Appendix G

Literature Review on

Transit Bus Maintenance Cost

Table of Contents

Contents **Page**

List of Figures

List of Tables

Note: This document was originally released in August 2016 and is available at https://www.arb.ca.gov/msprog/bus/maintenance_cost.pdf. This appendix contains minor changes from the original posting. A few new studies on zero-emission buses conducted by the National Renewable Energy Laboratory (NREL) have been released since the publication of this document. These NREL studies include:

- Zero Emission Bay Area (ZEBA) Fuel Cell Bus Demonstration Results: Sixth Report[1]
- The Zero-Emission Bus Evaluation Results: King County Metro Battery Electric Buses Report[2]
- Foothill Transit Agency Battery Electric Bus Progress Report[3]

This appendix does not include review of the data from these studies. However, similar to the previous NREL studies that staff has reviewed in the original discussion draft; these new studies reflect the snapshots of maintenance cost for a small number of buses. More effort is needed for long-term, continued study to accurately understand the life cycle maintenance cost.

A. Introduction

The Advanced Clean Transit Workgroup has been working towards developing a comprehensive analysis of the total cost of ownership of conventional buses to buses with advanced technologies. In past meetings, several questions arose about maintenance cost savings estimates for zero emission buses. This summary is a review of available empirical data to answer questions about what maintenance costs per mile should be used for battery electric and fuel cell electric buses when comparing total cost of ownership to a typical conventional bus. Other costs, such as capital and operating cost, will be addressed separately.

Zero emission bus manufacturers regularly include estimates of maintenance cost savings in total cost of ownership comparisons to conventional buses. Recently, battery

---

[1] National Renewable Energy Laboratory (NREL) (2017). Zero Emission Bay Area (ZEBA) Fuel Cell Bus Demonstration Results: Sixth Report. September 2017. Available: https://www.afdc.energy.gov/uploads/publication/zeba_fcb_rpt6.pdf.

[2] Federal Transit Administration (FTA) (2018). Zero-Emission Bus Evaluation Results: King County Metro Battery Electric Buses. February 2018. Available: https://www.transit.dot.gov/sites/fta.dot.gov/files/docs/research-innovation/115086/zero-emission-bus-evaluation-results-king-county-metro-battery-electric-buses-fta-report-no-0118.pdf.

[3] National Renewable Energy Laboratory (NREL) (2018). Foothill Transit Agency Battery Electric Bus Progress Report - Data Period Focus: Jan. 2017 through Dec. 2017. May 2018. Available: https://www.afdc.energy.gov/uploads/publication/foothill_transit_bec_progress_rpt.pdf.

electric bus manufacturers, including BYD, New Flyer, and Proterra, indicate there are substantial maintenance cost savings with battery electric buses compared to conventional buses. BYD estimates there is a $563 saving per month and $81,072 saving for the 12-year use of the bus[4]. Proterra estimates there are at least $135,000 maintenance cost saving over the lifetime of a bus[5] , which is about $938 saving per month. New Flyer estimates the maintenance cost savings of $124,000 over the life of their Xcelsior battery-electric bus (about $861 per month) compared to the same bus with a diesel or CNG engine)[6].

Transit fleets have questions about what the cost savings may be and whether there is empirical data to substantiate cost saving claims by bus manufacturers. This discussion paper describes several studies that have maintenance cost information and other published sources with the purpose of answering questions about maintenance costs for electric drive trains and propulsion systems as compared to conventional buses. This information will be incorporated into the full total cost of ownership analysis as appropriate.

In the early 2000's, hybrid electric drive systems were successfully incorporated into transit buses with battery electric and conventional diesel engines systems. There are now around 7,000 hybrids operating in the U.S., and some are approaching the end of their normal useful lives[7]. Trolley buses (with overhead wire systems) have been using electric drive systems for more than 50 years. Eight generations of fuel cell electric buses have been demonstrated in small numbers for more than fifteen years that contribute to the development of fuel cell technology that is now commercially available. There has been one fuel cell power plant in a transit bus that has accumulated over 22,000 hours and continues to operate, which has far surpassed the DOE/FTA 2016 target of 18,000 hours[8]. Battery electric buses are being sold commercially in the United States in small numbers, and most have been successfully operating in transit bus fleets for less than 5 years. There is no information on the midlife overhaul maintenance cost on BEBs from empirical data. A number of studies have evaluated

---

[4] BYD Motors Inc. (2015). BYD 40' K9 Electric Bus Lease Proposal prepared for: Anaheim Resort Transportation. June 18, 2015.
[5] Proterra (2015). Information provided by Proterra on November 23, 2015.
[6] New Flyer (2016). Personal Communication with David Warren, Director of Sustainable Transportation. February 10, 2016.
[7] Federal Transit Administration (FTA) (2014). 2014 Revenue Vehicle Inventory. 2014. Available: https://www.transit.dot.gov/sites/fta.dot.gov/files/2014%20Revenue%20Vehicle%20Inventory_0.xlsx.
[8] National Renewable Energy Laboratory (NREL) (2016). Zero Emission Bay Area (ZEBA) Fuel Cell Bus Demonstration Results: Fifth Report. June 2016. Available: http://www.nrel.gov/docs/fy16osti/66039.pdf.

operation and maintenance characteristics of different electric propulsion technologies compared to conventional buses in different fleets.

Available studies that were reviewed include those conducted by the National Renewable Energy Laboratory (NREL) from as early as 2004 to 2015. The NREL studies cover six transit agencies including the following:

- Foothill Transit fast-charging battery electric buses compared to compressed natural gas (CNG) buses[9]
- King County (KC) Metro Transit diesel hybrid buses compared to diesel buses[10]
- New York City Transit (NYCT) diesel hybrid buses compared to CNG buses[11],[12]
- Alameda-Contra Costa Transit (AC Transit) fuel cell electric buses compared to its diesel buses[13]
- SunLine Transit fuel cell electric buses compared to CNG buses[14]
- British Columbia Electric Railway (BC Transit) fuel cell electric buses compared to diesel buses[15]

These studies only reflect the snapshots of maintenance cost for a limited number of buses, and generally reflect costs associated with newer buses. Additional data is needed to complete a full life cycle maintenance cost analysis, including mid-life overhaul cost, but that is not the focus of this literature review.

More information is also available in a Stanford University independent study for its slow-charging battery electric buses. In addition, a 2004 Los Angeles Metro report[16], "*Electric Trolleybuses for the LACMTA'S Bus System (Report number 1302)*", also

---

[9] National Renewable Energy Laboratory (NREL) (2016). Foothill Transit Battery Electric Bus Demonstration Results. January 2016. Available: http://www.nrel.gov/docs/fy16osti/65274.pdf.
[10] National Renewable Energy Laboratory (NREL) (2006). King County Metro Transit Hybrid Articulated Buses: Final Evaluation Results. December 2006. Available: http://www.nrel.gov/docs/fy07osti/40585.pdf.
[11] National Renewable Energy Laboratory (NREL) (2006). New York City Transit (NYCT) Hybrid (125 Order) and CNG Transit Buses. November 2006. Available: http://www.nrel.gov/docs/fy07osti/40125.pdf.
[12] National Renewable Energy Laboratory (NREL) (2008). BAE/Orion Hybrid Electric Buses at New York City Transit. March 2008. Available: http://www.afdc.energy.gov/pdfs/42217.pdf.
[13] National Renewable Energy Laboratory (NREL) (2015). Zero Emission Bay Area (ZEBA) Fuel Cell Bus Demonstration Results: Fourth Report. July 2015. Available: http://www.nrel.gov/docs/fy15osti/63719.pdf.
[14] National Renewable Energy Laboratory (NREL) (2015). American Fuel Cell Bus Project Evaluation: Second Report. September 2015. Available: http://www.nrel.gov/docs/fy15osti/64344.pdf.
[15] National Renewable Energy Laboratory (NREL) (2014). BC Transit Fuel Cell Bus Project: Evaluation Results Report. February 2014. Available: http://www.nrel.gov/docs/fy14osti/60603.pdf.
[16] Arieli Associates Management, Operations and Engineering Consulting. Electric Trolleybuses for the LACMTA's Bus System - Report No.1302. 2004. Available: http://media.metro.net/projects_studies/atvc/images/1302-Trolleybuses%20for%20LACTMA.pdf.

identifies results of their comparison between electric trolley bus systems and internal combustion engines and is relevant because the electric propulsion system is similar to that used in battery electric buses.

B. Typical Bus Maintenance Costs

When evaluating different studies, the key to interpreting results is understanding general trends that affect maintenance costs. Maintenance costs are dependent on multiple variables including vehicle age, duty cycle, topography, fleet maintenance practices and several other factors. Most transit buses have regular mid-life costs for rebuilding or replacing major components within the typical 14 years they operate. Over time, the per-mile operating and maintenance cost (O&M) costs tend to increase and bus replacement becomes more cost effective than continuing to make repairs. Figure 1 shows a simple representation of how bus maintenance costs increase as buses age.[17] In addition, operating and maintenance costs vary across fleets, bus types, and operating environments. Comparisons of different technologies are most relevant if made on the same routes, average speeds and in the same fleet.

