶ Partnerships of this type can help bring vehicle costs down when new technology is being developed. Later in the same year, General Motors and Honda announced a partnership agreement aimed at developing a joint drivetrain technology that is both more capable and more affordable. As both are leaders in the technology development, their combined product is

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²²⁵ GCC, 2013b. Green Car Congress, “BMW and Toyota expand collaboration with work on fuel cell system, sports vehicle, light0weight technology, and Li-air battery” January 24, 2013 http://www.greencarcongress.com/2013/01/bmwtmc-20130124.html (accessed 1/24/13)
expected to perform better, leverage consolidation of component supply chains for costs, and bring products to market faster.\textsuperscript{227}

**III. B. FCEV’s Anticipated Role in Transport Sector:**
FCEVs are targeted to fit into both the LDV and heavy-duty vehicle (HDV) sectors, both for long-range applications. In particular, the long range and fast refueling times (under five minutes) make FCEVs well suited to demanding duty cycles for larger LDV platforms and HDV applications.

**III. C. FCEV Basic Technology Components:**
FCEVs are full electric drive vehicles where the propulsion energy typically supplied by a battery is supplied by hydrogen and a fuel cell stack that transforms the stored hydrogen into electricity as needed. The inputs of the electrochemical process for the fuel cell stack are oxygen and hydrogen, with the byproducts being electricity, water, and heat. The major components of the fuel cell system include the fuel cell stack, the hydrogen storage (tank), balance of plant (valves, safety release, vent, fill tubes, etc.), and a battery pack for dynamic load balancing/response, moving the motor directly, capturing braking regeneration, and energy storage. Additionally, the system includes coolant subsystems, an air handling subsystem with compressor-expander module (CEM) precooling, and humidification. A schematic of a typical automotive fuel cell system is shown in Figure 26.

The fuel cell stack is much like a battery in that it consists of an anode, a cathode, and dividing electrolyte membrane (thus the name of the type used for light-duty applications: proton exchange membrane fuel cell).\textsuperscript{228} Additional stack components include the gas diffusion layer (GDL) that helps transport hydrogen and oxygen from flow channels to the anode and cathode surfaces, as well as separator plates that divide each individual cell.

An on-board hydrogen storage system for LDVs consists of a 700 bar (70MPa or 10,000psi) hydrogen pressure vessel and the balance of plant (BOP). The tank is typically wound carbon fiber construction with a polymer liner. The BOP consists of devices such as the fill tube and port, temperature sensor, pressure gauge, pressure relief device, rupture disc, solenoid control valve, primary pressure regulator, manual ball valve, a check valve, and related data communications hardware.

\textsuperscript{228} EPA, 2016a.
Figure 26 - Schematic of Components Included in a Fuel Cell System

III. D. FCEV Technology Trends:
There have been numerous developments in fuel cell technology in recent years. The broad topics of recent technology trends include fuel cell stack size reductions through simplification, fuel cell durability, fuel cell platinum use reductions, hydrogen storage production developments, and the advent of the plug-in FCEV (FCPEV).

Fuel Cell Size: Recently, there have been significant gains in fuel cell volume reductions. An analysis of the Toyota Mirai design revealed some of the system simplifications that lead to these size reductions: innovative fuel cell stack designs that reduce balance of plant components, simplified humidity management via improved gas diffusion layer (GDL) designs to enhance water flow field design, and lower pressure design to reduce air compressor sizing. Contributing to the reduced size, higher fuel cell system power densities have been achieved.

via a thinner GDL, a thinner electrolyte, and a more reactive catalyst.\textsuperscript{231} Other simplifications to the broader system include consolidation of valve functions (stack inlet shut valve, flow diverter shut valve, stack outlet shut valve, and pressure adjustment valve), removal of the hydrogen diluter, and reducing the number of hydrogen storage tanks from four to two in the vehicles commercially available today.\textsuperscript{232}

The magnitude of the fuel cell system advances gained over the past decade can be seen in Figure 27 with the General Motors system. Many manufacturers have stated they can now fit the entire fuel cell system in the conventional vehicle engine compartment enabling the use of standard vehicle platforms and maintaining expected passenger space for FCEVs.

\textbf{Figure 27 - General Motors FCEV System Size Improvements Depicted Over a Ten-Year Period}\textsuperscript{233}

\begin{figure}[h]
\centering
\includegraphics[width=\textwidth]{figure27.png}
\caption{First-generation GM FCEV system (left), 2016 prototype (right).}
\end{figure}

\textit{Fuel Cell Durability:} Durability of the fuel cell stack has improved over 50\% in four years (see Table 9). In an effort to continue the durability improvement trend, Toyota has developed technology to observe and better understand the degradation process of the platinum catalyst in

\textsuperscript{231} Tejima, 2016. Tejima G. “2016 Technology Developments to Enable FCEV Manufacturing at Scale”, Toyota Motor Company presentation at the 2016 CARB Advanced Clean Cars Symposium: The Road Ahead September 27\textsuperscript{th}. https://www.arb.ca.gov/msprog/consumer_info/advanced_clean_cars/technology_developments_to_enable_fcev_manufacturing_atcale_go_tejima.pdf


the fuel cell at a scale not able to be studied before. Toyota explains, “…the mechanism behind the degradation phenomenon of platinum nanoparticles has not been fully understood. This is largely due to the technical difficulty in directly observing the nanometer-sized platinum particles in liquid electrolyte under applied electrochemical potentials.” Three platinum degradation mechanisms were described: ‘aggregation’ where multiple platinum particles migrate together and form into one large particle (lowers surface area), ‘dissolution and reduction’ where platinum ions move from one particle to another resulting in the same end state as in aggregation, and ‘fall off’ where carbon oxidization with high electrolytically potential causes the platinum particles to fall off. The durability issue directly affects the amount of platinum required to achieve and maintain adequate catalytic activity.

**Platinum Use:** As recently as 2012, platinum comprised 37% of the fuel cell system costs. Recent efforts have reduced the minimum amount of platinum required for fuel cell catalysts by fivefold. This area remains a key priority for U.S. DOE and auto manufacturer research efforts. Nano technology developed in the laboratory shows promise of even more reductions. The use of platinum coated nanoframes provides better surface area per mass of platinum and has achieved a threefold increase in mass activity. Past advancements include better platinum utilization through: improving active surface area, improved gas transport (and thus reactions), and improved proton transport (less loss of efficiency).

**Hydrogen Storage:** Past developments in hydrogen storage technologies have shown gains in performance and cost reductions. For example, in 2014, Toyota was able to leverage 100 years of textile industry experience to wind carbon fiber tanks six times faster than the industry standard at the time and at higher quality. Additionally, aluminum and steel lined tanks that were injection molded were replaced with polymer linings that are blow molded with better wall thickness accuracy, better containment of the hydrogen molecules, and better durability against stress from constant heat changes due to rapid hydrogen filling.

The current state of hydrogen storage technology consists of compressed hydrogen stored in carbon wound tanks at 700 bar (70MPa or 10,000psi). This technology is the best available current option when considering cost, volume, and weight collectively. Unfortunately, strength

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requirements can only be satisfied by a cylindrical shape, which possess difficulties for manufacturers to fit them into the vehicle. However, future packaging advancements may reduce the space needed for storage in the vehicle. For example, the concept of “conformable tubes” is being explored where thick but strong tubes can be wound back and forth in more convenient shapes than a large cylinder but are still long enough to store sufficient hydrogen and may offer up to a 20% storage density improvement (see Figure 28).  

Figure 28 - Conceptual Image of Conformable Tubes for Compressed Hydrogen Gas On-board Storage

![Conceptual Image of Conformable Tubes for Compressed Hydrogen Gas On-board Storage](image)

The future of hydrogen storage has several promising non-gaseous developments that are not yet fully developed for commercial production. A summary of the various technology alternatives and their 2015 status are shown in Figure 29 which represents the alternatives’ current performance projections. The plot indicates that cryo-compressed or liquid hydrogen may have weight and volume advantages to compressed gas. Chemical hydride storage may have equal weight characteristics but a slight advantage on volume.

Cryo-compressed hydrogen offers potentially 50% more storage capacity than gaseous storage given a design space typical of a passenger vehicle and accounting for additional tank insulation. There are also infrastructure advantages as it does not require the same high pressure (350bar or less) improving the cost of operating a refueling station and its associated reliability. Additionally, the hydrogen is already cold and therefore no communication with the vehicle is required for monitoring tank refueling temperatures as is currently done during fueling for gaseous high compression systems to ensure safety. However, the cost of the on-board storage tank, the cost of cooling the hydrogen, and the cost of boil-off in the vehicle remain

challenges of this technology. These are similar benefits and issues for liquid hydrogen systems.\textsuperscript{241}

Complex hydride, chemical hydride, and C-sorbent hydrogen storage technologies are not yet developed to performance specifications suitable for consumer goods and are subsequently cost prohibitive.

**Figure 29 - 2015 Status of Hydrogen Storage Technologies (Does not represent eventual potential)**\textsuperscript{242}

\begin{figure}
\centering
\includegraphics[width=\textwidth]{figure29.png}
\end{figure}

*FCPEVs:* Daimler has recently announced the pending release of the Mercedes-Benz GLC F-cell: the world’s first production fuel cell plug-in hybrid electric vehicle (FCPEV) (see Figure 30). The vehicle will have a 9kWh battery that will provide up to 30 miles of grid-supplied electric range on battery only, a combined total range of 300 miles, and will be an all-wheel drive SUV. A 4kg hydrogen tank compressed to 700-bar will provide the balance of the vehicle’s range.

Daimler claims a 30% reduction in fuel cell system size (from previous versions) that will fit entirely into the engine compartment and a 90% reduction in platinum for the stack therefore


substantially lowering costs. Daimler has indicated it believes this vehicle has the potential to improve the economics of the hydrogen fuel supply in light-duty transportation.\textsuperscript{243}

\textbf{Figure 30 - Preproduction Image of Model Year 2018 Mercedes GLC FCPEV}\textsuperscript{244}

Specifically, Daimler claims the FCPEV has the potential to partly mitigate one of the near term barriers to FCEV implementation, namely, a limited hydrogen fueling infrastructure. Since the GLC can travel 20-30 miles on battery alone, the battery may be able to provide a typical user with enough range to meet approximately one-third of their travel needs.\textsuperscript{245} Thus, the frequency with which a driver would need to visit a hydrogen refueling station could be reduced, depending on the size of the on-board hydrogen storage capacity. Based on standard travel and choice model principles, this will increase the distance a driver is willing to drive out of their way to refuel on hydrogen, which may be necessary given a limited hydrogen refueling infrastructure. Additionally, drivers may be less reliant on refueling stations overall as they have the option to plug in with electricity. These two factors combined may offer some mitigation to the interim limited access to infrastructure.

\textbf{III. E. FCEV Cost Trends:}
The cost of an FCEV has come down dramatically in recent years. For example, the 2015 Mirai FCEV costs $1/20^{th}$ that of the Toyota Highlander FCHV-adv, which was available for lease only in Japan starting in 2008\textsuperscript{246} (available for pilot fleets elsewhere). As the motor and power electronic components are not unique to the FCEV (they are similar and may even be shared

\begin{footnotesize}
\begin{itemize}
\item \textsuperscript{245} Based on comparable electric range from Ford C-Max and Fusion Energy eVMT results in Appendix G.
\item \textsuperscript{246} Tejima G. 2016 Technology Developments to Enable FCEV Manufacturing at Scale, Toyota Motor Company presentation at the 2016 CARB Advanced Clean Cars Symposium: The Road Ahead September 27th. \url{https://www.arb.ca.gov/msprog/consumer_info/advanced_clean_cars/technology_developments_to_enable_fecv_manufacturing_atcale_go_tejima.pdf}
\end{itemize}
\end{footnotesize}
with BEV and HEV drivetrain components), their manufacturing scale can be leveraged; but they are not discussed in this section. The cost split between the remaining systems is depicted in Figure 31 for both low volume production levels (current) and high volume production levels (future). As the cost of a FCEV is more than a conventional vehicle, the relative cost magnitude of each component is important to understand.

**Figure 31 - Percent Split between Fuel Cell System Components for Low and High Volume Production Levels**

![Figure 31](image)

**Fuel Cell System Cost:** These costs are projected for 500,000 units of production per year and have associated federal U.S. DOE targets in ‘$ / kW’ of power output capacity. A history of the high-volume cost projections, published by the U.S. DOE each year since 2006, is shown in Figure 32 along with their targets for 2020 and beyond. These targets are based on cost of ownership parity with hybrid drive technology and achievement of U.S. DOE target costs of hydrogen at the pump. As shown, the high volume cost projections for fuel cell systems has declined substantially.

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247 EPA, 2016a.
To get a better idea of current fuel cell production costs, the U.S. DOE cost projections are shown again in Figure 33 but this time with the additional axis of production volume. With the data shown, the evolution in cost variation according to production volume over the past several years can be assessed. What the costs could be if production was 500,000 units per year is reiterated at the front facing corner of the plot.

Pulling from these projections and fitting a curve, staff can produce estimates on any input value. For example, at 100,000 systems per year, an 80kW system is projected by this analysis to cost approximately $5,500; a 100kW system would cost approximately $6,200 (in 2014).

---

Hydrogen Storage Systems: A 2014 analysis estimated an on-board hydrogen storage system (tank and BOP) cost of $16.76/kWh (approximately $660/kg of storage capacity). Prior to 2020, using near term developments, these costs could be reduced to $12.99/kWh (approximately $510/kg) (2015 AMR). A summary of the storage costs and performance status versus U.S. DOE targets is shown in Table 11. Current compressed gas storage costs are twice ultimate targets and are not expected to fully reach the ultimate U.S. DOE targets in the near term.

Table 11 - Summary of Hydrogen Storage Targets for Performance and Cost with Status of Various Technologies

<table>
<thead>
<tr>
<th>Storage Technology</th>
<th>Cost ($/kWh), [$/kg]</th>
<th>Gravimetric Density (kWh/kg), [kgH2/kg system]</th>
<th>Volumetric Density (kWh/L), [kgH2/L]</th>
</tr>
</thead>
<tbody>
<tr>
<td>2020 DOE Target</td>
<td>10, [333]</td>
<td>1.8, [0.055]</td>
<td>1.3, [0.04]</td>
</tr>
<tr>
<td>Ultimate DOE Target</td>
<td>8, [266]</td>
<td>2.5, [0.075]</td>
<td>2.3, [0.07]</td>
</tr>
<tr>
<td>700 Bar Compressed</td>
<td>17</td>
<td>1.5</td>
<td>0.8</td>
</tr>
<tr>
<td>350 Bar Compressed</td>
<td>13</td>
<td>1.8</td>
<td>0.6</td>
</tr>
<tr>
<td>Metal Hydride</td>
<td>43</td>
<td>0.4</td>
<td>0.4</td>
</tr>
<tr>
<td>Sorbent</td>
<td>15-16</td>
<td>1.2</td>
<td>0.6-0.7</td>
</tr>
<tr>
<td>Chemical</td>
<td>17-22</td>
<td>1.1-1.5</td>
<td>1.2-1.4</td>
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</table>

249 EPA, 2016a.
IV. References


BMW, 2016c. BMWi, "DESTINATION WITHIN RANGE. PLENTY OF ENERGY LEFT. Ideal for
everyday use - range and charging for the BMW i3.",
14 October 2016]

August 2016].


September 2016]

BW, 2016. Business Wire, "24M Delivers Initial Quantity of Production-size Semisolid Lithium-
Delivers-Initial-Quantity-Production-size-Semisolid-Lithium-ion. [Accessed 19 October 2016].

CAE, 2016. CHAdeMO Association Europe, "CHAdeMO ANNOUNCES HIGH POWER
(150KW) VERSION OF THE PROTOCOL," 1 June 2016. : http://www.chademo.com/wp/wp-


Electronics," in EVS26, Los Angeles, 2012

Code & Standards Development," in Advanced Cleen Cars Symposium: The Road Ahead,
Diamond Bar, 2016
https://www.arb.ca.gov/msprog/consumer_info/advanced_clean_cars/wireless_charging_richard
_carlson.pdf


CERT, 2016. UC Riverside Center for Environmental Research & Technology. “Current
Research” http://www.cert.ucr.edu/research/tsr/cr.html

System”, April 5, 2016.


SAE 2010 Utility Factor Definitions for PHEVs Using Travel Survey Data (J2841 SEP2010) – Fig 9 


https://www.arb.ca.gov/msprog/consumer_info/advanced_clean_cars/technology_developments_to_enable_hydrogen_onboard_storage_manufacturing_at_scale_ned_stetson.pdf 


https://www.arb.ca.gov/msprog/consumer_info/advanced_clean_cars/technology_developments_to_enable_fecv_manufacturing_at_cale_go_tejima.pdf


Voelcker, 2016b. J. Voelcker, Green Car Reports, "Why new Tesla 100D battery may be crucial for the Tesla Model 3," 12 September 2016.  


Volvo, 2016a. Volvo Car Corporation, “Volvo Cars announces new target of 1 million electrified cars sold by 2025,”  


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Appendix D: Zero Emission Vehicle Infrastructure Status in California and Section 177 ZEV states

January 18, 2017
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I. Overview

This appendix will examine the status of zero emission vehicle (ZEV) infrastructure needed to support the ZEV regulatory “Mid-Range Case” compliance scenario (see Appendix A for details of this scenario development). This appendix reports on the current status of ZEV infrastructure in California and the Section 177 ZEV states,\(^1\) reviews published assessments of existing infrastructure, and provides updated synthesis of these prior works that incorporates the latest data available. In addition, this appendix addresses the question of whether trends in infrastructure development indicate sufficient charging and fueling deployment rates in order to meet the demands of the expected ZEV fleet. Finally, this appendix details one potential 2025 electric charging infrastructure network, and analyzes how this potential network address the needs of a ZEV fleet envisioned by the current ZEV regulation and how those needs may change with an evolving vehicle and infrastructure landscape.

Since the Air Resources Board (ARB or the Board) adopted the Advanced Clean Cars (ACC) regulation in 2012, several important State initiatives have been adopted to drive ZEV deployment through associated infrastructure development. Assembly Bill 8\(^2\) (AB 8; Perea, Statutes of 2013, Chapter 401), extended the funding programs of Assembly Bill 118\(^3\) (AB 118; Nunez, Statutes of 2007, Chapter 750). AB 8 provides an assured annual funding source of up to $20 million for hydrogen fueling stations administered by the California Energy Commission (Energy Commission) and establishes an annual cycle of assessment of infrastructure and vehicle deployment progress and needs. AB 8 additionally continues funding programs for plug-in electric vehicles (PEV), meaning battery electric vehicles or BEVs and plug-in hybrid electric vehicles or PHEVs, first established under AB 118, though the amounts are allowed to vary annually. In addition, Senate Bill 350\(^4\) (SB 350, De León, Statutes of 2015, Chapter 547) enabled investor owned utilities (IOU) to participate in transportation electrification through the funding of infrastructure using rate payer proceeds. SB 350 is significant for many reasons including the recognition of rate payer benefits from transportation electrification, including to non-PEV driving ratepayers. Overall, it is expected that this will significantly accelerate expansion of PEV infrastructure. These State actions have major direct impact on the deployment rate of the State’s ZEV infrastructure deployment, though additional complementary policies have also been instrumental, as further discussed in Appendix E.

II. Summary of PEV Infrastructure Status

California and Section 177 ZEV states have seen substantial investments in PEV infrastructure in the past several years, and accelerated investments are expected as new infrastructure efforts emerge. PEVs and related infrastructure are no longer nascent technology but are fully commercialized, viable alternative transportation modes. Modern PEVs have been around for over a decade. Although next generation vehicle and battery technology is improving, current

---

\(^1\) Section 177 of the Clean Air Act allows states in non-attainment of the Federal ozone standards to adopt California’s regulation. Nine states have adopted California’s ZEV regulation: Connecticut, Maine, Maryland, Massachusetts, New Jersey, New York, Oregon, Rhode Island, and Vermont.

\(^2\) Assembly Bill No. 8 (Perea, Statutes of 2013, Chapter 401).

\(^3\) Assembly Bill No. 118 (Nunez, Statutes of 2007, Chapter 750).

\(^4\) Senate Bill No. 350 (De Le León, Statutes of 2015, Chapter 547).
technology is firmly established and all signs reinforce the PEV’s place in the long term transportation future. Initial infrastructure challenges such as technical specifications, operability standards, communication protocols, signage, Americans with Disabilities Act (ADA) compliance specifications, and procuring funding for an initial infrastructure network have been addressed. Over $250 million of private capital has entered the national PEV infrastructure market, supported by emerging business cases for charging networks. However, challenges, including infrastructure serving multi-unit dwellings (MuD) and underrepresented communities, open access standards, and utility rate structures that employ prohibitive demand charges do remain. Some of the major success and findings within today’s PEV infrastructure landscape include the following:

- 14,048 Level 1, Level 2, and direct current fast charger (DCFC) public and private (non-residential) connectors are operational in California.
- 7,035 Level 1, Level 2, and DCFC public and private (non-residential) connectors are operational in Section 177 ZEV states.
- Declining PEV infrastructure costs and growth in the global PEV market may enable increased deployment of charging equipment overall, though local conditions (such as the age of wiring in existing housing stock of a local market) may cause geographic variation of adoption rates.
- Recent state investments in DCFC corridors, both north/south and east/west, will facilitate a PEV with no more than 85 miles of range to traverse the entire State of California.
- Passage of SB 350 will accelerate widespread transportation electrification by directing investor owned electric utilities to make investments that accelerate the use of PEVs, either through infrastructure capital investments, electricity rates, etc. SB 350 identifies the need for transportation electrification on sufficient scale to achieve 2030 transportation emission targets for greenhouse gas (GHG) and criteria emission reductions. Utility investments will complement efforts by the private sector and other government entities (e.g., California’s regional government infrastructure programs).
- The California Building Standards Commission (BSC) has revised the Green Building Standards (CALGreen) Code to mandate PEV infrastructure (electrical capacity) in new commercial, single family, and some multifamily dwelling units. This will lower the cost of future electric vehicle supply equipment (EVSE) installations at these sites.
- Employing scenario planning methods, National Renewable Energy Laboratory (NREL) has quantified the number of connectors needed to serve specific PEV deployments targets. Using these sufficiency forecasts ARB created ratios of required connectors per PEV in California and Section 177 ZEV states. Based upon a comparison of these ratios, it appears there may be sufficient infrastructure in many Section 177 ZEV states to support greater PEV deployments.
III. Electric Vehicle infrastructure Background and Basics
PEV infrastructure is the collection of hardware and systems that supply electrical power to a PEV. Broadly speaking, PEV infrastructure includes electricity generating facilities, transmission lines, and transformers. However, equipment and facilities upstream of a consumer’s electrical meter is the responsibility of the electric utility and is overseen by the California Energy Commission (Energy Commission) and the California Public Utilities Commission (CPUC). Therefore, the focus of this section will be on equipment “behind the meter,” specifically EVSEs, connectors, and charging stations.

EVSEs are devices that supply electrical power to a vehicle and are typically classified by their output power and referred to as Level 1 (120V), Level 2 (240V), or DCFC (400V), Level 1 being at the lowest level of power and direct DCFC being the highest.

Connectors are the hardware that physically attach to the vehicle. Nearly all connectors associated with Level 1 and Level 2 charging are designed to a common architecture standard specified by Society of Automotive Engineers (SAE) and is often referred to as SAE J1772. Connectors associated with DCFC generally fall into one of three types: CHAdeMO, SAE Combo Connector, or Tesla Connector. The maximum power levels associated with each of these unique standards is different and evolving. These three connector “standards” for DCFC are not interchangeable but Tesla does offer an adapter for their customers. BEVs are typically equipped to handle Level 1 and level 2 charging with optional DCFC capabilities. Most PHEVs are only equipped to handle Level 1 and Level 2 charging, and DCFC is not available for these vehicles, as it is not necessary.

Charging stations are locations with one or more EVSEs and associated equipment available for public or private use. The equipment that supplies power to a vehicle is not considered a “charging station,” but the EVSE along with special signage, dedicated parking spaces, pay terminals, etc. all comprise a “charging station.” Put another way, a gasoline pump is not considered a “gas station”, but gasoline pumps in combination with storage tanks, a canopy, price boards, signage, and other amenities comprise a “gas station.”

IV. PEV Infrastructure Costs
Since 2010, sales of EVSEs have grown substantially. Although EVSE costs have sharply declined over the same period, the purchase of a Level 2 home EVSE remains a financial investment for most consumers. Home charging costs in ARB’s 2012 rulemaking used cost figures contained in the draft 2010 Joint Agency Technical Assessment Report (2010 TAR), released by the United States Environmental Protection Agency (U.S. EPA), National Highway Traffic Safety Administration (NHTSA), and ARB. Those figures calculated a per vehicle cost of up to $1,616 for home EVSE charging infrastructure. Those costs have significantly declined over the past 5 years.
In November 2015, the U.S. Department of Energy (U.S. DOE) released a report titled, *Costs Associated With Non-Residential Electric Vehicle Supply Equipment.* This report provides the most recent compilations of EVSE costs and factors influencing cost trends. This report was a synthesis of various studies on the subject in addition to data collected from EVSE owners, electric utilities, manufacturers, and installers. This section summarizes costs associated with installation of non-residential electric vehicle (EV) infrastructure. These costs include: trenching to install conduit, electrical panel upgrades, meeting ADA requirements, and geographic labor rates.

Installation rates for home EVSEs (Level 2) can vary significantly by region. This could be due to variation in material costs across regions, geographic labor rates, and the age of existing housing stock. For example, a report by the Electric Power Research Institute (EPRI) found that between 10 and 20 percent of the installations studied required electrical upgrades. These upgrades are less necessary in geographic areas with newer housing stock where higher power electrical panels are more prevalent.

Table 1 and Figure 1, from the U.S. DOE’s *Costs Associated With Non-Residential Electric Vehicle Supply Equipment* report, illustrate the costs and price variation in EV infrastructure equipment and installation costs.

**Table 1 - Non-Residential EVSE Equipment and Installation Costs**

<table>
<thead>
<tr>
<th>EVSE Type</th>
<th>EVSE Unit* Cost Range (Single Port)</th>
<th>Average Installation Cost (per unit)</th>
<th>Installation Cost Range (per unit)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Level 1</td>
<td>$300 - $1,500</td>
<td>Not available</td>
<td>$0 - $3,000 **</td>
</tr>
<tr>
<td>Level 2</td>
<td>$400 - $6,000</td>
<td>≈ $3,000 EV Project</td>
<td>$600 - $12,700</td>
</tr>
<tr>
<td>DCFC</td>
<td>$10,000 - $40,000</td>
<td>≈ $21,000 EV Project</td>
<td>$4,000 - $51,000</td>
</tr>
</tbody>
</table>

* EVSE unit costs are based on units commercially available in 2015

** The $0 installation cost assumes the site host is offering an outlet for PEV users to plug in their Level 1 EVSE cord sets and that the outlet already has a dedicated circuit.

---

7 U.S. DOE 2015.
Part of the reason EVSE costs are declining is the global market for PEVs, which has grown from approximately 30,000 vehicles in 2010 to nearly 500,000 by 2015. This strong growth in PEV sales has led to solid growth in the EVSE market, which has led to technological and production efficiencies resulting in lower costs.

Navigant Research, a leading consulting firm that specializes in global clean technology markets, expects the global market for EVSE to grow from around 425,000 units in 2016 to 2.5 million in 2025, a compound annual growth rate (CAGR) of 22%. These sales figures include all EVSE units—residential and commercial, Level 1, Level 2, DCFC, and wireless charging. This affects costs; a Level 2 residential EVSE, formerly priced between $900 and $1,000 in 2013, is currently priced in the $500-$600 range for basic units and is expected to fall below $500 in the near term.

V. Where Drivers Charge
Charging of a PEV occurs in one of three places: at home, at the workplace, or at a public facility. Determining where PEV drivers charge and how they use non-home based infrastructure is an important topic for infrastructure planning. As a result, many studies and analyses have been published on charging patterns and behaviors of PEV drivers. ARB analyzed in-use data provided by automakers from eleven different PEV models, including charging data from a small subset of those vehicles. As displayed in Figure 2 and explained in greater detail in Appendix G, looking at the Nissan Leaf data shows most drivers are charging

---

8 U.S. DOE 2015
their vehicles at home, although this has declined from 81% of charge events in 2011 to 67% in 2014 in part as more workplace and public infrastructure has become available. Trends found in Figure 2 are similar to results from various other studies such as white papers from INL’s EV Project.\textsuperscript{11}

Figure 2 – Charging Location Trends: Nissan Leaf

The trends from these various studies can be summarized using a construct called the “charging pyramid.” New York State Energy Research and Development Authority (NYSERDA) developed one such “charging pyramid” (Figure 3) which graphically depicts the interconnected relationships between charger type, location, costs, and frequency of charge events. The majority of charging events occur at home, at lower costs, and over longer periods of time. Additionally, as power increases, charging time decreases, but costs increase - - leading to fewer charging events at that higher power level. As the charging pyramid depicts, the majority of charge events occur at low cost Level 1, followed by more expensive Level 2. The fewest charging events occur at DCFCs.

\begin{itemize}
  \item [\textsuperscript{11}] INL 2014, Idaho National Laboratory, “What Kind of Charging Infrastructure Did Nissan Leaf Drivers in The EV Project Use and When Did They Use It?” The EV Project, INL, 2014
  
\end{itemize}
VI. PEV Infrastructure Trends

VI.A. Trends in Station/Connectors
The number of charging stations and connectors in the U.S. are increasing at varied but continual annual rates. The U.S. DOE’s Alternative Fuel Data Center (AFDC) maintains a database of public and private charging stations and connectors dating back to the 1990s.

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Figure 4 and Figure 5, created using the AFDC database, clearly depict that PEV infrastructure in the U.S. has increased substantially over the past 5 years. In 2010, there were approximately 206 public and private (non-residential) Level 2 charging stations and 347 Level 2 connectors. Nationwide, there are over 16,000 public and private (non-residential) Level 2 charging stations and over 36,000 Level 2 connectors, as of January 1, 2017. The national totals represent nearly a 70-fold increase in the number of connectors and stations in the past 5 years.

California’s share of the national total equals over 3,700 Level 2 charging stations and over 11,000 Level 2 connectors. Additionally, California and Section 177 ZEV states’ share of the National Level 2 connectors is 45%.
**VI.B. Trends in DCFC EVSE power**

The trend in charging, in particular DCFC, is towards higher power which ultimately will enable significantly faster charging and facilitate shorter “refueling events” similar to hydrogen or gasoline. As detailed in Appendix C, batteries in BEVs are becoming larger, increasing the vehicle’s range and potentially increasing the need for DCFC.

As battery technology is evolving – increasing energy density, decreasing costs – so is the technology designed to recharge those batteries. In general, DCFC (specifically CHAdeMO and SAE Combo) standards currently support charging rates of up to 50 kilowatts (kW) for most installations. However, CHAdeMO announced on June 1, 2016 that its standard has been amended to support 150kW charging.13 Installations with the new 150kW standard (beginning in 2017) will be able to support current and previous vehicles that are capable of utilizing CHAdeMO DCFC equipment.

The SAE Combo standard is also being revised to support higher charging rates. The combined charging standard (CCS) effort is being led by an industry formed and supported group called The Charging Interface Initiative e.V. (CharIN e.V.). The CCS covers single-phase AC and three-phase AC and DC high-speed charging (in both Europe and the U.S.) all in a single, easy to use system.14 CharIN e.V. is working to get CCS supported charging standards to 150kW as quickly as possible, with the ultimate goal of supporting up to 350kW charging rates15 (over 7 times the current DCFC levels). This very high charge rate is intended to refuel a 200 mile BEV in a matter of minutes.

**VI.C. Trends in EV infrastructure related to Building Codes**

The clear trend with building codes and standards is toward developing sufficient requirements to support PEV charging. For example, as a result of ARB’s involvement, the Green Building Standards (CALGreen) Code has been revised to include more robust requirements for PEV charging infrastructure in new buildings. ARB staff have worked closely with the Building Standards Commission (BSC) and Housing and Community Development (HCD) to develop and incorporate provisions into the CALGreen Code that require installation of PEV charging infrastructure, such as increased panel capacity and conduit to support a dedicated 240 volt circuit, in new commercial buildings. Note, this infrastructure requirement does not include the EVSE unit. New single-family homes, duplexes, and townhouses with attached private garages must install similar PEV charging infrastructure. Multifamily dwellings with 17 or more units on the building site must install PEV charging infrastructure in 3 percent of total parking spaces. Currently, nonresidential buildings with parking lots that have a minimum of 51 spaces must install EV charging infrastructure in 3 percent of parking spaces. However, effective January 1, 2016.

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2017, the requirements are increasing such that parking lots with 10 or more parking spaces must install PEV charging infrastructure in about 6 percent of parking spaces.\textsuperscript{16}

Staff is planning to measure the rate of installation of EVSE chargers in new buildings to track progress towards the statewide goal of infrastructure to support 1 million ZEVs by 2020 as articulated in Governor Brown’s Executive Order B-16-2012. Specifically because the CALGreen code does not require the actual EVSE unit, staff intends to study how many sites add this final piece of hardware. Staff will also continue to provide suggested code changes based on future updates to projections for PEV charging infrastructure needs.

**VII. Status of the Infrastructure Networks in CA and Section 177 ZEV states**

The status of the national PEV infrastructure network is robust and growing. The PEV infrastructure network in California and Section 177 ZEV states is equally strong, if not more so than the national average. As detailed in Table 2, and displayed in Figure 4 and Figure 5 above, the total number of public and private connectors in California and the Section 177 ZEV states is over 21,000, which represents nearly 47\% of the national total.

### Table 2 - Number of Public and Private Connectors (non-residential)\(^{17}\)

<table>
<thead>
<tr>
<th>Publicly Accessible Connectors</th>
<th>Level 1</th>
<th>Level 2</th>
<th>DCFC</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>California</td>
<td>619</td>
<td>9,803</td>
<td>1289</td>
<td>11,711</td>
</tr>
<tr>
<td>Section 177 ZEV states</td>
<td>488</td>
<td>5,352</td>
<td>841</td>
<td>6,681</td>
</tr>
<tr>
<td><strong>Sub-Total</strong></td>
<td>1,107</td>
<td>15,155</td>
<td>2,130</td>
<td>18,392</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Privately Accessible Connectors (non-residential)</th>
<th>Level 1</th>
<th>Level 2</th>
<th>DCFC</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>California(^1)</td>
<td>408</td>
<td>1,902</td>
<td>27</td>
<td>2,337</td>
</tr>
<tr>
<td>Section 177 ZEV states(^1)</td>
<td>64</td>
<td>545</td>
<td>15</td>
<td>624</td>
</tr>
<tr>
<td><strong>Sub-Total</strong></td>
<td>472</td>
<td>2,447</td>
<td>42</td>
<td>2,961</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Public and Private Connectors Combined</th>
<th>Level 1</th>
<th>Level 2</th>
<th>DCFC</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>California Connectors(^2)</td>
<td>1,027</td>
<td>11,705</td>
<td>1,316</td>
<td>14,048</td>
</tr>
<tr>
<td>Section 177 ZEV states Connectors</td>
<td>552</td>
<td>5,897</td>
<td>856</td>
<td>7,305</td>
</tr>
<tr>
<td><strong>Total (CA &amp; Section 177)</strong></td>
<td>1,579</td>
<td>17,602</td>
<td>2,172</td>
<td>21,353</td>
</tr>
<tr>
<td><strong>NATIONAL TOTALS</strong></td>
<td>3,626</td>
<td>36,312</td>
<td>5,257</td>
<td>45,195</td>
</tr>
</tbody>
</table>

\(^1\) Does not include home charging  
\(^2\) Infrastructure funded by Energy Commission represents approximately 17\% of California's total  
Source: U.S. AFDC Database accessed 01/06/2017

### VII.A. Status of California Network – Installed and Currently Funded

Although California’s PEV infrastructure landscape could be robust, this singular synopsis ignores both the significant investment, and strategic planning efforts that have resulted in the State’s growing PEV infrastructure network. The Energy Commission, the State’s investor owned and municipal utilities, local government, private capital markets, and ARB have all contributed toward the health of the PEV infrastructure landscape. The following paragraphs will explore the contributions and investments by some of these key stakeholders.

VII.B. Electric Utility Investment

Perhaps the greatest catalyst in the current PEV infrastructure landscape is with the introduction of private and public electric utilities in the PEV infrastructure market. In 2015 California enacted SB 350 which directs the CPUC to guide IOUs investments in the widespread transportation electrification including the deployment of charging infrastructure. This law is very significant for several reasons: it will allow IOUs to ultimately commence "phase 2" electrification programs if they are determined to meet specific requirements thereby potentially greatly expanding infrastructure for PEVs and other mobile sources in California. In addition, SB 350 defines how ratepayers benefit from transportation electrification (reduced emissions, reduced impacts to public health and the environment, increased use of alternative fuels, renewable energy integration, and economic benefits), and therefore can participate, through utility rates, in the funding of electrification programs.

Currently, three of the State’s largest investor-owned electric utilities have proposed, or are in the process of, investing over $200 million in PEV infrastructure. These initial, pilot investments will result in over 12,500 connectors or “make readies” at over 1,000 sites, many in low income areas (10%). In addition, three IOUs have announced that if these pilot programs are successful, they plan to invest millions more in PEV infrastructure.

VII.C. Governmental Investment

The Energy Commission has invested nearly $50 million in PEV infrastructure and an additional $7.6 million in planning-related activities. Their coordinated planning, modeling, and investment activities have yielded the results shown in Table 3.

As detailed in Table 3 and displayed in Figure 6, the Energy Commission’s current and proposed investment in DCFC infrastructure will result in over 320 DCFCs and more significantly, the ability to traverse the entire State north/south as well as east/west in a BEV with a 85 mile range. Although not quantified here, a number of regional and local governments have funded the installations of EVSEs (for example air districts).

### Table 3 - Energy Commission Funded EV Charging Stations as of November 15, 2015

<table>
<thead>
<tr>
<th></th>
<th>Residential</th>
<th>Multiunit Dwelling</th>
<th>Commercial</th>
<th>Workplace*</th>
<th>Fleet</th>
<th>DC Fast Chargers</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>Installed</td>
<td>3,937</td>
<td>247</td>
<td>1,903</td>
<td>233</td>
<td>97</td>
<td>65</td>
<td>6,482</td>
</tr>
<tr>
<td>Planned</td>
<td>-</td>
<td>48</td>
<td>924</td>
<td>133</td>
<td>34</td>
<td>256</td>
<td>1,395</td>
</tr>
<tr>
<td>Total</td>
<td>3,937</td>
<td>295</td>
<td>2,827</td>
<td>366</td>
<td>131</td>
<td>321</td>
<td>7,877</td>
</tr>
</tbody>
</table>

Source: California Energy Commission. Does not include projects that have yet to be approved at a Commission business meeting. *An unspecified number of additional workplace charging stations are included in the commercial column, which were funded before workplace chargers were tracked separately.
VII.D. Private Investment
In addition to government and electric utility funding, significant private capital has flowed into the PEV infrastructure market. Nationally, Charge Point, EVgo, and Tesla are three of the largest private companies operating in the infrastructure space. These firms have invested hundreds of millions of dollars in EV infrastructure, networks, and related systems. These private investments have yielded over 7,700 charging stations and 21,000 connectors nationally, including nearly 3,000 DCFC connectors. As such, it is a testament to the strength of the infrastructure market and an affirmation of market confidence.

VII.E. Innovative Funding Opportunities
Recognizing the broad environmental benefits related to zero-emission vehicles and the need for additional resources to support the infrastructure for these vehicles, California is continually looking for innovative opportunities to direct new investments in PEV infrastructure.

One such opportunity arose in 2012 when the CPUC was negotiating a settlement with NRG Energy (NRG) over their involvement in the 2001 California electric power crisis. As a result of these negotiations, NRG agreed to install at least 200 DCFC stations across California including 20% in low income areas. In addition, NRG agreed to install infrastructure for “plug-in” Level 1 and Level 2 EVSEs. These “make readies” as they are commonly referred to, are being installed at MuDs, workplaces, and public interest sites.18

Figure 6 - Existing and Planned Statewide DCFC Network Corridors (Funded by Energy Commission)
In addition, Volkswagen in the proposed consent decree for actions related to the use of a “defeat device” on many of their light-duty diesel vehicles in the U.S., has agreed to invest $800 million over 10 years in California, and $1.2 billion in the other 49 states, in PEV infrastructure, consumer education, green cities, and in increasing ZEV access for the advancement of zero-emission vehicles technology. It is likely this investment will greatly increase infrastructure and access to infrastructure across California.

**VII.F. Status of the Network in the Section ZEV 177 States**

Although California is the leader in PEV infrastructure, public infrastructure in Section 177 ZEV States is healthy. In the context of their respective PEV fleets, Section 177 ZEV States’ infrastructure is more robust than California’s. One metric of infrastructure access is the ratio of public and workplace connectors to the number of PEVs on the road. In California the ratio of connectors to 1,000 PEVs is approximately 46. In Rhode Island, there are 234 connectors per 1,000 PEVs. In eight out of the nine Section 177 ZEV states, the ratio is higher than California’s. Only New Jersey, at 44 connectors per 1,000 PEVs, has a slightly lower ratio. Although this data does not determine if current infrastructure is “sufficient”, it does imply there are other reasons why PEV sales are lower in Section 177 ZEV states compared to California.

**Figure 7 - Ratio of Public and Workplace Connectors per 1,000 PEVs**

![Graph showing the ratio of public and workplace connectors per 1,000 PEVs for various states.](image)

**VIII. PEV Infrastructure Needs for Forecasted Demand in CA**

The topic of infrastructure sufficiency is important in answering questions related to infrastructure’s role in supporting or impeding the projected expansion of the PEV market as envisioned in the ZEV regulation. Specifically, does ample charging infrastructure facilitate PEV adoption or does insufficient infrastructure hinder adoption?

A statistical link between charging infrastructures and sales may exist but studies in this area are limited. However one such study to address this topic was released in October 2016 by the
International Council on Clean Transportation (ICCT). They issued a white paper titled *Sustaining Electric Vehicle Market Growth in U.S. Cities*. In this paper ICCT finds a statistical correlation between charging infrastructure and PEV market growth and that expansive charging networks in northern California and elsewhere are linked with higher PEV sales.\(^{19}\)

However, the larger question of what constitutes sufficient infrastructure remains. The issue of sufficiency is a particularly challenging question due to the evolving PEV/infrastructure landscape. Larger vehicle batteries with greater energy density, greater vehicle range, higher power charging, and an evolving PEV driver profile may make today’s charging behavior, which formed the foundation for research on sufficiency, profoundly different by 2020 and 2025.

However, despite the evolving nature of PEV charging and associated uncertainty, the importance of the “sufficiency” question motivated the Energy Commission to contract with the National Renewable Energy Laboratory (NREL) to investigate this issue. In May 2014, the Energy Commission released the *California Statewide Plug-in Electric Vehicle Assessment*\(^{20}\) which explored the issue of infrastructure sufficiency using scenario planning methods. A new analysis is forthcoming by NREL for the Energy Commission and is expected to be complete in 2017.

The 2014 NREL report estimated the number and type of EVSEs needed to meet the Governor’s goals in Executive Order B-16-2012 (infrastructure to support 1 million ZEVs by 2020) by estimating the total annual power demand for 902,000 PEVs.\(^{21}\) Using a set of equations solved simultaneously (Figure 8).

This report looked at two scenarios for charging; a “Home Dominant” scenario where the majority of charging occurs at home, and a “High Public Access” scenario where workplace and other public charging provide a greater percentage of the overall fleet charging requirements. It should be noted that even under the “High Public Access” scenario, the majority of charging events occur at home.\(^{22}\)

Scenario planning analysis is often used in emerging markets where there exists a high degree of uncertainty in the data and trends, as was the case with PEV infrastructure between 2010 and 2014. As scenario planning analysis continues to evolve, ARB is using the results of NREL’s assessment to bracket a high and low range for sufficient PEV infrastructure. To calculate this range, ARB examined the number of “charge points” required under these two scenarios and divided by the number of PEVs they are intended to serve. A ratio of “charge points” to PEV was calculated, and this ratio can be used as a metric in evaluating our progress in meeting PEV infrastructure goals. The Table 5 details these ratios:

---


\(^{21}\) PEV share of Governor Brown’s ZEV infrastructure goal for 1 million ZEVS + PHEVs by 2020

\(^{22}\) NREL 2014
Figure 8 - Equations to Calculate the Quantity of EVSEs Needed to Meet EO B-16-2012

The analytic approach involves calculating the number of EVSE stations through two equations, one being function of installed EVSE capacity and peak hourly demand (kW) and the other a function of electricity used by PEVs (kWh). These two equations are solved simultaneously to determine the total number of EVSE units.

\[
N_{i,j} = \frac{Q_{\text{total}} \cdot f_{i,j}}{m_{\text{event},i,j} \cdot \eta_j \cdot N_{\text{Chgpts/Stn}} \cdot N_{\text{Chgs/Chgpt}}}
\]

where,

\[
N_{i,j} = \text{Number of EVSE stations of type and location } i \text{ providing electricity to PEV type } j
\]

\[
Q_{\text{total}} = \text{Total kWh of electricity required for all PEVs (kWh/day)}
\]

\[
f_{i,j} = \text{Percent of total electricity provided by EVSE type } i \text{ to PEV type } j \text{ (percent)}
\]

\[
m_{\text{event},i,j} = \text{Average daily e-miles provided per charging event by EVSE type } i \text{ to PEV type } j
\]

\[
\eta_j = \text{Electricity consumption rate by PEV type } j \text{ (Wh per mile)}
\]

\[
N_{\text{Chgpts/Stn}} = \text{Average number of charge points per EVSE station}
\]

\[
N_{\text{Chgs/Chgpt}} = \text{Average number of charging events per charge point per day}
\]

\[
N_{i,j} = \frac{Q_{\text{total}} \cdot f_{i,j} \cdot d_{\text{hr,peak},i} \cdot (1 + \beta_{i,j})}{C_i}
\]

where,

\[
N_{i,j} = \text{Number of EVSE stations of type and location type } i \text{ providing electricity to PEV type } j
\]

\[
Q_{\text{total}} = \text{Total electricity provided to all PEVs (kWh/day)}
\]

\[
f_{i,j} = \text{Percent of total electricity provided by EVSE type } i \text{ to PEV type } j \text{ (percent)}
\]

\[
d_{\text{hr,peak},i} = \text{Percent of electricity provided during the peak hour of a typical day (percent per hour)}
\]

\[
\beta_{i,j} = \text{Capacity buffer for EVSE of type } i \text{ providing electricity to PEV type } j \text{ (percent)}
\]

\[
C_i = \text{Nominal installed capacity of EVSE type and location } i \text{ (kW)}
\]

---

Table 4 - Connectors Modeled by Scenario to Reach EO Targets (from NREL’s Statewide Assessment)\(^{23}\)

<table>
<thead>
<tr>
<th>Scenario/Charge Level</th>
<th>HOME</th>
<th>WORKPLACE</th>
<th>PUBLIC</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Level 1</td>
<td>Level 2</td>
<td>Level 1</td>
</tr>
<tr>
<td>Home Dominant Scenario</td>
<td>511,000</td>
<td>365,000</td>
<td>20,100</td>
</tr>
<tr>
<td>High Public Access Scenario</td>
<td>517,000</td>
<td>289,000</td>
<td>22,900</td>
</tr>
</tbody>
</table>

\(^{23}\) NREL 2014
Table 5 - Ratio of Connectors per PEV by Scenario Type (combining all charging levels)

<table>
<thead>
<tr>
<th>Scenario Type</th>
<th>HOME</th>
<th>WORKPLACE &amp; PUBLIC</th>
</tr>
</thead>
<tbody>
<tr>
<td>Home Dominant Scenario</td>
<td>0.971</td>
<td>0.1379</td>
</tr>
<tr>
<td>High Public Access Scenario</td>
<td>0.894</td>
<td>0.2406</td>
</tr>
</tbody>
</table>

The above ratios were derived from the total power demand calculated from equations in Figure 8. The total power demand is partially a function of the vehicle fleet mix (i.e., the more FCEVs in the fleet the less electric power demand and fewer EVSEs are needed). Therefore, a comparison of the NREL fleet mix to the ARB fleet mix is useful.

Figure 9 - NREL’s Fleet Mix vs ARB’s Mid-Range Input Scenario24 (2020)

Using NREL’s ratio of PEVs to connectors and the projected number of PEVs in ARB’s “mid-range” compliance scenario, ARB calculated the annual and cumulative number of PEVs, along with the annual and cumulative number of connectors to support the projected PEV deployment. These calculations are plotted in Figure 10 and Figure 11.

24 See Appendix A
Figure 10 - Cumulative Number of Workplace and Public Connectors Projected for the mid-range ZEV compliance scenario (through 2025)

Figure 11 - Cumulative Number of Home Connectors Projected for the mid-range ZEV Compliance Scenario (through 2025)
IX. Public Infrastructure Needs - Where We Need to Be (2025)

Building upon the forecasted charger needs from Figure 10 and Figure 11 the following questions arise:

1) What scale of infrastructure deployment is needed to meet projected demand? And

2) How will current actions in infrastructure development address this demand?

The first question of needed infrastructure was answered in the above analysis and figures. This second question is explored below. To show a reference of PEV infrastructure by 2025 from current programs, staff examined historical infrastructure data growth rates and used this to extrapolate a forecast to 2025, the results of which are shown in Table 6. As with any extrapolation, the conditions that influenced past trends need to be present moving forward or cease to be relevant. Table 7 expands upon this issue.

Table 6 - Projected Public and Private Connectors through 2025 vs NREL’s Forecasted Requirements (Level 1, Level 2, and DCFC)

<table>
<thead>
<tr>
<th></th>
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<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Current Connector Trends (extrapolated)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>809</td>
<td>3,624</td>
<td>7,653</td>
<td>12,989</td>
<td>15,001</td>
<td>20,628</td>
<td>26,759</td>
<td>33,344</td>
<td>36,795</td>
</tr>
<tr>
<td>Projected new connectors from state programs</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>1,750</td>
<td>7,000</td>
<td>14,143</td>
<td>21,286</td>
<td>28,429</td>
<td>32,000</td>
</tr>
<tr>
<td>Projected Connector Total</td>
<td>809</td>
<td>3,624</td>
<td>7,653</td>
<td>14,739</td>
<td>22,001</td>
<td>34,771</td>
<td>48,045</td>
<td>61,773</td>
<td>68,795</td>
</tr>
<tr>
<td>Estimated Connectors Needed under 2014 NREL Home Dominant Scenario</td>
<td>29</td>
<td>3,705</td>
<td>17,619</td>
<td>33,196</td>
<td>46,146</td>
<td>65,494</td>
<td>92,574</td>
<td>124,606</td>
<td>142,582</td>
</tr>
</tbody>
</table>

As Table 6 details, California may not be track to meet the suggested sufficiency thresholds as detailed in NREL’s Statewide Infrastructure Assessment. However, it should be noted that the NREL 2014 work in this area was an initial analysis and is being updated. Instead of using scenario planning methods, the updated analysis will develop a model that will use inputs such as actual travel data, expanded PEV driving range, and electricity rates that influence where drivers charge. This new approach should help answer the question of infrastructure sufficiency more fully. It is possible that this model will decrease the suggested number of connectors required to meet the charging needs of California’s 2025 fleet. In addition, the introduction of
BEVs with ranges of 200 to 250 miles priced comparable to their gasoline counterparts are starting to arrive. These "long range" BEVs could significantly lessen the dependence upon public and private Level 1 and Level 2 chargers, thereby making the projected connector numbers more closely aligned with the NREL’s projections.

Table 6 details a mathematical extrapolation of historic connector installation trends. As mentioned, for the extrapolation to hold, the factors that influenced the data being extrapolated needs to continue moving forward or cease to be relevant. The following Table 7 lists some of the conditions and complementary measures that influenced previous PEV infrastructure development and conditions that will be present in the future:

**Table 7 - California’s Infrastructure Programs and Complementary Policies - Past vs Future**

<table>
<thead>
<tr>
<th>Past</th>
<th>Mid/Long Term</th>
</tr>
</thead>
<tbody>
<tr>
<td>Government Investment in PEV</td>
<td>YES</td>
</tr>
<tr>
<td>Infrastructure</td>
<td></td>
</tr>
<tr>
<td>Utility Investment in PEV Infrastructure</td>
<td>EXISTING</td>
</tr>
<tr>
<td>Private Capital in PEV Infrastructure</td>
<td>EXISTING</td>
</tr>
<tr>
<td>Market</td>
<td></td>
</tr>
<tr>
<td>Consumer Awareness of infrastructure Options</td>
<td>LOW</td>
</tr>
<tr>
<td>PEV Infrastructure Requirements in Building Codes and Standards</td>
<td>EXISTING</td>
</tr>
<tr>
<td>Open Access – SB 454</td>
<td>NO</td>
</tr>
<tr>
<td>EVSE Costs</td>
<td>Declining</td>
</tr>
<tr>
<td>DCFC Charging Power</td>
<td>50kW</td>
</tr>
</tbody>
</table>

**X. Home Charging Infrastructure Needs - Where We Need to Be (2025)**

With regards to home charging infrastructure, Figure 11 depicts a significant number of connectors needed to accommodate a large scale PEV expansion. Due to a lack of reliable data on home charging infrastructure it is difficult to use NREL’s ratios and extrapolate current home charging trends to quantify potential gaps, if any, in projected home charging infrastructure. However, as noted earlier, between 80% – 85% of all charging occurs at home; in fact NREL’s infrastructure assessment used high access to home charging as a basis in both their scenarios. Therefore, it is reasonable to conclude that the majority of current PEV drivers have access to, or the ability to install, home charging infrastructure.
However, because the goal is to expand the number of potential PEV drivers, then targeted efforts to increase home charging infrastructure in non-traditional, single family housing will be needed. Approximately 50% of the State’s population lives in rental housing and a large percentage of the population lives in MuDs. Charging infrastructure in rental housing and MuDs presents unique challenges and may result in the need for more public charging infrastructure or dedicated resources to resolve these challenges.

Xi. Challenges and Opportunities with PEV Infrastructure

The PEV infrastructure environment, in its current state, has been in development and refinement for nearly a decade, and many of the initial challenges have been met: technical standards, communication protocols, signage and design guidelines have all been adopted. As a result of meeting these initial challenges, consumer acceptance, private capital investments, and electric utility involvement have followed. However, challenges and opportunities surrounding PEV infrastructure exist and the following paragraphs detail some of the more prominent issues.

Xi.A. Challenge - Multi-unit Dwelling (MuD)

Electric utilities estimate that over 80 percent of all current PEV charging occurs at home, usually in a garage with access to electrical power. However, nationwide, approximately 36 percent of households reside in rental housing with 60 percent of those households living in MuDs. Most MuDs do not provide EVSE or access to electrical power in proximity to parking and access to charging in MuDs is important. Specific challenges include:

- Physical Facilities: Age, existing electrical infrastructure, and physical layout of parking within a MuD all present unique challenges in installing and operating PEV infrastructure.

- Diversity: MuDs are comprised of a variety of structures from modern, urban high-rise buildings to sprawling, midrise suburban apartment complexes to low-density townhome condominiums. Given this physical diversity, there is no universal solution or standardized cost for providing EVSE access in MuDs.

- Economics: Costs associated with installing, maintaining, and operating EVSE needs to be accounted for; however, equitable distribution of these costs among building occupants, PEV drivers, and the building owner remains a challenge.

Xi.B. Challenge - Increasing Battery Capacity Impact on Infrastructure Needs

As explained in greater detail in Appendix C, vehicle battery costs are declining while energy density is increasing. Currently, most BEVs sold today have a range under 100 miles; the most common BEV on the road today, the Nissan Leaf, has a range of 84-107 miles depending upon the model year. Tesla vehicles are the primary exception, offering a range in excess of 200 miles but at a much higher price. However, General Motors has recently introduced the Bolt
EV, a BEV with a 238 mile EPA estimated range and a MSRP of $37,495 before incentives.\textsuperscript{26} The Bolt EV is currently available at GM dealers in California. Tesla has commenced orders on the Model 3, a BEV with an estimated 215 miles of range and a starting price of $35,000 before incentives.\textsuperscript{27} These developments hold the potential to alter the need for, and use of, public charging infrastructure in ways unknown. For example, larger battery packs will take longer to charge which may increase the demand for DC fast charging and decrease the demand for Level 1 and Level 2 public charging. However, it is also likely that longer range PEVs will charge less often which may also impact public charging infrastructure. These uncertainties require on-going analysis of the PEV market and charging behavior.

\textbf{XI.C. Challenge and Opportunity – Inductive Charging}

As detailed more fully in Appendix C, current PEV charging standards and protocols involve connected, conductive charging. PEV batteries are charged by physically attaching the vehicle to a power source via the EVSE. Currently, this physical connection is essential to almost all PEV charging.

However, some automakers, third party vendors, and charging providers have begun to develop wireless, inductive charging. Inductive charging uses an electromagnetic field to transfer energy between the vehicle and the power source where no physical connection is required. Although challenges with safety and efficiency still remain, INL is studying inductive charging and it appears that these challenges will be addressed and inductive charging will enter the marketplace well before 2025.

\textbf{XI.D. Opportunity – Electric Utility Involvement in PEV Infrastructure}

In addition to the electric utility investment as detailed above under SB 350, other state power companies and authorities are entering the PEV infrastructure sector. The New York Power Authority (NYPA) and others are collaborating in an initiative called ChargeNY which aims to reach 3,000 PEV charging stations to support an expected 30,000-40,000 PEVs on the road in New York by 2018.

The State of Oregon has introduced SB 1547 (Beyer), which allows their PUC to direct electric companies to file applications for programs to accelerate transportation electrification, including customer rebates for PEV charging and related infrastructure.

\textbf{XI.E. Opportunity – Vehicle Grid Integration}

PEVs store a large amount of energy in their on-board batteries. Current EVSE and charging specifications and protocols are intended to facilitate the one-way power transfer from the electrical grid to the vehicle. However, new protocols and standards are being developed and tested to facilitate the two-way transfer of energy from the vehicle back to the grid; this is referred to as vehicle grid Integration (VGI). VGI holds the potential to assist electric utilities in meeting their peak power demands by tapping a new source of power storage – a large PEV


fleet. Many programs across the nation are in place to study VGI including programs in California, Delaware, and at the U.S. Department of Defense. The Energy Commission, in coordination with the CalISO developed a Vehicle Grid Integration Roadmap in 2014 to outline a way to develop solutions that enable PEVs to provide grid services while still meeting consumer driving needs. CalISO and PUC have on-going policy actions to put this in place and tests are occurring, but implementation will take a number of years.

Pilot projects exist to experiment with the operational concepts. On the east coast, Delaware has been a long-standing leader in VGI research and grid service pilot experimentation. The U.S. Department of Defense (DOD) has become a leader in VGI pilot studies with a prominent project at the LA Air Force Base. This project, in partnership with CalISO, Energy Commission and the Southern California Energy (SCE) utility, is experimenting with a fleet of light-duty and medium-duty BEVs providing grid services while not being used. Grid pricing and long-term cost effectiveness are being evaluated. This typically involves studying the benefit to the grid (with payments to the vehicle owner) while also studying the impact on the vehicle battery’s life.

**XI.F. Opportunity – Utility Demand Response and Time of Use Rates (TOU)**

In broad terms, electrical power on the grid comes from central electric generation facilities. This electricity is owned or purchased by an electric utility and resold to its customers. Although most utility bills make the cost of electricity appear relatively uniform, the actual cost to procure electricity from a generator can vary greatly. Prices can spike (or fall) quickly and with little notice. Factors that affect the price of electrical power include temperature, weather, time of day, demand for power, availability of operational power plants, and many others.

Currently PEVs charge when they are parked, and most vehicles, including PEVs, are parked 96 percent of the time. Therefore, a PEV doesn’t need to be charging at all times when it is parked. This fact, coupled with emerging technologies that allows an electric utility to communicate with advanced EVSEs and control the power transfer, provides utilities a unique opportunity. Utilities could effectively manage PEV power demands in the broader context of regional grid operation, power generation and supply, local transformer capacity, and price fluctuations. The next generation of networked EVSEs provides a valuable opportunity for utilities to operate more efficiently and effectively.

In addition to hardware and emerging technology to control when PEVs charge, thereby striving to optimally balance load and supply, electric utilities (including eight utilities in California and three in Section 177 ZEV states) have introduced TOU electric rates. Simply put, TOU rates set higher and lower electric tariffs based upon predetermined times of the day. Historically speaking, electricity demand is cyclical and relatively predictable. Therefore, an electric utility

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can predetermine when demand will be high and set rates to discourage use during those periods. As mentioned, PEVs are typically parked longer than they need to fully charge, therefore customers can choose to charge their vehicles when TOU rates are low, thereby saving money and helping to smooth out peak electrical demand.

