California Environmental Protection Agency

AIR RESOURCES BOARD

TECHNOLOGY ASSESSMENT:
TRANSPORT REFRIGERATORS

August 2015

State of California
AIR RESOURCES BOARD

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EXECUTIVE SUMMARY

This executive summary presents the Air Resources Board (ARB or Board) staff's *Technology Assessment for Transport Refrigerators*.

1. What is a transport refrigeration unit?

A transport refrigeration unit (TRU) is defined in the TRU Airborne Toxic Control Measure at title 13 California Code of Regulations (13 CCR) section 2477.4(a)(91) as refrigeration systems powered by integral (inside housing) internal combustion engines designed to control the environment of temperature sensitive products that are transported in trucks and refrigerated trailers. TRUs may be capable of both cooling and heating.

This is an industry-accepted definition. If the engine powering the unit is diesel-fueled, then it is a TRU. If the refrigerator is powered some other way, besides a diesel engine, it is referred to as a transport refrigerator (TR).

Truck TRUs are used to refrigerate insulated cargo vans mounted on the frame of a straight truck. There are approximately 7,000 truck TRUs based in California. They emit 340 tons of nitrogen oxide (NO_x) and 13 tons of particulate matter (PM) per year. A straight truck cargo van that is equipped with a truck TRU is shown in Figure ES-1 (see red arrow).

Trailer TRUs are used to refrigerate insulated vans mounted on semi-trailers. There are approximately 20,400 trailer TRUs based in California and another 12,500 that are based outside of California and operate in California on any given day. They emit 4,043 tons of NO_x and 150 tons of PM per year. A trailer TRU is shown in Figure ES-2 (see red arrow).

Figure ES-2: Trailer TRU

Railcar TRUs are used to refrigerate railcars. There are approximately 1,300 railcar TRUs operating in California at any given time. They emit 158 tons of NO_x and 5 tons of PM per year. A railcar TRU is shown in Figure ES-3 (see red arrow).

2. What is a TRU generator set?

A TRU generator set (TRU genset) is defined in the TRU Airborne Toxic Control Measure at 13 CCR, section 2477.4(a)(93) as generator set that is designed and used to provide electric power to electrically driven refrigeration units of any kind. This includes, but is not limited to, gensets that provide electricity to electrically powered refrigeration systems for semi-trailer vans and shipping containers when they are not plugged into ocean-going ship electric power or dock shore power. There are approximately 7,800 TRU gensets operating in California at any given time, emitting 322 tons of NO_x and 9 tons of PM per year.

There are several types of TRU gensets. Industry refers to them as “pin-on” and “under-slung.” Pin-on TRU gensets are pinned onto the front of refrigerated shipping containers, just above the container’s all-electric refrigeration system, which is built into the shipping container. A pin-on TRU genset is shown in Figure ES-4 (see red arrow).

Figure ES-4: Pin-On TRU Genset

Under-slung TRU gensets are clamped to the frame rails of a trailer chassis that is designed for the sole purpose of transporting shipping containers on the roadway. This arrangement is also called a belly mount. Both pin-on and under-slung TRU gensets are designed to provide electric power for only one refrigerated shipping container. An under-slung TRU genset is shown in Figure ES-5 (see red arrow).

Figure ES-5: Under-slung TRU Genset

There is a third type of TRU genset that is designed to provide power for a number of refrigerated shipping containers. Several diesel generators are installed into a shipping container, which is often called a “powerpack.” These powerpack containers are loaded onto railcars and connected to about 10 refrigerated shipping containers on adjacent railcars. A powerpack is shown in Figure ES-6 (see red arrow).

Figure ES-6: Powerpack

3. Who manufactures TRUs and TRU gensets?

Two TRU original equipment manufacturers share the U.S. market: Carrier Transicold, a division of United Technologies, and Thermo King, a division Ingersoll-Rand. Each shares about 50 percent of the U.S. TRU market. These same manufacturers also produce the TRU gensets sold in the U.S. (market share information is not available).

4. What are ARB’s goals for this technology assessment?

This technology assessment provides an assessment of the current state and projected development of technologies that can be used for transport refrigeration over the next 5 to 10 years. The long-term objective is to transform transport refrigeration to using zero and near-zero emission technologies to meet air quality and climate change goals. Those goals are:

- Reduce GHG emissions by 40 percent by 2030, 80 percent by 2050, and
- Reduce diesel PM emissions by 85 percent by 2020.

5. What transport refrigeration technologies were assessed?

Staff looked at conventional and advanced technologies applicable to transport refrigeration systems, but focused on the following technologies for this report:

A. All-electric/plug-in/battery/vehicle generator TRs;
B. All-electric/plug-in/cold plate TRs;
C. Hydrogen fuel cell-powered TRs;
D. All-electric/plug-in/battery/solar-assist TRs;
E. Cryogenic TRs;
F. Alternative fueled engine TRs; and
G. Advanced power plant – Homogenous Charge Compression Ignition.

This does not represent the full universe of potentially applicable technologies. Staff focused on technologies showing potential for commercialization within the next 10 years. Going forward, staff proposes to continue to monitor and evaluate new technologies and product advancements.

6. How did staff categorize the stage of commercialization or deployment?

Staff assigned each technology to one of the following categories of commercial readiness or deployment:

- Demonstration phase: low number, specialty built;
- Pilot scale deployment: higher numbers but not yet commercial production volumes
- Early commercialization: commercially available, small fraction of new sales; or
- Commercialized: commercially available, fraction of new sales.

7. How do potential emission reductions of the evaluated technologies compare to conventional TRUs that are in use in 2015?

Greenhouse Gas Emission Reductions

Table ES-1 shows Well-to-Wheels (WTW) GHG emission rate comparisons between current baseline TRUs (new conventional 2015 TRUs fueled with 2015 fuel) and select technologies using 2020+ fuels. Well-to-Tank (WTT) and Tank-to-Wheels (TTW) GHG emission rates are also shown within the table. Adding WTT and TTW results in the total WTW value.[1] The right column shows the percent reduction of GHG emissions for each technology, compared to conventional TRUs. These comparisons are made to the corresponding baseline conventional truck or trailer TRU application (first two rows). For example, the cryogenic trailer TR is compared to the conventional trailer TRU (baseline) to give the percent reduction result shown in the right column ((11.01 – 4.5)/11.01 = 59 percent).

Table ES-1: WTW GHG Emission Rate Comparisons, 2015 Fuel (Baseline)

	GHG Emission Rate (kg/hr)			WTW Percent Reduction[1]
Equipment Type	**WTT**	**TTW**	**WTW**	
Conventional 2015 Trailer TRU, 2015 Fuel (Baseline)	2.93	8.08	11.01	N.A.
Conventional 2015 Truck TRU, 2015 Fuel (Baseline)	2.20	6.06	8.26	N.A.
All-Electric Plug-in/Battery/Solar Trailer TR	1.24	0	1.24	89%
All-Electric Cold Plate Truck TR	1.73	0	1.73	79%
All-Electric H2 Fuel Cell Trailer TR	4.24	0	4.24	61%
Cryogenic Trailer TR	4.5	0	4.5	59%
All-Electric Plug-in/Battery/Generator Truck TR	0.654	2.89	3.54	57%
CNG Truck TR	1.54	5.28	6.82	17%
CNG Trailer TR	2.05	7.04	9.09	17%
LNG Trailer TR	2.74	7.07	9.81	11%

Note 1. Comparisons are made to conventional truck TRU or conventional trailer TRU, as applicable.

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[1] Calculation of the WTT, TTW, and WTW emission rates and the assumptions for each of these comparisons are discussed in Chapter III and the appendices. GHG emission rate calculations rely on individual Low Carbon Fuel Standard (LCFS) carbon intensity (CI) values. Conventional TRU calculations use 2015 diesel fuel CI. Assessed TR technology calculations use CIs for a blend of renewable feedstocks to represent fuels on the market in 2020 and beyond under California’s various fuels policies.

All-electric TRs with various range extender strategies appear to come closest to meeting ARB's GHG emission reduction goals.

Figure ES-7 provides a visual comparison of Table ES-1 WTT, TTW, and taken together, the resulting WTW GHG emissions between new conventional 2015 baseline TRUs (left two columns) and select TR technologies using 2020+ fuels. All-electric TRs and their variations show significant emission reductions compared to conventional TRUs.

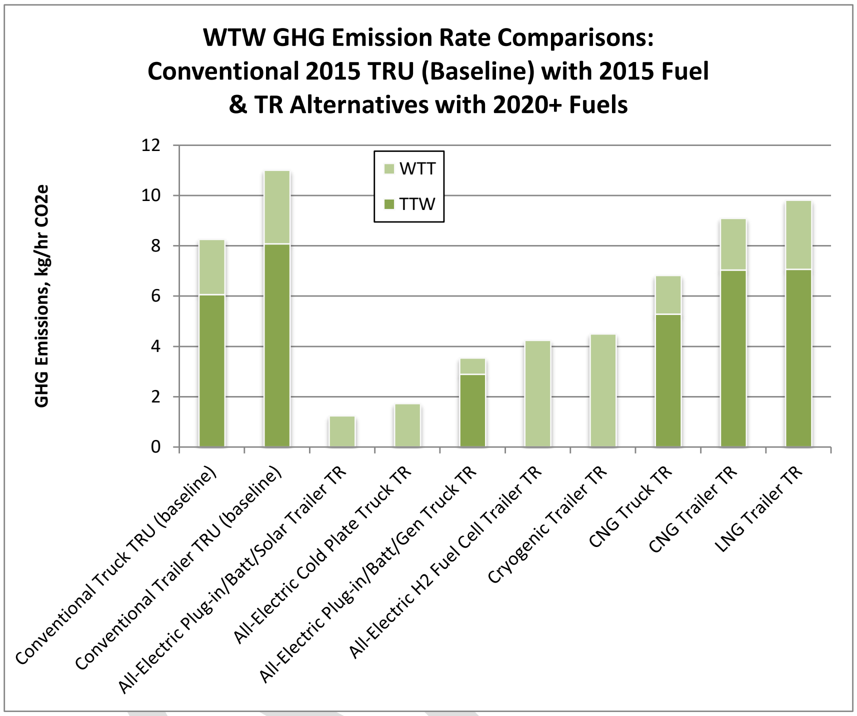

Figure ES-7:
WTW GHG Emission Rate Comparisons for 2015 Fuel (Baseline) and TR Alternatives

In the case of the all-electric trailer hydrogen (H_2) fuel cell (FC) TR, the WTT emission rate shown assumes on-site steam methane reformation (SMR) of 66 percent pipeline natural gas and 33 percent landfill gas converted to hydrogen (required by SB 1505 in 2020). Furthermore, producing H_2 by on-site solar photovoltaic (PV) electrolysis, would eliminate the WTT emissions if solar PV was on-site.

Table ES-2 (next page) shows more direct GHG emission rate comparisons between conventional TRUs[2] and select TR technologies, all using fuels that will be required in 2020 and beyond.[3] Similar to the above table, the right column shows the percent reduction of GHG emissions for each technology, compared to conventional TRUs with 2020+ fuel (first two rows).

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[2] Conventional TRU engines in 2020 and beyond are assumed to be similar to current TRU engines because there are no mandated requirements to improve fuel economy for these engines. So, GHG emissions changes would be due to required lower fuel CI values, not engine efficiency.

[3] Calculation of the WTT, TTW, and WTW emission rates and the assumptions for each of these comparisons are discussed in Chapter III and the appendices. In this case, conventional TRU calculations use CI values for diesel fuel that is required in 2020 and beyond, which are compared to select TR technologies also using CIs for a blend of renewable feedstocks to represent fuels on the market in 2020 and beyond, under California's various fuels policies.

Table ES-2: WTW GHG Emission Rate Comparisons, 2020+ Fuel

	GHG Emission Rate (kg/hr)			WTW Percent Reduction[1]
Equipment Type	**WTT**	**TTW**	**WTW**	
Conventional 2015 Trailer TRU, 2020+ Fuel	1.83	8.08	9.91	N.A.
Conventional 2015 Truck TRU, 2020+ Fuel	1.37	6.06	7.43	N.A.
All-Electric Plug-in/Battery/Solar Trailer TR	1.24	0	1.24	87%
All-Electric Cold Plate Truck TR	1.73	0	1.73	77%
All-Electric H2 Fuel Cell Trailer TR	4.24	0	4.24	57%
Cryogenic Trailer TR	4.5	0	4.5	55%
All-Electric Plug-in/Battery/Generator Truck TR	0.654	2.89	3.54	52%
CNG Truck TR	1.54	5.28	6.82	8%
CNG Trailer TR	2.05	7.04	9.09	8%
LNG Trailer TR	2.74	7.07	9.81	1%

Note 1. Comparisons are made to conventional truck TRU or conventional trailer TRU, as applicable.

As expected, the WTW percent reductions shown in Table ES-2 are less than those in Table ES-1 because diesel fuel CI values will be less in 2020 and beyond, compared to 2015 diesel fuel. Also of note, there are no requirements going forward for CI reductions for CNG and LNG in ARB's Low Carbon Fuel Standard, which means there are no renewable natural gas requirements. The result is that WTW GHG reductions for CNG and LNG will be less significant.

Figure ES-8 provides a visual comparison of Table ES-2 WTT, TTW, and WTW GHG emissions for conventional TRUs (left two columns) and select TR technologies using 2020+ fuels.

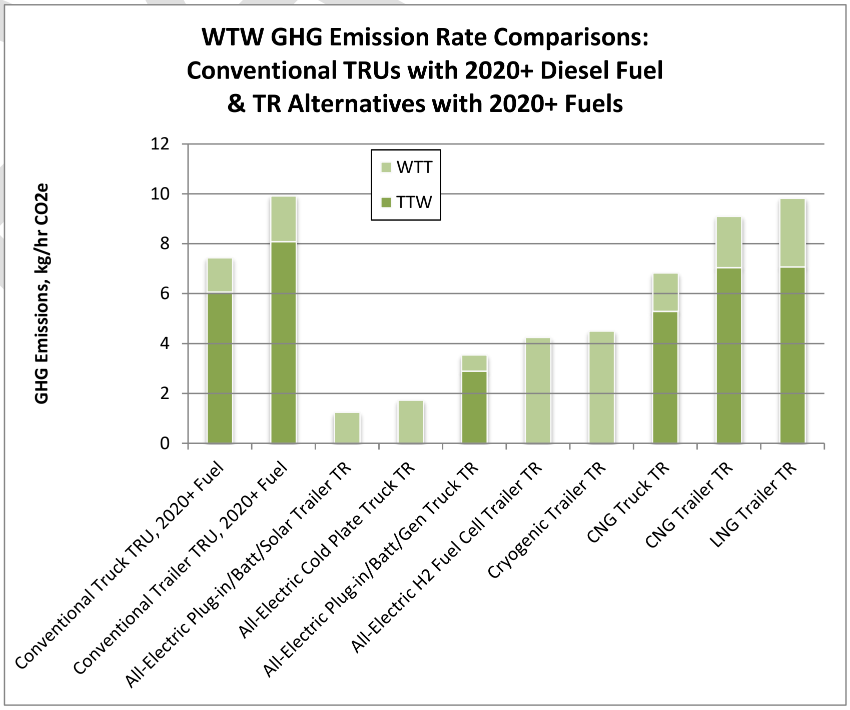


Figure ES-8:
WTW GHG Emission Rate Comparisons for 2020+ Fuels

Criteria Pollutant Emission Reductions

TTW criteria pollutant emission rates are compared in Table ES-3 for select TR technologies against conventional truck and trailer TRUs. WTT emissions are not evaluated; however, these upstream emissions are known to be a small percentage compared to TTW emissions for this sector, so they don't add much to the discussion.

Table ES-3: TTW Criteria Pollutant Emission Rate Comparisons

Equipment Type	$NMHC+NO_x$[1] (g/hr)	PM (g/hr)	Total CP (g/hr)	TTW Percent Reduction[2]
Conventional 2014 Truck TRU	37.9	0.79	38.69	-
Conventional 2014 Trailer TRU	57.5	1.23	58.73	-
All-Electric Plug-in/Battery/Solar Trailer TR	0	0	0	100%
All-Electric Cold Plate Truck TR	0	0	0	100%
All-Electric H_2 Fuel Cell Trailer TR	0	0	0	100%
Cryogenic Trailer TR	0	0	0	100%
All-Electric Plug-in/Battery/Generator Truck TR	4.88	0.14	5.02	87%
CNG Truck TR	28.99	NA[3]	28.99	25%
CNG Trailer TR	51.67	NA	51.67	12%

Note 1: "NMHC+NOx" means nonmethane hydrocarbons plus nitrogen oxides.
Note 2: Comparisons are made to conventional truck TRU or conventional trailer TRU, as applicable.
Note 3: "NA" means TTW emission factor "Not Available" for PM (relatively small compared to NMHC+NOx).

Figure ES-9 (next page) provides a visual comparison between new conventional 2014 TRUs (left two bars) and select TR technologies for TTW $NMHC+NO_x$ and PM criteria pollutant emission rates. Clearly, all-electric TR variations and cryogenic TRs have zero or significantly less criteria pollutant emissions compared to conventional TRUs. Also, emission rate benefits for CNG/LNG-powered TRs are not nearly as significant.

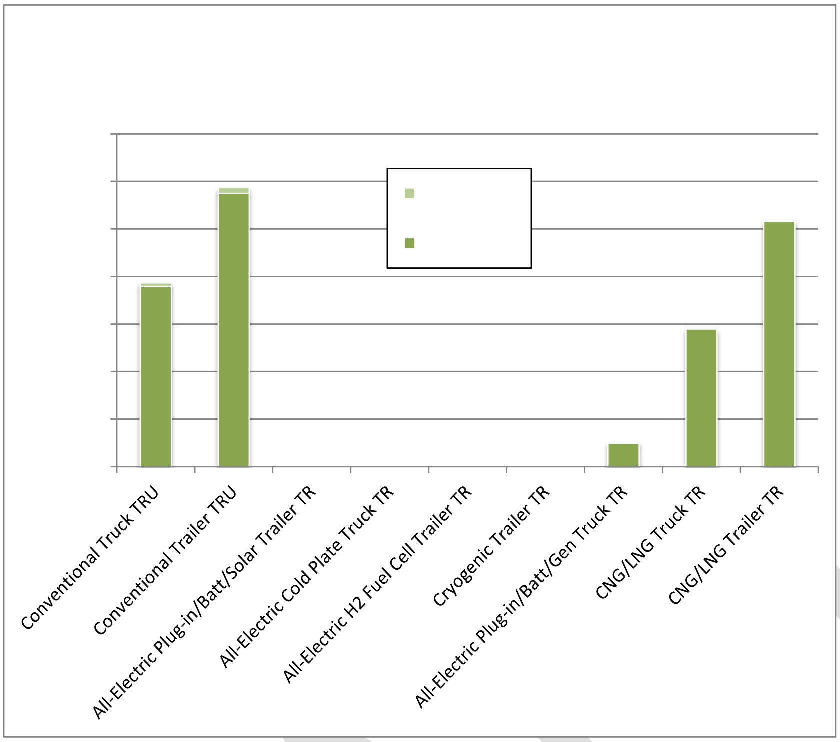


Figure ES-9:
TTW Criteria Pollutant Emission Rate Comparisons

8. What are the most promising technologies?

Table ES-3 summarizes the three most promising technologies and provides a brief listing of the reasons for this finding. A more detailed discussion is provided in Chapter IV.

Table ES-4: Most Promising TR Technologies

Technology	Reasons Why Technology is Promising
All-electric plug-in/battery/vehicle generator TR	• Significant potential emissions reductions • Truck retrofits are at pilot scale deployment (about 50) • Trailer TRs are at early commercialization stage for stationary applications • System integration for on-road trailer application is being developed
All-electric H_2 FC-powered TR	• Significant potential emission reductions • May be commercially available in the next five years if next-generation demonstrations are funded and expedited • Duty cycle, noise, payload impacts do not appear to be issues
Cryogenic TR	• Significant potential emission reductions • Commercially available now • Capital costs are roughly comparable to conventional TRUs • Significant maintenance cost savings

All of the “Most Promising” TR technologies have similar key performance parameter issues and deployment challenges:

- Limited fueling infrastructure currently exists;
- Fueling infrastructure costs are significant; and
- Limited range means these technologies are not an option for long-haul until publically accessible infrastructure is installed along major transportation corridors for Class 8 semi-trailers (e.g. electric power plugs, H_2 refueling, cryogenic fluid “refueling”); so until then, they are only potentially feasible for fleets that return to base each day where refueling infrastructure could be installed.

Significant improvements in energy efficiency are also possible for conventional TRUs. Many of these energy efficiency improvements could also help to make the TR technologies discussed herein more viable by extending their range (hours of operation between fueling). Section J in Chapter III discusses efficiency in more detail.

9. What are the main challenges to reducing emissions from transport refrigeration equipment?

Durability and reliability are serious issues due to food safety concerns. Extensive testing under real world conditions would be needed before TRU Manufacturers and their customers will trust a new technology to be at least as dependable and capable of maintaining temperature set points as the conventional technology it would replace. Extended down-time must be prevented through quick access to replacement parts and special components.

Range is a challenge. Long-haul carriers will not be good candidates for these technologies until publicly accessible refueling infrastructure is sufficiently available for Class 8 semi-trailers along transportation corridors. Grocery distribution and foodservice distribution fleets that return to base between routes may be good candidates for these technologies when they are commercially available. As these technologies become more widespread, infrastructure could eventually expand to the point that would support long-haul fleet operations. Funding and incentives could accelerate deployment of infrastructure.

Trucking is a very competitive industry and profit margins are very thin; so economics are a critical issue that makes widespread adoption of new technologies difficult. New technologies typically cost more. In many cases, the costs will come down as production numbers increase, due to economies of scale. If a new technology creates operating cost savings, due to reduced fuel or maintenance costs, over time those savings can make the initial capital investment worthwhile. But, if the incremental cost of a new technology is too great, some carriers may not have the cash or credit to make the investment at all, or in a significant number of units. Incentive funding programs are essential to overcome these hurdles. The value of these new assets at trade-in is also a concern if the rest of the industry has not yet accepted the new technology. If a new technology causes an impact on payload capacity, that can impact revenue because less payload means less revenue. Some technologies require costly infrastructure, such as fuel storage and dispensing equipment and specialized maintenance facilities.

Finally, the importance of operator safety can never be underestimated. Most TR technologies have potential safety issues that would require changes to normal operating procedures, training, and new equipment to manage these concerns.

10. What are the estimated per-equipment costs of the most promising technologies now, and at widespread deployment?

Capital costs for the most promising TR technologies are listed in Table ES-5 for comparison with conventional TRU costs. Further details are provided in the discussion below the table.

Table ES-5: Estimated Cost of TR Technologies Compared to Conventional TRU Costs

Technology	Capital Cost Per Unit	Conventional 2014 TRU Cost
All-electric plug-in/battery/ vehicle generator truck TR	$22,500	$18,000
All-electric H2 FC-powered trailer TR	$40,000-$50,000[1]	$28,000
Cryogenic truck TR	$16,000	$18,000
Cryogenic trailer TR	$29,000	$28,000

Note 1: Cost shown is for pilot demonstration phase unit. There should be better clarity of costs after the pilot demonstration phase is completed. At commercial production, costs would be significantly less due to economies of scale and material cost reduction advances.