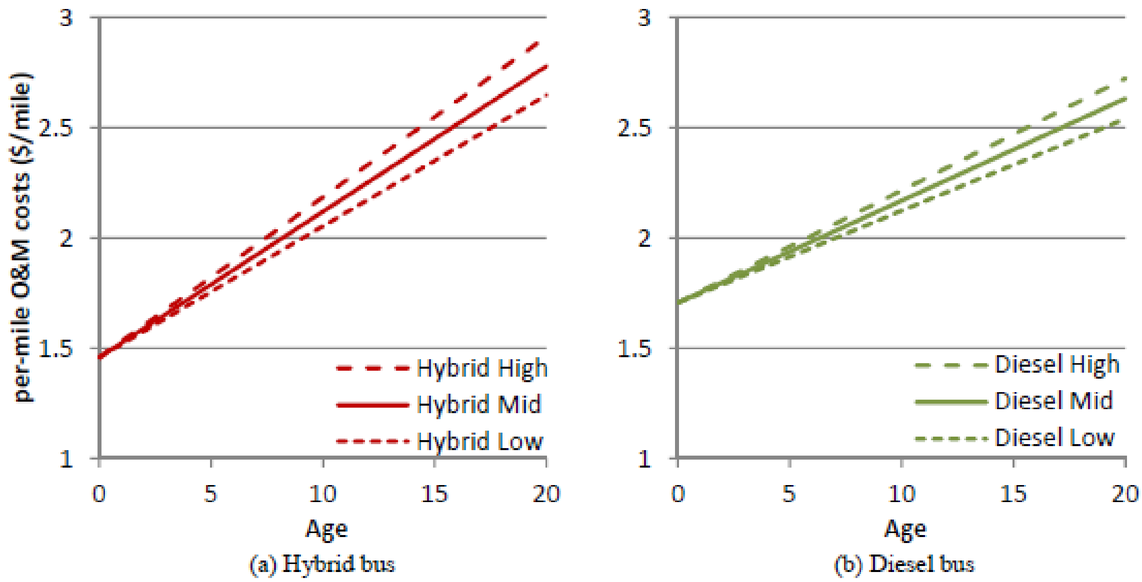
In addition, planned and unplanned maintenance and repair costs do not occur linearly for an individual vehicle and fluctuate by year and type of repair made. Figure 2 show results of the distribution of expected major component replacement and overhaul cost (propulsion and non-propulsion related costs) from a 2007 FTA report[18] for a 40-foot transit bus with an average of 35,000 miles per year. The study confirms there are major cost cycles that repeat throughout the bus life whether or not the transit agency conducts a major mid-life overhaul, which are roughly concurrent with drivetrain rebuild (the cost peaks at roughly 6 to 7 years and 12 to 14 years). The smaller peaks primarily represent replacement of components that have shorter expected lives including turbos, alternators, brakes, auxiliary batteries and other equipment. For conventional buses with internal combustion engines, the fuel system and engine need to be rebuilt about every 7 years. The report also identified the typical cost for replacing the propulsion system (including engine and transmission) for internal combustion engines for a large operator at around $47,000 in 2007.

---

[17] Feng and Figliozzi (2014). Vehicle Technologies and Bus Fleet Replacement Optimization: Problem Properties and Sensitivity Analysis Utilizing Real-World Data. Springer-Verlag, Berlin Heidelberg. DOI: 10.1007/s12469-014-0086-z. August 27, 2014. Available: https://www.researchgate.net/publication/261367990.

[18] Federal Transit Administration (FTA) (2007). Useful Life of Transit Buses and Vans - Report No. FTA VA-26-7229-07.1. April 2007. Available: https://www.transitwiki.org/TransitWiki/images/6/64/Useful_Life_of_Buses.pdf.

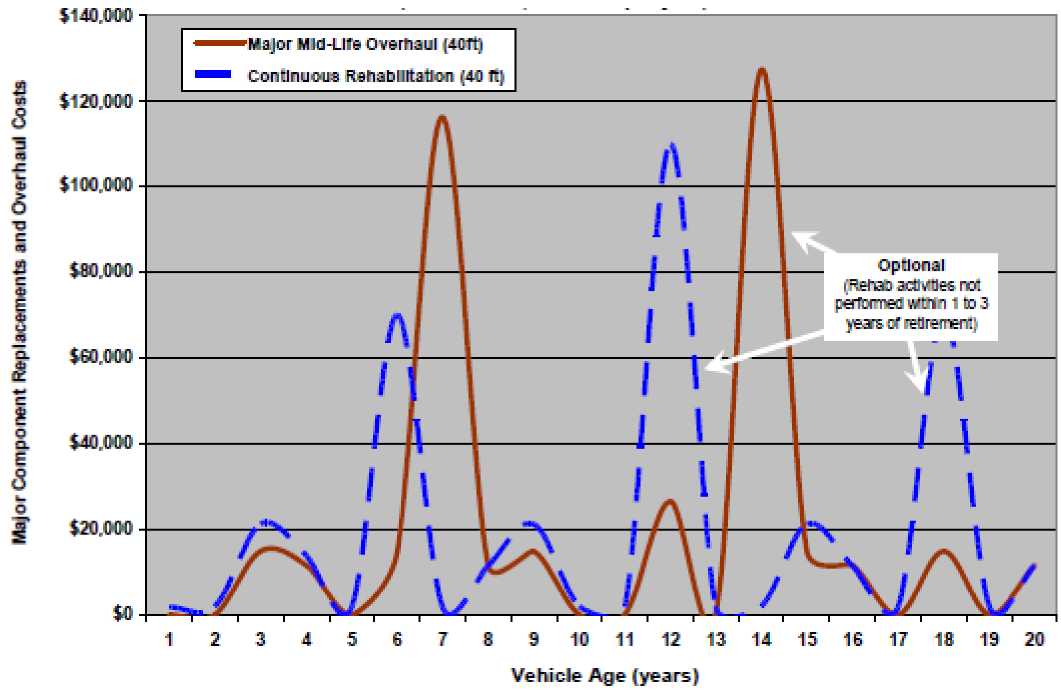
Figure 1: Operating and Maintenance Cost with Age (Diesel and Diesel Hybrid)



Source: ***Bus Fleet Type and Age Replacement Optimization: A Case Study Utilizing King County Metro Fleet Data, 2002*****. Figure 2, page 8**

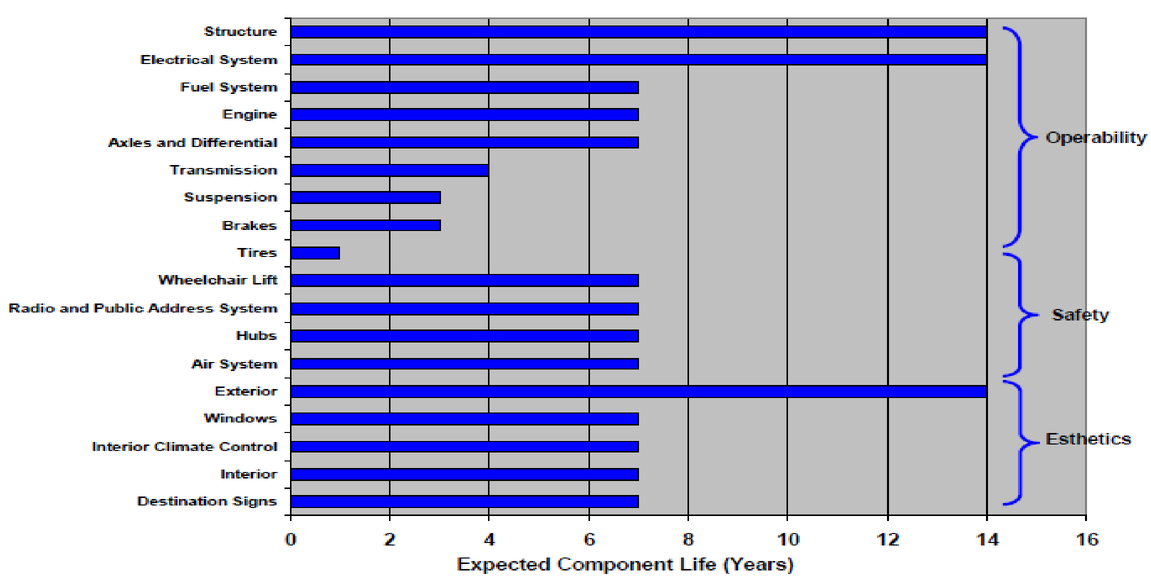
The actual frequency of repairs for a given fleet or bus is expected to vary, but some components are expected to need repairs more frequently than others. Figure 3 shows the typical useful life by component category. According to the report, many of the propulsion-related components of conventional buses typically last half of the bus life with other components needing to be replaced more frequently.

Figure 2: Life Cycle Cost Profile: Major Component Replacements and Overhauls



(Source: Federal Transit Administration, Useful Life of Transit Buses and Vans, Report No. FTA VA-26-7229-07.1, April 2007. Figure 7-4, page 91.)

Figure 3: Useful Life of Transit Buses and Vans



(Source: Useful Life of Transit Buses and Vans, Report No. FTA VA-26-7229-07.1, April 2007. Figure 6-1, page 70.)