Using simple market mechanisms that TOU rates provide, electric utilities can more effectively balance load and supply. Although TOU rates may not be for all consumers, they do provide an option for PEV drivers that can use the rate structure effectively. INL has studied the effect of TOU pricing has on power demand and has concluded that electric utilities, without TOU rates, can expect a median peak demand of 0.8 kW per day from each PEV in the service territory and this peak occurred at approximately 10 p.m. In contrast, electric utilities that offered TOU rates, can expect a median peak demand of 1.7 kW per day from each PEVs in the service territory. In the INL study this peak occurred within an hour of the start of the greatest incentive period.31

**XI.G. Opportunity FAST Act - Nationwide Alternative Fuel Corridors**

In December 2015, President Obama signed The Fixing America's Surface Transportation (FAST) Act. This bill not only authorized funding for traditional surface transportation projects, but section 1413 of the bill requires the U.S. Department of Transportation (U.S DOT) to designate corridors to improve mobility of passenger and commercial vehicles that employ electric, hydrogen fuel cell, propane, and natural gas fueling technologies across the U.S. by December 2016. Although the bill does not provide direct funding for alternative fuel infrastructure, the U.S. DOT can support these corridors through technical assistance, analytical support, peer review, marketing and branding. In addition, this bill amended the Congestion Mitigation and Air Quality Improvement (CMAQ) Program to give priority to designated EV and compressed natural gas corridors. This bill facilitates the planning activities required in the construction and implementation of nationwide PEV corridors.

**XI.H. Challenge and Opportunity - PEV Charging Impact on the Grid and Related Emissions**

As transportation becomes electrified, the energy supply will partially move from refineries to the electric grid. This means electricity demand will grow and electric utilities will need to plan for the new loads, both in terms of production supply and local distribution of power. Although the transportation electricity demand will remain small for a number of years, utilities, regulators and research entities are already managing this. Most prominently in the U.S., EPRI has led many programs to evaluate the growing impact.32 In California, the CPUC, ISO, and Energy Commission also are very active in this space.

In general, peak load demand will not be a problem for a few years as vehicle loads are still small, but will become more prominent post 2020. In California’s utility territories, with the growth of solar generation, daily grid generation profiles have peaks in the early afternoon when...
solar is high; but have problems in early evenings as homeowners return home turning everything on as solar production is declining. If PEVs are also plugged in at this time (early evening), it will amplify the grid management problem. Time-of-day grid pricing will help mitigate this and encourage charging late at night (or in the late morning at work). The CPUC and CalISO are actively exploring these pricing mechanisms.

DCFC is a more near-term issue with high power spikes on the grid currently at 50kW. The higher power levels being explored, 150kW and 350kW noted earlier, may create a strain on local grid distribution equipment, and may necessitate a dedicated power supply to the properties for the charging stations. On-site battery storage can also help mitigate the voltage spikes on the grid distribution equipment, but adds equipment costs. Storage costs may be worth the investment depending on electric load demand charges from grid providers.

With regards to the national grid emission impacts from transportation electrification, in September 2015 EPRI and National Resources Defense Council (NRDC) published the *Environmental Assessment of a full Electric Transportation Portfolio* to examine these impacts. The study authors examined two scenarios of the 2050 electric sector, a *Base GHG scenario* and a *Lower GHG scenario*. Both scenarios demonstrated lower grid emission by 2050, however the *Lower GHG scenario* showed greater reductions due to an increasing carbon price resulting in faster deployment of lower carbon electrical power generation technology. The study examined both GHG and criteria emission impacts.

XII. Summary of Hydrogen Infrastructure Status and Projections in California

California has been the focal point of fuel cell electric vehicle (FCEV) deployment in the U.S. and the related development of hydrogen fueling infrastructure. While early efforts grappled with the difficulties of establishing two nascent industries that are mutually dependent on one another (success of the FCEV market fundamentally depends on success of the hydrogen fueling network, and vice-versa), California’s current programs (most prominently Assembly Bill 8) are enabling growth of the first major FCEV and hydrogen fueling markets in the U.S. Major policy and technical hurdles have been overcome in recent decades thanks to the coordinated efforts of the State and industry partners.

The substantial progress made to date is helping address the issues of launching new technology markets, but stakeholders are also keenly aware of new challenges that will need to be addressed in order to move the industries into mainstream mass-market appeal. Managing and accelerating hydrogen fueling network growth, addressing economic hurdles of the hydrogen fueling business, and ensuring continual advancements in the retail customer experience are all at the forefront of today’s efforts. Major success and challenges within today’s industry are as follows:

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• 30 stations (retail and non-retail) are now open in California’s hydrogen fueling network, which is more than double the amount available at the end of 2015. Stations with full retail capability and amenities are now the standard in California and expected to comprise fueling networks in new markets across the United States.

• Station development timelines are improving, and benefitting from lessons learned during the process of contracting, permitting, constructing, and commissioning the earliest retail stations. Best practices based on these experiences are incorporated into the latest Energy Commission grant solicitation and may offer a blueprint for future development in Section 177 ZEV states.

• Use of the HyStEP device to validate new stations’ adherence to standardized fuel protocols has begun. Implementation of the device is alleviating burden previously placed on auto manufacturers to test and validate new stations.

• Fueling demand at hydrogen stations is rapidly growing. Developer FirstElement Fuel, who operates 16 stations currently, has shared that they fueled 1 million miles of FCEV travel in their first 9 months of operation. They anticipate reaching the second million only 60 days later and a total of 3.5-4 million by the end of 2016.

• Auto manufacturer projections of FCEV deployments indicate 43,600 FCEVs may be on California’s roads by 2022.

• Projected demand for hydrogen fuel is expected to exceed the capacity of the State-funded network of hydrogen fueling stations around 2020. As a result, stakeholders are devoting significant efforts to engage more private funds in the build-out of California’s hydrogen fueling network.

• Expansion of the hydrogen fueling network beyond the 100 station benchmark set in AB 8 is expected to particularly require increased participation of private funds, greater nameplate fueling capacity, and development of more cost-effective stations, with greater capacity for fuel dispensing per dollar invested.

• Hydrogen prices at the pump are forecast to decline over the next decade to approximately $11/kilogram (kg). At this price, hydrogen may be cost-competitive with gasoline.

• Station equipment technology and stakeholder diversity (including fuel providers, equipment providers, and station owners/operators) are growing.
• Renewable hydrogen content in the funded fueling network is expected to exceed Senate Bill 1505 requirements, at approximately 45%.

Further discussion of these major findings and other aspects of the developing hydrogen fueling network are discussed through the body of this Appendix.

XIII. Current Status of Hydrogen Infrastructure and Current and Projected Needs of California’s FCEV Market

XIII.A. Current development status of California’s hydrogen fueling network
California’s hydrogen fueling network currently contains 50 stations that are either operating or received a grant award for development and are currently in some phase of development (one station at Fountain Valley decommissioned at the end of 2016).

Figure 12 provides an overview of the status of development across the fueling network. The following list provides an overview of the station status terminology utilized in the figure. The definitions are common terminology used by the State (led by the consensus-building efforts of the Governor’s Office of Business and Economic Development [GO-Biz]) and stakeholders in the FCEV and hydrogen fueling infrastructure industries to assure consistent communication of individual station development progress.

The definition of Open- Non-Retail does not have a prescribed set of conditions, other than that it is a station funded under an early research and/or demonstration grant program (not originally intended to provide retail fueling service) but is nonetheless able to continue providing fueling service to early adopters of FCEVs. Approval for FCEV drivers to fuel at these stations varies according to the individual manufacturer of the vehicle. Some of these stations are expected to be upgraded so they can provide retail service, at which time they will need to demonstrate that all requirements of the Open- Retail definition have been met.

Open-Retail stations are defined by:

1. The station passed final inspection by the appropriate authority having jurisdiction (AHJ) and has a permit to operate.
2. The station operator has fully commissioned the station, and has declared it fit to service retail FCEV drivers. This includes the operator’s declaration that the station meets appropriate SAE fueling protocol, as required in California.
3. Two auto manufacturers have confirmed that the station meets protocol and fueling interface expectations (including point-of-sale), and their customers can fuel at the station.
4. The dispenser metering performance has been verified, enabling the station to sell hydrogen by the kilogram (pursuant to CCR Title 4, Division 9, Chapter 1).
5. The station is connected to the Station Operational Status System (SOSS).

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The remainder of the status definitions are as follows:

**Fully Constructed**: Construction is complete and station developer has notified the appropriate AHJ.

**Under Construction**: Construction at the site has started and is currently active.

**Approved to Build**: The station developer has approval from the AHJ to begin construction. Depending on the station developer or individual project, construction may begin immediately or a pre-mobilization effort to select construction crews and deliver equipment may first be necessary.

**Planning Approval**: The site plan for the station has been approved, which indicates that a hydrogen station can exist on the site, subject to meeting all building, fire, and electrical codes and standards.

**In Permitting**: The permit application is currently under review by the AHJ planning agency.

**Finishing Permit Apps**: The station developer is preparing site layout, engineering, and other documents for submittal to the AHJ. This process is often iterative and may actually occur several times throughout the permitting process.

**Establishing Site Control**: The station developer is actively seeking a new site and/or negotiating a new site lease agreement.
Figure 12 - Station Status as of December 5, 2016 (Source: Energy Commission and GO-Biz)

*Stations not included in this count:
Oakland (Transit only); Mobile Fueler; Thousand Palms (35MPa only);
Fountain Valley (closed Q4 2016)
Figure 13 – Historical and Projected Schedule of Hydrogen Fueling Station Openings

As Figure 12 shows, as of December 5th, there were 30 hydrogen fueling stations open across the state, with 25 of those providing a fully retail experience to FCEV drivers. Drivers that visit Open – Retail stations can expect to be able to simply drive up to the dispenser, pay with their preferred payment method, and receive a full fill within five minutes; all of this should be able to be accomplished regularly and reliably at an Open – Retail station. ARB’s expected schedule for achieving Open – Retail status for the remaining stations, as of June 2016, is shown in Figure 13. As of the June 2016, all remaining stations were expected to be completed by 2017. In addition, the Energy Commission’s Grant Funding Opportunity (GFO-15-605) is expected to add at least 16 State co-funded stations to the network. Contracts are expected to be signed in early 2017 and stations funded under that solicitation may begin opening as soon as 2018.

XIII.B. Current and projected FCEV deployments

In the most recent Annual Evaluation and Joint Agency Staff Report, ARB updated its count of FCEVs currently on California’s roads and projections for future FCEV deployments, shown in Figure 14. Based on California Department of Motor Vehicle records in October 2016, 925 FCEVs were registered in the state. This was lower than the end-of-year projection for 2016 previously made. Additionally, in June 2016 ARB projected 13,500 FCEVs on the road by 2019 and 43,600 by 2022. Each year, ARB reports then-current FCEV registrations and deployment projections based on annually updated auto manufacturer surveys. In 2016, ARB also provided a comparison of the latest deployment schedule projections and those from prior Annual Evaluations. While short-term deployment plans were found to be delayed by one year, the projections for 2020 and beyond were actually greater than previously reported. ARB reported that this near-term delay is likely a reaction to hydrogen fueling station development that has also been delayed by one year from previous expectations.

Although the pace of deployment has been slower than previously projected, there has still been significant growth. Since the ARB’s June 2016 report, media reports indicate that Toyota has released a further 371 vehicles in August alone, largely due to an employee incentive program initiated at the time. On a similar note, at the 2016 Advanced Clean Car Symposium organized by ARB and hosted by the South Coast Air Quality Management District, CEO and Co-Founder of FirstElement Fuel Joel Ewanick noted accelerating throughput in his company’s network of stations. Across their now 15 stations, Mr. Ewanick stated that 9 months elapsed before their network fueled 1 million miles of FCEV travel. The second million miles’ worth of fuel will be dispensed only 60 days after the first million (sometime in late September or early October) and by the end of 2016, the company estimates 3.5-4 million miles will have been fueled by their

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36 Energy Commission 2016a
37 ARB 2016a
39 ARB 2016a
40 Ibid.
network alone. Mr. Ewanick went on to note that two stations (which have opened in the past year) have completely run out of fuel. Their company previously expected the 180 kg/day dispensing capacity designed for their stations to be sufficient for years to come; they have now realized that much larger stations will need to be built into their network sooner in order to meet accelerating demand.\footnote{Ewanick 2016. Ewanick, Joel, First Element. “Status of the World’s First Retail Hydrogen Network and What’s Ahead.” Advanced Clean Cars Symposium: The Road Ahead. 27 September 2016. South Coast Air Quality Management District. Diamond Bar, CA. \url{https://www.arb.ca.gov/msprog/consumer_info/advanced_clean_cars/moving_toward_network_expansion_joel_ewanick.pdf}}

**Figure 14 - ARB’s 2016 Reported FCEV Registrations and Projections for Future Deployment\footnote{Energy Commission 2016a}**

Although the June Annual Evaluations report auto manufacturer-based projections of FCEVs only to 2022, there are other sources available for projecting FCEV deployments further in the future. One resource is the 2015 December Joint Agency Staff Report, prepared by the Energy Commission and ARB.\footnote{Energy Commission 2015} For the Staff Report, NREL prepared an analysis of FCEV market growth and fueling needs that extended to 2025. The “Expected” market growth was modeled after an argument made in the 2015 Annual Evaluation,\footnote{ARB 2015a} which pointed out that early FCEV deployment plans seemed to follow a power-law growth curve. That is, the more FCEVs...
expected on the road, the greater the expected acceleration in further deployment rates. This may be a reasonable deployment path, especially considering the interaction between FCEV and hydrogen fueling markets. As more FCEVs are released, further infrastructure development can be justified (due to improving throughput and business cases at individual stations), which in turn justifies increased FCEV deployment rates. However, acceleration after many years overestimates vehicle deployment expectations in this type of model; extrapolation is only reasonable for a handful of years.

**Figure 15 - Potential Trajectories of FCEV Deployment in California Beyond 2022 Horizon of Latest Auto Manufacturer Survey**

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46 ARB 2016a
48 A complete explanation of staff’s updated ZEV Calculator can be found in Appendix A of this report, and is posted at the following link: https://arb.ca.gov/msprog/zevprog/zevcalculator/zevcalculator.htm
In addition, as provided in the 2016 ZEV Scenario Compliance Calculator, ARB’s analysis of ZEV regulation compliance scenarios provides Midrange, Low Technology, and High Technology estimates of FCEV deployment rates out to 2025.\textsuperscript{50} All of these potential deployment trajectories are presented in Figure 15, along with the data provided in auto manufacturer surveys. Also included in the figure are linear and quadratic trajectories fit to the auto manufacturer survey data for 2017 to 2022. For all years 2017 to 2022, the data reported in the survey are consistently between the Midrange and High Technology scenarios. Additionally, extrapolating the survey data out to 2022 according to a quadratic nearly identically follows the ZEV Midrange compliance case. A quadratic fit does indicate a time-dependent acceleration in deployment, though the acceleration is not based on the on-the-road count at any moment in time.

At the high-volume extreme is the model utilized in the 2015 Joint Agency Staff Report, which assumes the deployment rate accelerates proportionally to cumulative vehicle deployment. Under this model, approximately 200,000 FCEVs would be expected on the road in 2025; this is roughly twice the Midrange scenario and a 60% increase over the High Technology scenario. Although the NREL model is higher than even the High Technology scenario, it is worth remembering that all ZEV compliance scenarios assess only the minimum requirements for compliance. Individual manufacturers and the industry as a whole may produce more vehicles than these compliance scenarios illustrate. Given substantial market success of FCEVs and appropriate levels of supporting infrastructure development, the projection according to the NREL model is a viable scenario for FCEV deployment in the 2025 timeframe.

At the opposite end is the Low Technology scenario, with less than 20,000 FCEVs on the road in 2025. Unless there is a complete failure of the FCEV and hydrogen markets, this scenario is unlikely. It assumes a long period of essentially stagnant market growth between 2018 and 2022, which does not match the auto manufacturer projections. Additionally, the cumulative deployment by 2025 is far below even the linear fit projection, which represents a case assuming no acceleration in market deployment out to 2025. FCEVs are a new technology that will be marketed to early adopters during this timeframe; acceleration in market deployment is a fundamental characteristic of new technologies in this time frame. Thus, the linear extrapolation is itself an extreme lower bound and the Low Technology scenario can be considered indicative only of the deployment that would occur in the case of market failure or extreme stagnation.

Both the 2015 and 2016 Annual Evaluations and Joint Agency Staff Reports have noted that business-as-usual rates of development in hydrogen fueling infrastructure are unlikely to keep pace with fueling demand beginning in 2020.\textsuperscript{51,52,53,54} Currently, infrastructure development is almost completely funded through competitive grant solicitations administered by the Energy Commission under the directives of AB 8 (AB 8; Perea, Chapter 401, Statutes of 2013). These grants provide up to 85% of the capital expense funds and an additional $300,000 for

\textsuperscript{50} See Appendix A for a complete explanation of the ZEV Calculator, and description of the mid-range case.
\textsuperscript{51} ARB 2015a
\textsuperscript{52} Energy Commission 2015
\textsuperscript{53} ARB 2016a
\textsuperscript{54} Energy Commission 2016a
operations and maintenance costs during the early years of station operation.\textsuperscript{55} Thus, to meet the needs of the vehicles included in auto manufacturer deployment plans prior to 2022, new funding mechanisms and/or sources of funds will likely need to be pursued.

The FCEV deployment projections shown in Figure 15 (other than the Linear and Low Technology scenario) represent success of the FCEV and hydrogen fueling market. The current heavy participation of State funds is during a time of high risk, when the FCEV market is first beginning to develop and success has not yet been demonstrated. It is expected that as the deployment progresses and the market proves itself, the perceived risk for private investment in hydrogen infrastructure will correspondingly decrease. This will in turn incentivize greater participation of private capital in the deployment of hydrogen fueling infrastructure. The State already anticipates providing supporting funds through AB 8 until at least 2023. Increased participation of private funds can therefore be expected to help fill the gap between expected hydrogen demand and the capacity that could be deployed by State funds alone. It is too early to determine the likely magnitude of private investment in 2020 and beyond, but ARB and the Energy Commission are expecting to gain insight into the willingness for private firms to participate through responses to the current GFO-15-605.

\textbf{XIII.C. Existing fueling market coverage}

Considering the volumes of vehicles estimated for 2022 and projected out to 2025, the FCEV market will likely remain in the early adopter phase for the better part of the next decade. ARB’s California Hydrogen Infrastructure Tool (CHIT) has been utilized in its Annual Evaluations to assess coverage needs to support growth in specifically this early market phase.\textsuperscript{56,57} (For a discussion of the concept of coverage, see “Fueling network design and analysis concepts” section below). Figure 16 shows a comparison of the areas identified through CHIT as the highest potential for successful FCEV deployment during the early adopter phase (termed “High Market Areas” in the figure) and the coverage provided by the 50 open and funded stations. As shown in the figure, large portions of the likely first adopter markets have some degree of coverage already provided by California’s planned 50 stations. The greatest concentration of coverage currently resides in the southern tip of the San Francisco Bay area, from Palo Alto down to Campbell and including parts of San Jose. Relatively high levels of coverage are also seen in West Los Angeles and Santa Monica, though the strength of the market in this region indicates that there is a need for additional stations. Other parts of Los Angeles and Orange counties have mid-range coverage with stations in some areas establishing the first signs of overlapping coverage to the local first adopter market. Additionally, several stations are open or funded that will provide coverage in important long-distance connector locations, travel destinations, and future secondary markets.

\textsuperscript{55} Energy Commission 2016b
\textsuperscript{56} ARB 2016a
\textsuperscript{57} ARB 2015a
While the currently open and funded network provides at least a base, though often non-redundant, level of coverage to so much of the early first adopter market, there are clear areas that have not yet begun to be addressed. San Francisco is a very high market potential area that does not yet have any stations providing a high degree of local coverage. Large portions of the San Diego market area likewise do not yet have coverage, nor does the stretch of coastal Orange County between Costa Mesa and Long Beach. Santa Cruz has also been identified as having a high potential market, though it does not yet have any fueling coverage. Though these gaps exist in the currently funded 50 station network, they have been identified through ARB’s
Annual Evaluations and the Energy Commission has incorporated these suggestions into GFO-15-605. Though available funds in the grant solicitation may not be able to establish fueling coverage in all the identified gaps, it is anticipated that the structure of GFO-15-605 will result in many of the gaps being filled and for coverage to be strengthened in areas that have been identified as needing their existing coverage augmented. ARB envisions CHIT as a living tool; future grant solicitations through the Energy Commission may continue to be informed by revised assessments in CHIT as the hydrogen fueling network continues to grow.

XIII.D. Hydrogen fueling capacity needs for projected FCEV deployments

Based on the information provided by auto manufacturers in the 2015 and 2016 annual surveys, the Energy Commission and ARB have projected potential capacity scenarios for California’s expected FCEV fleet out to 2022. In all scenarios, it has been shown that the annual allocation of $20 million available to the Energy Commission for hydrogen fueling stations through AB 8 will not be sufficient to meet the expected growth in hydrogen fueling demand.\(^58,59,60\) Through separate analyses, the 2015 and 2016 Annual Evaluations and the 2015 Joint Agency Staff Report projected that investment beyond these State funds would be necessary sometime around 2020. As shown in Figure 17, the hydrogen fueling demand will surpass network capacity in 2020 under business-as-usual assumptions of $20 million per year and consistent average hydrogen station daily fueling capacity (currently 180 kg/day). Assuming station cost reductions over time, the 2015 Joint Agency Staff Report still found a potential shortfall, though the gap was smaller by about 2,000 kg/day capacity. By 2022, assuming an average network utilization rate of 75% (the ratio of daily hydrogen dispensed to a station’s full capacity), more than 28,000 kg/day of capacity would need to be installed utilizing funds beyond the current AB 8 allocation.\(^61\) Projections for capacity need beyond 2022 are less certain, given the range of potential vehicle deployment scenarios presented above and considering that AB 8 in its current form expires in 2023.

While the challenge of a fueling capacity shortfall is significant, the State and partner organizations (like H2USA and the California Fuel Cell Partnership [CaFCP]) have been actively working to identify strategies to address the coming issue. The 2015 Annual Evaluation outlined a number of potential paths to pursue, and industry stakeholders are consistently proposing and discussing other options in public and private meetings. The Energy Commission has also begun to enact some of the suggested changes. The new solicitation GFO-15-605 significantly increased the minimum daily capacity requirement for all applications from the previous 100 kg/day to 180 kg/day.\(^62\) Potential and plans for capacity expansion without additional State funds has also been added as a required narrative item and scoring criterion in the new GFO. ARB and the Energy Commission anticipate that review of final applications to GFO-15-605 may reveal new trends and updated technology status of hydrogen fueling station equipment that could also improve the business-as-usual outlook. These agencies plan to continue to work

\(^{58}\) ARB 2015a  
\(^{59}\) ARB 2016a  
\(^{60}\) Energy Commission 2015  
\(^{61}\) Ibid.  
\(^{62}\) Energy Commission 2016b
with each other and stakeholders to monitor and assess the status quo of hydrogen fueling station technology and determine if further action is needed, either within or outside of the Energy Commission’s grant solicitation process.

**Figure 17 - Comparison of Fueling Needs and Potential Fueling Network Capacity under Various Scenarios**

Finally, Figure 15 provides an example of a previous assessment of fueling infrastructure sufficiency under a sample FCEV deployment scenario. In the 2012 CaFCP Roadmap, a prospective scenario based on aggregating projection data from auto manufacturers at the time showed a market launch of FCEVs would require deploying 53,000 total vehicles over a five to six year period. In the original Roadmap, this was assumed to occur between 2011 and 2017, with the assumption of correspondingly swift fueling infrastructure development. The actual history of the infrastructure deployment and thus vehicle deployment were slower; in the figure, the projected vehicle deployments have been shifted by 5 years, which aligns the Roadmap’s expectation of roughly 300 vehicles in 2011 with the realized 331 vehicles reported in April of 2016.

The goal of the Roadmap was to develop, assess, and communicate a plan for infrastructure deployment that could adequately support this FCEV rollout schedule. Through the use of the University of California-Irvine’s Spatially and Temporally Resolved Energy and Environment Tool (STREET; see “Fueling network design and analysis concepts” section below) model and iterative feedback with auto manufacturers, the Roadmap found that a total of 68 stations would be necessary to support the projected rollout of 53,000 FCEVs. Importantly, these 68

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63 ARB 2016a  
64 CaFCP 2012  
65 Ibid.
stations represented the minimum required in order to support a market launch, not necessarily ongoing development of the hydrogen fueling industry. The goal of the 68 stations was to provide at least single-station fueling coverage to FCEV early adopters that would match their expectations from experience with gasoline fueling. Thus, the stations could provide the projected 53,000 early adopters with convenient access to at least a single station within a 6-minute drive. The assessment did not consider redundancy to each early adopter nor did it consider questions of total throughput capacity of the network or individual stations. Additionally, the 68 stations were a specific set of 68; many were concentrated in five primary clusters of early adopter markets while others were hand-selected destination and connector fueling locations.

The development of stations that has occurred since the Roadmap release has historically taken longer than originally expected. However, under business as usual assumptions, ARB reported in its 2016 Annual Evaluation that close to this number of stations (66) could be open by 2019, at a time when the expected number of FCEVs on the road is expected to be 18,465, much lower than the 53,000 reported in the Roadmap as relying on 68 stations.\(^6\) Thus, the fueling network development is currently projected to be ahead of schedule of the Roadmap’s requirements on the basis of vehicle counts, though the timeline for all development has shifted back a number of years. Still, some issues remain to be resolved in addition to the capacity issue mentioned above (which was not even forecast in the Roadmap). Some of the currently-funded 50 stations are not within the same set as the 68 outlined in the Roadmap; thus, more than 68 total stations will likely need to be built in order to cover the target markets in the same way as CaFCP envisioned in the Roadmap. Additionally, questions of redundancy were not completely addressed in the Roadmap, though the importance of this consideration is becoming increasingly apparent as more experience is gained with the first adopter markets’ fueling behaviors. Finally, a development trajectory for the hydrogen fueling industry beyond early adopter coverage that addresses economic self-sufficiency of hydrogen fueling operations is not yet entirely clear.

These are all questions that ARB, CaFCP, the Energy Commission, GO-Biz, and others are continually striving to understand. Future plans for network development can be expected to be informed by and adjust according to lessons learned through driver and station operator experience and ongoing modeling and assessment of the hydrogen fueling network and its apparent gaps.

XIV. Hydrogen Fueling Station Technology Overview

XIV.A. History of California’s hydrogen fueling network development

The State of California has recognized that the success of the FCEV market and the hydrogen fueling market are inextricably connected. In order for FCEVs to make the expected


\(^{67}\) ARB 2016a

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contribution to achieving California’s ZEV market development goals, the hydrogen fueling station network must also be in place to provide reliable service. In 2007, the State passed Assembly Bill 118, which formally recognized the need for fueling stations to precede vehicle sales in order to provide the greatest opportunity for successfully building a FCEV consumer market. In addition, the bill set into place the first formal funding program for hydrogen refueling stations. In parallel, then-governor Schwarzenegger’s Hydrogen Highway program provided impetus for development of the first research and market demonstration stations to be installed and operated in the state.

These earliest stations provided fueling service to a small, hand-selected group of public FCEV drivers, who were driving demonstration or pre-commercial vehicles. These stations were often approved for use by individual auto manufacturers for drivers of their vehicles and were not completely open to the public. Many were behind fences requiring access authorization and use of the station would require release of liability agreements and fueling service contracts, as opposed to real-time purchase of fuel by the kilogram. Additionally, station hardware technology was still in its infancy; many standards and best practices for design and operation did not exist and the stations did not look like familiar fuel dispensers as they were not intended for retail service. The hydrogen dispenser at the left of Figure 18 is an example of one of these very early stations.

As station technology matured, hydrogen fueling station designs began to improve. Many would no longer be placed in areas with limited access, and the appearance and user interfaces would more closely approximate drivers’ experiences at gasoline stations. Fueling service contracts were still predominant, as there was not yet a legally defined certification method to allow sale of hydrogen by the kilogram. The center image in Figure 18 is an example of one of these stations. More recently, under the funding program established by Assembly Bill 8 (which extended Assembly Bill 118 [AB 118; Nunez, Chapter 750, Statutes of 2007]), stations are required to provide a fueling experience essentially identical to retail gasoline sales. Stations have familiar interfaces, can be placed anywhere on gasoline station property, are fully publically accessible, and can sell hydrogen by the kilogram without any need for access agreements or releases of liability. Additionally, all drivers of all FCEV models are equally able to fuel at any of these new stations. Examples are shown in the images on the far right of Figure 18.

The earliest retail stations encountered more development challenges than may have been anticipated. Examples include educating local jurisdictions about hydrogen, early difficulties with securing site control and lease agreements, and variations in permitting procedures across jurisdictions. The process of overcoming these challenges has provided valuable insight to station developers, the State, and local governments. This has in turn enabled the more recent stations to be built at a faster pace than previously observed. The Energy Commission has so far funded three sets of stations between 2009 and 2014, and the fastest average development times (from grant award to Open-Retail status) has fallen from 1,481 to 730 days (several

68 Assembly Bill No. 118 (Nunez, Statutes of 2007, Chapter 750).
69 Assembly Bill No. 8 (Perea, Statutes of 2013, Chapter 401).
stations are not yet complete, so these estimates are still currently developing and final values will be larger, though newer retail stations are still on track to develop faster than older stations).\textsuperscript{70} It is anticipated that as the retail station network continues to grow, development timelines will also continue to improve. Additionally, in its newest solicitation, the Energy Commission has incorporated some of these lessons and requires applicants to meet planning-based milestones (such as making contact with the local permit authorities) prior to distributing funds to any grantee.\textsuperscript{71}

Figure 18 - Evolution of California’s hydrogen fueling stations

Currently, almost all stations have a single dispenser able to dispense at both H70 (700 bar, 10,000 psi) and H35 (350 bar, 5,000 psi), though not typically at the same time. H70 is the current standard used by commercial FCEVs; some pre-commercial FCEVs utilized H35, and it can be utilized for a half-fill on H70 capable vehicles at times that the station’s H70 compression system may be unavailable. Stations have also progressed in their capability to provide increasing numbers of fills in a single hour without the need to recharge high-pressure storage.

\textsuperscript{70} Energy Commission 2016a
\textsuperscript{71} Energy Commission 2016b
tanks. Early stations were not designed for high-volume throughput, while current designs are required to fill at least three cars in an hour and some have shown capability for as many as six in an hour. Each fill can be achieved in approximately five minutes from a near-empty tank to greater than 97% state of charge. Daily fueling capacity has also grown, with today’s station designs typically able to fuel 50-100 (for dual-dispenser, simultaneous-fill designs) vehicles over the 12-hour peak fueling cycle. Finally, all stations are required to receive certifications for the accuracy of their dispensing; all stations certified to date are capable of metering fuel to within 5% accuracy, though requirements are currently set to become increasingly stringent in the future. Further discussion of potential designs for future stations is presented later in this Appendix.

Along with the more capable design features, retail hydrogen stations meet more stringent operational requirements. Particularly when the statewide or local network of fueling stations is still small, individual station availability becomes a critical factor for retail customer use. Stations can become unavailable for a number of reasons, including scheduled maintenance; compression, storage, and dispensing equipment malfunctions; point-of-sale malfunctions; utility and city servicing and project schedules; and unrelated construction projects at the host site. Station operators strive to minimize the service interruptions caused by these types of situations. The first retail stations to open have provided valuable lessons to station operators and other stakeholders, and there has been significant movement to anticipate and even avoid service interruptions that are now well-understood.

Additionally, reliable communication with the FCEV driver community must be available and provide accurate information about the operational status of stations, especially new stations. The CaFCP’s SOSS has for years provided station status information to consumers, though it is now also being used to communicate progress towards expected levels of reliability at new stations. Particularly through the efforts of GO-Biz and the CaFCP, industry consensus has been garnered for a standardized process of first declaring new stations as “New Station” for a minimum of 60 days. This designation communicates to drivers that the station operator may still be using this period to “debug” the station (operators can voluntarily choose to extend the New Station period). This empowers customers to make an informed decision about visiting a station that may not yet be proven to be as reliable as more established stations on the network.

Today and for the foreseeable future, the retail hydrogen station is the standard in California and likely to be the standard in new markets across the United States as well. Air Liquide is currently developing a dozen stations in the Northeast and public comments indicate that their stations will meet many, if not all, of the same retail service expectations of California’s hydrogen stations. The Energy Commission’s current GFO for new stations includes provisions that require greater performance metrics than previous grant solicitations and asks

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that applicants describe plans for future expansion and upgrades. This forward momentum for retail stations will be instrumental in supporting the growing FCEV market.

**XIV.B. Fueling network design and analysis concepts**

Planning the development of California’s hydrogen fueling infrastructure network has historically relied on two key concepts: coverage and capacity. Coverage refers to the geographical locations of stations and the areas and communities each station and the network as a whole are likely to serve. In nearly all assessments of coverage, a limit to the extent of coverage provided by any individual station is assumed based on convenience afforded to FCEV drivers; typically this limit is expressed in terms of drive time. For example, a FCEV driver will likely feel that a station they can drive to within 3 minutes offers convenient fueling opportunity (assuming the station is also consistently available and offers amenities similar to typical gasoline stations). However, that same driver would not consider a station 20 minutes away to be convenient. The first station provides coverage to that driver, while the second does not.

**Figure 19 - Sample Evaluation of Coverage at a 9-Minute Drive Time for Orange County Beach City Stations**
A visual representation is provided in Figure 19 and Figure 20. In both figures, three hydrogen fueling stations are shown along with the spatial extent of their coverage for 9 minute and 6 minute drive times, respectively. The metrics of 6 and 9 minute drive times are used here for illustrative purposes, though they are two of the six drive times (ranging from one to fifteen minutes) utilized in CHIT’s analysis of coverage provided by the funded and operational hydrogen fueling network in California. Several neighborhoods in the region are also highlighted. Typically, a given neighborhood is considered to have greater coverage when stations are reachable within a shorter drive time and when multiple stations are reachable within the limits of convenience.

By inspection of Figure 19 and Figure 20, it can be seen that Turtle Rock has the least coverage in this example as potential FCEV drivers can only reach the UC Irvine station within a nine minute drive and have no stations available within six minutes. The Corona Del Mar and South Costa Mesa neighborhoods have slightly greater coverage; they can each reach one station within a shorter six minute drive but do not have multiple options even at the nine minute extent. The Newport Beach and North Costa Mesa communities can each only reach one station within six minutes, but have two options within nine. Finally, the Newport Back Bay community has the greatest coverage since it can reach one station in six minutes and all three within nine.

In order for both the FCEV market and the hydrogen fueling market to be successful, coverage provided by the fueling stations must match well to the geographical locations of the expected market. In California, this typically means that the stations’ coverage must be matched to the locations where the expected FCEV first adopters live. In addition to these home-based
coverage stations, long-distance connector stations (such as along the north-south corridor on I-5) and travel/vacation destination stations (such as in Santa Barbara, Truckee, and other locations) need to be present in order to ensure FCEV drivers are able to travel around the state just as freely as gasoline vehicle drivers. The earliest effort to establish the set of stations that could meet the coverage needs of the first adopter market was the CaFCP’s *A California Road Map: The Commercialization of Hydrogen Fuel Cell Vehicles*, published in 2012. The roadmap identified five clusters (shown in green shading in Figure 21 and Figure 22) and the locations of stations within those clusters to provide sufficient coverage enabling the launch of California’s FCEV market.\(^{74}\) In addition, several connector and destination station locations were identified (though not shown in the figures).

**Figure 21 - Northern California Clusters and Suggested Station Locations in CaFCP’s 2012 Roadmap**\(^{75}\)

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\(^{74}\) CaFCP 2012

\(^{75}\) Ibid.
The locations identified in the CaFCP Roadmap were arrived at through a combination of computer modeling, carried out by STREET, and an iterative process of consensus-building among auto manufacturers. As shown in Figure 23, STREET has the capability to optimize prospective station placement along major roads within a given community. The goal of STREET’s optimization is to maximize coverage by minimizing the aggregate drive time to stations for FCEV early adopters within a given market. The stations identified through the roadmap effort provided a starting point for targeted development; State grant programs such as the Energy Commission’s several PONs utilized the roadmap and STREET as a guide for determining selection of awards in competitive bid processes.
As the network developed through the competitive bid process, several of the stations outlined in the CaFCP roadmap were established, along with several additional stations. In order to continually evaluate the coverage provided by the funded network and help determine locations...

77 Stephens-Romero 2010
78 ARB 2016a
where the Energy Commission’s next grant solicitation(s) should concentrate, ARB developed CHIT. CHIT performs assessments of the degree of coverage provided by the state’s funded hydrogen fueling network and identifies areas where it does not match well with the expected intensity of the local FCEV early adopter market. This is termed the coverage gap in CHIT evaluations. Figure 24 shows CHIT’s assessment of the coverage provided by the sub-network of funded stations in the San Francisco Bay area. Today, CHIT is used by the ARB in annual reporting and to make recommendations to the Energy Commission for the design of its hydrogen fueling station solicitations. It is also used within the latest solicitation’s (GFO-15-605) scoring method to help the Energy Commission determine its final awards.\textsuperscript{79}

Coverage-based analyses are also being used for station network design and planning in other areas of the country. In the northeast states, staff of the Northeast Electrochemical Energy Storage Cluster (NEESC) have been developing a plan for locating hydrogen fueling stations across several states.\textsuperscript{80} As opposed to California’s current efforts to support a private light-duty passenger vehicle market, the NEESC strategy focuses on light-duty fleets. As shown in Figure 25, the planning considers the locations and sizes of existing (non-FCEV) fleets, locations of existing support for hydrogen refueling, and demographic indicators to identify strategic locations where placement of FCEV fleets and associated refueling infrastructure may be most successful. In addition to this effort, Air Liquide and Toyota have publicly announced their plans to develop a dozen publicly-available hydrogen fueling stations in the northeast states, though their full plans and strategies have not been made publicly known.\textsuperscript{81}

\textbf{Figure 25 - NEESC FCEV Fleet-Based Planning Strategy}\textsuperscript{82}

\textsuperscript{79} Energy Commission 2016b
\textsuperscript{81} Air Liquide 2016
\textsuperscript{82} NEESC 2015
NREL has been studying strategies for expanding hydrogen fueling infrastructure from the initial networks in California and the Northeast to a nationwide system. NREL utilizes its Scenario Evaluation, Regionalization, and Analysis (SERA) model to complete this task. While SERA considers aspects of coverage through an analysis of an Early Adopter Metric, it also introduces consideration of individual station capacity and timing of individual station development. Analyzing and optimizing scenarios accounting for these various aspects of fueling network planning at such a large scale is especially challenging and NREL makes use of access to supercomputer clusters available through the national laboratories in order to develop its outputs.

Capacity evaluations like those in SERA introduce the second major aspect of hydrogen fueling network planning and analysis. Namely, a well-planned set of locations for hydrogen stations may still be insufficient to provide reliable and convenient fueling opportunities if the stations are not sized appropriately (locally or on the full network scale) for the expected size of the FCEV adopter market. Additionally, to help ensure the viability and stability of the fueling and vehicle markets’ growth, the timing of increasing station capacity needs to be carefully considered.

ARB’s CHIT tool also provides determination of expected capacity need and for the purposes of GFO-15-605 can assess the suitability of proposed station designs for the potential local market. This determination relies on projections of statewide FCEV on-road vehicle populations that are published by ARB each year.

In accordance with AB 8, for the past three years ARB has published its Annual Evaluation of Fuel Cell Electric Vehicle Deployment and Hydrogen Fueling Station Development. Each

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84 Ibid.
85 Assembly Bill No. 8
year, the report provides ARB’s latest information for the number of FCEVs on the road in California, auto manufacturer plans for future FCEV deployments (based on an annual survey), evaluation of hydrogen stations currently operating and under development in California, and an assessment of needs for new stations that includes consideration of coverage, capacity, and technical specifications. In the 2016 Annual Evaluation, ARB presented its analysis of needs considering the 50 existing open and funded stations. Figure 27 provides the analysis of coverage gap as determined by CHIT and accounting for these 50 stations. In the figure, brighter red areas have a greater need for coverage provided by new stations while deep blue areas have a very low need for new stations. Outlined Priority Areas signify “hot spots” where high coverage gap values coalesce and are significantly different from their surroundings. From discussions with stakeholders including auto manufacturers, several of the identified areas are in agreement with expectations for near-term priority development of local FCEV markets. ARB is currently working to include new considerations in CHIT evaluations that stakeholders have discussed in feedback to the agency. In particular, consideration of station availability, driving habits, and the timing of adding new stations to Priority Areas are all areas under current review.

Other models for planning a hydrogen fueling network can be found in technical literature. Several models make an argument for station placement along common travel routes as opposed to near the homes of first adopters. Others seek to optimize the opportunity that can be afforded by including dispatchable mobile refuelers in the network. ARB is currently investigating how these perspectives can improve the State’s hydrogen fueling infrastructure planning efforts. Additionally, the past efforts including the development of the CaFCP’s Roadmap have included substantial participation and feedback from stakeholders in the automotive and hydrogen fueling industries. ARB continues to communicate with these stakeholders and the public to ensure that its analysis methods meet the planning needs of the FCEV and hydrogen fueling markets. In particular, ARB’s development of CHIT has included stakeholders and the public through several scheduled events and private meetings; future developments of the tool will similarly consider this guidance.

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86 ARB 2016a
Figure 27 - ARB’s Analysis of Coverage Gap through CHIT as presented in the 2016 Annual Evaluation\textsuperscript{92}

\textsuperscript{92} ARB 2016a
XIV.C. Dispensed hydrogen production pathways and station design strategies

Although all hydrogen stored onboard light-duty FCEVs is in gaseous form at 700 bar (with the exception of some legacy vehicles still on the road today), there are many methods of producing, transporting and distributing, and finally dispensing the hydrogen. In total, there are no less than ten unique pathways that are currently utilized for producing hydrogen in California’s hydrogen fueling network, as shown in Figure 28 (groupings of pathways in the figure follow the modeling methods of ARB’s VISION model). Steam methane reforming (SMR), whether on-site or at a central facility, makes up a large portion of the total planned hydrogen throughput in the state. While the full process is more complex, SMR is essentially the conversion of methane in natural gas to hydrogen through combination with steam; typically, the actual SMR step is followed by a water-gas shift (WGS) reaction to convert product carbon monoxide (CO) into carbon dioxide (CO₂) and provide additional hydrogen yield.

Equation 1- Conversion of methane in natural gas to hydrogen

\[
\begin{align*}
\text{CH}_4 + \text{H}_2\text{O} & \xrightarrow{\text{SMR}} \text{CO} + 3\text{H}_2 \\
\text{CO} + \text{H}_2\text{O} & \xrightarrow{\text{WGS}} \text{CO}_2 + \text{H}_2 \\
\text{CH}_4 + 2\text{H}_2\text{O} & \xrightarrow{\text{TOTAL}} \text{CO}_2 + 4\text{H}_2 
\end{align*}
\]

The reactions above describe the basic steps in the SMR process. The actual source of the natural gas can vary, including conventionally recovered natural gas, biogas, agricultural waste gas, and other sources like those shown in Figure 28. Additionally, hydrogen can be produced by methods not involving SMR. Certain industrial processes generate hydrogen as a byproduct gas, which can be captured and distributed for FCEV consumption. Hydrogen can also be produced by electrolysis, which involves passing an electric current through water to generate hydrogen and oxygen. Hydrogen can additionally be produced at what is known as a trigeneration facility. While it is no longer in operation, the former Fountain Valley station featured this method. The Fountain Valley trigeneration system was sited at a wastewater treatment facility. Hydrocarbon-rich gasses from the on-site digesters were passed to a high-temperature fuel cell. This fuel cell could perform reformation of the hydrocarbons, generate electricity from the resulting hydrogen and CO₂, generate waste heat to be used in the digesters, and provide a slipstream of hydrogen to be purified for dispensing into FCEVs. One station in California even features hydrogen delivered directly via pipeline from a central SMR production facility; this previews what may be one of the most cost-effective methods of hydrogen transport in a future with wide-ranging FCEV adoption. While California’s hydrogen fueling network has been supplied with hydrogen from a wide variety of production methods, there are many others detailed in literature and are too numerous for an exhaustive review in this document.
Hydrogen fueling station design can depend on the final physical state (liquid or gaseous) and location of the source hydrogen production facility. For example, hydrogen delivered to a fueling station in liquid form requires the station to be equipped with a vaporizer in order to convert the hydrogen to gaseous state before dispensing into a vehicle. Meanwhile, if hydrogen is delivered to the station in gaseous form, this piece of equipment is not required. (Note that there are multiple other design considerations that represent tradeoffs in cost and technical capability between individual station designs; the optimal choice typically depends on the station developer’s strategy and perceived local throughput needs). Figure 29 provides some examples of different station design types, and highlights some of the major differences between the types of stations currently participating in California’s hydrogen fueling network. Note that multiple production pathways shown in Figure 28 may employ the same basic station design concepts, as long as the hydrogen delivery method is similar.
especially during the early years of FCEV deployment, establishing a hydrogen fueling network is expected to be a capital-intensive endeavor. Additionally, operating costs are expected to be high as throughput volumes of hydrogen at dispensers are not large enough to induce benefits of production scale, resulting in high procurement costs for station operators (and potentially high costs to the consumer). The grant solicitation programs enabled by AB 8 allow the State to help reduce the industry’s financial burden during this period of unknown market development pace and high investment risk. Table 8 provides the most recently published projection of capital costs for the 50 stations currently in California’s planned network. Indications from stakeholders are that these early-market costs are much higher than they may be as market volumes grow. As the network is still developing, the Energy Commission’s grant solicitations provide funds for up to 85% of the capital costs, with individual funding levels depending on an incentive structure that rewards faster station development.

93 Energy Commission 2015
94 Ibid.
Figure 30, based on NREL’s Hydrogen Station Cost Calculator calibrated to the station costs in Table 8, provides projections of the potential reductions in cost over the next decade.\(^95\) Note that in Table 8, Systems 1 and 4 are both 180kg/day stations with delivered gaseous hydrogen (with equipment and operations from two different providers with different strategies of transferring and storing fuel on-site), System 2 is a 350 kg/day station with liquid delivery, and System 3 is a 130 kg/day station with hydrogen produced on-site through electrolysis. An additional cost estimate is provided in Figure 30 for a very large station design (600 kg/day), which could enter the market sometime in the next decade if FCEV deployment volumes continue to grow; at this large nameplate capacity, this type of station is likely to be a liquid truck delivery station. Reductions in cost shown in the figure are based on validated general cost reductions observed in other industries and are the result of both industry learning and growing production volume. Even still, for the purposes of the 2015 Joint Agency Staff Report, NREL generated Figure 30 with an additional contingency factor that slowed cost reduction compared to standard models. Based on Figure 30, existing station design costs may fall by as much as 40-50% within the next decade.

Table 8 - Hydrogen Fueling Cost Projections as Reported in December 2015\(^96\)

<table>
<thead>
<tr>
<th>Equipment List</th>
<th>System 1</th>
<th>System 2</th>
<th>System 3</th>
<th>System 4</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ground Storage (gaseous or liquid)</td>
<td>$370,000</td>
<td>$222,000</td>
<td>$162,426</td>
<td></td>
</tr>
<tr>
<td>High-Pressure Tubes</td>
<td>$135,000</td>
<td>$53,000</td>
<td>$237,000</td>
<td></td>
</tr>
<tr>
<td>Electrolyzer</td>
<td>$1,008,000</td>
<td>$1,008,000</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Compressors</td>
<td>$270,000</td>
<td>$1,314,000</td>
<td>$147,000</td>
<td>$500,000</td>
</tr>
<tr>
<td>Chiller</td>
<td>$150,000</td>
<td></td>
<td>$123,000</td>
<td></td>
</tr>
<tr>
<td>Dispenser</td>
<td>$270,000</td>
<td></td>
<td>$392,000</td>
<td>$97,680</td>
</tr>
<tr>
<td>Point-of-Sale System</td>
<td>$20,000</td>
<td></td>
<td>$56,405</td>
<td></td>
</tr>
<tr>
<td>Connection to Utilities</td>
<td>$12,000</td>
<td>$42,000</td>
<td>$15,000</td>
<td>$200,000</td>
</tr>
<tr>
<td>Tubing and Valves</td>
<td>$150,000</td>
<td>$574,000</td>
<td></td>
<td>$48,635</td>
</tr>
<tr>
<td>Misc. Material and Equipment</td>
<td>$230,000</td>
<td></td>
<td>$113,000</td>
<td>$20,000</td>
</tr>
<tr>
<td><strong>Total Equipment and Material</strong></td>
<td><strong>$1,607,000</strong></td>
<td><strong>$1,930,000</strong></td>
<td><strong>$2,092,000</strong></td>
<td><strong>$1,552,146</strong></td>
</tr>
</tbody>
</table>

\(^95\) Ibid.
\(^96\) Energy Commission 2016a
In addition to capital costs, the Energy Commission’s grant solicitations currently provide funds to cover Operations and Maintenance costs (up to $300,000). A major motivator for this additional funding coverage is the high cost of hydrogen procurement to the station operator. This has been identified as a key factor in the economic viability of individual stations, especially during the early years of the FCEV deployment when hydrogen sales volumes are not expected to be very large. In addition, the high cost of hydrogen has a nearly proportional and direct effect on the cost that the FCEV driver may see at the pump. Figure 31 shows the current average price of hydrogen procurement as reported by operators of California’s open stations in 2015, potential reductions in procurement cost over time, and uncertainty bounds on this cost. In addition, the effect on the price to FCEV drivers at the pump is indicated by the “Central Price” trajectory.

The difference between the “Cost to Stations” and the “Central Price” would cover amortization of the station’s capital equipment cost, operations and maintenance costs including staff salaries, all applicable taxes, fees, and financing costs, and profit margin. Though not shown in

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97 Ibid.
98 Energy Commission 2016b
99 Energy Commission 2015
Figure 31, $11.11 per kilogram of hydrogen in 2025 is projected to be roughly equivalent to gasoline for expected vehicle technologies at that time; within a 20% margin of error, hydrogen may become cost-equivalent with gasoline as soon as 2021 (at $9.82 per kilogram) or as late as 2029 (at around $12 per kilogram). These conclusions are based on projections of gasoline costs rising from $2.89 per gallon in 2015 to $4.81 per gallon in 2025, conventional engine efficiencies rising from 28.6 mpg to 42.1 mpg, and FCEV efficiency rising from 72 mi/kg to 93.3 mi/kg over the same period.

Figure 31 - Hydrogen Cost Projections to Station Operators and to FCEV Drivers (shown as “Central Price”)\(^{100}\)

### XIV.D. Renewable hydrogen and sustainability

California’s hydrogen fueling network includes a range of station design types that are supplied by hydrogen produced through several different methods, as discussed above. These various pathways also result in various rates of carbon emissions and renewable energy implementation. ARB’s Low Carbon Fuel Standard (LCFS) program has performed analyses of several hydrogen production pathways that are currently in-use or proposed for use in California (in addition to a handful of early prospective pathways that eventually developed with slight alterations in today’s station network). As shown in Figure 32, when accounting for the

\(^{100}\) Ibid.
efficiency benefit of FCEVs over conventional internal combustion engines (ICEs), all hydrogen pathways have lower rates of carbon emissions than gasoline. In fact, some hydrogen pathways have been evaluated as having a negative carbon intensity (their lifecycle effectively sequesters carbon dioxide) and are among the least carbon emitting pathways analyzed for transportation fuels. The carbon emissions savings potential of hydrogen and FCEVs has been recognized as a significant element in ARB’s efforts to reduce transportation-related GHG emissions and the governor’s overall climate plan.

Figure 32 - Summary of ARB’s LCFS Program Evaluations of Hydrogen (and Other Fuel) Production Pathway Carbon Intensities

Each marker represents an individual certified fuel pathway carbon intensity (CI), adjusted by the Energy Economy Ratio (EER). The length of each bar indicates the range of carbon intensity that may be achieved by a fuel pathway. The wide range of carbon intensities is due to the life cycle emissions methodology of the LCFS; variations in feedstock types, origin, raw material production, processing efficiencies, and transportation all contribute to an individual producer’s fuel pathway CI. All valid CI values are shown, including those certified before 2016 which are set to expire on December 31, 2016. New and recertified pathways will be added to the figure as they are approved and posted.

1 The alternative fuel’s CI value is divided by its Energy Economy Ratio (EER) in order to obtain the EER-adjusted CI value, representing the emissions which occur from the alternative fuel per MJ of conventional fuel displaced.

102 Ibid.
In addition to addressing the carbon intensity of California's transportation sector, hydrogen fuel also addresses goals for renewable energy sourcing and sustainability of transportation fuel. Senate Bill 1505 (SB1505; Lowenthal, Chapter 877, Statutes of 2006) proposed a requirement that all hydrogen fuel sold in the state by operators receiving State co-funding should have at least 33% of its process and feedstock energy source by renewable resources. Additionally, once total sales reached 3.5 metric tons per year, the requirement would also apply to stations that are completely privately funded. ARB has not yet introduced a related regulation, though staff are currently working to include these provisions into the LCFS program. Additionally, the Energy Commission’s grant solicitations have historically required that all funded stations meet this 33% minimum, independent of any potential SB 1505-related regulation. Figure 33 shows ARB’s analysis of the current and projected (under business-as-usual assumptions) renewable content in California’s dispensed hydrogen transportation fuel. Once all 50 stations
are complete, it is expected that California’s network will exceed the 33% metric, with an aggregate potential for 45% renewably-sourced hydrogen.\footnote{ARB 2016a}

V. Forecasts for Hydrogen Infrastructure

\textbf{V.A. Characterizing future hydrogen stations}

The retail hydrogen stations being deployed today in California are the first examples of stations that have the capability to meet customer expectations of convenience, familiarity, and reliability. As discussed earlier, they also represent a great deal of technical advancement from the first set of stations that were deployed in the state. However, further advancements are still expected as the FCEV and hydrogen fueling markets grow over the coming years. As the FCEV market expands, demands on individual stations will become even greater and station specifications and design will have to accommodate the evolving market.

One of the most commonly expected trends for the future is that individual station daily fueling capacity will need to increase. As discussed in the section above, business-as-usual assumptions of station fueling capacity will not allow the State’s funding programs to meet projected demand. While additional (private or public) funds may increase the growth potential in the future, larger capacity stations will also play a key role in assuring the state’s fueling network capacity keeps pace with vehicle deployments. One major motivating factor is that larger stations not only make sense for the health and utility of the network, but they also make more financial sense for station operators.\footnote{Energy Commission 2015} Larger stations enable greater sales (assuming sufficient market demand) and therefore quicker payback periods and more attractive value prospects for investors and business owners. As shown in Table 9, which projects potential economic performance for various station designs in 2025, larger stations have more attractive financial performance and are more likely to be viable enterprises without State incentive funding. Note that the smallest stations, around 100 kg/day, may not be self-sufficient even by 2025; the revenue potential is simply too small to recover from the initial capital cost. Thus, station designs are likely to evolve to larger daily capacities and there may be a corresponding shift in production and delivery method to pathways that are better suited to the larger station design.

\textbf{Table 9 - Financial Performance for 2025 Stations without Incentives and with Capital Incentive Sufficient to Achieve a 10 Percent IRR}\footnote{Ibid.}

<table>
<thead>
<tr>
<th>Station Capacity</th>
<th>Delivered Liquid</th>
<th>Profitability Index</th>
<th>IRR</th>
</tr>
</thead>
<tbody>
<tr>
<td>600 kg/day</td>
<td>$0.00</td>
<td>16.8%</td>
<td></td>
</tr>
<tr>
<td>350 kg/day</td>
<td>$0.00</td>
<td>13.6%</td>
<td></td>
</tr>
<tr>
<td>180 kg/day</td>
<td>$0.04</td>
<td>9.1%</td>
<td>10.0%</td>
</tr>
<tr>
<td>100 kg/day</td>
<td>$0.00</td>
<td>0.0%</td>
<td>1.07%</td>
</tr>
</tbody>
</table>

\footnote{ARB 2016a} \footnote{Energy Commission 2015} \footnote{Ibid.}
In addition, today’s hydrogen fueling stations typically include only one dispenser and are only able to fill a single vehicle at a time. While vehicle deployments are just starting, this provides sufficient capability at hydrogen stations; there are not yet enough vehicles on the road that long lines at hydrogen dispensers are a concern. However, as deployment rates accelerate as shown in Figure 15, there will be an increasing need to assess, especially in the areas with the highest market potential, the need for and economic feasibility of including additional dispensers at a single station and to make any equipment upgrades necessary to allow simultaneous filling.

Ultimately, in a future with widespread adoption of FCEVs, hydrogen fueling stations will very closely resemble today’s gasoline fueling stations. Multiple islands, each with multiple dispensers capable of fueling simultaneously are expected to become the norm. This implies another potential change in siting hydrogen fueling stations. Today, nearly all stations are co-located at an existing gasoline station, which incurs its own set of additional negotiating, contracting, and permitting challenges. ARB expects that once very large stations become the norm (greater than 500 kg/day), standalone hydrogen stations may start to become a financially viable proposition and perhaps even a necessity for station design. These standalone stations may be placed on greenfield property where no fueling station currently exists or they may be conversions of existing gasoline stations. However, with the uncertainty of projected vehicle deployment rates, it is too early to pinpoint when this transition may occur or when the first example of such a standalone station is likely to appear.

Similar to the capability to perform simultaneous fills, stations are also likely to become increasingly capable of performing several back-to-back fills quickly and reliably. With many designs in today’s station network, certain equipment (mostly the high-pressure storage bank) requires a recharge period after a certain number of back-to-back fills. Requirements for back-to-back fill capability without a recharge delay have evolved in Energy Commission grant solicitations from three to a current requirement of five fills in an hour. ARB is aware that some stations are actually capable of providing even more back-to-back fills than the requirement. Additionally, the anticipated daily cycle of demand, even with large numbers of FCEVs on the road, implies that a given dispenser does not need to be capable of performing an unlimited number of back-to-back fills before requiring a recharge. However, back-to-back fill capability is not consistent across the current network and there is still room for improvement as the network grows.

Finally, ARB is confident that as hydrogen fueling networks continue to be established and expand in California, the U.S., and other parts of the world, there will be an increased move towards standardized and listed station designs and components. As hydrogen station deployment accelerates and production volumes increase, there will be a need for standardized definitions of component designs, capabilities, and manufacturing. Today, several groups are working to develop standards describing station design and performance requirements, but ARB has identified a need for harmonization amongst standards, especially those defined in separate regions. In addition to increased standardization, ARB has seen increased interest in listing of station components and designs, such as with a certification company like UL. Station

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109 Energy Commission 2016b
developers have seen that permitting may be faster and more likely successful in certain jurisdictions with UL listing of stations and components. Given the significant impact that permitting times can have on overall station development schedules, ARB anticipates much of the industry moving towards listing becoming more commonplace than it is today.

**XV.B. Future development of the hydrogen fueling network**

In addition to advancements and new paradigms in individual station design, the planning and development of the hydrogen fueling network is likely to evolve as FCEV deployment progresses. To date, the State’s efforts have been directed towards establishing a base level of coverage in areas with high potential for early market adoption of FCEVs. Although this focus will enable the launch of the FCEV market, it is not expected to be a sufficient network design for long-term viability and growth. For example, redundancy of coverage is currently considered through CHIT’s evaluation of degrees of coverage, but it will likely become an increasingly important factor when more FCEVs are on the road and primary markets branch off into nearby secondary markets.

Additionally, the currently funded network of 50 stations enables inter-regional travel between northern and southern California thanks to the station at Coalinga. Similar to redundancy in a local market, redundancy on this inter-regional corridor is necessary; multiple fueling options along the trip help minimize the risk of running out of fuel because any given station is unavailable. Moreover, the Coalinga station is the first true connector station in the state. More connectors are needed for travel along other similarly long routes, such as between the LA basin and Las Vegas, and between the San Francisco Bay Area and Oregon. Other connectors for inter-regional travel at smaller scales will also be necessary, such as between Riverside and San Diego, between the Sacramento Valley and the San Francisco Bay Area, and others. Connector stations may even eventually evolve to have their own design specifications separate from local market-serving stations, given the nature of the type of travel they enable.

Finally, destination travel has also been enabled by the currently funded network, with stations in Santa Barbara and Truckee. These stations allow travel to two of California’s many popular vacation and sightseeing destinations. As the network grows, customers will continue to expect increasing utility from the hydrogen fueling network and will expect to be able to reach all the same vacation and travel destinations as drivers of gasoline vehicles. Connector stations will help address this for some of California’s more remote destinations, but stations located at the vacation locales will also be necessary to ensure availability of fueling. Moreover, the current focus on coverage in California’s network development doesn’t necessarily emphasize redundancy of stations in these destination locations (though it does not preclude it, either). Eventually, redundancy will be necessary at vacation destinations, just like in the core adopter markets. In some cases, this could actually have the additional benefit of building a local secondary market; there are already indications of the potential for this type of development in Santa Barbara.

**XV.C. Future sources of hydrogen for FCEVs**

Much of the hydrogen currently dispensed for light-duty transportation is produced by conventional reformation of methane or reformation of biogas; a non-trivial amount is also
supplied by renewable electrolysis, typically on-site at the fueling station. Much of the conventionally produced hydrogen is currently sourced from the facilities that also supply hydrogen to other industries, such as oil refineries, semiconductor manufacturers, and food transportation companies. The hydrogen provided for vehicle fueling has at times been described as marginal excess within the industry. ARB is aware that most hydrogen production and liquefaction facilities are located outside of California and concentrated in the East Coast and Northeastern states. While this presents uncertainty for the future of sourcing hydrogen for high volumes of FCEV deployment, it also presents an opportunity for future development in line with the State’s goals for renewably-sourced and low-carbon energy.