All-electric plug-in/battery vehicle generator truck TR capital cost is about $22,500 compared to $18,000 for a conventional diesel truck TRU with similar cooling capacity. At this time, staff does not have the capital cost for an all-electric plug-in/battery trailer TR. Electric power plugs cost about $6,000 per loading dock plug and about $7,200 per parking area power pedestal plug.

Hydrogen fuel cell trailer TRs have been preliminarily estimated to cost between $40,000 and $50,000 for the prototype pilot demonstration phase, compared to about $28,000 for a conventional trailer TRU with similar cooling capacity. Cost figures at this phase of development are typically much higher than they will be when produced for the commercial market. Hydrogen fueling dispenser costs for TRs were not available.

As Table ES-5 indicates, the capital cost of a cryogenic truck TR averages about $16,000 (compared to $18,000 for a conventional truck TRU) and about $29,000 for a cryogenic trailer TR (compared to $28,000 for a conventional trailer TRU). Cryogenic fueling infrastructure can be leased for about $3,000 per month. In addition, the cargo van insulation needs to be thicker to extend range, which adds an unknown amount to capital costs.

Operating cost savings are possible for some of the technologies; however, staff was unable to collect the information needed to calculate payback periods at this time.

11. What additional work or information is needed to refine or improve this technology assessment?

Currently, there are significant data gaps that need to be filled. Staff learned of a number of demonstration projects that were in-process, or in the planning phase and still needing to be completed. For example, two hydrogen fuel cell TR projects have begun, as well as several cryogenic TR demonstrations in the U.S. Several all-electric TR projects and alternative fueled engine tests are in the planning phase. While advanced battery systems are used in electric vehicles, they are in the nascent stage of integration for the all-electric TR application. An advanced battery system demonstration project is in the planning phase for all-electric truck TRs, the results of which may help move this technology into all-electric trailer TRs. The results of the in-process technology demonstrations are not expected to be available until mid- to late 2016. Demonstration project reports should provide a better indication of technology readiness and staff is hopeful there will also be better capital, operating, and infrastructure cost information available at that time so that payback periods can be calculated.

12. What is staff's recommendation?

Longer-term

Staff recommends monitoring all of the planned and in-progress demonstration projects that are discussed in Chapter III for each of the zero and near-zero emissions technologies evaluated. The results of these demonstrations are needed to better understand how well they meet key performance parameters at this stage of development. Further development and demonstrations may be needed before some technologies can be considered commercially available. Staff believes significant progress is possible by 2030. It could be 2050 for some TR applications, such as long-haul due to infrastructure needs along transportation corridors. Therefore, a continuing effort is needed to fill the data gaps we have identified with regards to potential impacts to food safety, costs, savings, return on investment (ROI), and payback period. More meaningful recommendations to policy makers can be made when the results of these demonstrations are available.

If the pilot demonstration phase results continue to show promise, additional funding is needed to conduct larger-scale demonstrations of these technologies, going beyond the pilot demonstration phase in the next step toward commercialization. The full range of operating conditions needs to be explored. Additional design iterations may be needed to resolve the challenges posed by taking these technologies on the road.

Advanced battery systems also need to be designed and tested to provide electric power for all-electric trailer TRs while they are operating on the road. Advanced battery costs need to come down at least 50 percent before all-electric on-road operation will be viable. Partners and incentive funding are needed to develop and demonstrate all-electric plug-in advanced battery trailer TRs with adequate range.

When these technologies are commercially ready, incentive programs are needed to reduce economic barriers and accelerate deployment. Encouraging necessary energy/fueling infrastructure development with funding and incentive programs would address one of the key barriers to deployment. As production numbers increase, costs will come down and the economics will improve, making these technologies more attractive to other fleets.

Improved energy efficiency is key to the success of all of the technologies that were evaluated. Staff believes TRUs, TRs, and insulated vans can be further optimized to improve energy efficiency and reduce GHG and criteria pollutant emissions. Efficiency standards for insulated vans and mechanically refrigerated transport equipment are in effect in Europe and something similar is needed in the U.S. Staff recommends encouraging the U.S. Department of Energy (DOE) and the U.S. Environmental Protection Agency (EPA) to adopt ENERGYSTAR-like efficiency standards and SmartWay Technology incentives, respectively, that would include transport refrigeration and insulated van components. Better energy efficiency would improve key performance parameter compatibility for zero and near-zero emission technologies (e.g. lower battery costs, longer operating range, and reduced payload impacts).

Staff also believes there may be a need for new, more stringent off-road compression-ignition engine emissions standards for less than 25 hp engines, going beyond the current Tier 4 standards that are now in effect. The current Tier 4 standards for the less than 25 hp category do not meet the TRU Regulation's Ultra-Low-Emission TRU in-use standard. Currently, no new TRU engines are equipped with diesel particulate filters. So, new engines in the less than 25 hp category are still emitting too much diesel PM, resulting in public health risk near distribution centers that is too high. ARB has a research contract, launched in October 2014, to evaluate the feasibility, cost-effectiveness, and necessity of advanced PM and NOx emissions controls for the less-than 25 hp category. The report for this project will not be completed for at least 24 months (after October 2016). The results of this study are important to ARB's TRU program because we need near-zero criteria pollutant emissions for all of the TRU engine horsepower categories to adequately protect the public health.

Staff also believes it should continue to monitor other technologies that we did not have time and resources to evaluate during the current technology assessment. Staff should also look for opportunities to encourage energy saving innovations with conventional TRUs, which should translate into improved economics and reduced emissions.

Near-Term

Staff is proposing a near-term regulatory strategy to limit stationary operating time of fossil-fueled TRUs at certain locations under a phased compliance schedule. TRU fleets could use technologies that are currently commercially available, such as hybrid electric TRUs, TRUs equipped with electric standby, and cryogenic TRs. Hybrid electric TRUs and electric standby TRUs are powered by a diesel internal combustion engine when on the road and an electric motor when stationary and plugged into the electric power grid. Cryogenic TRs are discussed in detail in Chapter III, section E; but use a cryogenic fluid, such as liquid carbon dioxide or liquid nitrogen, to provide cooling. GHG and criteria pollutant (NO_x+NMHC and PM) emission reductions are possible to the extent stationary operations under fossil-fuel power are curtailed. More details on the types of fleets and stationary locations that would be affected in each phase will be developed during rulemaking.

I. INTRODUCTION AND PURPOSE OF ASSESSMENT

Purpose of the Technology Assessment

The technology assessments evaluate the current state and projected development of mobile source technologies and fuels. For each technology, the assessment will include a description of the technology, its suitability in different applications, current and anticipated costs at widespread deployment (where available), and emissions levels. These technology and fuels assessments support ARB planning and regulatory efforts, including those listed below.

- California's integrated freight planning
- State Implementation Plan (SIP) development
- Funding Plans
- Governor's ZEV Action Plan
- California's coordinated goals for greenhouse gas and petroleum use reduction

This technology assessment will focus on conventional and advanced technologies applicable to transport refrigeration systems, including all-electric plug-in/battery TRs, with various augmentations to extend on-road range, such as cold plates, hydrogen fuel cell-power, and solar photovoltaic systems; cryogenic refrigeration systems; alternative-fueled engines (e.g. CNG, LNG, and LPG); and advanced power systems (e.g. homogenous charge compression ignition).

Process

Staff conducted a literature search for each prospective technology. They contacted and interviewed people with knowledge and expertise in such technologies from various institutions, including national laboratories, university researchers, technology experts, engine manufacturers, original equipment manufacturers, dealers, fuel suppliers, retrofit companies, electric power companies, and engineering consultants, to name a few.

Technology Assessment Elements

Chapter II presents an overview of TRUs, including how fleets use TRUs, who makes them, the current population and emissions, and relevant air quality regulations. Staff has made a distinction between TRUs, which use diesel engines, and TRs, which use non-diesel technologies. Chapter III presents the following information for each technology.

1. ***Technology Description*** – A description of the technology and how it works is provided. The requirements for the technology including fueling needs, fuel storage, operating range, etc. is provided.

2. ***Technology Readiness*** – An assessment of the stage of development for each technology, with an assignment to one of the following categories:

- Demonstration phase: low number, specialty built;
- Pilot scale deployment: higher numbers but not yet commercial production volumes
- Early commercialization: commercially available, small fraction of new sales; or
- Commercialized: commercially available, fraction of new sales.

Completed or planned demonstration projects and the results are described, if available. A discussion is included of the scope of commercial introduction (number in use), how widely available it is (where, what types of fleets/applications), and sales rate estimates (current, five years and 10 years from now), if known.

3. ***Economics*** - Current costs (e.g. capital, operational, maintenance) are discussed, if known, at current production levels and anticipated costs if production could be expanded. A comparison is made to conventional technology costs, if known, both at current production levels and potentially widespread deployment levels. Potential returns on investment or payback period are discussed, if enough information is known.

4. ***Emissions Reductions*** – The per-unit emissions levels for GHG and criteria pollutants that can be achieved from the technology are discussed. The well-to-tank and tank-to-wheels emissions are discussed, as well as combined well-to-wheels emissions.

5. ***Technology Advantages*** – A description of the strengths of the technology.

6. ***Key Performance Parameter Issues and Deployment Challenges*** – A discussion of the issues that might make the technology less attractive for use by refrigerated carriers or operators. Deployment challenges that may impede its deployment or become a barrier to commercialization are also discussed.

Chapter IV provides staff's conclusions, with a summary of the most promising technologies, recommendations, and next steps.

II. OVERVIEW OF TRANSPORT REFRIGERATION UNITS AND THE REFRIGERATED TRANSPORT INDUSTRY

This chapter provides an overview of TRUs, the types of fleets that use them, the manufacturers, key performance parameters that need to be considered, the current population and emissions, typical purchase patterns, and the regulatory setting.

Transport Refrigeration Units (TRU) are diesel-powered refrigeration units that are installed on insulated cargo vans, rail cars and shipping containers used in transporting fresh produce, meat, dairy products, beverages, film, prescription drugs, and other temperature sensitive goods. Vapor compression refrigeration systems are used for transport refrigeration, which have four main components: a compressor, a condenser, control valves, and an evaporator, with blowers moving air across the condenser to reject heat and across the evaporator to produce cold air at a sufficient velocity to reach all parts of the cargo space. Figure II-1 shows a schematic of a typical single-stage vapor compression refrigeration system. R-404A is the refrigerant currently used in the majority of TRUs, which has a global warming potential (GWP) of 3,922 (EPA, 2011).

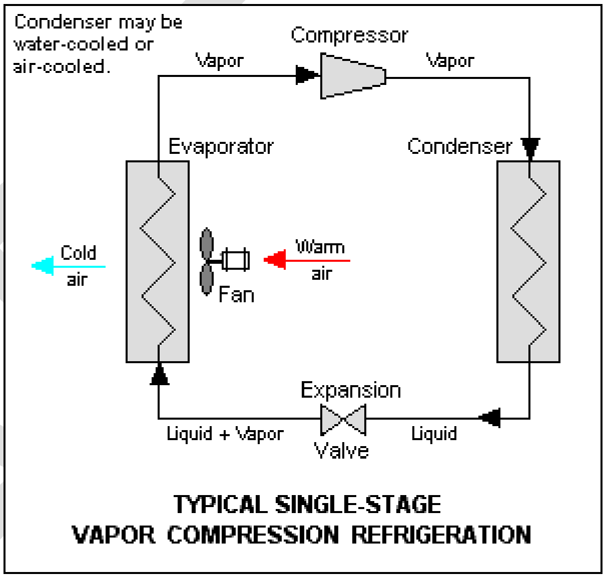


Figure II-1

TRU generator sets (genset) provide onboard electric power to electrically-driven refrigeration systems that are used in shipping containers and some semi-trailers when they are not plugged into ocean-going ship electric power or dock-side shore power. The electrically driven units powered by TRU gensets that are used on container units generally use R-134a refrigerant which has a GWP of 1430 (EPA, 2011).

Several types of vehicles are used to transport these perishable goods, including refrigerated straight trucks (20 percent) and refrigerated semi-trailers and railcars (about 80 percent).

A. Fleet Characterization

Many types of fleets transport perishable goods. Refrigerated trailer equipment has three primary market segments, as shown in Figure II.A-1 (Nuvera, 2013).

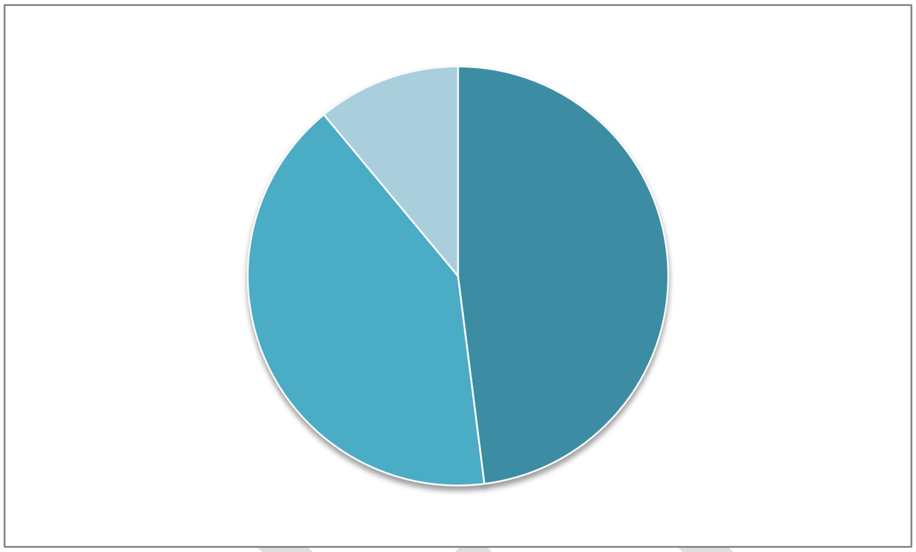


Figure II.A-1: Refrigerated Fleet Market Segments

For-Hire Fleets

For-hire refrigerated fleets haul goods for others – they do not own the goods they transport for customers, who are growers, shippers, processing plants, packing plants, and receivers. For-hire fleets can be further broken down, as shown in Figure II.A-2 (Nuvera, 2013).

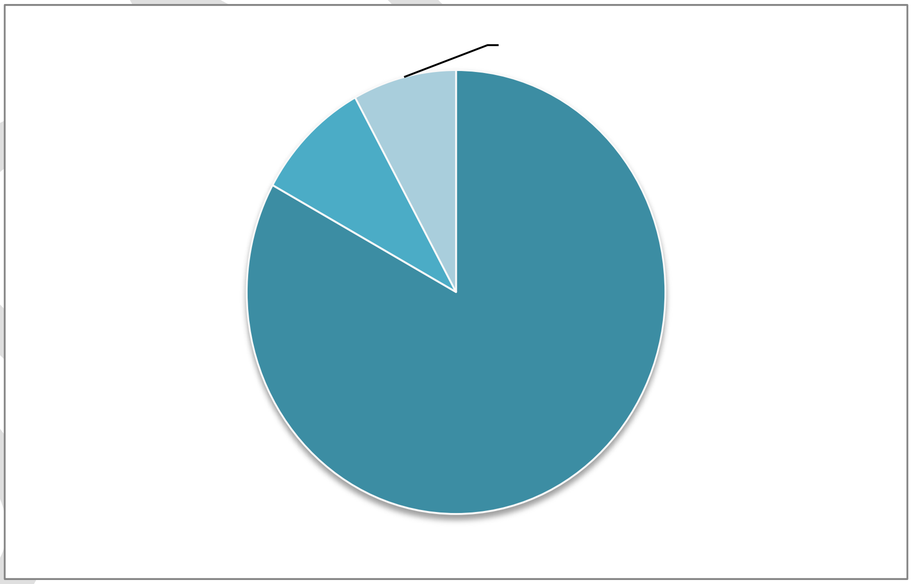


Figure II.A-2: For-Hire Fleets

Line-haul fleets transport freight between cities, points, or terminals. Owner-operators own and operate the vehicle they use to make a living. Intermodal trucking fleets transport intermodal shipping containers by truck between various modes of transport, such as between port terminals and rail terminals and vice versa.

Private Fleets

Private refrigerated carriers typically transport goods they own, but some fleets back-haul goods (transport goods on the return trip) owned by others to better utilize their assets. They typically return to base each day for reloading. Private carriers can be further broken down as shown in Figure II.A-3. (Nuvera, 2013)

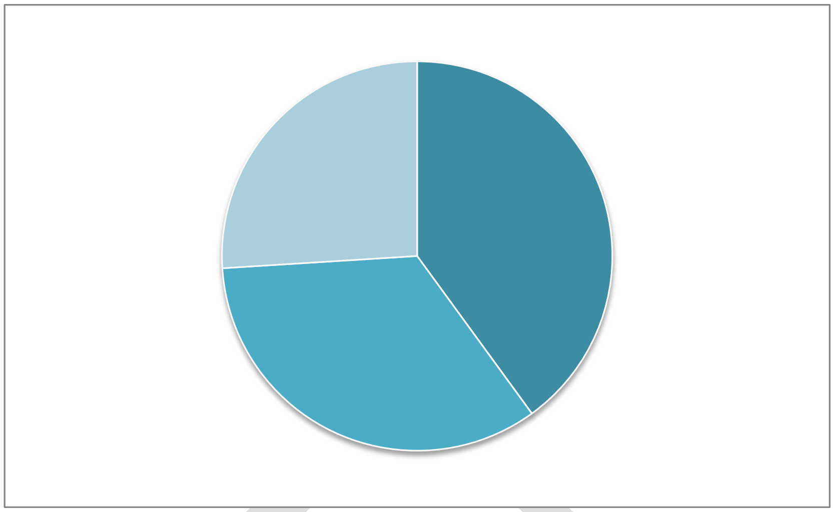


Figure II.A-3: Private Fleets

Leasing and Rental Fleets

Leasing and rental companies do not haul perishable goods. They rent or lease refrigerated equipment to the other two market segments.

Long-Haul vs. Short-Haul

Long-haul typically means the load is transported more than 300 miles from the pick-up point to delivery point. Short-haul means the haul distance is less than 300 miles. Food companies manufacture, process, and pack foods. Specialties include many miscellaneous perishable goods categories, such as film, flowers, and pharmaceuticals.

Food service fleets typically transport a combination of frozen goods, refrigerated goods, and dry goods (un-refrigerated). Each zone of the foodservice cargo van is separated by insulated bulkheads, with the frozen section typically up front, refrigerated zone in the middle, and dry goods in the back. The foodservice driver typically delivers to a number of customers along a route, such as to convenience stores, restaurants, and cafeterias.

Foodservice and grocery distribution are typically considered short-haul or regional, urban, or intercity. Many foodservice fleets use shorter refrigerated trailers and straight truck cargo vans for better maneuverability on urban routes.

Truck-Load vs. Less-Than-Load

Within the for-hire category, fleets can specialize to provide truck-load (TL) or less-than-load (LTL). TL carriers haul a full load of goods from a pick-up point and deliver that load to its destination and those goods may be all of the same type or a combination of several types. LTL carriers are hauling goods for several customers at any given time. TL and LTL carriers can be regional/short-haul or long-haul. TL carriers typically use 53-foot long trailers. LTL carriers may use shorter trailers if the route demands maneuverability. A small percentage of TL carriers may also use Longer Combination Vehicles (LCV), which consist of two or three shorter trailers pulled behind a single tractor, where allowed by state law outside California. A refrigerated TL carrier may also backhaul "dry" goods (similar to a non-refrigerated trailer) when refrigerated loads are not available in order to best utilize the asset.

B. Operational Characterization

TRUs are capable of being programmed to maintain an optimum set-point temperature for the product being hauled and in addition to cooling, they can provide heat to defrost the evaporator or warm the cargo space to protect products from cold weather. TRUs can also be programmed to shut off when the set-point temperature is reached, like a home refrigerator. Alternatively, they can maintain the set-point temperature while providing continuous air flow across the cargo space to disperse the heat of respiration - generated by the "living" product - and ethylene gas that is emitted by many types of produce, which if not dispersed, accelerates ripening and shortens shelf-life.

C. Manufacturers

TRUs and TRU generator sets are manufactured by Carrier Transicold, a division of United Technologies Corporation, and Thermo King, a division of Ingersoll-Rand. These two manufacturers each share approximately half of the U.S. market. Two other minor TRU manufacturers have recently entered the U.S. market -- Zanotti Transblock and Kingtec -- but they have less than one percent of the U.S. market, combined.

Containerized generators, sometimes called "powerpacks", are manufactured in relatively small numbers (averaging about a half-dozen per year) by Hewitt Equipment and Multimodal Engineering Corporation (MEC) for K-Line, a major ocean carrier. Power packs are loaded onto container railcars with a number of refrigerated containers to provide electric power to those containers during the land-leg of their journey.

Refrigerated (insulated) trailers, sometimes called reefers, are manufactured by Utility Trailer Manufacturing Co., Great Dane Trailers, Wabash National Corp., Hyundai Translead, Vanguard National Trailer Corporation, and Kidron. (ACT, 2015) Refrigerated straight trucks are manufactured by Brown Cargo Van, Cold Car USA, Delta-Waseca, Drake Truck Bodies, Hercules Manufacturing Co., Hulet Body Co., Intercontinental Truck Body, Johnson Refrigerated Truck Bodies, Kidron, Morgan Corp., Supreme Corp., and Utilimaster Corp. (Refrigerated Transporter, 2015) This is not an all-inclusive list.

D. Key Performance Parameters

Staff have identified key performance parameters that they believe refrigerated carriers consider in their purchase decisions. How well a temperature control technology meets these parameters may determine how well a potential transport refrigeration technology will penetrate the refrigerated transport market.

1. Ability to Perform the Duty Cycle

TRUs must be capable of maintaining the optimum “set point” temperature to ensure product integrity and providing fast “pull-down” (pre-cool) to prepare the cargo space for loading (typically in under 30 minutes), and to recover quickly from door openings that occur during deliveries. Trailer and railcar TRUs are rated at 20,000 to 68,000 British Thermal Units per hour (BTU/hr) cooling capacity depending on the thermostat set point. Straight truck TRUs are rated at 5,000 to 33,000 BTU/hr.

Most trailer and rail car refrigeration applications demand high performance cooling capacity and airflow. Foodservice delivery routes require cargo van doors to be opened frequently. Rapid cool-down after each delivery stop is required and the additional fan load and evaporator load for multiple cooling zones in a foodservice trailer also adds to the power demand on the engine. Most of the trailers used for grocery distribution and produce are at the 53-foot legal limit, and rail car applications can be up to 72 feet in length. As a result of this high performance requirement, most trailer and rail TRU engines have historically been rated between 25 and 50 horsepower (19-37 kW), with an average peak horsepower rating of 34 hp (25 kW). However, both of the major TRU original equipment manufacturers have recently redesigned most of their product lines to be more efficient and have more sophisticated control systems, so that TRU refrigeration systems demand less power from the engine. These improvements have resulted in more trailer TRUs equipped with engines with a peak horsepower rating just below the 25 hp (19 kW) threshold for off-road engine emissions standards, although on average the TRUs require approximately one-half of the peak horsepower during normal operation. Straight truck TRU engines are rated at less than 25 hp (19 kW), with an average peak horsepower of 14 hp (10 kW). Most TRU gen set engines have a peak horsepower rating near 30 hp (22 kW), but some are just below 25 hp (19 kW).