C. Literature Review of Available Bus Studies

The following sections provide a summary description of available reports that have transit bus cost information to compare different conventional propulsion technologies to electric drivetrains. None of the studies had any major mid-life overhaul costs because all tested buses were 6 years old or less and were not expected to need an overhaul. The main categories used by the studies include total maintenance costs, propulsion related maintenance costs, and preventative maintenance. Brake system repairs are included in the total maintenance category, but we separated those costs into its own category. The following are the descriptions of the categories we used (unless noted in the discussion):

- **Propulsion related maintenance cost** - Consists of repairs for exhaust, fuel, power plant system (engine, traction battery system, and fuel cell stack), propulsion system, non-lighting electrical system, air intake system, cooling system, and transmission and hydraulic systems. The regenerative braking system component repair costs are in this category because they are part of the electric or hybrid technology; however, the common brake system components such as brake pads and brake relines are not included in the propulsion related category.
- **Brake cost** – Includes replacement of brake pads, brake relines and other brake related repair cost that are not unique to regenerative braking systems.
- **Preventative maintenance inspections (PMI)** – Consists of labor for preventative maintenance inspections. Some PMI inspections are mileage based and others are time based.
- **Other maintenance** - Includes all repairs for cab, body and accessories, frame, steering and suspension, heating, ventilation and air conditioning (HVAC), lighting, general air system, axles, wheels and drive shaft, tires.
- **Total maintenance** – Is the sum of all of the above maintenance costs.

The labor price used in the NREL studies is $50 per hour and the studies occurred in different years. The Transit Agency Subcommittee and members from the Advanced Clean Transit Workgroup suggested making adjustments to reflect the costs at a labor rate of $100 per hour for a closer comparison to their current labor costs. Similarly, any repair parts costs from the studies were adjusted to reflect 2016 constant dollar by using the consumer price index to reflect the effects of inflation. All costs reflect both of these adjustments unless otherwise noted.

1) Foothill Transit Battery Electric Bus Study - 2016

NREL completed a study on Foothill Transit Agency's fast charging battery electric buses (BEBs) and compared those to conventional CNG buses. The report "*Foothill*

Transit Battery Electric Bus Demonstration Results" was published in January 2016. Foothill Transit deployed twelve 35-foot Proterra BEBs to evaluate the performance and costs of BEBs in regular service from April 2014 to July 2015. Line 291 was completely electrified for its high ridership and operation in a transit dependent community. Eight NABI CNG buses with a model year of 2014 were chosen as the baseline buses for comparison. However, these CNG buses were randomly dispatched in the whole service area and had almost twice the monthly mileage and speed. If these CNG buses were operated on comparable slow speed routes as the BEBs we would expect to see lower fuel efficiency and more brake wear per mile. Table 2 below summarizes the characteristic of the study.

Table 1: Characteristics of the Foothill Transit Study - 2016

Category	CNG	BEB
Model Year	2014	2014
Bus Age	New	New
Rated Power	280 hp @ 2,200 rpm	220 kW (295 HP) peak
Number of Buses	8	12
Test Period	10/14-07/15	04/14-07/15
Total sub-fleet mileage	364,373	401,244
Monthly average mile/bus	4,555	2,333
Daily average speed (miles/hour)	17.6	10.6
Fuel economy (miles/DGE)	4.5	17.5

The 12 BEBs have an average of 2,333 monthly operating miles per bus, an average speed of 10.6 miles per hour, 90 percent availability, and 17.5 mile per diesel gallon equivalent (DGE). The eight baseline CNG buses have an average of 4,555 monthly operating miles per bus, an average speed of 17.6 miles per hour, 94 percent availability, and 4.51 mile per diesel gallon equivalent (DGE). Despite the slower duty cycle (more stop and go driving), the BEBs in this report demonstrated a fuel economy almost four times of that of the CNG buses. The report also indicates the BEBs purchase prices included an extended propulsion battery warranty for 12 years, so there will not be a mid-life battery replacement cost. There is an expected midlife engine overhaul for the CNG buses, as is typical for all combustion engine buses.

Summary of Electric Drive System Costs

The buses in this study were not operated on the same routes or duty cycle which presents some questions about the comparison; however, this is the only study that compares battery electric buses to conventional buses in the same fleet. The tire damage ($0.04 per mile) for the BEB from a cracked curb on Line 291 is unique to this route and was not technology related. This cost does not represent a difference associated with the technology, so it is more appropriately reflected at the same cost per mile as the CNG buses or $0.01 per mile. The BEB operators failed to turn off the buses at the end of the shift, and that drained the low-voltage auxiliary batteries that needed to be replaced at a cost of $0.02 per mile. Although this is a cost associated with nearly silent operation of this battery electric bus, it is a driver training issue that can be avoided or addressed with warning indicators to notify the driver that the bus is still on. The total maintenance cost of BEBs and CNG buses shown below includes these two adjustments shown in Table 2 with the labor rate of $100 per hour. No brake relines were done on either bus type.

The maintenance costs for both the baseline CNG fleet and the BEB fleet are comparatively low during the testing period because they are new and under warranty. The propulsion related maintenance cost of the CNG buses is 33 percent of its total maintenance cost. The propulsion related maintenance costs for the BEBs are about $0.08 per mile lower than that of CNGs. The preventative maintenance inspection costs for the BEBs were $0.02 per mile higher, but it is unclear if the difference is a result of time based preventative maintenance inspection costs spread over substantially fewer miles between the technology groups. The BEBs had a $0.06 per mile (21%) lower total maintenance cost compared to the CNG bus. Maintenance cost per mile is expected to increase for both types of propulsion systems as they age. NERL is going to continue to monitor this fleet.

Table 2: Maintenance Cost Summary of Foothill Transit Study - 2016

Cost Category ($/mile) at labor cost $100/hr and adjusted to 2016 dollar	**CNG**	**BEB**	**Difference**
Propulsion-only maintenance	**0.09**	**0.01***	**-0.08**
Brake cost	0.00	0.00	0.00
Preventive maintenance inspections	0.12	0.14	+0.02
Other bus maintenance	0.07	0.07**	0.00
Total maintenance cost	0.28	0.22	-0.06

* Cost for low voltage auxiliary battery replacements on several buses ($0.02/mile) not reflected because it is a driver training issue.
** The tire damage ($0.04/mile) for the BEB from a cracked curb of Line 291 is unique to this route and was not technology related. The cost was reduced to $0.01/mile to be the same as CNG.

2) King County Metro Articulated Diesel Hybrid Bus Study - 2006

NREL published "*King County Metro Transit Hybrid Articulated Buses: Final Evaluation Results*" in December 2006 to compare performance between diesel and diesel hybrid electric articulated buses. The King County Metro Transit report (KCMT Report) covered a 12-month evaluation period (April 2005 through March 2006) of the New Flyer articulated 60-foot hybrid and diesel buses. Ten diesel hybrid buses from the

Atlantic Base depot and ten diesel buses from the Ryerson Base depot were selected for comparison. These ten diesel buses are identical to the hybrid buses except the hybrid buses have the GM Allison E^P 50 parallel hybrid system. The GM Allison E^P 50 parallel electric propulsion system has a drive unit that contains two motors. Each motor, which can also act as a generator, is capable of 75 kW continuous power and up to 150 kW peak power. The parallel hybrid propulsion system blends with both the Caterpillar engine power and the electric motor power. The energy storage system consists of nickel metal hydride batteries and operates with regenerative braking.

This study ensured that both propulsions have similar service, and duty and drive cycles during the evaluation period. Table 3 summarizes the characteristics of the study. For the first six months of the evaluation period, both provided downtown service at an average speed of 12.4 mph for Ryerson and 11.6 mph for Atlantic; for the second six months test period, the average speed are 12.3 mph for Ryerson conventional diesel buses and 10.5 mph for Atlantic diesel hybrid buses. An additional ten diesel hybrid buses were also placed at the South Base depot to serve different routes with higher monthly average mileage per bus. South Base hybrid buses have a higher average operating speed of 19.5 mph for the first six months and 18.1 for the rest of the testing period. The results of these additional ten hybrid buses are also included in this report.

Table 3: Characteristics of the KCMT Diesel Hybrid Study - 2006

Category	Diesel Ryerson 12 mph	Hybrid Atlantic 11 mph	Hybrid South Base 19 mph
Model Year	2004	2004	2004
Bus Age	1 year	1 year	1 year
Rated Power	330hp@2100rpm	330hp@2100rpm	330hp@2100rpm
Motor/ Generator	na	150 kW (201 HP) peak	150 kW (201 HP) peak
Number of Buses	10	10	10
Test Period	04/05-03/06	04/05-03/06	04/05-03/06
Total sub-fleet mileage	353785	371548	427331
Monthly average miles/bus	2949	3096	3957
Daily average speed (mile/hour)	12.4	11	18.8
Fuel economy (miles/DGE)	2.5	3.17	3.75

Summary of Electric Drive System Costs

The total maintenance costs and subcategories for each of the three set of buses are shown in Table 4. The propulsion related maintenance costs are 26 to 32 percent of the total maintenance cost for all three categories. The electric propulsion system repair was \$0.03 per mile in Atlantic Base hybrid buses and \$0.08 per mile for the South Base hybrid buses. The higher cost for the South Base hybrid buses was due to labor hours spent to troubleshoot problems with the cooling lines for the dual power inverter module. There was at least $0.05 per mile saving on the total maintenance costs for the hybrid buses compared to the conventional diesel buses although the difference is primarily from other bus maintenance costs that are not drive train related.