One concept that is currently gaining wide-ranging support at both the State and federal levels is the concept of hydrogen as an energy carrier to enable increased implementation of renewables on the electric grid. The base concept is a more holistic vision of the entire energy system, with hydrogen as intermediary between many primary and final energy resources. Several variations of this concept have gone by different names, such as power-to-gas (P2G) or hydrogen at scale (H2@Scale, per DOE).\textsuperscript{110,111} This type of system anticipates significant over-generation of electric power and energy in future scenarios with high penetration of renewable (solar, wind, etc…) resources on the electric grid. In order to capture this energy, the excess electric power can be directed towards large-scale deployment of electrolyzers. The electrolyzers convert the electric energy into hydrogen, which can be stored for later use. That later use can include conversion back to electricity through fuel cells at times of low renewable energy availability, conversion to methane and injection into the existing pipeline, injection into dedicated hydrogen pipelines, upgrading of biofuels, or distribution to hydrogen fueling stations for transportation fuel. In June of 2016, DOE revealed hydrogen at scale to be a candidate for its next “Big Idea;” if adopted by the White House administration, significant effort at the DOE can be dedicated to the concept.

In addition, many bio-derived and bio-mimicking hydrogen production pathways are currently under research. Conversion of biomass and bioliquids, through advanced fermentation pathways, are currently under development. Processes that directly utilize sunlight in synthetic photosynthesis are also progressing at the laboratory scale and may eventually play a significant role in increasing the degree of renewable energy implementation for hydrogen production. While ARB is tracking these developments, there is currently too much uncertainty to project the degree to which each of these options may supply the future hydrogen fueling network.


XVI. California’s Hydrogen Infrastructure Initiatives

XVI.A. State roles and collaboration
California has long been a leader in the nation and even the world in the implementation of hydrogen fueling infrastructure and deployment of FCEVs. Arriving at today’s retail fueling network has taken decades of policy, research, demonstration, development, and leadership in public and private organizations at all levels. At the State level in particular, several agencies work in cooperation to support the role of FCEVs in meeting the governor’s climate and air pollution goals and to help the industry overcome the hurdles of establishing and growing early FCEV and hydrogen markets.

In addition to the ZEV regulation itself, the ARB currently has two main roles as related to deployment of light-duty FCEVs. The ZEV regulation incentivizes the early and rapid development and deployment of FCEVs and BEVs as solutions to meeting the State’s greenhouse gas reduction goals and to meet federal ambient air quality standards. In order to support the consumers who purchase or lease an FCEV, the ARB also manages the Clean Vehicle Rebate Project, which provides a rebate to ZEV purchasers. For further discussion of complementary policies and rebates applicable to ZEVs, see Appendix E. In addition, with the passage of AB 8, ARB collaborates extensively with the Energy Commission to plan and develop the early hydrogen fueling network. ARB’s official role in this process is to track and analyze the progress of FCEV and hydrogen fueling deployment and to annually provide guidance to the Energy Commission on areas where additional funding for new infrastructure is most needed. ARB also provides recommendations of the capacities and station design features that are necessary at that time. While this is ARB’s official role, the agency also works closely on a day-to-day basis with the Energy Commission and other agencies to work on addressing challenges in the early network deployment as they arise and are identified.

Under AB 8, the Energy Commission is responsible for administering funding incentives to support the development of the early hydrogen fueling network. AB 8 allows the Energy Commission to utilize up to $20 million per year through 2023, until at least 100 stations are built or the network exhibits self-sufficiency. To date, all incentives administered by the Energy Commission have been in the form of cost-sharing grant programs, with the State providing up to 85% of capital costs and up to $300,000 to cover operations and maintenance expenses. The Energy Commission does have the flexibility under AB 8 to consider alternative funding structures should it find sufficient reason to do so. Examples of alternatives include loan loss guarantees, market assurance grants, low or no-cost loans, and tax incentive structures. Like the ARB, the Energy Commission collaborates with colleagues across agencies in capacities beyond this official role in order to ensure success of the early State co-funded hydrogen network and FCEV market.

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112 Assembly Bill No. 8
113 Ibid.
114 Energy Commission 2016b
115 Energy Commission 2015
The Governor’s Office of Business and Economic Development also has a key role in the coordinated State effort to establish hydrogen fueling statewide. In 2014, GO-Biz established a ZEV coordinator to facilitate public-private partnerships towards this common goal. The ZEV coordinator has been responsible for maintaining day-to-day contact with hydrogen fueling station developers to track and gather detailed information about the development process at individual stations and for the network as a whole. The ZEV coordinator has also been instrumental in building consensus among industry members and State agencies for key developments in the hydrogen station network, like the recently implemented practice of “Soft Opening” new stations. The ZEV coordinator also leads support in working with local jurisdictions where hydrogen stations are planned. The ZEV coordinator has helped educate local officials new to hydrogen fuel, explained the benefits for the local community and state, and expressed the State’s commitment to greenhouse gas reduction goals with FCEVs as a key enabling technology.

Finally, the California Department of Food and Agriculture’s Division of Measurement Standards (DMS) has been closely involved with the testing and certification of hydrogen station equipment. Currently, DMS tests and certifies new hydrogen dispenser equipment accuracy under the California Type Evaluation Program (CTEP). This program, which defines standards for dispenser accuracy classes, has allowed for the world’s first retail sale of hydrogen by the kilogram to occur in California. In addition, DMS tests hydrogen fuel quality at stations on a regular basis, at times and conditions typically defined as requirements within the Energy Commission’s grant solicitations. Like the remaining agencies, DMS also remains an active participant in ongoing discussions of anticipated challenges for the hydrogen fueling network and proposed solutions, especially for issues of certification and testing of new stations.

XVI.B. State initiatives

XVI.B.i. AB 8

In 2013, the State of California passed Assembly Bill 8. Among numerous other provisions, AB 8 directed ARB and the Energy Commission to cooperatively establish the state’s base hydrogen fueling network. AB 8 established the availability of up to $20 million annual in funds that could be managed by the Energy Commission towards this effort. Additionally, AB 8 established a bi-annual cycle of analysis and reporting to guide the decision-making process for continued investments year after year. Under AB 8, ARB is charged with analyzing the progress and projections of FCEV deployment and hydrogen fueling station development.\footnote{Assembly Bill No. 8} Every June, ARB synthesizes its analysis into an Annual Evaluation delivered to the Energy Commission that provides recommendations for location, capacity, and technical capability of new stations to be funded under AB 8. In order to complete this analysis, ARB has created the CHIT/CHAT tools, which together track the progress and allow ARB to perform geospatial analysis of future needs. In addition, ARB’s analysis relies on up-to-date FCEV registration data
from DMV, annual auto manufacturer surveys of future ZEV deployment plans, and open-source geospatial demographic data, primarily obtained from the U.S. Census Bureau.\footnote{ARB 2015a}

**Figure 34 - Annual Cycles of Analysis, Reporting, and Funding Under AB 8**

Every December, the Energy Commission leads the development of a Joint Agency (with ARB) Staff Report. The Staff Report is intended to provide insight on typical costs and timing of
developing hydrogen fueling stations. In addition, this analysis is synthesized into an estimate of the total time and State investment necessary to bring the network to either at least 100 fueling stations or the point where the network is self-sufficient. In order to make these assessments, the first Joint Agency Staff Report incorporated geospatial analysis through NREL’s SERA model, financial performance analysis through H2FAST, and Energy Commission-led analysis of grant contracts and individual project progress. Figure 34 shows the annual cycle of analysis, which leads to the two annual reports. Ultimately, the content of these reports guides the development of the Energy Commission’s (approximately) annual grant solicitations for hydrogen fueling infrastructure, such as the current GFO-15-605.

XVI.B.ii. ZEV Action Plan

In 2012, Governor Brown issued Executive Order B-16-12, requiring the State of California to accelerate ZEV adoption, with a goal of 1.5 million ZEVs deployed in California by 2025. In response, an interagency working group headed by the Governor’s Office released the first ZEV Action Plan in 2013, outlining several key actions for several State agencies to complete in order to ensure the Governor’s goals for ZEV adoption. Over the next few years, the agencies worked towards these goals alongside their existing ZEV-related programs, partnering with stakeholders across other agencies at various jurisdiction levels (State, County, City, etc…) and within industry as necessary. In 2016, the ZEV Action Plan was updated to report on progress made in the intervening time and provide any necessary adjustment of the Action Plan items. Action items in the 2016 update will help California state agencies retain focus and direction in efforts to support the growing FCEV market and hydrogen infrastructure network and include the following:

- Facilitate highway signage directing FCEV drivers to stations
- Increase availability of hydrogen stations in areas of low adoption and disadvantaged communities
- Incentivizing renewable hydrogen production
- Continue oversight of hydrogen fueling station operations and retail advertising and sale of hydrogen fuel, including development of new technologies and techniques for validating station performance and fuel quality
- Encourage integration of hydrogen production, storage, and dispensing into demand-side management of electric infrastructure and enable wider integration of renewables into the electric grid
- Coordinate with local jurisdictions to continue development of infrastructure plans and make use of available federal funding opportunities
- Explore deployment of hydrogen fueling stations at rest stops and Caltrans facilities
- Expand outreach efforts, including to local authorities and first responder agencies

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118 Energy Commission 2015
119 Energy Commission 2016a
- Participate in multi-state and international efforts to advance hydrogen and FCEV adoption and readiness
- Encourage State agency integration of FCEVs into their fleets

XVI.B.iii. HyStEP

As a means to support swift deployment of hydrogen fueling stations, the State of California has developed and begun implementing the Hydrogen Station Equipment Performance (HyStEP) program. Stations that are built in California are required to adhere to the dispenser protocol standard SAE J2601-2014.\textsuperscript{122} The J2601 standard defines acceptable hydrogen fueling pressurization rates, accounting for ambient conditions and system state, such as the temperature of hydrogen exiting the chiller and the starting pressure in the storage tank onboard the vehicle being fueled. Before a station can be opened to the public, the ability of the dispenser to follow these safety-based protocols must be validated.

While the standard exists, there is no entity that formally certifies individual dispensers are able to meet the protocol's requirements. For the past several years, the solution has been for individual auto manufacturers to individually coordinate with station developers and perform serial testing of a new station’s dispenser. This testing would provide confirmation of acceptance of the station’s dispenser by each individual auto manufacturer. While this provided comprehensive testing, it was often costly (both to the station developer and auto manufacturer) and would require an extended period of time to complete, as schedules would need to be coordinated between several business entities and re-testing would often be required, as shown in the top half of Figure 35.

In order to develop a path to a more expedited station confirmation process, several agencies and partners in California initiated the HyStEP program, built around the development of an appropriate testing device. With funding provided by the DOE Fuel Cell Technology Office under the H2FIRST project, Sandia National Laboratories and NREL contracted with Powertech Labs to develop and build the HyStEP device. Specifically, the device has been designed to carry out the test methods of CSA HGV 4.3, which is a prescribed testing method to measure that stations follow SAE J2601-2014.\textsuperscript{123,124} The HyStEP device is additionally able to test IrDA communications per the vehicle-station communications protocol SAE J2799.\textsuperscript{125} The ultimate goal is that the HyStEP device (or a similar future version) could be utilized by a certification agency or private entity to test new station dispenser performance and provide authoritative confirmation that the dispenser is able to operate within the expected bounds of the standard protocol. The vision, as shown in Figure 35, is for the single HyStEP test to be capable of

\textsuperscript{123} Ibid.
\textsuperscript{125} SAE 2014b. SAE International. J2799: Hydrogen Surface Vehicle to Station Communications Hardware and Software. April 2014. \url{http://standards.sae.org/j2799_201404/}
performing the same validation within a single week as is currently completed within several weeks under the serial auto manufacturer testing.

Currently, HyStEP is operated by ARB with staff from DMS to test new station dispenser performance. The device was first delivered to the State in December of 2015 and performed validation testing (of the device’s own performance) at the Santa Barbara and Diamond Bar stations with the participation of several auto manufacturers to provide comparative data. On May 27, 2016, the auto manufacturer advisory group of the CaFCP also provided a letter of support for the device and program, indicating acceptance of the device as a supplement to current auto manufacturer testing. To date, the HyStEP device has also tested the dispensers at the CSULA, Riverside, Woodland Hills, and Anaheim stations; several more station tests are expected by the end of the year. ARB expects to initiate drafting a plan to develop an independent certification program based on HyStEP, without requiring concurrent auto manufacturer testing.

Figure 35 - Current Serial-Testing of New Station Commissioning and Potential Single Device Testing with HyStEP (originally attributed to Terry Johnson of Sandia National Laboratories, Pacific Northwest National Laboratory, and the H2Tools program)
XVI.B.iv. HFS and CTEP

Similar to the HyStEP program, California has also been a leader in developing methods and programs to test and validate hydrogen dispenser meter accuracy. In order for fuel retailers to sell hydrogen to retail customers by the kilogram (as opposed to relying on signed service contracts), dispensing meters must be certified as capable of measuring dispensed fuel to within acceptable tolerances. Prior to 2014, no agency in the state had developed a meter accuracy testing method, device, or program. Thus, several agencies worked together to develop the Hydrogen Field Standard (HFS) and new hydrogen-specific subsections of the California Type Evaluation Program (CTEP), which provided the first capability in the world to certify hydrogen fueling dispensers as accurate enough to sell hydrogen fuel by the kilogram.

The program, currently operated by the Division of Measurement Standards at the California Department of Food and Agriculture, certifies station dispenser accuracy within one of four different classes, as shown in Table 10. The accuracy classes are expanded versions, based on those previously adopted into NIST Handbook 44.\(^{128}\) At the time of developing the HFS program, California recognized that the standards in Handbook 44 were too stringent for dispenser meters readily available on the market. Thus, less stringent standards were also incorporated into the HFS program. These expanded standards will sunset over time, so that industry remains incentivized to develop increasingly capable hydrogen fuel meters. To date, all certified dispensers have met the 5% accuracy class.\(^{129}\)

Table 10 - Accuracy Class Definitions used in HFS Program

<table>
<thead>
<tr>
<th>Accuracy Class</th>
<th>Acceptance Tolerance</th>
<th>Maintenance Tolerance</th>
</tr>
</thead>
<tbody>
<tr>
<td>2.0</td>
<td>1.5 %</td>
<td>2.0 %</td>
</tr>
<tr>
<td>3.0 *</td>
<td>2.00%</td>
<td>3.00%</td>
</tr>
<tr>
<td>5.0 *</td>
<td>4.00%</td>
<td>5.00%</td>
</tr>
<tr>
<td>10.0 **</td>
<td>5.00%</td>
<td>10.00%</td>
</tr>
</tbody>
</table>

In order to carry out the certification program, the HFS device was developed through the cooperative effort of ARB, the Energy Commission, CDFA, and NREL. The device, shown in Figure 36, is operated by CDFA and is now used to certify the accuracy of all dispensers used at California’s hydrogen fueling stations. As part of CTEP, certification of hydrogen dispenser accuracy with HFS is established for a given dispenser design. A hydrogen dispenser


\(^{129}\) DMS 2016
manufacturer thus has a particular design type-certified at the first station utilizing that design in the state. Type certification of a hydrogen dispenser requires several days to complete. Once certified to a given accuracy class, other copies of that design installed at other locations can then be certified to meet the same accuracy class with an abbreviated set of tests. This helps accelerate station commissioning and deployment. In addition, the actual dispenser testing may be performed by Registered Service Agents rather than CDFA, which allows flexibility in scheduling. Many local jurisdictions are registered as RSAs with CDFA, and to date one station developer has also become an RSA, offering their testing services to other developers.

**Figure 36 - HFS Device Being Set-Up to Perform a Station Accuracy Confirmation Test**

---

**XVI.B.v. LCFS**

ARB’s LCFS provides standards and a credit trading market for a broad range of fuel providers to produce and distribute transportation fuels that have progressively lower carbon content. While the program has thus far had a major focus on fossil fuel providers, recent activity has broadened the potential scope for inclusion of hydrogen fuel producers and retailers. Recently, ARB staff provided draft changes to the program which included provisions to count hydrogen as a mandatory regulated fuel (as opposed to an opt-in fuel), allow the fuel retailer to be the primary recipient of credits (as opposed to the fuel producer as is the case for fossil fuels), and incorporate aspects of SB1505’s requirements for hydrogen production to include at least 33%
renewable feedstock and process energy. These draft changes allow the existing LCFS program to be harmonized with the SB1505 requirements that have not yet been enacted through regulation and potentially provide means of improving the business case for hydrogen station developers and the cost of ownership for FCEV drivers.

In addition, in late 2015, the LCFS program began receiving increased interest from the hydrogen fueling industry. In November, AC Transit, which operates the Emeryville combined light-duty and bus hydrogen fueling station, became the first entity to join the LCFS program and produce credits through the production of hydrogen. The solar-powered electrolysis pathway that provides a share of the hydrogen dispensed on the light-duty side of the station was certified by LCFS staff with a 0 gCO₂/MJ carbon intensity. Subsequently, two other companies, LyTen and Fuel Cell Energy, had their hydrogen production pathways provisionally certified. A provisional certification signifies LCFS staff validation of the pathway’s calculated carbon intensity, though no facility has yet been built to demonstrate the technology. All of these pathways were certified with very low carbon intensities; several were even negative, signifying the pathway is effectively capable of sequestering carbon in the fuel production process. In its June 2016 Annual Evaluation, ARB discussed the potential impact that participation in the LCFS program can have on the business case for hydrogen fueling station operators. As indicated in Table 11, these low-carbon hydrogen production pathways have the potential to generate significant revenue that can represent a cost savings to the station operator and potentially the end consumer.

Table 11 - Carbon Intensities and Potential Revenue for new Hydrogen Pathways in LCFS Program

<table>
<thead>
<tr>
<th>Fuel Pathway</th>
<th>Applicant</th>
<th>Carbon Intensity (gCO₂/MJ)</th>
<th>LCFS Value ($/kg)</th>
</tr>
</thead>
<tbody>
<tr>
<td>HYGN009</td>
<td>LyTen</td>
<td>29.84</td>
<td>$2.30</td>
</tr>
<tr>
<td>HYGN006</td>
<td>AC Transit</td>
<td>0</td>
<td>$2.66</td>
</tr>
<tr>
<td>HYGN011</td>
<td>Fuel Cell Energy</td>
<td>-0.82</td>
<td>$2.67</td>
</tr>
<tr>
<td>HYGN008</td>
<td>LyTen</td>
<td>-46.91</td>
<td>$3.22</td>
</tr>
</tbody>
</table>

XVI.B.vi. Fuel Quality

Finally, the State has actively participated in the development of procedures and programs to certify hydrogen dispensed at fueling stations meets requirements as described in the standard.

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132 ARB 2016b
133 ARB 2016a
SAE J2719.\textsuperscript{134} Table 12 lists the contaminants whose presence is required to be tested for under J2719. All grants awarded by the Energy Commission require hydrogen quality testing prior to a station becoming open and at least once every three months thereafter.\textsuperscript{135} CDFA may also perform quality testing in response to any consumer reports of problems with hydrogen quality at specific dispensers.

Although a testing period of at least every three months is typically sufficient to ensure long-term achievement of high purity standards, there have been a few cases in which customers have received hydrogen fuel with high amounts of impurities. This has at times required auto manufacturers to tow the vehicles (under warranty) to their repair centers and spend significant amounts of time and effort flushing the fuel cell and hydrogen storage systems in order to remove the impurity. Typically, the impurities have not caused permanent damage to the fuel cell system, though certain impurities do have this potential. Thus, several agencies in California are working together along with private industry partners and the national laboratories in order to develop a device that could test hydrogen purity in real-time as the hydrogen is dispensed. Such a device would be in-line with the fueling dispenser hose, and would test for specific “canary species” that indicate degraded hydrogen purity. Such a device would not be expected to be able to carry out the full suite of testing for all contaminants as shown in Table 12 (which typically takes weeks to complete), but would provide station operators with an early warning system and allow them to shut down fueling operations before impurities are dispensed into several FCEV drivers’ tanks.

Table 12 - Hydrogen Fuel Contaminants Specified in J2719\textsuperscript{136}

<table>
<thead>
<tr>
<th>Impurity Source</th>
<th>Typical Contaminant</th>
</tr>
</thead>
<tbody>
<tr>
<td>Air</td>
<td>N$_2$, NO$_x$, (NO, NO$_2$), SO$_x$ (SO$_2$, SO$_3$), NH$_3$, O$_3$</td>
</tr>
<tr>
<td>Reformate hydrogen</td>
<td>CO, CO$_2$, H$_2$S, NH$_3$, CH$_4$</td>
</tr>
<tr>
<td>Bipolar metal plates (end plates)</td>
<td>Fe$_2$+, Ni$_2$+, Cu$_2$+, Cr$_3$+</td>
</tr>
<tr>
<td>Membranes (Nafion)</td>
<td>Na+, Ca$_2$+</td>
</tr>
<tr>
<td>Sealing gasket</td>
<td>Si</td>
</tr>
<tr>
<td>Coolants, DI water</td>
<td>Si, Al, S, K, Fe, Cu, Cl, V, Cr</td>
</tr>
<tr>
<td>Battlefield pollutants</td>
<td>SO$_2$, NO$_2$, CO, propane, benzene</td>
</tr>
<tr>
<td>Compressors</td>
<td>Oils</td>
</tr>
</tbody>
</table>

\textsuperscript{135} Energy Commission 2016b  
\textsuperscript{136} SAE 2015
XVII. References


Assembly Bill No. 118 (Nunez, Statutes of 2007, Chapter 750).

Assembly Bill No. 8 (Perea, Statutes of 2013, Chapter 401).


CPUC 2012, California Public Utilities Commission, Press Release, April 27, 2012,  
http://docs.cpuc.ca.gov/word_pdf/NEWS_RELEASE/165145.pdf


DMS 2016. California Department of Food and Agriculture Division of Measurement Standard. CTEP Certificate of Conformance Database Search.  


DMS 2016. California Department of Food and Agriculture Division of Measurement Standard. CTEP Certificate of Conformance Database Search.  


EPRI 2013, Electric Power Research Institute, Electric Vehicle Supply Equipment Installed Cost Analysis, December 6, 2013  
http://www.epri.com/abstracts/Pages/ProductAbstract.aspx?Productld=000000003002000577

EPRI/NRDC 2015, Electric Power Research Institute and National Resources Defense Council, Environmental Assessment of a full Electric Transportation Portfolio, September 17 2015, 
http://www.epri.com/abstracts/Pages/ProductAbstract.aspx?Productld=3002006881

September 2016. South Coast Air Quality
https://www.arb.ca.gov/msprog/consumer_info/advanced_clean_cars/moving_toward_network_expansion_joel_ewanick.pdf


Senate Bill No. 1505 (Lowenthal, Statues of 2006, Chapter 877).


Appendix E:
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I. Introduction

California needs to transform the light-duty vehicle sector to achieve its criteria pollutant and GHG emissions reduction goals. The first step in the multi-faceted approach to creating a market for zero-emission vehicles (ZEV), meaning battery electric vehicles (BEV) and fuel cell electric vehicles (FCEV), and plug-in hybrid electric vehicles (PHEV) in California was the adoption of the ZEV regulation in 1990. Subsequently a number of complementary measures were adopted to help address the needs of a new market, including incentive programs, infrastructure deployment, and the formation of public private partnerships.¹

Governor Jerry Brown issued two executive orders to support and strengthen the growing ZEV market in California. Executive Order (EO) B-16-2012 directed California to “encourage the development and success of zero-emission vehicles to protect the environment, stimulate economic growth and improve the quality of life in the State.”² EO B-16-12 sets a target of reaching 1.5 million ZEVs and PHEVs on California’s roadways by 2025. It also establishes a longer term target of reducing transportation-related greenhouse gas emission by 80 percent below 1990 levels by 2050. EO B-16-12 is reflected in calls for collective action to support ZEV commercialization that have resulted in agreements with other states and countries. These collective actions are intended to catalyze growth in both the national and international ZEV markets, allowing automakers to achieve economy of production scale and subsequently price parity with conventional internal combustion engine vehicles. Complementing EO B-16-12 is EO B-18-12,³ which ordered State agencies to identify and pursue opportunities to provide electric vehicle (EV) charging stations and accommodate future charging infrastructure demand at employee parking facilities in new and existing state buildings.

Nine other states have adopted California’s ZEV regulation: Connecticut, Maine, Maryland, Massachusetts, New Jersey, New York, Oregon, Rhode Island, and Vermont. These are called the Section 177 ZEV states, and together with California represent nearly 30 percent of light-duty vehicle sales in the United States.⁴ In 2013, seven of the nine Section 177 ZEV states and California signed a Memorandum of Understanding (MOU) committing to take the necessary steps to achieve a target of 3.3 million cumulative ZEV and PHEV sales by 2025.⁵

Achieving this target will require that California and the Section 177 ZEV states overcome barriers to the adoption of these vehicles. In April 2015, the National Academies of Science issued a report titled “Overcoming Barriers to Electric Vehicle Deployment,”⁶ which emphasized that ZEV regulatory requirements have been effective in increasing plug-in electric vehicle

1 This broader set of initiatives along with the ZEV regulation is commonly referred to as the California ZEV Program.
2 The full text for Executive Order B-16-2012 can be accessed at the following website: https://www.gov.ca.gov/news.php?id=17472
3 The full text for Executive Order B-18-2012 can be accessed at the following website: https://www.gov.ca.gov/news.php?id=17508
4 See Appendix B
(PEV), meaning BEVs and PHEVs, production. The report also stated that market success would not be achieved through vehicle requirements alone. The three main barriers noted were the high cost of technology, lack of fueling infrastructure, and low consumer awareness.

Initial research is beginning to evaluate the effectiveness of the varying complementary policies and their impact on ZEV sales and vehicle usage. However, the challenge with the main barriers (e.g., consumer awareness, fueling infrastructure needs, and incremental vehicle costs) is large enough that California has recognized the need to implement additional non-regulatory actions to support the market, beyond the current efforts described in this appendix. For example, major new initiatives are being launched with broad consumer awareness campaigns, as well as infrastructure investments with the help of electric utilities (via California Senate Bill 350), to help bridge the gap. Staff plans to more carefully study the impact of these complementary policies in the next several years, to inform regulation proposals and also the implementation of the complementary policies. Preliminary analysis has been conducted, and a discussion on consumer acceptance of ZEVs and PHEVs in response to current policies is included in Appendix B.

A recent study by the International Council on Clean Transportation (ICCT) begins to evaluate the effectiveness of current ZEV complementary policies on ZEV sales in local markets. The study, “Sustaining Electric Vehicle Market Growth in U.S. [United States] Cities,” develops statistical correlations between current ZEV sales and the presence of market enabling factors such as infrastructure, consumer campaigns, high occupancy vehicle (HOV) lane access, etc. Although this study cannot be used to forecast what policies are needed to support the 2025 ZEV regulation sales targets, it provides important insights about which factors are more or less influential in today’s market conditions. The statistical correlations show a combination of policies are needed to encourage ZEV sales, but these correlations will change in the coming years as ZEV market conditions change. Changes anticipated include the introduction of 200+ mile BEVs priced under $40,000 that will use infrastructure in a different way, the potential sunset of HOV exemptions for ZEVs in California in 2019, the potential expiration of federal vehicle tax incentives for several major automakers in the next few years, changing eligibility requirements for state purchase rebates, and other factors.

Prior ICCT analysis also studied this topic, including a 2014 study, “Driving Electrification – A Global Comparison of Fiscal Incentive Policy for Electric Vehicles,” which found that multiple factors influence PEV uptake. The study called out California as exemplifying “a comprehensive electric-drive strategy that goes beyond fiscal incentives.” As noted above, staff intends to study the market carefully, in partnership with other agencies, as well as academic researchers, to ensure new policies are adequately informed.

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7 See Appendix D for staff’s assessment of PEV infrastructure in California and the Section 177 ZEV states.
Norway provides an example beyond California of the type of uptake that is achievable with an aggressive suite of complementary policies. As in the United States (U.S.), three of the most important motivators in Norway for ZEV sales are fuel savings, time savings derived from access to lesser-congested roads, and financial incentives (a sales tax exemption) associated with vehicle purchase. But, in addition to the U.S. equivalent of reduced utility rates, HOV lane access, and vehicle purchase incentives, Norway also offers free ferries, parking and charging and lower road fees. The largest incentive by far is the sales tax waiver. As a result, PEVs in Norway are generally less expensive than their ICE counterparts. These policies in aggregate have allowed PEV uptake in Norway to achieve critical mass, growing to 6 percent by 2013 and 30 percent by late 2016.

The take away from the existing research of U.S. markets and the Norwegian experience is that California and the Section 177 ZEV states will need to continue to be creative in identifying and implementing complementary policies that promise a more rapid ZEV uptake. The need to accelerate ZEV sales in the coming years, coupled with the projection of continued high incremental costs for ZEVs through 2025, highlights that existing complementary policies are important but insufficient to ensure California and the Section 177 states meet the 2025 targets.

This appendix discusses the suite of complementary policies that are being pursued at the international, federal, state, and local levels to address these and other barriers to a robust and growing ZEV market. Those policies include financial incentives such as vehicle tax credits, rebates, registration fee reductions or exemptions, lower electric utility rates, and high-occupancy vehicle lane exemptions. This appendix also discusses necessary activities to promote partnership-building, the development of quasi-governmental organizations to coordinate activities, and initiatives to grow infrastructure, encourage research and development, and conduct outreach and education. It concludes with a discussion of the organizations that are working to promote ZEVs, the broader agreements between California and other countries and states, and commitments to increase the number of ZEVs in government fleets.

II. Tax Credits, Rebates, Grants, and Exemptions
Consumer incentives play an important part of market development when the cost of new technology is high. The starting manufacturer’s suggested retail price (MSRP) of most PEVs on the market today is between $25,000 and $35,000, with many models being offered at prices twice as high. When compared with a sales-weighted average MSRP of $25,000 for all passenger cars, it is clear that incentives can help some consumers with their purchase decision of a ZEV or PHEV by reducing prices to be closer to the price range of conventional vehicles. When asked, currently 70% of current PEV owners (who received a vehicle rebate

---


12 See Appendix B, Section III.A.4 for further analysis on MSRPs for PEVs.
from California) indicated the federal and state purchase incentives played either an extremely or very important role in their purchase decision.\textsuperscript{13} This section explores the current monetary incentives offered on the Federal and State level.

\textbf{II.A. Federal}

\textbf{II.A.1. Qualified Plug-In Electric Drive Motor Vehicle Tax Credit}
The Qualified Plug-in Electric Drive Motor Vehicle Tax Credit varies by the capacity of the vehicle’s battery pack, awarding a $2,500 credit for vehicles with a five kilowatt-hours (kWh) battery and an additional $417 credit per kWh up to a maximum of $7,500. The tax credit begins phasing out for each manufacturer when its nationwide cumulative sales of qualified PEVs reach 200,000 vehicles. Based on historic sales rates, staff estimates at least four manufacturers would reach this threshold prior to 2025. Leading manufacturers General Motors and Nissan would reach it first possibly by 2022 followed by Ford and Tesla, though increasing sales of existing vehicles and introduction of new products would likely accelerate this timeline. An extension of the tax credit is not being discussed in Congress, which may create challenges for forthcoming products. Most PEVs are leased, and in these transactions, the automotive dealer generally applies for the credit. In turn, the dealer typically applies the credit as a down payment, reducing monthly lease payments accordingly.

\textbf{II.A.2. Alternative Fuel Infrastructure Tax Credit}
Fueling equipment for natural gas, liquefied petroleum gas (propane), liquefied hydrogen, electricity, ethanol, or diesel fuel blends containing a minimum of 20% biodiesel installed between January 1, 2015, and December 31, 2016, is eligible for a tax credit of 30% of the cost, not to exceed $30,000. Permitting and inspection fees are not included in covered expenses. Fueling station owners who install qualified equipment at multiple sites are allowed to use the credit towards each location. Consumers who purchased qualified residential fueling equipment prior to December 31, 2016, may receive a tax credit of up to $1,000. Unused credits that qualify as general business tax credits, as defined by the Internal Revenue Service (IRS), may be carried backward 1 year and carried forward 20 years.

\textbf{II.A.3. State Energy Program (SEP)}
The State Energy Program (SEP) is a federally funded, state managed program that provides grants to states for programs geared towards energy efficiency and renewable energy. SEP also facilitates state-based activities such as supporting and identifying transportation programs that accelerate use of alternative fuels. To date, the program has awarded $67 million to 103 competitive projects in 36 states. While Section 177 ZEV states should not overlook SEP as a potential ZEV infrastructure financing mechanism – Hawaii and Nevada have used SEP grants to install a small number of PEV EVSEs – it is doubtful that this program is scalable to the level necessary to support the broader infrastructure needs of the Section 177 ZEV states.

\textbf{II.A.4. Fuel Cell Motor Vehicle Tax Credit}
The Fuel Cell Motor Vehicle Tax Credit allows for a tax credit up to $8,000 for qualified light-duty vehicle purchases depending on vehicle’s fuel economy. The tax credit will expire on

\textsuperscript{13} See Appendix B, Section III.C.2.d for further analysis of the role of incentives in purchase decisions.
December 31, 2016. Multiple trade associations, along with other industry partners, are working to ensure that a tax credit is available beyond the December 31, 2016 expiration date.\textsuperscript{14}

II.A.5. Alternative Fuel Excise Tax Credit
The Alternative Fuel Tax Credit allows suppliers to receive a $0.50 per gallon federal tax credit for the liquefied hydrogen that is sold for the use of motor vehicles. This tax credit has been extended multiple times but has an expiration date of December 31, 2016.

II.A.6. Airport ZEV and Infrastructure Incentives
Under this program, public airports can receive funding for up to 50\% of the eligible cost to obtain on-road ZEVs that are specifically used for the airport as well as provide the fueling infrastructure to support such vehicles. This incentive is provided under the Clean Air Act and priority is given to airports in nonattainment areas. The Federal Aviation Administration has awarded $24.5 million in grants so far.

II.B. States
More than half of all U.S. states have incentives. Addressed here are incentives offered by California and the Section 177 ZEV states. Other states with notable programs to advance ZEV adoption are also recognized.

<table>
<thead>
<tr>
<th>State</th>
<th>Rebates, Tax Credits or Exemptions</th>
<th>Utility Discounts</th>
<th>HOV Access</th>
<th>Charger Incentive</th>
</tr>
</thead>
<tbody>
<tr>
<td>California</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
<td>Varies</td>
</tr>
<tr>
<td>Connecticut</td>
<td>Yes</td>
<td>Yes</td>
<td>No\textsuperscript{15}</td>
<td>Yes</td>
</tr>
<tr>
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\textsuperscript{15} There only 38 HOV lane miles divided among 3 limited access highways in Connecticut.
\textsuperscript{16} Conventional hybrids and PHEVs are allowed to access HOV lanes in New Jersey. New Jersey has a HOV lane between exits 11 and 14 on the New Jersey Turnpike. This represents about 30 miles of roadway in both directions.
\textsuperscript{17} New York’s consumer incentive program is under development and will commence shortly.
\textsuperscript{18} Vermont offers EVSE financing: http://www.driveelectricvt.com/charging-stations/financing
II.B.1. California

At the state level, the ARB’s Clean Vehicle Rebate Project (CVRP),\(^{19}\) created under Assembly Bill (AB) 118 in 2007 and now primarily funded by proceeds from California’s greenhouse gas cap and trade program provides rebates of $5,000 for FCEVs, $2,500 for BEVs, and $1,500 for those PHEVs that meet the definition of transitional ZEV or TZEV.\(^{20}\) Since its inception in April 2010, CVRP has provided $340 million in rebates to incentivize the sale or lease of more than 160,000 FCEVs, BEVs and PHEVs.\(^{21}\) This represents almost three-quarters of ZEVs and PHEVs sold since 2010 in California. To ensure the most effective use of funding, the CVRP guidelines are reviewed annually. Recent program changes include income caps, a PHEV range requirement, and a greater emphasis on getting ZEVs into disadvantaged communities. For example, supplemental targeted scrap and replacement incentive funding – which, in aggregate with CVRP, can provide up to $9,500 – is available for lower-income consumers.

**Figure 1 - Cumulative PEV* CVRP Rebates**

*In addition, over 500 FCEV rebates have been processed since 2010.

\(^{19}\) For eligibility requirements and a list of eligible vehicles, go to https://cleanvehiclerebate.org/eng.

\(^{20}\) A transitional zero emission vehicle (TZEV) is a PHEV certified to meet the 150,000 mile super ultra low emission vehicle (SULEV) exhaust emission standard, the zero evaporative emission standard, 150,000 mile on-board diagnostic requirements, and a performance and defects warranty of 15 years or 150,000 miles on the emission control components and 10 years or 150,000 miles on the zero-emission energy storage device used for traction poser (such as a battery, ultra-capacitor, or other electric storage device.

\(^{21}\) CVRP.2016. Clean Vehicle Rebate Project. “CVRP Rebate Statistics” http://cleanvehiclerebate.org/eng/rebate-statistics (ARB generated Figure 1 using these rebate statistics)
The California Energy Commission (Energy Commission) has also provided grants for the placement of electric vehicle supply equipment (EVSE) throughout the state. Currently active Energy Commission grants will establish a direct current fast charging network along the two major north-south corridors – Interstate 5 and Highway 99 – eliminating gaps in the West Coast Electric Highway. The Energy Commission has also provided grants to 10 communities throughout the state to assist those communities in developing their ZEV readiness plans. Finally, the California Pollution Control Financing Authority administers an EVSE program for small businesses.

Locally, four air districts provide vehicle incentives: the Antelope Valley Air Quality Management District provides a rebate of $1,000 to residential consumers; the Bay Area Air Quality Management District provides a rebate of $2,500 to agency fleets; the San Joaquin Valley Air Pollution Control District (SJVAPCD) provides $3,000 to consumers, up to $9,500 for low-income consumers, and up to $20,000 to public agencies; and the South Coast Air Quality Management District (SCAQMD) provides up to $9,500 for low-income consumers. The City of Riverside and El Dorado County provide rebates of $500 and $1,000, respectively, and the Transportation Authority of Marin provides rebates of $2,500 to fleets. One electric utility, the Sacramento Municipal Utility District (SMUD) also provides vehicle rebates of $300 to PEV consumers in SMUD territory. These local vehicle rebates are in addition to the federal tax credit and CVRP rebate.

Five electric utilities and the SCAQMD provide rebates of up to $1,000 for residential EVSEs. Four utilities provide rebates of up to $1,000 for workplace EVSE, and the SJVAPCD provides grants of up to $50,000 for public agencies and businesses. In addition to the local rebates and grants, NRG EVgo provides free EVSE wiring at businesses and apartment buildings in California.

II.B.2. Section 177 ZEV States

II.B.2.i Connecticut
At the state level, the Connecticut Department of Energy and Environmental Protection created the Connecticut Hydrogen and Electric Automobile Purchase Rebate (CHEAPR) program for highway-capable FCEVs, BEVs, and PHEVs. CHEAPR provides $5,000 rebates for the purchase or lease of a new FCEV; $750 rebates to PHEVs or BEVs with fewer than 10 or 20 kilowatt-hours of battery capacity, respectively; $1,500 rebates to PHEVs or BEVs with 10-18 or 20-25 kilowatt-hours of battery capacity, respectively; and $3,000 to PHEVs or BEVs with greater than 18 or 25 kilowatt-hours of battery capacity, respectively. Additionally, the registration fee for ZEVs is less than half the cost of a registration for a regular passenger vehicle. Pure ZEVs are also exempt from emissions testing, the associated $40 administrative fee, the two-year $20 testing fee, and the $5 greenhouse gas reduction fee.

EVCONNECTICUT, a PEV Charging Infrastructure Grant Program, makes funding – up to 100 percent of the project cost – available to municipalities, state agencies, and private businesses to install EVSE. Under the program, Connecticut placed 214 Level 2 EVSEs along main transportation corridors in the state and funded direct current fast chargers (DCFC) at two
service (travel) plazas. The Level 2 EVSEs and DCFCs installed under this program must be available to the public at no cost for three years.

The Connecticut Clean Fuel Program, administered by the Department of Transportation provides grants to municipalities and public agencies for the purchase, operation, and maintenance of alternative fuel vehicles. To date, this program has awarded ten grants for 7 BEVs, 11 PHEVs, and 10 neighborhood electric vehicles (NEV).

Connecticut has earmarked $450,000 for the development of future hydrogen refueling infrastructure.

II.B.2.ii Maryland
At the state level, Maryland offers a PEV tax credit of up to $3,000 based on the battery capacity of the vehicle in kilowatt-hours. Maryland's Department of the Environment is working to extend this tax credit, which has already provided 4,369 tax credits, and possibly increase the amount of funding per year in anticipation of growing sales. The Maryland Energy Administration offers a rebate equal to 50 percent of the cost of qualified EVSE and installation up to a maximum of $900 for individuals, $5,000 for businesses, and $7,500 for retail service stations.

Maryland’s Departments of the Environment and Transportation, the Maryland Energy Administration, and the Maryland Attorney General’s Office developed a $2 million Electric Vehicle Infrastructure Program to install dual standard (CHAdeMO and SAE Combo) DCFCs at 21 locations across the state. To date, the program has issued 743 rebates totaling almost $1.3 million. Approximately 70 percent of the rebates have been residential, but approximately 73 percent of the total has been commercial. The state also provided $1 million in funding for Level 2 EVSEs at eight of the state’s passenger rail facilities.

II.B.2.iii Massachusetts
Massachusetts Offers Rebates for Electric Vehicles (MOR-EV) and is a Department of Energy Resources program, funded through the Regional Greenhouse Gas Initiative proceeds, that offers rebates of up to $1,500 for PHEVs and $2,500 for customers of BEVs. To date, MOR-EV has rebated almost 2,700 PEVs. PEVs with an MSRP of $60,000 or more are limited to a rebate of $1,000. Massachusetts also provides grant funding for public and private fleets to purchase alternative fuel vehicles and infrastructure, as well as idle reduction technology.

The Massachusetts Electric Vehicle Incentive Program (MassEVIP) is a Department of Environmental Protection program that provides incentives to eligible municipalities, state agencies, and state universities and colleges for the acquisition of PEVs and the installation of Level 2 dual-head EVSEs. Incentives for BEVs are $7,500 per vehicle, while incentives for PHEVs are $5,000 per vehicle. Incentives for dual head Level 2 EVSEs range from $7,500 to $13,500 and are dependent upon the number of PEVs acquired. MassEVIP’s Workplace Charging Program has awarded funding for 161 vehicles and 444 EVSEs of which 341 have been installed.
Massachusetts exempts vehicles powered exclusively by electricity from state motor vehicle emissions control inspections.

**II.B.2.iv New Jersey**

New Jersey exempts new or used ZEVs sold, rented or leased in the state from state sales tax. It also exempts these vehicles from annual use taxes.

The “It Pay$ to Plug In” workplace charging grant program provides grants to employers to offset the cost of purchasing and installing EVSE. The New Jersey Department of Environmental Protection will reimburse applicants up to $250 per Level 1 EVSE and up to $5,000 per Level 2 EVSE. To date, the program has provided grants to 35 applicants for the installation of approximately 100 Level 2 EVSEs. Additionally, Public Service Electric and Gas (PSE&G) has provided a total of 60 free EVSEs for 11 locations belonging to employers who have five or more employees committed to owning PEVs. PSE&G retains ownership of the EVSE, and the employer pays electricity and installation costs.

New Jersey exempts vehicles powered exclusively by electricity from state motor vehicle emissions control inspections.

**II.B.2.v New York**

New York is developing a consumer rebate program to be administered by New York State Energy Research and Development Authority (NYSERDA) that will provide rebates of up to $2,000 to eligible FCEVs, BEVs, and PHEVs.

New York is also developing two municipal rebate programs that will be administered by the Department of Environmental Conservation. The first program is a business tax credit of 50 percent of the cost of purchasing and installing an EVSE (capped at $5,000). The credit is solely for business use. The second program will provide rebates of between $750 and $5,000 for BEVs, PHEVs, or FCEVs purchased or leased by municipalities (including counties). The combined budget for the infrastructure and vehicle programs this fiscal year (April 1, 2016 through March 31, 2017) is $3 million. The legislation includes an expiration date of April 1, 2023. Funding will be determined each year.

In 2012 and 2013, NYSERDA selected more than 20 partners to install Level 2 EVSEs. They were selected with a diversity of geography, business models, and location types in mind, and span public, workplace, multi-family, and fleet charging settings. NYSERDA contributed an average of about 65% of the EVSE and installation costs, and did not dictate the business model the EVSE owner was required to use for generating value from the EVSE. To date they have installed nearly 700 EVSEs statewide. NYSERDA is also planning upcoming programs to bring down the cost of EVSE installations through initiatives such as a purchasing collaborative, further incentives for workplace and multi-family charging, and a pilot of an EVSE leasing model.

New York exempts vehicles powered exclusively by electricity from state motor vehicle emissions control inspections.
II.B.2.vi Oregon
Oregon provides fleet, business, and residential tax credits. The state’s Energy Incentives Program provides both fleet and refueling infrastructure tax credits to trade, business, or rental property owners with a business site in Oregon, or to Oregon non-profit organizations, tribes, or public entities. The fleet credit is for 35 percent of the certified incremental cost of projects to replace two or more alternative fuel vehicles (including those fueled by electricity or hydrogen). The infrastructure credit is for 35 percent of the certified cost of projects to purchase and install fleet, public, multi-unit dwelling, and workplace EVSEs. Oregon additionally offers a tax credit for 50 percent of the cost of residential EVSEs, up to $750.

II.B.2.vii Rhode Island
Driving Rhode Island to Vehicle Electrification (DRIVE) is a new PEV rebate program administered by the Rhode Island Office of Energy Resources. DRIVE provides $500 rebates to PEVs with fewer than 7 kilowatt-hours of battery capacity, $1,500 to PEVs with 7 to 18 kilowatt-hours of battery capacity, and $2,500 to PEVs with greater than 18 kilowatt-hours of battery capacity.

The Rhode Island Charge Up! Program offers incentives to state agencies and municipalities interested in installing EVSE at publically accessible facilities, and supports the purchase or lease of EVs for integration into public sector fleets. Qualified public sector applicants may be eligible to receive a total award of up to $75,000 to support their adoption of clean transportation solutions.

The Office of Energy Resources awarded $781,225 in American Reinvestment and Recovery Act Funding to site and install a network of 50 publicly available Level 2 EVSEs. The Office of Energy Resources encourages operators of publicly available EVSEs to make fueling available for free.

Rhode Island exempts vehicles powered exclusively by electricity from state motor vehicle emissions control inspections.

II.B.2.viii Vermont
Drive Electric Vermont is partnering with Vermont auto dealers to offer a point-of-sale incentive of $750 for PEVs with fewer than 15 kilowatt-hours of battery capacity and $1,000 for PEVs with 15 or more kilowatt-hours of battery capacity. The program also incentivizes dealers $250. Funding is limited to the first 200 consumers.

II.B.3. Other States
II.B.3.i Colorado
Colorado offers an income tax credit of up to $6,000 for purchase of a PEV. The Colorado Energy Office (CEO) and Regional Air Quality Council (RAQC) provides grants to support PEV adoption in fleets. RAQC grants cover 80 percent of the incremental cost of a qualified PEV, up to $8,260. Both CEO and RAQC grants fund 80 percent of the cost of EVSE, up to $6,260.
II.B.3.ii Georgia
Georgia offers an income tax credit of 10 percent of the cost of an EVSE, up to $2,500. Georgia also exempts vehicles powered exclusively by electricity from state motor vehicle emissions inspections.

II.B.3.iii Washington
Washington exempts ZEVs from state sales and use tax. Washington also exempts vehicles powered exclusively by electricity from state motor vehicle emissions testing.

III. Utility Rate Reductions
In general, utilities in California promote energy conservation using a tiered pricing structure. Under this structure, the unit price of a kilowatt-hour of electricity increases above given usage thresholds. As a result, the addition of PEV charging to a home’s energy consumption could result in part or all of the additional incremental energy use being priced at a higher rate than that for the rest of the home. To incentivize PEV charging, some utilities offer a variable rate structure called time-of-use (TOU) pricing. Under this pricing structure, homeowners are charged varying energy rates depending on the time of day and the season when the energy is used. The benefit to the consumer of TOU pricing is that it allows homeowners who charge PEVs during off-peak hours (typically very late evening to early morning in the warmer half of the year and evening to mid-morning in the cooler half of the year) to do so at a rate that is discounted below that of the tiered rate structure. TOU periods often coincide with inactivity periods for most homeowners’ vehicles. The benefit to the utility is twofold. First, the utility can curtail charging during peak periods, which limits the need to bring online electricity produced by typically more expensive and dirtier power plants that only operate during periods of peak demand. Second, the utility can improve the efficiency of those power plants that are operated 24 hours per day by balancing the load over more hours.

More than 60% of California respondents aware of special rates offered by their utilities use or plan to use EV electricity price rate for charging at home, though when including those with utilities that do not offer such rates or are unsure of what rates they use, the share falls to 40%. However, in Massachusetts only about 10% of consumers use or plan to use EV rates, which likely reflects more limited availability as Northeast utilities are only beginning to offer charging discounts.22 As more states work with their utilities to help make electricity price rates available, consumers could be further convinced to purchase a PEV. Continued engagement with utilities will also become more important as more renewable electricity sources are incorporated which may modify the optimal charging times for vehicles.

Figure 2 below graphically illustrates the cost savings that can be obtained by a consumer charging a 30 kilowatt-hour Nissan LEAF during off-peak hours versus charging under a standard tiered pricing structure within the three largest IOUs (representing approximately 80 percent of PEV charging) in California.

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22 See Appendix B, Section III.C.1.e for more CVRP Consumer Survey and MOR-EV Survey results pertaining to intention and use of EV rates.
III.A. California
The three large investor owned utilities (IOU) and five publicly owned utilities (POU) in California provide lower TOU rates (often in conjunction with a second meter). A sixth POU provides a per kilowatt-hour discount, and a seventh POU provides flat monthly rates.

III.B. Section 177 ZEV States and Other States
As there are more than 500 electric utilities in the U.S. and rates are continually under review, the count of utilities offering TOU pricing targeted to PEV charging during times when there is excess capacity is constantly changing. Some utilities encourage PEV owners to use TOU rates that were previously in place, while others have established separate TOU pricing specifically for PEV owners. As the number of PEVs on the road increase, many utilities outside of California are beginning to explore TOU pricing through pilot programs, while some are holding open proceedings to establish permanent programs.

IV. HOV Lane Access
Another way government has incentivized ZEVs and PHEVs is through exemptions on the use of HOV lanes. This was an incentive that worked well with conventional HEVs, helping spur demand in California in the early 2000s. As described in Appendix B, early PEV consumers reported HOV lane access as a top motivation in their PEV purchase decision given the level of congestion found on California’s freeway network. As seen in Figure 73 of Appendix B, greater than 50 percent of the respondents to that survey said that HOV lane access was either

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23 See Appendix B, Sections III.C.2.c. and III.C.2.d. for further analysis of PEV purchase motivations and the role of incentives based on California CVRP Consumer Survey data.
very or extremely important. However, HOV lane access is set to expire for PEVs in California, and few other states offer HOV lane access, or have limited HOV lane miles available. HOV lanes do not exist in all states, in some cases because congestion is not an issue. Therefore, exemptions for ZEVs in HOV lanes do not currently have the same value for drivers in all states. California’s experience at least appears to warrant additional research into the level to which HOV lane access in other ZEV states could serve as a PEV uptake motivator.

**IV.A. Federal**

**IV.A.1. High Occupancy Vehicle (HOV) Lane Exemption**
The U.S Department of Transportation (U.S. DOT) is tasked with planning and executing HOV lane programs. HOV lanes, also known as carpool lanes, allow vehicles to operate in designated lanes with a specified number of passengers in the vehicle. Qualifying inherently low-emission vehicles (ILEV) and hybrid electric vehicles (HEVs) displaying a state-issued exemption sticker are allowed to operate in HOV lanes regardless of the number of passengers. Although it is a federal policy, states are responsible for issuing and enforcing the exemption. The exemption for ILEVs ends September 20, 2019 and the exemption for remaining vehicles ends September 30, 2025.

**IV.B. California**
California issues white decals to operators of federally inherently low-emission vehicles (BEV/FCEV) and green decals to qualifying PHEVs. These decals allow single occupant access to HOV lanes. Decal distribution for both white and green decals is unlimited and provides HOV lane access until January 1, 2019.

**IV.C. Section 177 ZEV States**
Maryland and New York allow PEV single occupant access to HOV lanes. New Jersey allows conventional hybrids and PHEVs to access HOV lanes.

**IV.D. Other States**
Arizona, Colorado, District of Columbia, Florida, Georgia, North Carolina, Tennessee, Utah, Virginia, allow single occupant access to HOV lanes. Colorado and Arizona do not grant access to new ZEVs and PHEVs, but allow vehicles that have previously received exemption to travel in HOV lanes to continue to do so.

**V. State Level Initiatives, Coalitions, and Actions**
PEV consumer awareness is low, both in California, and across the Section 177 ZEV states. Often government can help increase awareness through broad campaigns and initiatives.24

Additionally, as charging and hydrogen infrastructure is often cited as a barrier to consumer acceptance of ZEVs and PHEVs, state and local governments can play either a direct role in funding or installing infrastructure or a more indirect, though equally relevant, role streamlining

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24 See Appendix B, Section III.B for additional discussion of current consumer awareness levels and barriers to adoption.
the permitting process for these installations or establish best practices for other property managers or site hosts. Governments and supporting partners can also help to coordinate the multiple, simultaneous efforts to reduce redundancy and ensure an efficient deployment of infrastructure.

V.A. California

V.A.1. Regional Planning
The Energy Commission has awarded PEV readiness grants to more than ten regions throughout the state to create a unified statewide approach to the planning and implementation of PEV charging infrastructure and other market supporting actions. These grants have allowed communities to develop planning strategies for distribution of charging with interregional corridor plans or sub-regional planning studies. The California PEV Collaborative and the Energy Commission aligned their respective programs in 2012 such that the U.S. Department of Energy (U.S. DOE) Clean Cities grants focused on five core readiness elements communities will need near-term (“capacity building”), while the Energy Commission grants allowed the communities to expand PEV readiness in other, more substantial ways in the long term.25

V.A.2. PEV Resource Center
The PEV Resource Center26 is an online buying guide that provides consumers with information on PEV technology, maintenance and costs, charging and charging infrastructure, incentives, and safety. The local search function allows consumers to identify all federal, state, and local incentives available within a given zip code. The PEV Resource Center website is hosted by DriveClean,27 an ARB-maintained online buying guide that provides consumers with greenhouse gas and smog ratings information for clean and efficient light-duty vehicles regardless of fuel or technology.

V.A.3. Building Code Development
ARB staff has worked with the Building Standards Commission (BSC) and Housing and Community Development (HCD) to develop building standards that require installation of PEV charging infrastructure in new commercial buildings and homes. The Green Building Standards (CALGreen) Code includes requirements for PEV charging infrastructure in new buildings to support future installation of Level 2 charging stations. All new single and two-family dwellings and townhouses with attached private garages must install PEV charging infrastructure. Multi-family dwellings with 17 or more units on the building site must install PEV charging infrastructure in 3 percent of total parking spaces. Non-residential buildings with parking lots that have 51 spaces or more, must install PEV charging infrastructure in 3 percent of parking spaces. Effective January 1, 2017, parking lots with 10 or more parking spaces must install PEV charging infrastructure in about 6 percent of parking spaces.

All new buildings must install raceway, which is the conduit or pipe that future wiring can be pulled through, and must provide adequate panel capacity to support future Level 2 charging.

25 Since this alignment, the Energy Commission has funded additional EV readiness efforts and information can be found at their program website: http://www.energy.ca.gov/2013-ALT-01/documents/Regional_Readiness_Grants.pdf
26 Access the PEV Resource Center: http://driveclean.arb.ca.gov/pev/
27 Access DriveClean: http://driveclean.arb.ca.gov/
New buildings must also identify that the building is PEV-capable as part of the site plan, on the electrical panel, and at the termination point for the raceway. The CALGreen Code requirements for PEV charging infrastructure in new construction will help to meet California’s demand for EV charging in 2020 and beyond. However, because it is not required in the CALGreen Code, it will be essential for EVSEs to be installed in these new buildings to ensure the charging spaces become fully “PEV-ready” and available for immediate use by PEV drivers. ARB staff is planning to measure the rate of installation of PEV chargers in new buildings to track achievement of statewide goals. ARB staff will also continue to provide suggested code changes based on future updates to projections for PEV charging infrastructure needs.

V.B. Section 177 ZEV States

V.B.1. Connecticut
State, local, and non-government entities have worked alone and in collaboration to advance the ZEV MOU, clean fuels, and fueling. The Connecticut Electric Vehicles Infrastructure Council is comprised of state agencies, municipalities, and industry, and laid the foundation to prepare Connecticut for rapid and seamless integration of ZEVs into the market. The Connecticut Automotive Retailers Association supports the design and implementation of incentives and dealer awards and encourages auto dealers to install free public PEV charging at their local dealerships. The Connecticut Department of Energy and Environmental Protection issues annual grant awards (Connecticut’s four U.S. DOE’s Clean Cities coalitions) to conduct outreach to advance alternative fuel vehicles and to work with fleets. Connecticut’s Green Bank aims to leverage public funds to encourage greater private investment in clean technology for transportation. Finally, the Connecticut Fund for the Environment and local Sierra Club have been actively conducting outreach and education to promote ZEV public policy.

On the infrastructure side, Connecticut has begun installing EVSEs in state parks with large visitor turnout and is growing the state’s hydrogen refueling network. For example, the City of Hartford, the Connecticut Center for Advanced Technology, a private developer and an automaker are collaborating to leverage the build of a hydrogen station at the junction of two major highways in Hartford, halfway between New York City and Boston.

V.B.2. Maine
Maine recently partnered with the Province of Quebec to establish a PEV corridor between Quebec City and Old Orchard Beach, Maine, a popular tourist destination for Quebecois by summer 2017. The joint task force includes state agencies, Maine Turnpike Authority, Hydro-Quebec, Central Maine Power, Quebec Transportation and Department of International Relations, Efficiency Maine Trust, Greater Portland Council of Governments (GPCOG) and Electric Mobility Northeast.

GPCOG received a grant from Central Maine Power to install 17 Level 2 EVSEs in central and southern Maine. GPCOG also received a grant from Nissan to lease a Leaf for several years and promote the vehicle to several municipalities and area businesses, which resulted in 5 municipalities and 1 business purchasing or leasing a PEV and installing 14 EVSEs.
Electric Mobility Northeast is working with Nissan and a grocery chain to install 5 DCFC stations in central and southern Maine.

Maine has adopted a policy to promote the development, implementation, availability, and use of smart grid technology. The policy includes the goal of integrating advanced electric storage and peak-reduction technologies, such as PEVs, into the electric system.

**V.B.3. Maryland**

Maryland’s Electric Vehicle Infrastructure Council (EVIC), established through legislation introduced in 2011, works to collaboratively promote PEVs. EVIC was charged with the evaluation of incentives for the ownership of ZEVs and the purchase of PEV charging equipment; the development of recommendations for a statewide infrastructure plan; and the development of other potential policies to promote the successful integration of ZEVs into Maryland’s communities and the transportation system.

EVIC has been instrumental in shepherding legislation establishing or extending HOV lane access, tax credits for vehicles, and rebates for charging infrastructure. As a result of their action plans and infrastructure efforts, there are now charging stations at many transit stations throughout the state.

Maryland’s Departments of the Environment and Transportation and the Maryland Energy Administration, are working with a private contractor to develop a state-funded education and outreach program for EV. The focus areas of the program are to: (1) promote ZEVs (using outreach and education materials and vehicle and charger incentives), (2) identify potential workplace charging locations, and (3) conduct outreach to property owners of both commercial and residential properties.

**V.B.4. Massachusetts**

The Massachusetts Zero-Emission Vehicle Commission (ZEV Commission) is comprised of individuals from the Executive Office of Energy and Environmental Affairs, the Departments of Transportation, Energy Resources, and Environmental Protection, the Division of Standards, City of Boston, a second community named by Massachusetts Municipal Association as well as stakeholders from the environmental and business communities, utilities, auto dealers, refueling equipment and automakers, and parking company owners/operators.

The ZEV Commission will study the economic and environmental benefits and costs of increased use of ZEVs. The ZEV Commission is tasked with filing an action plan to the legislature and providing guidance to the Commonwealth on ZEV related matters including but not limited to encouraging the purchase and lease of ZEVs (in part, through incentives), further expanding access to refueling infrastructure; and identifying strategies for removing barriers to ZEV deployment.

The Mass Drive Clean Campaign is a “first in the nation” state-sponsored ZEV test drive program. Eight test drive events were held primarily at workplaces in 2015. The 2016 campaign expands to 16 events.
V.B.5. New Jersey
The New Jersey Department of Community Affairs has developed a streamlined permitting
guide to installing EVSE at residences. The document describes the instances under which a
permit would be required.

V.B.6. New York
New York’s Departments of Environmental Conservation and Transportation and NYSERDA
were a driving force behind the formation of the Transportation Climate Initiative (TCI).