Current TRUs are powered by diesel engines and designed to allow independent operation. Many fleets have a ratio of approximately two trailers to each tractor; so, many times the TRU is operating without the tractor in proximity, such as in “drop and hook” logistical operations. This is a consideration for alternative technologies that potentially rely on the tractor to assist the TRU in some manner (e.g. provide electric power to the refrigerator).

As insulated bodies age, their ability to resist the intrusion of heat lessens as insulating foam degrades. Normal insulated body degradation is generally estimated at 5 percent per year. Additionally, there may be operational damage which allows water intrusion, such as accidental penetration of the walls with fork trucks or exterior damage from the trailer impacting something during maneuvering. Doors and seals may also degrade or be damaged over time, allowing in more heat. This could result in up to an additional 5 percent annual deterioration depending on maintenance and repair practices and wear and tear. Current TRU designs are sized to have a significant performance safety factor in order to continue to perform acceptably as the insulated bodies degrade over time.

Many distribution fleets are also utilizing more electrical power on their trailers for value-added purposes, such as providing interior lighting for night deliveries, powering lift gates, or charging pallet jacks that drivers use during deliveries. Fleets rely on the TRU to provide electric power for these devices.

2. Noise Pollution

Diesel-powered TRUs can produce an unacceptable amount of noise, which is a problem when deliveries points are near residential areas, hotels, hospitals, and nursing homes. Local noise ordinances have been adopted in some areas that effectively ban TRUs while operating in diesel mode. Some current TRUs come equipped, either as standard or an option, with an “electric standby” feature that allows them to be plugged into electrical power when stationary (similar to a home refrigerator) and allow the diesel engine to be turned off to reduce noise, as well as operating costs and emissions. This option is growing in popularity.

3. Durability/Reliability

TRUs are equipped with diesel engines that are categorized as off-road compression-ignition engines. TRU fleet owners are willing to pay more for increased reliability because many high-value loads of perishable goods can be worth hundreds of thousands of dollars and a few are worth a million dollars. TRUs have specialized diesel engines that meet more robust specifications than a general use off-road diesel engine. Vibration impacts caused by roadway travel can damage engines. TRU owners also demand long service intervals, so engines are over-sized for lower load factors and the lube oil sump capacity is much greater than a general-purpose diesel engine.

4. Operating Range

For TRUs, range is the number of hours between refueling (for motor vehicles, range is miles between refueling). Regional operations, such as grocery and foodservice distribution require a minimum of 8 to 10 hours on average between refueling, for either continuous or start-stop engine operation. Many of these have some amount of overnight routes where stores/customers may be 300 miles away. The driver goes out and makes a big delivery loop, stays overnight, then comes back. With federal Hours of Service rules, there may be an increase in this practice, which requires more on-board fuel storage capacity. Local deliveries also need 8 to 10 hours of operation between refueling, with numerous temperature pull-downs after door openings for deliveries.

Long-haul operations need to be able to operate for several days between refueling. Depending on the type of load, the TRU engine may operate continuously or on start-stop mode, but there are few, if any door openings enroute.

The standard size TRU diesel fuel tank is 50 gallons, which allows for approximately three to four days of TRU operation between refueling. Some fleets opt for larger tanks (up to 120 gallons) because of the operational savings of infrequent refueling, opting to refuel approximately only once a week. The extended range between fueling also allows fleets more flexibility and reduced costs in their operations, such as avoiding refueling during weekend and strategically purchasing fuel at certain locations or at certain times to reduce cost. Since rail TRUs are unattended during use and trips may exceed a week, they may be equipped with fuel tanks up to 500 gallons to allow several weeks of extended use between fueling.

5. Payload Impacts

Maximizing the payload carrying capacity for a refrigerated van generally improves the economics. This applies to both available space and weight. Cargo space is the limiting factor for light, less dense cargo. When space is used up before the gross vehicle weight rating (GVWR) is reached, that is when industry says the load has “cubed” out. Cargo weight is the limiting factor for heavier, dense cargo. When the GVWR is reached before the space is used up; that is when industry says the load has “grossed” out. A temperature control technology or excessively thick cargo van insulation that uses up valuable cargo space or is heavier than a conventional TRU or insulating system will reduce one or both of these types of payload capacity and would have an undesirable impact on potential revenue and the rate of return for the equipment. Cargo space impacts may potentially degrade the overall environmental impact of the truck/trailer system if it results in more loads/trips and less fuel efficient goods movement.

6. Fuel Infrastructure Availability

The fueling infrastructure for a new technology would need to be established as market penetration occurs. For long-haul carriers, the refueling or recharging infrastructure needs to be at least available at regular intervals along the major transportation corridors. Foodservice and grocery distribution private fleets typically refuel at their home terminals or distribution centers before dispatch; but there are times when these fleets dispatch their equipment for long-haul loads, when they must refuel at truck stops. Rail operations must have fuel available at depots. The tractor consumes – by far – the majority of diesel fuel. For example, at 65 MPH, a tractor pulling a 40,000 pound trailer getting 6.5 MPG would consume 10 gallons of diesel fuel per hour compared to a TRU’s consumption of approximately 0.8 gal/hr. Since the majority of fuel is consumed by tractors, fleet preference is that the TRU fuel source match the tractor instead of having two different sources of fuel, otherwise the comparative minority of secondary type of fuel used by the TRU can be an operational penalty.

7. Cost and Return on Investment (ROI)/Payback Period

Capital Costs

Profit margins are slim in the food transport industry. Capital costs must be held to a reasonable level to stay within budget, provide a short payback time, and avoid creating a financing obstacle.

Operating Costs

Diesel fuel cost increases and volatility create uncertainty in the long-term planning process. Alternatives that reduce operating costs and offer greater stability may have a competitive advantage. For example, recent expansion of natural gas availability at a cost that competes well with diesel could open the way for increased use of hydrogen fuel cells or engines powered by natural gas. Alternatively, replacing diesel engines with electric drive systems can reduce maintenance costs because there are fewer moving parts, less lubrication, reduced consumables (such as belts), and they do not leak fuel and lubricants. However, maintenance costs associated with new technologies can be significant if new tools, training, and parts inventory are needed during the transition. Longer maintenance intervals create less down-time and lower operating costs. Labor costs associated with refueling or recharging must be considered. Lighter equipment also reduces transportation costs.

A new technology must be cost-effective on a life-cycle basis. An acceptable ROI or payback period is a huge driver and residual value at trade-in should be included in this analysis. Also to be considered is any associated infrastructure costs; for example, the special fueling system required for fuel cells or cryogenic units or the special service bays and safety precautions required when servicing natural gas systems.

8. Safety

Potential new safety risks may be associated with new technologies and must be evaluated and managed. For example, electric power plugs for trailer eTRUs typically use 460-volt three-phase power, and direct injection cryogenic systems can displace oxygen to low levels where there are potential asphyxiation concerns. These can be managed with operating procedures, safety interfaces, and monitoring systems. The importance of safety cannot be underestimated. Special training to ensure safe use of new technologies would be an additional expense. Also to be considered is the analysis of current or development of future codes and standards related to alternative technologies.

E. Population and Emissions Summary

The population of TRUs and TRU gensets operating within California on any given day consists of equipment that is based in California as well as those based outside of California and operating temporarily in California. Likewise, the emissions that occur within California come from that mix of equipment. Table II-1 lists TRU populations and emissions for TRUs and TRU gensets for 2015, as impacted by phased-in implementation of the TRU Regulation. (ARB, 2011a).

Table II-1: 2015 TRU Population and Emissions

Input	Truck TRUs	Trailer TRUs	Railcar TRUs	TRU Gen Sets
Daily California-based Population Operating in California	7,100	20,400	1,300	4,800
Daily Out-of-State-Based Population Operating in California	-	12,500	-	3,000
Annual Engine Activity in California (hp-hrs/yr)	75,228,000	872,106,000	34,255,000	80,989,000
NOx Annual California Emissions (tons/yr)	341	4,043	158	322
PM Annual California Emissions (tons/yr)	13	150	5	9

F. Typical Purchase Patterns and Average Age

TRU purchases follow cyclic economic conditions. Trailer TRU average age ranges from 5 to 6 years, but age can be much longer during tougher economic times when financing is more difficult. Most single-temp TRUs go through several ownerships, starting with long-haul owners. Better reliability is needed for long-haul because rescuing a load after a TRU failure is more difficult when the load is further away from the home terminal. Second- and third-generation owners tend to operate regional and then local routes later in life, as they get older and less reliable. Optionally, the TRUs are used for stationary cold storage when the trailer is no longer road-worthy, or they may be sold overseas for use in developing countries. Multi-temp TRUs typically have only one lifetime owner (due to very fleet-specific specifications), but may be converted to single temp units and used by regional or local fleets. Truck TRUs mounted to straight truck cargo vans typically have a life commensurate with the insulated box or the vehicle body, typically between 5 and 10 years depending on the duty cycle.

G. Regulatory Setting

In all states, the off-road engines used to power TRUs are required to meet federal standards. However, California is authorized under the federal Clean Air Act (CAA), Section 209(e)(2)(A), to adopt and enforce emission standards and other requirements for off-road engines and equipment not subject to federal preemption, provided California’s standards are at least as health-protective as the federal standards. In order to receive this authorization, California must apply for and receive approval from the U.S. EPA.

Federal nonroad (off-road) compression ignition engine emission standards are set forth for new engines in title 40 Code of Federal Regulations (40 CFR) Part 89. California has harmonized with federal emission standards, as set forth in title 13 California Code of Regulations (13 CCR), Article 4, sections 2420-2427, under “Heavy Duty Off-road Diesel Cycle Engines.” The off-road engine standards (Tiers) vary, depending upon the engine model year and maximum rated power. U.S. EPA adopted more stringent Tier 4 standards for the control of emissions from nonroad compression ignition engines in 2004 and ARB approved equivalent off-road standards in 2005. (ARB, 2005) Table II-2 (next page) shows the standards for Tier 1 through Tier 4.

It is worth noting that NMHC+NOx and PM emission standards for <25 hp engines are much less stringent, compared to other horsepower categories because more stringent standards were not considered cost-effective when U.S. EPA adopted Tier 4 standards in 2004 and ARB harmonized with those standards. Control technologies for NMHC+NOx and PM are currently being evaluated for lower horsepower categories and if they are found to be cost-effective going forward, may lead to more stringent new engine emissions standards.

Table II-2: Off-Road Compression-Ignition (Diesel) Engine Standards [NMHC+NOx/CO/PM in g/bhp-hr (g/kW-hr)]

HP (kW)	1995	1996	1997	1998	1999	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010	2011	2012	2013	2014	2015+
< 11 (8)	See Table 2 footnote (a)					7.8 / 6.0 / 0.75 (10.5 / 8.0 / 1.0)					5.6 / 6.0 / 0.60 (7.5 / 8.0 / 0.80)			5.6 / 6.0 / 0.30^{a} (7.5 / 8.0 / 0.40)							
≥ 11 (8) < 25 (19)						7.1 / 4.9 / 0.6 (9.5 / 6.6 / 0.80)					5.6 / 4.9 / 0.60 (7.5 / 6.6 / 0.80)			5.6 / 4.9 / 0.30 (7.5 / 6.6 / 0.40)							
≥ 25 (19) < 50 (37)	-				7.1 / 4.1 / 0.60 (9.5 / 5.5 / 0.80)					5.6 / 4.1 / 0.45 (7.5 / 5.5 / 0.60)				5.6 / 4.1 / 0.22 (7.5 / 5.5 / 0.30)					3.5 / 4.1 / 0.02 (4.7 / 5.5 / 0.03)		
≥ 50 (37) < 75 (56)	-			- / 6.9 / - / -^{b} (- / 9.2 / - / -)						5.6 / 3.7 / 0.30 (7.5 / 5.0 / 0.40)				3.5 / 3.7 / 0.22^{c} (4.7 / 5.0 / 0.30)					3.5 / 3.7 / 0.02^{c} (4.7 / 5.0 / 0.03)		
≥ 75 (56) < 100 (75)														3.5 / 3.7 / 0.30 (4.7 / 5.0 / 0.40)				0.14/ 2.5/ 3.7/ 0.01^{b,d} (0.19/ 3.4 / 5.0 /0.02)			0.14 (0.19) 0.30 (0.40) 3.7 (5.0) 0.01^{b} (0.02)
≥ 100 (75) < 175 (130)	-								4.9 / 3.7 / 0.22 (6.6 / 5.0 / 0.30)				3.0 / 3.7 / 0.22 (4.0 / 5.0 / 0.30)								
≥ 175 (130) < 300 (225)	-	1.0 / 6.9 / 8.5 / 0.40^{b} (1.3 / 9.2 / 11.4 / 0.54)							4.9 / 2.6 / 0.15 (6.6 / 3.5 / 0.20)			3.0 / 2.6 / 0.15^{e} (4.0 / 3.5 / 0.20)					0.14 / 1.5 / 2.6 / 0.01^{b,d} (0.19/ 2.0 / 3.5 /0.02)			0.14 (0.19) 0.30 (0.40) 2.6 (3.5) 0.01^{b} (0.02)	
≥ 300 (225) < 600 (450)						4.8 / 2.6 / 0.15 (6.4 / 3.5 / 0.20)															
≥ 600 (450) ≤ 750 (560)																					
Mobile Machines > 750 (560)	-					1.0 / 6.9 / 8.5 / 0.40^{b} (1.3 / 9.2 / 11.4 / 0.54)						4.8 / 2.6 / 0.15 (6.4 / 3.5 / 0.20)					0.30 / 2.6 / 2.6 / 0.07^{b} (0.40 / 3.5 / 3.5 / 0.10)				0.14 (0.19) 2.6 (3.5) 2.6 (3.5) 0.03^{b} (0.04)
GEN >750 (560) ≤1207 (900)																					0.14 (0.19) 0.50 (0.67) 2.6 (3.5) 0.02^{b} (0.03)
GEN>1207 (900)																	0.30 / 0.50 / 2.6 / 0.07^{b} (0.40 / 0.67 / 3.5 / 0.10)				

a) The PM standard for hand-start, air cooled, direct injection engines below 11 hp (8 kW) may be delayed until 2010 and be set at 0.45 g/bhp-hr (0.60 g/kW-hr).
b) Standards given are NMHC/NOx/CO/PM in g/bhp-hr (or g/kW-hr).
c) Engine families in this power category may alternately meet Tier 3 PM standards [0.30 g/bhp-hr (0.40 g/kW-hr)] in 2008-2011 in exchange for introducing final PM standards in 2012.
d) The implementation schedule shown is the three-year alternate NOx approach. Other schedules are available.
e) Certain manufacturers have agreed to comply with these standards by 2005.

🟨 : Tier 1 🟧 : Tier 2 🟥 : Tier 3 🟦🟪 : Tier 4 Interim / Final

Federal and California fuel standards specifically apply to manufacturers and distributors rather than to mobile sources or their operators. Nevertheless, these standards directly affect the fuel used in mobile sources, including transport refrigeration units. Fuel standards for sulfur content, aromatic content, and other fuel components and parameters play a critical role in meeting emission standards. Federal commercial fuel standards are set forth in 40 CFR Part 80 and California fuel standards are set forth in 13 CCR sections 2281 and 2282. In July 2003, a revision to CCR title 13, section 2281 was adopted by the ARB which allows only very low sulfur diesel (<15 ppm) in diesel fuel starting in June 2006. Activities involving California nonvehicular diesel fuel are also subject to this requirement as if it were vehicular fuel. U.S. EPA adopted a similar sulfur restriction that went into effect in 2006 for on-road fuel use and in 2010 for nonroad fuel use. Fuel suppliers for California must meet both federal and California fuel standards.

Several sections of the California Health and Safety Code (HSC) provide ARB with authority to adopt Airborne Toxic Control Measures (ATCM). HSC sections 43013(b) and 43018 provide broad authority for adopting measures to reduce Toxic Air Contaminants (TAC) and other air pollutant emissions from vehicular and other mobile sources. HSC section 39618 classifies refrigerated trailers as off-road mobile sources under ARB jurisdiction.

The Board identified diesel particulate matter (PM) as a TAC and in October 2000, ARB published a "Risk Reduction Plan to Reduce Particulate Matter Emissions from Diesel-fueled Engines and Vehicles." (ARB, 2000) In the Diesel Risk Reduction Plan, ARB identified TRU emissions associated with refrigerated warehouse distribution centers as creating potential cancer risks and included off-road engines in the plan to reduce diesel PM emissions.

On February 26, 2004, the Board approved for adoption the TRU ATCM, establishing in-use performance standards for TRUs and TRU gen sets that would be phased in commencing on December 31, 2008. The Office of Administrative Law approved the TRU ATCM, which was codified at 13 CCR, section 2477 on November 10, 2004, and the regulation became effective 30 days later upon being certified by the California Secretary of State. (ARB, 2004) Amendments to the TRU ATCM were adopted in 2010 and 2011 (ARB, 2011b; ARB, 2012).

Implementation of the TRU ATCM began in 2009. Model year 2007 and older TRUs and TRU gensets should have been in compliance with the TRU ATCM's in-use performance standards by the end of 2014. The TRU ATCM's in-use performance standard must be met on a phased compliance schedule. Each year the next model year must meet the in-use performance standards by the end of the seventh year after the model year. For example, model year 2008 units must meet the in-use performance standards by December 31, 2015. The in-use performance standards can also be met when new engines meet new engine standards that meet the TRU ATCM's most stringent in-use performance standards. That is the case for new engines rated at 25 to 50 hp that meet Tier 4 "final" new engine standards that went into effect

January 1, 2013. That is not the case for new engines rated at less than 25 hp because Tier 4 new engine standards do not meet the most stringent in-use performance standards under the TRU ATCM. Currently, no new TRU engines are equipped with diesel particulate filters. So, new engines in the less than 25 hp category are still emitting too much diesel PM, resulting in public health risk near most, if not all, distribution centers that is too high.

At this time, there are no additional new or in-use engine standards (other than those described above) that have been promulgated that will be going into effect in future years.

The refrigerants used in mechanical vapor compression refrigeration systems and the blowing agents used in foam insulation are regulated by U.S. EPA under the stratospheric ozone protection provisions of the CAA at Section 605(a) and 612(c). The Significant New Alternatives Policy (SNAP) Program at 40 CFR Part 82 allows U.S. EPA to effectively ban the use of certain high GWP refrigerants and blowing agents from specific uses. The SNAP Program evaluates and regulates substitutes for the ozone depleting chemicals that are being phased out. U.S. EPA periodically proposes changes to the status of substitutes that were previously listed as acceptable when other substitutes are available for the same uses that pose lower overall risk to human health and the environment. ARB has proposed prohibiting high-GWP hydrofluorocarbon refrigerants, which can be hundreds to thousands of times greater than carbon dioxide. For example, R404A, the refrigerant currently used in most TRUs, has a GWP of 3,922, meaning one pound of R404A is equivalent, from a global warming perspective, to 3,922 pounds of carbon dioxide. (EPA, 2011)

III. ASSESSMENT OF POTENTIAL TRANSPORT REFRIGERATOR TECHNOLOGIES

This chapter provides an assessment of select zero and near-zero emissions transport refrigerator technologies that have the potential to reduce GHG emissions and criteria pollutant emissions. Hybrid electric TRUs and TRUs equipped with electric standby are not considered zero or near-zero emissions technologies, so they are not addressed in this report. As described in Chapter II, technology descriptions, technology readiness, economics, emissions reductions, technology advantages, and key performance parameter issues and deployment challenges are discussed for each technology. The following technologies are assessed below:

A. All-electric/plugin/battery/vehicle generator TRs;
B. All-electric/plug-in/cold plate TRs;
C. Hydrogen fuel cell-powered TRs;
D. All-electric/plug-in/battery/solar-assist TRs;
E. Cryogenic TRs;
F. Alternative fueled engine TRs; and
G. Advanced power plant – Homogenous Charge Compression Ignition.

Section H of this chapter compares GHG emissions of select TRs against conventional TRUs. Section I compares criteria pollutant emissions of select TRs against conventional TRUs. Section J discusses how improved thermal efficiency of the insulated cargo van and mechanical efficiency of the refrigeration system can reduce fuel use and related GHG and criteria pollutant emissions.

A. All-Electric Plug-In/Battery/Vehicle Generator TRs

1. Technology Description

All-electric TR applications have been developed to provide temperature control and eliminate tailpipe emissions (e.g. NOx, PM, and GHG). In this application, the refrigerator's compressor is driven by an electric motor.

Stationary and Non-Stationary TRs

For stationary cold storage applications, conventional diesel TRUs can be converted to all-electric TR, using plug-in shore power. The diesel engine powering the compressor and fans is removed and replaced with electric motors to drive those components. Figure III.A-1 shows Electric Reefer Solutions' conversion of a Thermo King TRU to all-electric TR.

Figure III.A-1: Converted All-Electric TR

One of the TRU original equipment manufacturers (OEM), Carrier Transicold, currently offers an all-electric plug-in trailer TR for stationary storage applications. Small truck TRs are commercially available that run off the truck battery and generator for local deliveries.

For non-stationary, on-road applications, the TR can be powered by rechargeable batteries and a DC-to-AC inverter. The drawback of this approach is the space occupied by these components and their weight, which may add up to more than the removed engine, which may reduce available payload.

Aura Systems offers an on-road truck TR called the Auragen System, which uses a high-efficiency induction generator mounted on the truck engine to produce electrical power when the truck engine is running. When the truck engine is not operating, the TR is plugged into shore power.

Figure III.A-2 shows how the Auragen System architecture separates the power generation from the power delivery through a 400V direct current (DC) buss. The power buss is connected to an inverter to supply alternating current (AC) loads and to the power supply to support DC loads and battery charging. (Auragen, 2012)

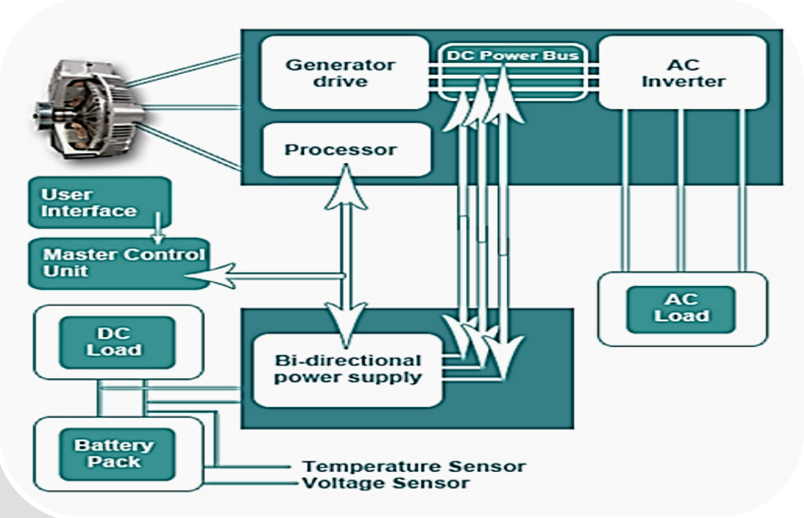


Figure III.A-2:
Auragen System Architecture

<u>Electric Power Plugs and Infrastructure</u>

The technologies described above all require access to externally provided electrical energy that is compatible with the on-board equipment. Stationary trailer TRs rely solely on electricity from the grid (power plug infrastructure, also known as “shore power”). On-road all-electric TRs, such as the Auragen System, must also be plugged in to recharge the batteries and run the refrigerator while stationary (e.g. for initial chill-down and after loading, while parked waiting for dispatch).