Table 4: Maintenance Costs of the KCMT Bus Study – 2006

Cost Category ($/mile) at labor cost $100/hr and adjusted to 2016 dollar	Diesel Ryerson 12.4 mph	Hybrid Atlantic 11 mph	Hybrid South Base 18.8 mph
Propulsion-only maintenance	**0.22**	**0.23**	**0.24**
Brake cost	0.00	0.01	0.01
Preventive maintenance inspections	0.09	0.10	0.09
Other bus maintenance	0.55	0.47	0.42
Total maintenance cost	0.86	0.81	0.76

The propulsion-related maintenance cost was $0.01 to $0.02 per mile higher for hybrids and there were no brake costs during the test period. There were no major brake repairs or relines in any of the three study groups. During this study, the hybrid buses accumulated 37,155 to 42,733 miles and the conventional diesel buses accumulated 35,279 miles; therefore, no conclusions can be drawn about brake reline cost differences. No estimate was provided in the report to identify the typical brake reline period for the fleet. The PMI labor for the hybrid buses was about the same as conventional diesel buses indicating little difference in PMI costs. Overall, the maintenance cost of the hybrid system was cost neutral compared to the conventional buses in this study.

3) NYCT Diesel Hybrid Bus Study - 2006

NREL published "*New York City Transit (NYCT) Hybrid and CNG Transit Buses*" in November 2006 to compare performance between new CNG and diesel hybrid electric buses. A summary of the study characteristics are shown in Table 5. The test period was a 12 months evaluation (October 2004 through September 2005) of the new Orion VII low floor buses with CNG propulsion (equipped with Detroit Diesel Corporation Series 50G CNG 8.5 liter engine) and diesel series hybrid propulsion (equipped with BAE Systems' HybriDrive propulsion system with a 5.9 liter engine). The hybrid buses have a smaller size of engine, but are slightly heavier. Ten of each kind were compared with the same age and bus platform. The buses were operated on similar duty-cycles and used common maintenance practices, but were at different locations. The average speed for CNG buses at West Farms Depot was 6.4 mph, while the average speed for diesel hybrid buses at Mother Clara Hale Depot was 6.3 mph. This low speed is associated with a lot of stop-and-go driving and is reflected in the low fuel economy compared to other drive cycles.

Table 5: Characteristics of the NYCT Diesel Hybrid Bus Study - 2006

Category	CNG (West Farm Depot)	Diesel Hybrid (Mother Clara Hale Depot)
Model Year	2002	2002
Bus Age	3 Years	3 Years
Engine	8.5L CNG	5.9 L diesel
Rated Power	275hp@2100rpm	275hp@2100rpm
Generator	na	160 HP continuous
Number of Buses	10	10
Test Period	10/04-09/05	10/04-09/05
Total sub-fleet mileage	275,444	284,443
Monthly average (miles/bus)	2,295	2,370
Daily average speed (mile/hour)	6.4	6.3
Fuel economy (miles/DGE)	1.7	3.2

Summary of Electric Drive System Costs

This study compares the diesel hybrid bus with the CNG bus. A summary of the maintenance related costs are shown in Table 6. The results of this report show a slight saving on total maintenance costs for hybrid bus even though hybrid buses comprise two propulsion systems. The average propulsion-related maintenance costs for CNG and diesel hybrid are 26 percent and 31 percent of the total maintenance cost, respectively.

Table 6: Maintenance Cost of the NYCT Diesel Hybrid Bus Study - 2006

Cost Category ($/mile) at labor at $100/hr and adjust for 2016 dollar	CNG (West Farm Depot)	Diesel Hybrid (Mother Clara Hale Depot)
Propulsion-only maintenance	**0.60**	**0.71**
Brake cost	0.32	0.07
Preventive maintenance inspections	0.24	0.36
Other bus maintenance	1.17	1.16
Total maintenance cost	2.32	2.30

The propulsion system costs of CNG buses was $0.11 lower than that of the diesel hybrid. The diesel hybrids had significantly lower brake repair costs with a savings of $0.25 per mile in the study period showing that regenerative braking can provide substantial savings. The hybrid buses with regenerative braking had 69% lower brake repair cost (hybrid $0.07 per mile vs CNG $0.32 per mile). For this study it results in a

$6,885 savings for each bus during the one year test period. During the testing period, the 10 CNG buses had nine four-wheel relines (after approximately 18,000 miles), and the 10 hybrid buses had none (after about 28,000 miles per bus). However, it is not clear from this study when brake relines are likely to be needed on the diesel hybrid buses which could result in a bigger savings the longer they operate without relines. The PMI for the diesel hybrid buses in this study were higher by $0.12 per mile. The report indicated the hybrid bus had 50% more labor spent on the scheduled maintenance. However, additional unscheduled activities were included in the defined PMI by NYCT bus fleet mechanics, which typically were not included in the PMI category in other studies. The report indicates there should be no difference in PMI labor between the CNG and hybrid buses. The total maintenance costs for the diesel hybrid buses were comparable to that of CNG buses.

This study confirms that regenerative braking provides significant savings compared to conventional brakes. In general, brake wear and repair costs are expected to be dependent on duty cycle. The savings from reduced brake wear is expected to be lower per mile for buses with higher average speeds than were seen in this study because they have less stop and go driving and would be expected to have fewer brake relines and brake system repairs.

4) NYCT Diesel Hybrid Bus Study - 2008

The 2008 New York City Transit report (NYCT Report), *BAE/Orion Hybrid Electric Buses at New York City Transit,* covered the evaluation of the performance of Gen I and Gen II new Orion VII low floor hybrid-electric diesel buses equipped with BAE Systems' HybriDrive propulsion systems. The differences between Gen II and Gen I are Gen II has the exhaust gas recirculation (EGR) system and the battery software system was updated. The characteristics of the study are shown in Table 7.

Table 7: Characteristics of NYCT Diesel Hybrid Bus Study - 2008

Category	Gen II Diesel Hybrid Year One	Gen I Diesel Hybrid Year One	Gen I Diesel Hybrid Year Two
Model Year	2004	2002	2002
Bus Age	2 years	2 years	3 years
Engine	5.9L diesel with EGR	5.9L diesel w/o EGR	5.9L diesel w/o EGR
Rated Power	275 hp at 2100 rpm	275 hp at 2100 rpm	275 hp at 2100 rpm
Number of Bus	10	10	10
Test Period	01/06-01/07	10/04-09/05	10/05-09/06
Fuel cost ($/mile)	0.66	0.50	0.56
Total sub-fleet mileage	246,926	284,443	263,130
Monthly average miles/bus	2,134	2,370	2,295
Fuel economy (miles/DGE)	3.0	3.2	3.2

Ten of each generation of hybrid buses with the same bus platform operated on similar duty-cycles and with similar maintenance practices for comparison, but the tests were performed at different times for both generations of the hybrid buses at similar ages.

The buses were randomly dispatched at all standard bus routes. The average speed of Gen II hybrid buses at the Manhattanize (MTV) Depot was 6.07 mph for evaluation year one, while the average speed for Gen I hybrid buses at the Mother Clara Hale Depot was 6.13 and 5.7 mph for the evaluation year one and year two. The average monthly mileage of Gen II hybrid is 10 percent and 7 percent lower than Gen I hybrid in the first and second evaluation year. The Gen II hybrid employed EGR and had 6 percent lower fuel economy compared to the Gen I hybrid in the first and second evaluation year.

Summary of Electric Drive System Costs

This study was designed to compare changes in an early hybrid system design to the next generation with most characteristics remaining the same. A summary of the maintenance related costs is shown in Table 8. There was no separate labor hour and part cost for propulsion–only maintenance cost, brake cost, and other bus maintenance cost in the report. Thus, only the PMI and the total maintenance cost could be adjusted to reflect a $100 per hour labor rate. The propulsion related maintenance cost could not be calculated to reflect a $100 per hour labor rate.

Table 8: Maintenance Costs of the NYCT Diesel Hybrid Bus Study - 2008

Cost Category ($/mile) at labor at $100/hr and adjust for 2016 dollar	Gen II Hybrid Year One	Gen I Hybrid Year One*	Gen I Hybrid Year Two
Propulsion-only maintenance	na	0.71	na
Brake cost	na	0.07	na
Preventive maintenance inspections	0.26	0.36	0.40
Other bus maintenance	na	1.16	na
Total maintenance cost	1.39	2.30	2.58
***** The data for Gen I Hybrid Year One is from the NYCT Diesel Hybrid Bus Study-2006			

During the testing period, Gen II hybrids did not accumulate enough miles to have brake relines. PMI inspections were lower by $0.14 per mile and total maintenance costs declined from $2.3 with Gen I to $1.39 per mile with Gen II showing a significant improvement from the first generation.

There were 13 single battery failures for hybrid Gen I prior to the evaluation period. The software change for the hybrid propulsion system for hybrid Gen II was made to improve its ability to identifying faulty batteries and to reduce the overall number of traction batteries removed with no true failure. There was no traction battery failure for

Gen II hybrid during the evaluation period. The electric propulsion related maintenance cost of the Gen II hybrid at a labor rate of $50 is $0.039 per mile, which is 78% lower than that of Gen I hybrid in evaluation year one at a $50 per hour rate.