The New York State Interagency ZEV Workgroup was established in January 2014, with initial
participation by nine key agencies: the Departments of Environmental Conservation,
Transportation, Motor Vehicles, Public Service, and State (Codes Division), the Office of
General Services, the Thruway Authority, the Power Authority, and NYSERDA. The workgroup
has since expanded to include 18 state agencies and two New York City agencies (Citywide
Administrative Services and Transportation). This group is working from the Multi-State ZEV
Action Plan\textsuperscript{28} to address New York specific items while several members work closely with the
other MOU signatory states on regional issues.

V.B.7. Oregon
Since 2009, Oregon has been involved in multiple in-state initiatives to complement the
mandatory ZEV program, including the Governor’s Alternative Fuel Vehicle Infrastructure
Working Group, Transportation Electrification Executive Council, Ten-Year Energy Plan, and
Statewide Transportation Strategy.

Oregon is now reorganizing the way its state agencies collaborate to effectively implement
actions needed to facilitate increasing adoption of ZEVs. Previous limited-duration committees
addressing issue clusters (energy, transportation, global warming, etc.) are expected to be
replaced by groups more directly focused on promoting ZEVs. Oregon’s Departments of
Transportation, Environmental Quality, and Energy, as well as Business Oregon and the
Transportation Research and Education Consortium, are the leading agencies in these efforts.
In the future, other agencies and organizations are expected to join the core groups including
the Department of Administrative Services, Building Codes, electric utilities, the Oregon PUC,
Oregon cities, and the public/private partnership Drive Oregon.

V.B.8. Rhode Island
The Rhode Island ZEV Working Group (working group) – comprised of the State’s Departments
of Environmental Management and Transportation, Office of Energy Resources, and the Ocean
State Clean Cities Coalition – was established to expand access to refueling infrastructure,
encourage ZEV procurement (partly through incentives), and identify strategies to remove
barriers to deployment. The working group is collaborating with state and quasi-state agencies,
municipalities, private and nonprofit companies, auto dealers, and utility providers. Their goals
include creating a Rhode Island ZEV implementation plan based on the multi-state ZEV,
spurring market growth through private, municipal, consumer and dealership incentives,

\textsuperscript{28} TCI and the Multi-State ZEV Action Plan are discussed in the Broader Agreements and Alliances Section.
quantifying necessary infrastructure and planning for the future, and expanding consumer awareness.

V.B.9. Vermont
In response to the damage caused by Tropical Storm Irene, and in acknowledgment of projections of more frequent and more intense storms in the future, Governor Shumlin convened a Climate Cabinet in May 2011. The Climate Cabinet is chaired by the Secretary of the Agency of Natural Resources, includes senior officials from eight state agencies, and supports both the expansion of the State’s market for EV, and the electrification of the state’s own motor pool. The State’s Agency of Transportation, Department of Motor Vehicles, Department of Environmental Conservation, and Agency of Natural Resources as well as Drive Electric Vermont, the Vermont Clean Cities Coalition, and the Vermont Energy Investment Corporation are just some of the participants in the Climate Cabinet activities.

In 2014, the same year Vermont joined the multi-state MOU, the Climate Cabinet developed a Vermont ZEV Action Plan and formed a multi-agency ZEV implementation team to support and drive its implementation. In 2015, the Cabinet worked closely with the Department of Public Service to prepare an updated Comprehensive Energy Plan (CEP) for Vermont. CEP puts a major focus on the transition from fossil fuels to the use of ZEV and LEV technologies as an integral step, striving to make 10 percent of the total light-duty passenger fleet electric by 2025.

Drive Electric Vermont is a statewide coalition of policy makers, industry leaders, and ordinary citizens that meets regularly to coordinate and expand efforts to expand the PEV market in Vermont. The coalition was initially formed and funded through a memorandum of understanding between the Agency of Transportation, the Agency of Natural Resources, the Vermont Public Service Department, and a nonprofit called the Vermont Energy Investment Corporation that convenes and manages the coalition. The program is working to increase: (1) PEV awareness and vehicle purchases, (2) availability of workplace and public charging infrastructure, and (3) state and local policy support.

Working with DEV, the State also reached an agreement with Quebec-based Electric Circuit to establish a “Green Corridor” between Burlington, Vermont and Montreal. This 138-mile corridor currently has over 40 charging stations. Government officials on both sides of the border hope the corridor will help promote PEV tourism in the region.

VI. Federal Initiatives, Coalitions, and Actions

VI.A. Clean Cities
The U.S. DOE Clean Cities Program encourages cities to reduce petroleum use across the United States. Nearly 100 Clean Cities Coalitions provide a national network of regional partnerships, projects, and technical expertise. California has 12 Clean Cities Coalitions; the nine Section 177 ZEV states have 18 coalitions combined.
Clean Cities has awarded $400 million for alternative fuel and vehicle projects. In 2011, $8.5 million was awarded for 16 regional PEV readiness projects, including projects in California, New York, and Oregon.

**VI.B. EV Everywhere**
EV Everywhere is a U.S. DOE project to expand the PEV market across the U.S. through partnerships, outreach, and research and development. More than 250 employers have joined the EV Everywhere Workplace Charging Challenge in committing to support and provide workplace charging. These efforts have resulted in more than 600 workspaces with over 5,500 charging stations accessible to nearly 1 million employees. EV Everywhere recently provided nearly $2.5 million for “Plug In Electric Vehicle Local Showcases.” Almost $1.5 million was awarded to ride and drive projects focused in Connecticut, Massachusetts, Oregon, Rhode Island, and Vermont.

**VI.C. Fixing America’s Surface Transportation Act – Designation of Alternative Fuel Corridors (FAST Act)**
Under the Fixing America’s Surface Transportation Act (FAST) Act, formerly called the National Alternative Fuels Corridors Act, the U.S. Secretary of Transportation is required to designate national fueling corridors for electric, hydrogen, propane, and natural gas vehicles. The goal is to improve the mobility of vehicles by increasing alternative fuel infrastructure across the country. The initial deadline is December 2016; every five years the fueling corridor will be evaluated for strategic infrastructure expansion.

The FAST Act also authorizes the General Services Administration (GSA) Administrator, or the head of a Federal agency, to install, construct, operate, and maintain on a reimbursable basis a battery recharging station (or allow, on a reimbursable basis, the use of a 120-volt electrical receptacle for battery recharging) in a parking area that is in the custody, control, or administrative jurisdiction of the GSA or the Federal agency for the use of only privately owned vehicles of Federal employees and others who are authorized to park in such area to the extent such use by only privately owned vehicles does not interfere with or impede access to the equipment by Federal fleet vehicles.

**VII. Supporting Organizations**
This appendix has already discussed some of the barriers to ZEV deployment and adoption and many of the policies that have been put in place to diminish those barriers. Supporting organizations, which are typically public-private partnerships, are essential to understanding barriers and identifying solutions to grow the ZEV market. The members of these partnerships can include government, non-governmental organizations, universities, and vehicle and infrastructure companies. Members convene, collaborate, and communicate on emerging ZEV market trends. They also work together, harnessing the collective expertise of their members, to address challenges and promote the technology.
VII.A. California

The PEV Collaborative is a partnership between California public and private entities charged with a goal to accelerate the PEV market. This organization is comprised of 47 members representing automakers, infrastructure providers, utilities, government agencies, environmental non-profit organizations, academic institutions, and the California Legislature. The PEV Collaborative has developed resources on multi-unit dwellings and workplace charging installations, conducted a regular webinar series on relevant topics, and coordinates a PEV Ride-and Drive Series at regional fairs and special events. Analysis of the survey responses from these ride and drives indicates that 76% of participants were more likely to consider acquiring a PEV after test driving one. The impact of exposure to PEVs through participation in ride and drive events and car-sharing programs has been shown to have a positive effect on attitudes towards PEVs and increase interest in PEV adoption.29

“Drive The Dream” is a signature event for the PEV Collaborative, in which business leaders and Governor Brown engage and announce investments in workplace charging and other incentives to advance the PEV market. Following successful California events in 2013 and 2015, the PEV Collaborative co-sponsored “Drive the Dream Vermont” in Fall 2015.

VII.A.2. California Fuel Cell Partnership
The California Fuel Cell Partnership (CaFCP) is a collaboration of 36 government agencies, automakers, and energy and fuel cell technology providers. CaFCP is committed to promoting FCEV commercialization with its concomitant energy efficiency, air quality, and greenhouse gas emission benefits. CaFCP members collaborate on activities that advance the technology such as codes and standards development for the design, construction and operation of hydrogen refueling stations, first responder training, and consumer education and outreach. Examples of the success of this collaboration include development of the Hydrogen Station Equipment Performance (HySTEP) device, which will reduce the time to commission new stations, and the technology to meter dispensed hydrogen so that stations can be certified to sell the fuel.

VII.B. Section 177 ZEV States

VII.B.1. Northeast States for Coordinated Air Use Management (NESCAUM)
NESCAUM is an association of air pollution regulatory agencies from Connecticut, Massachusetts, Maine, New Hampshire, New York, New Jersey, Rhode Island and Vermont. The association provides scientific, technical, analytical, and policy assistance to ZEV programs for its member states and additional states implementing the ZEV and low-emission vehicle regulations. NESCAUM also coordinates implementation of the Multi-State ZEV Action Plan and activities of the multi-state ZEV Implementation Task Force.


E - 20
VII.C. National

VII.C.1. Electric Drive Transportation Association
The Electric Drive Transportation Association (EDTA) is an industry trade association promoting hybrid, PHEV, BEV, and FCEV drive technologies and infrastructure. EDTA conducts public policy advocacy, provides education and awareness, and enables industry networking and collaboration. EDTA is comprised of more than 70 members and partners including vehicle and equipment manufacturers, energy companies, technology developers, component suppliers, government agencies and others.

VII.C.2. Fuel Cell & Hydrogen Energy Association (FCHEA)
The Fuel Cell and Hydrogen Energy Association (FCHEA) is a trade partnership that aims to accelerate fuel cell and hydrogen energy technology commercialization. FCHEA is comprised of a multi-tiered membership of 51 members representing automakers, component and system manufacturers, fuel producers and providers, government laboratories and agencies, and utilities.

VII.C.3. H2USA
H2USA is a public/private collaboration to promote the success of hydrogen fuel cell vehicles and fueling infrastructure across the U.S. The organization is comprised of 44 participants representing energy companies, automakers, government agencies, fuel cell suppliers, non-profit organizations, and materials and components suppliers.

VII.C.4. Plug In America (PIA)
Plug-In America (PIA) is a non-profit PEV advocacy group. PIA expresses that their goal is to “accelerate the shift to plug-in vehicles powered by clean, affordable, domestic electricity to reduce our nation’s dependence on petroleum, improve air quality and reduce greenhouse gas emissions.” PIA works with consumers, policymakers, automakers and others. In 2015, through their National Drive Electric Week events in 41 states and 7 Canadian provinces, PIA reached out to more than 130,000 potential PEV consumers.

VII.C.5. Sierra Club
The Sierra Club is a non-profit environmental organization focused on resource conservation. Its “Rev Up EVs” campaign has been deployed in ten key states. Member volunteers visited local dealers to see, ask about, and test drive electric cars, and then provided feedback on the experience to the organization. The Sierra Club has used these findings to advocate for best practices that encourage EV sales. The Sierra Club continues to help ZEV advocates, the auto industry, and government agencies learn what is working well and what could be improved in the EV marketplace.

VIII. Broader Agreements and Alliances
To date, California’s ZEV program has resulted in the placement of several hundred thousand ZEVs and PHEVs on California roads and a growing network of ZEV charging and hydrogen fueling stations. The ZEV program has also influenced ZEV policy around the world. Increasing collaboration at the state, national, and international levels has helped – and will continue to help – address challenges to ZEV market expansion, including global technology development.
and cost reduction and thus, will allow California to achieve its emission reduction targets. There is much to learn from each region’s experience, and these joint efforts are important in tackling the remaining hurdles to ZEV growth in California and beyond.

**VIII.A. State Level**

**VIII.A.1. California ZEV Action Plan**

The role of EO B-16-12, which directs state government to help accelerate the market for ZEVs in California, was previously mentioned. Governor Brown’s EO B-16-12 established several milestones for success. The ZEV Action Plan, developed in 2013, identifies those specific strategies and actions that 11 California state government agencies will need to take to meet the milestones of the executive order. The 2016 ZEV Action Plan, released in October 2016, outlines progress to date and identifies new actions that state agencies will take in continued pursuit of those same milestones. The 2016 plan places greater emphasis on consumer awareness (both vehicle options and benefits), vehicle affordability, convenient refueling infrastructure, the integration of ZEVs into state government fleets, and the growth of the ZEV market outside of California. It also broadens California’s zero-emissions focus to include medium- and heavy-duty vehicles and freight applications. The 2016 plan commits the state to: (1) meeting a ZEV purchase goal of 50 percent by 2025 for its government fleet, and (2) equipping at least 5 percent of the workplace parking spaces at state facilities with charging station infrastructure. The 2013 and 2016 ZEV Action Plans provide a mechanism for multiple state agencies to work together for successful implementation.

**VIII.B. Multi-State Level**

**VIII.B.1. Multi-state ZEV MOU, ZEV Action Plan, and ZEV Task Force**

In October 2013, California signed a MOU with Connecticut, Massachusetts, Maryland, New York, Oregon, Rhode Island, and Vermont to collaborate on strategies for transforming the transportation sector over the next 11 years, with the ultimate goal being to significantly reduce greenhouse gas and smog-causing emissions. Since then, interested stakeholders, including state regulators, the auto industry, infrastructure developers, and others have shared information and best practices to help move this groundbreaking effort forward. On the heels of the release of the 2013 California ZEV Action Plan, the MOU states released a Multi-state ZEV Action Plan in May 2014. The plan identifies 11 key actions to be taken by the plan’s partners to build the market, provide consistent codes, standards, and tracking, and improve the ZEV driver’s experience. The Multi-state ZEV Task Force, comprised of members from each state and coordinated by NESCAUM, is addressing the action items in the plan, including advancing infrastructure needs and supporting ZEV sales.

**VIII.B.2. Transportation Climate Initiative (TCI)**

TCI consists of the environmental, energy and transportation agencies from 11 Northeast and Mid-Atlantic states (Connecticut, Delaware, Maryland, Maine, Massachusetts, New Hampshire,  

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New Jersey, New York, Pennsylvania, Rhode Island, and Vermont) as well as the District of Columbia. TCI’s Clean Vehicles and Fuels Workgroup has been intimately involved in advancing ZEV technology and enabling policies in both Section 177 ZEV states and non-Section 177 jurisdictions. For example, TCI developed branding of the Northeast Electric Vehicle Network, which is not just a network of EVSEs but a network of more than 100 companies, organizations, and jurisdictions that have pledged to work to support EV use. They have also successfully applied for various federal grants to develop materials such as best practices guidelines for a variety of ZEV audiences.

VIII.B.3. Pacific Coast Collaborative (PCC)
Alaska, British Columbia, California, Oregon and Washington make up the Pacific Coast Collaborative (PCC). PCC establishes a formal basis for cooperative action, a forum for leadership and information sharing, and a common voice on issues facing Pacific North America. PCC is committed to supporting and promoting innovation and the adoption of new transportation technologies including ZEVs and PHEVs. To accelerate adoption of these new technologies and stimulate private infrastructure investment, the Pacific coastal jurisdictions are working to establish a "green highway" for alternative fuel vehicles, including ZEVs and PHEVs along the Interstate 5/Highway 99 corridor leading from Southern California to Whistler, British Columbia.

VIII.C. International Level

VIII.C.1. International ZEV Alliance (IZA)
The International ZEV Alliance (IZA) is a collaboration of national and subnational governments working together to accelerate the adoption of ZEVs around the world. The participants set ambitious, achievable long-term targets for ZEV deployment, take actions to achieve those targets as appropriate in each jurisdiction, and encourage and support other jurisdictions in setting and achieving ambitious ZEV targets. The IZA counts among its members California, Connecticut, Maryland, Massachusetts, New York, Oregon, Rhode Island, and Vermont, all of whom are also members of the Multi-state ZEV MOU Task Force.

VIII.C.2. Netherlands MOU
The PEV Collaborative, signed an MOU with a similar Dutch partnership, Coast-to-Coast E-Mobility, in October 2013. California Environmental Protection Agency signed a Letter of Intent with the Dutch Ministry of Environment endorsing the MOU and pledging further cooperation. The California Energy Commission signed an MOU in March 2015 with the Vice Governor of the Netherlands to collaborate on best practices for ZEV infrastructure implementation.

VIII.C.3. Japanese Memorandum of Cooperation
On September 5, 2014, Governor Brown and Japanese Ambassador Sasae signed a Memorandum of Cooperation (MOC), pledging coordination on ZEV development. This MOC opened the door for collaboration with Japan’s Department of New Energy and Industrial Technology Development (NEDO) on a research project, which will result in 30-50 DC fast chargers in Northern California travel corridors allowing travel from the Pacific Ocean to Lake Tahoe.
VIII.C.4. Chinese MOU
One day later, on September 6, 2014, the University of California, Davis and the China Automotive Technology and Research Center signed a five-year MOU establishing the China-U.S. ZEV Policy Lab. The policy lab will promote ZEV-related policy design and vehicle development, helping speed ZEV commercialization in China and the U.S. The ARB and China’s National Development and Reform Commission co-chair the policy lab’s advisory board, and witnessed the MOU signing.

IX. Vehicle Acquisition and Fuel Use Requirements for Fleets
Broad government actions can help promote technology and increase awareness. Federal, state, and local governments can lead by example by including ZEVs and PHEVs into vehicle fleets. Current fleet initiatives are discussed below.

IX.A. Federal
Under the Energy Policy Act (EPAct) of 1992, 75 percent of new light-duty vehicles acquired by covered federal fleets must be alternative fuel vehicles (AFV). The AFV designation was amended in 2008 to include HEVs, FCEVs, and advanced lean burn vehicles. Federal fleets are also required to use alternative fuels in dual-fuel vehicles unless the U.S. DOE determines an agency’s vehicle requests qualify for waivers; grounds for a waiver include lack of alternative fuel availability and cost restrictions (per EPAct 2007, section 701).

Additional requirements for federal fleets were included in the Energy Independence and Security Act of 2007, including low GHG-emitting vehicle acquisition requirements (Section 141), federal fleet conservation requirements (Section 142), and renewable fuel infrastructure installation requirements (Section 246).

To address these requirements, U.S. DOE promulgated Executive Order 13693, issued in March 2015, which requires federal agencies with 20 vehicles or more to improve fleet and vehicle efficiency through the elimination of non-essential vehicles and achieve a 30 percent reduction of fleet-wide GHGs relative to a fiscal year (FY) 2014 emissions baseline by FY 2025. Covered agencies must also install telematics systems on certain new vehicles; submit annual vehicle acquisition data; ensure that by December 31, 2020, and December 31, 2025, 20 percent and 50 percent, respectively, of light-duty vehicle acquisitions are ZEVs or PHEVs; and plan to install charging and other infrastructure to support new ZEV and PHEV acquisitions.

IX.B. California
Governor Brown’s EO B-16-12 requires "that California’s state vehicle fleet increase the number of its zero-emission vehicles through the normal course of fleet replacement so that at least 10 percent of fleet purchases of light-duty vehicles be zero-emission by 2015 and at least 25 percent of fleet purchases of light-duty vehicles be zero-emission by 2020."

California’s Department of General Services (DGS) Office of Fleet and Asset Management issued Management Memo 13-04 in January, 2013 providing direction to all state agencies under the Governor’s executive authority regarding how to meet the fleet ZEV purchase requirements. Through June 2016, DGS has approved for purchase more than 450 ZEVs for
use in the DGS fleet. This number does not include ZEVs that have been placed in other state agency fleets.

**IX.C. Section 177 States**

Connecticut has begun integrating ZEVs into the State fleet; many Connecticut towns and municipalities have PEVs in town fleets.

Under the Massachusetts Electric Vehicle Incentive Program, municipalities and state agencies have acquired PEVs and installed charging stations. To date municipalities have purchased 216 PEVs and installed 72 charging stations and state agencies have acquired 19 PEVs and installed 76 charging stations.

New York State’s DOT will be acquiring a fleet of 24 PHEVs that will be distributed for use mostly at its equipment and crew depots. Six level two, networked chargers have been purchased to service a portion of the PHEV fleet but most of the cars will utilize level I chargers.

Oregon requires 10 percent ZEVs in fleet purchases.

Rhode Island requires that a minimum of 25 percent of new light-duty state fleet purchases and leases will be ZEVs by 2025. In achieving energy reduction goals, state agencies are also encouraged to install additional EVSEs at State properties.
X. REFERENCES


http://cleanvehicleresbate.org/eng/rebate-statistics

Markowitz, FCHEA President. September 2016


Hanley 2016. Steve Hanley, Gas2.0.org (article) “Norway May Pull Back on Some EV
Incentives,” February 29, 2016; http://gas2.org/2016/02/29/norway-may-pull-back-on-some-ev-
incentives/


Vehicle Market Growth in the U.S. Cities” October 2016. http://www.theicct.org/leading-us-city-
electric-vehicle-2016

MOU 2013. Memorandum of Understanding. October 24, 2013, Can be accessed and
downloaded at http://www.zevstates.us/about-us/, click on “Memorandum of Understanding”

Vehicles” https://www.nap.edu/catalog/21725/overcoming-barriers-to-deployment-of-plug-in-
electric-vehicles

3/24/2016];

Young 2013. Angelo Young, International Business Times (article). “Tesla Owners In Norway
Get $134,000 Tax Break, Which Is More Than The Base Price Of The Model S.” December 13,
price-model-s-1507740
Appendix F:
Scenario Planning: Evaluating impact of varying plug-in hybrid electric vehicle (PHEV) assumptions on emissions

January 18, 2017
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Introduction

The California Air Resources Board (ARB or the Board) previously explored the importance of zero-emission vehicle (ZEV) technologies in meeting California’s long-term climate change and air quality goals using scenario planning in the Mobile Source Strategy\(^1\) report released in May 2016. In that document, staff presented and discussed post 2025 scenarios incorporating various mobile source sector strategies to achieve long-term emissions reductions for both greenhouse gases (GHG) and criteria pollutants. The light-duty vehicle (LDV) advanced vehicle strategies build upon prior staff analysis in the Advanced Clean Cars (ACC) rulemaking staff reports from December 2011.\(^2\) This report includes new LDV scenarios that represent sensitivity analyses relative to the Cleaner Technologies and Fuels scenario in the Mobile Source Strategy.

The ARB Vision model\(^3\) was the primary modeling tool used to assess the emissions impacts of the various scenarios, accounting for both mobile source and upstream fuel production emissions. The structure of the Vision model is shown in Figure F-1 below.

**Figure 1 - VISION Model Overview**

![VISION Model Overview](image)

In brief, the Vision model allows users to assess transportation well-to-wheel (WTW) emission impacts from changes in both downstream vehicle emissions and upstream fuel production.

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\(^3\) ARB. 2016b. Air Resources Board. Vision Program. July 17, 2016. [https://www.arb.ca.gov/planning/vision/vision.htm](https://www.arb.ca.gov/planning/vision/vision.htm)
variables in future year forecasts to 2050. In the downstream portion, users can modify variables such as vehicle technology sales fractions, fuel efficiencies, and vehicle activity. In the upstream portion, users can modify such variables as fuel blends and renewable fuel consumption. Most variables can be modified annually from 2010 to 2050. The model includes all mobile source sectors in ARB’s inventory, and for light-duty and heavy-duty sectors, relies on ARB’s EMFAC 2014 fleet inventory as a foundation.4

One of the primary scenarios presented in the Mobile Source Strategy, using the VISION 2 platform, was the Cleaner Technologies and Fuels (CTF) scenario. The objective of that scenario was to highlight a potential pathway for meeting the 2050 GHG emission reductions target (80% below 1990/2020 levels), as well as identifying strategies for meeting 2031 oxides of nitrogen (NOx) emission reductions in the South Coast Air Basin (SCAB) needed for attainment with national ambient air quality standards for ozone. The CTF scenario incorporated a number of strategies for the LDV sector including the following:

- Increased pure ZEV and plug-in hybrid electric vehicle (PHEV) sales (100% of new vehicle sales by 2050), beyond regulation minimum compliance in 2025.
- Progressive increase in fuel economy (all technology types), beyond 2025 CAFE compliance values.
- Progressive increase in PHEV electric vehicle miles travelled (eVMT) fractions (40% in 2025 to 60% in 2050 combined for passenger car and light truck classifications).
- Reduced growth in overall vehicle miles travelled (VMT) in future years (15% below baseline by 2050).
- Increased fractions of renewable sources for all fuel types.

Figure 2 and Figure 3 highlight the key assumptions in the CTF scenario regarding PHEV and ZEV sales and fuel economy increases in the LDV fleet, respectively. The figures also highlight the role PHEVs could play in the future years. Specifically, in the CTF scenario, PHEVs comprise approximately one third of total ZEV (which also includes battery electric vehicle or BEV and fuel cell electric vehicle or FCEV) new vehicle sales in 2050.

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In regards to fuel economy (new vehicle, on-road performance), the CTF scenario assumes PHEVs will experience an increase in fuel economy from approximately 60 miles per gallon-gasoline equivalent (mpg-ge) in 2025 to approximately 125 mpgge in 2050. Compared to other technologies like gasoline, BEVs and FCEVs, the PHEVs experience a more aggressive growth in fuel economy. This is due to the assumption that the gasoline engine in the PHEV will increase in fuel economy in addition to the electric propulsion providing a higher eVMT fraction in future model years. As the eVMT fraction increases from 40% to 60%, PHEVs begin to achieve vehicle efficiencies that more closely resemble a BEV than a gasoline vehicle.

Regarding the eVMT fraction assumption, some current vehicles such as the 2017 Chevrolet Volt are likely to already exceed the near term and long term estimated eVMT fractions. However, this eVMT assumption is a weighted average for the entire passenger car and light truck combined fleet. Accordingly, it would account for some vehicles such as smaller passenger cars having a higher fraction of eVMT while other vehicles such as large SUVs or trucks that could have a lower fraction of eVMT.
Figure 3 - Fuel Economics in the CTF Scenario

Although the CTF scenario shows PHEVs play a significant role in all years through 2050, they are not a pure ZEV technology. PHEVs have internal combustion engines that emit GHGs and other criteria pollutants through tailpipe and evaporative emissions. The potential for these vehicles to emit such pollutants is highly dependent on parameters such as driving/charging behavior, fuel economy, and eVMT fractions as well as the onboard controls and durability of emission control systems. The impact of such parameters on GHG and criteria pollutant emissions would become even more prominent if PHEVs comprise a higher fraction of LDV fleet in the future. In order to assess the potential impacts of changes in PHEV parameters and higher PHEV sales fractions, staff developed several PHEV-focused VISION sensitivity scenarios to assess how the presence of PHEVs in the LDV fleet may affect California’s ability to meet its statewide GHG and criteria pollutant emission targets in the future. The development of these scenarios and the inputs to the VISION model are described in the next section.

Development of scenarios and VISON model inputs

As previously described, the ability of PHEVs to control GHGs and criteria pollutants is dependent on vehicle parameters such as eVMT fractions and fuel economy, and on driving and
charging behaviors. Such impacts become even more pronounced if PHEV sales fractions increase in the future. With that in mind, staff developed five sensitivity scenarios using the VISON model. These scenarios can be categorized into three basic groups and are described in detail below. Group A and B scenarios address a sensitivity study on PHEV variables, whereas the Group C scenario addresses sensitivity on fuel economy assumptions for all technology types. As such, Group C is placed at the end of the chapter.

I.A. Scenarios (A1 and A2)
These scenarios explore how changes in assumptions about PHEV eVMT fractions alone would impact statewide emissions in future years, while maintaining technology sales fractions from the CTF scenario. Specifically, staff developed a low eVMT fraction scenario (A1) where eVMT fractions would decrease from 40% eVMT (the baseline eVMT fraction in the CTF) to 35% in 2050. Staff also developed a high eVMT fraction scenario (A2) where eVMT fractions would increase from 40% eVMT in 2025 to 85% in 2050. These two scenarios equally bound the baseline CTF scenario (which assumes a growth to 60% eVMT by 2050) with alternative assumptions representing 25% higher and lower eVMT by 2050. The range of eVMT forecasts could be the result of numerous factors including faster/slower progress in vehicle technology, changes in consumer driving and charging behavior from influences such as energy and fuel costs, or availability of charging and refueling infrastructure. Figure 4 displays the change in eVMT fraction assumptions over time for the new scenarios as well as the CTF for comparison purposes.

Figure 4 - Group A Scenario eVMT Fractions

I.B. Scenarios (B1 and B2)
These scenarios build upon the Group A scenarios by using the same eVMT fraction assumptions as in Group A, but simultaneously increasing the PHEV sales fraction to
approximately 88% in 2050 instead of approximately 33% in the CTF scenario. This was done by keeping the same total ZEV sales fraction from 2025 to 2050 but allowing PHEVs to make up a larger portion of the total relative to the CTF scenario. In the B1 scenario, these higher PHEV sales were combined with the higher eVMT fractions used in Scenario A2. In the B2 scenario, higher PHEV sales were combined with the lower eVMT fractions used in A1. Figure 5 provides a graphical representation of the fleet technology profile and PHEV sales fractions for the Group B scenarios.

Figure 5 - PHEV Sales Fractions and Fleet Technology Profile in Group B Scenarios

It should be noted that in all five of these scenarios, the total WTW biomass usage was kept constant to ensure LDV’s portion of the limited feedstock (fuel source) did not change. Specifically, the total available biomass was fixed for use across all fuel types, including liquid biofuel consumption, as well as biomass used to produce electricity and hydrogen. For example, as hydrogen fuel consumption was decreased in scenarios A and B, more biomass was available for liquid biofuel use in PHEV vehicle consumption. If alternate scenarios were created where biomass is not used to produce hydrogen or electricity, then the biomass usage would be isolated to only the PHEV liquid biofuel consumption.

I.C. Summary of Results for Groups A and B

The relative impacts of the four A and B scenarios on WTW GHG emissions, tank to wheel (TTW) NOX and TTW volatile organic compounds (VOC) emissions are shown in Figure 6,
Figure 7, and Figure 8, respectively. Each of the pollutants followed the same trend for all four scenarios. Specifically, there were increased emissions under the B1 and B2 scenarios and the A1 scenario. Only under the A2 scenario (higher eVMT growth, no increase in PHEV sales fraction) did emissions decrease. When using the CTF scenario PHEV sales trajectories, higher and lower eVMT growth rates shows a modest sensitivity of less than ±7.5% change in projected GHG emissions by 2050. When combined with higher PHEV sales trajectory, however, the projected impact from the eVMT sensitivity ranged from a 16% to 60% increase in GHG emissions showing a much greater sensitivity to how the PHEVs are used in the fleet.

**Figure 6 - WTW GHG Emissions for Group A and B Scenarios relative to CTF.**
Note that the axis on the right side of the graph applies to calendar year 2050 only.

For the NOx and VOC results shown in Figure 7 and Figure 8 below, the results were directionally similar. Only scenario A2 (higher eVMT growth, no increase in PHEV sales fraction) showed lower emissions than the CTF scenario. Similar to the GHG results, the higher and lower eVMT growth combined with baseline PHEV sales fractions shows a very modest sensitivity of less than ±7% change in projected NOx emissions by 2050 (0.8 tons per day (tpd) statewide). For VOC emissions statewide, the impact was ±3%. However, when combined with higher PHEV sales fractions, the projected impact ranged from an approximate 16% to 56% increase in NOx emissions and an approximate 20% to 33% increase in VOC emissions statewide by 2050 revealing a greater sensitivity to the eVMT growth assumptions.

One note regarding the projected NOx and VOC emissions is that these projections utilized the EMFAC 2014 model. As noted in other appendices, ARB has been recently evaluating unique criteria pollutant emission impacts of PHEVs regarding the frequency of engine starts and the emissions from those starts and the findings of that testing have not yet been incorporated into
the EMFAC model. Further, ARB’s inventory staff are also updating many of the assumptions regarding emission rates that will impact these projections and are targeting a revised version for 2017.

Figure 7 - Vehicle Statewide NOx Emissions for Group A and B Scenarios relative to CTF. Note that the axis on the right side of the graph applies to calendar year 2050 only.
An alternate “high PHEV fleet” scenario could be created (not done in VISION here) where total FCEV fleet vehicle volumes remain the same as the CTF scenario, and additionally PHEV fleet-wide electricity usage remains the same as the fleet-wide BEV VMT they replace (modeled as an increasing eVMT factor for new vehicle PHEVs). Specifically, it could assume PHEVs only displace BEVs and not any FCEVs compared to the CTF scenario. This combination of assumptions could result in a scenario with the exact same GHG emissions as the CTF scenario. However, to achieve the same electricity usage with PHEVs, the increasing eVMT assumption for new vehicle PHEVs would have to increase dramatically faster than ARB assumed in Figure F-4; an assumption ARB staff do not believe is possible.

Figures 9 and 10 below show the combined fuel demand results from Scenarios A and B. Fuel usage is a strong indicator for emissions impacts in the scenarios. Fuel types modeled in the LDV scenarios, and shown in Figures 9 and 10, include a gasoline blend, electricity and hydrogen. All three of these fuel types include varying blends of fossil based fuels as well as zero carbon and renewables. For the gasoline blend, the liquid fuel components include petroleum gasoline blendstock (CARBOB), ethanol from an increasingly more sustainable feedstock (moving away from corn), and renewable gasoline with a low carbon intensity. Hydrogen and electricity both include a large shift to renewable sources becoming mostly decarbonized by 2050.
In Figure 9, total fuel usage is shown. Fuel usage is reduced in A2-H (higher eVMT than CTF) as expected resulting in lower emissions shown earlier. In scenario B1-H where eVMT is higher than CTF but with more PHEVs in the fleet, total fuel usage is approximately the same as the CTF scenario, but there is more demand of gasoline blend fuel (and less hydrogen fuel demand). Because the gasoline blend fuel has a higher carbon intensity per unit consumed than hydrogen or electricity, the well-to-wheel emissions of B1-H are higher than CTF as shown in Figure 6.

**Figure 9 - Total fuel usage (gasoline blend, electricity, and hydrogen) in CTF and Scenarios A and B (million gallons gasoline equivalent)**

Figure 10 below shows a more specific portion of total fuel usage, the bio-based fuels from the gasoline blend, electricity and hydrogen. In the CTF scenario, bio-electricity and bio-hydrogen are part of the overall supply. For Scenarios A and B, the fraction of electricity and hydrogen supplied by bio-fuels was not changed, but as total electricity or hydrogen demand changes, so does the use of bio-based fuels. However, for the gasoline blend fuel, the renewable gasoline blend ratio was varied in Scenarios A and B such that the total bio-based fuel usage remained approximately the same as the CTF scenario (~900 million gallons gasoline equivalent, or MGGE). This was done to mimic a fixed supply constraint of bio-based fuels for LDVs in all scenarios. As a result of this, renewable gasoline usage increased substantially in Scenario B as bio-hydrogen was scaled back. Ethanol blends are fixed at 10% by fuel volume, but vary in the scenarios proportional to total gasoline blend usage.
Figure 10 - Bio-based fuel usage in CTF and Scenarios A and B (million gallons gasoline equivalent)

**I.D. Scenario (C1)**

This scenario was developed to investigate the sensitivity of fuel economy improvement assumptions on future year GHG emissions. Specifically, the 2025 to 2050 annual fuel economy improvement rates for all technology types (i.e., gasoline, BEV, FCEV, and PHEVs) were lowered from 2.9% improvement per year to 2.3% improvement per year, which represents a 20% reduction in the annual improvement rate. Figure 9 provides a graphical comparison of the fuel economy growth rate of gasoline vehicles in the CTF scenario and Scenario C. The objective of this scenario was to quantify the magnitude of increased GHG emissions in 2050 and subsequently determine the required increase in ZEV sales rate from 2025 to 2050 in order to offset the increased GHG emissions in 2050.
I.E. Summary of Results for Group C

In Scenario C, as the new vehicle fuel efficiency growth rates were slower for future years, fleet-wide GHG emission reductions are smaller (less GHG reduction benefits) compared to the CTF scenario. Specifically, the LDV 2050 GHG emissions went up by 2 MMT CO$_2$e, or approximately 9% of the LDV sector’s 2050 GHG WTW inventory. To compensate for this impact, Scenario C modeled an increased rate of ZEV and PHEV sales to increase the overall efficiency of the fleet. The same technology sales mix used in CTF was assumed (approximately 1/3 each of BEVs, FCEVs, and PHEVs for the total ZEVs) and resulted in an increased sales rate needing to reach 100% ZEV sales by 2048 instead of 2050, adding an additional 1.4 million ZEVs and PHEVs to the fleet by the end year. The yellow line in Figure 10 represents the increase in CO$_2$ emissions over time in this scenario. As shown in the graph, the increased CO$_2$ emissions due to lower fuel economy are eventually offset to the original CTF levels in 2050 due to accelerated ZEV and PHEV sales.
Figure 12 - Scenario C Emission impacts

Risk:
Lower fuel efficiency increased GHG by 9% (2 mmt). To offset increased GHG, an additional 1.4 Million ZEV+PHEVs are needed by 2050 (100% ZEV + PHEV sales by 2048).
References

https://www.arb.ca.gov/regact/2012/zev2012/zevisor.pdf

https://www.arb.ca.gov/planning/sip/2016sip/2016mobsrc.htm

https://www.arb.ca.gov/planning/vision/vision.htm

https://www.arb.ca.gov/msei/categories.htm#onroad_motor_vehicles
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I. Introduction

In 2012, the California Air Resources Board (ARB or the Board) adopted the Advanced Clean Cars (ACC) program, including increased requirements for the zero-emission vehicle (ZEV) regulation. When the increased requirements for the ZEV regulation were adopted, only two manufacturers had certified plug-in hybrid electric vehicles (PHEV), and little was known about how those vehicles would be driven, what the emissions benefits could be, how often those vehicles would be plugged in, or how the second or third owners of the vehicles would drive or charge the vehicles. Knowing there was much to learn about PHEVs and range extended battery electric vehicles (BEVx), the Board directed staff in Resolution 12-11 to study “in-use data for range extended battery electric vehicles and plug-in hybrid electric vehicles, and, if warranted, propose appropriate modifications to treatment and credits for these vehicle types”.

Soon after the Board adopted the ACC regulations, manufacturers (notably, Honda, Toyota, Ford, and General Motors) requested (both in front of the Board and during meetings with staff) that staff be directed to study the electric vehicle miles traveled (eVMT) from PHEVs as compared to BEVs. Manufacturers (General Motors, Ford, Toyota, and Honda) submitted trip level data to Idaho National Laboratory (INL) for analysis, which was later presented to the Board at its October 2014 hearing. Since 2014, manufacturers have submitted the same trip level data (as well as additional data and data from other manufacturers) for ARB to analyze.

This Appendix G describes the in-use trip level vehicle data collected from various PHEVs, BEVs, and BEVxs. To provide a complete picture of how “ZEV-like” a PHEV is, staff analyzed two metrics, electric only trips (e-trips) and zero emission vehicle miles travelled (zVMT). As seen from the data, driving data from the same vehicle model can vary widely dependent on when and under what driving conditions the data was collected. Vehicles with similar electric ranges have varied eVMT and zVMT. The data also shows that EV project participants were a limited set of very early adopters and vehicles purchased by a broader group were less interested in maximizing %eVMT and %zVMT. Although newer PHEVs have higher VMT, their average annual eVMT and zVMT remains constant. When possible, staff looked at data based on California being the “home state”, and leased vehicles vs. purchased vehicles, and seasonal differences. Staff also analyzed the activity data received from manufacturers to better understand the likely impacts on criteria pollutants such as hydrocarbons (HC) and oxides of nitrogen (NOx) from the various PHEVs.

This analysis will lead into Appendix I, which describes various ways to use data in this analysis in alternative credit schemes for PHEVs, BEVxs, and BEVs.

II. Data Overview

Seven manufacturers submitted data for eleven different plug-in vehicle (PEV) models, which includes PHEVs, BEVxs, and BEVs. The data reported varied widely across manufacturers,

---

1 Toyota Plug-in Prius and Chevrolet Volt
2 A description of INL’s analysis is found on page 52. A description of the Department of Energy’s EV Project is found on page 51.
and therefore analysis was limited for some models. This section will describe the type of data provided to staff, organized by manufacturer, as well as the number of vehicles included in each data set.

II.A. Description of Data from Manufacturers

II.A.1. BMW

II.A.1.i. Type and Number of Vehicles in Sample

Vehicle data was provided for both the i3 BEV and the i3 with range extender (REX) which is the only vehicle to date that is designated as a BEVx in the ZEV regulation. The number of BEV and BEVx vehicles sold in each year (not necessarily the model year), are listed in Table 1.

Table 1 - Number of Vehicles in the BMW Dataset

<table>
<thead>
<tr>
<th>Vehicle</th>
<th>Type of Plug-in Electric Vehicle</th>
<th>Model Year/ Retail Year/ 1st Record Date</th>
<th>Number of Vehicles</th>
</tr>
</thead>
<tbody>
<tr>
<td>BMW i3 BEV</td>
<td>BEV</td>
<td>Retail Year = 2014</td>
<td>2,525</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Retail Year = 2015</td>
<td>1,654</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Retail Year = 2016</td>
<td>14</td>
</tr>
<tr>
<td>BMW i3 REX</td>
<td>BEVx</td>
<td>Retail Year = 2014</td>
<td>2,976</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Retail Year = 2015</td>
<td>5,296</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Retail Year = 2016</td>
<td>37</td>
</tr>
</tbody>
</table>

II.A.1.ii. Location of Vehicles in Sample

BMW provided a national dataset. There was no global positioning system (GPS) flag in the data to break out the California or Section 177 ZEV state vehicles.

II.A.1.iii. Driving Data Provided

BMW provided ARB with summary data tables that included, for each vehicle, the total vehicle miles travelled (VMT) along with the corresponding total number of days since the vehicle was placed into service (sold or leased). A retail sales date was provided for each vehicle. Unlike the data provided by most other manufacturers, the BMW data did not include details about individual vehicle trips and thus, provided for more limited analysis in understanding how the vehicles were being used.

II.A.1.iv. Charging Data Provided

No charging data was provided by BMW in the data sample.

II.A.1.v. Data Exclusions and Filtering

For the BMW data sets, there was no additional processing of the data required prior to analysis as only summary data (total miles and days) and no individual trip data was provided. However, BMW indicated that the raw data attached have been filtered for read out errors such as counter resets, data transmission errors caused by mobile network connection loss and battery

---

3 Through the provisions of the Clean Air Act identified as Section 177, nine states have adopted California’s ZEV regulation: Connecticut, Maine, Maryland, Massachusetts, New Jersey, New York, Oregon, Rhode Island, and Vermont. These nine states are commonly referred to as the Section 177 ZEV states.
disconnects during dealer visits. Data collection was carried out through BMW internal Tele Service Report (TSR) with customer consent.

II.A.2. FORD

II.A.2.i. Type and Number of Vehicles in Sample
Vehicle data was provided for the Focus BEV, the Fusion Energi PHEV and the C-Max Energi PHEV. Details on the number of vehicles and model years within each vehicle are provided in Table 2 below.

Table 2 - Number of Vehicles in the Ford Dataset

<table>
<thead>
<tr>
<th>Vehicle</th>
<th>Type of Plug-in Electric Vehicle</th>
<th>Model Year/ Retail Year/ 1st Record Date</th>
<th>Number of Vehicles</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ford Focus Electric</td>
<td>BEV</td>
<td>Retail Year = 2012</td>
<td>457</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Retail Year = 2013</td>
<td>1,239</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Retail Year = 2014</td>
<td>1,648</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Retail Year = 2015</td>
<td>858</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Retail Year = 2016</td>
<td>7</td>
</tr>
<tr>
<td></td>
<td></td>
<td>unknown</td>
<td>9</td>
</tr>
<tr>
<td>Ford C-Max Energi</td>
<td>PHEV</td>
<td>Retail Year = 2013</td>
<td>5,017</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Retail Year = 2014</td>
<td>2,897</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Retail Year = 2015</td>
<td>2,020</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Retail Year = 2016</td>
<td>6</td>
</tr>
<tr>
<td></td>
<td></td>
<td>unknown</td>
<td>313</td>
</tr>
<tr>
<td>Ford Fusion Energi</td>
<td>PHEV</td>
<td>Retail Year = 2013</td>
<td>3,258</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Retail Year = 2014</td>
<td>4,927</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Retail Year = 2015</td>
<td>3,389</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Retail Year = 2016</td>
<td>768</td>
</tr>
<tr>
<td></td>
<td></td>
<td>unknown</td>
<td>500</td>
</tr>
</tbody>
</table>

II.A.2.ii. Location of Vehicles in Sample
The data provided by Ford included truncated global positioning system (GPS) data for each trip which allowed for a determination of the vehicle’s approximate location (only to within a hundred mile quadrant). As seen in Table 3, this data was used by ARB to determine if a vehicle was primarily being operated within California. Based on an analysis of the data, approximately 41% of the vehicles had the majority of their trips within California. The Ford Focus Electric had the largest proportion of trips in California and the C-Max Energi had the lowest.

Table 3 - Number of Ford Vehicles for California Trips

<table>
<thead>
<tr>
<th>Vehicle</th>
<th>VINs with Trip Data</th>
<th>VINs with &gt;50% of trips in CA</th>
<th>% of VINs with &gt;50% CA trips</th>
</tr>
</thead>
<tbody>
<tr>
<td>FORD C-Max Energi</td>
<td>10,253</td>
<td>3,617</td>
<td>35.3%</td>
</tr>
<tr>
<td>FORD Focus Electric</td>
<td>4,218</td>
<td>2,128</td>
<td>50.5%</td>
</tr>
<tr>
<td>FORD Fusion Energi</td>
<td>12,842</td>
<td>5,439</td>
<td>42.4%</td>
</tr>
<tr>
<td>TOTAL</td>
<td>27,313</td>
<td>11,184</td>
<td>40.9%</td>
</tr>
</tbody>
</table>
Ford provided additional data fields that indicated the “Home State” for each vehicle based on its own algorithm to determine the location of the vehicle. Ford’s data field provided similar results compared to the staff’s analysis; with only a slightly larger number of vehicles designated as California vehicles as seen in Table 4.

Table 4 - Number of Ford Vehicles for California Designated “Home State” Vehicles

<table>
<thead>
<tr>
<th>Vehicle</th>
<th>Vehicle Counts</th>
<th>Vehicle Counts with CA as Home State</th>
<th>% of Vehicles with CA as Home State</th>
</tr>
</thead>
<tbody>
<tr>
<td>FORD C-Max Energi</td>
<td>10,253</td>
<td>4,394</td>
<td>42.9%</td>
</tr>
<tr>
<td>FORD Focus Electric</td>
<td>4,218</td>
<td>2,421</td>
<td>57.4%</td>
</tr>
<tr>
<td>FORD Fusion Energi</td>
<td>12,842</td>
<td>5,545</td>
<td>43.2%</td>
</tr>
<tr>
<td>TOTAL</td>
<td>27,313</td>
<td>12,360</td>
<td>45.3%</td>
</tr>
</tbody>
</table>

II.A.2.iii. Driving Data Provided
Ford provided ARB with a large data set that included 125 data fields for each record, however, many of the fields were not relevant to the analysis. The relevant data fields related to driving included: trip information that allowed ARB to determine fuel and electricity used for the trip; the time, date, and distance of the trip; and information about the battery state of charge.

II.A.2.iv. Charging Data Provided
The data provided included charging information indicating time and date of charging, type of charging (e.g., level 1, level 2), and information about the amount of charging that occurred during each event.

II.A.2.v. Data Exclusions and Filtering
For the Ford data set, the trip and charge data was extracted from the manufacturer’s data set to prepare for data consolidation in ARB’s analysis.

II.A.3. GENERAL MOTORS

II.A.3.i. Type and Number of Vehicles in Sample
General Motors provided ARB with data from the Chevrolet Volt PHEVs that were included in the EV Project. The EV project is described later in Section 7 of this Appendix. This data set is limited in that it reflects a small number of vehicles relative to what GM has subsequently sold as well as that it represents a subset of early vehicle owners that were provided charging equipment and voluntarily participating in a program to study their charging habits. Details regarding the number of vehicles and model years are provided in Table 5 below.

Table 5 - Number of Vehicles in the General Motors Dataset

<table>
<thead>
<tr>
<th>Vehicle</th>
<th>Type of Plug-in Electric Vehicle</th>
<th>Model Year/ Retail Year/ 1st Record Date</th>
<th>Number of Vehicles</th>
</tr>
</thead>
<tbody>
<tr>
<td>Chevrolet Volt</td>
<td>PHEV</td>
<td>MY= 2011</td>
<td>207</td>
</tr>
<tr>
<td></td>
<td></td>
<td>MY= 2012</td>
<td>1,129</td>
</tr>
<tr>
<td></td>
<td></td>
<td>MY= 2013</td>
<td>817</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Unknown</td>
<td>1</td>
</tr>
</tbody>
</table>
II.A.3.ii. Location of Vehicles in Sample
General Motors provided a national data set and a field denoting a State for each Chevrolet Volt based on its own algorithm. No additional location information was provided as a means to verify or independently determine whether the vehicle was primarily used in California. Based on the data set received, as shown in Table 6, approximately 31% of the vehicles were California based vehicles.

Table 6 - Number of General Motors Vehicles for California Designated “Home State” Vehicles

<table>
<thead>
<tr>
<th>Model Year</th>
<th>Total Vehicle Counts</th>
<th>CA Vehicle Counts</th>
<th>% CA Vehicles</th>
</tr>
</thead>
<tbody>
<tr>
<td>2011</td>
<td>207</td>
<td>53</td>
<td>25.6%</td>
</tr>
<tr>
<td>2012</td>
<td>1,129</td>
<td>294</td>
<td>26.0%</td>
</tr>
<tr>
<td>2013</td>
<td>817</td>
<td>330</td>
<td>40.4%</td>
</tr>
<tr>
<td>Unknown</td>
<td>1</td>
<td>0</td>
<td>0.0%</td>
</tr>
<tr>
<td>TOTAL</td>
<td>2,154</td>
<td>677</td>
<td>31.4%</td>
</tr>
</tbody>
</table>

II.A.3.iii. Driving Data Provided
General Motors provided ARB with pre-processed data tables along with raw data tables for the sample vehicles. The driving data allowed staff to determine: the fuel and electricity used for the trip; the time, date, and distance of the trip; and information about the battery state of charge.

II.A.3.iv. Charging Data Provided
General Motors did not provide any location (home/work/other) or type (levels) data on charges. However, staff came up with a logic for determining what counted as a charge and were able to calculate total charge count.

II.A.3.v. Data Exclusions and Filtering
GM data utilized for this analysis is the same dataset included in the EV Project. As shown in Table 6, this dataset only spans over 2011 – 2013 model years. More information on EV project is provided in Section 7 of this Appendix.

II.A.4. HONDA

II.A.4.i. Type and Number of Vehicles in Sample
Vehicle data was provided for both the Honda Fit BEV and the Honda Accord PHEV. Table 7 provides details on the number of each vehicle and model year that were provided.

Table 7 - Number of Vehicles in the Honda Dataset

<table>
<thead>
<tr>
<th>Vehicle</th>
<th>Type of Plug-in Electric Vehicle</th>
<th>Model Year/ Retail Year/ 1st Record Date</th>
<th>Number of Vehicles</th>
</tr>
</thead>
<tbody>
<tr>
<td>Honda Fit</td>
<td>BEV</td>
<td>First Record Date in CY2012</td>
<td>80</td>
</tr>
<tr>
<td></td>
<td></td>
<td>First Record Date in CY2013</td>
<td>559</td>
</tr>
<tr>
<td></td>
<td></td>
<td>First Record Date in CY2014</td>
<td>6</td>
</tr>
<tr>
<td>Honda Accord</td>
<td>PHEV</td>
<td>First Record Date in CY2012</td>
<td>189</td>
</tr>
</tbody>
</table>
II.A.4.ii. Location of Vehicles in Sample
The Honda dataset was a national dataset with no GPS information provided. However, most of those vehicles were sold in CA.

II.A.4.iii. Driving Data Provided
Honda provided ARB with a trip data table for each selected vehicle. Each vehicle’s trip data table provides the records for each key-off event. The driving data allowed staff to determine: the fuel and electricity used for the trip; the time, date, and distance of the trip; and information about the battery state of charge.

II.A.4.iv. Charging Data Provided
Honda provided ARB with a charge data table for each selected vehicle. Each vehicle’s charge data table provides the records for each charge-off event. The charging data allowed ARB to determine the time, the presumed location (home/not home), the type of charging (e.g., level 1, level 2) for Fit EV charge events, and the battery state of charge information for both the Accord PHEV and the Fit EV.

II.A.4.v. Data Exclusions and Filtering
Data was excluded for vehicles that had accumulated less than 90 days-worth of trips and for all research and testing vehicles. All data records prior to a vehicle’s retail start date were excluded. For the Honda Accord PHEV, additional records were excluded for vehicles with less than 1000 miles and for all vehicles when a customer does not have a paired phone to transmit data. For the Honda data set, the trip and charge data was extracted from the manufacturer’s data set to prepare for data consolidation in ARB’s analysis.

II.A.5. NISSAN

II.A.5.i. Type and Number of Vehicles in Sample
Vehicle data was provided for the Nissan Leaf BEV. Table 8 below provides details on the number of each vehicle and model year that were provided.

<table>
<thead>
<tr>
<th>Vehicle</th>
<th>Type of Plug-in Electric Vehicle</th>
<th>Model Year/ Retail Year/ 1st Record Date</th>
<th>Number of Vehicles</th>
</tr>
</thead>
<tbody>
<tr>
<td>Nissan Leaf</td>
<td>BEV</td>
<td>MY = 2011</td>
<td>4,052</td>
</tr>
<tr>
<td></td>
<td></td>
<td>MY = 2012</td>
<td>2,867</td>
</tr>
<tr>
<td></td>
<td></td>
<td>MY = 2013</td>
<td>4,043</td>
</tr>
<tr>
<td></td>
<td></td>
<td>MY = 2014</td>
<td>1,155</td>
</tr>
<tr>
<td></td>
<td></td>
<td>MY = 2015</td>
<td>98</td>
</tr>
</tbody>
</table>
II.A.5.ii. Location of Vehicles in Sample
Data was provided for vehicles determined by Nissan to be California-based vehicles. Nissan only sent data for vehicles with greater than 50% of trips in CA so all records sent are considered California based vehicles. For those vehicles, data was provided for vehicle trips within and outside of California, which can be approximated by using the truncated GPS data fields. Data provided to ARB included a subset of the vehicles from the EV Project (i.e., only the California-based vehicles) as well as additional California-based vehicles that were not a part of the EV Project.

II.A.5.iii. Driving Data Provided
Nissan provided ARB with a trip data table and a vehicle table. A data dictionary was also provided. The vehicle table allowed ARB to determine the model year, on-board charger rating, and purchase agreement data that indicated whether the vehicle was purchased or leased and, if leased, the annual mileage limitations of the lease agreement (i.e., 12,000 or 15,000 annual miles pre-paid). The data also indicated whether the vehicle was privately owned or purchased for a fleet. The driving data allowed ARB to determine the time, date, and distance of the trip, and information about the battery state of charge.

II.A.5.iv. Charging Data Provided
Nissan provided ARB with a charge data table. The charging data allowed ARB to determine the time and date of charging events, the type of charging (e.g., level 1, level 2, direct current or DC fast charge), information about the battery state of charge (SOC), and information about the charging location (inferred location of home/work/other per Nissan proprietary algorithm).

II.A.5.v. Data Exclusions and Filtering
Data for 2011 through 2012 model year vehicles was subject to a trip-by-trip approval by the driver to transmit the data to Nissan. As a result, a significant portion of the trip data is missing for these model years. Data for 2013 through 2015 model year vehicles was subject to a monthly approval by the driver and resulted in more complete data records. Data was excluded for vehicles that had accumulated less than 90 days worth of trips and for records with odometer values less than 124 miles (200 kilometers) to avoid transport and dealer use. Some additional records were excluded due to invalid data in critical fields. For the Nissan data set, the trip and charge data were extracted from the manufacturer’s data set to prepare for data consolidation in ARB’s analysis.

II.A.6. TESLA

II.A.6.i. Type and Number of Vehicles in Sample
Tesla provided ARB with data for Model S BEVs. Table 9 below tabulates the number of vehicles in the sample set that were placed in service each year (not necessarily model year).
Table 9 - Number of Vehicles in the Tesla Dataset

<table>
<thead>
<tr>
<th>Vehicle</th>
<th>Type of Plug-in Electric Vehicle</th>
<th>Model Year/ Retail Year/ 1st Record Date</th>
<th>Number of Vehicles</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tesla Model S</td>
<td>BEV</td>
<td>First Record Date in CY2012</td>
<td>229</td>
</tr>
<tr>
<td></td>
<td></td>
<td>First Record Date in CY2013</td>
<td>18,749</td>
</tr>
<tr>
<td></td>
<td></td>
<td>First Record Date in CY2014</td>
<td>10,967</td>
</tr>
<tr>
<td></td>
<td></td>
<td>First Record Date in CY2015</td>
<td>7,690</td>
</tr>
</tbody>
</table>

II.A.6.ii. Location of Vehicles in Sample
The data included vehicles placed in the United States.

II.A.6.iii. Driving Data Provided
Tesla provided ARB with a pre-filtered summary table that included the beginning and ending odometer and dates, the recorded miles and days, and the annual run-rate (the annualized vehicle miles travelled based on 365 days per year).

II.A.6.iv. Charging Data Provided
No charging data was provided in the Tesla data sample.

II.A.6.v. Data Exclusions and Filtering
Tesla provided ARB with a pre-filtered summary table that only included vehicles that had at least 30 days of recorded data and a minimum of 3,000 recorded odometer miles. For the Tesla data set, there was no additional processing of the data required prior to analysis as only summary data (total miles and days) and no individual trip data was provided.

II.A.7. TOYOTA

II.A.7.i. Type and Number of Vehicles in Sample
Toyota provided ARB with data for Prius PHEVs. Table 10 below provides details of the number of vehicles by year the vehicle was placed in service (not necessarily model year) that were included in the sample.

Table 10 - Number of Vehicles in the Toyota Dataset

<table>
<thead>
<tr>
<th>Vehicle</th>
<th>Type of Plug-in Electric Vehicle</th>
<th>Model Year/ Retail Year/ 1st Record Date</th>
<th>Number of Vehicles</th>
</tr>
</thead>
<tbody>
<tr>
<td>Toyota Prius</td>
<td>PHEV</td>
<td>First Record Date in CY2013</td>
<td>1,423</td>
</tr>
<tr>
<td></td>
<td></td>
<td>First Record Date in CY2014</td>
<td>100</td>
</tr>
</tbody>
</table>

II.A.7.ii. Location of Vehicles in Sample
Toyota provided a national dataset with no GPS information.

II.A.7.iii. Driving Data Provided
Toyota provided ARB with trip data tables for each selected vehicle. The driving data allowed ARB to determine: the fuel and electricity used for the trip; the time, date, and distance of the trip; and information about the battery SOC.
II.A.7.iv. Charging Data Provided
Toyota provided ARB with charge data tables for each selected vehicle. The charging data allowed ARB to determine the time and date of charging events and information about the battery SOC.

II.A.7.v. Data Exclusions and Filtering
For the Toyota data set, the trip and charge data was extracted from the manufacturer’s data set to prepare for data consolidation in ARB’s analysis.

II.B. Summary Tables of Manufacturer-Provided Data
Table 11 summarizes the vehicle counts per manufacturer for the data that was provided to ARB. Cumulatively, data was provided from seven manufacturers for more than 90,000 vehicles.

<table>
<thead>
<tr>
<th>Vehicle</th>
<th>Type of Plug-in Electric Vehicle</th>
<th>Model Year/Retail Year/1st Record Date</th>
<th>Number of Vehicles</th>
</tr>
</thead>
<tbody>
<tr>
<td>BMW i3 BEV</td>
<td>BEV</td>
<td>Retail Year = 2014-2016</td>
<td>4,193</td>
</tr>
<tr>
<td>BMW i3 REX</td>
<td>BEVx</td>
<td>Retail Year = 2014-2016</td>
<td>8,309</td>
</tr>
<tr>
<td>Ford C-Max Energi</td>
<td>PHEV</td>
<td>MY=2013-2016*</td>
<td>10,253</td>
</tr>
<tr>
<td>Ford Focus Electric</td>
<td>BEV</td>
<td>MY=2012-2016*</td>
<td>4,218</td>
</tr>
<tr>
<td>Ford Fusion Energi</td>
<td>PHEV</td>
<td>MY=2013-2016*</td>
<td>12,842</td>
</tr>
<tr>
<td>GM Chevrolet Volt</td>
<td>PHEV</td>
<td>MY=2011-2013*</td>
<td>2,154</td>
</tr>
<tr>
<td>Honda Fit</td>
<td>BEV</td>
<td>First Record Date in CY2012-2014</td>
<td>645</td>
</tr>
<tr>
<td>Honda Accord</td>
<td>PHEV</td>
<td>First Record Date in CY2013</td>
<td>189</td>
</tr>
<tr>
<td>Nissan Leaf</td>
<td>BEV</td>
<td>MY=2011-2015</td>
<td>12,215</td>
</tr>
<tr>
<td>Tesla Model S</td>
<td>BEV</td>
<td>First Record Date in CY2012-2015</td>
<td>37,635</td>
</tr>
<tr>
<td>Toyota Prius</td>
<td>PHEV</td>
<td>First Record Date in CY2013-2014</td>
<td>1,523</td>
</tr>
</tbody>
</table>

*Unknown – Some vehicles were not identified as a specific model year

Tesla provided summary data on the largest number of vehicles. Ford provided detailed trip and charge data for the largest number of vehicles.