Electric plug-in infrastructure at a facility is typically connected to the electric power grid through power conditioning equipment to provide compatible electric power for the TR. Hybrid electric and electric standby-equipped TRU manufacturers offer many options on the type of electric power used by the TRU or TR. For example, 40 volt DC; or single phase or three-phase AC at various voltages such as 120, 220, 240, 408, or 460 volt. Standardization would improve compatibility between equipment and infrastructure.

Power outlets at distribution centers are located at the loading docks, mounted along exterior walls, and in parking area power pedestals.
Figure III.A-3 shows a power plug at a loading dock. Figure III.A-4 shows a power plug at a parking area pedestal.

Figure III.A-3: Loading Dock Power Plugs

Figure III.A-4: Parking Area Power Plug Pedestal

Power plug connectors must be compatible, otherwise adaptors are necessary. The power outlet is de-energized when the operator connects a power cord between the unit and outlet and is energized after the connection is made. Figure III.A-5 shows an example of power plug connectors used for a three-phase 460 volt application.

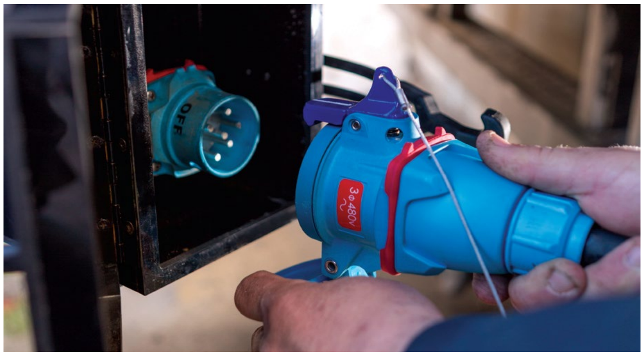


Figure III.A-5: Power Plug Connectors

A plug sharing program called NomadPower is growing at private facilities (with a fee) in Europe, financed by the European Union: https://www.nomadpower.eu/en/home/

Batteries

As indicated above, batteries may be used to power all-electric TRs when shore power or vehicle power is unavailable or insufficient. Historically, lead-acid (Pb-A) absorbed glass mat (AGM) batteries were used for these applications. Deep cycle AGM batteries are designed to discharge between 45 percent and 75 percent of their capacity, but they are heavy, and depending on the number needed, create a payload impact and cause additional wear and tear on the truck or trailer. Therefore, their use has been very limited. Figure III.A-6 shows an example of an AGM battery.

Lithium-ion batteries are popular in other applications, such as electric vehicles, because of their higher energy density and have been used for the all-electric TR applications. Lithium-ion batteries are lighter and take up less space. They have no memory effect if they are repeatedly only partially discharged before being recharged and they are capable of high charge/discharge rates. Li-ion batteries also have a long life, if managed properly. Li-ion batteries currently cost more than other chemistries, but the cost is falling rapidly. A few early applications had safety issues that have been corrected through improved battery management systems, protection features built into the modules, and methods of communicating battery condition to the system controller. New electrolytes are being developed that eliminate the dendrite growths that short-circuit Li-ion batteries and could usher in the development of more powerful and practical next generation high-efficiency batteries such as lithium-sulfur, lithium-air, and lithium-metal batteries. (PNNL, 2015a) Recharging Li-ion batteries below 32 °F or above 113 °F may degrade battery performance, so heaters, coolers, and slow charging is necessary. Figure III.A-7 shows an example of a Lithium-Ion battery.

**Figure III.A-6:
AGM Deep Cycle Battery**

**Figure III.A-7:
Lithium-Ion Battery**

While Li-ion batteries are the most likely to be used in all-electric plug-in/battery TRs of the future, other types of batteries, such as "flow batteries" are in development that could potentially be used in mobile applications (PNNL, 2015b) and may reduce safety concerns. Flow batteries convert the chemical energy in two electrolytes (stored in two tanks) to electrical energy by pumping these liquids past a membrane held between two electrodes. Ions are exchanged through a selective membrane while both fluids circulate on each side of the membrane. Flow batteries are rapidly recharged by replacing the electrolytes – at a filling station – while recovering the spent fluids that can then be re-energized and used again. Energy output is generally less than that of a Li-ion battery but can operate at more extreme temperatures (as cold as -4 °F and as warm as 122 °F) than a Li-ion battery and the electrolytes are not corrosive, like many other battery types. Further development is needed before they are ready for on-road applications. Figure III.A-8 shows a flow battery schematic.

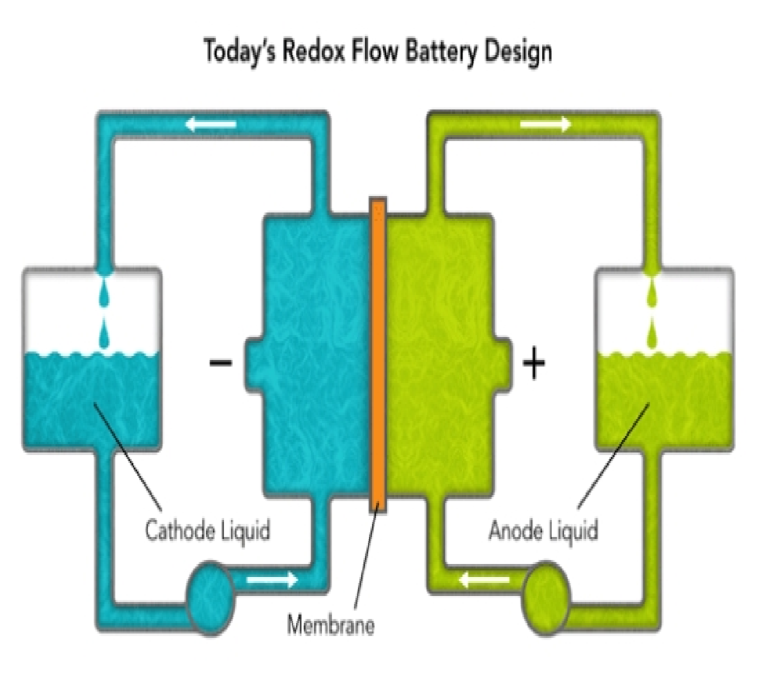


Figure III.A-8: Flow Battery (Greg Stewart/SLAC)

A much more comprehensive discussion of batteries is included in ARB's "Technology Assessment: Heavy and Medium-Duty Battery Electric Trucks and Buses."

Insulated Van Thermal Efficiency and Refrigeration System Efficiency

Any improvements in the thermal efficiency of refrigerated van insulation would reduce the load on the refrigeration system. And, any improvements in the efficiency of the refrigeration system and the electric motor driving the compressor would correspond to a reduced demand on the batteries, which would translate into longer range or fewer batteries (and lower cost and cargo impacts). Section J of this chapter discusses efficiency in more detail.

2. Technology Readiness

All-electric TRs are commercialized and used to a much larger degree in Europe, driven by much higher fuel costs (fuel is not subsidized) and strict noise ordinances (all-electric TRs are much quieter than diesel-powered TRUs). Their use in the U.S. is growing, but not yet widespread.

In the U.S., all-electric plug-in TR technology for stationary cold storage use has been in commercial use for at least 20 years. Electric Reefer Solutions has converted thousands of trailer TRUs to all-electric TRs for stationary plug-in use. Carrier Transicold offers their all-electric Vector 8100, which is an original equipment trailer TR designed for stationary plug-in use. Battery systems for on-road operations are feasible, but too heavy using lead-acid batteries with reasonable range. Advanced battery systems have been designed for on-road TR use and costs are decreasing, improving economics.

Thermo King currently offers its model B-100 for use on small refrigerated truck vans, which is an all-electric plug-in/battery/vehicle generator system.

The Auragen truck engine generator retrofit has been available for several years and they have retrofitted about 50 truck TRs. The refrigerated trailer Auragen System is still in the pre-demonstration conceptual design phase, using an umbilical connection between the tractor engine-mounted or transmission power-take-off generator and trailer TR.

Packaging oversized generators under the hood on the vehicle engine is a challenge due to available space. Using a transmission power-take-off (PTO) with a frame-mounted oversized generator is an option, using direct mount, shaft-drive. As EV truck tractors are developed, incorporating an all-electric TR into the system may be feasible.

Publicly accessible electric power plug infrastructure that is configured for TRUs is currently limited to 29 sites scattered across the U.S., with six of those located in California. All of these provide 460 V 3-phase power, which is the most prevalent and appears to be the standard that industry is moving toward for trailer hybrid electric and electric standby. They can also step down to 230 V 3-phase for the older units that have that configuration. (Bates, 2015) A map is available at Shorepower's Website at: http://www.shorepowerconnect.com/PurchaseService

3. Economics

The installed capital cost to convert a conventional trailer TRU to an all-electric TR for stationary cold storage is about $12,000. The cost of an original equipment all-electric TR for stationary cold storage is about $23,000. The new all-electric trailer units use more efficient scroll compressors, that have lower maintenance and down-time costs, and longer life compared to a conventional trailer TRU. The installed capital cost for a conventional single-temperature trailer TRU is about $28,000. Depending on fuel costs and operating conditions, fuel savings can be significant.

For the Auragen System, the capital cost of a mid-sized truck TR is $22,500, installed. This is $4,000 greater than the $18,500 installed capital cost of a conventional diesel truck TRU with comparable cooling capacity; but, the savings realized in operating costs (e.g. fuel, maintenance, reduced down time), results in a payback period that is typically about two years. (Auragen, 2012).

As discussed before, electrical infrastructure costs must be included to determine upfront costs for all-electric systems. Those costs can be significant depending on the infrastructure needs and the number of units served. The cost of a generic power plug for trailer TRs at a loading dock is about $6,000, while the cost of a power plug pedestal in a parking area is about $7,200. These costs are similar for truck TR power plugs. Financing for this infrastructure is available from Shorepower, thus avoiding large upfront capital expenditures. (Shorepower, 2014a; Shorepower, 2014b))

Battery costs are coming down over time: Pb-A batteries at a rate of two to three percent per year and Li-ion at a faster rate of nine to ten percent per year. Pb-A batteries are currently about $213 per kilowatt-hour (kWh) in 2015 and will be about $188/kWh in 2020, while Li-ion batteries costs currently range from about $280 to $450/kWh and will be about $200 to $275/kWh in 2020. (Roland Berger, 2012; Pillott, 2012) Li-ion battery costs can vary widely, depending on cell capacity, performance needed, and the number being produced. For example, all-electric TRs do not need the quick ramp up power that electric vehicles need, but production numbers would be nowhere near those of EVs. Therefore, advanced battery cost estimates based on EV batteries are a challenge.

4. Emission Reductions

Greenhouse Gas (GHG) Emissions

Staff conducted Well-to-Tank (WTT) and Tank-to-Wheels (TTW) emission rate analyses. Combining these two analyses provides a Well-to Wheels (WTW) result.

The incremental diesel fuel use rate of the straight truck engine due to the additional load from the Auragen system to power a truck TR is 0.29 gal/hr. The estimated WTT and TTW GHG emission rates for this fuel use rate are as follows:

WTT	0.654 kg/hr CO_2e
TTW	2.89 kg/hr CO_2e
WTW	**3.54 kg/hr CO_2e**

The estimation of this fuel rate and the WTT and TTW emission rates are shown in Appendix III.A-1. These emission rates do not account for the electricity used while plugged into shore power for initial chill-down, battery re-charging, and refrigerator operation when the TR is parked, waiting for dispatch because the electric power consumed can vary significantly depending on how the TR is used.

The industry-average diesel fuel use rate for a 2015 conventional truck TRU is about 0.6 gal/hr. The WTT, TTW, and WTW GHG emission rates for this conventional truck TRU fuel use rate were calculated for 2015 baseline fuel and the fuels that will be required in 2020 and beyond:

	2015 Fuel	2020+ Fuel
WTT	2.20 kg/hr CO$_2$e	1.37 kg/hr CO$_2$e
TTW	6.06 kg/hr CO$_2$e	6.06 kg/hr CO$_2$e
WTW	**8.26 kg/hr CO$_2$e**	**7.43 kg/hr CO$_2$e**

The calculations for conventional TRUs are shown in Appendix III.A-2. These estimates result in about 57 percent (2015 Fuel) and 52 percent (2020+ Fuel) reduction in the WTW GHG emission rate if a truck Auragen System is used instead of a conventional truck TRU. As indicated above, the percent reduction does not account for plug-in electric power use while stationary.

Criteria Pollutant Emissions

TTW emission rates for the criteria pollutants NMHC+NO$_x$ and PM are compared in Table III.A-1 for a conventional truck TRU and the Auragen System's parasitic load on a mid-sized truck vehicle engine. WTT emissions were not addressed; however, they are expected to be small compared to TTW emissions.

Table III.A-1: Auragen System -
TTW Criteria Pollutant Emission Rate Comparisons

Equipment Type	NMHC+NO$_x$ (g/hr)	PM (g/hr)	Total CP (g/hr)	Percent Reduction
Conventional Truck TRU	37.9	0.79	38.69	-
Auragen Truck TR	4.88	0.14	5.02	87%

The TTW criteria pollutant emission rates are reduced about 87 percent with the Auragen System, as compared to a conventional truck TRU. Calculations behind the values shown in Table III.A-1 are in Appendices III.A-1 and III.A-2.

5. Technology Advantages

All-electric TRs have significant advantages over the conventional diesel-fired truck TRUs. The all-electric systems are quieter, cleaner, require less maintenance, and generate less waste, a lot of which is considered hazardous (e.g. lube oil, worn belts and air, fuel, and lube filters).

From an environmental standpoint, as discussed above, emissions of both criteria pollutants and GHG emissions are significantly reduced. Since electrification of TRUs reduces diesel PM emissions at distribution centers and other locations where TRUs congregate, near-source public health risks are minimized.

6. Key Performance Parameter Issues and Deployment Challenges

Key performance parameter issues for all-electric TRs include range (for systems that don't include an over-sized generator driven by the vehicle engine) and capital costs for equipment and infrastructure.

Operating range for an all-electric truck TR with an oversized vehicle engine-mounted generator would not be an issue. However, since oversized generators on truck tractors with power umbilical cords to the trailer TRs have not been developed and commercialized, operating range for all-electric trailer TRs would be limited by the amount of energy available in the on-board battery system, the thermal efficiency of the insulated cargo van, mechanical efficiency of the refrigeration system, and efficiency of the electric motor driving the refrigeration compressor. Therefore, use of this type of technology in trailer TRs may be limited to return-to base fleets that can connect to shore power when back at base to recharge batteries.

Capital costs for all-electric fleets must include costs for adding electrical plug-in infrastructure, not just at the loading docks but also within parking areas. Electric power infrastructure must be compatible with the TRs electric drive system. Private fleets can specify compatible equipment and infrastructure for their return-to-base operations, so they would be good candidates. However, for-hire fleets typically visit many distribution centers and would not have control over infrastructure at those locations, so compatibility with the power source and connectors can be an issue, as well as who pays for that power or how it is paid for.

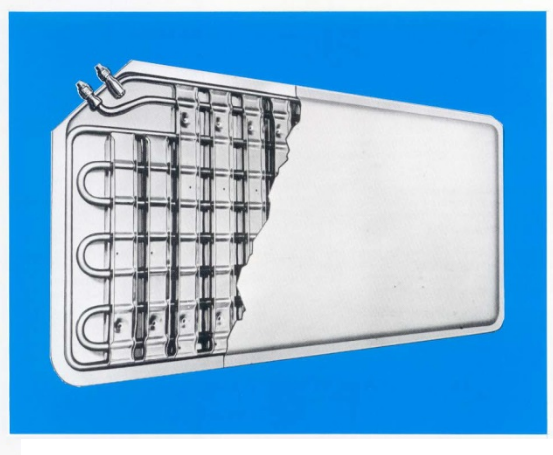
While electric power plugs are increasingly available at truck stops for cab comfort, very few are currently available with the compatible power rating necessary for hybrid electric TRUs (e.g. voltage, phase, and current rating). Long-haul fleets cannot currently depend on compatible electric power at public rest areas or truck stops and it will take some time for this infrastructure to be installed along major transportation corridors at sufficient intervals. Safety issues related to using electric power must also be managed.

Advanced battery costs are currently a barrier, but those costs are decreasing fairly quickly. Improved thermal efficiency of the insulated van, the mechanical efficiency of the refrigeration system, and the efficiency of the electric motor would effectively reduce the battery storage capacity needed for adequate range. Incentives or subsidies are needed to help increase advanced battery production numbers and improve economies of scale. Tesla's battery "gigafactory" in Nevada may help influence faster downward cost trends.

B. All-Electric Plug-In Cold Plate TRs

1. Technology Description

All-electric TR applications using eutectic cold plates have been developed to provide temperature control while on the road, away from grid-connected electric power plugs. A sheet metal shell, with cooling coils built inside, holds the eutectic fluid. The fluid used in cold plates is a mixture of water and salts (e.g. sodium and potassium salts) that form a eutectic solution that has the lowest possible melting/freezing point. Cold plates are similar to the gel packs used in lunch boxes and ice chests, but much bigger. A TR is used to chill the cold plates before perishable goods are loaded. The refrigerator's evaporator coils are built into the sheet metal shell, as shown in Figure III.B-1. The refrigeration unit is plugged into shore power and runs until the eutectic plates are frozen.



The eutectic plate system is designed to provide refrigeration in the cargo area of the truck by absorbing the heat load coming through the walls, ceiling, floor and doors and any heat generated by the load itself (e.g. from produce respiration). All of the eutectic salt mixture's constituents go through a phase change, from solid state to liquid simultaneously within the plates as they absorb this heat load. The plates are mounted on the ceiling and/or interior walls or as partitions of the cargo area. Figure III.B-2 shows an example of a partition mount configuration. Figure III.B-3 shows a wall and ceiling mount configuration. The system can offer single or multi-temp applications.

Figure III.B-2: Partition Mount (Johnson Truck Bodies)

Figure III.B-3: Wall and Ceiling Mount (Johnson Truck Bodies)

Once the eutectic plates are frozen and the product is loaded, the TR is unplugged and the truck begins the refrigerated deliveries. This refrigeration system provides cooling for daily runs of 10 to 12 hours. Such limited range means that cold plate TRs are only used by return-to-base fleets, not long-haul.

Some systems include fans and evaporator-blowers that run off rechargeable batteries. Historically, lead-acid absorbed glass mat (AGM) batteries were used for these applications. Deep cycle AGM batteries are designed to discharge between 45 percent and 75 percent of their capacity, but are too heavy and, depending on the number needed, create a payload impact and cause additional wear and tear on the truck or trailer. Therefore, lead-acid batteries have had limited use for this type of application. Figure III.A-6 (previous section) shows an example of an AGM battery. Lithium-Ion batteries are popular in other applications because of their higher energy density and could be used for the all-electric TR applications to extend their range. The Lithium-Ion batteries are lighter and take up less space but they currently cost more than lead-acid batteries. Figure III.A-7 (previous section) shows an example of a Lithium-Ion battery.

Once the cold plates are spent, they must be refrozen by plugging the TR into a single-phase or 3-phase electric power source. Cold plates are refrozen in-place in the cargo area, which requires 6 to 8 hours of stationary plug-in time. Electric power infrastructure is required, similar to what was described in the previous section. In addition to recharging (refreezing) the cold plates, the batteries can also be recharged while plugged into shore power.

Any improvements in the thermal efficiency of the insulated van would reduce the load on the refrigeration system. Improvements in the efficiency of the refrigeration system would also correspond to a reduced demand on the electric drive motors and batteries. Combining these with high-efficiency refrigeration system drive motors would extend range or require fewer batteries at lower cost and cargo impacts. Section J of this chapter discusses efficiency in more detail.

2. Technology Readiness

All-electric TRs with cold plates are commercialized, having been in use for over 50 years, and their designs have improved over the years along with the refrigeration system. The current market share for truck refrigeration is about 20 percent cold plates and 80 percent mechanical/diesel powered. (Dole, 2014)

In the United States (U.S.), the majority of cold plates are produced by one company, Dole Refrigeration. They have over 100 standard cold plate sizes plus numerous made-to-order custom-sized cold plates. They produce about 10,000 cold plates a year and are sold to companies that design and manufacture refrigerated trucks using cold plates. Depending on the refrigeration needs, a refrigerated truck system can be fitted with 2 to 8 (or more) cold plates. Dole estimates about 1,000 new refrigerated trucks per year are produced with their cold plates and refrigeration system.

3. Economics

Upfront capital costs for an installed eutectic cold plate TR is typically less than a mechanical (diesel) system. Adding plug-in power capabilities at a fleet's terminal will add to the capital costs of the cold plate system if plug-in power is not already available.

There are very little maintenance costs associated with a eutectic cold plate system because the only moving parts are in the refrigeration system, which use a scroll compressor with only a few moving parts, and fans (if used). Operating costs (no fuel use and little maintenance) are 80 percent lower than mechanical systems. (Johnson, 2014) The life cycle of a cold plate system can be 15 or more years, while a mechanical system life cycle is about 5 to 7 years with proper maintenance.

As discussed before, electrical infrastructure costs must be included to determine upfront costs for all-electric systems. Those costs can be significant depending on the infrastructure needs and the number of units served.

4. Emission Reductions

Greenhouse Gas Emissions

Staff conducted Well-to-Tank (WTT) and Tank-to-Wheels (TTW) emissions analyses for all-electric plug-in cold plate TRs. Combining these two analyses provides a Well-to-Wheels (WTW) result.

The average electricity usage for chilling the cold plates is 6.0 kW-hr/hr. All-electric refrigeration for cold plates does not produce any TTW emissions. The estimated WTT, TTW, and additive WTW GHG emission rates for this electricity use rate are.

WTT	1.73 kg/hr CO_2e
TTW	0.00 kg/hr CO_2e
WTW	**1.73 kg/hr CO_2e**

The calculations are shown in Appendix III.B-1.

The industry-average diesel fuel use rate for a 2015 conventional truck TRU is about 0.6 gal/hr. The WTT, TTW, and additive WTW GHG emission rates for this conventional truck TRU fuel use rate were calculated for 2015 baseline fuel and the fuels that will be required in 2020 and beyond:

	2015 Fuel	2020+ Fuel
WTT	2.20 kg/hr CO_2e	1.37 kg/hr CO_2e
TTW	6.06 kg/hr CO_2e	6.06 kg/hr CO_2e
WTW	**8.26 kg/hr CO_2e**	**7.43 kg/hr CO_2e**

These calculations are shown in Appendix III.A-2.

These estimates result in about 79 percent (2015 Fuel) and 77 percent (2020+ Fuel) reductions in WTW GHG emissions when using an all-electric plug-in cold plate TR instead of a conventional truck TRU.

Criteria Pollutant Emissions

TTW emission rates for the criteria pollutants NMHC+NO_x and PM are compared in Table III.B-1 for a conventional truck TRU and the all-electric plug-in cold plate TR. WTT emissions were not addressed; however, they are expected to be small compared to TTW emissions.