5) AC Transit Fuel Cell Electric Bus Study - 2015

NREL completed the report "*Zero Emission Bay Area (ZEBA) Fuel Cell Bus Demonstration Results: Fourth Report*" in July 2015 to demonstrate the performance of fuel cell electric buses (FCEBs). Three groups of buses were selected for comparison during the period of November 2013 through December 2014: 4 Van Hool diesel buses with a model year of 2009, 10 Gillig diesel buses with a model year of 2013, and 12 FCEBs with a model year of 2010. The 2010 model year FCEBs are built by Van Hool with a US Hybrid fuel cell power system and EnerDel lithium-based energy storage system. The 2009 Van Hool diesel buses are the same Van Hool A330L low floor model as FCEBs and have similar physical characteristics to the FCEBs, but they are out of warranty and have over 4 times as much of the mileage compared to the FCEBs. The mileage of three of the Van Hool diesel buses at the beginning of the test were over 200,000 miles. No engine or mid-life rebuilds were in this study. Gillig buses are several years newer and have similar mileage as FCEBs. Additional data for these buses was available in the Appendix of the *AC Transit Fuel Cell Electric Bus Study* about these buses, but the study only included the most current year of evaluation data for comparison.

The characteristics of this study are summarized in Table 9. During the testing period, the 12 FCEBs operated 417,757 miles in total with an average speed of 8.5 mph. There is no specific data regarding diesel vehicles' speed in this report; however, the average monthly miles suggest that the diesel Gillig buses and the diesel Van Hool buses are operated in very high speed duty cycle with little stop and go driving.

Table 9: Characteristics of the AC Transit FCEB Study - 2015

Category	Diesel Van Hool	Diesel Gillig	Fuel cell
Model Year	2009	2013	2010
Bus Age	4 years	1 year	3 years
Rated Power	280 hp @ 2,200 rpm	280 hp @ 2,200 rpm	120 kw (161 HP)
Number of Bus	4	10	12
Test Period	11/13-12/14	11/13-12/14	11/13-12/14
Total sub-fleet mileage	226,169	685,681	417,757
Monthly average miles/bus	4,349	4,898	2,487
Fuel economy (miles/DGE)	3.95	4.36	7.23

Total maintenance cost for FCEBs during the report period were lower than the comparable 2009 Van Hool diesel buses. As expected, both older buses had higher maintenance cost than the new 2013 Gillig diesel buses. The average availability of was 72% for FCEBs, 82% for the Van Hool and 88% for the Gillig buses. The low availability of the FCEBs is because one of the FCEB had extended downtime for 14 months because of a bus cooling system problem that is not related to the fuel cell technology. The availability of the FCEBs would be 78% if the bus is removed from the dataset. Bus-related maintenance (separate from the fuel cell, hybrid, and traction battery systems) was the main reason of the highest percentage of unavailability for the FCEBs. About 80% of the total maintenance was bus-related issues, including bus air compressors, cooling systems, and a DC-DC converter, with the fuel cell electric buses which resulted in higher costs for several months during the evaluation period. The high cost of these bus related parts was the primary factor for the increases. The 2009 Van Hool diesel buses experienced a number of issues that are typical for buses at this level of mileage, where three of the buses had over 260,000 miles at the end of test period. Costs were accrued for work on brakes, axles, fire suppression systems, cooling systems, HVAC, and turbochargers. The 2013 Gillig buses accumulated about 68,568 miles each during the test period and had maintenance costs for brakes, charging system, fire suppression system, and a window replacement.

Summary of Electric Drive System Costs

A summary of the maintenance related costs is shown in Table 10. The Gillig buses are not directly comparable to the older buses in the study. They are new, and their maintenance costs are not representative of the costs expected with older buses. The FCEBs are more comparable in age to the Diesel Van Hool buses. The propulsion related maintenance costs for the FCEBs were 31% higher than that of the Van Hool diesel buses. The PMI of FCEB was $0.09 and $0.06 higher than diesel Gillig and diesel Van Hool, respectively.

Table 10: Maintenance Costs of the AC Transit FCEB Study - 2015

Cost Category ($/mile) at labor $100/hr and adjust to 2016 dollar	Diesel Van Hool	Diesel Gillig	Fuel Cell
Propulsion-only maintenance	**0.29**	**0.10**	**0.38**
Brake cost	0.11	0.02	0.02
Preventive maintenance inspections	0.13	0.10	0.19
Other bus maintenance	0.58	0.22	0.36
Total maintenance cost	1.10	0.44	0.95

The majority of the propulsion related maintenance costs for the Van Hool diesel buses were for the exhaust system and cooling system. The majority of the propulsion related maintenance costs for the Gillig diesel buses were for the engine. For the fuel cell electric buses, the electric drive system cost $0.12/mile, which consists of 32% of total propulsion system costs and 13% of the total maintenance cost, respectively. The bus cooling system contributed 21% of the total propulsion cost for the FCEBs. Power plant system repairs accounted for 19% of the total propulsion system costs.

Diesel Gillig did not have any major brake job done even though the whole bus fleet reached the average 90,000 miles. The older FCEBs have regenerative braking and had low brake costs that were the same as the conventional diesel Gillig. The diesel Van Hool had higher brake costs.

During the test period, the FCEBs encountered some non-recurring cost, such as, labor for shuttling buses between depots, research/training activities, and extra fueling related time and costs when operated away from the main fueling location. Once the Emeryville maintenance bay is completed, shuttling the buses between depots will not be necessary and the costs for all non-recurring activities should be eliminated completely.

6) SunLine Transit FCEB Study - 2015

NREL published the study "*American Fuel Cell Bus Project Evaluation: Second Report*" in September 2015 to demonstrate the performance of fuel cell electric buses (FCEBs). That study covered FCEBs operated at SunLine Transit Agency from March 2013 through June 2015. Four FCEBs were included in that study: one prototype FCEB manufactured in 2011 that operated during the entire 28-month testing period; and three additional FCEBs manufactured in 2014 that operated for 12 months, 7 months, and 2 months, respectively. Five New Flyer CNG buses (2008 model year) were selected as baseline vehicles for comparison. The Appendix of that report covers the 40 months data for both the 2011 model year FCEB and 2008 model year CNG. That data was also included in this discussion. During the evaluation period, the average speed of the FCEBs and CNG buses is 16.3 and 16.8 mph, respectively. The average availability of the FCEBs was 66% and 88% for CNGs. The primary issues that kept FCEBs out of service were general bus issues (54%), the hybrid propulsion (18%), and the fuel cell system (16%). For the CNG baseline buses, 49% of the downtime was attributed to engine issues.

The SunLine Transit Report summarizes the fuel economy, fuel cost per mile, fleet mileage and average speed for the two fleets. Table 11 summarizes these results.

Table 11: Characteristics of the SunLine Transit FCEB Study - 2015

Category	CNG	Fuel cell
Model Year	2008	FC3 from 2011 FC 4-6 from 2014
Bus Average Age	5 years	1-2 year old
Rated Power	280 hp @ 2,200 rpm	150 kw (201 HP) for FC
Number of Bus	5	4
Test Period	03/12-06/15	03/12-06/15
Total sub-fleet mileage	670,440	108,947
Monthly average mile/bus	4789	2223
Average Speed	16.3	16.8
Fuel economy (miles/DGE)	3.22	6.72

The FCEBs had a fuel economy 2 times that of the CNG buses, and the total maintenance cost was the same as that of CNG. The FCEBs' parts cost was low because they were still under warranty at the testing period; SunLine's CNG buses were manufactured in 2008 and are out of warranty. Each of CNG buses had accumulated more than 220,000 miles at the beginning of the test. The high mileage also contributes to increased costs for engine and other propulsion system maintenance. The CNG buses continue to experience engine issues that are typical for buses approaching the mid-point of expected life. FCEBs and CNG bus groups had the highest percentage of maintenance cost on propulsion related; cab, body, and accessories; and PMI.

Summary of Electric Drive System Costs

This study covers a 40-month period for CNG and FC3, which is longer than most other studies. The study period for FC4, FC5 and FC6 are 12, 7 and 2 months, respectively. The test period for FC5 and FC6 are less than 1 year and considered too short to be representative. Table 12 shows the SunLine Transit FCEBs (FC3 and FC4) and CNG bus maintenance cost summary. Since only FC3 and CNG bus ran the same data period for 40 months, therefore the parenting of propulsion related system costs are examined alone showing they were 69% higher for the FC3 compared with the older CNG buses ($0.59/mile vs. $0.35/mile). The brake repair for FC3 and CNG is $.02/mile and $.04/mile, respectively. The majority of the propulsion related maintenance costs for the FCEBs has been labor, balance of plant problems and overheating for the traction battery. The engine issues for the CNG buses were highest in the power plant category. FC4 only covered 12 months study period, the total maintenance cost of FC4 was lower than FC3. Part of the cost reduction may due to advancement in the FC system design, including a separate cooling system for batteries, a simplified power conversion system, software upgrades, and an improved radiator design to increase integrity.

Table 12: Maintenance Costs of the SunLine Transit FCEB Study - 2015

Cost Category ($/mile) at labor at $100/hr and adjust for 2016 dollar	CNG MY 2008 40 months	FC3 MY 2011 40 months	FC4 MY 2014 12 months
Propulsion-only maintenance	0.35	0.59	0.35
Brake cost	0.04	0.02	0
Preventive maintenance inspections	0.14	0.17	0.09
Other bus maintenance	0.32	0.3	0.17
Total maintenance cost	0.84	1.08	0.61

7) BC Transit FCEB Study - 2014

NREL released the "*BC Transit Fuel Cell Bus Project: Evaluation Results Report*" published in February 2014 to demonstrate the performance of fuel cell electric buses. British Columbia Transit (BC Transit) started to deploy FCEBs in Whistler, Canada, in early 2010.