Table 12 provides the record counts for the trip and charge data provided by the manufacturers by vehicle type. Minor differences in vehicle counts may occur in different data sets.
### Table 12 - Summary of Number of Vehicles

<table>
<thead>
<tr>
<th>Vehicle</th>
<th>Type of Plug-in Electric Vehicle</th>
<th>Trip Data</th>
<th>Charge Data</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>BMW i3 BEV</strong></td>
<td>BEV</td>
<td>Total miles &amp; days for 4,193 vehicles (no individual trip data)</td>
<td>None</td>
</tr>
<tr>
<td><strong>BMW i3 REX</strong></td>
<td>BEVx</td>
<td>Total miles &amp; days for 8,309 vehicles (no individual trip data)</td>
<td>None</td>
</tr>
<tr>
<td><strong>Ford C-Max Energi</strong></td>
<td>PHEV</td>
<td>13,813,288 individual records for 10,253 vehicles</td>
<td>12,880,589 individual records for 10,162 vehicles</td>
</tr>
<tr>
<td><strong>Ford Focus Electric</strong></td>
<td>BEV</td>
<td>4,940,786 individual records for 4,218 vehicles</td>
<td>5,074,632 individual records for 4,222 vehicles</td>
</tr>
<tr>
<td><strong>Ford Fusion Energi</strong></td>
<td>PHEV</td>
<td>15,557,891 individual records for 12,842 vehicles</td>
<td>14,535,732 individual records for 12,897 vehicles</td>
</tr>
<tr>
<td><strong>GM Chevrolet Volt</strong></td>
<td>PHEV</td>
<td>3,058,146 individual records for 2,154 vehicles</td>
<td>1,623,088 individual records for 2,154 vehicles</td>
</tr>
<tr>
<td><strong>Honda Fit</strong></td>
<td>BEV</td>
<td>817,874 individual records for 645 vehicles</td>
<td>175,108 individual records for 645 vehicles</td>
</tr>
<tr>
<td><strong>Honda Accord</strong></td>
<td>PHEV</td>
<td>180,575 individual records for 189 vehicles</td>
<td>41,972 individual records for 189 vehicles</td>
</tr>
<tr>
<td><strong>Nissan Leaf</strong></td>
<td>BEV</td>
<td>26,129,430 individual records for 12,215 vehicles</td>
<td>6,556,654 individual records for 12,215 vehicles</td>
</tr>
<tr>
<td><strong>Tesla Model S</strong></td>
<td>BEV</td>
<td>Total miles &amp; days for 37,635 vehicles (no individual trip data)</td>
<td>None</td>
</tr>
<tr>
<td><strong>Toyota Prius</strong></td>
<td>PHEV</td>
<td>2,206,174 individual records for 1,523 vehicles</td>
<td>449,434 individual records for 1,523 vehicles</td>
</tr>
</tbody>
</table>

### III. Analysis Methods for OEM Data Provided

#### III.A. Calculation methods

To assess the relative performance of the BEVs and PHEVs, several different ways of categorizing the total vehicle usage were studied. In almost all cases, comparisons were made relative to the total annual miles of the vehicle or VMT. In this analysis, total VMT was calculated as the annual miles traveled, regardless of the energy source (e.g., electricity, gasoline).
A recent method to quantify the behavior of PHEVs is to look at the portion of total VMT that is a result of electric operation or electric vehicle miles traveled (eVMT). For this analysis, the calculated eVMT represents an estimate of the grid energy apportioned miles traveled. eVMT is generally considered a good representation of a vehicle’s greenhouse gas (GHG) benefits, since most GHG emission occur during a vehicle’s operation (as opposed to its engine start emissions). For blended PHEVs like the Ford, Honda, and Toyota models in this analysis, apportioning miles traveled to the grid or to gasoline power is not a simple task as there are periods of operation where both energy sources are being used to propel the vehicle. Details are provided below for some of the techniques used to apportion such blended miles to the most appropriate category.

While eVMT does appear to reasonably represent the GHG performance of a PHEV, the non-linearity of criteria pollutant emissions (e.g., hydrocarbons, oxides of nitrogen) led staff to explore additional ways to categorize the usage that might relate better to the criteria pollutant performance. Two such metrics included electric only trips (e-trips) and zero-emissions vehicle miles traveled (zVMT). The computed e-trips represent the number of trips without any internal combustion engine (ICE) operation. Given the dominant impact of initial engine start-up on criteria pollutant emissions, this metric might provide an indication of start-up emissions that are avoided. However, as it only counts the number of trips without engine operation, short trips and long trips are equally weighted. Thus, staff also considered the sum of all e-trip miles, or zVMT. This represents the portion of total VMT that is met with trips that mimic a BEV with no directly-emitted criteria pollutant emissions and can provide a relative perspective of the criteria pollutant benefit.4

As noted above, the calculation of eVMT is fairly complicated for blended hybrids and varied somewhat based on the available data in the sample. In general terms, the analysis used a method to assess typical gasoline only consumption rates and grid energy only consumption rates and then use those typical values to apportion miles traveled while both energy sources were being used. However, the details varied as to how that was accomplished in each of the manufacturer’s data sets.

The Toyota and General Motors data sets provided the computed data; therefore staff did not have to process the data further before analysis for eVMT. For the Ford data set, the eVMT data used in this analysis was calculated by multiplying the VMT by the electric usage ratio. This ratio is computed by dividing the electric energy consumed by the total energy (gas plus electric) consumed. This calculation required assumptions to be made for vehicle fuel economy. A conversion rate of 0.07112 gallons per kilowatt-hour (kWh) was used based on the assumed rates of 38 miles per gallon and 370 watt-hours per mile. These rates were based on the United States Environmental Protection Agency (U.S. EPA) labels for miles per gallon.

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4 See Appendix H for test results from ARB’s in-house PHEV testing.
(mpg)$^5$ for the 2015 model year Ford C-Max Energi and Fusion Energi PHEVs. The formula used for eVMT for Ford is as follows:

$$eVMT_{Ford} = \frac{0.7112 \times electric\_consumption}{((0.7112 \times electric\_consumption + gas\_consumption)}$$

For the Honda Accord PHEV, eVMT was calculated using the logic provided by Honda in their documentation describing the data fields. The average fuel economy (mpg) was calculated for each vehicle as the sum of the cumulative gasoline engine powered charge sustaining (CS) miles divided by the cumulative CS fuel consumed. For each trip, the grid energy powered charge depleting (CD) miles were computed as the total distance minus the CS miles. The eVMT was computed by taking the CD mode miles and subtracting the product of the average mpg by the CD mode fuel consumption.

Trips were analyzed for all individual trip records where the vehicle moved. The formulas vary by manufacturer depending on the data fields that were provided and specific context, but in general, the calculations for eTrips and zVMT are as follows:

$$eTrips = \text{True if}$$
- electricity (battery energy) consumption $> 0$ and
- gasoline consumption $= 0$ and
- distance $> 0$
- and vehicle average speed $> 0$

$$zVMT = \text{cumulative miles traveled for records where eTrips are True}$$

The percentage of eVMT and zVMT were multiplied by the odometer change based VMT to scale up the eVMT and zVMT miles where the odometer changes exceeded the recorded VMT in the manufacturer data sets which included odometer data. Scaling up the eVMT and zVMT based on the odometer changes assumes that the non-reported miles would reflect the same usage patterns as those reported. This was only done for the Honda dataset. Ford, Toyota and Honda provided odometer data that could be scaled up to match the odometer differences.

### III.B. Data output format

The trip data was consolidated into a table that reflected a record for each vehicle identification (ID) with the type of vehicle and model year, the start and end date and time, the start and end SOC percentage, the vehicle miles and the eVMT (in miles), the gas and/or electricity consumed, the average speed, and the starting odometer reading. For each trip record, the time period in days and the change in the SOC were computed. The charge data was consolidated into a table that reflected a record for each vehicle ID with the type of vehicle and model year, the start and end date and time, the type of charge, the start and end state of

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charge percentage, and the charge location. For each charge record, the time period in days and the change in the SOC were computed. The trip and charge data were summarized into monthly and annualized data sets by summing per individual vehicle the number of trips or charges, changes in date/time in days, mileage changes by type (VMT, eVMT, zVMT), changes in states of charge by appropriate groupings (such as by type of charge and location of charge). The odometer changes over time per vehicle were also computed.

The annualized and monthly data set were filtered to only utilize results for records that had VMT within 85% of the odometer change over the time period. Filtering also excluded records for vehicles that did not have at least 24 days in the monthly data set or at least 30 days for the annualized data set, and excluded records if the odometer change exceeded one million miles. These filtering selections were used to better represent the activity of these vehicles by filtering out data with extreme values that might skew the data results.

III.C. Discussion of uncertainties in results due to data issues

The voluntary data sets provided by the OEMs were pre-processed and pre-filtered in a variety of ways prior to receipt at ARB, further described in Section II.A; there was no standardized reporting method process. The data received represents a limited number of vehicles over varying time periods. The algorithms for capturing data vary across the OEMs and interpretation of the data sets relied on and is limited by the information provided by each OEM.

There are some issues with the resolution of the data captured, specific to each OEM's data set, for which different post-processing and filtering methods might produce different results. For instance, some records may show no gas fuel consumption with electric energy consumption above zero, but for which no eVMT was recorded though the VMT is noted as above zero. This would indicate that there is a low end threshold for the electric mileage captured (no or truncated decimals). Thus, a sum of the eVMT would exclude miles when the electric energy consumed was very small. If instead of the eVMT, the VMT is summed whenever electric energy consumed is above zero while the gas energy consumption was zero, this sum could be higher than the sum of the designated electric miles.

Inferred charge location data is based upon proprietary algorithms using trip and charge data and vary by OEM. These algorithms may not provide 100% accurate results.

Missing data can result in understated results, such as for trips or mileage per day computations that use the sum of the trips or miles data divided by the number of days across a time period. Computing such rates relies on an assumption that all trip and mileage data in that time period have been accounted for which is not always the case. When available, the actual odometer change over time has been used to avoid using the understated mileage sums resulting from missing records.

In virtually all of the data samples, some trip data may not have been captured for a variety of reasons such as lack of cellular service coverage or manufacturer specific parameters that excluded certain types of trips. The missing trips become noticeable when differences in a vehicle’s odometer readings significantly exceed the sum of the individual trip distances logged.
As discussed above in the processing steps, staff excluded data with odometer differences (i.e., difference between year-start and year-end odometers) that exceeded 85% of reported annual VMT prior to computing average rates (e.g., if more than 15% of the data was missing, the data was excluded). Additionally, for vehicles with some missing data (but less than 15%), if odometer data was available, the sum of individual trip distances were scaled up to match the odometer reading differences. This scaling factor was also applied on eVMT and zVMT.

IV. Trip Results

IV.A. Annual means for each vehicle model

To compute the VMT values, the data was filtered based on the type of data that was received from each manufacturer, as is noted in Table 13 for BEVs and Table 14 for PHEVs. Filtering the data sets using alternative methods could provide different results. The mean is a good measure for a normal distribution in which case it will have a similar value to the median. The median is usually better for a skewed distribution. Tesla reflects this more than the others as there are some high mileage outliers that do not represent the majority of the vehicles.

<table>
<thead>
<tr>
<th>Type of Vehicle</th>
<th>VMT – Mean</th>
<th>VMT - Median</th>
</tr>
</thead>
<tbody>
<tr>
<td>BMW i3 BEV¹</td>
<td>7,916</td>
<td>7,544</td>
</tr>
<tr>
<td>Ford Focus Electric²</td>
<td>9,741</td>
<td>9,392</td>
</tr>
<tr>
<td>Honda Fit³</td>
<td>9,789</td>
<td>9,466</td>
</tr>
<tr>
<td>Nissan Leaf²</td>
<td>10,294</td>
<td>9,989</td>
</tr>
<tr>
<td>Tesla Model S¹</td>
<td>13,494</td>
<td>12,334</td>
</tr>
</tbody>
</table>

¹No filtering (OEM provided summary data per vehicle, not individual trip data)
²Filtered to only include vehicles with >30 days, based on odometer differences (not VMT per trip sum)
³Filtered to only include vehicles with >30 days, based on VMT per trip sums (no odometer data was provided)

For some of the PHEVs, as noted in Table 14, the eVMT and zVMT were scaled up by multiplying by the odometer changes divided by the VMT trip sums, prior to computing the means and medians in order to provide more comparable results. For example, if the individual trip data captured 8,000 miles of operation, of which 4,000 were electric miles (or 50% eVMT) but the odometer reflected 10,000 actual miles of operation, the results were scaled to show that 5,000 (or 50%) of the 10,000 actual miles were electric miles.

Except for Tesla, the BEVs generally have lower annual total VMT than PHEVs. However, PHEVs VMT can be analyzed in various ways including eVMT and zVMT which is also listed in Table 14. The next section will focus on VMT, eVMT, zVMT and e-trips.
### Table 14 - Annual VMT for PHEV Vehicles

<table>
<thead>
<tr>
<th>Type of Vehicle</th>
<th>VMT - Mean</th>
<th>VMT - Median</th>
<th>eVMT - Mean</th>
<th>eVMT - Median</th>
<th>zVMT - Mean</th>
<th>zVMT - Median</th>
</tr>
</thead>
<tbody>
<tr>
<td>BMW i3 REX BEV&lt;sup&gt;1&lt;/sup&gt;</td>
<td>9,063</td>
<td>8,387</td>
<td>8,356</td>
<td>7,841</td>
<td>unknown</td>
<td>unknown</td>
</tr>
<tr>
<td>Ford C-Max Energi&lt;sup&gt;2&lt;/sup&gt;</td>
<td>13,920</td>
<td>12,841</td>
<td>4,574</td>
<td>4,546</td>
<td>2,525</td>
<td>2,305</td>
</tr>
<tr>
<td>Ford Fusion Energi&lt;sup&gt;2&lt;/sup&gt;</td>
<td>15,076</td>
<td>13,897</td>
<td>4,776</td>
<td>4,692</td>
<td>2,368</td>
<td>2,014</td>
</tr>
<tr>
<td>GM Chevrolet Volt&lt;sup&gt;2&lt;/sup&gt;</td>
<td>12,403</td>
<td>11,698</td>
<td>8,924</td>
<td>8,815</td>
<td>7,313</td>
<td>7,135</td>
</tr>
<tr>
<td>Honda Accord&lt;sup&gt;3&lt;/sup&gt;</td>
<td>15,221</td>
<td>14,766</td>
<td>3,246</td>
<td>3,108</td>
<td>1,471</td>
<td>1,337</td>
</tr>
<tr>
<td>Toyota Prius&lt;sup&gt;4&lt;/sup&gt;</td>
<td>15,283</td>
<td>14,159</td>
<td>2,304</td>
<td>2,175</td>
<td>589</td>
<td>318</td>
</tr>
</tbody>
</table>

<sup>1</sup>No filtering or scaling (OEM provided summary data per vehicle, not individual trip data)

<sup>2</sup>Filtered to only include vehicles with >30 days & VMT sum within 85% of odometer change; Trip sums scaled up by Odometer changes/VMT sum

<sup>3</sup>Filtered to only include vehicles with >30 days, based on VMT per trip sums (no odometer data was provided)

<sup>4</sup>Filtered to only include vehicles with >30 days & VMT sum within 85% of odometer change; Odometer changes were slightly less than VMT sums so no scaling was appropriate

### IV.B. Annual Percent VMT, eVMT, zVMT, and e-trips

This section summarizes the annual percent VMT, eVMT, zVMT and e-trips across model types and with conventional ICE vehicles VMT. BEV and PHEV data was calculated as described in III above. Updated annualized mileage for ICE vehicles used in the following chart was computed using odometer readings for passenger cars from calendar year 2001 through 2014 statewide California Smog Check program data. Relative to older data, the new statewide average VMT for ICE passenger car vehicles did not reflect any significant difference (e.g., due to recessionary years). Paired odometer readings per individual vehicle identification number (VIN) from consecutive biennial inspections were used to compute the mileage changes which were annualized to 365 days per year for annual mileage rates. For relatively new vehicles, similar to the majority of the PHEVs and BEVs in this data set, smog check data has more limited record counts as most vehicles are not required to have smog checks until they are older; however, there are inspections required for a subset of vehicles including those that have been re-sold or that have been transferred from out of state into California and those inspections were the primary source used to determine annualized mileage in the first few years of a vehicle’s life.

Figure 1 below provides the average annual VMT, eVMT, and zVMT by vehicle model for all vehicles in the sample. Note that for BEVs, eVMT and zVMT are equal to their overall VMT and so only VMT is shown for simplification. Based on the data provided by the OEMs, it appears that Ford, Honda, and Toyota PHEVs have similar overall annual mileage to conventional gasoline-powered vehicles. The GM Volt PHEV and the Tesla Model S have slightly lower annual mileage rates. The rest of the PHEVs and BEVs have much lower annual mileage rates. Between similar range BEVs, annual VMT varies, most notably the BMW i3 has a much lower annual average.
In comparing the PHEV eVMT to BEV eVMT, blended-type PHEVs (Ford PHEVs, Honda Accord, and Toyota Prius) have less than 40% eVMT. zVMT is even lower, ranging from 10-25% for blended PHEVs. GM Volts, however, have significantly higher eVMT (75%) and zVMT (~60%) than the other PHEVs analyzed in this dataset.

Figure 1 - Annualized Mean VMT, eVMT and zVMT results by vehicle type

![Chart: Annualized Mean VMT, eVMT & zVMT Results by Vehicle Type](chart)

For the Ford and GM PHEV datasets, ARB received some information to differentiate California vehicles. To take a closer look at annual mileage by vehicle type per model year, Figure 2 compares the annual mileage nationally (including California vehicles) for these vehicles and compares them to California vehicles.
Figure 2 above shows the average annual mileage by PHEV per model year across the U.S. including California vehicles. For example, the 2013 model year Ford C-Max Energi data given to ARB included trips in 2013, 2014, 2015, and 2016 calendar years. The average annual mileage reported in Figure 2 above represents an average of all four years for the 2013 model year vehicles. Although newer PHEVs have higher VMT, their average annual eVMT and zVMT remained constant. This may mean that as these vehicles were purchased by a broader group of consumers than the earliest adopters, there was less consumer interest in maximizing %eVMT and %zVMT or that the newer purchasers had less access or desire to use charging. It is also possible that some or all of the %eVMT and %zVMT reductions may be due to gas prices reductions that occurred during this period; an owner may not be motivated to charge the battery as frequently if they consider gas to be inexpensive.

For comparison, vehicles that were designated as California based vehicles\(^6\) are plotted on the same graph. Though varied by model year and vehicle type, the average annual mileage for California based vehicles was approximately 10% higher than the average annual mileage for nationwide vehicles (including those based in California).

Next, ARB staff looked at BEVs and their annual VMT difference with California drivers. Figure 3 shows the average annual mileage by vehicle model per model year for BEVs across the US

\(^6\) See IV Data Overview for description of how vehicle trip records were designated by location.
(including California) and for California only vehicles. Like the PHEVs where VMT increased for newer model year vehicles, so did BEV VMT. However, for BEVs, this means eVMT and zVMT also increased, where, with the exception of the GM Volt, it had remained mostly constant for PHEVs over each model year. Relative to Nissan Leafs, the Ford Focus BEVs in California had only slightly increased average annual mileage. While this may be partially explained by an increase in electric range (~11 miles) by the Nissan Leaf over that timeframe while the Focus BEV’s range remained unchanged, it should be noted that several of the increases in VMT from model year to model year in the Leaf were at times when the range did not increase (e.g., 2011-2012, 2014-2015).

Figure 3 - Annual Mileage by Vehicle Type per Model Year for BEVs for US and CA vehicles

Staff was also interested in the effect of lease agreements on driving behavior. Nissan provided such information in their data. Based on sales or lease agreement information, the Nissan Leaf data set provided identifying flags to determine whether a vehicle was privately owned or purchased for a fleet, and whether a vehicle was purchased or leased. If leased, identifying flags were also provided for whether there were 12,000 or 15,000 pre-paid annual miles specified in the lease agreement.

Shown in Table 15, cumulatively, over 97% of the Nissan Leaf vehicles were purchased or leased for private use rather than for use in a commercial fleet. Accordingly, no analysis was attempted to quantify differences in fleet usage relative to privately owned usage.

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7 Nissan only submitted California data for ARB's analysis. See II.A.ii FORD for breakdown of Ford data set by location.
### Table 15 - Nissan Leaf Fleet Vehicles vs. Private Vehicles

<table>
<thead>
<tr>
<th>Model Year</th>
<th>% Fleet Vehicles</th>
<th>% Private Vehicles</th>
<th>% Unknown</th>
</tr>
</thead>
<tbody>
<tr>
<td>2011</td>
<td>4.1%</td>
<td>74.8%</td>
<td>21.1%</td>
</tr>
<tr>
<td>2012</td>
<td>2.8%</td>
<td>96.3%</td>
<td>0.9%</td>
</tr>
<tr>
<td>2013</td>
<td>1.4%</td>
<td>98.3%</td>
<td>0.3%</td>
</tr>
<tr>
<td>2014</td>
<td>0.8%</td>
<td>98.8%</td>
<td>0.4%</td>
</tr>
<tr>
<td>2015</td>
<td>2.1%</td>
<td>97.9%</td>
<td>0.0%</td>
</tr>
</tbody>
</table>

Cumulatively, over 71% of the Nissan Leaf vehicles were leased rather than purchased at the initial transaction, as shown in Table 16. For model year 2015, the percentage of vehicles purchased has significantly increased (and the percentage of vehicles leased has significantly decreased). However, the vehicle counts for model year 2015 are very low so additional data would be needed to confirm this initial observation.

### Table 16 - Nissan Leaf Leased Vehicles vs. Purchased Vehicles

<table>
<thead>
<tr>
<th>Model Year</th>
<th>% Leased Vehicles</th>
<th>% Purchased Vehicles</th>
<th>% Unknown</th>
</tr>
</thead>
<tbody>
<tr>
<td>2011</td>
<td>34.4%</td>
<td>50.3%</td>
<td>15.3%</td>
</tr>
<tr>
<td>2012</td>
<td>80.2%</td>
<td>19.7%</td>
<td>0.1%</td>
</tr>
<tr>
<td>2013</td>
<td>89.0%</td>
<td>11.0%</td>
<td>0.0%</td>
</tr>
<tr>
<td>2014</td>
<td>80.6%</td>
<td>19.4%</td>
<td>0.0%</td>
</tr>
<tr>
<td>2015</td>
<td>68.0%</td>
<td>32.0%</td>
<td>0.0%</td>
</tr>
</tbody>
</table>

The Nissan Leaf data indicated 8,276 out of a total of 12,194 vehicles were leased (rather than purchased) at the initial transaction. Cumulatively, approximately 67% of the vehicles had lease provisions stipulating 12,000 pre-paid annual miles compared to approximately 24% with 15,000 pre-paid annual miles.

### Table 17 - Pre-paid Annual Miles for Leased Nissan Leaf Vehicles

<table>
<thead>
<tr>
<th>Model Year</th>
<th>% 12,000 pre-paid annual miles</th>
<th>% 15,000 pre-paid annual miles</th>
<th>% Unknown</th>
</tr>
</thead>
<tbody>
<tr>
<td>2011</td>
<td>20.5%</td>
<td>10.8%</td>
<td>3.1%</td>
</tr>
<tr>
<td>2012</td>
<td>56.9%</td>
<td>19.8%</td>
<td>3.5%</td>
</tr>
<tr>
<td>2013</td>
<td>57.3%</td>
<td>18.6%</td>
<td>13.1%</td>
</tr>
<tr>
<td>2014</td>
<td>62.3%</td>
<td>18.0%</td>
<td>0.3%</td>
</tr>
<tr>
<td>2015</td>
<td>54.6%</td>
<td>13.4%</td>
<td>0.0%</td>
</tr>
</tbody>
</table>

While the mileage caps for leases do not physically limit additional vehicle operation, some correlation of the mileage cap to the annual VMT would be expected. And as shown in Figure 4, when comparing the annual VMT of all vehicles in the sample to vehicles leased with a 12k or 15k mileage cap, the average VMT is indeed shorter for vehicles with 12k leases and longer for vehicles with 15k leases. Given the selection of the lease terms during the initial purchase of the car, it would be expected for drivers with lower annual VMT needs to select the lower terms and those with higher needs to select a higher mileage cap. Nonetheless, the data suggests
that the vehicles themselves are capable of meeting higher annual VMT demands despite their electric range or charging limitations.

Figure 4 - Nissan Leaf Initial Year Annual Miles by Model Year and Lease Terms

IV.C. Average monthly plots for percent eVMT and zVMT, and e-trips for PHEVs

Monthly averages for usage shows seasonal variability which cannot be shown in annual averages. Staff plotted monthly averages for the Ford, Honda, Toyota, and General Motors PHEV data sets as shown in Figure 5, 6, 7, 8, 9, and 10. For the BEV vehicles (BMW i3, Ford Focus EV, Honda Fit EV, Nissan Leaf, and Tesla Model S), the %eVMT, zVMT, and e-Trips would all be 100%, and therefore are not included in these results. The Ford data set provided truncated GPS data to determine which vehicles had the majority of their trips within California so separate California specific plots were also provided in the following results.

PHEV mean %eVMT, %zVMT, and %e-Trip results were based on data that was filtered to only include vehicles with more than 24 consecutive days of trip data and cumulative VMT calculated from individual trips that were within 85% of the VMT calculated from odometer change. For the Honda Accord PHEV, no odometer data was provided so filtering was limited to vehicles with more than 24 days of trip data.

For the Ford PHEVs, Figure 5 through Figure 8 show relatively consistent monthly trends with an observable decrease in electric vehicle usage in the winter months. Generally, all three metrics follow the same trends although percent e-Trips shows a slightly more pronounced drop in winter months which may be due to initial short periods of engine on operation to meet cabin

8 Filtering the data sets using alternative methods could provide different results.
heating and defrost demands. As could be expected, the seasonal impact is substantially larger in the nationwide sample than in the California only sample.

Figure 5 - Average Monthly %eVMT, %zVMT & %e-Trips for Ford C-Max Vehicles - All Trips

<table>
<thead>
<tr>
<th>Month</th>
<th>2013</th>
<th>2014</th>
<th>2015</th>
</tr>
</thead>
<tbody>
<tr>
<td>Jan</td>
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Figure 6 - Average Monthly %eVMT, %zVMT & %e-Trips for Ford C-Max Vehicles - CA Trips

<table>
<thead>
<tr>
<th>Month</th>
<th>2013</th>
<th>2014</th>
<th>2015</th>
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<td>Jan</td>
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</table>
Figure 7 - Average Monthly %eVMT, %zVMT & %e-Trips for Ford Fusion Vehicles - All Trips

Figure 8 - Average Monthly %eVMT, %zVMT & %e-Trips for Ford Fusion Vehicles - CA Trips
For the GM Volt vehicles, the monthly data also shows a seasonal impact with a small drop in electric vehicle usage during the winter months. While the magnitude of the impact on the nationwide sample appears to be smaller than observed on the Ford PHEVs, the California only data follows similar trends as the Ford data with a very small seasonal impact.

Figure 9 - Average Monthly %eVMT, %zVMT & %e-Trips for GM Volt Vehicles - All Trips

Figure 10 - Average Monthly %eVMT, %zVMT & %e-Trips for GM Volt Vehicles – CA Trips
For both the Honda and Toyota PHEVs in Figure 11 and Figure 12, similar but smaller seasonal impacts were observed. The Honda dataset, while not limited to California cars, is predominantly California cars and only had one winter period during the data sample. The Toyota data was nationwide and did show a slightly larger seasonal impact than the Honda but still a relatively minor change in vehicle usage.

**Figure 11 - Average Monthly %eVMT, %zVMT & %e-Trips for Honda Accord Vehicles - All Trips**

<table>
<thead>
<tr>
<th></th>
<th>Mean %eVMT</th>
<th>Mean %zVMT</th>
<th>Mean %eTrips</th>
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</thead>
<tbody>
<tr>
<td>Mar</td>
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**Figure 12 - Average Monthly %eVMT, %zVMT & %e-Trips for Toyota Prius Vehicles - All Trips**

<table>
<thead>
<tr>
<th></th>
<th>Mean %eVMT</th>
<th>Mean %zVMT</th>
<th>Mean %eTrips</th>
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<tbody>
<tr>
<td>Mar</td>
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G - 24
In general, the results indicate that electric vehicle usage varies across different seasons with the highest eVMT occurring during summer months and the lowest occurring during the holiday season months (Nov - Jan). However, while electric usage does vary, it does not appear to vary significantly, and varies to an even smaller degree in California-based vehicles.

**IV.D. Analysis of factors affecting eVMT**

While most of the analysis shown is comparing the usage across different PHEV models, staff also analyzed data within a PHEV model to understand some of the factors that may be influencing the observed performance. In Figure 13 below, the small dots reflect the eVMT of each individual car in the sample while the large dots show the average eVMT for that PHEV model. From the figure, it is apparent that there is significant variation as to the calculated eVMT for individual vehicles within the models. While not shown, figures showing absolute eVMT (miles) rather than eVMT percent or showing zVMT rather than eVMT, look similar in terms of substantial variability among the individual vehicles within a model. The figure also shows BEVs, which are the dense line along the y-axis value of 100% eVMT. This reinforces that substantial variability also occurs in individual BEV users with respect to how many annual miles they drive. With BEVs, however, all of the miles that are traveled are grid-powered electric miles.

*Figure 13 - Variability for eVMT*

From the data received from OEMs, the Ford PHEV data represented the largest set of detailed PHEV data from actual customer cars. The Ford data was analyzed to try and determine if there were clear factors or trends observable that were common among the drivers that were achieving higher eVMT than others. First, staff compared the eVMT, both on a percent eVMT
and an absolute eVMT annual miles basis, to the average number of trips taken per day for each vehicle. Figure 14 and Figure 15 show that there was no identifiable correlation between the average number of trips taken per day and the observed eVMT for the individual vehicle.

**Figure 15 - Percent eVMT vs. trips/day**

When looking at average trip length (miles) versus percent eVMT (Figure 16 and 17), a slight trend appears in the direction that would be expected. That is, the longer the average trip length, the lower the observed eVMT percentage. However, this trend is not apparent when looking at percent eVMT rather than absolute eVMT. For vehicles with shorter average trip lengths, there is still considerable variation spanning the entire range from 0% to 100% in eVMT percentage.

**Figure 17 - Percent eVMT vs. Trip Length**

A different observation is made when looking at average daily VMT versus eVMT (Figure 18 and Figure 19). For eVMT percentage, the data shows a similar trend to the previous figures such that the higher the average daily miles traveled, the lower the eVMT percentage as well as significant variation from 0%-100% eVMT for vehicles averaging the fewest miles per day. In the absolute eVMT figure, however, the opposite trend is observed with an increase in daily miles traveled correlating slightly to an increase in absolute eVMT.
Staff also analyzed charging habits to see if a correlation was apparent to calculated eVMT. In Figures 20 and 21 below, the average number of charging events per day was compared to percent and absolute eVMT. From the staff’s analysis, this parameter appeared to have the strongest correlation to eVMT, especially when looking at absolute eVMT. Consistent with what would be expected, more frequent charging measured as average number of charge events per day generally correlates to higher eVMT. The data was also analyzed versus the number of Level 2 charging events per day. A similar, but slightly weaker, trend was observed indicating increased Level 2 charge events per day correlated to higher eVMT. Further analysis is needed to determine if the higher charging events per day are a result of increased usage of ‘away from home’ charging (e.g., public infrastructure, workplace charging) or from vehicle owners who are using home charging more frequently (e.g., plugging in at home between errands or other daily trips).

Regarding charging behavior, the relative usage of Level 2 charging was also analyzed to look for an influence on eVMT. Figure 22 and Figure 23 below show eVMT versus the percentage of charging events that used Level 2 charging to see if using the faster and higher power charging equipment for a larger share of the charging events would correlate with higher eVMT. For these Ford PHEVs, however, there is no identifiable trend in either percent or absolute eVMT for vehicles using Level 2 charging for a larger share of the total charging events.
V. Charge Results

V.A. Data provided
All the manufacturers provided various levels of charge data and generally fall into one of three categories. The first category is those that provided charge, charge type, and charge location information. Nissan, Figure 24 to Figure 31, and Ford, Figure 32 to Figure 34, provided that data and the figures show the distribution of charge events. The second category is manufacturers who provided limited charge event data. This included data for the Honda Fit, Figure 35 to Figure 37, and for the GM Volt, Figure 38. The last category is manufacturers who did not provide any charge event information and are excluded from this analysis. BMW and Tesla did not provide any charge data. The Honda Accord PHEV charge data also has no date and time, no charging type, and no location information. The Toyota Prius PHEV charge data did not provide any charging type or location information.

V.B. Charging capability
The Ford Fusion Energi and C-MAX Energi have an all-electric label range of 19 miles, and can be fully charged on a 240 Volt Level 2 charger in approximately 2.5 hours, or 7 hours on a 120 Volt Level 1 charger. The Ford Focus EV has a label range of 76 miles and can be fully charged in 3.6 hours from a Level 2 charger, or approximately 18-20 hours on a Level 1 charger. Each of these vehicles is sold with a Level 1 convenience charge cord which can charge the vehicle from any standard 120V household outlet.
V.B.1. Nissan Plots
The next set of graphs provide data regarding the Nissan Leaf charging locations, charge type, purchased versus leased vehicles, and fleet versus private vehicles. Later in the section, the charge information is then plotted against average VMT and eVMT for the Nissan Leafs.

The percentage of Nissan Leaf charge events taking place at home has decreased approximately 15% from the 2011 model year to the 2015 model year as the percentage of charge events at work and other locations has been increasing. This trend can be seen in Figure 24.

Figure 24 - Nissan Leaf Charge Location Percentages

The percentage of Nissan Leaf charge events occurring using Level 2 (240V) has decreased over 30% as the charge events at Level 1 (120V) have increased significantly and the DC charge events have increased slightly as seen in Figure 25.
The Nissan Leaf vehicles that were purchased rather than leased show slightly higher rates of Level 2 charging events and lower rates of Level 1 charging events compared to the vehicles that were leased. This trend is seen in Figure 26.
Nissan Leaf vehicles that were purchased as fleet vehicles did not show much of a difference in the charging types though the Level 2 rates were slightly higher and the Level 1 were slightly lower than the vehicles purchased for private usage. However, the percentage of cars identified as fleet vehicles was a very small percentage of the total vehicles. This can be seen in Figure 27. No definitive conclusions are drawn here but the data is presented in Figure 27.

Figure 27 - Nissan Leaf Charge Type Percentages for Fleet vs. Private Vehicles

The Nissan Leaf leased vehicles with 12,000 pre-paid miles in the lease agreements showed slightly higher rates of charging events at Level 1 and less at Level 2 relative to those vehicles that had been leased with a pre-paid 15,000 miles as seen in Figure 28.
Looking at overall trends for the Nissan Leaf in Figure 29, the Nissan Leaf Level 1 charging event rates generally increased over time and model year for charging at home and decreased over time for charging at work or other locations. The Level 2 charging event rates showed the opposite trend (decreasing at home/increasing at work and other locations). This information is important to plan infrastructure and for marketing the vehicles. However, this trend might change as stronger ZEVs come to the market with a higher all-electric range.
Figure 30 shows monthly average VMT trends for Nissan Leaf vehicles both with and without any DCFC events. **NOTE: Nissan Leaf has 100% eVMT/zVMT/eTrips, average VMT is needed to show more miles with DCFC.**

**Figure 30 - Nissan Leaf Average VMT by DCFC events**

Figure 31 shows annualized average mileage trends for Nissan Leaf vehicles by the percentage of DCFC events. Since the vehicle number is small, few meaningful conclusions can be made from these data. However, it appears that DCFC does have some positive effect on the average monthly VMT for Nissan Leafs in this data sample.

**Figure 31 - Nissan Leaf Average mileage by percentage of DCFC events**
V.B.2. Ford Plots
The next set of plots show charge events with type of charging and average monthly trends for the Ford dataset to evaluate if there are seasonal variations in charge events and %eVMT, %zVMT and %eTrips data.

The percentage of charges by type (240V, 120V, or DC) do not show changes over time for the Ford C-Max vehicle. As shown in Figure 32, the changes in the percentages of eVMT, zVMT and eTrips appear to show seasonal variations with decreased activity in the winter months (unrelated to charging types).

Figure 32 - Ford C-Max Average Monthly %eVMT, %zVMT, %eTrips and % Charge Counts by Type

The Ford Fusion Energy data, illustrated in Figure 33, showed very similar trends to the C-Max vehicles.
As shown in Figure 34, the Ford Focus BEV also showed a steady trend in the types of charging over time. However, compared to the Ford PHEVs, the Ford BEV showed a significantly higher percentage of charging at Level 2 and significantly less at Level 1. However, there are no seasonal trends seen for charging activity.

In summary, the changes in the percentages of eVMT, zVMT and eTrips appear to show seasonal variations with decreased activity in the winter months; however, this is unrelated to charging types for Ford PHEVs (C-Max, and Fusion Energi) and the Ford Focus Electric.
V.B.3. Honda Plots
The next set of plots show the data for the Honda Fit. The charge location information provided for the Honda Fit vehicles shows an increasing percentage of unknown charging locations over time. This makes it difficult to determine if changes over time reflect an actual change, such as a decreasing percentage of home charging, or whether that was due to more home charge events being categorized as unknown charging locations as the recorded charge counts increased. The data is graphed in Figure 35.
The recorded charge types for the Honda Fit did not show a similar trend in that the unknown charge type percentages were extremely low. However, as the recorded charge counts increased from mid-2013 forward, the percentage of Level 2 charging events decreased as the Level 1 events increased. This is shown in Figure 36.

To summarize, reviewing the percentage of Honda Fit charges by type and location, the majority of the charging events are occurring at home at Level 2. It is difficult to determine any other trends due to both the increased overall counts over time as well as the increased unknown location counts over time. The data is summarized in Figure 37.
V.B.4. General Motors Plots

Chevrolet Volt did not provide information on the type or location of charges. Therefore, a comparison of the average monthly number of charges, and the average charging time (hours) per charge is shown in the Figure 38. California vehicles show a higher average charge time (hours per charge) with a lower number of charges per month as compared to non-California vehicles.

Figure 38 - GM Volt Monthly Charging
VI. Analysis of activity relevant to understanding criteria pollutant emission benefits

Staff also analyzed the activity data received from manufacturers to better understand the likely impacts on criteria pollutants such as hydrocarbons (HC) and oxides of nitrogen (NOx) from the various PHEVs. In addition to the e-trips and zVMT metrics discussed earlier, staff looked at other factors that could be used to help predict tailpipe emissions from the vehicle. Because tailpipe emissions of criteria pollutants are very dominant at initial engine start and generally much lower and well controlled after the initial engine start, tailpipe emissions can be categorized as start emissions (i.e., emissions associated with the initial engine start event of a trip) and running emissions (i.e., emissions associated with any subsequent engine operation later in the trip). For modern day vehicles, the start emissions represent the vast majority of tailpipe emissions. Accordingly, the analysis of the activity data focused on understanding factors that would influence start emissions.

Start emissions are currently modeled in ARB’s EMFAC emission inventory model by looking at the number of engine starts per day as well as the conditions of those starts relevant to predicting the emission rate of the engine start. Because PHEVs can have trips where the engine is not used at all, the in-use data was analyzed to determine not only the total number of vehicle trips per day but specifically the number of trips per day that actually had an ICE start. Table 18 below shows the results of this analysis for the PHEVs. For comparison, the table also includes a value for conventional gasoline cars that was based on the 2012 the California Household Travel Survey (CHTS) results. In general, the table shows that the PHEVs are being used for a similar number of trips per day but only a portion of those are trips where the engine actually is used. For the PHEV with the most electric capability in our study, the GM Volt, the vehicles are averaging only 0.88 trips per day where the engine starts, 22% of all trips taken in the vehicle. For PHEVs with less electric capability, the fraction of trips with an engine start is larger, with engine operation occurring on 86-91% of all trips. The Ford PHEVs were excluded from this analysis because of a data anomaly that prevented accurate logging of all short trips (< 3 kms). Based on the other data sets, the number of such short trips is significant and prevents a valid comparison to the other vehicles.

Table 18 - Approximate Trips per Day

<table>
<thead>
<tr>
<th>Source of Data</th>
<th>Vehicle - Technology</th>
<th>Total # of All Trips per day</th>
<th>Total # of ICE Trips per day</th>
</tr>
</thead>
<tbody>
<tr>
<td>CHTS 2012</td>
<td>ICE vehicles (Conventional)</td>
<td>4.75</td>
<td>4.75</td>
</tr>
<tr>
<td>GM</td>
<td>GM Volt (PHEV)</td>
<td>3.96</td>
<td>0.88</td>
</tr>
<tr>
<td>Honda</td>
<td>Honda Accord (PHEV)</td>
<td>4.15</td>
<td>3.80</td>
</tr>
<tr>
<td>Toyota</td>
<td>Toyota Prius (PHEV)</td>
<td>4.66</td>
<td>4.02</td>
</tr>
</tbody>
</table>

For light-duty gasoline vehicles, the primary factor influencing the emission rate of the start emissions is the temperature of the catalyst at the time of the start. When the engine is started, a colder catalyst will require a longer period of time to warm up to the light-off temperature, at which a high conversion efficiency of pollutants is achieved. Generally, a good surrogate for estimating catalyst temperature is the time between vehicle trips (“soak time”) because it reflects the period of time the engine is off and the catalyst can cool down to ambient temperature. As shown in Figure 39, the current version of ARB’s EMFAC 2014 model uses a multiplicative adjustment factor to adjust the projected emission rate from the start based on the soak time. The data is normalized to the emission rate of an overnight soak, like the official emission test procedures where start emissions are measured, and the emission rate is adjusted on a pollutant specific basis for shorter soak time engine starts. While this figure shows what is used in the current model, it should be noted that ARB is currently working on updates to the EMFAC model including modified adjustment factors based on new test data.

Figure 39 - EMFAC2014 Adjustment Value for Start Emissions

On PHEVs, however, the engine is not utilized on every vehicle trip so the soak time analysis must not look at the soak time from the last trip to the current trip but rather the soak time between the last trip where the engine was operated to the current trip where the engine is operated. Because the provided data could only identify if the engine was operated during a trip but not the exact point within the trip where it did, the analysis could not determine the exact engine off to engine on soak times. But the times between key off and key on trip events for the starts and ends of such trips were available and thus were used to calculate the soak time between trips where the engine was used. Figure 40 below shows the distribution of soak times calculated from the manufacturer data. Again, data for conventional cars from the 2012 CHTS is included for reference and shows that the distribution for the PHEVs is shifted slightly to the right indicating a lower fraction of hot restarts (very short soak times) and a higher fraction of
cold starts (longer soak times). The shift is more pronounced on the stronger PHEVs (e.g., GM Volt). Directionally, this makes sense as PHEVs have fewer trips where the engine does start and consequently, longer soak times between the trips where the engine does start. As noted above, the data from the Ford PHEVs was omitted from this analysis given the data logging anomaly.

**Figure 40 - Comparison of Approximate Soak Time Distributions in Minutes**

To understand the full impact of start emissions, the assumptions in the EMFAC model for PHEVs will need to be updated to include both the new data on starts per day as well as the new distribution of soak time to estimate the emission rates. As a first step, however, staff examined the overnight soaks (720 minutes or longer) to gauge the impact of PHEV behavior on overnight cold start emissions. By combining the results of the average starts per day with the frequency of overnight soaks from the soak time distribution, Table 19 was created. For reference, the conventional vehicles are included which show approximately 12% of trips are overnight cold starts which translates to an average of 0.56 such starts per day. For the GM Volt, while a much higher fraction (38%) of the starts are overnight cold starts, the very low number of trips per day where the engine starts results in an average of only 0.33 overnight cold starts per day. For the Honda and Toyota PHEVs, the slightly higher frequency of overnight soaks combined with only a slightly lower number of starts per day results in an average overnight cold starts per day that is very close to that of conventional cars. However, as these
PHEVs do have a lower number of engine starts per day, it is expected that the full modeling will still show some reduction in cumulative engine start emissions relative to conventional vehicles.

Table 19 - Approximate Cold Starts per Day

<table>
<thead>
<tr>
<th>Source of Data</th>
<th>Vehicle - Technology</th>
<th>Total # of ICE Trips per Day</th>
<th>% of Cold Start Trips (Overnight Soak)</th>
<th>Number of Cold Starts per Day</th>
</tr>
</thead>
<tbody>
<tr>
<td>CHTS 2012</td>
<td>ICE vehicles (Conventional)</td>
<td>4.75</td>
<td>11.86%</td>
<td>0.56</td>
</tr>
<tr>
<td>GM</td>
<td>GM Volt (PHEV)</td>
<td>0.88</td>
<td>37.55%</td>
<td>0.33</td>
</tr>
<tr>
<td>Honda</td>
<td>Honda Accord (PHEV)</td>
<td>3.80</td>
<td>15.29%</td>
<td>0.58</td>
</tr>
<tr>
<td>Toyota</td>
<td>Toyota Prius (PHEV)</td>
<td>4.02</td>
<td>15.88%</td>
<td>0.64</td>
</tr>
</tbody>
</table>

VII. Literature Review

The majority of eVMT research to date has focused on four methodologies: 1) simulations based on non-PEV household travel data, 2) empirical data obtained from short-term loaned PEVs, 3) surveys of PEV owners, and 4) empirical data from actual PEV households. Diverse studies using these four methods agree that eVMT and PHEVs inherent capacity to decrease GHG emissions depend upon driving and charging behavior, driving conditions, the regional energy generation mix, and specific PEV vehicle design. Overall, research is still lacking on how real-world PEV owners use their vehicles in the household context, and analysis of the household eVMT profile.

VII.A. Simulated eVMT based on non-PEV household travel data

The majority of studies simulated PEV performance based on data collected through GPS logging and travel surveys, taken mostly by non-PEV drivers. These studies looked at the theoretical effect that vehicle design, battery capacity, drive patterns, and charging strategies of PEVs would have on petroleum consumption and GHG emissions. Overall, these studies concur that PEVs can have a significant impact on the reduction of petroleum use, but that reduction of GHG emissions is highly dependent on the regional energy generation mix where vehicles are charged.\textsuperscript{10,11,12,13,14,15} In addition, driving conditions and driver behavior also impact...
GHG benefits, with greatest benefits achieved when usage of CD mode is maximized. Several studies have determined that frequent recharging of PHEVs can reduce PHEV gasoline consumption and decrease operating costs. A recent modeling study, which used GPS data from travel surveys to calculate second-by-second speed profiles of different trip types, including the effect of ambient temperature, concluded that 87% of vehicles trips driven on a given day across the whole U.S. could be accomplished with the 24-kWh Nissan Leaf based on a single charge per day. This result translates into a potential gasoline reduction of 60.9%. The percent of vehicle driven days that could be replaced with the Leaf was 84-93% across twelve different metropolitan areas, while it was 80.8% for rural areas.

VII.B. Empirical data from PEV loaners

In order to obtain actual on-road data from PHEVs, three early studies funded by Toyota loaned prototype Toyota Prius Plug-in vehicles equipped with on-board data loggers to households for a limited term basis. As these studies occurred before PHEVs were commercially available, hybrid Toyota Prius vehicles were converted into plug-in versions for each of these studies. A study of 25 households that had access to a prototype Prius Plug-in for 4-6 weeks in northern California found that 20% did not plug-in on a daily basis while 20% plugged-in more than once a day. Although a PHEV with a 5-kWh battery has the potential to reduce petroleum usage by up to 60% below the usage of a comparable HEV, average petroleum displacement in this study was only 14% (Davies, 2013). A study of 125 households that were each loaned one prototype Prius Plug-in for 1 year throughout the U.S. found that 40% of the drivers plugged in the vehicle once a day on days it was driven, but 40% did not plug it in at
Aggressive opportunistic charging after each trip was estimated to result in approximately the same fuel savings as increasing the battery size by a factor of five. The third Prius Plug-in prototype study loaned the vehicle for 9-weeks to 142 households in Boulder, Colorado. Of the participating households, only 6% were not satisfied with their PHEV experience, while 76% were dissatisfied with the electric range.

There have been several BEV loaning studies that found drivers with high mileage and those with frequent trips of short distance lifestyles can cover most of their travel needs with a BEV. A study in England of twelve households with access to one of several BEV models, including Nissan Leaf and Peugeot iOn, for six months found that these vehicles were not charged every day. A similar study that gave 75 German households access to BMW ActiveE for three months concluded that even users who have high daily mobility needs can meet their travel needs with a BEV. A study of 72 Irish households with loaned i-MiEV for four months concluded that trips were predominantly frequent in number per day and short in distance. However, it was not clear whether this trend was caused by the new BEV users being anxious about the range of their vehicle or whether it was based on consumer preference.

VII.C. Surveys of PEV households

ARB sponsored surveys of households with new PEVs in California show that although PHEVs with smaller batteries drive more miles, they have less eVMT compared to longer range PHEVs and BEVs as a consequence of battery size, public charging availability, and charging behavior. Based on the self-reported driving and charging behavior, the maximum potential eVMT calculated for the Chevrolet Volt and Toyota Plug-in Prius, without workplace charging, was 80% and 26%, while the estimated eVMT was 55 and 16%. PHEVs with smaller batteries tend to charge less often, both overall and at home, compared to longer range PHEVs and BEVs. The percentage of PHEVs that are not charged is inversely proportional to battery range. A total of 14%, 6% and 2% of respective Toyota Plug-in Prius, Ford C-MAX/Fusion Energi, and Chevrolet Volt households self-reported not charging these vehicles in the last 30 days. Interestingly, drivers of PHEVs with smaller batteries were not able to find as many charging opportunities in the same areas compared with higher range PHEV and BEV drivers.

29 The Mitsubishi i-MiEV is sold as the Peugot iOn in Europe
35 Tal, 2014.
36 Nicholas, 2016a.
37 Tal, 2014.
When looking specifically at BEVs driven in California, factors such as body style, self-selection, commute, access to charging infrastructure and sharing of vehicles all seem to play a role in determining eVMT, in addition to electric range.\(^{38}\) Range alone does not explain reported eVMT. For example, the self-reported annual eVMT of the Fiat 500e (7,912 miles) is much lower than expected given its all electric range of 87 miles compared with other BEVs of similar range such as the Honda Fit EV and the Chevrolet Spark EV (11,049 and 9,167 miles). Although the Tesla Model S and Toyota RAV4 EV have very different electric ranges greater than 100 miles (265 vs 113 miles), both vehicles get fairly similar annual eVMT (12,174 vs 11,519 miles) (Nicholas, 2016). The Honda Fit EV had the highest annual eVMT (11,049 miles) of the BEVs with an electric range below 100 miles, followed by Nissan Leaf (9,511 miles), Ford Focus Electric (9,442 miles), Chevrolet Spark EV (9,167 miles), BMW i3 (8,169 miles), Fiat 500e (7,912 miles) and lastly, the Smart Fortwo (6,690 miles). Additionally, the overall share of household eVMT is not dictated by vehicle range alone. For example, the Fiat 500e and the Toyota RAV4 EV contributed to the smallest and largest share of household eVMT (~37-49%).

A separate ARB sponsored survey of used PEV owners estimated the total annual miles driven by used PEV owners based on self-reported odometer readings at the time of survey completion and time of purchase.\(^{39}\) Comparing these results with those from a survey of new PEV owners reveals that used PHEVs tend to be driven more than new PHEVs. For example, the used Ford Fusion Energi and Chevrolet Volt were driven 15,692 and 12,000 median annual miles while the new versions were driven 12,600 and 10,800 median annual miles. Furthermore, respondents with smaller battery PHEV models were more likely to use their PEV as a conventional hybrid vehicle. For example, 30% of used Prius Plug-in owners reported they plugged in their vehicle four times or less in the last 30 days. In contrast, less than 15% of new Prius Plug-in owners reported plugging in their vehicle four times or less in the last 30 days. Thus, as used PHEVs with smaller batteries are driven more and are plugged in less than similar new PHEVs, the percent eVMT they are able to achieve must be decreasing compared to new PHEVs. The usage trends for used BEVs are mixed depending on their battery size. While the used Tesla Model S was driven more than the new Tesla Model S (12,798 versus 11,200 median annual miles), used BEVs with smaller electric range were driven less than the new version of the same BEVs. For instance, the used and new Nissan Leaf vehicles were driven 7,836 and 9,400 annual median miles.

A recent Norwegian survey of PEV consumers determined that BEV owners utilized their vehicles more for all types of trips, but less on vacation than PHEV and ICE households.\(^{40}\) In contrast to results from California PEV owner surveys, the BEV drivers have a longer work commute than PHEV or ICE owners in Norway. This could be a result of the different set of tax policies and incentives between the two regions. Different BEV models have different eVMT profiles in Norway too. The Tesla Model S was driven the most per year on average (14,520

\(^{38}\) Nicholas, 2016a.
miles) followed by the Kia Soul EV (10,986 miles), Volkswagen E-Golf (10,372 miles), Nissan Leaf (9,849 miles), BMW i3 (9,505 miles), and the Renault Zoe (9,300 miles). In general, Norwegian PHEV owners self-reported to have driven 55% of the time in all electric drive mode ranging from 38% for the Prius Plug-in to 83% for the Opel Ampera.41

ARB sponsored surveys of households with new PEVs in California show that, although PHEVs with smaller batteries drive more miles, they have less eVMT compared to longer range PHEVs and BEVs as a consequence of battery size, public charging availability, and charging behavior.42,43 Based on the self-reported driving and charging behavior, the maximum potential eVMT calculated for the Chevrolet Volt and Toyota Plug-in Prius, without workplace charging, was 80% and 26%, while the estimated eVMT was 55 and 16%.44 PHEVs with smaller batteries tend to be charged less often, both overall and at home, compared to longer range PHEVs and BEVs.45 The motivation to plug in a PHEV was found to be a function of electric range recovered during the charge event and accordingly, PHEVs with longer range are more likely to be plugged in when empty versus smaller range PHEVs at a similar level of depleted charge. The percentage of PHEVs that are not charged is inversely proportional to battery range, and this percentage has roughly doubled for new PEV drivers between 2015 and 2016 as gasoline prices have decreased.46 Interestingly, drivers of PHEVs with smaller batteries were not able to find as many charging opportunities in the same areas compared with higher range PHEV and BEV drivers.47

When looking specifically at BEVs driven in California, factors such as body style, self-selection, commute, access to charging infrastructure and sharing of vehicles all seem to play a role in determining eVMT, in addition to electric range.48 Range alone does not explain reported eVMT. For example, the self-reported annual eVMT of the Fiat 500e (7,912 miles) is much lower than expected given its all electric range of 87 miles compared with other BEVs of similar range such as the Honda Fit EV and the Chevrolet Spark EV (11,049 and 9,167 miles). Although the Tesla Model S and Toyota RAV4 EV have very different electric ranges greater than 100 miles (265 vs 113 miles), both vehicles get fairly similar annual eVMT (12,174 vs 11,519 miles) (Nicholas, 2016). The Honda Fit EV had the highest annual eVMT (11,049 miles) of the BEVs with an electric range below 100 miles, followed by Nissan Leaf (9,511 miles), Ford Focus Electric (9,442 miles), Chevrolet Spark EV (9,167 miles), BMW i3 (8,169 miles), Fiat 500e (7,912 miles) and lastly, the Smart Fortwo (6,690 miles). Additionally, the overall share of

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41 Figenbaum, 2016.
42 Tal, 2014.
44 Tal, 2014.
46 Nicholas, 2016b
47 Tal, 2014.
48 Nicholas, 2016a.
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**VII.D. Empirical data from PEV households and fleets**

Perhaps the most accurate method to study eVMT is to obtain high-resolution driving and charging data during a long period of time (>1 year) directly from real-world PEV households. One pioneering study that utilized vehicle telematics to do this was the “EV Project” from the INL funded by the US DOE. The driving and charging profiles of 1,867 Chevrolet Volt and 4,038 Nissan Leaf vehicles were studied between 2012-2013 in 22 metropolitan areas across the

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51 Figenbaum, 2016.
United States, including San Diego, Los Angeles, and San Francisco. 52 Parameters recorded for this study by the Volt and Leaf telematics systems include key-on and key-off events, odometer, EV-mode odometer, number of trips, gasoline fuel economy, battery state of charge (SOC), and the number, type and location of charging events. Participants of the “EV Project” that lived in 13 cities received a free level 2 EVSE for their home and up to $1,200 to cover installation expenses.

As illustrated in Table 20, Volt vehicles accumulated more annual VMT with an average of 12,238 miles while the Leaf vehicles only achieved 10,352 miles. Despite having a smaller electric range, Volt drivers averaged only 6% fewer annual eVMT than the Leaf drivers. On average, Volt drivers charged more often (1.5 charges per day on days driven) and tended to deplete their batteries prior to recharging compared with Leaf drivers (1.1 charges per day on days driven) who tended to recharge with significant range left in their batteries. The “EV Project” participants that had access to workplace charging had higher annual VMT than overall project participants; Volt and Leaf drivers with access to workplace charging accumulated an average of 13,759 and 11,882 miles per year. A separate analysis by INL based on these “EV Project” Leaf vehicles with workplace charging concluded that workplace charging can serve as a virtual range extender. 53 At least 14% of Leaf vehicles needed workplace charging to complete their daily commutes most of the time, while 42% of vehicles needed it at least 5% of commuting days. On days when these drivers charged at work, they drove an additional 15% more miles than when they did not charge at work. The top 100 mileage Leaf and Volt vehicles participating in the “EV Project” had an average annual VMT of 19,048 and 25,088 miles respectively. 54 Although these high mileage PEVs were charged away from home more often, at least two thirds of the charging was still done at home. The high mileage Leaf and Volt vehicles in the “EV Project” were charged away from home 34% and 21% of the time compared to just 20-22% and 14-17% for all Leaf and Volt vehicles. 55 It is unclear whether the high mileage Volt vehicles in this study had a different eVMT profile.

INL also analyzed the travel data supplied by different car manufacturers for a variety of other PEVs, as shown in Table 20. 56 Smaller range PHEVs tend to be driven longer distances than larger battery PHEVs and BEVs. There was a wide range of average percent eVMT for different PHEVs increasing with electric range, spanning from 16% for the Toyota Prius Plug-in to 75% for the Volt. One of the strengths of the “EV Project” is the large sample size. However, there may be biases present in the data because the telematics systems used to obtain the data were only available for the higher trim of some of these vehicle models, such as the Prius Plug-in.

55 INL, 2015.
Table 20 - Annualized statistics of PEVs from INL\textsuperscript{57,58} and UCD\textsuperscript{59} studies

<table>
<thead>
<tr>
<th>PEV</th>
<th>Study</th>
<th>Mean Annual VMT</th>
<th>Mean Annual eVMT</th>
<th>% Annual eVMT by PEV</th>
<th>Annual Average HH VMT</th>
<th>% Annual eVMT by Household</th>
<th>% Trips without ICE Starting</th>
<th>Sample Size</th>
</tr>
</thead>
<tbody>
<tr>
<td>Toyota Prius Plug-in</td>
<td>INL</td>
<td>15,136</td>
<td>2,484</td>
<td>16.4%</td>
<td>NA</td>
<td>NA</td>
<td>NA</td>
<td>1,523</td>
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<tr>
<td></td>
<td>UCD</td>
<td>12,268</td>
<td>2,829</td>
<td>23.1%</td>
<td>19,112</td>
<td>14.8</td>
<td>21.9</td>
<td>18</td>
</tr>
<tr>
<td>Ford C-MAX Energi</td>
<td>INL</td>
<td>12,403</td>
<td>4,069</td>
<td>32.8%</td>
<td>NA</td>
<td>NA</td>
<td>NA</td>
<td>5,368</td>
</tr>
<tr>
<td>Ford Fusion Energi</td>
<td>INL</td>
<td>12,403</td>
<td>4,337</td>
<td>35.0%</td>
<td>NA</td>
<td>NA</td>
<td>NA</td>
<td>5,803</td>
</tr>
<tr>
<td>Ford C-MAX &amp; Fusion Energi</td>
<td>UCD</td>
<td>11,778</td>
<td>4,982</td>
<td>42.3%</td>
<td>20,289</td>
<td>24.6</td>
<td>56.2</td>
<td>18</td>
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<tr>
<td>Chevrolet Volt</td>
<td>INL</td>
<td>12,238</td>
<td>9,112</td>
<td>74.5%</td>
<td>NA</td>
<td>NA</td>
<td>NA</td>
<td>1,867</td>
</tr>
<tr>
<td></td>
<td>UCD</td>
<td>11,122</td>
<td>8,186</td>
<td>73.6%</td>
<td>18,316</td>
<td>44.7</td>
<td>87.2</td>
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<tr>
<td></td>
<td>GM</td>
<td>NA</td>
<td>NA</td>
<td>74%</td>
<td>NA</td>
<td>NA</td>
<td>NA</td>
<td>&gt;48,000</td>
</tr>
<tr>
<td>Nissan Leaf</td>
<td>INL</td>
<td>9,697</td>
<td>9,697</td>
<td>100.0%</td>
<td>NA</td>
<td>NA</td>
<td>NA</td>
<td>4,038</td>
</tr>
<tr>
<td></td>
<td>UCD</td>
<td>10,230</td>
<td>10,230</td>
<td>100.0%</td>
<td>23,575</td>
<td>43.4</td>
<td>NA</td>
<td>18</td>
</tr>
<tr>
<td>Ford Focus Electric</td>
<td>INL</td>
<td>9,548</td>
<td>9,548</td>
<td>100.0%</td>
<td>NA</td>
<td>NA</td>
<td>NA</td>
<td>2,196</td>
</tr>
<tr>
<td>Honda Fit EV</td>
<td>INL</td>
<td>9,680</td>
<td>9,680</td>
<td>100.0%</td>
<td>NA</td>
<td>NA</td>
<td>NA</td>
<td>645</td>
</tr>
<tr>
<td>Honda Accord Plug-in</td>
<td>INL</td>
<td>14,986</td>
<td>3,336</td>
<td>22.3%</td>
<td>NA</td>
<td>NA</td>
<td>NA</td>
<td>189</td>
</tr>
</tbody>
</table>

An analysis by General Motors (GM) of more than 48,000 Volt vehicles with active OnStar accounts between October 2013 and September 2014 in the U.S. and Canada concluded that 74% of the miles driven on these vehicles were eVMT.\textsuperscript{60} Similar driving and charging parameters were analyzed as in the “EV Project.” A 70% reduction in cold starts compared to conventional gasoline vehicles under the same driving conditions was quantified. Finally, this study estimated that the second generation Volt will achieve 80% eVMT assuming the same driving and charging patterns.