Table III.B-1: All-Electric Plug-in Cold Plate TR -
TTW Criteria Pollutant Emission Rate Comparisons

Equipment Type	NMHC+NO_x (g/hr)	PM (g/hr)	Total CP (g/hr)	Percent Reduction
Conventional Truck TRU	37.9	0.79	38.69	-
All-electric plug-in cold plate Truck TR	0	0	0	100%

The TTW emissions are reduced 100 percent with the all-electric plug-in cold plate TR, as compared to a conventional truck TRU. Calculations behind the values shown in Table III.B-1 are in Appendices III.A-2 and III.B-1.

5. Technology Advantages

All-electric TRs have significant advantages over the conventional diesel truck TRUs. The all-electric systems are quieter, require less maintenance, and generate less waste, a lot of which is considered hazardous (e.g. lube oil, worn belts and air, fuel, and lube filters). Installed costs of a cold plate TR are less than a conventional diesel TR.

From an environmental standpoint, emissions of both criteria pollutants and GHG emissions are significantly reduced. Since electrification of TRUs reduces diesel PM emissions at distribution centers and other locations where TRUs congregate, near-source public health risks are minimized.

6. Key Performance Parameter Issues and Deployment Challenges

Key performance parameter issues include limited operating range, which restricts the use of cold plate TRs to return-to base fleets. Use of vehicle engine-mounted oversized generators, as described in the previous section, could extend the on-road delivery range of these systems in straight truck applications. Payload space is impacted by cold plates and fans (if used) reducing the amount of goods that can transported and cold plate mounting can affect the ability to easily load and unload goods from the cargo space. In addition, cold plate weight can limit payload due to gross vehicle weight limits. For these reasons, cold plates are used mostly in straight truck TRs and rarely, if ever, seen in semi-trailer TRs in the U.S.

Capital costs for eutectic cold plate fleets may include costs for adding electrical infrastructure at the loading docks and parking areas. As discussed in more detail in the previous section, electric power infrastructure must be compatible with the TR, so all-electric TRs with cold plates work best for private return-to-base fleets and are generally not a good fit for for-hire fleets, including long-haul fleets. More standardization of electric power load ratings, voltages, and connectors is needed as well as more public access points along major transportation corridors. The cost barriers discussed in the previous section for infrastructure and batteries also apply here.

C. Hydrogen Fuel Cell-Powered TRs

1. Technology Description

Fuel cells (FC) are described in much more detail in the ARB document titled" Technology Assessment: Medium- and Heavy-Duty Fuel Cell Electric Vehicles." A very brief description of how PEM FCs work is provided here.

Hydrogen (H_2) PEM FCs are devices that convert H_2 and oxygen to water, creating electricity and some heat in the process. PEM stands for polymer exchange membrane or proton exchange membrane. Figure III.C-1 shows schematically how a H2 PEM FC works in a car, but it is the same for any application.

H_2 molecules enter the cell on the anode side of the FC, get distributed across the membrane surface and catalytically dissociated, releasing the electrons, which are conducted out through the anode to the load, shown here as a light bulb. The hydrogen ions (protons) diffuse through the proton exchange membrane to the cathode side of the FC. Air enters the cathode side of the FC and oxygen molecules are distributed across the membrane surface.

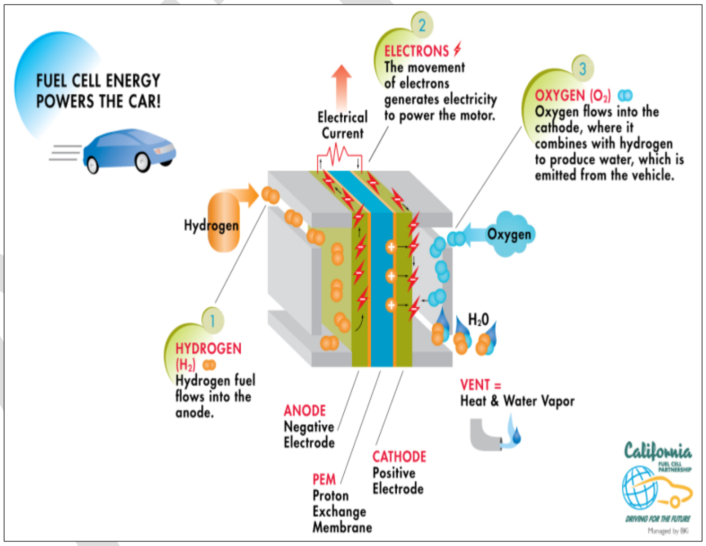


Figure III.C-1: How Fuel Cells Work (CaFCP)

The electrons return from load through the cathode to a catalytic surface, where they recombine with hydrogen ions and oxygen to form water. The water serves as the electrolyte which hydrates the membrane to keep it functional and stable. Some heat is created in the process, but all of this typically occurs at 60 to 80 °C (140 to 180 °F).

A number of FCs is stacked together to form the FC stack, which is the primary system, as shown in Figure III.C-2. As more FCs are stacked together, the power capacity of the stack increases. The power needed for the initial chill-down of the van typically determines the peak power capacity for transport refrigerators.

Figure III.C-2: Fuel Cell Stack

"Balance of plant" components include energy storage (batteries may be used to provide power in excess of nominal power during peak loads), filters, flow meters, an air compressor, air humidifier, a DC-to-AC inverter, a DC-to-DC converter, cooling system for the stack, batteries, and DC-to-DC converter (e.g. coolant pump, intercooler, radiators, and fans), protective devices, sensors, an electronic control unit, system controller, cables, and connectors.

An on-board H_2 storage tank rated for high pressure, 350 bars (5,000 psi) or 700 bars (10,000 psi), is also necessary, sized to provide adequate range. At these pressures, tanks must be specialized carbon fiber composite cylinders. Tank size is limited because tank cost is significant. This results in range limitations of about 10 hours of operation between refueling. Since there are currently no public H_2 refueling stations that are configured for Class 8 semi-trailers, this technology is limited to fleets that return to base each day for daily on-site H_2 refueling. Figure III.C-3 shows such an on-site H_2 dispenser that is supplied by PlugPower.

There are several H2 production processes that are currently being used, several are listed here; but, a more detailed, comprehensive discussion and description is included in the document titled "Technology Assessment: Medium- and Heavy-Duty Fuel Cell electric Vehicles":

- Steam methane reformer (SMR) using pipeline natural gas and/or methane generated from waste water or landfill gas, and
- Proton electrolyzer powered by grid or renewable solar PV electricity.

There are also several H_2 supply options, which are also discussed in more detail in the document titled "Technology Assessment: Medium- and Heavy-Duty Fuel Cell electric Vehicles."

- Central plant production and delivery to end-use dispenser storage tanks via tube trailers in either gaseous or liquid form;
- On-site SMR or electrolysis with storage and compression to dispensing pressures; and
- Pipeline H_2 from nearby central plant H_2 production facility with on-site storage and compression to dispensing pressures.

For low-volume use that is less than 100 kilograms (kg) per day, a specialty gas supply company can produce H_2 at its central facility with SMR or electrolysis and deliver it to the fleet's terminal in carbon fiber/composite cylinders mounted on a skid or via tube trailer. Compression and dispensing equipment may be provided on a separate skid. For larger scale needs, typically greater than 100 kg per day, an on-site SMR/dispenser system may be appropriate. Infrastructure costs are significant, as discussed later.

Any improvements in the thermal efficiency of insulated van insulation would reduce the load on the refrigeration system. Also, any improvements in the efficiency of the refrigeration system and the electric drive motor would correspond to a reduced electric power demand on the FC and less hydrogen fuel use. This in turn, would translate into longer range or a smaller FC and/or hydrogen fuel tank (and lower capital and operational costs). Section J of this chapter discusses van thermal efficiency and refrigeration system efficiency in more detail.

2. Technology Readiness

FC-powered transport refrigeration systems are in the demonstration phase of commercialization. Over 6,000 H_2 FC-powered forklifts are now in use at numerous refrigerated distribution centers, including Sysco Foodservices, Whole Foods, H-E-B Grocers, Central Grocers, Winco Foods, Krogers, Wegmans, Associated Wholesale Grocers, and Walmart. (FCTO, 2014) Extending FCs to transport refrigeration systems is logical because the H_2 fuel dispenser capital costs at a distribution center can then be spread across more equipment (possibly including FC-powered electric yard trucks), resulting in a more efficient use of those assets.

Staff is currently aware of two H_2 FC demonstration projects related to transport refrigeration that are in the design and build stage. One H_2 FC transport refrigeration system demonstration projects for refrigerated trailers and one demonstration project for portable containerized H_2 FC (also called a “powerpack”) are described below.

Pacific Northwest National Laboratories (PNNL), under the U.S. Dept. of Energy’s (DOE) Office of Energy Efficiency and Renewable Energy (EERE) published a solicitation on July 24, 2015, requesting proposals for the development and demonstration of FC-powered TR for refrigerated trucks. The system is intended to be designed as a retrofit to existing TRUs on medium or heavy duty short-haul trucks. Contract awards for this project will not be known until late 2015.

<u>Trailer FC TR Demonstration</u>

U.S. DOE’s PNNL funded a H_2 FC demonstration project for the semi-trailer TR application under a $650,000 contract. The project partners (Nuvera Fuel Cell, Thermo King, Sysco Foodservices, and H-E-B Groceries) provided matching funds and labor. (PNNL, 2013)

As a first step, starting in May 2013, Nuvera and Thermo King prepared a “Phase I Business Case Report” for PNNL under Contract Number 205394, published August 30, 2013 (Nuvera, 2013). That document describes the purpose of Phase I (5 months) as establishing the business case for the product and developing the system concepts. Phase II is when a working prototype for a 53-foot insulated trailer will be designed, built, and a safety plan developed. Phase III is when the prototype system will be demonstrated for 400 hours by Sysco Foodservices, Riverside, California and another 400 hours by H-E-B Groceries, San Antonio, Texas. A report will be published mid- to late 2016.

Nuvera will use their Orion^{TM} FC stack (PEM) in conjunction with a Thermo King Precedent C-600 single-temp TRU equipped with electric standby (Block, 2014b). The FC system is rated at 17 kW continuous in cycle sentry mode and 33 kW peak power (gross).

“Balance of plant” components include the cooling system, air compressor, filters, fans, pumps radiators, DC/DC converter, DC/AC inverter, etc. The hydrogen storage tank will be incorporated into the same mounting frame as the rest of the FC system. The entire prototype FC system will be designed so that it can be in the same envelop and under-slung trailer chassis frame mounting configuration as a Thermo King SGSM 3000 TRU genset. An illustration of this packaging is depicted in Figure III.C-4. (Nuvera, 2013)

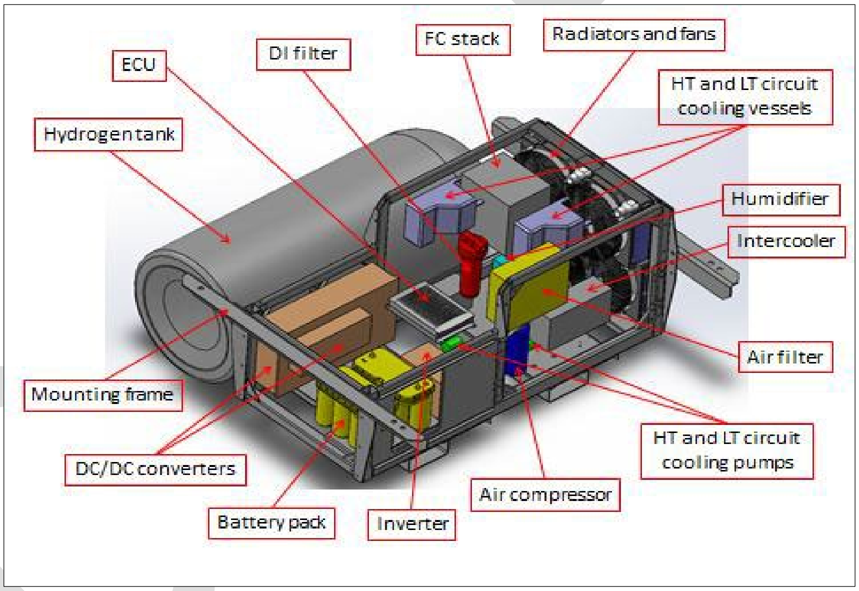


Figure III.C-4: Nuvera-Thermo King H_2 FC Prototype

The Nuvera Orion^{TM} FC is sized to account for start-up load spikes. The fuel use rate was estimated to be about 0.40 kg per hour, six kg per day. The on-board carbon fiber composite H_2 fuel storage tank will be sized for eight to 10 kg of H_2 at 350 bars (5,000 psi), which will provide an operating range of eight to 10 hours operation per day. This pressure is compatible with the Sysco’s FC forklifts, but tanks rated at 700 bars (10,000 psi) are also being considered, if necessary to extend range. Air Products is supplying H_2 fuel to H-E-B with a mobile refueler at a cost of $10 to $12 per kg.

The commercial version of this FC system will weigh less than a conventional diesel-powered TRU, so there will be no payload impacts. The commercial version for trailers will be re-packaged into the TRU housing, with the fuel tank mounted under-slung on the trailer frame. A battery or ultra-capacitor may be added for load-leveling in the commercial version so that the fuel cell stack can be optimized to reduce fuel consumption and extend range. This system is only intended for return-to-base fleets (e.g. regional grocery and foodservice distribution), not long-haul.

The FC system shown in Figure III.C.4 could also be used as an under-slung TRU genset for a refrigerated shipping container loaded onto a trailer chassis, provided the fuel tank has adequate capacity for the typical 300-mile range from a port terminal.

Nuvera believes the FC-powered TRU market will be 3 to 5 percent of the market in five years and 15 to 20 percent of the market 10 years from now (Block, 2014). ACT Research has compiled trailer TRU sales from 2010 through 2014, and although sales are cyclic, the average was about 30,000 units per year. (ACT, 2014) The resulting FC-powered production rates would be roughly 900 to 1,500 units per year in 2020 and 4,500 to 6,000 units per year in 2025.

Portable Containerized H_2 FC Demonstration

Sandia National Laboratories, under U.S. DOE-EERE and U.S. DOT Maritime Administration (MARAD) has funded a portable containerized H_2 FC demonstration project to provide electric power to refrigerated shipping containers (also called reefer containers) at Port of Honolulu to reduce GHG emissions and improve energy efficiency. The partners in this project are Sandia, Hydrogenics, Young Brothers, Foss Maritime, the Hawaii Natural Energy Institute, the American Bureau of Shipping, the U.S. Coast Guard, and the Hydrogen Safety Panel. DOE-EERE's and MARAD's long-range goal is to decrease air emissions from maritime sources and decrease fossil fuel use by catalyzing development of commercially-viable technology that can be widely used at other ports and other off-grid locations. (Sandia, 2014)

Sandia is providing technical expertise in H_2 and fuel cells, codes and standards, system design, safety systems, data collection, and analysis of both operations and business case for deployment.

Hydrogenics is supplying a portable containerized FC with H_2 storage. Containerized FCs are a standard Hydrogenics product line; however, past applications have been stationary. (Sookhoo, 2014) Additional design criteria have been added for this special mobile, marine application to facilitate daily movements and salt water spray at docks and on barges that move between the Hawaiian Islands on the open sea. Figure III.C-5 (next page) shows Hydrogenics' containerized H_2 FC Generator.

Figure III.C-5: Containerized H2 FC Generator
(Hydrogenics Corp.)

Young Brothers, a subsidiary of Foss Maritime Co., transports shipping containers that come through Port of Honolulu to and from the other Hawaiian Islands. Shipping containers arrive at the port on ocean-going vessels, get stacked on the dock, and plugged in to large containerized diesel generators, which provide the electric power for about 20 to 30 refrigerated shipping containers while they are on the dock. These generators are one of the many sources of air pollution at the port.

When reefer containers are loaded onto a barge which ferries the containers to other islands, they are plugged into containerized diesel generator sets. The number of reefers dictates the number of diesel generators for the voyage and they nearly always run at less than 100 percent load. At the island destination, the reefers are unplugged, the reefer containers and gensets are unloaded onto the dock, the reefers are plugged back into the gensets and sit waiting for drayage trucks to take the reefer containers to distribution centers. The reverse process is used for outbound perishable goods. On these return trips the number of reefers is less and the diesel generators typically run at very low loads. Figure III.C-6 shows one of the Young Brothers barges.

Figure III.C-6: Young Brothers' Barge at Port of Honolulu
(Joe Pratt, Sandia National Labs)

The portable containerized H_2 FCs would replace the conventional diesel generator containers. Detailed engineering and design was completed mid-2014, followed by fabrication, assembly, and training. At least six months of deployment at Port of Honolulu and the other Hawaiian Islands will start late June 2015. A project report is expected in mid- to late 2016.

Sandia studied the reefer container process and its power needs. They found that there may be significant economic savings if FC systems replace diesel gensets because FC systems are more efficient at load-following when low amounts of power are needed. The diesel gensets are over-sized to handle load spikes at start-up and they are relatively inefficient running at low loads. FCs can use batteries or ultra-capacitors to manage these spikes and reduce the size of the FC stack.

Hydrogenics Corp. will design and build the prototype containerized FC unit. The prototype will provide power for 10 reefer containers. Each reefer container uses 5 to 10 kW on average. So they are designing for 120 kW gross (100 kW net after system losses). Tentative plans call for four 30 kW FCs, a H_2 storage system, and power conversion equipment housed in a 20-foot shipping container.

Final decisions on the details of H_2 fuel supply had not been made as of this writing. Hawaii Natural Energy Institute (HNEI) is discussing options with Hickman Air Force Base because they have electrolysis H_2 production and compression equipment. HNEI is serving as the facilitator to work out the details of getting the H_2 to the ports. HNEI owns hydrogen tube trailers, which could be an option for transporting H_2 fuel.

Preliminary design concepts have storage tanks filling about half of the 20-foot container with 60 to 90 kg of H_2 at 5,000 psi. They need enough fuel for at least 12 hours of operation for a 5 to 10 reefer container cluster at the docks and at least 60 hours for a reduced number of containers while on the ocean barges.

Containerized portable H_2 FCs may have multiple applications. In addition to use as an inter-island dock/barge generator, they could be used as temporary stationary generators for cold-ironing at the docks. They may also find a role as powerpacks for a cluster of refrigerated containers on intermodal railcars. Hydrogenics has expressed some uncertainty about the potential commercial deployment of powerpacks, but believe they will produce 10 to 20 in the next five years and maybe more if other ports see the value. At these relatively small production numbers, the cost reductions due to economies of scale may be fairly small.

H_2 Fuel Supply and Dispensing Appliances

A more detailed discussion of H_2 fuel supply is provided in the ARB document titled "Technology Assessment: Medium- and Heavy-Duty Fuel Cell electric Vehicles.". As mentioned above, specialty gas suppliers produce H_2 fuel at central locations, typically using SMR. The H_2 gas is then typically chilled and liquefied to increase the amount of fuel that can be transported to the dispensing site. Cryogenic liquid H_2 is delivered in high pressure composite tanks, mounted on a skid with regasification, compression, storage, and dispensing equipment. H_2 can also be delivered as a gas in tube trailers that unload to on-site storage tanks, compressors and dispensing equipment. On-site H_2 generation systems are also commercially available, such as the Nuvera PowerTap on-site reformer. Plug Power offers their GenFuel system. Hydrogenics' HyLYZER uses electrolysis to produce H_2. A growing number of generation systems are commercially available. (FCTO, 2014)

3. Economics

At this time, the capital costs of FCs for refrigerated transport are somewhat uncertain. However, since Sysco Foodservices and H-E-B Groceries both participated in demonstrations of FC forklifts and subsequently converted a large number to FC power, it seems fairly likely that that their interest in FC-powered transport refrigerators for the current demonstrations is an indication that they anticipate a positive economic outcome. FC system suppliers involved in the current demonstrations have been reluctant to predict costs associated with transport refrigeration FCs. However, a National Public Radio blog cited $40,000 as the capital cost of a H_2 FC system for a trailer refrigerator, based on an interview with PNNL's FC project leader, Kristen Brooks. The author went on to say that the cost of a conventional diesel engine-driven TRU is $20,000 to $30,000. (NPR, 2013) The same article quoted the Mr. Brooks saying, "The price of FCs is quickly dropping." U.S. DOE has funded research that has enabled PEM FC cost reduction of more than 50 percent since 2006 and more than 35 percent since 2008, partially due to a five-fold reduction in the use of platinum in FCs. (FCTO, 2014) As previously discussed above, under the Nuvera/Thermo King/ Sysco demonstration project, using the FC market share predicted by Nuvera and ACT Research data for refrigerated trailer production, staff predicts the production of 900 to 1500 FC TRs per year by 2020 and 4,500 to 6,000 units per year by 2025. At these production rates, capital costs would likely drop another 25 to 35 percent by 2025 due to economies of scale, compared to small volume production for the current demonstration phase. (Pratt, 2013; Battelle, 2013)

FCs are eligible for the federal Business Energy Investment Tax Credit (ITC) - 30 percent until the end of 2016. This credit is capped at $1,500 per half kilowatt. To qualify, the FC electricity-only generation efficiency must be 30 percent or greater. (Energy, 2014) The Obama Administration has called for the extension of clean energy tax credits as part of his "All-of-the-Above" energy strategy. (Energy, 2012)

H_2 suppliers and manufacturers of SMR equipment have been hesitant to allow staff to publish H_2 fueling infrastructure costs for TRs because they consider this to be proprietary information. These contacts were similarly noncommittal about the cost of maintenance on a H_2 FC system for transport refrigeration, but there was consensus that FC system maintenance should be less than a diesel engine-powered TRU because a diesel engine has so more moving parts. There should be better clarity on costs after the demonstration projects are completed and reports are available in mid- to late 2016.

FCs are twice as efficient as diesel engines/generators and perform better at partial loads (Nuvera, 2014; Pratt, 2013); so there is an economic advantage with regards to fuel consumption. Young Bros.' fuel cost analysis showed that the FC is the more cost-effective solution when diesel fuel cost is $4.00 per gallon and H_2 can be purchased for $5/kg or less. (Pratt, 2013; Pratt, 2014a) Delivered H_2 fuel costs vary from $4 to $7 per kilogram for cryogenic liquid H_2 and $13 to $15 per kilogram for H_2 gas. (Petrecky, 2014) The cost of H_2 fuel produced on-site with a Nuvera PowerTap SMR that has access to pipeline natural gas is $10 to $12 per kilogram, "all-in" (e.g. inclusive of infrastructure capital costs, installation, maintenance, utilities, etc.) at a consumption rate of 50 kg/day. (Block, 2014; Nuvera, 2013)

Nuvera found that as the number of FC-equipped transport refrigerators increases and H_2 consumption exceeds 250 kg per day, the "all-in" cost of H_2 is likely to drop to $6 to $8 per kilogram in the next few years. Nuvera also concluded that if users have enough hydrogen generation capacity to also fuel FC-powered forklifts and yard hostlers, the refueling infrastructure costs can be spread across more equipment, as asset utilization is more efficient; therefore, at current natural gas and electricity rates, the cost of H_2 becomes the incremental cost of generation, resulting in $2.50 per kilogram. (Nuvera, 2013)

Nuvera and Thermo King analyzed 54 cases for the incremental cost of the trailer FC transport refrigerator compared to conventional diesel-powered TRUs, cost of diesel fuel, and the cost of hydrogen, with and without the federal ITC. (Nuvera, 2013)

The parameters investigated and their cost ranges were:

- FC incremental cost (\$21,000 to \$36,000);
- Diesel pricing (\$4 to \$8/gallon); and
- H_2 price (\$2.50 to \$12.00/kg).