The FCEBs are 42-foot, low-floor buses built by New Flyer with a hybrid electric propulsion system that includes a Ballard Power Systems fuel cell and lithium phosphate batteries. These 20 buses were tested from April 2011 to March 2013, but there was no directly comparable baseline fleet. Table 13 lists the characteristics of the study.

Table 13: Characteristics of the BC Transit FCEB Study - 2014

Catergory	FCEB
Model Year	2009
Bus Average Age	2
Rated Power	150 kw (201 HP) for FC
Number of Buses	20
Test Period	4/11-3/13
Total sub-fleet mileage	1,318,830
Monthly average (mile/bus)	2748
Average Speed (mph)	na
Fuel economy (miles/DGE)	4.53

This was the largest FCEB deployment in North America. There were challenges faced and lessons learned in this deployment. The Whistler resort area has a particularly challenging duty cycle for buses with wide temperature between the seasons, the temperature can occasionally drop to −13°F and rise to 95°F for short durations. Steep grades and heavy passenger loading with added weight from ski gear, icy roads and melting snow made it the harshest operating conditions during peak winter season. Some of the challenges during the testing period include bus-related problems and programmatic issues, as well as market developments with manufacturers that affected the availability of parts. Other challenges included issues with the air compressor, traction motor, and controller for the fuel cell; battery balance issues; and fuel cell balance of plant issues. The hydrogen was delivered from 2,889 miles away from Becancour, Quebec to the fleet. In addition, there were recurring costs for sending the fuel cell stack back to Ballard periodically to perform a dry-out procedure, which could lengthen the fuel cell stack life.

Summary of Electric Drive System Costs

With this study, there were no baseline buses for direct comparison. In addition, the challenges associated with availability of parts for these particular buses presents questions about how those issues affected costs and whether they are representative of today's market. This study compared the results for the FCEBs with maintenance costs for a typical diesel bus in the BC Transit fleet and concluded that the total maintenance cost of FCEBs was 58 percent higher than maintenance service cost for a typical diesel bus. Table 14 shows the total maintenance costs for the FCEBs.

Table 14 Maintenance Costs of the BC Transit FCEB Study - 2014

Cost Category ($/mile) at labor at $100/hr and adjust for 2016 dollar	FCEB
Propulsion-only maintenance	1.70
Brake cost	0.09
Preventive maintenance inspections	0.33
Other bus maintenance	0.65
Total maintenance cost	2.77

The propulsion related, PMI and cab, body and accessories had the highest maintenance cost, consisted of 61%, 11% and 11% of the total maintenance cost, respectively. The highest repair costs were with the power plant system, electric motor propulsion and the cooling system categories. They are $0.20, $0.24 and $0.15 per mile, respectively. During the average 65,942 miles accumulated per bus in the testing period, the brake repair costs were $0.09/mile.

8) Stanford University BEB Evaluation - 2015

Stanford University delivered a presentation "*Electric Buses at Stanford*" demonstrating the performance of the battery electric buses (BEBs) at the 2015 CA Higher Education

Sustainability Conference at San Francisco State University in San Francisco[19]. Stanford University operates 79 shuttle buses covering services areas of core campus, off-campus, and trans-bay service. Stanford University began using BYD 40-foot BEBs for campus routes in 2013; and the daily mileage is around 125-145 miles. These campus routes have similar stop-n-go drive cycles as those in urban congested areas. The maintenance cost for the three BEBs during the September 2013 to April 2014 were \$0.16, \$0.17 and \$0.42 per mile, respectively in 2016 dollars. There was no detailed breakdown on different cost categories nor data of comparable conventional buses.

9) LACMTA Electric Trolley Bus Study 2004

A 2004 Metro report, "*Electric Trolleybuses for the LACMTA'S Bus System (Report number 1302)*", studied the operating cost of trolley buses in comparison to conventional diesel and CNG buses. The report states the following regarding maintenance costs:

> the cost of maintaining a modern trolleybus is certainly lower than for a diesel and in San Francisco the difference amounts to about 68:100 for trolleybus/diesel bus or, approximately 56% of that for a CNG bus. The maintenance cost of the overhead wiring and substations is an extra burden, which must be carried by the trolleybus operator. However, even taking this into account, the total maintenance costs of the trolleybus system, and vehicles should be at least 20% less than for diesel/CNG buses, based on experience elsewhere. The comparative fuel costs are very similar[20] .

This study did not include a lot of details about how the costs were determined, but did conclude that long term maintenance and operation of electric drive systems should be substantially lower than conventional systems.

If the typical average mid-life maintenance cost of a CNG or diesel transit bus \$0.85 per mile[21] as indicated by the Transit Subcommittee. The maintenance cost savings of trolley buses of 32 and 44 percent lower than a comparable diesel or CNG bus,

---

[19] Stanford University (2015). Electric Buses at Stanford - California Higher Education Sustainability Conference (CHESC). June 16-18, 2015. Available: https://www.ovmagazine.nl/wp-content/uploads/2015/11/ThomasWard_Jun173113Adams4.15pm_000.pdf.

[20] Arieli Associates Management, Operations and Engineering Consulting (P.10). Electric Trolleybuses for the LACMTA's Bus System - Report No.1302. 2004. Available: http://media.metro.net/projects_studies/atvc/images/1302-Trolleybuses%20for%20LACTMA.pdf.

[21] Provided by Transit Agency Subcommittee (Cost subgroup) on 2/9/2016.

respectively translates into about $0.27 per mile to $0.37 per mile lower than the maintenance cost of a comparable conventional bus.

Electric trolleybuses and battery electric buses are powered by similar electric propulsion systems with the primary difference on the power source (large battery vs overhead wires). Therefore, it is reasonable to use trolleybus' maintenance costs as an indicator of BEB's expected maintenance cost. Trolley buses have been in use for decades. We also recognize that trolley buses are kept 18 or more years, much longer than standard transit buses.

D. Combined Results

To date, only the Foothill Transit Battery Electric Bus Study directly compares a battery electric bus to a conventional bus fleet. The study shows there is a maintenance cost saving for a new battery electric bus compared to a new CNG bus in its first year of operation. The study period was not long enough to have any brake relines or other repair cost information and does not answer questions about long-term maintenance costs.

The NYCT hybrid bus study shows a greater than 75 percent brake costs savings from regenerative braking on diesel hybrid buses compared to conventional buses during the study period. We recognize that brake repair frequency (and associated costs) are also dependent on average speed or duty cycle as seen from results of other studies that showed few or no brake repairs for conventional buses that needs to be explained.

We found that we could use empirical data from different studies to evaluate costs and frequency of repair patterns between studies to better estimate costs for the useful life of a bus. The results we found are consistent with detailed FTA studies on total cost of ownership and maintenance cost trends described at the beginning of this document.

We recognize care needs to be taken to account for factors that influence the comparison of different technologies especially when the buses that are being compared are not of the same age or are not operated on the same duty cycle. Another factor to consider is that relatively short (1 year) studies are useful in answering some question, but a short study period can also influence the apparent cost if taken out of context. For instance, a one year study that has no brake reline cost may suggest a much lower cost for brake repairs than if the study began in year two for the same bus.

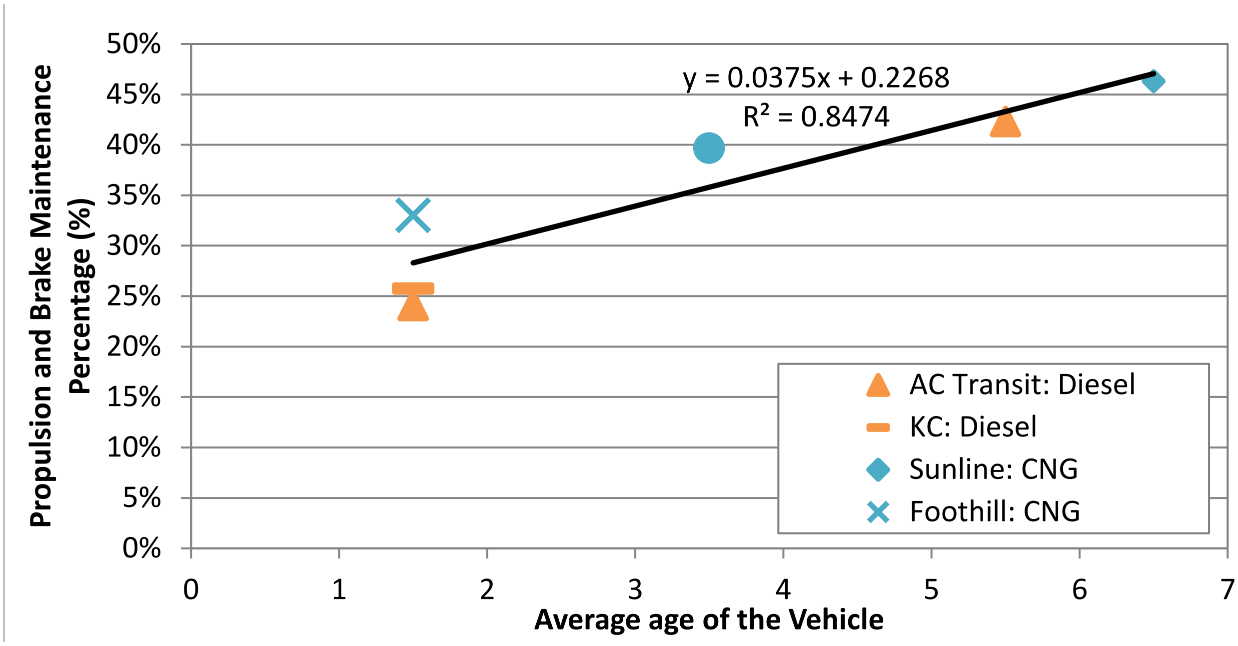
In the following sections we describe additional analysis and conclusions regarding what the data supports in terms of the best way to represent typical maintenance costs for zero emission buses compared to conventional buses.