ARB and the California Energy Commission are sponsoring a project at the University of California Davis (UCD) to study consumers’ actual usage of PEVs in California. The goal of this project is to quantify eVMT within the household context among a variety of different electric range PHEVs (Toyota Plug-in Prius, Chevrolet Volt, and the Ford Fusion/C-MAX Energi), BEVs (Nissan Leaf and Tesla Model S), and BEVs with a range extending internal combustion engine

\textsuperscript{57} Francfort,2015, \textsuperscript{58} Carlson, 2015. \textsuperscript{59} Nicholas, 2016b \textsuperscript{60}Duhon, 2015.
This study is collecting detailed driving and charging data utilizing a specialized data-logger that records key-on and key-off events, odometer, speed, acceleration, state of charge, location of vehicle, and charging event (location, duration, level). This study completed the first year of logged data on all the vehicles from 18 Plug-in Prius, 18 Fusion/C-MAX Energi, 18 Chevrolet Volt, and 18 Leaf households.61

As presented at the September 2016 Advanced Clean Car Symposium,62 the average annual VMT of participants in the UCD study is fairly similar to the INL study (Table 20), except for the Prius Plug-in which was about 3,000 miles less in the UCD study. The percent annual eVMT by PEV was roughly similar for the Volt but higher for the Prius Plug-in and Energi models in the UCD study relative to the INL study, in part because vehicles that did not plug in were excluded from the UCD study. Differences in the results of the two studies could be due to the sampling selection, size, location, available infrastructure, or other biases inherent in these studies. The timing of each study could also affect the results, with the UCD study collecting data more recently (2015-2016) over the data used in the INL study (2012-2013). One of the strengths of the UCD study is that it is quantifying the percent eVMT per household based on total VMT across all vehicles. The percent eVMT per household is lowest for the smaller battery PHEVs as the vehicles are used more for overall driving in the household despite not having enough electric range in the PHEV to meet the driving needs. In the household study, the choice of vehicle in the context of ICE usage is also explored. The study does find that the electric range of both the Chevrolet Volt and Nissan Leaf are maximized so that the vehicles are more likely to be used instead of the ICE on days where all driving can be accomplished on one charge, but less so for the Plug-in Prius, Ford Fusion Energi and Ford C-Max Energi. It is unclear the degree to which this maximization of use within electric range is due to customers matching the vehicle purchase to driving patterns or whether the vehicle architecture encourages maximization of electric range post-purchase.

While the Nissan Leaf households have the largest average eVMT, they also have the largest household VMT and therefore, not the highest percent eVMT by household. In the UCD study, Nissan Leaf households also had more vehicles and drivers per household than the other PEVs, resulting in higher household miles in ICES and a lower percent eVMT for the household. The overall household VMT is smallest for the Chevrolet Volt households, so they have the highest percent eVMT by household.

The percent of trips without an ICE starting were also quantified.63 The Volt achieved 87% of its trips without the gasoline engine, whereas only 22% of the trips in the Prius Plug-in did not use the ICE. Furthermore, over one-sixth of the Prius Plug-in, one-twentieth of the C-MAX Energi, and one-thirteenth of the Fusion Energi engine starts were determined to have been high-power

61 Nicholas, 2016b
https://www.arb.ca.gov/msprog/consumer_info/advanced_clean_cars/pev_data_from_uc_davis_household_study_first_year_michael_nicholas.pdf
63 Nicholas, 2016c.
cold starts, which tend to emit more criteria pollutants than a normal cold start thus potentially mitigating some of the environmental benefits of PHEVs.

The UCD project is continuing with data collection, including all the models listed above. The next two 1-year phases of the study began in the early and late fall of 2016, respectively, and a final phase of data collection will begin in fall 2017. Because this project is providing unique data that will be used to inform future policies, ARB is sponsoring a similar project focused on the household-level driving and fueling of emerging technology zero-emission vehicles including Toyota Prius Prime, Chrysler Pacifica, Chevrolet Bolt and Toyota Mirai. This new project will commence in early 2017.

VIII. Summary

This Appendix G describes staff analysis of the in-use trip level vehicle data collected from various plug-in hybrid electric vehicles (PHEV), battery electric vehicles (BEV), and range extended BEVs (BEVx). In-use trip and charge data, including more than 500,000 individual records for more than 94,000 vehicles from seven major OEMs (BMW, Ford, GM, Honda, Nissan, Tesla, and Toyota), were analyzed to assess the relative performance of the BEVs and PHEVs. The analysis found that the lower range (75-100 mile) BEVs are, on average, being driven less each year than longer range (Tesla) BEVs or PHEVs. When looking at eVMT, the analysis confirmed the longer range/higher electric only capability PHEVs resulted in a higher fraction of electric miles than shorter range PHEV. However, even the strongest PHEV (GM Volt) achieves only about 75% of the electric miles that a typical lower range BEV like the Nissan Leaf travels in a year. Data shows that newer model year BEVs and PHEVs are being driven more than earlier model years but it varies among PHEV models as to whether the percentage of eVMT is staying constant or dropping in conjunction with the increase in total miles. The impact of leasing terms (mileage caps) appears to have a large influence on annual VMT as Nissan Leafs with 15,000 mi/year lease terms averaged significantly higher VMT than those with 12,000 mi/year lease terms. There is substantial variability within each PHEV vehicle model as to how individual vehicles are being used and some weak correlations are observed where, as average daily VMT increase, the relative eVMT percentage tends to decrease while the eVMT absolute miles increases. Slightly stronger correlations are observed with average number of charge events per day where an increase in charge events per day consistently shows overall increases in both percent and absolute eVMT.

Regarding charging, the Nissan Leaf was studied and the data shows that newer model year Leaf owners are generally using less Level 2 charging and more Level 1 charging. Usage of DC fast charging is also showing a slight increase and increased usage appears to correlate to higher annual VMT.

The activity data was also studied to better understand criteria pollutant (primarily HC and NOx) impacts of the PHEVs. The zVMT metric showed similar, but more pronounced, trends than eVMT with the shorter range and lower all electric capability PHEVs having a very small portion of their total VMT from “BEV-like” trips where no criteria pollutants were emitted. PHEVs do show some reduction in engine starts per day with the GM Volt showing the largest reduction with only ~20% of the number of starts per day as a conventional car. PHEVs do, however,
average longer time periods of engine off time between trips such that a larger share of the engine starts are cold starts, where emissions are the highest. Cumulatively, start emissions are likely reduced by having fewer starts per day but the higher fraction of cold starts offsets part of this reduction.

Several studies have been conducted to understand how BEVs and PHEVs are being used and while the same general trends are observed, calculated metrics or averages continue to shift based on the actual data sample studied. The differences observed in where vehicles are used, age and model year of the vehicles, and the driving needs and charging behavior of the individual owner can have a significant impact.
IX. References


Figenbaum, 2016, Figenbaum, E. and M. Kolbenstvedt, Learning from Norwegian Battery Electric and Plug-in Hybrid Vehicle Users: results from a survey of vehicle owners. 2016, Institute of Transport Economics, Norwegian Centre for Transport Research: Oslo


I. Introduction
The California Air Resources Board (ARB or the Board) directed staff to study in-use data for plug-in hybrid electric vehicles (PHEV), including how these vehicles are driven, charged and their criteria pollutant emission impacts. This appendix will focus on the PHEV testing conducted at ARB to help quantify criteria pollutant emissions under real world driving conditions.

There is a distinct difference among PHEVs in the market today. Most PHEVs are “blended”, the engine can start to help power the vehicle before the battery is fully depleted. These vehicles can have an initial internal combustion engine (ICE) start under high-power demands even when the battery state of charge (SOC) is high. This occurs in cases where, even though the battery has sufficient charge, the electric portion of the drivetrain is not sufficient to meet the desired vehicle torque and the ICE must be started to help meet that immediate torque demand. The other type of PHEV is commonly referred to as “non-blended”, “US06 capable”, or “extended range electric vehicle (EREV)”. This vehicle depletes the battery first, and only when the battery is depleted, turns the ICE on to power the vehicle. The Chevrolet Volt, Toyota Prius Prime, and BMW i3 REX\(^1\) are non-blended PHEVs available today.

PHEVs generally have their operation classified in one of two ways. While the vehicle is operating on electric only power, supplied by the grid, it is considered to be ‘charge depleting’ (CD) operation. When the vehicle is operating on ICE power (gasoline engine), it is considered to be ‘charge sustaining’ (CS) operation. For non-blended PHEVs, the vehicle would normally operate in CD mode until the grid energy is used up/battery depleted and then the vehicle would transition to CS mode. For blended PHEVs, the categorization is more complicated as both grid energy and the ICE can be used simultaneously, during CD operation, to power the vehicle. As noted above, generally this occurs when the vehicle power demand is higher than what the electric only propulsion system can provide and the vehicle starts the engine to combine the electric and ICE power to meet the vehicle demand. As a result, blended PHEV CD operation introduces a unique driving condition where the initial engine start of a trip occurs at a time where there is an immediate need for the engine to provide significant power and torque to help propel the vehicle. Such starts, referred to here as “high-power” cold-starts, can have different emission characteristics relative to the initial engine start of a conventional vehicle which typically occurs with the vehicle stopped, in park/neutral, and with a very low immediate torque demand. Given the unique start-up conditions that blended PHEVs can encounter, staff developed a test program to determine if real world high-power cold-starts may yield higher exhaust emissions than those observed during the regulated emission test cycles which are conducted for vehicle exhaust emission certification.

For this testing, staff evaluated the cold start emissions of several blended PHEVs believed to be representative of currently available PHEVs. The vehicles tested include the 2013 Ford

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\(^1\) For purposes of the zero emission vehicle (ZEV) regulation, the BMW i3 REX is categorized as a range extended battery electric vehicle, or BEVx, and earns additional credits relative to the other PHEVs. However, in operation, the vehicle behaves like a non-blended PHEV and will not turn on the ICE until the battery is depleted.
Fusion Energi PHEV, 2013 Toyota Prius PHEV, and a 2016 Hyundai Sonata PHEV. The results of the testing are summarized in this appendix.

II. Developing the Test Cycles
In a conventional vehicle, the cold start emissions are captured in emission certification test cycles. While manufacturers must meet numerous applicable standards over various cycles, only the Federal Test Procedure (FTP) captures cold-start emissions during the test. Other test cycles, like the US06 portion of the supplemental FTP (SFTP) either have the engine already running when the test starts or have the vehicle fully warmed up in advance so the initial engine start is a ‘hot’ start. The FTP test cycle is designed to represent urban driving and captures a cold start at the beginning of the test cycle. The US06 test cycle captures so-called “off-cycle” emissions resulting from more aggressive driving (from higher speeds and accelerations). Requiring manufacturers to meet standards for both moderate and more aggressive driving conditions helps ensure emissions are well controlled in the full spectrum of driving encountered in the real world. Blended PHEVs, however, provide for a unique condition not fully represented by either the FTP or US06 in cases where the initial engine start occurs while the vehicle is already in motion and in need of a more immediate delivery of power and torque from the engine.

To capture these high-power cold-starts, staff needed to develop unique test cycles. To re-create real world high-power cold-start exhaust emissions in a controlled laboratory environment, staff procured a 2013 Ford Fusion Energi, a blended PHEV, to conduct an on-road drive in El Monte, CA. During the on-road drive, an on-board diagnostics (OBD) scan-tool and laptop was used to record data of different types of driver/vehicle actions that caused the ICE to start during CD operation. The drive trace of the on-road driving is provided in Figure 1 below.

Figure 1 - Complete On-Road Drive Trace

![Complete On-Road Drive Trace](image)
As seen from the trace above, a blended PHEV uses the ICE to supplement battery/electric motor power during CD operation. The blue in Figure 1 is the engine speed (rpm) and each spike in the graph represents an engine start event. The green line is the decreasing SOC of the battery indicating the depletion of grid energy during the drive. After the battery is depleted (not shown in Figure 1), the blended PHEV switches to CS operation where battery SOC is maintained at a certain level while the vehicle is driven and the vehicle behaves like a conventional hybrid with limited electric drive capability. From the trace above, staff developed six acceleration cycles and took the vehicle on the dynamometer to measure emissions. These acceleration cycles are described in Table 1 below:

<table>
<thead>
<tr>
<th>Table 1 - Acceleration cycles developed for the dynamometer</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Acceleration 1</strong></td>
</tr>
<tr>
<td><strong>Acceleration 2</strong></td>
</tr>
<tr>
<td><strong>Acceleration 3</strong></td>
</tr>
<tr>
<td><strong>Acceleration 4</strong></td>
</tr>
<tr>
<td><strong>Acceleration 5</strong></td>
</tr>
<tr>
<td><strong>Acceleration 6</strong></td>
</tr>
</tbody>
</table>

The maximum acceleration rates of these six acceleration cycles were compared to the maximum rates during the FTP and US06 test cycles to provide perspective on the aggressiveness of the driving condition. Figure 2 below compares the maximum FTP acceleration rate, 3.3 miles per hour, per second (mph/s) with the maximum acceleration rate of the US06, 8.4 mph/s.

**Figure 2 - Acceleration Rates for the FTP and US06 Test Cycles**

![Figure 2 - Acceleration Rates for the FTP and US06 Test Cycles](image-url)
For the six acceleration cycles developed by staff, the maximum acceleration rates range from 4 mph/s to 7 mph/s. Thus, the acceleration cycles fall in-between the FTP and US06 cycles in terms of acceleration rates. For emission testing purposes, each of the individual acceleration cycles was used as a separate emission test cycle to measure high-power cold-start emissions on a dynamometer with exhaust emission analyzers.

III. Finding a Method to Compare Test Cycle Emissions

The next step was to develop a method to compare real world high-power cold-start emissions to the emission levels required by the emission standards. Staff used the following assumptions:

- All the vehicles tested are certified to the super-ultra-low-emission vehicle (SULEV) emission standard on the FTP.

- The FTP consists of a cold start (bag 1) and transient (bag 2). Repeat testing in the laboratory shows that hydrocarbon (HC) and oxides of nitrogen (NOx) emissions are dominated by the initial engine start. As shown in Figure 3 below for a typical SULEV vehicle, 65-80% of the total HC and NOx emissions for an FTP emission test are emitted in the first 40 seconds of the test. By 120 seconds into the test, over 90-98% of the total emissions are emitted.

Using the composite gaseous mass-weighted equation from the official emission test procedures, a theoretical maximum emission level from the cold start of the FTP test was calculated.

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2 Section G.5.5.2.2 (Equation 1) California Exhaust Emission Standards and Test Procedures for 2018 and Subsequent Model Zero-Emission Vehicles and Hybrid Electric Vehicles, (Amended: September 3, 2015).
Equation 1 - Composite Gaseous Mass-Weighted Equation

\[ E_{\text{emission}, \text{FTP comp}} = 0.43 \left( \frac{M_c}{D_c} \right) + 0.57 \left( \frac{M_h}{D_h} \right) \]

where:
- \( M_c \) = mass of emissions from cold test (bag 1)
- \( D_c \) = distance traveled in cold test (bag 1)
- \( M_h \) = mass of emissions from hot test (bag 2)
- \( D_h \) = distance traveled in hot test (bag 2)

To determine the maximum cold-start exhaust emissions that are allowed during a FTP, staff solved for the mass emissions from a cold-start exhaust test, \( M_c \) (Equation 2 below) assuming standard distances for the test cycle and the Low Emission Vehicle (LEV) III SULEV standard for the emission level.

Equation 2 – Solve for \( M_c \)

\[ \frac{E_{\text{emission}, \text{FTP comp}} - 0.57 \left( \frac{M_h}{D_h} \right)}{0.43} \left( D_c \right) = M_c \]

\( E_{\text{emission}, \text{FTP comp}} = 0.030 \) grams/mile (LEV III SULEV30 standard)
- \( D_c = 7.45 \) miles
- \( M_h = 0 \) grams (assuming there are no emissions from hot test)

Solving for \( M_c \) yields 0.520 grams which represents the maximum NMOG+NOx exhaust emissions that are allowed during a FTP cold-start exhaust test (Equation 3).

Equation 3 – Determining maximum NMOG+NOx exhaust emissions

\[ \frac{0.030 - 0}{0.43} \left( 7.45 \right) = M_c = 0.520 \text{ grams} \]

By calculating this in a total grams unit, instead of grams/mile like the emission standards, the emissions from the acceleration cycles can then be compared to the 0.520 grams maximum limit from Equation 3 to get a relative sense of the emissions from high-power starts.

IV. Summary of the Results
For the laboratory testing portion of the study, in total, three blended PHEVs (2013 Ford Fusion Energi PHEV, 2013 Toyota Prius PHEV, and 2016 Hyundai Sonata PHEV) were procured for testing. Dynamometer derivations for each blended PHEV were performed according to the provisions from each manufacturer. California Phase 3 fuel was used for this study. Each set
of test cycles received a minimum of 1 overnight soak and 1 minimum 4-hour soak/forced cool-down with vehicle fan. To provide a relative comparison to the six acceleration cycles, exhaust emission modal analysis and bag analysis were performed on the FTP cycle, US06 cycle, and the acceleration cycles. The acceleration cycles were performed in CD operation to investigate high-powered cold-starts. The FTP cycle and US06 cycle were performed in CS operation and CD operation, time permitting. Of note, while the official test procedures for the US06 include a warmed up engine (hot start), for this testing, the test procedure was modified to include a cold start on the US06 to provide further comparison for the emissions from a more aggressive driving schedule where a high-power cold start could occur. As such, the emission results for the US06 cycles provided in the figures below cannot be compared to the applicable US06 standard. The test results of the 2013 Toyota Prius PHEV, 2013 Ford Fusion Energi, and 2016 Hyundai Sonata PHEV are shown in the following figures.

**Figure 4 - 2013 Toyota Prius Plug-In Hybrid**

When comparing the 2013 Toyota Prius PHEV (see Figure 4) cold-start exhaust emissions to the 0.520 grams NMOG+NOx maximum limit from Equation 3, the FTP results are significantly below the limit. The cold-start US06 results, while more variable, are also fairly close to the FTP test levels. However, all of the acceleration tests were significantly higher and averaged around 5 to 8 times higher than the FTP test levels. When examining individual NOx and NMOG emission levels instead of the combined result, NOx emissions were roughly 10 to 18 times higher than the FTP NOx emission levels, and NMOG emissions were about 5 to 8 times higher than the FTP NMOG emission levels.
When comparing the 2013 Ford Fusion Energi (see Figure 5) cold-start exhaust emissions to the limit from Equation 3, the FTP emissions were also below the theoretical limit as expected. For the cold-start US06, emission levels were 2 to 3 times higher than the FTP emissions. With respect to the acceleration cycles, the emissions varied considerably from levels similar to the US06 or higher but were typically near the theoretical limit and approximately 2.5 to 3 times the FTP emission levels. When examining individual NOx and NMOG emission levels, NOx emissions were about 2 to 4 times higher than the FTP NOx emission levels, and NMOG emissions were about 2 times higher than the FTP NMOG emission levels.

For the 2016 Hyundai Sonata PHEV (see Figure 6), the FTP emissions were below the limit from Equation 3. Cold-start US06 emissions were higher than the limit and approximately 3 times FTP levels. The acceleration cycle emissions varied significantly from levels around 2 times the FTP levels and just below the calculated limit to levels around 5 times higher than the FTP test levels. When examining individual NOx and NMOG emission levels, NOx emissions were about 3 to 6 times higher than the FTP NOx emission levels, and NMOG emissions were about 3 times higher than the FTP NMOG emission levels.
V. Relative Impact of High-Power Starts

While the testing focused on quantifying emissions from high-power starts, not all blended PHEV initial engine starts would be considered such starts. From previous testing used to develop modified certification test procedures for PHEVs and to study PHEVs for other purposes, staff found that PHEVs are generally capable of robustly controlling initial engine start emissions under non-high power start conditions such as when the vehicle is operated in CS mode or when the vehicle transitions from CD to CS mode when the battery is nearly depleted. As such, staff is also working with other data sets to understand how often high-power start conditions occur for blended PHEVs to understand the cumulative emission impacts. One data source of note is a household study being conducted for ARB by UC Davis that is collecting second by second data of PHEVs. Preliminary analysis for this study was presented at ARB’s Advanced Clean Cars Symposium in September 2016\(^3\) (shown in Figure 7) and found 25-59% of initial engine starts on the Ford and Toyota PHEVs could be high-power engine starts.

Figure 7 - Frequency of High Power Starts

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To provide further perspective on the impact of these high power starts, a preliminary analysis was done to estimate the daily HC and NOx emissions from these PHEVs relative to a conventional vehicle certified to the LEV II SULEV emission standards. The Hyundai Sonata PHEV was not included in this analysis because activity data was not available to estimate the frequency of high-power starts for the vehicle. For the conventional vehicle, FTP emission data submitted to ARB for the in-use verification program of nearly 1,000 vehicles certified as partial zero emission vehicles was used to estimate typical daily emissions of non-PHEV, gasoline SULEV certified vehicles. Average bag 1 emissions were assumed to be all cold start emissions, average bag 2 emissions were assumed to be all running emissions, and average bag 3 emissions were assumed to be all hot start emissions.

For simplification, soak times were consolidated into three categories of hot starts (less than 60 minutes), intermediate starts (60 minutes to 720 minutes), and cold starts (greater than 720 minutes). Data from the 2013 California Household Travel Study\(^4\) was used to determine the distribution of the soak times and average starts per day for the conventional vehicle as described in Appendix G. For the conventional vehicle, the hot and cold start emissions were used to estimate an intermediate start emission rate of approximately half of the cold start rate.

For the PHEVs, emission rates were estimated for hot starts, intermediate starts, and cold starts in both normal and high power start conditions. For all normal starts, high power hot starts, and running emission rates, similar values to the conventional vehicle were used. For the high power cold and intermediate starts, the results from ARB’s testing were used for the cold starts and scaled down and used for the intermediate starts. The emission rates were then combined with the additional activity data for the PHEVs from section VI of Appendix G to determine starts per day and distribution of soak time conditions. And, for comparison purposes, all of the activity data (VMT, eVMT, and starts/day) for the PHEVs was scaled to match the 15,000 annual miles used for conventional vehicles.

Figure 10 below shows the estimated HC plus NOx tailpipe emissions. The figure separately shows start emissions (cumulative from all start conditions) and running emissions (cumulative from all operation with the engine on after the initial start). For perspective in comparing the daily tailpipe emission estimates, the bar on the figure labeled as “Conventional SULEV” represents the typical emission levels estimated from FTP testing of non-PHEV vehicles certified to the LEV II SULEV standard as described above. For the GM Volt, no high power starts were assumed given the design of the vehicle which effectively precludes such operation. As seen in the figures, estimated daily emissions from the GM Volt are approximately 25% of those from a conventional vehicle due largely to the significantly fewer trips per day where the engine starts. For the Ford and Toyota blended PHEVs, the distribution of high power starts in each soak region was estimated from Figure 7 above. The figures show reduced running emissions due to the portion of miles driven electrically on these PHEVs. However, the increase in start emissions from high power starts results in total daily emissions that can be

equal to or even higher than conventional vehicles. For the Ford PHEV, it should also be noted that additional estimates had to be made to adjust the number of starts per day and distribution of soak times given a data logging anomaly that caused very short trips to not be logged. Further details of this anomaly are provided in Appendix G.

**Figure 8 - Estimated Daily Tailpipe HC+NOx Emissions**

However, significant further analysis needs to be done to validate these estimates. An update of emission factors is underway which will be incorporated into a future version of ARB's EMFAC vehicle emission inventory model. More data is needed to determine the distribution between hot and cold starts and the relative emission levels as the higher emissions from high-power starts appears to be most prominent on cold starts. Further, this data represents first generation blended PHEVs that may not be representative of future PHEVs in terms of starts per day, distribution of soak times, or frequency of high power starts. As more capable PHEVs with longer electric range and higher electric only power capabilities are introduced, fewer overall engine starts would be expected and, as the GM Volt analysis shows, this can result in much lower criteria pollutant emissions. On the other hand, the introduction of PHEV architectures on larger and heavier vehicle platforms could, directionally, reduce the electric range and power levels that can be met without the engine resulting in a significant number of engine starts still occurring each day.

Staff has also begun discussions with the vehicle manufacturers to discuss emission control strategies and alternatives that may provide for more robust emission control in these conditions. At a minimum, additional effort by manufacturers could be used to ensure start-up strategies used to accelerate catalyst light-off are enabled under as broad of starting conditions as possible to mitigate the initial burst of emissions before the catalyst achieves light-off.
temperature. Additional control measures could include design considerations for sizing and location of close-coupled catalysts, or the use of additional aftertreatment controls such as hydrocarbon adsorbers, or electrically-heated catalysts to further reduce initial engine start emissions. Engine start strategy modifications might also be used to start the engine slightly earlier to provide additional time for the catalyst to warm-up before high power or torque demand in a high power start condition. Staff plans to continue to study this area and work with vehicle manufacturers to ensure any adverse impacts are eliminated or minimized on future vehicles.

VI. Summary
The testing confirms that cold-start emissions can be significantly higher under high-power demand conditions relative to more traditional engine start conditions however the cumulative impact on emissions from this fraction of starts has not yet been determined. Staff will continue to bring additional vehicles into the lab to conduct further testing and, as noted earlier, has begun discussions with the vehicle manufacturers to discuss emission control strategies and alternatives that may provide for more robust emission control in these conditions. It is also important to note that all of the vehicles tested are first generation PHEVs and most manufacturers are expected to introduce more capable second generation PHEVs. To the extent future blended PHEVs have stronger electric propulsion systems and longer range, they should be able to reduce the frequency of trips with an engine start including those with a high-power engine start. As one example, the Toyota Prius Prime is Toyota’s second generation PHEV and is designed to primarily operate as a non-blended PHEV, thereby eliminating all high-power engine starts. However, as more manufacturers enter the PHEV market and PHEVs are introduced on larger and heavier vehicle platforms, blended PHEVs will likely continue to play a significant role and warrant continued evaluation to ensure in-use start emissions are controlled as robustly as possible.
VII. References


California's Advanced Clean Cars Midterm Review

Appendix I: Alternative Credits for Zero Emission Vehicles and Plug-in Hybrid Electric Vehicles

January 18, 2017
I. Introduction
In 2012, the California Air Resources Board (ARB or the Board) adopted the Advanced Clean Cars (ACC) program, including increased requirements for the zero emission vehicle (ZEV) regulation), and directed staff in Resolution 12-11 to study “in-use data for range extended battery electric vehicles and plug-in hybrid electric vehicles, and, if warranted, propose appropriate modifications to treatment and credits for these vehicle types”. Appendix G describes in detail the in-use trip level vehicle data collected from various plug-in hybrid electric vehicles (PHEV), battery electric vehicles (BEV), and range extended BEVs (BEVx). This appendix will explore various crediting methods for PHEVs and BEVxs using the results from the Appendix G analysis.

I.A. Findings
Staff’s alternative credit cases have relatively the same trend line when compared to the credit system in the current regulation. In general, BEVs would continue to earn more credits than PHEVs. In some of the alternative cases, vehicles (both BEV and PHEV) would earn more credits, meaning that, without being coupled with a corresponding increase to the overall stringency of the regulation, manufacturers would be required to produce fewer vehicles to meet the regulatory credit obligation. In general, it is in the best interest of ARB to maintain a stable foundation for crediting these vehicles rather than shift to credit structures based on usage, which is inherently dynamic. Therefore, staff does not recommend to base credits for BEVs and PHEVs on in-use averages from historical vehicles. One alternative that did appeal to staff is Alternative 6, basing vehicle credit on “label” range, as opposed to urban dynamometer drive schedule (UDDS) test electric range. This alternative may help reduce the total number of credits per vehicle, while still crediting vehicles based on what matters to consumers.

II. Credits for PHEVs, BEVs, and BEVxs

II.A. 2009-2017 Model Year Credits: PHEV
Credits for PHEVs prior to 2018 model year are a combination of “allowances”. First, a partial zero-emission vehicle (PZEV) allowance of 0.2 is earned for a vehicle meeting super-ultra-low-emission (SULEV) emission standard under the Low-Emission Vehicle (LEV) regulation, and a zero evaporative emissions requirement, and offering a 15-year/150,000 mile emission system warranty, and offering a 10-year/150,000 mile battery warranty. Second, PHEVs qualify for a zero-emission vehicle miles traveled (zero-emission VMT) allowance, calculated from the vehicle’s equivalent all electric range (EAER) and utility factor (UF). Lastly, PHEVs qualify for an advanced componentry allowance, which is a list of additional criteria related to the vehicle’s

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2 Vehicle can certify to SULEV 20 or 30 exhaust emission standard (CCR 1961.2(a)(a) or 1961(a)(1).
3 CCR 1962.1(c)(2) “Baseline PZEV Allowance”
power, performance, and ability to complete either the urban dynamometer drive schedule (UDDS) or US06 drive schedule for 10 miles in all-electric mode.5,6

Listed below in Table 1 are the previously and currently certified PHEVs (that qualify as a transitional zero emission vehicle, or TZEV7) and the corresponding credits earned by the vehicle for the model year listed. Assuming the vehicles remain unchanged, these PHEVs will continue to earn this same amount of credit through the 2017 model year if delivered for sale in California or the Section 177 ZEV states.8

Table 1 - Current credit values for certified TZEVs

<table>
<thead>
<tr>
<th>Model year</th>
<th>Model</th>
<th>PZEV Allowance</th>
<th>Zero-Emission VMT Allowance</th>
<th>Advanced Componentry Allowance</th>
<th>Total Credit</th>
</tr>
</thead>
<tbody>
<tr>
<td>15</td>
<td>*Toyota Prius PHEV</td>
<td>0.2</td>
<td>0.83</td>
<td>0.35 Type E</td>
<td>1.38</td>
</tr>
<tr>
<td>14</td>
<td>*Honda Accord PHEV</td>
<td>0.2</td>
<td>1.052</td>
<td>0.67 (Type F12–14)</td>
<td>1.922</td>
</tr>
<tr>
<td>15</td>
<td>Ford C-Max Energi</td>
<td>0.2</td>
<td>1.27</td>
<td>0.57 (Type F)</td>
<td>2.04</td>
</tr>
<tr>
<td>15</td>
<td>Ford Fusion Energi</td>
<td>0.2</td>
<td>1.27</td>
<td>0.57 (Type F)</td>
<td>2.04</td>
</tr>
<tr>
<td>15</td>
<td>Chevrolet Volt</td>
<td>0.2</td>
<td>1.39</td>
<td>0.8 (Type G)</td>
<td>2.39</td>
</tr>
<tr>
<td>15</td>
<td>Mercedes S550E</td>
<td>0.2</td>
<td>1</td>
<td>0.57 (Type F)</td>
<td>1.77</td>
</tr>
<tr>
<td>15</td>
<td>Cadillac ELR</td>
<td>0.2</td>
<td>1.39</td>
<td>0.8 (Type G)</td>
<td>2.39</td>
</tr>
</tbody>
</table>

*Models have been discontinued or are being replaced with other models

II.B. 2009-2017 Model Year Credits: BEV
Through 2017 model year, a BEV earns credit according to its certified UDDS all electric range (AER) and its ability to completely charge or exchange the vehicle’s battery pack9 in under 15 minutes. Vehicle credits are binned into “types” according to the vehicle’s range and fast refueling capability, as shown in Table 2 below for 2015 through 2017 model years.

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5 CCR 1962.1 (c)(4) “PZEV Allowance for Advanced ZEV Componentry”
6 Note that PHEVs must have 20 miles all-electric range to receive a rebate from California’s Clean Vehicle Rebate Program, beginning November 1, 2016. More information can be found at the following website: https://cleanvehiclerebate.org/eng/eligibility-guidelines
7 PHEVs are referred to as transitional zero-emission vehicles (TZEV) in the ZEV regulation (California Code of Regulations or CCR 1962.1 and 1962.2). PHEVs do not have to certify as a TZEV to be sold in California, but must certify as a TZEV to earn credit in the ZEV regulation. For this document, PHEVs and TZEVs are one and the same.
8 Section 177 of the Clean Air Act allows other states to adopt California’s regulations. Nine states have adopted California’s ZEV regulation: Connecticut, Maine, Maryland, Massachusetts, New Jersey, New York, Oregon, Rhode Island, and Vermont. These states are referred to as Section 177 ZEV states.
9 In 2013, the Board approved battery swaps (when accurately demonstrated to the Executive Officer and documented) to qualify under the definition of “fast refueling capable” under Type III, Type IV, and Type V ZEV Credits. Access the following link for documents related to this rulemaking: http://www.arb.ca.gov/regact/2013/zev2013/zev2013.htm
Table 2 - 2015-2017 credit values for BEVs

<table>
<thead>
<tr>
<th>Type</th>
<th>Range Qualification</th>
<th>Credit (2015-2017)</th>
<th>Examples</th>
</tr>
</thead>
<tbody>
<tr>
<td>Type 0</td>
<td>&lt;50 miles</td>
<td>1</td>
<td>n/a</td>
</tr>
<tr>
<td>Type I</td>
<td>&gt;50, &lt;75 miles</td>
<td>2</td>
<td></td>
</tr>
<tr>
<td>Type I.5</td>
<td>&gt;75, &lt;100 miles</td>
<td>2.5</td>
<td>Mitsubishi i-MiEV</td>
</tr>
<tr>
<td>Type II</td>
<td>≥100 miles</td>
<td>3</td>
<td>Fiat 500e, Nissan Leaf, Chevy Spark EV, BMW i3, Ford Focus EV, Kia Soul EV</td>
</tr>
<tr>
<td>Type III*</td>
<td>≥100 miles + fast refueling</td>
<td>4</td>
<td></td>
</tr>
<tr>
<td>Type IV</td>
<td>≥200 miles + fast refueling</td>
<td>5</td>
<td></td>
</tr>
<tr>
<td>Type V</td>
<td>≥300 miles + fast refueling</td>
<td>9</td>
<td>Tesla Model X, Model S</td>
</tr>
</tbody>
</table>

*Vehicles can qualify as a Type III through either definition listed

II.C. 2009-2017 Model Year Credits: BEVx

The BEVx was a vehicle category added in the 2012 ACC rulemaking for the ZEV regulation. The following description from the 2011 Initial Statement of Reasons (ISOR) explains the purpose of the vehicle category:

“The proposed vehicle is closer to a BEV than to a PHEV: a vehicle with primarily zero-emission operation equipped with a small non-ZEV fuel auxiliary power unit (APU) for limited range extension. Manufacturers proposing this type of vehicle describe it as having reduced performance while operating in APU mode that allows drivers to find a charging location, and discouraging non-zero-emission driving. Most of these vehicles are expected to have a zero-emission range of 80 miles or greater. This vehicle has substantially more range than currently announced PHEVs, with electric range comparable to full function BEVs and will probably require ground-up BEV design. Manufacturers believe that the APU will be a relatively high-cost option on top of an existing, full function (100+ mile), BEV.”

BEVxs are treated similarly to BEVs, in that they earn credit according to the vehicle’s UDDS AER per the same schedule as BEVs, but are not allowed to meet more than half of the portion of a manufacturer’s requirement that must be met with credits from pure ZEVs. Currently, there is only one certified BEVx, the BMW i3 REX. And like the BMW i3, it earns 3 credits per vehicle.

II.D. 2018 and subsequent model year credits: PHEV

In 2012, the Board adopted a simplified credit system for PHEVs for 2018 and subsequent model years. In general, the simplifications targeted a reduction in per vehicle credits to a level of approximately half of the previous credit levels and much simpler criteria for determining the credits. First, in order to even be eligible for credit under the ZEV regulation, PHEVs must have a minimum of 10 miles AER on the UDDS test cycle, meet the SULEV30 or lower emission standard, meet the zero evaporative emissions standard, and carry the same long-term

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emission system and battery warranties that earlier PHEVs were required to have. Second, instead of combining a series of allowances, credits are based on the vehicle’s EAER on the UDDS test cycle, and awarded according to the follow calculation:

\[ \frac{EAER_{UDDS}}{100} + 0.3 \]

For PHEVs that are able to meet the higher speeds and accelerations of the US06 test cycle for at least 10 miles in all electric mode (without the engine turning on), an additional 0.2 credits is given.

\[ \frac{EAER_{UDDS}}{100} + 0.3 + 0.2 \]

The formulas above resulted in credit levels per PHEV that were approximately half of what they were under the pre-2018 model year formulas and were based on a linear format that did not rely on more complicated non-linear fleet utility fraction calculations. For the US06 capable PHEVs, the additional 0.2 in the calculation was recognition that, while such PHEVs had not yet been produced and studied, there was an expectation that they would be used in a manner more similar to BEVs and thus, credited on the exact same formula as BEVs. However, PHEVs are only allowed to earn up to a maximum of 1.3 credits per vehicle, and therefore are not provided additional credit for ranges greater than 80 miles EAER. Additionally, with the exception of intermediate volume manufacturers, PHEVs are only allowed to be used to fulfill a portion of a manufacturer’s annual ZEV credit requirement.

II.E. 2018 and subsequent model year credits: ZEV and BEVx

Also as part of the 2012 ACC amendments, the Board simplified the credit structure for ZEVs and BEVxs. As noted above, simplifications targeted an approximate 50 percent reduction in the credits per ZEV and a linear relationship between an expected minimum 50 mile range ZEV earning 1.0 credits and an expected maximum 350 mile range ZEV earning 4.0 credits. Credits are linearly based on the vehicle’s UDDS test range, according to the following equation:

\[ \frac{EAER_{UDDS}}{100} + 0.5 \]

As adopted, US06 capable PHEVs, BEVxs, and BEVs use the same formula for credits. ZEVs are allowed to earn up to a maximum of 4 credits per vehicle, and therefore are not provided additional credit for ranges greater than 350 miles UDDS test range. Consistent with the pre-2018 requirements, BEVxs are only allowed to fulfill a portion of the manufacturer’s annual pure ZEV requirement.

III. Stakeholder requests for review of the current credit structure

Starting with public comments during the 2013 amendments to the Board, manufacturers (notably, Honda, Toyota, Ford, and General Motors) requested (both in front of the Board and

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11 CCR 1962.2 (c)(2)(A) through (D) “TZEV Requirements”
during meetings with staff) that staff be directed to study the electric vehicle miles traveled from PHEVs as compared to BEVs. The United States Departments of Energy (U.S. DOE) sponsored a data collection project on thousands of early plug-in electric vehicle drivers throughout the U.S. from 2012 through 2014, which was called the EV project. For a complete description of the EV Project, see Appendix G. Manufacturer comments asserted that according to EV Project data, “[General Motors] Volt drivers [drove] nearly 40% more zero-emission miles than [Nissan] Leaf drivers” and that staff should review and update credits for TZEVs and ZEVs. In 2014, Idaho National Laboratory (INL) staff presented to the Board an analysis of EV Project data, as well as additional data from Ford, Toyota, and Honda on electric vehicle miles traveled (eVMT). The manufacturers took the INL analysis for their 2014 proposal to make PHEV and BEV credits equivalent (and increase the portion of the requirement that manufacturers could meet with credits from PHEVs). Since 2014, manufacturers have submitted the same trip level data (as well as additional data and data from other manufacturers) for ARB to analyze.

IV. Alternative Credit Structures

Staff analyzed cumulative and trip level data from seven manufacturers for eleven different plug-in electric vehicle (PEV) models. For each vehicle, staff calculated each vehicle’s annual vehicle miles travelled (VMT), annual electric VMT (eVMT), and zero-emission VMT (zVMT), which are summarized in Table 3 below.

<table>
<thead>
<tr>
<th>Type of Vehicle</th>
<th>VMT - Mean</th>
<th>eVMT - Mean</th>
<th>zVMT - Mean</th>
</tr>
</thead>
<tbody>
<tr>
<td>Toyota Prius (PHEV)</td>
<td>15,283</td>
<td>2,304</td>
<td>589</td>
</tr>
<tr>
<td>Honda Accord (PHEV)</td>
<td>15,221</td>
<td>3,246</td>
<td>1,471</td>
</tr>
<tr>
<td>Ford C-Max Energi (PHEV)</td>
<td>13,920</td>
<td>4,574</td>
<td>2,525</td>
</tr>
<tr>
<td>Ford Fusion Energi (PHEV)</td>
<td>15,076</td>
<td>4,776</td>
<td>2,368</td>
</tr>
<tr>
<td>Chevrolet Volt (PHEV)</td>
<td>12,403</td>
<td>7,442</td>
<td>5,829</td>
</tr>
<tr>
<td>BMW i3 (BEVx)</td>
<td>9,063</td>
<td>8,387</td>
<td>N/A</td>
</tr>
<tr>
<td>BMW i3 (BEV)</td>
<td>7,916</td>
<td>7,916</td>
<td>7,916</td>
</tr>
<tr>
<td>Ford Focus Electric (BEV)</td>
<td>9,741</td>
<td>9,741</td>
<td>9,741</td>
</tr>
<tr>
<td>Honda Fit (BEV)</td>
<td>9,789</td>
<td>9,789</td>
<td>9,789</td>
</tr>
<tr>
<td>Nissan Leaf (BEV)</td>
<td>10,294</td>
<td>10,294</td>
<td>10,294</td>
</tr>
<tr>
<td>Tesla Model S (BEV)</td>
<td>13,494</td>
<td>13,494</td>
<td>13,494</td>
</tr>
</tbody>
</table>

13 See Appendix G for complete staff analysis of OEM provided trip level data.
For the Appendix G analyses, General Motors provided data from Volts participating in DOE’s EV Project. According to this data, total Volt VMT is ~12,400 on average, eVMT is approximately 9,000 (72%), and zVMT is ~7,300 (59%). However, these EV Project numbers may not be representative of later generation (and current) Volt eVMT and zVMT. According to a General Motor’s press release, Volts drive 60% of their miles on grid-powered energy.\(^{14}\) This could be due to the fact that EV Project participants were early adopters and were given no-cost Level 2 charging.\(^{15}\) Therefore, for the purposes of this appendix, staff adjusted the Volt eVMT number to 7,442 (60%), and assuming eVMT tracks with zVMT, the adjusted zVMT is 5,829 (47%).

The definition of eVMT is miles attributed to grid energy. For blended PHEVs where, by design, the gasoline-powered engine and the grid energy powered electric drive system can simultaneously be used to propel the vehicle, eVMT includes the portion of these blended miles that are attributed to grid energy. Generally, staff has found that eVMT is a good indicator of a vehicle’s greenhouse gas (GHG) benefit. However, eVMT does not appear to accurately represent the criteria pollutant (e.g., hydrocarbons, oxides of nitrogen) benefits. To capture the criteria pollutant benefits of the vehicles, staff analyzed electric only trips (e-trips) which are trips where the internal combustion engine (ICE) did not start at any time during the trip. Additionally, staff looked at zVMT which is the cumulative miles attributed to e-trips.\(^{16}\) These three metrics will be explored in each of the alternative credit scenarios below.

### IV.A. Alternative 1: Electric and Zero-Emission Miles Based

The first alternative would be a simple credit structure, based solely on the average eVMT and zVMT (miles). A scaling factor is proposed to convert the annual miles to a per vehicle credit value that is in the range of approximately +/- 1.0 credits to ensure this credit structure could fit with the existing regulation requirements. Staff created the following credit equation for these alternatives:

**Alternative 1 (a)**

\[
Credit = \frac{(eVMT)}{10,000}
\]

**Alternative 1 (b)**

\[
Credit = \frac{(zVMT)}{10,000}
\]

This alternative credit structure would result in all vehicles earning significantly less credits than the current credit structure as depicted in Figure 1 and Figure 2. It is also clear under this credit structure that BEVs with similar test AER would earn different credits based on driving patterns of previous drivers (of possibly different vehicle models). The most negatively impacted by this type of credit structure would be longer range BEVs which have an appeal to the growing PEV market, but are only driven so far.

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\(^{15}\) For complete description of United States Department of Energy (U.S. DOE) EV Project, see Appendix G.

\(^{16}\) For complete description of how each of these metrics were calculated, see Appendix G.
VI.B. Alternative 2: Credit normalized to Nissan Leaf eVMT vs. PHEV eVMT (miles)

The first alternative scenario looks at PHEV eVMT (in terms of actual or absolute miles) compared to annual average Nissan Leaf eVMT (which is in every case equal to its VMT). The Leaf was chosen as a comparison vehicles since it is a representative 100-mile (certified UDDS range) BEV with the highest sales volume, and was the largest set of trip data for BEVs that
staff was able to analyze. Additionally, as stated above, manufacturers have made similar comparisons between their PHEVs and Leafs.

The following equation was used to calculate this alternative scenario:

\[
Credit = 1.77 \times \frac{eVMT}{Leaf\ eVMT}
\]

Where, 1.77 is equal to what the 2015 model year Leaf would earn for credits according to the adopted 2018 and subsequent model year regulation, and based on its certified UDDS range for 2015 model year, and where Leaf eVMT is equal to 10,294 miles.

This alternative shows how PHEVs (and other BEVs) stack up against the Leaf in terms of eVMT derived from staff’s analysis. Each PHEV (and BEV) is earning a percentage of what a Leaf earns, based on the vehicle’s eVMT.

This credit alternative would slightly bring PHEV credit values closer to ZEV credit values. As shown in Figure 3 below, this credit scenario raises the number of credits for most PHEVs. The exception to this would be the Toyota Prius which loses 0.07 credits. BEVs, dependent on their VMT would lose credit value, though many of the BEV models analyzed have similar AER. The Model S would lose the most from the current credit calculation (40% loss), but would still earn ~30% more than the Leaf.

**Figure 3 - Alternative 2: Credits based on % eVMT vs Leaf**

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17 2015 model year Nissan Leaf: 127 certified UDDS AER
VI.C. Alternative 3: Credit normalized to Leaf zVMT vs. PHEV zVMT (miles)

Sticking with the Leaf as the credit baseline, the next alternative shows PHEVs compared in terms of each vehicle’s zVMT, which is a better indicator of its criteria pollutant benefit rather than its GHG benefit (i.e., eVMT). As with Alternative 2, the eVMT, zVMT, and VMT are all equal for BEVs, and therefore are not shown in this alternative.

The equation used for this alternative is the same as the Alternative 2, but replaces eVMT with zVMT, as shown below:

\[ \text{Credit} = 1.77 \times \frac{z\text{VMT}}{\text{Leaf } z\text{VMT}} \]

Where 1.77 is equal to the current Leaf credit, calculated according to the 2018 and subsequent model year currently written in the regulation, based on its certified UDDS range for 2015 model year. The Leaf zVMT is equal to 10,294 miles.

This credit alternative shows how PHEVs measure up against the Leaf in terms of zVMT. Each PHEV is earning a percentage of what a Leaf earns, based on the vehicle’s zVMT. As shown in Figure 4 below, this credit scenario reduces the number of credits for all of the PHEVs. The Toyota Prius would lose the greatest amount of credits (~80%). However, the Chevrolet Volt would earn approximately the same amount of credits as the current credit structure.

**Figure 4 - Alternative 3: Credits based on % of zVMT vs Leaf**
**VI.D. Alternative 4: Credit normalized to Tesla eVMT and zVMT vs. PHEV eVMT (miles)**

Given the analysis is intended to look at credit alternatives for future model years (2018 or later), Alternative 4 (a) uses a BEV that is more representative of the electric range of BEVs staff expects to see emerging over the next several model years: the greater than 200 mile Tesla Model S. The same general equation was used; however, the credit used in the equation is equal to what Tesla would earn in 2018 and subsequent model years, and the denominator for the equation changes to Tesla’s annual average VMT. The equation for this alternative is shown below:

$$Credit = 3.91 \times \frac{eVMT}{Model\ S\ VMT}$$

Where, 3.91 is equal to Tesla Model S credit, calculated according to the 2018 and subsequent model year currently written in the regulation, and based on its certified UDDS range for 2015 model year,\(^{18}\) and where Tesla Model S eVMT is equal to 13,494 miles.

All PHEVs would see a significant increase in credit under this alternative. BEVs would also earn more credit, since certified range does not necessarily correlate with VMT. In particular, the Leaf would earn 2.98 credits under this case, which is almost double what it would earn under the current credit structure for BEVs. Doubling credits for a shorter range vehicle creates less incentive to make a longer range vehicle. This also means that manufacturers can meet their current credit requirement with fewer cars.

Staff also compared vehicles on the basis of zVMT with the Model S. The equation for this slight variation is shown below:

$$Credit = 3.91 \times \frac{zVMT}{Model\ S\ VMT}$$

As expected, credits are higher for BEVs and PHEVs when credits are based on zVMT and compared to the Model S because the number the percent zVMT is being multiplied by is higher. However, raising the amount of credit for all vehicles does not necessarily change the relationship between the technologies. BEVs (particularly 100 mile range BEVs) are earning more than PHEVs, though some of the gap is filled. But fewer vehicles could be expected without a subsequent raising of the entire ZEV requirement if all vehicles earn more credit.

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\(^{18}\) 2015 model year Model S: 328 certified UDDS AER
VI.E. Alternative 5: Credits based on eVMT and zVMT normalized to ICE VMT

Instead of comparing to a BEV, another way to credit both BEVs and PHEVs would be to compare to typical conventional ICE car VMT. This could be a way to credit vehicles based on their ability to be a full replacement for an ICE vehicle. As VMT also decreases with each year a vehicle gets older, the average VMT for the first five years of age is used for the ICE VMT data, because this compares well with the average age of vehicle data given to ARB to analyze for various PEVs. The five year average for ICE VMT is 14,598 miles. The following equations were developed for this alternative credit structure:

\[
\text{Credit} = 4 \times \frac{eVMT}{ICE\ VMT}
\]

\[
\text{Credit} = 4 \times \frac{zVMT}{ICE\ VMT}
\]

Where, 4 is equal to maximum number of credit earned by any vehicle,

Where, ICE VMT is equal to 14,598 miles.

All BEVs would see a credit boost except the Tesla Model S, which would earn slightly less credit. What is interesting about this credit structure is that it results in lower range BEVs
becoming much closer in credits to long range BEVs than the current structure based on the vehicle’s all electric range. All PHEVs would also see increased credits when using eVMT. However, when considering PHEV zVMT, longer range PHEVs would receive more credit, but lower range PHEVs would receive less credit.

Figure 6 - Alternative 5: Credits based on eVMT and zVMT normalized to ICE VMT (5 year average)

VI.F. Alternative 6: Current ZEV credit scheme using EPA label range
The last alternative credit structure considered was using EPA label range instead of UDDS range. UDDS is a drive cycle that only represents city (urban) driving and is the primary cycle used for criteria pollutant emission testing. EPA label range represents the approximate number of miles that can be travelled in combined city and highway driving. EPA label range is based on the UDDS cycle plus several others that incorporate higher speeds and accelerations as well as colder and hotter weather conditions. While conventional cars use 5-cycle testing to determine their label values, electric vehicles determine their label values slightly differently. PEVs are able to do 2-cycle testing (also known as the UDDS and highway cycles) and multiply it by 0.7 to determine their label range (instead of the additional three cycles to determine their full 5-cycle weighted range). A direct substitution of the EPA label range for the UDDS certification number could utilize the same credit equation as what is currently in the regulation for PHEVs and BEVs but would directionally lower the credits for all

cars (as the EPA label range is always shorter than the UDDS cycle range). This approach would also have the benefit of using a range value that is more commonly available in the public domain as the label ranges are widely disclosed while UDDS ranges are typically only reported in certification documentation submitted to ARB and U.S. EPA.

Figure 7 - Alternative 6: EPA label range vs. UDDS based credits

Overall, the credits would decrease per vehicle because a vehicle’s EPA label EAER range is lower than its UDDS EAER. BEVs would see the most significant reduction in credit losing proportionally more credit than PHEVs. However, this could increase the number of vehicles to be delivered from each OEM because each vehicle would be generating less credit.

VI.G. Alternative 7: Other Credit Structures

Staff has been asked to also consider crediting vehicles based on various other factors such as total battery pack kilowatt hours (kWh), footprint, utility, etc. Staff has not developed a specific proposal to evaluate the effect of any of these factors on the overall credit structure. Directionally, however, these factors are not based on any analysis of how the vehicle performs or is used, but rather rewards attributes of the vehicle such as technical content or perceived consumer utility.

For instance, basing credit on battery size rewards the volume of a particular component (like battery cells) which could, theoretically, help promote high volumes to bring down cost. And such structures have been considered and even utilized in past ZEV credit structures (e.g., advanced technology partial zero-emission vehicles (AT PZEV) earned additional ZEV credits based on defined technical components being included on the vehicle). However, such metrics generally ignore how efficiently those components are being used in each vehicle (e.g., two similar sized cars with similar electric range but with one being much less energy efficient and thus, requiring a larger battery pack, would be rewarded with additional credits for its inefficiency). Further, the current credit process based on electric range largely achieves much
of the same effect in that manufacturers are adding battery capacity to increase the range and thus, earn more credits. Lastly, the current and projected sales volumes for ZEVs in CA (and the Section 177 ZEV states) represent only a portion of the global sales volumes for ZEVs. Accordingly, an adjustment to the ZEV credit structure would likely have less effect on helping push volumes to appreciably higher levels than the global market is already demanding.

Regarding credit structures that would base credits on vehicle attributes such as size of the vehicle, footprint of the vehicle, market segment of the vehicle, or other measures of vehicle utility such as seating capacity, interior volume, or cargo capacity, there is even less nexus connecting these attributes to the performance of the ZEV. Supporters suggest that such an approach would better ensure a wider range of product offerings that would appeal to a larger segment of the new car buyers. Directionally, staff agrees that broader offerings could help build the ZEV market. However, even under the current credit structure, manufacturers have created and announced upcoming product offerings within the next five years in nearly every vehicle segment with a variety of vehicle configurations. While it is true that a larger share of these offerings are in the small and midsize car and small sport utility vehicle segments, these three segments make up over 75% of all new vehicle sales in California and is exactly the market segments ZEV need to be in to achieve significantly higher volumes. Given the 300 to 400 or more models (and over 1,300 unique variants within those models) offered for sale every year in California, it does not appear feasible to define a few key vehicle attributes for the credit structure that correctly identify the utility or features that ensure broad appeal of the vehicle.

VII. Conclusion and summary
Each of these alternative credit cases has relatively the same trend line when compared to the current credit structure. In general, a 100 mile (UDDS) BEVs would continue to earn more than PHEVs. In some of the alternatives, all vehicles (both BEV and PHEV) would earn more credits, meaning that, without being coupled with a corresponding increase to the overall stringency of the regulation, manufacturers would be required to produce fewer vehicles to meet the regulatory credit obligation. This would be the opposite direction the Board has indicated it wants the regulation to go in. The Board has stated its interest in providing more certainty to vehicle volumes, rather than more credits per vehicle.20

All of these cases are based on analyses of different metrics quantifying how current PHEVs are being operated. Unfortunately, these metrics are ever-changing numbers, based on consumer’s charging and usage patterns. These numbers are dynamic and will change over time because vehicle offerings and technology are rapidly changing, which means vehicle credits could go up or down based on consumer driving habits, energy prices, vehicle range, infrastructure availability, etc. It is in the best interest of the OEMs and ARB to maintain a stable foundation for crediting these vehicles rather than propose a credit structure based on usage, which is inherently dynamic.

Lastly, consumers value range. In a 2015 survey of PEV drivers, among those responding they would replace their PEV with a PHEV, current PHEV drivers indicate an average desired all-electric range of 40-50 miles while almost all current BEV drivers indicate a range of around 80 miles.\textsuperscript{21,22} For a mandate structure, ZEV regulation credits being based on range is appropriate since that structure values what the consumer values. Other ARB and EPA fleet average regulations appropriately credit PHEVs on their environmental benefits.

It is important to point out that the list of above alternative is not all inclusive, nor have these alternative structures been evaluated for economic or environmental impacts. In any future rulemaking process, staff will continue to meet with stakeholders to discuss various credit alternatives, and receive input on improving the regulation in future years.

\textsuperscript{21} See Appendix B, Section VII for a description of the CVRP Consumer survey results.
\textsuperscript{22} See Appendix B for complete description and analysis of consumer attitudes towards ZEVs and PHEVs.
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I. Introduction

PM emissions from light- and medium-duty vehicles are regulated as part of the Low-Emission Vehicle (LEV) program. Under LEV III, the PM standard for passenger cars, light-duty trucks, and medium-duty passenger vehicles was initially lowered from 10 mg/mi to 3 mg/mi over a phase-in period from 2017 through 2021 model year vehicles. Ultimately, with a phase-in spanning 2025 through 2028 model years, the 1 mg/mi PM standard will further reduce the health impacts of PM and will help ensure the continued development of low-PM engine technology. Both standards were phased in to provide flexibility.

The need to simultaneously lower GHG and criteria emissions, including PM, is driving significant innovation in gasoline engines with gasoline direct injection (GDI) likely to be a key technology. While GDI is a very important technology for reducing tailpipe CO2 emissions, it does come with the potential to increase PM emissions compared to conventional port fuel injection (PFI) systems. Data on PM emissions from production vehicles in the 2011 time frame using PFI and GDI technology from a study by Delphi Powertrain Systems suggests that, directionally, PM mass emissions from GDI systems are higher than PFI systems as shown in Figure 1 below.

![Figure 1 - Vehicle emission measured on EURO 4 production vehicles](image)

Mitigation of the impact of PM emissions on public health is of paramount concern to ARB. Given the expected continued trend in increased GDI system usage and the potential for

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increased PM emissions as a result, the Board adopted the 3 and 1 mg/mi standards to ensure continued progress towards reducing PM emissions from all sources in California. While the staff demonstrated the feasibility of meeting the 1 mg/mi standard at the time of adoption, the Board also recognized there is a significant technical challenge and manufacturer resource challenge to meet the 1 mg/mi standard while also reducing GHG emissions and fleet average emissions to a LEV III SULEV30 emission level. Consequently, the Board directed staff at the board hearing in 2012 to re-evaluate the measurement feasibility, the technical feasibility, and the timing of the 1 mg/mi PM standard.

In September 2015, ARB, in collaboration with the U.S. EPA, industry, and other stakeholders, presented the findings of an extensive study that evaluated the feasibility of measuring PM emissions at the levels required to comply with the LEV III 1 mg/mi standard. Several of these studies were focused on investigating concerns regarding the limitation of the gravimetric measurement method that has been historically used in vehicle testing to determine PM mass. From the study, ARB staff concluded that the gravimetric method specified for vehicle emission testing in 40 Code of Federal Regulations (CFR) Part 1065/1066 is suitable for measuring PM mass emissions at the sub 1 mg/mi level. While the measurement review included evaluation of alternative measurement metrics including PMP based SPN and black carbon, the findings supported the gravimetric method as the most appropriate metric for controlling PM in California. This conclusion was based on evaluations of the potential sources of measurement variability, determination of the PM measurement precision, and a comparison of collocated measurements of selected sampling options described in 40 CFR Part 1066.

To assess the technical feasibility of the 1 mg/mi PM standard, ARB staff re-examined the status of PM emission control by testing current vehicles as well as updating staff’s assessment of current and future PM control strategies and technologies. ARB conducted tests to determine PM emissions and composition from currently available vehicles using engine technologies most representative of future vehicles which is described in Appendix K. This appendix provides a review of PM formation, the effects of GDI technology on PM and a control technology evaluation based on literature review and meetings with OEMs, suppliers, and PM control experts.