The assumptions that Nuvera and Thermo King used in their net present value (NPV) analysis are listed below:

- 20 kW (net) FC output
- FC twice as efficient as diesel engine
- 12 year trade cycle
- 2,000 hours operation per year
- Fuel cost escalation: 2.9 percent for diesel; 2.7 percent for H_2
- 75 percent hauling fresh goods (+35 °F set point) with continuous cycle sentry
- 25 percent hauling deep frozen (-20 °F set point) with start-stop cycle sentry
- Diesel ICE annual maintenance costs are \$3,400 more than FC

The results of those case studies indicate FC transport refrigerators may be economically viable in some cases. The tables that were presented in the Nuvera/Thermo King NPV case study are reproduced here in Tables III.C-1 and III.C-2 (next page). The green shaded areas of these tables indicate cases where savings are expected to create positive NPV, while yellow shaded areas are marginal cases (the tipping point into negative NPV). Without the federal ITC (Table III.C-1), for the full range of TRU incremental costs, there were savings when the price of diesel fuel is at \$4 per gallon and H_2 cost \$2.50 per kg. Savings also resulted for the lower end of the TRU incremental cost when the price of H_2 was \$4/kg and diesel was at \$4 or greater per gallon. With the federal ITC (Table III.C-2), savings were greater and more cases had a positive NPV.

The annualized savings and return on investment/payback period of FC transport refrigerators will be clearer after the refrigerated trailer FC demonstration project is completed and the incremental capital costs, refueling infrastructure costs, and operational costs are provided.

Table III.C-1: Net Present Value Cases without ITC

Hydrogen Cost per kg	TRU Incremental Cost	Diesel at $4.00/gal	Diesel at $6.00/gal	Diesel at $8.00/gal
$2.50	$21,000	$15,518	$51,099	$86,680
$4.00	$21,000	$2,997	$38,578	$74,159
$6.00	$21,000	($28,290)	$7,292	$42,873
$8.00	$21,000	($59,576)	($23,995)	$11,587
$10.00	$21,000	($90,863)	($47,500)	($19,700)
$12.00	$21,000	($122,149)	($86,568)	($50,986)
$2.50	$28,000	$8,018	$43,599	$79,180
$4.00	$28,000	($4,503)	$31,078	$66,659
$6.00	$28,000	($35,790)	($208)	$35,373
$8.00	$28,000	($67,076)	($31,495)	$4,087
$10.00	$28,000	($98,363)	($62,781)	($27,200)
$12.00	$28,000	($129,649)	($94,068)	($58,486)
$2.50	$36,000	$518	$36,099	$71,680
$4.00	$36,000	($12,003)	$23,578	$59,159
$6.00	$36,000	($43,290)	($7,708)	$27,873
$8.00	$36,000	($74,576)	($38,995)	($3,413)
$10.00	$36,000	($105,863)	($70,281)	($34,700)
$12.00	$36,000	($137,149)	($101,568)	($65,986)

Table III.C-2: Net Present Value Cases with ITC

Hydrogen Cost per kg	TRU Incremental Cost	Diesel at $4.00/gal	Diesel at $6.00/gal	Diesel at $8.00/gal
$2.50	$21,000	$21,818	$57,399	$92,980
$4.00	$21,000	$9,297	$44,878	$80,459
$6.00	$21,000	($21,990)	$13,592	$49,173
$8.00	$21,000	($53,276)	($17,695)	$17,887
$10.00	$21,000	($84,563)	($48,981)	($13,400)
$12.00	$21,000	($115,849)	($80,268)	($44,686)
$2.50	$28,000	$16,568	$52,149	$87,730
$4.00	$28,000	$4,047	$39,628	$75,209
$6.00	$28,000	($27,240)	$8,342	$43,923
$8.00	$28,000	($58,526)	($22,945)	$12,637
$10.00	$28,000	($89,813)	($54,231)	($18,650)
$12.00	$28,000	($121,099)	($85,518)	($49,936)
$2.50	$36,000	$11,318	$46,899	$82,480
$4.00	$36,000	($1,203)	$34,278	$69,959
$6.00	$36,000	($32,490)	$3,092	$38,673
$8.00	$36,000	($63,776)	($28,195)	$7,387
$10.00	$36,000	($95,063)	($59,481)	($23,900)
$12.00	$36,000	($126,349)	($90,768)	(55,186)

4. Emissions Reductions

GHG Emissions

Staff conducted Well-to-Tank (WTT) and Tank-to-Wheels (TTW) emission rate analyses. Totaling the results from these two provides a Well to Wheels (WTW) result.

The WTT analysis for H_2 FC systems takes into account the emissions associated with H_2 production through to the end-use refueling dispenser. There are several possible cases. One case is central SMR H_2 production with liquefaction, transport, regasification and compression into the dispenser storage tank. A second case is similar to the first, but without liquefaction and regasification steps. A third case is on-site SMR with compression into the dispenser storage tank. Staff's GHG emission rate estimates, shown in Appendix III.C-1, used a carbon intensity factor for on-site SMR with 2/3 North American natural gas and 1/3 renewable gas to meet the 2020 and beyond statutory requirements. See ARB's Technology Assessment: Fuels Assessment document for more details on how carbon intensity factors are derived.

For the trailer transport refrigerator H_2 FC technology, staff used the fuel use rate estimate of 0.4 kg/hr provided by Nuvera for the PNNL trailer FC demonstration project (Block, 2015). The trailer transport refrigerator demonstration will not use a battery for load leveling, so there will be no need to re-charge the battery at the distribution center by plugging into the grid (no grid electric power consumption is expected for battery charging). The demonstration will be completed and a report published in mid- to late 2016, so inputs can be updated and emissions recalculated at that time.

The TTW analysis for H_2 FCs is simplified by the fact that FCs only produce water and some heat. The WTT, TTW, and WTW GHG emission rates for this H_2 fuel rate of a FC-powered trailer transport refrigerator sum as follows:

WTT	4.24 kg/hr CO_2e
TTW	0.0 kg/hr CO_2e
WTW	**4.24 kg/hr CO_2e**

The industry-average diesel fuel use rate for a 2015 conventional trailer TRU is about 0.8 gal/hr. The WTT, TTW, and WTW GHG emission rates for this conventional trailer TRU fuel use rate were calculated for 2015 baseline fuel and the fuels that will be required in 2020 and beyond:

	2015 Fuel	2020+ Fuel
WTT	2.93 kg/hr CO_2e	1.83 kg/hr CO_2e
TTW	8.08 kg/hr CO_2e	8.08 kg/hr CO_2e
WTW	**11.01 kg/hr CO_2e**	**9.91 kg/hr CO_2e**

The calculations for conventional TRUs are shown in Appendix III.A-2.

These estimates result in about a 61 percent (2015 Fuel) and 57 percent (2020+ Fuel) reductions in WTW GHG emissions if H_2 FC-powered transport refrigerators are used instead of conventional diesel TRUs.

Criteria Pollutant Emissions

TTW emissions rates for criteria pollutants NMHC+NO_x and PM are compared in Table III.C-3 for a conventional trailer TRU and a H_2 FC Trailer TR. WTT emissions were not addressed; however, they are expected to be small compared to TTW emissions.

Table III.C-3: All-electric H_2 Fuel Cell TR - TTW Criteria Pollutant Emission Rate Comparisons

Equipment Type	NMHC+NO_x (g/hr)	PM (g/hr)	Total CP (g/hr)	Percent Reduction
Conventional Trailer TRU	57.5	1.23	58.73	-
All-Electric H_2 FC Trailer TR	0	0	0	100%

The calculations for the values shown in the above table are in Appendices III.A-2 and III.C-1. As indicated in the above table, the WTW criteria pollutant emission rate would be reduced 100 percent if a H_2 FC trailer TR is used instead of a conventional trailer TRU.

5. Technology Advantages

H_2 FCs are more efficient than diesel engines and perform better at partial loads. (Pratt, 2014b) How much more efficient depends on the size of diesel engine being compared and its application. For the size used in trailer TRUs, fuel cells are at least twice as efficient (Nuvera, 2013). Figure III.C-6 shows this relationship for 350 hp diesel generators.

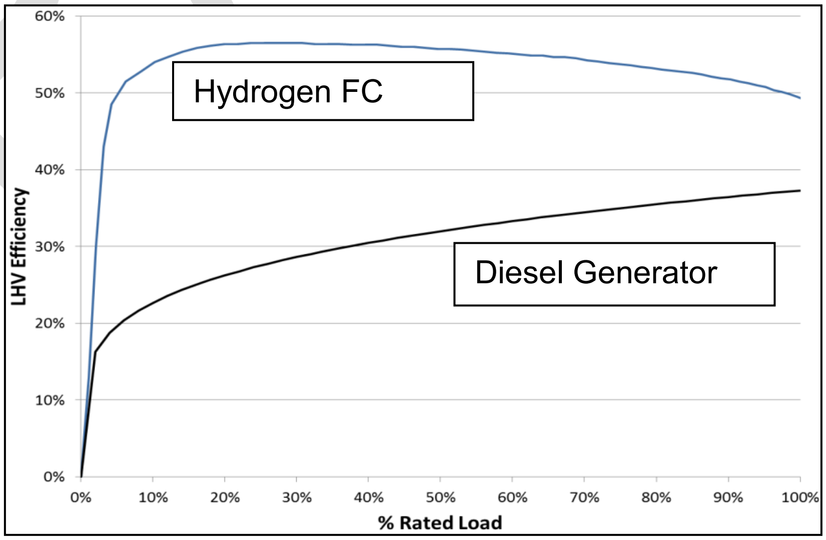


Figure III.C-7: Fuel Cell vs. Diesel Genset Efficiency (Joe Pratt, Sandia National Laboratories)

As indicated above, WTW GHG emissions would be reduced about 22 percent. In addition, FCs are very quiet compared to a diesel engine, and produce zero tail pipe emissions so near-source exposure to diesel PM from TRUs would be eliminated, reducing public health risk near distribution centers and other facilities where TRUs congregate. They also have fewer moving parts, which likely results in reduced repair, maintenance, and downtime costs.

6. Key Performance Parameter Issues and Deployment Challenges

As mentioned previously, private fleets that return to base each day and install H_2 fueling infrastructure at their home base would be good candidates for the short- to mid-term. Until publicly accessible H_2 fueling infrastructure that is configured for Class 8 semi-trailers is installed along major transportation corridors, long-haul applications may not be viable.

Although capital costs for FCs are coming down rapidly, they are currently more expensive than conventional diesel-fueled TRUs. The demonstrations that are currently in process need to be completed. A second generation design (that eliminates the diesel engine and packages the fuel cell inside the housing with the refrigeration system) needs to be demonstrated at larger scale numbers.

To the extent that advanced batteries are used, the cost issue discussed in previous sections will also be a hurdle for this technology.

H_2 fueling infrastructure is relatively expensive and may be in addition to conventional diesel fueling equipment, if the fleet continues to use diesel fuel for their truck tractors. The cost of H_2 infrastructure may be leveraged to acceptable levels if the facility also uses H_2-fueled material handling forklifts.

D. All-Electric Plug-In/Battery/Solar-Assist TR

1. Technology Description

High-efficiency monocrystalline silicone solar photovoltaic (PV) cells are mounted on a flexible support foundation in modules so they can withstand road vibration and shock. These PV modules are mounted on top of the refrigerated van's roof to capture solar irradiation and convert it to direct current (DC) electricity using the photovoltaic effect. Figure III.D-1 shows a refrigerated truck with a roof-mounted solar array that provides electric power for ancillary functions, reducing the load on the vehicle alternator.

Figure III.D-1: Solar Powered Refrigerated Truck

A solar charge controller is used to optimize the power coming from the PV cells and manage the electric power delivery to the on-board deep-cycle absorbed glass mat (AGM) or newer advanced batteries (e.g. lithium-ion). An inverter converts DC voltage to alternating current (AC) to power an electrically driven refrigerator, controls, and condenser and evaporator fans. If the solar array cannot maintain sufficient battery charge while on the road due to clouds, or night operations, the vehicle's generator can fill in.

Figure III.D-2 (next page) illustrates eNow Energy's solar powered idle reduction technology, which could be used to extend the range of all-electric plug-in battery truck transport refrigerators. A similar concept could be applied to trailer transport refrigerators. (eNow, 2014)

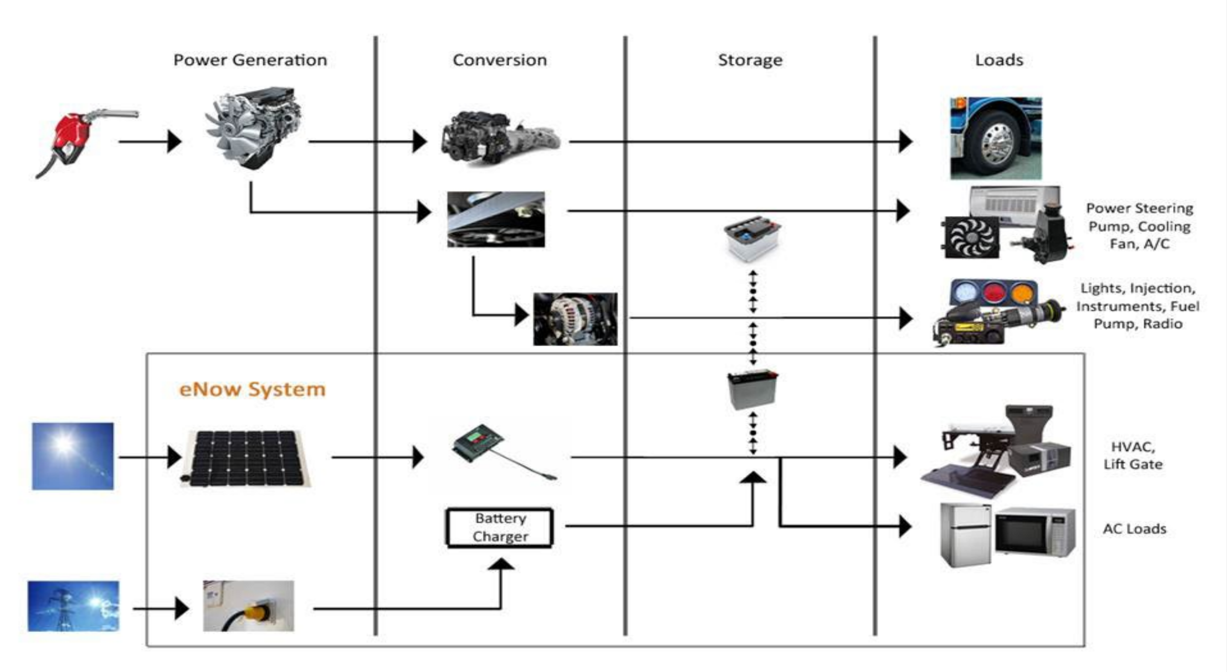


Figure III.D-2: eNow Energy's Solar Idle Reduction Technology

Most of the cooling capacity and power demand of a conventional TRU is reserved for a quick initial chill-down of the van prior to loading. (Kulkarni, 2007) The initial chill-down for an all-electric plug-in battery system with solar assist would be achieved by plugging the electrically-powered refrigerator into the grid. Refrigerator loads can also be heavier after a door opening on a multi-stop delivery route, but this can be minimized by using good operating procedures and door curtains to prevent the cold air in the cargo space from escaping. Battery backup would likely be necessary to recover from these delivery point door openings. The load on the refrigeration system to maintain the temperature set point after chill-down is much less, and depends on the temperature set point, the amount and condition of the van insulation, ambient temperature, solar irradiation heat load, product being hauled, and other factors.

An all-electric transport refrigerator installed on a conventional 53-foot insulated trailer with normal insulation thickness of 2 inches used for stationary cold storage needs about eight to 10 kW of electric power input. (Kiefer, 2014) This establishes the approximate power that the inverter needs to deliver from the solar panels and battery backup with no optimization of the refrigeration system or insulated trailer van. On-road operations typically require more cooling power than stationary cold storage.

The electric power that is produced by a 53-foot long by 8-foot wide trailer roof-mounted solar array with an area of about 39 m^2 would <u>not</u> be sufficient to meet the 8 to 10 kW load demand throughout the day for stationary operations. The power needs for on-road operations is greater, at 15 to 20 kW. Battery power is certainly necessary, but how much energy storage is needed to achieve acceptable range without payload impacts would depend on how thermally efficient the insulated van is and how efficient the refrigeration system is. Any improvements in the thermal efficiency of refrigerated van insulation would reduce the load on the refrigeration system. And any improvements in the efficiency of the refrigeration system and electric motor would correspond to a reduced demand on the batteries, which would translate into longer range or fewer batteries (and lower cost and cargo impacts). Section J of this chapter discusses efficiency in more detail.

As mentioned above, a battery pack is necessary that is sized to provide on-road power when the solar array cannot keep up with the load demand. Absorbed glass mat (AGM), deep cycle marine batteries have been used for this purpose; but, they are too heavy, resulting in impacted payload capacity and additional wear and tear on the truck or trailer. However, they are less expensive than advanced batteries. Figure III.A-6 (previous section) shows an AGM deep cycle battery.

Advanced batteries, such as lithium-ion (Li-ion) batteries, have a greater energy density (e.g. smaller and lighter weight) compared to lead-acid batteries, so there would be no impact on payload capacity and no modification to the vehicle's drive or suspension systems is necessary. When used with a battery management system, Li-ion batteries are safe and have a long life. Li-ion batteries are more expensive, but the costs are coming down fast as production numbers increase. Li-ion batteries have been used successfully in material handling equipment (e.g. forklifts), so adequate performance in TRs is anticipated. Figure III.A-7 (previous section) shows a Li-ion battery.

As mentioned above, a DC-to-AC inverter is needed to convert DC power from the solar array and batteries to AC power for the refrigeration compressor, electronic controls, and condenser and evaporator fans. High efficiency scroll compressors can be driven by DC inverter systems that vary the frequency to control compressor speed, which provides a more energy efficient, precise temperature control.
(Kulkarni, 2007; Daikin, 2014a)

Electric power plug infrastructure is necessary at the home terminal in the parking area to facilitate the initial pre-chill of the van prior to loading, for charging the all-electric system's batteries, and to power the refrigerator while waiting for dispatch.
Figure III.A-4 (previous section) shows a parking area power plug pedestal.

Some distribution centers also install electric power plugs at the loading docks so they can run the transport refrigerator while they are loading. Figure III.A-3 (previous section) shows power plugs next to a loading dock door.

2. Technology Readiness

Demonstration projects have been completed; however, further progress toward pilot scale deployment was apparently not attempted. Therefore, staff believes the all-electric/battery/plugin/solar assist transport refrigeration technology is still in the demonstration phase. These projects are discussed below.

University of Southampton/Sainsbury Solar Transport Refrigerator Demonstration

Figure III.D-3: Sainsbury Solar Refrigerated Trailer

In 1997, the United Kingdom's Department of Trade and Industry, Renewable Energy Programme funded the design, build, and demonstration of one first generation and two second generation solar trailer transport refrigerators for grocery distribution. (EndsReport, 2000) The University of Southampton and Sainsbury plc, a grocery store chain with stores in southwest England, were partners in this project. Staff believes this demonstration concluded in 2002. Several reports were published. (Bahaj, 1998; Bahaj, 2000; Bahaj, 2002) Numerous attempts to contact the author of the reports and Sainsbury refrigerated fleet managers to fill in data gaps and request clarification were unsuccessful. It is unclear if there were any further steps toward commercialization. Figure III.D-3 shows one of the Sainsbury solar refrigerated trailers.

The PV solar powered multi-temp refrigeration systems were designed by the University of Southampton for a refrigerated trailer. A 35 m^2 array of monocrystalline silicon PV solar cells was mounted on the roof of an insulated semi-trailer. The array generated about 4.4 kW of DC electric power, which was connected to a charge controller, battery, and inverter. The inverter drove an optimized refrigeration system, designed to require a fraction of the power normally required by conventional diesel-powered TRUs. This solar trailer was used to transport produce from Sainsbury's distribution center to grocery stores in South-East England. Truckload deliveries typically only took two to three hours, usually during peak daylight hours and to a single store. The system was designed to be capable of longer trips (up to six hours) and multiple delivery stops.

The reports indicate the actual deliveries were successful year-round, even during an unusually hot summer; however, battery storage was necessary to allow operation during cloudy conditions and night deliveries. Lead-acid batteries were mounted under the trailer frame rails (belly mounted). One advantage cited for a solar-powered refrigeration system is that the energy requirement of the refrigeration system is greatest at times of the day and seasons when the solar insolation is also greatest.

Sandia National Laboratories/SunDanzer

Sandia National Laboratories sponsored a feasibility study for a solar powered transport refrigerator trailer that was conducted by SOLUS (a small company now called SunDanzer). (Bergeron, 2001) In that study, the average power input to the refrigeration system for a 53 foot trailer was estimated to be about 5,000 Watts. This estimate was based on an average thermal load of about 3,000 Watts. The thermal load was estimated by assuming thicker than normal insulation (e.g. 3 inches in floor, 4 inches in walls and roof), limited door openings, interior temperature of 0 °F, and an average summer U.S. ambient temperature of about 100 °F. The coefficient of performance (COP) used for the refrigeration system was 0.6 at 0 °F, which was based on published compressor data at that time. COP is the ratio of refrigeration system cooling output to energy or work input. So, 3,000 Watts/0.6 = 5,000 Watts.
It may be worthwhile to note that a COP of 0.6 appears to be the lower range of COP for a modern refrigeration compressor. A published report on a study conducted at Purdue University compared scroll compressors to reciprocating compressors (Purdue, 2002b) and showed COPs ranged between 1.8 and 2.5. Another study out of UC Davis reported COPs for TRUs ranging between 0.6 and 2.4. (Mader, 2007) Use of more recent, efficient refrigeration compressors will improve the feasibility of solar refrigeration systems.

The conceptual design in the Sandia/SunDanzer feasibility study considered battery power, auxiliary power, and amount of phase change material (PCM, e.g. cold plates) to supplement solar power. Performance modeling was conducted using hourly solar insolation and ambient temperature data for four U.S. cities over a one year period.

A spreadsheet model was used to vary performance parameters, such as the amount of PCM used, the amount of auxiliary/battery power used, trailer van insulation condition, and the efficiency of the refrigerator and controls. Various set point temperatures and perishable products (including produce that generate additional thermal load due to respiration) were also modeled.

Development costs for a single pilot test solar refrigerated trailer were estimated. This included an optimized refrigerator and insulated trailer. The economics at this phase were “not compelling”, according to the report’s author. There have been a lot of changes to the economic picture since this report, for instance, diesel has gone from $1.50 per gallon to nearly $4.00 per gallon and solar module prices have dropped from $5 per watt to under $1 per watt. Other improvements since this report include better power electronics for variable speed motor drives and other converters, reduced cost in vacuum panel insulation and a better understanding of the TRU system, operation and trade-offs involved in efficiency, uniform temperature, reliability, etc.

The report recommended further optimization of the refrigeration system design and trailer van insulation. That work was not completed.