1. Propulsion vs Total Maintenance Costs

For conventional buses, FTA studies show the propulsion-related maintenance cost (without brake reline and repair costs) normally consists of a quarter to a third of the total maintenance cost.[22] The KCMT and NYCT studies both showed a slight saving in total maintenance cost for diesel hybrid buses even with an additional electric propulsion system. The propulsion related maintenance cost (without brake repair costs) in KCMT and NYCT studies consisted of 27-30 percent of the total maintenance cost, which is consistent with FTA studies for conventional buses. However, we have determined that brake related costs should also be included when comparing maintenance costs for conventional buses to those with electric drive systems because regenerative braking substantially reduces brake reline frequency and associated brake repair costs. Figure 4 shows the percentage of propulsion plus brake maintenance cost as a percentage of total maintenance costs by bus age from the available studies. We see from the figure that propulsion plus brake maintenance costs for conventional buses are about 45 to 50 percent of total maintenance costs at the mid-life of a conventional bus. If the average total maintenance cost of a conventional bus at its mid-life is $0.85 per mile, the propulsion plus brake maintenance cost of a typical conventional bus is about $0.40 per mile. This represents an upper bound on the potential cost savings from propulsion plus brake related maintenance with electric drive systems.

[22] Federal Transit Administration (FTA) (2007). Transit Bus Life Cycle Cost and Year 2007 Emissions Estimation – Final Report FTA-WV-26-7004-2007.1. July 2, 2007.

Figure 4 Conventional Bus Propulsion Plus Brake Maintenance Costs



2. Propulsion-Related Maintenance Costs

The Foothill study showed that the electric drive propulsion system for a BEB could save $0.08/mile in its first year of operation when compared to a similar conventional CNG bus. The propulsion related maintenance cost of BEBs in Foothill study is $0.01/mile, which is 4.5 percent of its total maintenance cost. Currently there are no other studies that directly compare a BEB to a conventional bus. Because both buses are new and under warranty this costs is primarily an indicator of differences in normal maintenance costs that are frequent, like oil changes, but does not provide information about how those cost will change as components begin to fail and are repaired as part of scheduled or unscheduled maintenance. We believe the $0.08 per mile cost differences from this study are a lower bound estimate of propulsion system related repair cost savings and recognize that other repair costs are not reflected in this study because it only represents the first year of operation.

We know from FTA total cost of ownership studies and empirical data that conventional bus maintenance plus brake repair costs increase significantly with age as described in section B of this report. Internal combustion engines have expected repairs or failures that are common like turbo failures, spark plug replacements (CNG), alternator replacement, and other common repairs that are expected to occur at least once during the life of the bus.

For electric drivetrains we see that diesel hybrid buses have no significant difference in maintenance costs with the addition of the electric drive train and added complexity of integrating two systems. Although we currently do not have empirical data on the long-term use of electric drivetrains, we have information from trolley bus evaluations that conclude their cost of operation is substantially lower than conventional CNG and diesel buses in the same application. For an electric drive motor on a bus there is no expected electric motor repair or maintenance needed other than a potential bearing replacement during the typical useful life of a bus. Another area of potentially higher repair and maintenance costs could be with battery cell repair and diagnosis, but battery or cell replacement cost are covered by warranty for most of the useful life of the bus. BYD includes a 12-year battery warranty in the standard bus price, other manufacturers offer a 4 to 6 year warranty for batteries that are expected to be replaced at mid-life and most offer extended warranties as options. Any associated cost with repairing batteries under warranty are not likely to be borne by the transit agency depending on the arrangement with the manufacturer.

3. Preventative Maintenance Inspections

Nearly all of the studies had PMI cost information; however, there appears to be no discernable pattern when compared by bus age, technology type, or miles travelled. Therefore, the data in these studies suggest that PMI cost differences are small or not significant when comparing different technology buses.

4. Regenerative Braking

Regenerative braking uses batteries to supply additional power during acceleration and hill climbing and reduces brake wear, heat build-up, and brake reline frequency. Brake wear and repair frequency is also expected to be dependent on duty cycle. Buses with frequent stop and go driving are expected to have higher brake repair frequency and costs per mile than buses that have high speed routes and travel longer distances between stops.

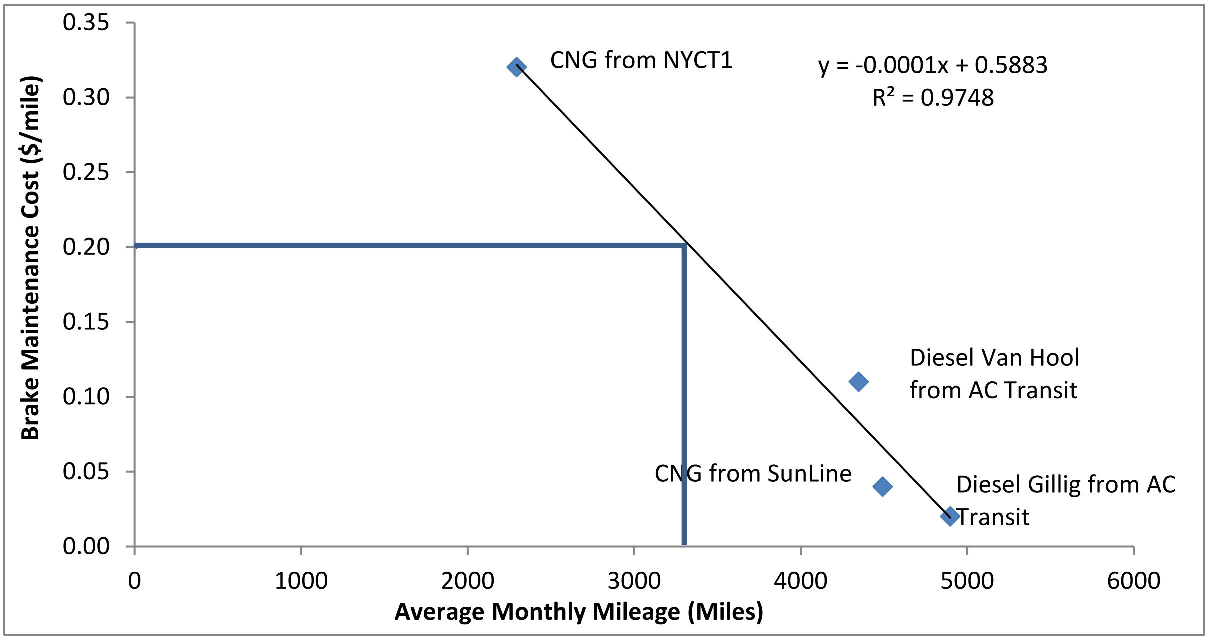
In the NYCT report, the hybrid buses use regenerative braking which saved 78% on brake repair cost (Hybrid-$0.07/mile vs CNG $0.32/mile) and resulted in a $6,885 cost saving per bus during the year of evaluation. During the testing period, CNG bus had nine four-wheel relines and the hybrid buses had none. The study showed a conclusive savings during the test period; however, the cost per mile does not fully reflect the costs of relines done before the study period started. There was additional data in the reports for these same buses that include odometer readings and brake reline history for these buses.

When using all of the data available in the reports, the Generation I diesel hybrids in the NYCT Hybrid Study average 55,067 miles before requiring the first brake relines. The CNG buses from the NYCT Diesel Hybrid study averaged 25,554 miles before requiring their first brake reline. These costs are expected to repeat regularly during the life of the buses at these intervals. It is appropriate to compare the results of these two studies because the vehicles were operated in essentially the same duty cycle, same average speed and by the same transit fleet. This comparison shows that regenerative braking reduces the number of brake relines and other brake repair costs by about 55 percent. The cost savings are the same when comparing first 2-wheel relines or first 4-wheel relines between the CNG buses and hybrid bus test fleets.

When looking at brake repair costs from other studies, several conventional buses appeared to travel more than 50,000 miles on the odometer without any significant brake repair cost. For instance, CNG buses in the SunLine and the diesel Gillig buses in the AC transit study accumulated more than 60,000 miles and did not need brake relines. These buses also operate at high average speeds that could explain longer intervals between brake relines.