Overall, test results and updated technology evaluation support staff’s original assessment that the 1 mg/mi standards are technically challenging but achievable by 2025 at very low to no cost. Advances to in-cylinder PM control facilitated by improved engine and fuel injection systems have substantially reduced PM emissions on newly re-designed engines. Given the available lead time, manufacturers can use the knowledge they gain from in-use operation of the current generation of engines to redesign subsequent engines to meet the 1 mg/mi standard in the 2025 time period. In cases where more flexibility is needed for particularly challenging engines, the additional cost of a gasoline particulate filter (GPF) may be warranted to effectively control PM. To be most effective in-use, PM control technology needs to reduce PM emissions for all

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driving conditions including high speed transient operation and cold weather conditions. Accordingly, the need for additional PM standards and test procedures should be evaluated to ensure robust control strategies are utilized and in-use PM emissions are minimized.

I.A. General PM Formation
There are three general sources of light-duty vehicle exhaust PM emissions: lubrication oil, fuel composition, and rich combustion. Particles from these sources vary in composition and can be classified by physical state as volatile, semi-volatile, and solid or by their chemical composition as organic and inorganic. Inorganic particles include ash and oxides of sulfur that can only be controlled by eliminating precursors from the combustion chamber. Inorganic PM control is the same regardless of vehicle technology and so is not central to this GDI based PM control analysis. The increased PM typically associated with GDI vehicles is most commonly the result of a rich condition in the combustion chamber during a combustion event.

Organic PM includes elemental carbon particles that are in the solid phase and organic carbon which generally makes up the volatile and semi-volatile fraction of PM. The physical states of the volatile and semi-volatile compounds depend on a number of factors such as exhaust temperature, composition, vapor pressure, and concentration. Elemental carbon and organic carbon make up the majority of gravimetrically measured PM emissions and appropriately are the focus of this document.

Elemental carbon, also known as black carbon or soot, is comprised solely of carbon atoms and is the result of pyrolysis within the combustion chamber caused by a localized lack of oxygen and extreme heat and pressure. In this process, the hydrogen atoms dissociate from the carbon chain and the remaining carbon atoms form bonds with each other forming elemental carbon. Elemental carbon is the sooty, black material typically associated with older diesel car or truck exhaust, but it also often makes up between 50%-80% of PM emissions from modern GDI-equipped vehicles. The in-cylinder characteristics that affect the (Elemental Carbon/Organic Carbon) EC/OC ratio are specific to an engine’s design and the control strategy, but some generalizations can be made. Elemental carbon is generally formed in areas where fuel exists without any oxygen and combustion occurs as a diffusion flame. One of the areas that can be a large source of elemental carbon is on the injector tip. Fuel that remains on the injector tip after an injection event can turn into elemental carbon before it can evaporate because the injector is often substantially hotter than the cylinder wall or piston.

Organic carbon is formed in similar ways to elemental carbon, but it forms when there is insufficient oxygen to complete combustion. The result of incomplete combustion generally is that the most stable hydrocarbons, often aromatic rings, are not converted to CO2 and H2O. These hydrocarbons generally exit the combustion chamber in the gas phase and if they remain that way, are oxidized as they pass through the catalyst. However, some of these hydrocarbons condense onto solid particles or nucleate to form new particles before passing through the catalyst and result in organic carbon PM. Gasoline exhaust particles are often a heterogeneous particle containing both solid elemental carbon and liquid organic carbon within the same particle.
I.B. Gasoline Direct Injection - Technical Overview

A basic understanding of GDI systems is important to understand PM formation and control strategies. A more complete description of the GDI technology and technology trends can be found in the 2016 Draft Joint-Agency Technical Assessment Report (2016 TAR).\(^3\) The increased PM typically associated with GDI vehicles is the result of a rich condition in the combustion chamber during a combustion event. The rich condition can be localized or homogeneous as discussed further in the PM Formation and Controls section.

GDI injection systems have two major components that relate to PM emissions. First, the high pressure fuel pump that determines the fuel pressure at the injector, typically between 150 and 400 bar. Second, the fuel injectors themselves, which inject the pressurized fuel into the combustion chamber. The fuel pressure, injector design, and integration can have a substantial effect on PM emission rates.

Figure 2 - GDI fuel system and components\(^4\)

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II. PM Formation and Controls for GDI Vehicles

There are two paths for effective PM control from GDI equipped vehicles: in-cylinder control or the use of aftertreatment such as gasoline particulate filters (GPF). GPFs efficiently control PM for all operational modes but they do represent added hardware, at some expense, for manufacturers to integrate solely for PM control. GPFs are discussed in detail in the “Gasoline Particulate Filters (GPFs)” section, Section III. In-cylinder control is a balancing act between GHG, HC+NOX, and PM emissions. Reducing GDI PM emissions means controlling enrichment that can occur from one of three mechanisms. First, impingement and liquid droplets; this is where injected liquid fuel makes contact with the cylinder wall, piston, or injector tip, or fuel droplets do not evaporate and completely mix during an injection and combustion event. Second, areas of localized enrichment within the combustion chamber such as cases where a control strategy targets localized areas with the injection to achieve stable combustion. Third, homogenous rich combustion such as when a control strategy commands enrichment for component protection, catalyst conversion, or due to high speed transient operation. Additionally, some PM formation conditions are independent of GDI technology such as fuel and oil effects and measures to ensure those mechanisms are minimized are necessary for all vehicles to meet the 1 mg/mi future standard.

I.A. Impingement and Droplet Evaporation

Enrichment due to incomplete fuel evaporation in GDI engines occurs when fuel is impinged onto the walls of the combustion chamber, does not completely mix with the air charge, or remains on the injector tip due to coking. During the combustion event, any fuel that has not vaporized burns as a soot-forming diffusion flame that increases PM emissions.

Enrichment due to slow fuel evaporation is a function of temperature, droplet size, air speed, and time. Temperature, as it relates to fuel evaporation includes the air in the cylinder, the cylinder and piston surfaces, and the fuel. Time is affected by both injection timing, usually measured in degrees before top-dead-center, and overall engine speed. Droplet size is affected by injector design and fuel pressure. Finally, air speed is determined by intake shape, valve location, and the velocity of the fuel injected into the cylinder. Temperature, time, droplet size, and air speed are all important parameter for PM control strategies and vary under different engine operational conditions.

High torque operation generates PM emissions because the mass of fuel that must be injected into the cylinder is large, thereby increasing the chance of impingement on cylinder walls or the piston. High torque at low engine speed can generate additional PM because the piston isn’t moving away from the fuel spray as quickly as it does at high speed; however this is offset by the increased residence time the charge has to completely mix before combustion. High torque at high engine speed, resulting in high power, tends to result in increased PM emissions because the large amount of fuel that is injected does not have enough time to completely evaporate and mix resulting in localized rich areas that form PM. A subset of high torque operation is spray collapse. This is a condition where the higher pressure in the cylinder causes the injected fuel cloud to collapse onto its self after being injected and results in reduced mixing and localized rich areas within the cylinder.
High torque impingement and injection spray collapse can be exacerbated by highly boosted downsized engines because a large amount of fuel has to be injected into a relatively small, highly compressed combustion chamber.

Finally, cold starts generate more PM emissions because of slower evaporation of fuel and because of some catalyst heating strategies used to reduce light off time. Cold engine and ambient conditions inherently generate PM because of slower vaporization on cold components with colder intake air. The effects of slower evaporation are exacerbated on GDI systems that more routinely have impingement such as spray guided systems that rely on injected fuel making contact with wall or piston surfaces.

II.B. Impingement and Droplet Evaporation Control

Engineering a low PM emitting engine by eliminating rich combustion requires that PM control be simultaneously considered as manufacturers design the engine to comply with future GHG and criteria emission standards. By implementing appropriate design measures during an engine redesign, the cost to achieve good PM control can be very low. In-cylinder PM control strategies can be broken down into three main categories: fuel injection component and control improvements, and engine hardware improvements.

II.B.1. Fuel Injection System

Improvements to fuel injection hardware are central to controlling in-cylinder PM formation. Improvements can include increased fuel pressure, improved injector spray patterns, and reduced injector tip wetting. The fuel injectors on a GDI system are the heart of the injection system. The injector must accurately meter fuel as it is injected into the combustion chamber at extreme pressures. Injectors can be grouped by actuation type; solenoid vs. piezo, and injector tip type; inwardly opening vs. outwardly opening.

In a conventional solenoid configuration, the pintle is pulled away from the injector tip holes to allow fuel to spray into the combustion chamber as shown in Figure 3. Solenoid GDI injectors are less expensive, but accurately controlling fuel metering over multiple injections for PM control can be challenging.


A piezoelectric, or piezo, actuated system as shown in Figure 4, applies a current to a stack of piezos that respond by opening the conical tip of an outwardly opening injector. Piezo injectors are often used in diesel applications and are generally more expensive than solenoid injectors, but they can meter fuel very accurately over very short injection durations.

Injector tips come in two general types, inwardly opening and outwardly opening, as shown in Figure 5. Most solenoid injectors use an inwardly opening design. The first burst of fuel that sprays through the holes is not steady state and is known as the ballistic portion of the injection. This portion tends to atomize very well but because the fuel flow rate is non-linear, quantity control is challenging.

The pintle in an outwardly opening injector, as the name implies, opens outward into the combustion chamber. The conical shape of the pintle tip results in a hollow cone of fuel being injected into the combustion chamber that maximizes surface area and reduces evaporation times. Outwardly opening injector tips are often used in conjunction with piezo actuators.
II.B.1.i. Software Improvements
Manufacturers use a variety of software improvements to control PM emissions. Engine management strategies include: optimized injection timing, improved accuracy in fuel metering, and multiple injections per combustion event. These strategies reduce impingement during all operational modes, which is especially valuable during cold start when the combustion chamber is cold. Optimizing fuel evaporation time and charge mixing can be accomplished using early injection timing which increases the dwell timing in the cylinder and multiple short injections, which result in smaller droplets and more complete mixing. Multiple injections per combustion event historically decreased accuracy in fuel metering which led to some rich combustion events. However, recent improvements in injector control and feedback allow more accurate metering even with multiple injections. Multiple injections are an especially effective strategy to control impingement during high torque operation at low engine speeds.

II.B.1.ii. Fuel System Pressure
The simplest way to reduce droplet size and directionally reduce PM emissions is to increase the fuel rail pressure. Systems in production today typically run at pressures between 100 and 200 bar, with a majority of the newer systems operating in the upper portion of that range. Recent improvements to injectors and pumps have allowed fuel pressures to increase to between 300 and 400 bar. Increases in fuel pressure reduce PM emissions because the droplets are smaller, the penetration distance into the combustion chamber is similar or decreased as shown in Figure 6, and mixing is increased. Smaller droplet size increases surface to volume ratio which leads to faster evaporation. The smaller droplets also experience higher aerodynamic drag on a mass basis which makes each droplet slow down much faster and limits penetration distance to avoid impingent on cylinder or piston surfaces. The energy that is given up to the air also results in increased charge mixing. Increased fuel system pressure does come at an overall energy cost to the engine as the parasitic pump loads reduce overall engine efficiency. However, the effect is small and, in a fully optimized design, most or all of that additional load can be offset by an increased combustion rate in the engine during the combustion event, which is a result of improved air/fuel mixing and increased charge motion. In addition, increased fuel pressure and multiple injections can greatly reduce the effect of injector coking.

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7 Hoffmann, 2014.
II.B.1.iii. Injector Tip Forming

It is essential that the injected fuel spray pattern matches the combustion chamber shape to reduce impingement. Injector tip manufacturing is continually improving to achieve more control on spray shape and distance to reduce impingement and improve mixing. Given the recent emphasis on PM control caused by the near term 3 mg/mi and future 1 mg/mi standards, many promising designs are still being developed and not yet commercially available but are expected to be available for mass production in the next few years and wide-scale deployment shortly thereafter.

In a side mounted injection system, manufacturers and suppliers have learned that the spray pattern needs to be asymmetrical to minimize impingement. The best way to accomplish this is with precisely made holes at exact angles. The design of the holes in the tip of an injector can have a great effect on the spray of the fuel injected into the cylinder. The use of lasers to drill the holes allows optimized geometry including hole angle, diameter, and taper. A properly designed injector tip can result in side mounted injectors with asymmetric spray patterns as shown in Figure 7 that greatly reduce fuel impingement and improve atomization.
A second advancement is the use of counter bored holes as shown in Figure 8, which allow more accurate control of hole diameter to length ratio and fuel penetration distance.

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II.B.1.iv. Outwardly Opening Injectors
The advantage of outwardly opening injectors is reduction of injector tip coking, very good fuel mixing because the sheet of injected fuel is very thin, and lower fuel pressures, often in the 150 bar range. At this time, however, asymmetric injection is not possible with such a design so the injectors must be center mounted to maximize the benefits. Second, outwardly opening injectors are often piezo driven, which allows for very fast response times, but can significantly increase the cost for the injector and the injector control system. Some research is being conducted to drive outwardly opening injectors with conventional injector solenoids. Solenoid driven outwardly opening injectors, along with engines designed for center mount injectors, greatly reduce impingement and droplet based PM but they are not yet commercially available.

II.B.1.v. Combination PFI/GDI
A fuel injection system that uses both port and direct fuel injection can effectively control PM by behaving like a PFI vehicle for all conditions except those that require the GDI’s knock resistance characteristics. There are a variety of vehicles using this technology today including many Toyota vehicles for sale in California. Generally, the technology is added to maintain accurate fuel control for all fuel flow demands and to reduce parasitic losses from the high pressure pump, but an added benefit is PM emission characteristics similar to PFI vehicles.

II.B.1.vi. Durability of Fuel Injection Components
Degradation of fuel injection system components can lead to increased PM emissions over the useful life of vehicles. However, improvements to control strategies and improvements to injector technology including injector holes, system pressures, and harder injector tips can reduce the rate of deterioration from hole erosion or deposit formation and ensure PM control for the useful life.

II.B.2. Engine Improvements
Changes to the engine hardware can optimize injector location, improve intake air tumble, and match the combustion chamber shape to injector spray pattern to ensure a homogeneous combustion charge. These types of improvements are best done in conjunction with engine redesigns where all effects can be simultaneously evaluated. With appropriate lead time, such changes can be integrated into normally scheduled redesigns or new engine introductions and the associated design features necessary for good PM control can be incorporated for little or no cost.

II.B.2.i. Matching Spray Pattern to Combustion Chamber Shape
The combustion chamber shape must match the injector spray shape. This can be done through changes to the spray pattern as discussed above or combustion chamber shape. The piston top is the simplest and most effective way to control combustion chamber shape. Designs that allow the injection event to occur earlier while reducing liquid fuel contact will effectively reduce PM emissions.

The fuel spray pattern can be affected by injector location and injector tip design as previously discussed in the Fuel Injection System section. There are two primary fuel injector location options for GDI technology: side mounted and center mounted. In a side mounted configuration, as shown in Figure 9, the spray pattern needs to be asymmetric and the injected
fuel may use the piston bowl, the top of the piston, and the cylinder wall to help define the shape of the fuel spray. Any fuel contact with the combustion chamber walls can result in impingement and higher PM emissions. However, improved injector designs, especially with regard to modified spray patterns and multiple injections per firing event, combined with improved air flow control into the cylinder, are being utilized to reduce impingement and improve mixing. Side mounted injectors have the advantage of not interfering with the spark plug location and provide manufacturers increased flexibility in manufacturing and under hood packaging.

**Figure 9 - Side Mounted GDI Injector**\(^\text{12}\)

In a center mount configuration, as shown in Figure 10, the injector is centrally mounted and located above the piston, which is similar to a diesel engine design. This allows the use of a symmetric spray pattern, including outwardly opening injectors, which helps avoids contact with the cylinder walls and results in lower PM emissions. Center mounted systems can be more challenging to integrate and are often only able to be implemented when a whole-head redesign is being done and engine/vehicle packaging allows for it.

**Figure 10 - Center Mounted GDI Injector**\(^\text{13}\)

**II.B.2.ii. Increased Tumble**

Tumble is the term used to describe the air motion in the cylinder caused by the intake runner and valve geometry as shown in Figure 11. Tumble generally improves charge mixing which leads to quicker and more complete combustion thus reducing PM emissions as well as criteria

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\(^{13}\) GCC, 2006.
and GHG emissions. Increased tumble also helps control injector tip temperatures and reduces evaporation time of any impinged fuel. In some cases, manufacturers have resorted to variable position tumble or swirl control valves on in the intake to alter the tumble in different operating conditions but most designs rely solely on intake manifold, runner, and intake valve designs and strategies to achieve the desired flow characteristics.

**Figure 11 - Intake Air Tumble**

![Intake Air Tumble](image)

**II.B.2.iii. Thermal Management**
Thermal management is important inside the combustion chamber to ensure complete evaporation of fuel, and outside the combustion chamber to ensure that enrichment for component protection is not needed. Inside the engine, the two primary areas that need careful temperature control are the injector tip and the top of the piston. Ideally both are kept at a temperature that ensures quick evaporation without risking fuel pyrolysis. Injector tip temperature is primarily controlled through heat conduction into the head and coolant. Piston temperature is best controlled with a combination of oil squirts below the piston and the material properties of the piston itself.

Thermal management is also important to reducing the need for enrichment for component protection. Components exposed to the exhaust gas such as the exhaust valves, turbocharger (where applicable), and catalyst can indirectly lead to PM emissions when the engine goes into enrichment to reduce or avoid exhaust gas temperatures that could damage these components. The need for good emission control over all operating conditions and the increasingly stringent criteria pollutant and GHG emission standards has greatly reduced the number and duration of enrichment events for component protection during conventional driving. Manufacturers are designing systems to be more robust and avoid the need for enrichment by utilizing components such as valves, turbochargers, and catalysts with improved materials that can withstand higher

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temperatures without damage. Manufacturers are also using redesigned systems such as integrated exhaust manifolds to provide additional thermal control of exhaust temperatures to minimize high temperature excursions.

**II.B.2.iv. Durability of Engine Hardware to Control PM**

Base engine hardware like combustion chamber shape and injector location do not change as the engine ages but items like spray pattern can deteriorate as deposits form on the injector tips or the holes in the nozzle of the injector erode. However, improvements in the control system provide significant feedback on the operation and allow the system to compensate for some of this change. Further, improvements in the materials and manufacturing processes used for the injector are being made to reduce erosion and deposit formation as the injector ages.

Additionally, increased oil consumption can theoretically occur as the system ages from oil getting by the rings or through the PCV system, into the combustion chamber, and forming PM during combustion events. However, since the advent of stringent NOx emissions with the LEV II and successor programs, manufacturers have already been implementing design improvements to cylinder walls and piston rings to minimize deterioration and virtually eliminate oil consumption. These changes were necessary to avoid catalyst poisoning from oil consumption that would jeopardize the ability to meet the LEV II or LEV III standards for the full useful life of the vehicle.

**II.C. Localized Enrichment**

Controlled localized enrichment, or stratified charge, is a phenomenon that is possible with GDI. In this mode a small amount of fuel is injected very late in the compression stroke and targeted to create a rich kernel around the spark plug that ensures stable combustion. However, the rich combustion around the spark plug results in increased PM emissions.

**II.C.1. Cold Start Catalyst Light Off**

Some catalyst light off strategies used to quickly heat the catalyst for HC+NOx emission control make use of very late combustion to maximize the temperature of the exhaust gas exiting the cylinder. The intent of the operation is to increase the temperature of the exhaust gases to facilitate rapid warm-up of the catalyst up to a temperature region where it has very high HC and NOx conversion efficiency. However, very late combustion (with late spark timing) is a more difficult condition to initiate combustion and combustion stability limits are often the limiting factor. With GDI systems, fuel can also be injected very late and result in a localized rich area near the spark plug so combustion can be robustly initiated at even later spark timing than a homogenous mixture in the cylinder would allow. While this is very effective at creating stable combustion with very late spark timing, the localized area of rich mixture around the spark plug results in increased PM emissions.

**II.C.2. Cylinder Deactivation**

Several vehicles now use engines employing a cylinder deactivation system whereby several of the engine’s cylinders are not used during periods of operation like low or steady speed operation where total vehicle power demands are moderate. During cylinder re-activation, immediately following a period of cylinder deactivation, a late injection and late ignition is often used to temporarily reduce the cylinder specific power and promote a smooth transition in
engine torque output while reducing noise, vibration, and harshness (NVH) impacts. The effect is similar to the catalyst light off strategy mentioned above, where the condition around the spark plug is slightly rich to ensure stable combustion and thus results in additional PM formation.

**II.D. Localized Enrichment Control**

**II.D.1. Software Improvements**

A variety of engine management strategies can be used to reduce PM emissions during catalyst light-off and cylinder deactivation. Reducing the mass of fuel injected around the spark plug during stratified combustion will help control PM but can cause increased hydrocarbon emissions so would likely need to be coupled with other strategy or hardware changes to control hydrocarbon emissions. Software improvements can be implemented quickly and likely account for some of the lower PM emission results from newer GDI systems tested by ARB and noted in Appendix K. Engine management is also an essential part of hardware improvements such as catalyst location and design but, OEMs must be careful when implementing new control strategies to maintain control of HC+NOx and GHG emissions.

Engine management changes can be quite durable against PM emissions degradation over the useful life of the vehicle. For many conditions, improved feedback control strategies allow a control strategy to adapt and continue to effectively control PM emissions as the hardware components age.

**II.D.2. Catalytic Converter**

Indirectly, improved three-way catalyst design, including location and composition, can reduce PM emissions by reducing light-off time, thereby decreasing the duration of operation in a mode that may generate higher PM while trying to warm-up the catalyst. The location of the catalyst generally represents a need to balance packaging, exposure to very high exhaust temperatures in more extreme operating conditions, and the need to achieve very quick light-off at start-up to mitigate cold start emissions. The further downstream, the cooler the catalyst will run but the harder it is to quickly achieve the high temperatures needed for light off. Substantial improvements for the last decades have resulted in catalysts that are much more thermally stable and capable of exposure to high temperatures without excess degradation allowing for closer location to the exhaust manifold. Additionally, the substrates have often become smaller and lighter to reduce the thermal mass and warm-up faster minimizing the length and severity of catalyst light-off strategies. And, as noted earlier, improved thermal management of the exhaust such as water-cooled integrated exhaust manifolds are being used to reduce peak exhaust temperatures, allowing for the catalyst to be located closer to the manifold itself. For turbocharged engines, where the turbo is located upstream of the catalyst, manufacturers are also considering exhaust bypass systems that would allow exhaust gas to bypass the turbo during cold start to facilitate early catalyst light-off. The durability of a catalytic converter is a function of time at elevated temperatures, so controlling catalyst temperature is essential for complete useful life catalyst operation.
II.D.3. Mild Hybrid
Mild hybrids, such as the 48-volt system described in the draft 2016 TAR\textsuperscript{18} are projected to play an important role for vehicle to meet low GHG standards. The need for localized enrichment can be greatly reduced or eliminated by leveraging mild hybrid technology. For example, a 48-volt system with a belt-assisted starter-generator can be used to motor the engine during cold start, this can reduce the need for stable combustion and facilitates late ignition timing without the need for stratified combustion. Similarly a mild hybrid system can be used in conjunction with cylinder deactivation to smooth out the transition as cylinders are reactivated.

II.E. Homogeneous Enrichment
During limited modes of operation, it may be important to operate slightly rich of stoichiometric to promote stable combustion, cool exhaust gas temperature to protect components, maximize engine power, or for optimal catalyst conversion. Historically, homogeneous enrichment was more commonly used for component protection but increasingly stringent standards and newer technology such as improved high temperature alloys used in exhaust components, catalyst substrates and washcoats with improved high temperature stability, and other exhaust thermal management technologies like water-cooled integrated exhaust manifolds have allowed manufacturers to greatly reduce, if not eliminate, the conditions where such enrichment is needed in all but the most extreme conditions.

From an emissions perspective, homogeneous rich operation with a lambda less than one is rarely called for in any modern engine control strategy because the stringent LEV III emission standards require very high catalyst conversion efficiencies and conversion is optimal when the exhaust gas remains very close to stoichiometric operation. Short, slightly rich excursions can be tolerated given today’s catalysts can continue to effectively convert HC and CO emissions in such conditions but control systems are generally biased to avoid any similar lean excursions as the resulting increase in NOx emissions is significant. These rich excursions can, however, cause increased PM.

II.E.1. Stop/Start
A vehicle equipped with a stop/start system needs to start smoothly and dependably for user satisfaction and safety. One way this can be accomplished is with a slightly rich charge during the restart with the consequence being increased PM emissions.

II.E.2. Deceleration Fuel Cut
During a deceleration fuel cut, the exhaust flow through the catalyst is essentially ambient air, resulting in the catalyst being temporarily saturated with stored oxygen. While stored oxygen is critical for HC and CO conversion in the catalyst, efficient reduction of NOx emissions requires minimal stored oxygen to ensure a sufficient number of sites available to promote the necessary chemical reactions. In normal operation, fuel control systems effectively dither around stoichiometric exhaust concentrations to provide opportunity for storage and release of oxygen in sufficient quantities to satisfy the needs for both HC/CO conversion and NOx conversion. However, following a prolonged deceleration fuel cut event, the saturated oxygen status of the

\textsuperscript{18} EPA, 2016.
catalyst necessitates temporary rich operation to remove the stored oxygen on the catalyst and the rich operation can result in increased PM emissions.

**II.E.3. Transient Engine Operation**
Good fuel control during transient engine speed and load operation is critical for all pollutant emissions and is not unique to PM emissions. Reliably controlling PM emissions requires that each combustion event avoid areas of rich combustion and properly meter fuel and air with good mixing for complete combustion.

**II.F. Homogeneous Enrichment Control**
A variety of engine management strategies can be used to reduce PM emissions during situations where enrichment may have historically been used. The most direct way is to eliminate the need for the enrichment. And, as noted above, for enrichment used for component protection, manufacturers have increasingly been moving in the direction of higher temperature components and better exhaust thermal management to eliminate the need to use enrichment as a high exhaust temperature countermeasure.

For other situations, alternate control and hardware solutions may be necessary. For example, for additional GHG reductions, manufacturers are exploring many stop/start systems that are coupled with an electrical assist (e.g., belt-assisted starter-generator, ‘mild’ hybrid system) that uses electrical power to help initially propel the vehicle and reduce the dependence on as quick of a restart of the engine that many 12 volt stop/start systems have. Improved technologies for cylinder deactivation like the Tula skip-fire system have significantly more dynamic control of the system and can eliminate the need for rich operation when re-activating cylinders as well as reduce or eliminate the amount of ambient air that flows through the catalyst during a deceleration fuel cut event by disabling cylinders rather than simply cutting off injected fuel. Reducing or eliminating enrichment for transient operation is consistent with continual improvements manufacturers have been making to the engine management system to more precisely calculate and inject the correct amount of fuel during very dynamic changes in air flow. Such improvements lead to reduced fuel consumption, reduced HC+NOx emissions, and reduced PM emissions.

**II.G. PM formation - Oil Control**
Oil consumption can lead to organic and inorganic PM emissions. Engine lubrication oil contains metal-based additives such as zinc and sulfur and when oil gets into the combustion chamber during a combustion event, those additives either oxidize into solid particles such as SOx, or the metals turn to ash and are emitted as solid particles in the sub-23 nm size range. Additionally, the long chain and ring hydrocarbons that help keep engine oil viscous at high temperature and reduce its decomposition rate, do not combust completely. Lubrication oil based PM is not a significant source of PM on modern cars because oil control has steadily improved as the LEV programs have implemented emissions standards that require longer catalyst durability.
III. Gasoline Particulate Filters (GPFs)

Post-combustion control in the form of the gasoline particle filter (GPF) is another option available to reduce PM. A GPF can be used to filter and oxidize particles that are emitted from the engine during all modes of operation as shown in Figure 12. Conceptually, a GPF is a wall-flow filter placed in the exhaust stream that traps PM as it exits the engine and can periodically or continuously be cleaned through a process called regeneration.\textsuperscript{17} GPFs are similar in concept to their diesel counterparts, diesel particulate filters (DPFs) which have been used predominantly on all new diesel engines since 2007, however there are some differences between a diesel and gasoline application of a particulate filter. Unlike DPFs that require periodic intrusive operation to regenerate the accumulated PM, GPFs tend to continuously regenerate because gasoline exhaust is significantly hotter and normal operation includes enough variance in temperature and oxygen content from events like deceleration fuel cut to promote regeneration of the stored PM.\textsuperscript{18} A continuously or near-continuously regenerating PM filter never builds up a soot layer which has the advantage of keeping back pressure to a minimum but the disadvantage of a slightly lower filtration efficiency because the presence of a soot layer actually increases the filter efficiency. Recent advances in filter porosity design have reduced filter backpressure to help avoid any increase in CO\textsubscript{2} emissions that would result from a more restrictive exhaust system.\textsuperscript{19,20} Relative to total GHG emissions, any increase in tailpipe CO\textsubscript{2} emissions from the use of a GPF can also be partially offset by an associated further decrease in black carbon, a powerful short lived climate pollutant.\textsuperscript{21} The GPF can be manufactured with or without a catalyst washcoat to serve the role of either a dedicated GPF or integrated as part of the three way catalyst system.


While only a subset of one production vehicle built for the European market currently is equipped with a GPF, the upcoming European particle number standards may result in increased usage of GPFs on GDI vehicles and several manufacturers have announced their intent to equip some of their vehicles with GPFs for the European market. However, it is not yet clear if GPFs will be used as a long term control technology or if they will primarily be used as a bridge technology until manufacturers can sufficiently refine in-cylinder control strategies during scheduled engine redesigns. While not yet in mass production, GPF technology is rapidly evolving and will be a viable technology for manufacturers to use in the near future. Additional work is still needed to ready the technology for wide-scale deployment, especially for California or the U.S. markets where durability and onboard diagnostic (OBD) requirements are more rigorous than in other global markets but staff expects these hurdles can and will be met in upcoming years. GPFs do represent added cost to a manufacturer and based on today’s knowledge and meetings with GPF manufacturers, staff estimates the costs to equip a vehicle with a GPF system meeting US requirements to likely have a direct manufacturing cost between $70 and $100\textsuperscript{23} for a catalyzed GPF (which, with mark-up to retail price, would be approximately an $84 to $150 increase in the price of the vehicle to the consumer). However, given the early state of development for GPFs and the history of catalyst suppliers (who are also the primary GPF suppliers), staff expects continued improvements in design, materials, and manufacturing as well as cost reductions as a result of high volume production would likely lead to even lower costs by the time GPFs are ready for wide-scale deployment.

\textbf{III.A. Durability}

During the useful life of a vehicle, the GPF porosity decreases due to ash loading with the result being increased filtration efficiency. While this directionally reduces PM emissions by increasing

\textsuperscript{22} Kattouah, 2013 a
the filter efficiency, it can also increase backpressure which could adversely affect tailpipe CO2 emissions. Mechanical failure due to high temperature exposure is likely the primary failure mode that could result in increased PM emissions. Such failures could allow engine out PM to go unfiltered and the impact would depend on the degree of failure and engine out PM emission rate. A robust OBD system would be needed to ensure timely detection and repair of such failures and would likely require added sensors to effectively determine the proper function of the GPF.

IV. Fuel Effect on PM Emissions

Gasoline is a complex mixture of hundreds of hydrocarbons with molecular carbon numbers ranging from C4 to C15. Depending on the sources of the crude oil, refining processes, and blending practices, the profiles of chemical compounds in the gasoline can vary widely. For decades, U.S. EPA and ARB have regulated many gasoline bulk properties, such as Reid Vapor Pressure (RVP), distillation temperature (T50 and T90), and benzene, olefins, aromatics, oxygenates, and sulfur content, in order to reduce harmful air pollutants from vehicle exhaust.

Many studies have shown that gasoline fuel’s physical and chemical properties, such as T50, T90, ethanol content, and aromatic contents, play an important role in vehicle PM emissions. Incomplete combustion leads to vehicle PM emissions. Gasoline components with low vapor pressures require more time to evaporate than high vapor pressure compounds. One study has demonstrated that a substantial reduction in PM emissions could be achieved by eliminating fuel components with lower vapor pressures, specifically any hydrocarbon with a carbon number of 10 to 12. In addition, gasoline aromatic components can have a strong impact on the PM emissions due to their stable conjugated double bond structures that are relative difficult to combust completely. A test that evaluated an increased content of higher carbon number aromatics in various test cycle from a lean-burn 2003 MY GDI vehicle concluded that the aromatic fuel content had greater impact on PM emissions than distillation characteristics. Several studies have shown the impact on PM emissions of ethanol content in the fuel varies depending on the vehicle hardware especially the type of fuel injection system. Vehicles equipped with GDI systems were more likely to have a PM emission reduction as ethanol content increased, while vehicles with PFI systems tended to increase or showed no effects on PM emissions.

For both California and U.S. EPA standards, vehicle certification is conducted using official certification fuel while operating on a specific test driving cycle. The California LEV III certification fuel (LEV III cert. fuel) specifications are based on average commercially available fuel sold in California, including 10v% ethanol. The specifications of both the LEV III and previous LEV II certification fuels and the federal Tier 3 certification fuel are shown in Table 1 and Table 2. Use of Tier 3 certification gasoline is also allowed as an alternative to California certification gasoline for both LEVII and LEV III passenger cars, light-duty trucks, and medium-duty vehicles.

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Octane (R+M)/2</td>
<td>91 (min)</td>
<td>87-88.4; 91 (min)</td>
</tr>
<tr>
<td>Sensitivity</td>
<td>7.5 (min)</td>
<td>7.5 (min)</td>
</tr>
<tr>
<td>Lead</td>
<td>0-0.01 g/gal (max); no lead added</td>
<td>0-0.01 g/gal (max); no lead added</td>
</tr>
<tr>
<td>Distillation Range:</td>
<td></td>
<td></td>
</tr>
<tr>
<td>10% point</td>
<td>130-150 °F</td>
<td>130-150 °F</td>
</tr>
<tr>
<td>50% point</td>
<td>200-210 °F</td>
<td>205-215 °F</td>
</tr>
<tr>
<td>90% point</td>
<td>290-300 °F</td>
<td>310-320 °F</td>
</tr>
<tr>
<td>EP, maximum</td>
<td>390 °F</td>
<td>390 °F</td>
</tr>
<tr>
<td>Residue</td>
<td>2.0 vol.%</td>
<td>2.0 vol.%</td>
</tr>
<tr>
<td>Sulfur</td>
<td>30-40 ppm by wt.</td>
<td>8-11 ppm by wt.</td>
</tr>
<tr>
<td>Phosphorous</td>
<td>0.005 g/gal (max)</td>
<td>0.005 g/gal (max)</td>
</tr>
<tr>
<td>RVP</td>
<td>6.7-7.0 psi</td>
<td>6.9-7.2 psi</td>
</tr>
<tr>
<td>Olefines</td>
<td>4.0-6.0 vol. %</td>
<td>4.0-6.0 vol. %</td>
</tr>
<tr>
<td>Total aromatic Hydrocarbons</td>
<td>22-25 vol.%</td>
<td>19.5-22.5 vol.%</td>
</tr>
<tr>
<td>Benzene</td>
<td>0.8-1.0 vol.%</td>
<td>0.6-0.8 vol.%</td>
</tr>
<tr>
<td>Multi-substituted Alkyl Aromatic Hydrocarbons</td>
<td>12-14 vol.%</td>
<td>13-15 vol.%</td>
</tr>
<tr>
<td>Oxygenate</td>
<td>10.8-11.2 vol.% (MTBE)</td>
<td>9.8-10.2 vol.% (Ethanol)</td>
</tr>
<tr>
<td>Additives</td>
<td>Sufficient</td>
<td>Sufficient</td>
</tr>
<tr>
<td>Copper Corrosion</td>
<td>No. 1</td>
<td>No. 1</td>
</tr>
<tr>
<td>Gum, washed</td>
<td>3.0 mg/100mL (max)</td>
<td>3.0 mg/100mL (max)</td>
</tr>
<tr>
<td>Oxidation Stability</td>
<td>1000 minutes (min)</td>
<td>1000 minutes (min)</td>
</tr>
<tr>
<td>Specific Gravity</td>
<td>Report</td>
<td>Report</td>
</tr>
<tr>
<td>Heat of combustion</td>
<td>Report</td>
<td>Report</td>
</tr>
<tr>
<td>Carbon</td>
<td>Report wt.%</td>
<td>Report wt.%</td>
</tr>
<tr>
<td>Hydrogen</td>
<td>Report wt.%</td>
<td>Report wt.%</td>
</tr>
</tbody>
</table>
Table 2 - Federal Gasoline Emission Test Fuel Specifications

<table>
<thead>
<tr>
<th>Fuel Property</th>
<th>Units</th>
<th>Specifications</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td><strong>General</strong></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Testing</td>
</tr>
<tr>
<td>Antiknock Index (R+M)/2</td>
<td>-</td>
<td>87.0-88.4</td>
</tr>
<tr>
<td>Sensitivity (R-M)</td>
<td>-</td>
<td>7.5 minimum</td>
</tr>
<tr>
<td>Dry Vapor Pressure Equivalent (DVPE)</td>
<td>kPa (psi)</td>
<td>60.0-63.4 (8.7-9.2)</td>
</tr>
<tr>
<td>Distillation 10% evaporated</td>
<td>°C (°F)</td>
<td>49-60 (120-140)</td>
</tr>
<tr>
<td>50% evaporated</td>
<td>°C (°F)</td>
<td>88-99 (190-210)</td>
</tr>
<tr>
<td>90% evaporated</td>
<td>°C (°F)</td>
<td>157-168 (315-335)</td>
</tr>
<tr>
<td>Evaporated final boiling point</td>
<td>°C (°F)</td>
<td>193-216 (380-420)</td>
</tr>
<tr>
<td>Residue</td>
<td>milliliter</td>
<td>2.0 maximum</td>
</tr>
<tr>
<td>Total aromatic Hydrocarbons</td>
<td>volume %</td>
<td>21.0-25.0</td>
</tr>
<tr>
<td>C6 Aromatics (benzene)</td>
<td>volume %</td>
<td>0.5-0.7</td>
</tr>
<tr>
<td>C7 Aromatics (toluene)</td>
<td>volume %</td>
<td>5.2-6.4</td>
</tr>
<tr>
<td>C8 Aromatics</td>
<td>volume %</td>
<td>5.2-6.4</td>
</tr>
<tr>
<td>C9 Aromatics</td>
<td>volume %</td>
<td>5.2-6.4</td>
</tr>
<tr>
<td>C10+ Aromatics</td>
<td>volume %</td>
<td>4.4-5.6</td>
</tr>
<tr>
<td>Olefins</td>
<td>mass %</td>
<td>4.0-10.0</td>
</tr>
<tr>
<td>Ethanol Blended</td>
<td>volume %</td>
<td>9.6-10.0</td>
</tr>
<tr>
<td>Ethanol confirmatory</td>
<td>volume %</td>
<td>9.4-10.2</td>
</tr>
<tr>
<td>Total Content of Oxygenates Other Than Ethanol</td>
<td>volume %</td>
<td>0.1 maximum</td>
</tr>
<tr>
<td>Sulfur</td>
<td>mg/kg</td>
<td>8.0-11.0</td>
</tr>
<tr>
<td>Lead</td>
<td>g/liter</td>
<td>0.0026 maximum</td>
</tr>
<tr>
<td>Phosphorus</td>
<td>g/liter</td>
<td>0.0013 maximum</td>
</tr>
<tr>
<td>Copper Corrosion</td>
<td>-</td>
<td>No.1 maximum</td>
</tr>
<tr>
<td>Solvent-Washed Gum content</td>
<td>mg/100mL</td>
<td>3.0 maximum</td>
</tr>
<tr>
<td>Oxidation Stability</td>
<td>minute(min)</td>
<td>1000 minimum</td>
</tr>
</tbody>
</table>

**IV.A. PM Index- PMI**

Researchers from Honda R&D have proposed a predictive model, termed PM index (PMI), to quantify the relationship between gasoline properties and PM emissions based on fuel composition (Aikawa, 2010). PMI is defined as follows:

\[
PM \text{ Index} = \sum_{i=1}^{n} \left( \frac{DBE_i + 1}{V.P(443K)_i} \times W_i \right)
\]
Whereas $DBE_i$ is the double bond equivalent, based on the total numbers of hydrogen, carbon, nitrogen, and oxygen atoms in the gasoline component “i”; $V.P (443K)_i$ is the vapor pressure of component (i), at 443 K; and $Wt_i$ is the weight percentage of the component “i”.

The double bond equivalent and vapor pressure reflects individual component’s chemical and physical properties which is related to PM forming potential; and the weight percentage reflects that the component’s concentration is proportional to the effect on PM emissions. Gasoline fuel consists of at least 300 components and the PMI sums each component’s contributing value. With the structure of the model, the greater the resulting sum, the more PM the fuel would be expected to cause a vehicle to emit. The PMI suggests that low-volatility aromatics in gasoline are responsible for a large share of PM emissions. ARB used six different fuels to assess PMI values and the results show that the aromatic components contribute to approximately 90% of the PMI value as shown in Figure 13. Within the aromatics components, naphthalenes in particular, which are high in DBE value (7) and low in vapor pressure, contribute ~15% to the total PMI and yet only represent ~0.5 v% of gasoline fuel. On the other hand, paraffins make up greater than 60 v% of gasoline fuel, but contribute only ~7% to total PMI. The contribution from oxygenates and olefins is insignificant to the PMI value.

**Figure 13 - Chemical group contribution to PMI value from different fuels.**

Note: Fuels include E6, E10 vehicle testing fuels, two commercially available fuels (Market 1 and 2), LEV II, and LEV III California certification fuels.

Several, but not all, studies have reported a strong correlation between PMI and vehicle emissions. Typically, this was done by using a laboratory modified test fuel where individual or specific groups of hydrocarbons are added to the base fuel to investigate the emission impacts associated with the specific fuel parameters or to vary PMI values$^{33,34}$ (Aikawa, 2010; Butler, 2015).
The correlation studies between PMI and vehicle emissions are summarized chronologically in Table 3.

<table>
<thead>
<tr>
<th>PMI range</th>
<th>Vehicles</th>
<th>Fuel injection system</th>
<th>correlation</th>
</tr>
</thead>
<tbody>
<tr>
<td>~0.9-2.3 (3 commercial fuels)</td>
<td>2009 MY</td>
<td>2 L turbocharged wall-guided GDI, equipped with TWC</td>
<td>( R^2 = 0.9826 ) (PM vs. PMI)</td>
</tr>
<tr>
<td>~1.0-4.0 (special blends)</td>
<td>Engine</td>
<td>2.4 L PFI naturally aspirated.</td>
<td>( R^2 = 0.9774 ) (Soot vs. PMI)</td>
</tr>
<tr>
<td>1.44-1.58 (3 commercial fuels)</td>
<td>2010 MY</td>
<td>Wall-guided GDI</td>
<td>No clear correlation</td>
</tr>
<tr>
<td>1.10-1.87</td>
<td>2012 MY</td>
<td>5 GDIs and 2PFIs</td>
<td>( R^2=0.80-0.96 ), except for one PFI no sensitivity</td>
</tr>
<tr>
<td>0.9-2.7 (special blends)</td>
<td>4 vehicles (2007-2009 MYs)</td>
<td>3 PFI and 1 GDI</td>
<td>2 PFI and the GDI showed high sensitivity to PMI</td>
</tr>
<tr>
<td>0.85-2.10 (special blends)</td>
<td>15 vehicles (2008 MY)</td>
<td>PFI</td>
<td>5 of the 15 showed little or no sensitivity to PMI</td>
</tr>
</tbody>
</table>

Very high correlation was demonstrated by Aikawa et al., for a single GDI vehicle and a naturally aspirated engine. U.S. EPA conducted a comprehensive evaluation which was performed for the EPAct/V2/E-89 gasoline fuel effects program\(^{35}\) (Sobotowski 2015; Butler 2015). Emission data were collected for a fleet of 15 high-sales cars and light trucks with PFI systems from the MY2008 using 27 test fuels over the LA92 or Unified Cycle Driving Schedule. The study found a significant interaction between ethanol and fuel components and a wide variation in sensitivity to PMI across the 15 vehicles. Five of the 15 test vehicles showed little or no PM emissions sensitivity to ethanol or PMI, indicating the interaction of fuel properties with vehicle engine technology is important when modeling the effects of fuel properties. Overall, a positive correlation between PMI and PM emissions indicates that low volatility compounds, particularly heavy aromatics, have a strong influence on PM emissions from LD vehicles.

Sixteen California market fuels (12 obtained in the period of 2013 to 2014 and 4 from 2010), along with LEV II and LEV III cert. fuels, were analyzed (by detailed hydrocarbon analysis conducted by SWRI) and their PMIs were calculated. These fuels’ PMI values ranged from 1.2 to 1.7. Emission testing conducted in ARB’s laboratory was on a very narrow span of the PMI range, more consistent with what is expected in the range of commercial fuels, and no clear


correlation was observed.\textsuperscript{36} The lack of correlation could be due to the narrow range of the PMI as well as large vehicle test-to-test variability.

Certification fuel does not specify the exact concentration of individual fuel components; therefore the PMI values of a cert. fuel can also vary. However, ARB’s cert. fuel specifications reflect an average of California market fuels. The LEV III cert. fuel used for ARB’s evaluation of PM emissions from low GHG engine technology vehicles\textsuperscript{37} has a PMI value of 1.41. The potential range for PMI for LEV III cert. fuel is most likely in a narrow span since the formula of the PMI calculation is only based on the fuel composition and the specifications essentially allow a limited range of components.

Data was also received from the U.S. EPA on testing of recent model year vehicles tested on two different fuels. The testing included vehicles with technology that is likely to be found in the future low GHG emission fleet, including a number of GDI vehicles. The test fuels used represented typical certification fuels for Tier 2 fuel (90 octane, 0% ethanol) and Tier 3 fuel (87-88 octane, 10% ethanol) with PMI values of 1.86 and 1.52, respectively, as shown in Table 4.

<table>
<thead>
<tr>
<th>Table 4 - EPA Cert Fuel PMI</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tier 2 Fuel PMI</td>
</tr>
<tr>
<td>1.86</td>
</tr>
</tbody>
</table>

According to the PMI, the percent difference shown would predict that the PM emissions from the Tier 3 fuel blend would be 18% lower than the PM emissions on the Tier 2 fuel blend. The PM emission test results shown in Table 5 confirm that advanced low GHG technology vehicles follow the same trend as previous studies found; PM emission projections based on PMI are highly depend on vehicle technology. Not only is the average impact of the vehicles below a 6% increase, rather than the predicted 18% decrease, the individual impact varies widely from a 45% decrease to a 60% increase.


\textsuperscript{37} See Appendix K
Table 5 - EPA PM Test Results for Tier 2 and Tier 3 Fuel

<table>
<thead>
<tr>
<th>MY</th>
<th>Model</th>
<th>Engine</th>
<th>Tier 2 fuel PM Emissions (mg/mi)</th>
<th>Tier 3 Fuel PM Emissions (mg/mi)</th>
<th>Emissions Rate Percent Change</th>
</tr>
</thead>
<tbody>
<tr>
<td>2014</td>
<td>Ram 1500</td>
<td>3.6L V6 PFI</td>
<td>0.11</td>
<td>0.06</td>
<td>-45%</td>
</tr>
<tr>
<td>2016</td>
<td>Acura ILX</td>
<td>2.4L I4 GDI</td>
<td>0.18</td>
<td>0.27</td>
<td>50%</td>
</tr>
<tr>
<td>2013</td>
<td>Nissan Altima</td>
<td>2.5L I4 PFI</td>
<td>0.60</td>
<td>0.34</td>
<td>-43%</td>
</tr>
<tr>
<td>2016</td>
<td>Honda Civic</td>
<td>1.5L I4 GDI</td>
<td>0.67</td>
<td>0.55</td>
<td>-18%</td>
</tr>
<tr>
<td>2015</td>
<td>Ford F150 Eco-Boost</td>
<td>2.7L V6 GDI</td>
<td>3.34</td>
<td>4.12</td>
<td>23%</td>
</tr>
<tr>
<td>2013</td>
<td>Chevrolet Malibu</td>
<td>2.4L I4 GDI</td>
<td>2.59</td>
<td>3.06</td>
<td>18%</td>
</tr>
<tr>
<td>2016</td>
<td>Chevrolet Malibu</td>
<td>1.5L I4 GDI</td>
<td>2.66</td>
<td>2.63</td>
<td>-1%</td>
</tr>
<tr>
<td>2014</td>
<td>Mazda 3</td>
<td>2.0L I4 GDI</td>
<td>1.26</td>
<td>2.02</td>
<td>60%</td>
</tr>
<tr>
<td>2016</td>
<td>Chevrolet Silverado 1500</td>
<td>4.3L V6 GDI</td>
<td>1.47</td>
<td>1.59</td>
<td>8%</td>
</tr>
<tr>
<td>2015</td>
<td>Volvo S60 T5</td>
<td>2.0L I4 GDI</td>
<td>0.84</td>
<td>0.89</td>
<td>6%</td>
</tr>
</tbody>
</table>

From the studies and testing done to date, staff finds the scientific underpinnings of the PMI model are sound but the effects of vehicle technology on PM emissions can dwarf any impacts from fuel properties especially in the expected range of PMI from actual commercial fuels in California. Currently, most of the PMI data has been generated using PFI and some early GDI engines and primarily using laboratory modified fuel that may not be representative of the types of variation expected in commercial fuel. The correlation between PM emissions and PMI were highly variable according to the most recent U.S. EPA results. The results from early GDI systems also may not be representative of future GDI vehicles as total PM emissions from newer GDI systems are already substantially lower. As discussed in Appendix J, GDI systems are still undergoing significant improvements in avoiding in-cylinder PM formation which may dramatically change any previously observed relationship to fuel properties. Accordingly, staff finds the current PMI model is not a good indicator of the PM tailpipe emissions especially in the range of expected PMI for certification or commercial fuel.
V. Conclusion
To answer the Board’s question regarding feasibility of meeting the 1 mg/mi standard from a
technology perspective, the new test results and updated technology evaluation support staff’s
original assessment that the 1 mg/mi standards are technically challenging but achievable by
2025 at very low to no cost. Staff expects this will predominantly be done with in-cylinder
control as engine and fuel injections systems are refined over the next engine design cycles.
Given the substantial PM reductions down to 1.2 to 1.5 mg/mi already observed in testing
(Appendix K) on newer designed engines in anticipation of the 3 mg/mi standard, manufacturers
are well on track to understanding and effectively controlling PM emissions on the FTP cycle.
With the additional lead time, manufacturers should be able to incorporate the knowledge they
gain from in-use operation of these vehicles and improved injection system controls into future
engine redesigns. GPFs could also be used to effectively control PM and provide
manufacturers additional flexibility especially for particularly challenging engines. While there
are additional per vehicle part costs associated with a GPF solution, there may be cases where
a manufacturer finds such costs are offset by savings in design, manufacturing, calibration,
testing resources, or other trade-offs associated with ensuring good in-cylinder PM control on
engine redesigns.

Regarding the Board’s question of earlier implementation than 2025 model year for the 1 mg/mi
standard, from a technology standpoint, earlier implementation would likely necessitate that
GPFs play a larger role. This is because the shorter lead time may not be sufficient to update
all engine designs during a normal redesign cycle or to incorporate the newest injection control
system components. As noted earlier, this would also result in increased cost to comply with
the standards and may result in a temporary solution as manufacturers eventually are able to
redesign the engine and eliminate the need for the GPF.

The technology exists to control PM for all driving conditions, but changes to the current
standards are needed to ensure manufacturers effectively implement it. Comprehensive PM
control technology will ensure Californian’s exposure to PM emissions is reduced regardless of
where they live or what time of year it is.
VI. References


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California's Advanced Clean Cars Midterm Review

Appendix K: PM Emission Testing Results

January 18, 2017

California Environmental Protection Agency
Air Resources Board
I. Introduction

To assess the particulate matter (PM) emissions of currently available low greenhouse gas (GHG) emitting engines, a vehicle testing campaign was conducted at the California Air Resources Board. Vehicles were chosen to represent a variety of low-GHG technologies, particularly targeting newer engines that were expected to have powertrains representative of future technologies. These engines may have undergone recent revisions that likely would have considered compliance with the upcoming 3 mg/mi PM standard. Staff tested vehicles and conducted gravimetric PM emission measurements to look at mass emission levels during the certification driving cycles and real time PM emissions measurements to qualitatively determine where in the driving cycle PM emissions occur. A total of 15 vehicles were tested and the results of the testing are summarized in this appendix.

II. Test Procedures and Test Methods

Testing was conducted in light-duty test cells at the ARB Haagen-Smit Laboratory (HSL) in El Monte, California. Each test cell is equipped with a 48-inch single-roll electric chassis dynamometer, a constant volume sampler (CVS), and one or more PM$_{2.5}$ sampling systems that meet requirements defined by 40 CFR Part 1065. The PM gravimetric analyses meet the requirements in 40 Code of Federal Regulations (CFR) Part 1066, and followed the approved gravimetric analysis and filter media handling techniques.$^{1,2,3}$

The typical CVS flowrate of the federal test procedures (FTP) test cycle at ARB is 350 standard cubic feet per minute (scfm). The test fuel was California Phase III certification-grade gasoline containing 10% ethanol.

Real time PM emission measurements were also drawn from the CVS tunnel near where the PM mass samples were drawn. Real time instruments were operated according to each instrument’s manufacturer protocol. Solid particle number (SPN) was measured with a PMP-compliant method (d50 of 23nm) using either a Horiba Solid Particle Counting System (MEXA-2000 SPCS) or AVL solid particle counter (489 APC), both of which consist of a volatile particle removal unit and a Condensation Particle Counter (CPC). Black carbon (BC) was measured with an AVL Micro Soot Sensor (MSS 483), which quantifies BC with photoacoustic spectroscopy at 808nm. SPN measurements were recorded at 1 Hz frequency and BC measurements at 1 Hz or higher frequency. Additional PM metrics from TSI Engine Exhaust Particle Sizers (EEPS) and either TSI or Grimm CPC were also collected, but are not included in this document.

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On-board diagnostics (OBD) data was also collected from most vehicles tested. Some of the parameters that were collected include vehicle speed, engine speed, lambda ratios, mass air flow, calculated load values, cylinder 1 advance timing, and throttle and accelerator positions.

PM mass tunnel blanks (filtered dilution air sampled at the end of the CVS) were collected regularly and were generally equivalent to <0.1 mg/mile. One higher-emitting vehicle, a Ford F-150, which was tested with tunnel blanks that reached up to approximately 0.5 mg/mi, as noted in the testing results below. Earlier work has measured tunnel blank values of $2 \times 10^9$ particles/km for SPN and 0.15 mg/mile for BC.\(^4,5\)

**Driving Cycles**

LDV PM emission standards are tied to specific driving cycles on a chassis dynamometer. The driving cycle is intended to represent a specific duty or activity of a vehicle during its operation. The two most relevant drive cycles for LDV PM emission standards are the standard Federal Test Procedure (FTP) cycle and the high speed, high acceleration portion of the Supplemental FTP (SFTP or US06).

Emission tests results presented later will be given primarily for these two cycles. Some vehicles were also tested on other cycles for research purposes. The California Unified Cycle (UC) was also used and it was originally developed by ARB for use in inventory modeling of emissions from light-duty vehicles. The Worldwide Harmonized Light Duty Test Cycle (WLTC) is of interest for comparison to European vehicle emission standards. However, testing done on the WLTC was done using FTP methods, not Worldwide Harmonized Light Vehicles Test Procedures (WLTP) methods, for determining vehicle test weights and road loads so the results are not directly comparable to testing done in accordance with the official WLTP requirements. For some vehicles, the Highway test cycle was also used. However, the test results for cycles other than the FTP and US06 are not analyzed because the data was limited and was for research purposes.

**Federal Test Procedure Driving Cycle**

The FTP consists of two urban dynamometer driving schedules (UDDS) run in series (Figure 1). Each UDDS is divided into two phases, with a start phase running for 505 seconds and a stabilized phase running for an additional 864 seconds. The first UDDS is considered a cold start test because the engine is started in a "cold" condition after an overnight engine off 'soak' period. The second UDDS is considered a hot start test because it begins with a "hot" engine from a car that has been sitting with the engine off for 10 minutes after the first UDDS ends. The stabilized phase in both UDDS cycles is assumed to have the same emissions; therefore, it

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is typically not run after the hot start. This “three-phase” driving schedule is commonly referred to as an FTP-75. The FTP-75 has a total distance travelled of 11.04 miles, an average speed of 21.2 miles per hour (mph), and a total duration of 1874 seconds. The emission result is a weighted average where the cold start and stabilized phase (the first UDDS cycle) is weighted at 43 percent and the hot start and stabilized phase (equivalent to the second UDDS) is weighted at 57 percent.

**Figure 1 - The FTP test cycle speed trace**

![FTP Test Cycle Speed Trace](image)

**II.A.1 Supplemental Federal Test Procedure (SFTP or US06) driving cycle**

The US06 was developed to reflect aggressive, high speed, and high acceleration driving behavior. The US06 driving cycle is shown in Figure 2. It is a hot start test typically run with a prep cycle to ensure the car is warmed up; the US06 test immediately follows the prep cycle without an engine off or restart. The US06 cycle represents an 8.01 mile route with an average speed of 48.4 mph, maximum speed of 80.3 mph, maximum acceleration rate of 8.46 mph/sec, and duration of 596 seconds. The higher acceleration rates and speeds of the US06 cycle lead to higher engine loads, which historically often led to higher PM emission rates.

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II.A.2 Selection of Vehicles

As discussed in Appendix J, the light duty vehicle fleet is moving towards gasoline direct injection (GDI) technology to comply with the Low Emission Vehicle (LEV III) greenhouse gas (GHG) standards. GDI technology was of particular concern in terms of PM emission impacts when the more stringent standards were first adopted in 2012. Test results from early GDI equipped engines showed significantly higher PM emissions than conventional port-fuel injector (PFI) systems. The 3 mg/mi PM emission standard for the FTP starts phasing in 2017 and will be fully implemented by 2021. Some manufacturers have already redesigned their engines to meet this standard. The US06 PM standard of 6 mg/mi starts phasing in 2017 for vehicles complying with the 3mg/mi FTP standard and will be fully implemented by 2021. However, vehicles in 2017 and 2018 will be certified to interim higher standards of 10 mg/mi for the US06.

Given the rapidly increasing fraction of the fleet utilizing GDI equipped engines, testing for this program primarily targeted GDI engines. The chosen technologies included:

- Atkinson cycle GDI
- Dual PFI/GDI systems
- Downsized turbocharged GDI
- GDI with Piezo injectors
- GDI plug-in hybrid electric vehicles (PHEV)
- PFI hybrid or PHEV

Table 1 summarizes the vehicles tested and corresponding engine technologies, including fuel injection, turbocharging, engine displacement, model year, and improved control strategies.

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### Table 1 - Overview of low-GHG engine technologies tested

<table>
<thead>
<tr>
<th>Engine technology category</th>
<th>Model year</th>
<th>Make</th>
<th>Model</th>
<th>Engine</th>
</tr>
</thead>
<tbody>
<tr>
<td>Atkinson cycle GDI, high compression ratio, small displacement</td>
<td>2015</td>
<td>Mazda</td>
<td>3</td>
<td>2.0L SkyActiv</td>
</tr>
<tr>
<td>PFI+GDI systems</td>
<td>2012</td>
<td>Lexus</td>
<td>IS350</td>
<td>3.5L 2GR-FSE</td>
</tr>
<tr>
<td></td>
<td>2015</td>
<td>Subaru</td>
<td>BRZ</td>
<td>2.0L</td>
</tr>
<tr>
<td></td>
<td>2016</td>
<td>Toyota</td>
<td>Tacoma</td>
<td>3.5L Atkinson V6</td>
</tr>
<tr>
<td>Downsized turbocharged high BMEP GDI</td>
<td>2015</td>
<td>Ford</td>
<td>F-150</td>
<td>2.7L turbo</td>
</tr>
<tr>
<td></td>
<td>2014</td>
<td>Ford</td>
<td>Fiesta</td>
<td>1.0L turbo</td>
</tr>
<tr>
<td></td>
<td>2014</td>
<td>Mini</td>
<td>Cooper</td>
<td>2.0L turbo</td>
</tr>
<tr>
<td></td>
<td>2016</td>
<td>VW</td>
<td>Jetta</td>
<td>1.4L turbo</td>
</tr>
<tr>
<td>Downsized turbocharged GDI with Piezo injectors</td>
<td>2014</td>
<td>Daimler</td>
<td>CLA 250</td>
<td>2.0L turbo</td>
</tr>
<tr>
<td>GDI General</td>
<td>2015</td>
<td>GM</td>
<td>Malibu</td>
<td>2.5L</td>
</tr>
<tr>
<td></td>
<td>2015</td>
<td>Honda</td>
<td>Accord</td>
<td>2.4L</td>
</tr>
<tr>
<td>PFI Hybrid/PHEV</td>
<td>2013</td>
<td>Chevy</td>
<td>Volt</td>
<td>1.4L</td>
</tr>
<tr>
<td></td>
<td>2013</td>
<td>Toyota</td>
<td>Prius Plug-in</td>
<td>1.8L</td>
</tr>
<tr>
<td></td>
<td>2016</td>
<td>Toyota</td>
<td>Prius</td>
<td>1.8L</td>
</tr>
<tr>
<td>GDI PHEV</td>
<td>2016</td>
<td>Hyundai</td>
<td>Sonata Plug-in</td>
<td>2.0L</td>
</tr>
</tbody>
</table>

### III. Test Results:

**Summary and Analysis of Gravimetric Test Results**

A total of 15 vehicles were tested, of which 9 were GDI vehicles, 3 were dual GDI/PFI systems, and 3 were PHEV with PFI.
Average and individual test results for each vehicle for FTP-75 and US06 are presented in Table 2. In general, each vehicle was tested at least three times for FTP and US06, but due to occasional sampling or analysis issues, not all tests have valid PM mass measurements.