U.S. DOE – ARPA-E/eNow Energy/Yardney Technical Products

Yardney Technical Products and eNow Energy recently began work on a demonstration project of a solar powered refrigerated trailer. Their goal is to reduce the fuel consumed by the truck and refrigerated trailer combo through incorporation of renewables and optimal utilization of an energy-dense Li-ion battery system. The Li-ion battery will be equipped with a wireless battery management system to enhance performance and reduce battery pack weight and cost. The team's project is funded under a cooperative agreement with the U.S. Department of Energy's Advanced Research Project Agency – Energy (ARPA-E), and is a continuation of an Advanced Management and Protection of Energy-Storage Devices project led by Lawrence Livermore National Laboratories and Yardney Technical Products. This demonstration project is an R&D activity, so it is premature to project sales rate estimates at this time. A report is expected in late 2015.

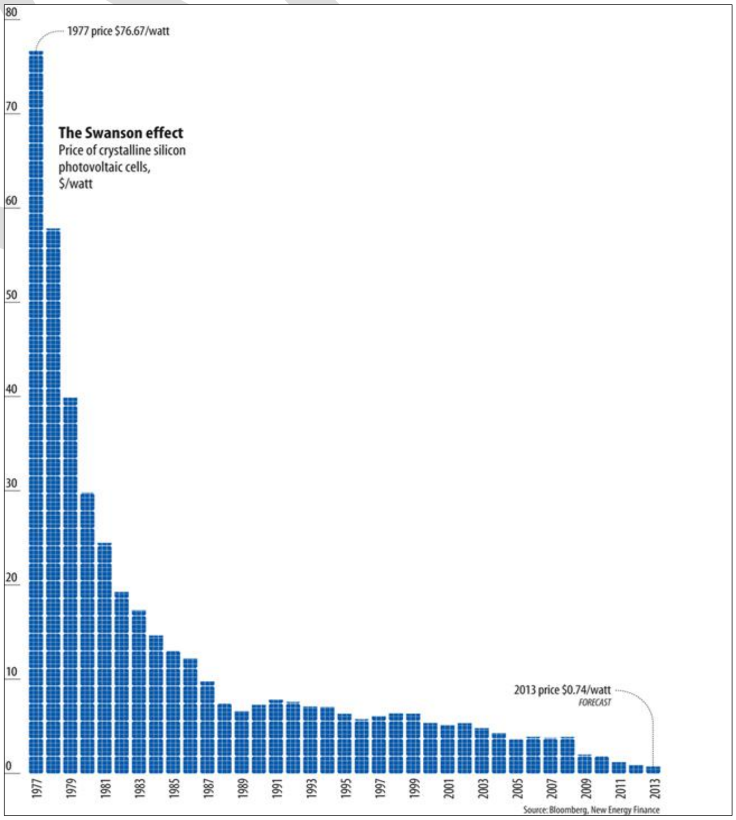
PV Kits for Battery Charging and Small Parasitic Loads

Both of the major TRU manufacturers currently offer solar PV kits for conventional TRUs that are sized to provide power to offset parasitic loads that tend to drain batteries over time and cause failed engine start-up. These TRU OEM systems are not intended to provide enough power for refrigeration load.

3. Economics

The capital costs of the solar PV refrigerator in the University of Southampton/Sainsbury demonstration project was about 30,500 £ ($52,000 in 2014 dollars), installed with PV modules, as reported in 2002. (Bahaj, 2002)

The cost of solar PV modules has dropped significantly since the project report in 2002, which showed 10,000 £ ($17,100 in 2014 US dollars) for the cost of a 4.4 kW PV array. Figure III.D-4 shows the price history of PV cells in U.S. dollars per kW from 1977 to 2013. (Bloomberg, 2014) This graph visually illustrates significant drops in PV cell price. Staff expects PV module prices would follow the same trend.



Source: Bloomberg, New Energy Finance

Figure III.D-4: PV Cell Cost Trend

Staff expects that the costs of many other components, such as inverters, may have also gone down since production numbers have gone up due to rapid deployment of solar systems. Figure III.D-5 shows the installed price of residential and commercial solar systems dropping about 50 percent since 2002. (SunShot, 2014)

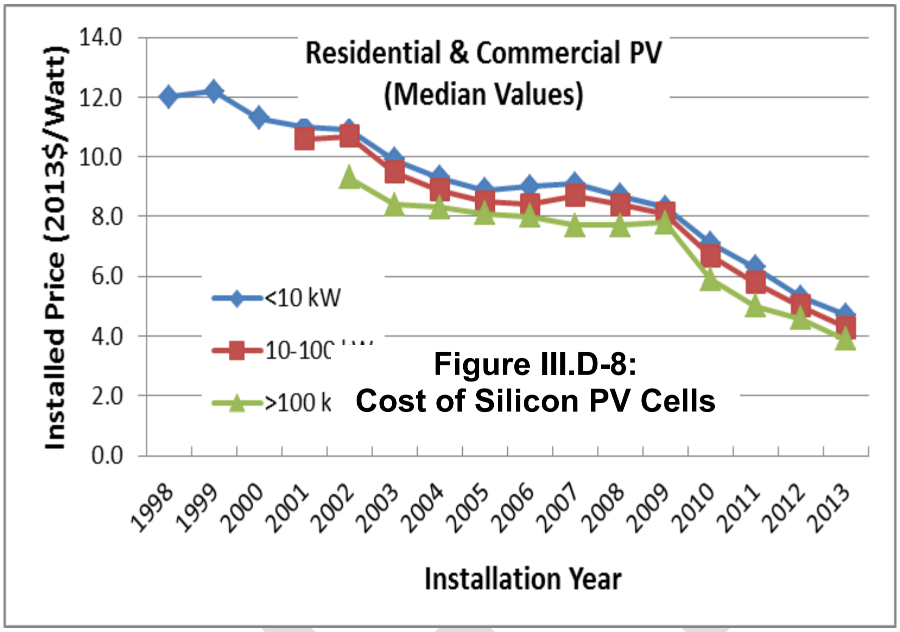


Figure III.D-5:
Installed Cost of Residential and Commercial PV

The 2002 University of Southampton/Sainsbury report (Bahaj, 2002) discussed the economics of their solar powered refrigerated transport trailers. They estimated lifetime operating savings that resulted in a 16-year payback period, which is unacceptable to many. However, the author did not account for the fuel savings resulting from eliminating the diesel TRU engine and, as discussed above, the costs of solar PV modules and installations have gone down significantly. Staff found several other issues and assumptions in the reports that needed clarification. As of this writing, the report author and fleet manager have not responded to requests for clarification. However, if an updated design is demonstrated in the future, staff expects the payback period would probably be more acceptable.

The University of Southampton/Sainsbury report also did not address infrastructure costs. Power plug costs for loading dock plugs, sized for trailer transport refrigeration system pull-down are about $6,000 per loading dock space and $7,200 per parking area power pedestal. (Shorepower, 2014a)

When further pilot demonstrations of optimized components and systems are completed, the commercial design configuration is settled, and production numbers increase, the capital costs should decrease significantly compared to pilot system costs. There is insufficient information available at this time to estimate updated costs and evaluate the economics of this technology.

4. Emissions Reductions

GHG Emissions

Staff conducted Well-to-Tank (WTT) and Tank-to-Wheels (TTW) emissions analyses. Totaling the results from these two provides a Well to Wheels (WTW) result.

The WTT analysis takes into account the emissions associated with electricity generation and transmission for charging on-board batteries. The University of Southampton/Sainsbury demonstration project reports indicated battery back-up daily usage was heaviest in August at 28 kW-hr/day (delivered from the inverter) and lightest during December at 2.1 kW-hr/day. Daily delivery activity was 6 hrs/day. (Bahaj, 2002)

The following assumptions are used:

- Average inverter output = 15 kW-hr/day (Summer-Winter Average)
- Battery charge/discharge efficiency = 85 percent (Wholesalesolar, 2014a)
- Inverter efficiency = 80 percent (GoSolarCalifornia, 2014; Solar-Facts, 2014)
- Battery charge time = 6 hours
- Battery charger efficiency = 85 percent (Wholesalesolar, 2014b)

The hourly electric energy consumption for charging on-board batteries would be 4.3 kW-hr/hr. WTT, TTW, and the additive WTW GHG emission rates for the all-electric plug-in/battery/solar-assist trailer TR technology at this electricity usage rate sum as follows:

WTT	1.24 kg/hr CO_2e
TTW	0.0 kg/hr CO_2e
WTW	**1.24 kg/hr CO_2e**

The calculations for the above values are shown in Appendix III.D-1.

The industry-average diesel fuel use rate for a 2015 conventional trailer TRU is about 0.8 gal/hr. The WTT, TTW, and the additive WTW GHG emission rates for a conventional trailer TRU at this fuel use rate sum were calculated for 2015 baseline fuel and the fuels that will be required in 2020 and beyond:

	2015 Fuel	2020+ Fuel
WTT	2.20 kg/hr CO_2e	1.37 kg/hr CO_2e
TTW	6.06 kg/hr CO_2e	6.06 kg/hr CO_2e
WTW	**8.26 kg/hr CO_2e**	**7.43 kg/hr CO_2e**

The calculations for the above values are shown in Appendix III.A-2.

These estimates indicate that use of an all-electric plug-in/battery/solar-assist trailer TR instead of conventional diesel trailer TRU would result in about 89 percent (2015 Fuel) and 87 percent (2020+ Fuel) reductions in the WTW GHG emission rate.

Criteria Pollutant Emissions

TTW emission rates for the criteria pollutants NMHC+NO_x and PM are presented in Table III.D-1 for conventional trailer TRU and all-electric plug-in/battery/solar-assist trailer TR comparisons. WTT emissions were not addressed; however, they are expected to be small compared to TTW emissions.

Table III.D-1: All-electric Plug-in/Battery/Solar-Assist - TTW Criteria Pollutant Emission Rate Comparisons

Equipment Type	NMHC+NOx (g/hr)	PM (g/hr)	Total CP (g/hr)	Percent Reduction
Conventional Trailer TRU	57.5	1.23	58.73	-
All-electric plug-in/battery/ solar-assist TR	0	0	0	100%

The calculations for the values shown in Table III.D-1 are in Appendices III.A-2 and III.D-1. As shown in Table III.D-1, all-electric plug-in/battery/solar-assist TRs would produce zero tail pipe emissions. The TTW criteria pollutant emission rate would be reduced100 percent if an all-electric/plug-in/battery/solar-assist trailer TR is used instead of a conventional trailer TRU.

5. Technology Advantages

All-electric, plug-in battery with solar assist transport refrigerators have very quiet operation compared to a conventional diesel TRU. They also have much fewer moving parts compared to a diesel TRU, which may mean they have reduced repair, maintenance, and downtime costs. And since there are zero tailpipe emissions (e.g. diesel PM), public health risks would be minimized near distribution centers and other locations where TRUs congregate. Also, regulatory compliance costs for the TRU regulation would be eliminated and the refrigerated motor carrier would gain valuable public relations benefits with their customers and communities.

6. Key Performance Parameter Issues and Deployment Challenges

All-electric/battery/plugin/solar-assist TRs are not feasible for long-haul for-hire commercial carrier applications in the near-term. This is because there are currently only a few publicly accessible electrified truck stops that are configured for use by Class 8 semi-trailers that could provide plugs for charging batteries and operating all-electric transport refrigerators. As mentioned previously, all-electric/ plug-in/battery/solar-assist transport refrigerators will be limited to use by return-to-base fleets, which are typically private fleets, such as grocery distribution and foodservice distribution.

Hauling frozen products may not be possible until there are major improvements in refrigerator efficiency and insulated van thermal efficiency that would reduce the demand on batteries and solar PV system.

Only private fleets that can install electric power plug infrastructure at their home base would be good candidates in the short- to mid-term. Electric power plug infrastructure is relatively expensive and may be in addition to conventional diesel fueling equipment.

Staff believes this technology is still in the demonstration phase. Although demonstrations of solar transport refrigerators were completed over a decade ago, the results were, at best, unclear. Since then, there have been technology advances in key components that would likely improve performance, range, and economics. All-electric/battery/plug-in/solar-assist systems may not be commercially available within the next five years. The demonstrations that are currently being planned need to be completed and second generation designs demonstrated to provide updated key performance parameter information.

Although capital costs for all-electric/battery/plug-in/solar-assist may be coming down rapidly, they are currently much more expensive than conventional diesel-fueled TRUs. The payback period is unknown for updated, optimized systems.

E. Cryogenic TRs

1. Technology Description

A cryogenic fuel (liquid nitrogen, liquid carbon dioxide or liquid air) is contained in a refillable storage tank on the truck or trailer near the cargo space. When cooling is needed, valves are opened to allow the liquid to flow and expand to a gas phase, transferring the cooling to the cargo space usually via a heat exchanger. The cool exhaust gas is released into the atmosphere. Generally, if a heat exchanger is used, the gas is released external to the cargo space and it is considered indirect cooling. Direct cooling involves the cooling gas being released internal to the cargo space, and safety processes must be in place to prevent entry when there is an oxygen deficient atmosphere.

The following three figures show depictions of indirect and direct cryogenic cooling:

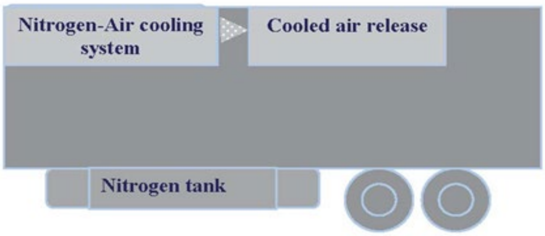


Figure III.E-1: Indirect Liquid Nitrogen Cooling Components (Pedolsky, 2010)

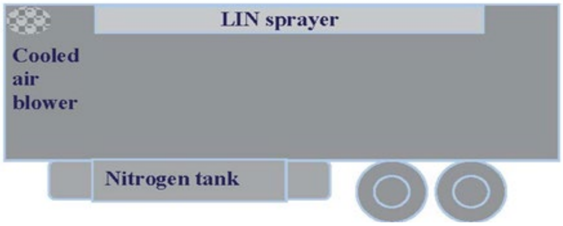


Figure III.E-2: Direct Liquid Nitrogen Cooling Components (Pedolsky, 2010)

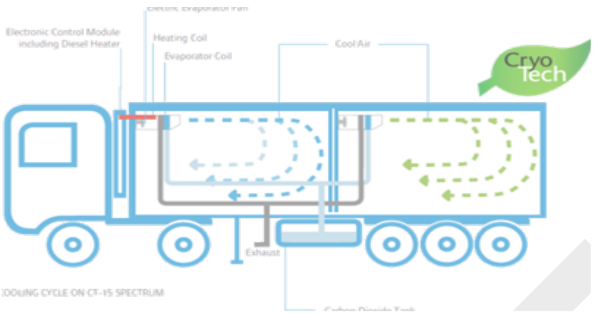


Figure III.E-3: Indirect Liquid Carbon Dioxide Cooling Components - Multi-Temp TR (Thermo King, 2013)

The primary components of a cryogenic TR are the cryogenic storage tank, a means to dispense the cryogenic fuel and transfer cooling (either sprayers in direct systems or heat exchangers in indirect systems), and fans to circulate air. In addition, controllers and flow regulators are needed to meter the dispensing of the cryogenic fluid to properly control the desired temperature. Often, redundant electronic sensors and controllers are used to ensure desired temperatures are maintained and safety systems are robust. The cryogenic TR has much fewer moving parts than a conventional TRU as it does not require an engine or compressor. Some of the equipment is handling cryogenic liquids, so the materials must be compatible with very cold temperatures.

The cryogenic storage tank is manufactured to American Society of Mechanical Engineers (ASME) specifications and Department of Transportation (DOT) codes for the temperatures and pressures involved. The tanks are sized to provide adequate range, and are available in sizes of 330 liters (87.2 gallons) to 1,100 liters (290.6 gallons). Tanks are usually placed under the chassis, but occasionally are placed in other locations. Tanks are generally manufactured in the country of use to ensure that they meet all applicable standards. Range is dependent on door openings and van thermal efficiency, but is usually less than 24 hours.

Efforts are underway to increase efficiencies by further utilizing the cool exhaust gas to generate power for ancillary equipment which requires electrical service. Reflect Scientific increases the efficiency of the TR by using a patented power generator using cool exhaust and heat to create potential to turn an alternator or generator.

The Dearman Engine Company is developing a TR which operates using liquid air or LN_2 while using the cargo as a heat source to “boil” the liquid air or LN_2 to produce a high pressure gas at constant temperature for power. This Dearman engine contains a heat exchange fluid that facilitates high rates of heat exchange and gas expansion in the cylinder. The power generated by the Dearman engine is used to power ancillaries such as fans, defrosters and a downsized refrigerator for additional cooling. See Figure III.E-4 for a diagram of the cylinder operation within the Dearman engine.

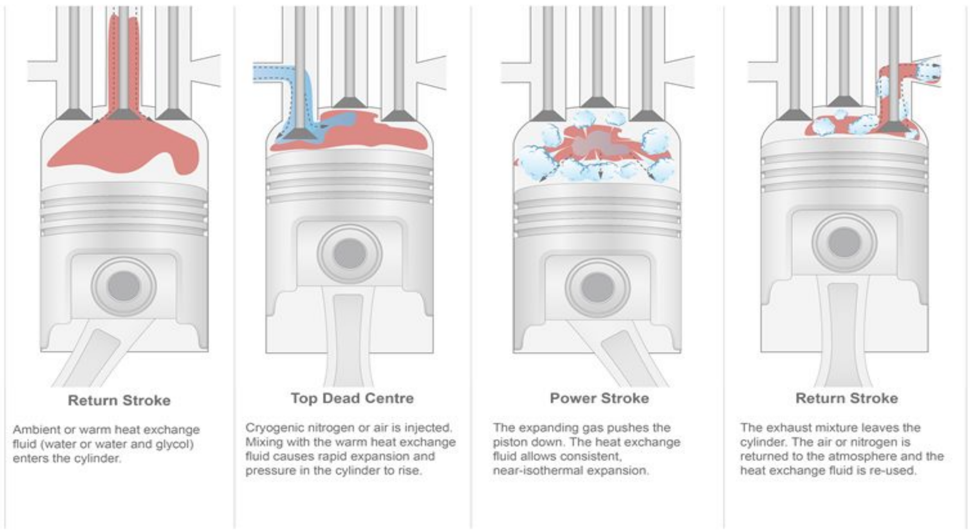


Figure III.E-4 Operating Principles of the Dearman Engine (Dearman Engine Company, 2015)

Direct TRs continue to improve the safety aspects to prevent entry into oxygen deficient atmospheres. The Boreas TR contains safety features designed for ISO 26262 Functional Safety Critical Systems Compliance and implemented using redundant high-reliability electrical/electronic methods. They have also added fans in strategic locations to minimize time to safe when venting and maximize cooling efficiency when loading.

Cryogenic Fuel Supply and Dispensing Appliances

Commercial cryogenic TRs currently either use liquid carbon dioxide (LCO_2) or liquid nitrogen (LN_2). LCO_2 is collected as a byproduct from petroleum refining. LN_2 is produced by the liquefaction of air and separation of nitrogen via cryogenic distillation. Both are fairly stable commodities, but proximity to the manufacture site affects cost and availability. On rare occasion, a manufacturer shutdown may impact the availability of the cryogen.

Cryogenic liquid infrastructure for public use is almost nonexistent in the US, so this technology is generally limited to fleets that return to base daily and can refuel on-site. The refueling infrastructure consists of a bulk storage tank and a dispenser with a LN_2 fill pipe. Dispensers can be gravity or pump fill. The gravity dispensers can be very slow to fill dependent on the temperature and pressure differentials between the dispensing tank and the receiving tank. In the U.S., many fleets prefer a quick fill system which takes about the same time as a diesel refueling. Dispensers can be configured to fill a single tank or multiple tanks as needed. Most cryogen suppliers lease the tanks and dispensers on a monthly basis.

2. Technology Readiness

Pure cryogenic TRs have been in commercially available in Europe for more than a decade. About 0.5 percent of all truck and trailer TRs sold in Europe use cryogenic temperature controls. (Ambaruch, 2014) In Europe, the cost of cryogenic fuel is comparable to the cost of diesel. They have historically been used for truck TRs as cooling capacity is limited by the size of the cryogenic storage tank and trucks have a smaller volume to cool than trailers, but many newer generation products are for trailer units. The technology is only viable where the cryogen fuel is readily available and cost-effective compared to diesel. Private fleets with return to base operations that have refueling capability are the focus market in the U.S. because public access to liquid nitrogen and liquid carbon dioxide refueling is very rare.

This technology is in the pilot scale deployment phase in the U.S. Several demonstration projects have been performed in the U.S. beginning in 1999. Two of Thermo King's SB III-CR LCO_2 trailer units were field tested in local delivery service by In-N-Out Burgers in California between May 1999 and July 2000 (Little, 2001). Sysco Foods in Texas also demonstrated both trailer and truck LCO_2 Thermo King units around 2000 (Viegas, 2014). Safeway has demonstrated a number of cryogenic TRs starting in 2001, which were successful, as indicated by the increasing numbers of units. (Gavrilov, 2014a; LaBau, 2015). The 22 currently active Safeway cryogenic trailers were plumbed for nitrogen use by Boreas in 2013 and have been in operation since then. (Norvell, 2015) The most recent demonstrations in the U.S. were field tests of LN_2 Cryometrix AZE trailer units from Reflect Scientific by medium-size carriers in Utah between October 2013 and May 2014 (Bowdish, 2014a). Twenty (20) additional Boreas TRs installed by Wabash on new trailers delivered to Safeway in February 2015 will undergo demonstration of fan upgrades and multi-zone capability in Summer 2015. (Norvell, 2015)

ThermoKing/In-N-Out Burger Field Test

The Thermo King demonstrations were partially funded by a grant from the South Coast Air Quality Management District (SCAQMD) under "Demonstration of Cryogenic Refrigeration Technology in Truck Trailers". Progress reports were written by ARCADIS Geraghty & Miller, Inc., and a final report by prepared by Arthur D. Little. The results showed that the units offered very high capacity and temperature control performance similar to that of the diesel-mechanical control units. The units demonstrated high reliability, and required very little maintenance. The capacity of the on-board tank was consistently adequate, but required modification of operating practices to eliminating lengthy pre-cool and standby operation during door openings. Very unusual shutdowns in LCO_2 production caused curtailment of deliveries and reduced operation with these test units. The tests concluded that while the demonstration was successful, there was an operating cost disadvantage at that time in the U.S. (Little, 2001; ARCADIS, 2000)

Thermo King continues to produce the Cryotech indirect LCO_2 (R-744) system at their European facility in Galway, Ireland as the CT-15 Spectrum multi-temp trailer unit, the CT-10 Spectrum multi-temp truck unit, and the CT-10 single temp truck unit. They have produced over 1,000 units for use in Europe. One of their product brochures is shown in Figure III.E-5 below. (Viegas, 2014)

Figure III.E-5: Thermo King Cryotech Brochure (Thermo King, 2013)

They have also become a leader in CO_2 fill systems and are piloting CO_2 filling stations at their dealerships in Sweden, Norway, and the Netherlands. They jointly own technology for high-speed cryogenic fill with Yara, which is a spinoff from Hydrogas. (Viegas, 2014)

<u>ecoFridge/Air Liquide/Safeway</u>

Safeway performed a cryogenic TR pre-commercial demonstration from 2001 to 2011 using ecoFridge TRs and LN_2 supplied by Air Liquide. The demonstration grew from one to three, to 23 units and was described by the manufacturer and LN_2 supplier as successful. (Gavrilov, 2014a; LaBau, 2014; LaBau, 2015). See Figure III.E-6 for a picture of a Safeway trailer with LN_2 tank.