To remove variability about brake costs occurring within or outside the test period we evaluated all available data (from all studies) with brake repair costs and a corresponding odometer reading to determine if there was a brake repair cost relationship that could be established. Despite the fact that we were comparing data from different fleets and studies, we found a strong correlation between brake repair costs and average miles traveled per month for conventional buses. Figure 5 shows the brake cost and average monthly mileage of the conventional buses from all available data in the studies where odometer and brake reline data is available and the data period is long enough to expect a reline to occur for at least some buses in the technology group. We did not use average speed because information about average speed was not available from all studies. The graph confirms that brake costs per mile decline for duty cycles that have higher average monthly mileage. Average miles per month is an indicator of the duty cycle for a given fleet where shorter distances per month (and slower speeds) are indicative of more stop and go cycles that are expected to result in more frequent brake repairs. For challenging stop and go duty cycles such as the NYCT cycle (6.3 mph) the brake repair costs are highest. For a faster speed duty cycle where there is less stop and go driving we see lower brake repair frequency and costs and would expect less savings from regenerative braking compared to conventional vehicles.

Figure 5: Brake Cost for Conventional Bus Fleets



By using the results of the graph with the conclusion that brake repair costs are less than half for a bus with regenerative braking we can estimate the cost for a typical bus. For a typical bus fleet with the annual mileage 40,000 miles, the average monthly miles is about 3,300 miles, and the brake cost for a conventional buses is about $0.20/mile. Regenerative braking is expected to lower brake repair costs by about 55 percent as shown by the NYCT study. We conclude that the brake related repair costs for a bus with regenerative braking should be about $0.11 per mile lower than a typical conventional bus on the same duty cycle.

E. Conclusions

Although there is limited data in available bus studies and most are with buses that are relatively new, the available data does support the claim that buses with electric drive trains have significantly lower maintenance costs. The savings from these studies do not reflect differences from any major mid-life overhaul costs which need to be accounted for separately. Information from the studies support the following conclusions.

- Electric drive propulsion systems of BEBs in the Foothill study was $0.08/mile lower than conventional buses in the first year of operation when new (without brake repair costs).

- Regenerative braking reduces brake reline frequency and associated repair costs by about 55 percent. For a typical bus operating about 40,000 miles per year the cost savings associated with regenerative braking is about $0.11 per mile.
- Empirical data from these studies shows at least $0.19 per mile savings for an electric drive bus compared to a typical bus that travels 40,000 miles per year.
- The results of this evaluation are consistent with manufacturer estimates of savings for battery electric buses that are on the order of $0.25 per mile for the full life of the bus.
- The LACMTA report on trolley buses compared to conventional buses supports a savings estimate of 30 to 40 percent compared to a conventional bus (or about $0.27 to $0.37 per mile).
- Midlife engine overhauls, battery replacements or fuel cell replacements are additive to the costs from the studies evaluated in this paper.
- Brake wear and brake maintenance costs are higher for slow speed cycles compared to higher speed cycles
- Preventative maintenance inspection costs have no clear pattern of cost between technologies and differences are deemed to be insignificant

The electric drive system cost savings from these studies are expected to be a lower bound estimate because they do not reflect expected higher repairs for engine component failures that are expected later in the life of the bus (turbos, hoses, belts…) whether included in planned maintenance or unscheduled maintenance. Battery repair costs are often covered by warranty (with the bus purchase or with extended warranties) and are not expected to result in significant increases in maintenance costs for transit agencies as buses age. We also know that trolley buses have a minimum useful life of 15 years as opposed to 12 years for a standard transit bus and several transit fleets will regularly operate them 20 years before replacement. Longer useful lives are associated with better durability. Trolley buses have been in use for decades and are an indicator of long-term expectation for electric drive buses regardless of the propulsion energy source.

FCEBs share the same advantages of regenerative braking and other propulsion-related (electric drivetrain) advantages; however, the fuel cell system is still in the early commercialization stage for heavy-duty applications and it is unclear what fuel cell replacement or rebuild costs will be with the latest generation fuel cell. It is common to have a steep learning curve, in the early commercialized stage of an advanced technology, and for the maintenance staff to need time to learn how to maintain and troubleshoot and diagnose repairs associated with the advanced components and systems. Both AC transit and SunLine transit are continuing to work towards overcoming these types of problems in the near future. Fuel cell system repair experience and improvements in next generation fuel cell system designs are likely to continue reducing maintenance costs.

Reference List G

The following documents are the technical, theoretical, or empirical studies, reports, or similar documents relied upon in proposing these regulatory amendments, identified as required by Government Code, section 11346.2, subdivision (b)(3). Additionally, each appendix references the documents upon which it relies, as required by Government Code, section 11346.2, subdivision (b)(3).

Note: Each “Explanatory Footnote” is a footnote containing explanatory discussion rather than referencing specific documents relied upon.

1. National Renewable Energy Laboratory (NREL) (2017). Zero Emission Bay Area (ZEBA) Fuel Cell Bus Demonstration Results: Sixth Report. September 2017. Available: https://www.afdc.energy.gov/uploads/publication/zeba_fcb_rpt6.pdf.

2. Federal Transit Administration (FTA) (2018). Zero-Emission Bus Evaluation Results: King County Metro Battery Electric Buses. February 2018. Available: https://www.transit.dot.gov/sites/fta.dot.gov/files/docs/research-innovation/115086/zero-emission-bus-evaluation-results-king-county-metro-battery-electric-buses-fta-report-no-0118.pdf.

3. National Renewable Energy Laboratory (NREL) (2018). Foothill Transit Agency Battery Electric Bus Progress Report - Data Period Focus: Jan. 2017 through Dec. 2017. May 2018. Available: https://www.afdc.energy.gov/uploads/publication/foothill_transit_bec_progress_rpt.pdf.

4. BYD Motors Inc. (2015). BYD 40' K9 Electric Bus Lease Proposal prepared for: Anaheim Resort Transportation. June 18, 2015.

5. Proterra (2015). Information provided by Proterra on November 23, 2015.

6. New Flyer (2016). Personal Communication with David Warren, Director of Sustainable Transportation. February 10, 2016.

7. Federal Transit Administration (FTA) (2014). 2014 Revenue Vehicle Inventory. 2014. Available: https://www.transit.dot.gov/sites/fta.dot.gov/files/2014%20Revenue%20Vehicle%20Inventory_0.xlsx.

8. National Renewable Energy Laboratory (NREL) (2016). Zero Emission Bay Area (ZEBA) Fuel Cell Bus Demonstration Results: Fifth Report. June 2016. Available: http://www.nrel.gov/docs/fy16osti/66039.pdf.

9. National Renewable Energy Laboratory (NREL) (2016). Foothill Transit Battery Electric Bus Demonstration Results. January 2016. Available: http://www.nrel.gov/docs/fy16osti/65274.pdf.

10. National Renewable Energy Laboratory (NREL) (2006). King County Metro Transit Hybrid Articulated Buses: Final Evaluation Results. December 2006. Available: http://www.nrel.gov/docs/fy07osti/40585.pdf.

11. National Renewable Energy Laboratory (NREL) (2006). New York City Transit (NYCT) Hybrid (125 Order) and CNG Transit Buses. November 2006. Available: http://www.nrel.gov/docs/fy07osti/40125.pdf.

12. National Renewable Energy Laboratory (NREL) (2008). BAE/Orion Hybrid Electric Buses at New York City Transit. March 2008. Available: http://www.afdc.energy.gov/pdfs/42217.pdf.

13. National Renewable Energy Laboratory (NREL) (2015). Zero Emission Bay Area (ZEBA) Fuel Cell Bus Demonstration Results: Fourth Report. July 2015. Available: http://www.nrel.gov/docs/fy15osti/63719.pdf.

14. National Renewable Energy Laboratory (NREL) (2015). American Fuel Cell Bus Project Evaluation: Second Report. September 2015. Available: http://www.nrel.gov/docs/fy15osti/64344.pdf.

15. National Renewable Energy Laboratory (NREL) (2014). BC Transit Fuel Cell Bus Project: Evaluation Results Report. February 2014. Available: http://www.nrel.gov/docs/fy14osti/60603.pdf.

16. Arieli Associates Management, Operations and Engineering Consulting. Electric Trolleybuses for the LACMTA's Bus System - Report No.1302. 2004. Available: http://media.metro.net/projects_studies/atvc/images/1302-Trolleybuses%20for%20LACTMA.pdf.

17. Feng and Figliozzi (2014). Vehicle Technologies and Bus Fleet Replacement Optimization: Problem Properties and Sensitivity Analysis Utilizing Real-World Data. Springer-Verlag, Berlin Heidelberg. DOI: 10.1007/s12469-014-0086-z. August 27, 2014. Available: https://www.researchgate.net/publication/261367990.

18. Federal Transit Administration (FTA) (2007). Useful Life of Transit Buses and Vans - Report No. FTA VA-26-7229-07.1. April 2007. Available: https://www.transitwiki.org/TransitWiki/images/6/64/Useful_Life_of_Buses.pdf.

19. Stanford University (2015). Electric Buses at Stanford - California Higher Education Sustainability Conference (CHESC). June 16-18, 2015. Available:

https://www.ovmagazine.nl/wp-content/uploads/2015/11/ThomasWard_Jun173113Adams4.15pm_000.pdf.

20. Arieli Associates Management, Operations and Engineering Consulting (P.10). Electric Trolleybuses for the LACMTA's Bus System - Report No.1302. 2004. Available: http://media.metro.net/projects_studies/atvc/images/1302-Trolleybuses%20for%20LACTMA.pdf.

21. Explanatory Footnote.

22. Federal Transit Administration (FTA) (2007). Transit Bus Life Cycle Cost and Year 2007 Emissions Estimation – Final Report FTA-WV-26-7004-2007.1. July 2, 2007.