Table 2 - Summary of PM mass results from vehicles tested at CARB

<table>
<thead>
<tr>
<th>Vehicle</th>
<th>FTP</th>
<th>US06</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Average Mass (mg/mi)</td>
<td>Indiv. test Mass (mg/mi)</td>
</tr>
<tr>
<td>2015 Mazda 3 2.0 liter GDI 4,000 miles</td>
<td>1.46</td>
<td>1.30</td>
</tr>
<tr>
<td>2012 Lexus IS350 3.5 liter GDI+PFI 40,000 miles</td>
<td>5.64</td>
<td>5.55</td>
</tr>
<tr>
<td>2015 Subaru BRZ 2.0 liter GDI+PFI 15,000 miles</td>
<td>0.96</td>
<td>0.91</td>
</tr>
<tr>
<td>2016 Toyota Tacoma 3.5 liter GDI+PFI 51,000 mi</td>
<td>0.40</td>
<td>0.34</td>
</tr>
<tr>
<td>2015 Ford F150* 2.7 liter turbo GDI 15,000 mi</td>
<td>5.50*</td>
<td>5.08*</td>
</tr>
<tr>
<td>2014 Ford Fiesta 1.0 liter turbo GDI 26,000 miles</td>
<td>1.41</td>
<td>1.01</td>
</tr>
<tr>
<td>2014 Mini Cooper 2.0 liter turbo GDI 28,000 mi</td>
<td>0.43</td>
<td>0.49</td>
</tr>
</tbody>
</table>

* indicates data collected during a special emission test in addition to the FTP and US06 tests.
<table>
<thead>
<tr>
<th>Model</th>
<th>Year</th>
<th>Engine Size</th>
<th>Fuel Type</th>
<th>Mileage</th>
<th>Cold Start 1</th>
<th>Cold Start 2</th>
<th>Cold Start 3</th>
<th>FTP Total 1</th>
<th>FTP Total 2</th>
</tr>
</thead>
<tbody>
<tr>
<td>2016 VW Jetta TSI</td>
<td>2016</td>
<td>1.4 L GDI</td>
<td>L2ULV</td>
<td>5000 mi</td>
<td>0.28</td>
<td>0.21</td>
<td>0.25</td>
<td>1.00</td>
<td>0.13</td>
</tr>
<tr>
<td>2014 Mercedes CLA</td>
<td>2014</td>
<td>2.0 L GDI</td>
<td>L2ULV</td>
<td>30000 mi</td>
<td>0.28</td>
<td>0.12</td>
<td>0.34</td>
<td>0.34</td>
<td>0.64</td>
</tr>
<tr>
<td>2016 Chevy Malibu</td>
<td>2016</td>
<td>2.5 L GDI</td>
<td>ULEV</td>
<td>18000 mi</td>
<td>7.03</td>
<td>6.35</td>
<td>6.73</td>
<td>2.05</td>
<td>0.77</td>
</tr>
<tr>
<td>2016 Honda Accord</td>
<td>2016</td>
<td>2.4 L GDI</td>
<td></td>
<td></td>
<td>0.89</td>
<td>0.67</td>
<td>0.99</td>
<td>1.26</td>
<td>0.85</td>
</tr>
<tr>
<td>2013 Chevy Volt</td>
<td>2013</td>
<td>1.4 L PHEV</td>
<td>PFI</td>
<td>8000 mi</td>
<td>0.32</td>
<td>0.19</td>
<td>0.46</td>
<td>0.11</td>
<td>0.11</td>
</tr>
<tr>
<td>2013 Toyota Prius</td>
<td>2013</td>
<td>1.8 L PHEV</td>
<td>PFI</td>
<td>25000 mi</td>
<td>0.12</td>
<td>0.23</td>
<td>0.15</td>
<td>0.11</td>
<td>0.24</td>
</tr>
<tr>
<td>2016 Toyota Prius</td>
<td>2016</td>
<td>1.8 L HEV</td>
<td>PFI</td>
<td>5000 mi</td>
<td>0.19</td>
<td>0.23</td>
<td>0.12</td>
<td>0.14</td>
<td>0.14</td>
</tr>
<tr>
<td>2016 Hyundai Sonata</td>
<td>2016</td>
<td>2.0 L PHEV</td>
<td>GDI</td>
<td>6000 mi</td>
<td>1.22</td>
<td>1.01</td>
<td>1.71</td>
<td>1.60</td>
<td>1.45</td>
</tr>
</tbody>
</table>

*Ford F-150 was tested in a CVS tunnel with higher tunnel blanks of up to 0.5 mg/mi

Most of the vehicles tested were under 1.5 mg/mi over the FTP cycle, which is significantly less than earlier fleets of GDI vehicles. The three major exceptions with higher emissions were the 2012 Lexus IS350, the 2015 Chevrolet Malibu, and the 2015 Ford F-150. All three of these vehicles had very high cold start emissions, which accounted for the majority of the total FTP emissions.

The 2015 Mazda 3 with an Atkinson cycle GDI engine emitted 1.5 mg/mi over the FTP cycle, but US06 emissions were very well controlled at 0.6 mg/mi. As with many GDI vehicles,

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8 ARB, 2012.
emissions were cold start dominant, although at a significantly lower level than earlier generation GDI vehicles.

The Lexus IS350 was an early implementation of a dual GDI/PFI systems, and calibration may not have targeted low PM emissions for the 2012 model year – although emissions were over 5 mg/mi, these results were not atypical for GDI engines at the time. Like many earlier GDI vehicles, the majority of these emissions were on cold start, and US06 emissions (with no cold start) were significantly lower at 1.3 mg/mi.

It is worth noting that more recently introduced GDI/PFI engines such as the 2015 Subaru BRZ and 2016 Toyota Tacoma, were much lower emitting on the FTP just a few model years later. The Toyota Tacoma, in particular, was very low emitting with average FTP emissions below 0.5 mg/mi while the Subaru BRZ emitted an average of 1.0 mg/mi over the FTP cycle. However, both of these more recent GDI/PFI vehicles were found to have US06 emissions that were higher than many of the GDI only vehicles tested in this campaign, a characteristic which is more similar to a conventional PFI only vehicle.

The Ford F-150 with a 2.7-liter turbocharged GDI engine was also measured at over 5 mg/mi over the FTP cycle, once again with the vast majority of emissions occurring during cold start. In this case, the catalyst light-off strategy and calibration used by Ford for this particular vehicle may have traded off higher PM emissions for quicker catalyst light off to minimize hydrocarbon and oxides of nitrogen emissions as staff observed indications that the vehicle remained in and/or returned to a modified spark timing and engine speed strategy commonly associated with a catalyst light-off strategy even after the completion of the first hill on the FTP. This vehicle was tested in a CVS tunnel with higher tunnel blanks, equivalent of up to 0.5 mg/mi, but the overall emissions were significantly higher than the tunnel blanks. This vehicle was also tested with a prototype GPF as described below, which was tested in a CVS tunnel with near-zero tunnel blanks.

Like the Ford F-150, the Ford Fiesta was equipped with a downsized, turbocharged GDI ‘EcoBoost’ Ford engine. However, the small displacement 1.0-liter engine in the Fiesta was found to have much lower PM emissions especially at cold start, with an average of 1.4 mg/mi over both the FTP and US06 cycles which appears to be more representative of the newer GDI fleet. This vehicle was also equipped with a small close-coupled catalytic converter that was located close to the exhaust manifold and the vehicle appeared to rely less on an extended use of a catalyst light-off strategy like the F-150.

The 2014 Mini Cooper S is equipped with a 2.0 liter direct injected turbocharged engine and results show emissions were very well controlled on the FTP at 0.4 mg/mi and slightly higher on the US06 at 1.2 mg/mi. As with many other well-controlled GDI vehicles, the Mini showed good control over all portions of the FTP cycle, with somewhat higher emissions during cold start.

The 2016 Volkswagen Jetta and 2014 Mercedes CLA were the lowest emitting GDI vehicles tested, both averaging 0.3 mg/mi over the FTP cycle. As with the Honda Accord, both the VW and Mercedes appear to have very well controlled PM emissions on cold start. The Mercedes,
which is equipped with Piezo fuel injectors, also had very low US06 emissions at 0.3 mg/mi. The VW Jetta averaged 1.0 mg/mi over the US06 cycle.

The 2016 Chevrolet Malibu emissions were more similar to the earlier GDI fleet, with FTP emissions of 7.0 mg/mi and US06 emissions of 2.1 mg/mi. As with the 2012 Lexus, a major proportion of the PM emissions occurred during cold start. This vehicle was also tested after being retrofit with a prototype GPF as described below.

Although the 2015 Honda Accord is the same model year, naturally aspirated and similar displacement to the Chevy Malibu, FTP emissions were significantly lower for the Accord at an average of 0.9 mg/mi. The difference appears to be due especially to much lower PM emissions on cold start with the Honda. US06 emissions were only moderately lower at 1.3 mg/mi versus 1.6 mg/mi for the Chevy Malibu.

A total of four hybrid electric vehicles were tested, the 2013 Chevrolet Volt, 2013 Toyota Prius and 2016 Hyundai Sonata were PHEVs tested in charge sustaining mode to mimic a conventional HEV. The 2016 Toyota Prius was a conventional HEV. The two Priuses and the Volt were equipped with PFI systems and were very low emitting over both test cycles. The PFI hybrids were found to have average mass emissions of no higher than 0.3 mg/mi over both FTP and US06 cycles. The fourth PHEV vehicle tested, a 2016 Hyundai Sonata, was equipped with a GDI engine and resulted in emissions more similar to other current GDI vehicles at 1.1 mg/mi over the FTP cycle and 1.6 mg/mi over the US06.

Staff also tested prototype gasoline particulate filters (GPFs) for controlling PM emissions. This technology appears capable of meeting the future 1 mg/mi standard, even for particularly challenging engines. For this testing, two newer GDI engines were selected that had gone through a partial redesign cycle, but would not yet readily meet the 3 mg/mile standard. The two vehicles selected were the 2015 Ford F-150 and 2016 Chevrolet Malibu, with emission rates of 5.6 mg/mi and 7 mg/mi respectively over the FTP cycle. Both vehicles were retrofit with catalyzed GPFs that replaced the second catalyst in the exhaust stream. On the F-150, this catalyst is housed in the same can as the first converter (see Figure 3) while on the Malibu, it is mounted in a typical underfloor position (see Figure 4).
Without the GPF, both vehicles had fairly high FTP PM emissions and would need further improvements to meet the 3 mg/mi standard. The emission reductions from GPF testing are shown in Table 3. On the FTP, an 88% reduction was observed for both vehicles and brought...
emissions to a level below 1 mg/mi. The effectiveness of the GPFs on the US06 were somewhat lower, reducing PM emissions by 72% and 54% respectively for the F-150 and Malibu. The results from both vehicles show that GPFs are an effective control technology to meet future 1 mg/mi PM standards, even for vehicles that are substantially higher in PM emissions.

Table 3 - GPF Emissions Results

<table>
<thead>
<tr>
<th>Description</th>
<th>Average of FTP (mg/mi)</th>
<th>Average of US06 (mg/mi)</th>
<th>FTP GPF Effectiveness (%)</th>
<th>US06 GPF Effectiveness (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>2015 FORD F150</td>
<td>5.5</td>
<td>3.9</td>
<td></td>
<td></td>
</tr>
<tr>
<td>2015 FORD F150 W/GPF</td>
<td>0.6</td>
<td>1.1</td>
<td>88%</td>
<td>72%</td>
</tr>
<tr>
<td>2016 CHEV MALIBU</td>
<td>7.0</td>
<td>2.1</td>
<td></td>
<td></td>
</tr>
<tr>
<td>2016 CHEV MALIBU W/GPF</td>
<td>0.8</td>
<td>0.9</td>
<td>88%</td>
<td>54%</td>
</tr>
</tbody>
</table>

As part of the GPF testing, CO₂ and gaseous pollutant emissions were also measured, with the CO₂ results tabulated in Table 4. While the data shows a slight decrease in CO₂ emissions, the magnitude is within the typical driver and measurement variability, particularly as testing was done with different drivers and in different test cells. These results confirm that the increased backpressure from the GPF, even in a retrofit application, did not have a significant impact on CO₂ over the FTP and US06 cycles. In addition, gaseous pollutant emissions were generally equivalent or better than the stock exhaust configuration.

Table 4 - CO₂ Emissions Analysis for GPFs

<table>
<thead>
<tr>
<th>Description</th>
<th>Average of FTP CO₂ (g/mi)</th>
<th>Average of US06 CO₂ (g/mi)</th>
<th>FTP Percent CO₂ increase</th>
<th>US06 Percent CO₂ increase</th>
</tr>
</thead>
<tbody>
<tr>
<td>2015 FORD F150</td>
<td>391</td>
<td>476</td>
<td>NA</td>
<td>NA</td>
</tr>
<tr>
<td>2015 FORD F150 W/GPF</td>
<td>386</td>
<td>455</td>
<td>-1%</td>
<td>-4%</td>
</tr>
<tr>
<td>2016 CHEV MALIBU</td>
<td>333</td>
<td>321</td>
<td>NA</td>
<td>NA</td>
</tr>
<tr>
<td>2016 CHEV MALIBU W/GPF</td>
<td>330</td>
<td>314</td>
<td>-1%</td>
<td>-2%</td>
</tr>
</tbody>
</table>

III.B Real time Measurement Summary and Analysis

While not an equivalent substitute to gravimetric analysis for accurately determining PM mass, real time measurements allowed an investigation of when PM emissions were occurring within the test cycles. While PM emissions are generally known to be generated primarily during cold start or under high engine load, which held true for the vehicles tested in this program, the
emission profiles varied. For many of the tested GDI vehicles, the overall FTP emissions were dominated by cold start while high engine speed/load transients were well controlled. These vehicles generally resulted in higher FTP emission results, but lower US06 emission results. At the other extreme were vehicles with low cold start emissions, but with higher emissions under high load, which was most common with some of the combination GDI/PFI vehicles and is a similar trend to results from traditional PFI system vehicles.

An example of a cold-start dominant emission profile is shown in Figure 5. These measurements were taken from a 2015 Mazda 3, which had phase-weighted PM emissions of approximately 1.3 mg/mi in this test. Both the PM mass from filter weights and the real-time PM measurements show that most of the PM emissions occurred on cold start, with phase 1 emissions of over 5 mg/mi, and very low phase 2 and 3 emissions of approximately 0.2 mg/mi. The real-time plots indicate that PM emissions were well controlled within a few minutes of the cold start.

**Figure 5 - 2015 Mazda 3 GDI emissions on FTP cycle.**

Some vehicle emission results were dominated by high load transients, such as the Subaru BRZ with a 2.0 liter engine equipped with both GDI and PFI systems, as shown in Figure 6. Although overall emissions are only moderately lower than the Mazda 3 at approximately 0.9 mg/mi, these emissions were more evenly distributed throughout the test with phase 1
emissions about 1/4\textsuperscript{th} of those observed from the Mazda and phase 2 and 3 emissions approximately 4 times those of the Mazda.

**Figure 6 - 2015 Subaru BRZ GDI/PFI over the FTP cycle.**

The US06 cycle does not include a startup event, so PM emissions are primarily generated during high load transients (periods of acceleration). Figure 7 shows an example of US06 emissions from the 2015 Honda Accord.

While a number of the earlier generation of GDI vehicles as well as PFI vehicles often generated higher emissions during US06 than on FTP cycles, this was not the case for many of the newer GDI vehicles tested. In this GDI fleet, US06 emissions were often similar or less than the corresponding FTP emissions, although test-to-test variability was higher.
III.C Summary of BC results

Earlier work had suggested that the ratio of black carbon (BC) to total PM mass may vary slightly depending on engine technology, for example PFI versus GDI, so this correlation was also investigated for this test fleet. BC was measured using AVL Micro Soot Sensors (MSS), with full results for all tests presented in the Attachment Table A-1.

As with earlier test vehicles, black carbon and PM mass was well correlated over the FTP cycle with a BC/mass ratio of 0.73, with $R^2$ of 0.89, as shown in Figure 8. However, over the US06 cycle a number of vehicles were found to have significantly lower black carbon to PM mass ratios, though this again was comparable to earlier results. The US06 correlation is shown in figure 9, with an overall BC/mass ratio of 0.42 with an $R^2$ of 0.72.

The BC to total PM mass ratio for GPF equipped vehicles shows that the GPFs appear to reduce PM mass and black carbon approximately proportionally, as both the Ford F-150 and Chevy Malibu do not have significantly altered BC/mass ratios when equipped with a GPF.
Figure 8 - Correlations between PM mass and black carbon emissions on the FTP cycle

**BC to PM mass correlations**

**FTP tests only**

- Vehicle emissions
- Equipped with GPF
- Line fit (low emitters only)

\[ y = 0.73 \times x - 0.077, \quad R^2 = 0.89 \]

Figure 9 - Correlations between PM mass and black carbon emissions on the US06 cycle

**BC to PM mass correlations**

**US06 tests only**

- Vehicle emissions
- Equipped with GPF
- Line fit

\[ y = 0.42 \times x - 0.04, \quad R^2 = 0.72 \]
III.D Variability

One of the major concerns expressed by vehicle manufacturers with meeting stringent future PM standards is variability. However, the PM emissions of GDI vehicles are usually dominated by cold-start emissions on the FTP cycle, which is relatively consistent from test-to-test. Since US06 cycles have no cold start event, PM emissions primarily occur during acceleration events (high load transients). This can lead to more variability, particularly since the US06 cycle includes much more aggressive speeds and accelerations, which can contribute to greater driver variability.

Table 5 summarizes the standard deviations and coefficient of variance (COV) for the vehicles tested in this program, with total averages and standard deviations shown at the bottom. Although overall average emissions were similar between the two cycles, with an average of 1.8 mg/mi for the FTP cycle and 1.4 mg/mi for US06, the standard deviation of all FTP cycles is much lower at 0.26 mg/mi, compared to 0.60 mg/mi for the US06 cycle.

Table 5 - Standard deviations over FTP and US06 cycles

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<th>US06</th>
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<td>SD (mg/mi)</td>
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<td>5.64</td>
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Total average | 0.26 | 0.60
Figure 9 presents an example of how real-time measurements can show where the variability is coming from. This figure shows two consecutive US06 cycles with the same car, same driver, and no violations. The blue trace is real-time black carbon, and the red trace is the accumulated total BC. The most important difference is at the beginning of the third hill, indicated by the black arrows at the bottom. On the left hand trace, there is very little black carbon emitted at that point, but on the right, the same part of the test accounts for the largest spike of BC in that test. The accumulated total shows just how significant that spike was in the overall BC emissions. However, one caveat of this example is that this was a very low PM emitting vehicle, so small events like this can contribute proportionally more to the total than they would for higher emitting vehicles.

In this case, there was a subtle difference in acceleration rate, though it is not visible in these figures. The second test was somewhat closer to the theoretical acceleration of the cycle while on the first test, the driver smoothed out the acceleration slightly, but was still within bounds of acceptable driving.

Figure 9 - Example of US06 variability with the same vehicle and driver

This may appear to suggest that differences between actual speeds of the vehicle will help constrain variability. However, Figure 10 shows another example of US06 variability, once again with consecutive US06 tests. In this example, the green and orange boxes below are
zoomed-in versions of the area in question, with arrows pointing to their location in the test, once again highlighting the same part of two different tests.

In this case, there was no appreciable difference in acceleration rate – here, the actual speed is shown in grey and the theoretical speed in pink. The left and right hand sides are virtually identical regardless of zoom level. However, there were observable differences in some OBD parameters – here showing the calculated load value in orange, and the throttle position in green. Although the vehicle speed was consistent on either test, the driver applied a more aggressive throttle movement in the second test. Calculated load briefly hit 100%, and throttle position was significantly higher at that point than the first trace. This seems to have a big impact on the black carbon emissions immediately afterwards.

This example seems to indicate that even very brief throttle activity can lead to differences in PM emissions, even when actual speed shows very little difference from test to test – so this variability is not random, but is created because the driver input can vary. This additional variability in the US06 cycles is part of the rationale that was used to justify the higher US06 standards.

However, such events are not observed for all vehicles, suggesting that some vehicles may have a PM control strategy that is less sensitive to driver actions than others. ARB will continue to investigate such strategies, to identify possibilities that might be capable of minimizing in-use PM emissions.

It should also be noted that, although both of these examples show higher emissions on the second run-through of the test, that isn't always the case. In some other cases, the first US06 cycle produced higher PM emissions.
IV. Summary of Results

The testing conducted at ARB indicates that many of newer GDI vehicles are emitting significantly lower PM levels than the first generation of GDI technologies. For the FTP cycle, most of the newer GDI vehicles tested here would easily meet the upcoming 3 mg/mi standard. As most GDI vehicles (particularly higher-emitting GDI vehicles) have cold-start dominant PM emissions, controlling cold start PM emissions appears to be the most critical factor to robustly meet the future 1 mg/mi standard. In lieu of or in combination with good PM control, GPFs are a feasible alternative to reduce PM emissions to below 1 mg/mi.

For US06 emissions, most of the newer GDIs tested are emitting well below the upcoming 6 mg/mi standard, with an average of only 1.6 mg/mi. However, with no cold start and more aggressive driving, test-to-test variability is significantly higher with the US06 cycle than it is for FTP cycle. Much of the US06 variability could be due to driver activity, which may not always be reflected in the actual speed of the vehicle. However, aggressive throttle activity is likely to also occur in the real world, and some PM control strategies may be less sensitive to driver input than others thereby providing more robust in-use control.
V. References


VI. Attachment: All test results

Most vehicles were tested at least three times each on the FTP and US06, sometimes up to six times per cycle. For most vehicles, additional test cycles were also completed including the Worldwide Harmonized Light Duty Test Cycle (WLTC), Unified Cycle (UC), and/or Highway (HW15) cycle. Table 6 shows all vehicle results, both as the average for each test cycle for each car, as well as individual test results. Total mass is phase-weighted gravimetric PM mass, total BC is collected with AVL microsoot sensors, and total SPN is collected with either AVL or Horiba solid particle counters (PMP-compliant method, 23nm d50). The two vehicles tested with prototype GPFs are separately listed for testing with and without the GPFs and denoted with bold and darker shading.

### Table 6 - Full PM test results

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<th>Average BC (mg/mi)</th>
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<td>2.45E+12</td>
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<tr>
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<td>2.0 ltr turbo GDI</td>
<td>28,000 mi</td>
<td>US06</td>
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<tr>
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<td></td>
<td></td>
<td></td>
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<td></td>
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<tr>
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<td>2016</td>
<td>1.4 liter GDI turbo</td>
<td>5,000 mi</td>
<td>US06</td>
<td>0.98</td>
<td>0.18</td>
<td>1.01E+12</td>
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</table>

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<table>
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<th>Model Year</th>
<th>Engine Type</th>
<th>Drive</th>
<th>Test Cycle</th>
<th>CO&lt;sub&gt;2&lt;/sub&gt; Emissions (g/mi)</th>
</tr>
</thead>
<tbody>
<tr>
<td>2014 Mercedes CLA</td>
<td>2.0 liter GDI turbo</td>
<td>30,000 mi, L2ULV</td>
<td>FTP</td>
<td>3.57E+11</td>
</tr>
<tr>
<td>2016 Chevy Malibu</td>
<td>2.5 liter GDI</td>
<td>18,000 mi, ULEV</td>
<td>US06</td>
<td>2.40E+12</td>
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<tr>
<td>2016 Chevy Malibu</td>
<td>With GPF</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2016 Honda Accord</td>
<td>2.4 liter GDI</td>
<td>27,000 mi, SULEV</td>
<td>US06</td>
<td>8.97E+11</td>
</tr>
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</table>

**2014 Mercedes CLA**
- Engine: 2.0 liter GDI turbo
- Drive: 30,000 mi, L2ULV
- Test Cycle: FTP
- CO<sub>2</sub> Emissions: 3.57E+11

**2016 Chevy Malibu**
- Engine: 2.5 liter GDI
- Drive: 18,000 mi, ULEV
- Test Cycle: US06
- CO<sub>2</sub> Emissions: 2.40E+12

**2016 Chevy Malibu With GPF**
- Engine: 2.5 liter GDI
- Drive: 18,000 mi, ULEV
- Test Cycle: US06
- CO<sub>2</sub> Emissions: 8.97E+11

**2016 Honda Accord**
- Engine: 2.4 liter GDI
- Drive: 27,000 mi, SULEV
- Test Cycle: US06
- CO<sub>2</sub> Emissions: 8.97E+11
<table>
<thead>
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</thead>
<tbody>
<tr>
<td>2013 Chevy Volt 1.4 liter PHEV PFI 8,000 mi, PZEV</td>
<td>0.32</td>
<td>0.11</td>
<td>1.05E+12</td>
<td>4.71E+11</td>
<td>0.46</td>
<td>0.11</td>
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<td>4.71E+11</td>
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<tr>
<td>2013 Toyota Prius 1.8 liter PHEV PFI 25,000 mi L2SUL</td>
<td>0.12</td>
<td>0.33</td>
<td>1.88E+11</td>
<td>2.04E+11</td>
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<td>0.24</td>
<td>1.88E+11</td>
<td>2.04E+11</td>
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<td></td>
</tr>
<tr>
<td>2016 Toyota Prius 1.8 liter HEV PFI 5,000 mi LEV3 SULEV30</td>
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<td>0.14</td>
<td>0.05</td>
<td>0.05</td>
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<td>0.05</td>
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<td></td>
<td></td>
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</tr>
<tr>
<td>2016 Hyundai Sonata 2 liter PHEV GDI 6,000 mi, L2LEV</td>
<td>1.22</td>
<td>2.31</td>
<td>2.29E+12</td>
<td>3.30E+12</td>
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<td>3.30E+12</td>
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</table>

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I. Introduction

I.A PM Health Effects
California experiences some of the highest concentrations of PM2.5 in the nation.\(^1\) The majority of California’s population lives in areas that exceed the National Ambient Air Quality Standard for PM2.5.\(^2\) This standard is set by the U.S. EPA, and is designed to protect human health and the environment from exposure to harmful levels of PM2.5. As part of the standard setting process, U.S. EPA assesses scientific studies that link exposure to PM2.5 to health effects, including hospitalization due to respiratory illness, and premature death from cardiopulmonary disease.\(^3\) The U.S. EPA has determined that both long-term and short-term exposure to PM2.5 plays a “causal” role in premature death, meaning that a substantial body of scientific evidence shows a relationship between PM2.5 exposure and increased mortality, a relationship that persists when other risk factors such as smoking rates and socioeconomic factors are taken into account\(^3\). These effects are also evidenced by a number of studies that have linked daily exposure to PM2.5 with hospitalization for heart and lung related causes, as well as an increase in emergency room visits, exacerbation of asthma, and other respiratory diseases\(^3\). Black carbon is a significant component of particle matter pollution, which has been linked to adverse health impacts and climate change.

In addition, research studies have found that traffic pollution specifically may be associated with a number of health impacts including slower lung development,\(^4\) increased symptoms and medication use in asthmatic children,\(^5,6\) and even increases in the development of asthma in children.\(^7\) A recent analysis in the Children’s Health Study\(^8\) demonstrated that both regional particulate matter pollution and local near roadway exposures impact children’s health independently, resulting in reduced lung function.

In “The State of the Air 2016”,\(^9\) the American Lung Association found that even with continued improvement in air quality, many people live where the air is unhealthy for them to breathe.


Based on year-round and short-term PM exposure, Los Angeles reported its best air quality ever. However, Bakersfield returned to the top of the most-polluted list for year-round and short-term PM exposures. California cities hold the top 5, and top 4, positions on the lists of worst cities for year-round and short-term PM exposures, respectively. Studies show that cleaning up particle pollution has immediate health benefits and the United States could prevent approximately 34,000 premature deaths a year by lowering annual levels of particle pollution by 1 µg/m. Reductions in air pollution can be expected to produce rapid improvements in public health and fewer deaths within the first two years of reduced exposure.

I.B Black Carbon

Black carbon (BC) is a strong light-absorbing component of fine particulate matter (PM) produced during incomplete combustion of fuels. Black carbon contributes to climate change, both directly by absorbing sunlight and giving off heat, and indirectly by depositing on snow and accelerating snow melt or by interacting with clouds and affecting cloud formation. Both on global and regional scales, black carbon also causes climate change through its contribution to warming and its suppression of precipitation. California may be especially vulnerable to the climate effects of BC. Global warming affects summer water supplies in California that rely predominantly on runoff from mountain snowpack located within the State as well as in the Rocky Mountains (via the Colorado River). Furthermore, a warmer atmosphere over already dry regions, combined with less mountain runoff during the summer months, enhances conditions conducive for wildfires. An increase in the number and intensity of wildfires would add to the number of black carbon particles, further increasing the attendant climate impacts.

Unlike longer-lived greenhouse gases, BC has a very short atmospheric lifetime, only a week or two. Consequently, it has a strong correlation with regional emission sources and, correspondingly, its emission reductions have immediate climate and public health benefits. A comprehensive review article suggests that BC is the second most important human-caused emission in terms of its climate forcing in the present-day atmosphere; only carbon dioxide (CO₂) is estimated to have a greater climate forcing impact. Furthermore, theoretical modeling and laboratory experiments demonstrate that coatings on BC can enhance BC’s light absorption. The mechanism for this enhancement is one in which the coating acts as a lens to focus radiation into the absorbing BC core. Increases in BC coating result from a combination of changing sources and photochemical aging processes. Therefore, reducing BC emissions provides near-term climate benefits, complementing efforts to reduce CO₂ emissions.

Airborne PM represents a complex mixture of organic and inorganic substances that originate from a number of natural and man-made sources. Black carbon is a component of PM, and the scientific literature has shown a consistent association between PM2.5 exposure and hospitalizations and premature death. In 2010, ARB estimated that the number of annual PM2.5-related premature deaths is approximately 9,000 in California.\textsuperscript{15} Thus, black carbon mitigation measures and the associated decline in PM provide both immediate climate benefits and important health and economic co-benefits. ARB has taken significant action in the past two decades to reduce PM and black carbon emissions, but more must be done to meet the State’s climate and air quality goals.

II. Estimated emission benefits of the 1 mg/mi standard
The projected emission benefit from the 1 mg/mi standard was updated using EMFAC 2014 to calculate the PM2.5 benefits. Table 1 below summarizes the phase-in of the LEV III 1 mg/mi FTP PM standards which begins phasing in with 25% of vehicles in MY 2025, and full compliance by MY 2028.

<table>
<thead>
<tr>
<th>Percent of vehicles meeting the 1 mg/mi standard</th>
<th>2025 MY</th>
<th>2026 MY</th>
<th>2027 MY</th>
<th>2028 MY</th>
</tr>
</thead>
<tbody>
<tr>
<td>25%</td>
<td>50%</td>
<td>75%</td>
<td>100%</td>
<td></td>
</tr>
</tbody>
</table>

For the analysis, FTP composite emission rates for future GDI vehicles were estimated to be 1.5 mg/mi and 0.7 mg/mi for vehicles certified to the 3 mg/mi and 1 mg/mi certification standards, respectively. The emission rate of 1.5 mg/mi for vehicles complying with the 3 mg/mi standard was based on the current test results shown in Appendix K, older ARB test results of low PM emitting vehicles, manufacturer information about expected compliance levels, and experience with historical criteria pollutant compliance. Similarly, the emission rate of 0.7 mg/mi for vehicles complying with the 1 mg/mi standard was based on a subset of the test results shown in Appendix K combined with analyzing the distribution of PM emissions during the test cycle to estimate a likely distribution that would lead to a composite test result, with some headroom, for compliance with the 1 mg/mi standard.

II.A Results of the analysis
The results of the analysis are provided in statewide tons per year of PM2.5 benefits. Results are also provided for the San Joaquin Valley basin given the particular focus on further PM reductions needed in that region. For reference, mobile sources are projected to emit 25,000 tons per year statewide and 3,000 tons per year in the San Joaquin Valley Air Basin in 2035.\textsuperscript{16}


Figure 1 below shows the statewide benefits estimated from the standard approach 200 tons/year, or 0.55 tons/day, by 2050.

Figure 1 - Statewide tons per year of PM2.5 benefits

For the San Joaquin Valley, the estimated benefits are shown in Figure 2 below. Relative to the statewide benefits, the benefits are smaller but not insignificant, approaching 25 tons/year, or 0.07 tons/day, in 2050.

Figure 2 - San Joaquin Valley tons per year of PM2.5 benefits
II.A.1 Earlier implementation of the standard
The Board directed staff in the Resolution, “that in the interest of the Board’s goal of reaching the proposed 1 mg/mi PM standard before the 2025 timeframe”, staff should assess the feasibility of implementing the standard earlier than adopted. Appendix J provides staff’s assessment of the status of PM control technology including the readiness of technology for an earlier implementation. However, to provide perspective on the impact of earlier implementation, staff analyzed the incremental emission benefit of earlier implementation of the 1 mg/mi PM standard.

II.A.2 Assumptions for early implementation analysis
Staff analyzed the incremental emission benefit of phasing in the 1 mg/mi PM standard immediately following the last year of the 3 mg/mi phase-in. The evaluated phase-in is shown in Table 2 below and, respective to regulatory process and lead time requirements, represents the earliest possible phase-in of the 1 mg/mi standard. The scenario effectively reflects an implementation of the 1 mg/mi standard three years earlier than scheduled.

Table 2 - Early phase-in of 1 mg/mi PM standard scenario

<table>
<thead>
<tr>
<th></th>
<th>2022 MY</th>
<th>2023 MY</th>
<th>2024 MY</th>
<th>2025 MY</th>
</tr>
</thead>
<tbody>
<tr>
<td>Percent of vehicles meeting the 1 mg/mi standard</td>
<td>25%</td>
<td>50%</td>
<td>75%</td>
<td>100%</td>
</tr>
</tbody>
</table>
II.B Results of emission benefit analysis

The results of the analysis are provided in tons per year of PM2.5 benefits for both statewide and for the San Joaquin Valley basin. Staff used EMFAC 2014 to estimate the environmental benefits of earlier implementation. The statewide emissions results are shown in Figure 3 and while they show the maximum incremental emission benefits approach 50 tons/year, or 0.13 tons/day in 2027, the benefits decrease subsequent to that. By 2040, the earlier implementation results in just over 12 tons/year, or 0.03 tons/day, of annual and benefit and no additional annual benefit by 2050. For perspective, total statewide exhaust PM emissions from light-duty vehicles are estimated to be 2.2 tons/day in 2040 so the earlier implementation would reflect an approximate 1% increase in benefits.

Figure 3 - Statewide PM Emissions benefits in tons per year

Looking at the San Joaquin Valley Air Basin, the emission benefits from earlier implementation are shown in Figure 4. Maximum emission reductions are less than 5 tons/year, or 0.01 tons/day. By 2040, benefits are less than 1.5 tons/year, or 0.004 tons/day. By 2025, the tentative deadline for compliance requested in the recently proposed San Joaquin Valley SIP, the early implementation would provide less than 0.01 tons/day of benefit which represents less than a 1% reduction in on-road mobile source estimated PM emissions in the SJV or less than 0.01% relative to all PM sources in the SJV.
II.C PM Inventory for Black Carbon

Over the past several decades, California’s actions to improve air quality, fight climate change, and protect public health have resulted in significant short-lived climate pollutant reductions including black carbon. California has cut anthropogenic black carbon emissions by over 90 percent since the 1960s, and existing measures are projected to cut mobile source emissions by 75 percent and total anthropogenic emissions by nearly 60 percent between 2000 and 2020. These reductions have come from strong efforts to reduce on-road vehicle emissions, especially diesel particulate matter. Car and truck engines used to be the largest sources of black carbon emissions in California, but California’s existing air quality policies will virtually eliminate black carbon emissions from on-road diesel engines within 10 years.

Black carbon emission reduction programs from the transportation sector in California include:

- **Cleaner trucks and buses**: Current regulations will reduce black carbon emissions from existing trucks and buses by 80% in 2020, compared to 2000 levels.
- **Off-road and construction equipment**: New engine standards for off-road vehicles will reduce their black carbon emissions by 60% in 2020, compared to 2000 levels.
- **Clean fuel rules**: Clean Fuel Specifications enable cleaner vehicle technologies for both cars and trucks. The Low Carbon Fuel Standard provides a strong financial incentive to develop clean fuel alternatives that lead to little or no emissions of black carbon.
- **Cleaner freight technologies**: The Air Resources Board has developed a Sustainable Freight Strategy that will move California to a near-zero emission freight transport by 2050.
- **Funding for cleaner cars and trucks**: Approximately $1.6 billion has been distributed over the past 15 years to clean up diesel engines and reduce black carbon emissions.
California’s black carbon emissions inventory relies on PM inventories coupled with speciation profiles that define the fraction of PM that is black carbon. The sources that emit black carbon are well understood from a control prospective and major anthropogenic (e.g., non-forestry) sources are regulated in California. The major anthropogenic sources of black carbon in 2013 include diesel-fueled mobile sources, fuel combustion and industrial processes, and residential fireplaces and woodstoves. Off-road mobile emissions account for over a third of statewide anthropogenic black carbon emissions. On-road mobile sources account for nearly a quarter of emissions, primarily from on-road diesel combustion. On-road gasoline and brake and tire wear emissions are smaller.

As pointed out earlier, cutting emissions of short-lived climate pollutants such as black carbon provides a significant pathway for slowing the impacts of climate change. ARB’s proposed short lived climate pollutant reduction strategy (reducing black carbon emissions by 50 percent and other SLCPs by 40 percent below current levels by 2030) rightly points out California’s impressive track record in reducing black carbon emissions from mobile sources over the past fifty years through implementation of stringent particle mass emission standards for new vehicles and engines. The adopted 3 mg/mi and 1 mg/mi standards continue this work to reduce PM and black carbon emissions from the light-duty sector. California is committed to continuing to reduce emissions of black carbon to meet ongoing air quality and climate targets.

II.C.1 Assumptions for Black Carbon benefit calculations

Estimated black carbon emission reductions were calculated for the incremental emission benefit of the 1 mg/mi standard based on the BC to total PM regression as described in Appendix K. From recent testing, approximately 75% of gravimetric PM is made up of black carbon and this fraction was assumed for all of the estimated PM benefits calculated above for the 1 mg/mi standard.

Since BC concentrations vary spatially, it is difficult to quantify its global warming potential (GWP), and there are significant variations in the GWP values for BC emissions assigned to different regions. Regional differences in atmospheric BC concentrations, and hence the warming effects of BC, depend upon the regional climate, radiation properties, and deposition pathways. Conclude that the GWP value varies by about ±30 percent between emitting regions.

Bond et al. recommend a global mean BC GWP of 900 for the 100-year time horizon commonly used in calculating CO2 equivalent benefits. This should be considered a conservative estimate for fossil fuel BC forcing in California, as a 20-year time horizon (GWP of 3,200) gives a better perspective on the speed at which BC controls will impact the atmosphere relative to CO2 emission controls.

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18 Bond, 2013.
19 Bond, 2013.
II.C.1 Black Carbon – summary of benefits
Black carbon emissions reductions are calculated based on the BC to total PM regression as described in Appendix K. Overall 75% of gravimetric PM is made up of black carbon. Using the assumptions and methodology noted above, Based on the inventory analysis the black carbon benefits were calculated in units of CO2 equivalent million metric tons (MMTCO2e) for direct comparison to other 100-year GWP calculations of GHG benefits. The statewide black carbon benefits in 2050 are estimated to be resulting MMTCO2e for the 1 mg/mi standard in 2050 is 0.12 MMTCO2e. When compared to the 2050 target of 85 MMTCO2e for all sources in California, and with 15 MMTCO2e of that 85 attributed to for all light duty vehicles, in 2050 the climate change benefit from the light duty 1 mg/mi PM standards is small but directionally helpful. When utilizing the 20-year GWP values (3200) instead of the 100-year values, the benefits are calculated to be 0.43 MMTCO2e in 2050. Further, the increased localized sensitivity to black carbon in California as noted earlier and the immediate benefits from further reductions support continued aggressive actions to reduce all sources where feasible and are consistent with ARB’s proposed short lived climate pollutant reduction strategy.

III. Summary of health effects and emission benefit calculations
The relationship between PM exposure and health effects is well documented in that increased exposure leads to cardiopulmonary disease. The black carbon fraction of PM also has a strong GWP, between 900 and 3200 times more powerful than CO2, making even small reductions in black carbon directionally beneficial to meeting California’s GHG reduction goals. The PM and black carbon benefits from the 1 mg/mi standard are small but appreciable however the incremental benefits associated with earlier implementation are so small as to be below the margin of error of the health effects analysis method.
IV. References


California's Advanced Clean Cars Midterm Review

Appendix M:
California GHG Technology Trends

January 18, 2017
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At the 2012 Advanced Clean Cars (ACC) rulemaking, the California Air Resources Board (ARB or the Board) asked staff to examine whether a shift in California's fleet mix to larger vehicles and the reclassification of cars as trucks that deviates from what was projected in the original rule would impact the expected benefits of LEV III GHG regulation (Resolution 12-11). As discussed in the 2016 draft joint-agency Technical Assessment Report (2016 TAR), it is expected that nationwide, the mix of new vehicle sales will shift to more trucks and fewer cars than was originally projected in 2012. In terms of the California fleet, as will be shown below, the trends are similar but the overall impact on GHG emissions is different because of a larger fraction of car sales in California’s market. The Board also asked staff to study any changes in the footprint size for cars and trucks to evaluate any impacts on emission benefits. This is also reviewed here.

I. Introduction
The calculation of greenhouse gas (GHG) emission benefits associated with the California Pavley and Low-Emission Vehicle (LEV III) GHG regulations (LEV III GHG) requires assumptions about the future relative fraction of cars and trucks sold in the California fleet as well as the sizes (footprint) of the vehicles sold to determine the actual carbon dioxide (CO₂) emission targets that will apply. The 2011 Initial Statement of Reasons (ISOR) analysis for the ACC LEV III rulemaking projected CO₂ emission targets based on assumptions about future car/truck sales splits and vehicle footprints.¹ Specifically, staff used the EMFAC 2011 model to project future car/truck sales splits in California while new vehicle footprints were kept at the California 2008 fleet baseline value (45.1 and 52.3 square feet for cars and trucks, respectively). The car sales ratios (fraction of new light-duty vehicle sales that meet the passenger car definitions applicable to GHG and Corporate Average Fuel Economy or CAFE standards) and footprint assumptions for the 2012 – 2025 model years used in the ACC ISOR are shown in Figure 1.

Based on these assumptions, staff calculated the CO₂ emission targets for each model year from 2012 to 2025 and determined the percent annual changes in CO₂ emission targets relative to the 2008 baseline CO₂ target. These percent annual changes were subsequently used to adjust the real world CO₂ emission factors in the EMFAC 2011 LDV inventory model, which could then be used to calculate real world CO₂ emission reductions for new vehicles in California from 2012 to 2025. The projected CO₂ emission targets and relative changes in CO₂ emission target for cars, trucks and the combined fleet are shown in Table 1, which is taken from Table III-A-3-3 of the ACC LEV III ISOR:
Table 1 - Projected targets for light-duty vehicle gCO₂/mile emission rates

<table>
<thead>
<tr>
<th>Model year</th>
<th>Car</th>
<th>Truck</th>
<th>Combined light-duty</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>gCO₂/mi</td>
<td>Annual change</td>
<td>gCO₂/mi</td>
</tr>
<tr>
<td>Baseline</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2008-2011</td>
<td>291</td>
<td>0%</td>
<td>306</td>
</tr>
<tr>
<td>2012</td>
<td>265</td>
<td>2.9%</td>
<td>240</td>
</tr>
<tr>
<td>2013</td>
<td>250</td>
<td>2.7%</td>
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</tr>
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<td>238</td>
<td>3.0%</td>
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<tr>
<td>2020</td>
<td>185</td>
<td>3.0%</td>
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</tr>
<tr>
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<td>164</td>
</tr>
<tr>
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<td>3.0%</td>
<td>156</td>
</tr>
<tr>
<td>2023</td>
<td>158</td>
<td>3.0%</td>
<td>149</td>
</tr>
<tr>
<td>2024</td>
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<td>143</td>
</tr>
<tr>
<td>2025</td>
<td>144</td>
<td>3.0%</td>
<td>137</td>
</tr>
</tbody>
</table>

Average change, (2016-2025) 4.9% 4.1% 4.5%

Change, 2009-2016 -23% -23% -23%
Change, 2016-2025 -32% -32% -32%
Change, 2008-2025 -51% -51% -51%

Notes: Car, truck, overall targets shown are based on projected sales of vehicles by footprint, category (ultimate gCO₂/mile levels are determined by end-of-year sales); the original California GHG standards for model years 2009-2011 are based on a different two-category system (FC/LDT1 and LDT2) than the car and truck system of the 2012-2010 federal standards and proposed 2017-2025 standards; Difference of individual columns may not match due to rounding.

Since the 2012 ACC rulemaking, new data concerning car/truck sales splits and vehicle footprints for vehicles sold in California have become available for the 2012 - 2014 model years. Specifically, staff acquired nationwide car/truck sales splits and vehicle footprint data from the annual manufacturer performance reports released by the United States Environmental Protection Agency (U.S. EPA) combined with California-specific sales information provided by the vehicle manufacturers. These annual reports are developed from nationwide sales data submitted by individual auto manufacturers and are required by law to be made available to the public. In order to acquire California-specific data from these reports, staff requested information from individual auto manufacturers in the same format they submitted to the U.S. EPA, but constrained to vehicles sold only in California. The specific manufacturer and model year data acquired are shown in Table 2. The combined sales volumes for the manufacturers who submitted such data to ARB represent approximately 90% of total nationwide vehicle sales in the 2012 – 2014 model year timeframe. Based on this data, staff developed new projections of California car/truck sales splits and vehicle footprints, which were then used to calculate modified CO₂ emission targets for the combined car/truck vehicle fleet.
Table 2 - California car/truck sales and footprint data. 
An “X” in the box indicates data were available for the specific manufacturer and model year

<table>
<thead>
<tr>
<th>Manufacturer</th>
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<th>2014</th>
</tr>
</thead>
<tbody>
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<td>X</td>
</tr>
<tr>
<td>Fiat Chrysler</td>
<td>X</td>
<td>X</td>
<td>X</td>
</tr>
<tr>
<td>Ford</td>
<td>X</td>
<td>X</td>
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</tr>
<tr>
<td>GM</td>
<td>X</td>
<td>X</td>
<td>X</td>
</tr>
<tr>
<td>Honda</td>
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<td>X</td>
<td>X</td>
</tr>
<tr>
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<tr>
<td>Mercedes</td>
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<td>X</td>
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<tr>
<td>Mitsubishi</td>
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<td>X</td>
<td>X</td>
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<td>X</td>
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<td>Porsche</td>
<td>X</td>
<td>X</td>
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<td>X</td>
<td>X</td>
</tr>
<tr>
<td>Toyota</td>
<td>X</td>
<td>X</td>
<td>X</td>
</tr>
<tr>
<td>Volvo</td>
<td>X</td>
<td>X</td>
<td></td>
</tr>
</tbody>
</table>

II. Methodology
The calculation of new California CO₂ emission targets required two steps. The first step involved using the actual California sales/splits and vehicle footprint data from the performance reports to calculate new combined CO₂ emission targets for the 2012 – 2014 model years. The second step involved the forecasting of new car/truck sales splits and vehicle footprints for future model years. A detailed description of the second step is provided below for the car/truck sales splits and footprint projections.

II.A. Car/Truck Sales Split Projections
The car/truck sales split projections were based on two data sources. The first source was the 2012 – 2014 performance report data. These data were used to derive a three-year trend line in the car sales ratio. This trend line showed a decrease in the car sales ratio from 2012 to 2014. The second data source was the 2016 Annual Energy Outlook (AEO) published by the Energy Information Administration. This report projects nationwide car/truck sales splits from 2014 to 2040 based on assumptions about economic growth and future fuel price forecasts. ARB used this data source for the future car/truck sales projections to be consistent with the analyses done for the federal mid-term evaluation.

For this analysis, staff examined car/truck sales splits associated with three AEO scenarios: the reference case, the high oil price case, and the low oil price case. In regards to the low oil price and high oil price cases, AEO incorporates assumptions regarding future global oil demand and investment in the oil sector. Figure 2 below shows the crude oil prices projected in the AEO for each of the cases with crude oil barrel prices varying from just over $50 in 2015 to approximately $40, $90, and $190 in 2025 for the low oil price, reference, and high oil price

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cases, respectively. Figure 3 shows the resultant projected price per gallon for gasoline in each of these three cases starting at $2.52 per gallon in 2015 and following different trajectories to reach approximately $2.00, $3.00, and $4.75 per gallon for the low oil price, reference, and high oil price cases, respectively.

Figure 2 - Oil Prices for AEO 2016 Projections

![Crude Oil Prices (2015 $/barrel)](chart)

- **High Oil Price**
- **Reference Case**
- **Low Oil Price**
In all three of these scenarios, the AEO projects a continuing decrease in car sales ratios beyond 2014 before bottoming out at a particular future year (dependent on which AEO scenario is being utilized). At that point, the decline ends and car sales ratios begin to increase steadily (or flatten in the low oil price scenario) through 2025. For this analysis, staff used the slope of the three-year trend line in car sales ratio from the actual California fleet 2012 through 2014 model year performance reports to extrapolate the decline out to the “bottom out” year of the AEO projections. The car sales ratios after that year were then projected to rise consistent with the relative annual increase in the AEO trend lines for each scenario. The 2014 to 2025 projected car sales ratios are shown in Figure 4, Figure 5, and Figure 6 for the reference, high fuel price case, and low fuel price case, respectively.
Figure 4 - Projected car sales ratios based on AEO reference case trends

Figure 5 - Projected car sales ratios based on AEO high oil price case trends
Figure 6 - Projected car sales ratios based on AEO low oil price case trends

Table 3 summarizes the car sales percentages in tabular form. Note that shaded cells reflect actual data for the California fleet while the unshaded cells represent future projections. Also of note is that the actual car share in 2012 through 2014 turned out to be significantly higher than projected for the original rulemaking. Despite the recent decline in car sales and projected continuation of that trend for the next 1 to 7 years in the various AEO scenarios, the updated car sales ratio for 2025 is still higher than the original 2012 ACC projections.
II.B. Vehicle Footprint (FP) Projections

In order to assess the impact of larger footprints on CO₂ emission targets in California, staff used the California-specific 2012 – 2014 performance report data in conjunction with the 2015 U.S. EPA Trends Report to calculate future footprints. Specifically, a seven-year nationwide footprint trend line was derived from the Trends Report for 2008 to 2014 and used to calculate an average annual growth rate for both cars and trucks (Figure 7).

Table 3 - Summary of Projected Car Sales Ratios

<table>
<thead>
<tr>
<th>Model Year</th>
<th>ACC ISOR</th>
<th>AEO Reference</th>
<th>AEO High Fuel</th>
<th>AEO Low Fuel</th>
</tr>
</thead>
<tbody>
<tr>
<td>2012</td>
<td>0.65</td>
<td>0.73</td>
<td>0.73</td>
<td>0.73</td>
</tr>
<tr>
<td>2013</td>
<td>0.64</td>
<td>0.72</td>
<td>0.72</td>
<td>0.72</td>
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<tr>
<td>2014</td>
<td>0.63</td>
<td>0.70</td>
<td>0.70</td>
<td>0.70</td>
</tr>
<tr>
<td>2015</td>
<td>0.62</td>
<td>0.69</td>
<td>0.69</td>
<td>0.69</td>
</tr>
<tr>
<td>2016</td>
<td>0.62</td>
<td>0.68</td>
<td>0.74</td>
<td>0.68</td>
</tr>
<tr>
<td>2017</td>
<td>0.61</td>
<td>0.67</td>
<td>0.76</td>
<td>0.67</td>
</tr>
<tr>
<td>2018</td>
<td>0.61</td>
<td>0.68</td>
<td>0.77</td>
<td>0.66</td>
</tr>
<tr>
<td>2019</td>
<td>0.61</td>
<td>0.71</td>
<td>0.79</td>
<td>0.64</td>
</tr>
<tr>
<td>2020</td>
<td>0.61</td>
<td>0.73</td>
<td>0.81</td>
<td>0.63</td>
</tr>
<tr>
<td>2021</td>
<td>0.60</td>
<td>0.74</td>
<td>0.82</td>
<td>0.62</td>
</tr>
<tr>
<td>2022</td>
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<td>0.75</td>
<td>0.83</td>
<td>0.62</td>
</tr>
<tr>
<td>2023</td>
<td>0.60</td>
<td>0.75</td>
<td>0.83</td>
<td>0.62</td>
</tr>
<tr>
<td>2024</td>
<td>0.61</td>
<td>0.76</td>
<td>0.84</td>
<td>0.62</td>
</tr>
<tr>
<td>2025</td>
<td>0.61</td>
<td>0.76</td>
<td>0.84</td>
<td>0.62</td>
</tr>
</tbody>
</table>
The average annual growth rates were then used to project future California footprints using the 2014 performance report footprint data as a starting point. Once this was completed, new CO₂ emission targets were calculated using the footprint curves for the adopted national GHG standards through 2025. The projected footprints and the associated CO₂ emission targets are provided in Figure 8 and Table 4, respectively.
After the new CO₂ targets were generated for cars and trucks, staff combined the results with the previously calculated car sales ratio projections to calculate new combined CO₂ emission targets under the various scenarios.
The California and national fleets are showing a very slight increase in the sales weighted footprint of the combined fleet but it is not yet clear if the constructs of the GHG standards are influencing this trend. In its 2015 Trends Report, U.S. EPA looked at the sales-weighted average footprint for new cars and trucks sold nationwide for the 2008 through 2014 model years and projected for the 2015 model year. In the analysis done by ARB based on these data, the average footprint of a new car has increased by 0.8 square feet (approximately 1.8 percent) and the average footprint of a new truck has increased by 1.5 square feet (approximately 2.8 percent) within this time period. When combined with the increasing share of the market from truck sales, the combined car/truck fleet-wide average footprint has increased relative to what was originally projected.

The biggest influence appears to be a higher share of truck sales that generally have a larger footprint than cars rather than a significant increase in the average footprint within the car or truck segment itself. However, given the substantial lead time necessary to redesign base vehicle platforms including parameters that determine the footprint, it is probably too early to determine the impact of standards adopted only four years ago.

Of note, however, is that U.S. EPA’s more recent 2016 Trends Report, which was released subsequent to this analysis by ARB, shows that the actual 2015 model year resulted in a smaller sales-weighted average footprint for trucks than the 2014 model year while the footprint for cars remained virtually unchanged. Accordingly, ARB’s analysis likely over-estimates the growth in truck footprint and, therefore, represents a conservative estimate of GHG reductions in this scenario.

III. Calculation of Future CO₂ Emission Targets

Staff developed four scenarios to gain a better understanding of the potential impacts of changes in future car/truck sales splits and increased footprints on CO₂ emission targets. These four scenarios are described below.

Scenario 1: Assume future car sales ratios follow the AEO reference scenario.

Scenario 2: Assume future car sales ratios follow the AEO high oil price scenario.

Scenario 3: Assume future car sales ratios follow the AEO low oil price scenario.

Scenario 4: Assume future car sales ratios follow the AEO reference scenario and that car and truck footprints increase according to the projections described in the previous section.

For each of these scenarios, staff calculated a combined (car plus truck) CO₂ emission target for each of the model years from 2012 to 2025.

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IV. Results

The results from each of the four scenarios are summarized in Table 5 below. The original CO$_2$ emission targets from the ACC ISOR are provided for comparison purposes. The results are shown graphically in Figure 9. In the first three scenarios, the initial CO$_2$ emission targets in 2012 are below the ACC ISOR value and continue to remain below the ISOR values out to 2025. In the fourth scenario, the initial CO$_2$ emission target is also below the ACC ISOR value but begins to exceed the ISOR values in 2014 and continues to stay at or above the ISOR values out to 2025. The lower CO$_2$ emission targets in the first three scenarios for all model years are expected given the higher car sales ratios in those model years. In the fourth scenario, the larger footprints beginning in 2015 begin to offset the benefits of the higher car sales ratios.

Table 5 - Combined Car/Truck CO$_2$ (g/mile) Emission Targets in Different Scenarios

<table>
<thead>
<tr>
<th>Model Year</th>
<th>ACC ISOR</th>
<th>AEO Reference</th>
<th>AEO High Fuel</th>
<th>AEO Low Fuel</th>
<th>AEO Reference + FP Changes</th>
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</thead>
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<td>2025</td>
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<td>157</td>
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<td>167</td>
</tr>
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V. Additional Analyses

In the draft 2016 TAR, U.S. EPA revised their forecast for the 2025 average car, truck, and combined CO₂ emission targets based on updated projections of car/truck sales splits and vehicle footprints. The updated compliance scenario shows the nationwide combined fleet average is projected to be 175 gCO₂/mile in 2025 model year instead of 163 gCO₂/mile as originally projected in 2012. The primary cause for the higher carbon emissions is a shift in the nationwide car/truck fleet mix to a larger share of trucks than was projected in 2012. Some stakeholders have expressed concern with the fleet mix change resulting in a higher GHG emissions nationwide in 2025 than anticipated and have asked what would be required to get the 2025 fleet back to the original projections of 163 gCO₂/mile. The following analysis considers only changes in stringency, costs, and technology mix. First, the stringency of the standard would have to increase by approximately 5.7% per year from 2021 to 2025 to achieve the original CO₂ fleet average target. The U.S. EPA OMEGA model was used to calculate the incremental costs and incremental technology penetration rates needed to achieve the original 163 gCO₂/mile target in the nationwide fleet. For the analysis, all of the input files and baseline fleet assumptions were those used for the draft 2016 TAR and are described in detail in the TAR. Subsequent updates to the input files and baseline fleet done by U.S. EPA for the Proposed Determination are not reflected in this analysis.

The incremental costs associated with achieving the 163 gCO₂/mile target in 2025 are shown in Table 6 below. These results indicate manufacturers would incur approximately $500 in additional per vehicle incremental costs to achieve the original CO₂ target, above and beyond
the costs ($894) estimated by U.S. EPA for the fleet in the draft 2016 TAR to reach 175 gCO₂/mile. In regards to technology penetration rates compared to the draft 2016 TAR findings, the modeling results show manufacturers would need to utilize higher amounts of several technologies including mild 48 Volt hybrids (33% vs. 18%), Atkinson engines (58% vs. 44%), cooled EGR (70% vs. 53%), and more efficient transmission systems (61% vs 39%).

**Table 6 - Incremental costs* needed to achieve 163 gCO₂/mile targets in 2025**

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<th>Manufacturer</th>
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<th>Truck</th>
<th>Combined</th>
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</thead>
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<tr>
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<tr>
<td>Fleet</td>
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<td>$500</td>
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</tbody>
</table>

* Above and beyond the costs estimated by U.S. EPA for the compliance fleet in the draft 2016 TAR for 175 gCO₂/mile.

**VI. Summary and Conclusions**

When considered in total, the newer and more accurate information regarding footprint and car/truck share in the California fleet does result in a different projection of GHG benefits than originally estimated for the 2012 ACC rulemaking. With the data available today, staff now know that the actual car share was much higher than the approximate 63 percent assumed in the 2012 rulemaking and, despite a recent shift to trucks, California car sales are still higher than 63 percent today. Even when applying the trends from the recent AEO 2016 projections to the California fleet mix starting point, the 2025 projections for California result in a higher car share than the original assumption.

When combined with the increasing share of the market from truck sales, the combined car/truck fleet average footprint has increased relative to what was originally projected. The biggest influence appears to be a higher share of truck sales that generally have a larger footprint than cars rather than a significant increase in the average footprint within the car or truck segment itself. However, a slight increase in the sales-weighted average footprint has been observed within both the car and truck segment.
Accordingly, the combined new car/truck fleet average in California for the 2025 model year is now projected to be 158 gCO₂/mile when using the AEO Reference case and in the range of 153 to 167 gCO₂/mile in the various scenarios explored. Only in the sensitivity case using the AEO Reference, coupled with an increase in footprint, does the combined new car/truck fleet average exceed what was estimated in the original 2012 ARB rulemaking. This revised projection is independent of the national fleet analysis in the 2016 TAR given the different car/truck market trends in California.

At the national level, modeling of compliance scenarios has projected that the fleet will now be at 175 gCO₂/mile in 2025 and not reach the 163 gCO₂/mile target as originally projected in the 2012 federal rulemaking due to the increased fraction of projected truck sales in the national fleet. Additional analyses of the nationwide fleet using the U.S. EPA’s OMEGA model found it would require an additional $500 per vehicle, above and beyond the $894 projected in the draft 2016 TAR to meet the current standards, to meet more stringent 2022 through 2025 model year standards sufficient to bring the national fleet to the original projected fleet-wide average of 163 gCO₂/mile in 2025. As expected, the modeling also showed higher levels of advanced technologies would need to be deployed on vehicles, primarily in advanced gasoline engines, transmissions, and mild hybrid systems while projected levels of advanced electrification such as plug-in hybrids and battery electric vehicles remain at levels below 5%, collectively.
VII. References