Figure III.E-6: Safeway Trailer with LN_2 Tank

Figure III.E-7: natureFridge
Source: http://naturefridge.com

A subsequent private company, ecoFridge Production Company LTD, Ukraine continues to produce direct LN_2 refrigeration systems, now known as natureFridge TRs. ecoFridge now has produced over 200 units for commercial use in Europe and Africa. The units are manufactured in Ukraine with the tanks manufactured and assembled in the country of use. Figure III.E-7 (previous page) shows the natureFridge system. (Gavrilov, 2014b)

Reflect Scientific Field Test

Recent field-testing of the Reflect Scientific Cryometrix AZE was described in a presentation to ARB staff. This is an indirect injection, closed-cycle liquid nitrogen system. Data was collected from round trip transport with mid-trip refueling, starting from Salt Lake City (SLC), then to Los Angeles and back to SLC in October 2013 carrying refrigerated goods. Data was collected from a second round-trip transport from SLC to Denver in March 2014 carrying frozen goods. The data showed successful runs with a usage of 0.23 to 0.26 gal LN_2/°F/hr. The mid-trip refueling added a layer of logistics, but demonstrated the possibility of expanding the range of their equipment to accommodate long-haul fleets as well as short-haul return to base operations. (Bowdish, 2014a)

Reflect Scientific is actively marketing their cryogenic system in the US. While they are currently in pilot scale deployment, they feel they could scale up production very quickly. See Figure III.E-8 for a photograph of a Cryometrix unit (Bowdish, 2014b)

Figure III.E-8: Cryometrix AZE
Source: http://www.cryometrix.com/trucks.php

Boreas/Air Liquide/Safeway

JFE Industries originally shipped 22 Boreas direct LN_2 single zone TRs to Safeway in Northern California in June 2013 for initial beta testing. The TRs were retrofitted on trailers which were previously configured for liquid nitrogen usage. These units continue operation and have provided data for additional beta testing of 20 TRs with improved fan configurations and two zone potential in 2015. The 2015 beta units were manufactured by Boreas and installed on new trailers built specifically for cryogenic TRs at the Wabash production facility in Michigan, demonstrating trailer OEM installation, and will be tested for two zone capability in mid-2015. See Figure III.E-9 for a diagram of the Boreas architecture (Norvell, 2015)

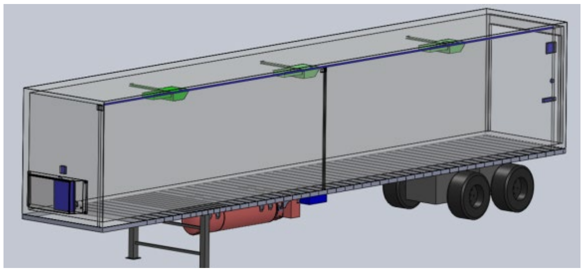


Figure III.E-9 Boreas TR Architecture (Norvell, 2015)

Air Liquide

Air Liquide produces the Blueeze^{TM} indirect LN_2 system. They also have purchased Messer Grieshiem which manufactures a direct LN_2 system. Between the two products, over 1,000 units have been produced for use in Europe. Figure III.E-10 shows a photograph of a Blueeze^{TM} unit. (LaBau, 2014)

Figure III.E-10: Air Liquid Blueeze^{TM} (LaBau, 2014)

Linde

Linde produces the Frostcruise^{TM} indirect LN_2 system for use in Europe. They have produced nearly 100 commercial units to date. Figures III.E-11 and III.E-12 show information on the Linde system. (Ewig, 2014a)

Figure III.E-11: Linde Frostcruise^{TM} (Linde, 2012)

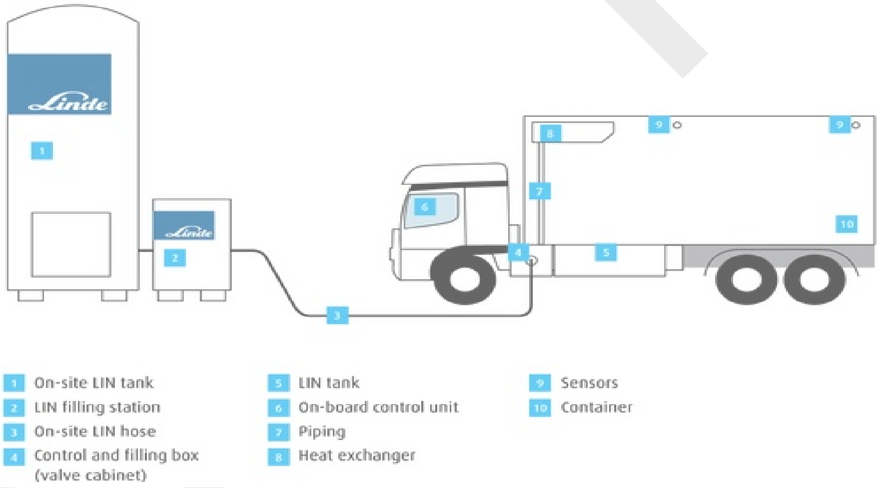


Figure III.E-12: Linde Liquid Nitrogen Transport Refrigeration System Diagram (Linde, 2012)

Dearman Engine Demonstrations

Dearman engines in TRs manufactured by the Dearman Engine Company are being demonstrated on-vehicle in the United Kingdom (UK) in a joint project with MIRA, Air Products and Loughborough University funded by Innovate UK. Sainsbury's, a UK supermarket, is on the project advisory board. Testing will take place later this year in the UK with a back to base distribution operator. Further back to base demonstrations and fleet trials within and outside the UK are planned for 2016. (Lingwood, 2015) See Figure III.E-13 for a picture of a Dearman Engine Company TR. (Owen, 2014)

Figure III.E-13
Dearman Engine Company TR
Source: Dearman Engine Company

3. Economics

At this time, the initial capital costs of pure cryogenic refrigerated transport have been estimated from international costs. The cost of a pure cryogenic truck TR is about $16,000. The cost of a comparable conventional truck TRU is about $12,000. So, the direct cryogenic truck TR is about 33 percent greater cost than the conventional truck TRU (16/12 = 1.33). Indirect cryogenic trailer TRs range from about $23,000 to about $35,000, so an average of $29,000 is used for the comparison to a conventional trailer TRU, which costs about $26,000. This comparison shows the cryogenic trailer system cost is about 12 percent greater than a conventional trailer TRU (29/26 = 1.12).

Fuel storage and dispensing infrastructure costs have to also be considered. While a semi-permanent dispensing system was installed during the 1999 In-N-Out demonstration for $10,000 and a 13-ton LCO_2 tank was leased for $270/month (Little, 2001), most current suppliers lease a combination tank storage and dispensing system. Cost ranges from $1,500/month for a LN_2 gravity feed system to $3,000/month for a LN_2 quick fill system with dual dispensers. When infrastructure costs can be spread over multiple cryogenic transport refrigerators, the more units that you have, the lower the per-unit cost. In the example calculation below, the cost for a single unit is estimated, so the gravity feed system is used, although most fleets are expected to go with a fast-fill system for multiple units. In the recent Reflect Scientific field tests, micro bulk deliveries of LN_2 were arranged at predetermined locations to directly refill the on-board storage tanks. A photograph of a cryogenic fill station is shown in Figure III.E-14.

Figure III.E-14: LN_2 Fill Station
(Air Liquide, 2009)

Operating costs for cryogenic fuels have been estimated for 2,000 hours of annual operation to be consistent with conventional diesel hours. Hourly fuel use is estimated to vary from 6.3 to 10.6 gallons/hour, and 8.6 gallons/hour is often used as a good estimate for trailer models. Cost of liquid nitrogen is estimated from $0.36/gallon to $0.56/gallon, so the average of $0.46/gallon will be used to estimate costs.

Maintenance costs are much lower with the pure cryogenic systems than with conventional diesel system as there are very few moving parts. Costs for maintenance are estimated at $0.05/hour (EcoFridge, 2014a) for a total of $100 annually for cryogenic systems and $0.825/hr (TK Services, 2014) for a total of $1,650 annually for conventional TRU.

Annual operating costs for a trailer cryogenic TR and a conventional TRU are listed in Table III.E-1. Totals show very similar operating costs for both systems.

Table III.E-1: Annual Operating Cost Comparison for Trailer Cryogenic TR and Trailer Conventional TRU

Operating Costs	Cryogenic TR	Conventional TRU
Fuel (e.g.LN_2 or diesel)	$7,900[1]	$6,400[2]
Maintenance	$100[3]	$1,650[4]
Total Operating Costs/Year	$8,000	$8,050

Table III.E-1 Notes:
1. LN_2 annual use: 8.6 gal/hr for 2,000 hrs at $0.46/gal
2. Diesel annual use: 0.8 gal/hr for 2,000 hrs at $4.00/gal
3. Cryogenic maintenance costs: $0.05/hr for 2,000 hrs
4. Conventional maintenance costs: $0.825/hr for 2,000 hrs

4. Emission Reductions

GHG Emissions

Staff conducted Well-to-Tank (WTT) and Tank-to-Wheels (TTW) emission rate analyses. Totaling the results from these two provides a Well-to-Wheels (WTW) result.

The WTT analysis considers emissions associated with the production, distribution, and dispensing of LCO_2 and LN_2. While carbon dioxide is a GHG, feedstock CO_2 is a gaseous byproduct of petroleum refining and is considered to be emitted during the refinery process, so those emissions are not attributed to production of cryogenic CO_2. We do not have energy data for the compression and liquefaction of gaseous CO_2 to LCO_2, so this analysis was solely for LN_2. LN_2 is produced by the liquefaction of air and separation of liquid nitrogen via cryogenic distillation. Electricity powers the process to separate LN_2 from air. Emissions associated with both the generation of electricity in California and transport of LN_2 from the production site to storage at the dispensing site for the cryogenic TR are included in the WTT results.

The TTW analysis looks at the system from dispensing to the on-board cryogen tank through the release of the cryogen to the atmosphere. Cryogenic TR systems do not use an internal combustion engine for operation -- there are no tailpipe emissions associated with the cryogenic LN_2 coolant venting to atmosphere and such venting does not contain greenhouse gases or criteria pollutants. Therefore, TTW GHG and CP emissions are zero.

Calculations and assumptions for the cryogenic trailer TR are presented in Appendix III.E-1. The resulting cryogenic trailer TR WTT and TTW GHG emission rates for cryogenic trailer TRs sum to WTW GHG emission rates as follows:

WTT	4.5 kg/hr CO_2e
TTW	0.0 kg/hr CO_2e
WTW	**4.5 kg/hr CO_2e**

The industry-average diesel fuel use rate for a 2015 conventional trailer TRU is about 0.8 gal/hr. The WTT, TTW, and additive WTW GHG emissions for this conventional trailer TRU fuel rate were calculated for 2015 baseline fuel and the fuels that will be required in 2020 and beyond:

	2015 Fuel	2020+ Fuel
WTT	2.20 kg/hr CO_2e	1.37 kg/hr CO_2e
TTW	6.06 kg/hr CO_2e	6.06 kg/hr CO_2e
WTW	**8.26 kg/hr CO_2e**	**7.43 kg/hr CO_2e**

The calculations for the above conventional trailer TRU values are shown in Appendix III.A-2. These estimates result in about 59 percent (2015 Fuel) and 55 percent (2020+Fuel) reductions in the WTW GHG emission rate if this cryogenic trailer TR is used instead of conventional diesel TRU.

Criteria Pollutant Emissions

TTW emission rates for the criteria pollutants NMHC+NO_x and PM are presented in Table III.E-2 for conventional trailer TRU and cryogenic trailer TR comparisons. WTT emissions were not addressed; however, they are expected to be small compared to TTW emissions.

Table III.E-2: Cryogenic Trailer TR -
TTW Criteria Pollutant Emission Rate Comparisons

Equipment Type	NMHC+NOx (g/hr)	PM (g/hr)	Total CP (g/hr)	Percent Reduction
Conventional Trailer TRU	57.5	1.23	58.73	-
Cryogenic Trailer TR	0	0	0	100%

The calculations for the values shown in Table III.E-2 are in Appendices III.A-2 and III.E-1. As shown in Table III.E-1, cryogenic TRs would produce zero tail pipe emissions. The TTW criteria pollutant emission rate would be reduced100 percent if a cryogenic trailer TR is used instead of a conventional trailer TRU.

5. Technology Advantages

Cryogenic TRs are successful in Europe mainly due to widespread noise regulations for deliveries and much higher diesel fuel costs compared to the U.S. The cryogenic systems are extremely quiet compared to conventional diesel TRUs due to the absence of the diesel engine and associated equipment. Cryogenic TRs also have much faster cool downs and temperature recovery after door openings as they are not limited by the engine operation. In addition, maintenance is significantly reduced due to the lack of a diesel engine and other associated moving parts. Cryogenic TRs have also been reported to cause less product dehydration compared to conventional TRUs. (Gavrilov, 2014b).

From an environmental standpoint, emissions of both criteria pollutants and GHGs are significantly reduced. The use of cryogens eliminates both the use of high GWP refrigerants and emissions associated with the use of diesel.

6. Key Performance Parameter Issues and Deployment Challenges

Key performance parameters issues include range, capital costs and operating costs, availability and ease of refueling, and safety issues around potentially oxygen deficient atmospheres.

Operating range is limited to the size of the on-board tank and the rate of release for the cryogenic fuel. This generally restricts range to daily deliveries and fleets that return to base every day to “refuel.” However, a recent demonstration combined cryogenic supplier coordination with the refrigerated transport delivery route to provide refill of the cryogenic tank at designated locations along the route, starting in Salt Lake City, Utah, delivering a load to Los Angeles, California and returning to Salt Lake City with a back-haul load.

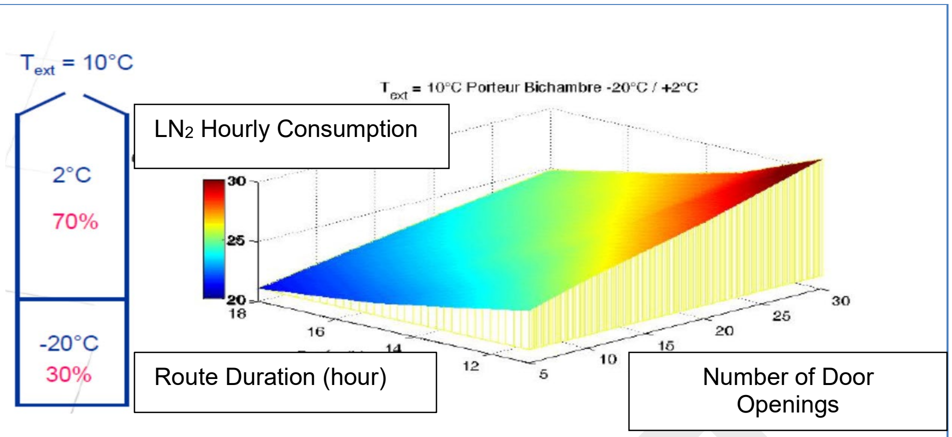


Figure III-E-15: Diagram of Fuel Usage per Temperature, Route and Door Openings (Air Liquide, 2009)

Rate of release for the cryogenic fuel is affected by temperature differential between atmospheric and product temperature, door openings, and thermal efficiency of the cargo van. Minimizing door opening frequency and duration will minimize need for temperature recovery. See Figure III.E-15 (previous page) for a graphical representation of an Air Liquide modeling tool which calculates hourly LN_2 consumption.

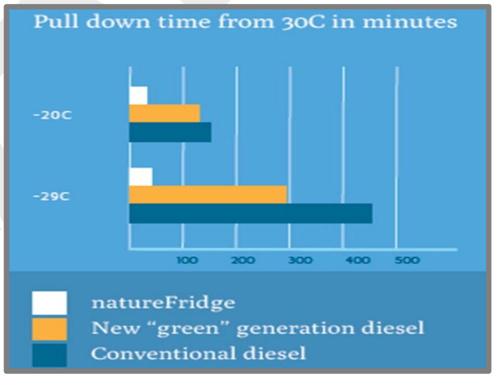


Figure III.E-16: Comparison of Temperature Recovery (EcoFridge, 2014b)

After door openings, the cryogenic system has excellent temperature recovery. See Figure III.E-16 for a chart comparing cryogenic temperature recovery with conventional TRU temperature recovery.

As is the case with all TR technologies, the thermal efficiency of the cargo van is extremely important to minimize fuel usage. In the U.S., new trailers have reduced insulation to maximize cargo space, whereas many European countries have added insulation to maximize thermal efficiency, making cryogenic TRs more viable. These countries have adopted the United Nation's International Carriage of Perishable Foodstuffs (commonly referred to as "ATP" in the U.S.) which contains standards for insulated and refrigerated equipment used for the transport of refrigerated foods. Improved thermal efficiency of cargo vans may cause capital cost increases and cargo space impacts that affect revenue. Use of door curtains and other operating procedure modifications may also help conserve cryogenic fluid, but with slightly increased capital and operating costs.

As discussed above, initial capital costs of cryogenic TRs are higher than conventional diesel TRUs. In addition, fuel storage and dispensing infrastructure adds to the cost due to lack of availability of public cryogenic dispensing facilities. Some facilities choose to capitalize storage and dispensing infrastructure, but most currently lease the equipment from the cryogen supplier making it an operating expense. The durability of the cryogenic TRs is good as there are fewer mechanical parts, but parts which contact the cryogenic fuel must be fabricated with materials that can withstand the low temperatures associated with cryogenic materials. In addition, cryogenic storage tanks have periodic certification requirements.

Operating costs for cryogenic fuel vary based on contracts and manufacturing issues. In addition, cryogenic fuel distribution costs can vary dependent on the distance from the generation point. In the U.S., the cost of diesel fuel is generally much less expensive than the cost of the cryogenic fuel, but in Europe the cost of diesel is comparable to the cost of cryogenic fuel. Lower maintenance costs on the cryogenic system partially balance the increased fuel costs.

Availability of cryogenic fuels is occasionally disrupted with impact to schedules. Also, refueling with cryogen can often be more time consuming than refueling with diesel. Suppliers have improved the refuel time since first generation models, and now have quick-fill options that compare to diesel fueling times. Handling of cryogenic fuels requires additional training to ensure that safety issues are addressed. Materials that are handling cryogens can be very cold, raising the possibility of skin burns. Also, care must be taken in cargo spaces to ensure there is no entry to an oxygen-deficient atmosphere.

F. Alternative Fueled Engines

1. Technology Description

The purpose of this section is to highlight the benefits and technical feasibility challenges of replacing diesel fueled TRUs with Compressed Natural Gas (CNG), Liquefied Natural Gas (LNG), and Liquefied Petroleum Gas (LPG). CNG and LNG are methane, while LPG is a mixture of butane and propane. Alternative fuels are described in more detail in the Alternative Fuel section of the overarching Truck Technology Assessment. A brief description of how alternative fuels work is provided here.

Fuels

Alternative fuels such as natural gas and propane have been used as combustion substitutes to gasoline for a long time. Their popularity has increased due to the boom from the unconventional gas exploration which has rendered it cheap and plentiful as seen in Figure III.F-1, showing the Department of Energy's Alternative Fuels Data Center chart on estimated consumption of alternative fuels by alternative fueled vehicles (AFV) (AFDC, 2014f).

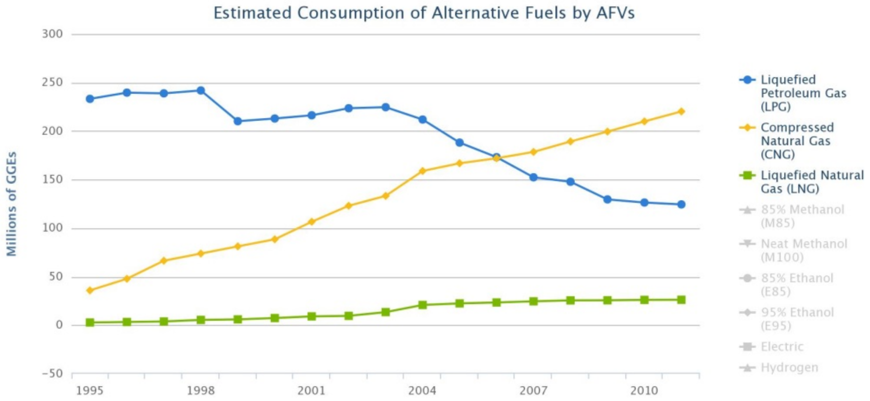


Figure III.F-1: Estimated Consumption of Alternative Fuels by Alternative Fueled Vehicles (AFDC, 2014f)

According to Navigant Research, the percentage of heavy and medium duty vehicles running on diesel is anticipated to fall from 79 percent in 2014 down to 76 percent by 2035 as diesel vehicles are supplanted by AFVs. (Transport Topics, 2014a) The shift to alternative fueled powered engines is also affected by the cost of diesel fuel. As shown in Figure III.F-2 (next page), the price of diesel is very volatile. Since this chart was published (October 2014), the price of diesel had plummeted to $2.754 per gallon on April 13, 2015, but has climbed since then to $2.854 per gallon on May 4, 2015. Transport Topics 2015a) As shown in this figure, the price of CNG is relatively stable.

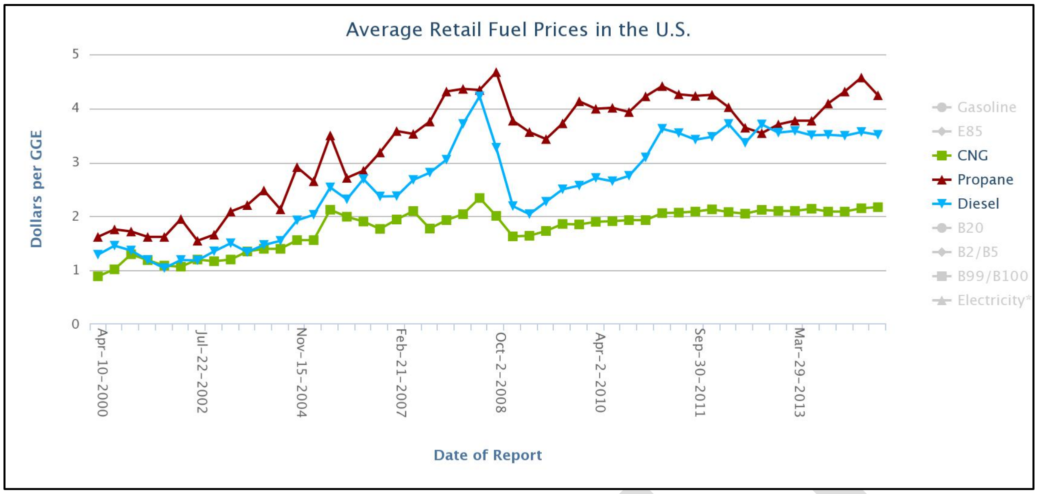


Figure III.F-2: Average Retail Fuel Prices in the US (AFDC, 2014h)

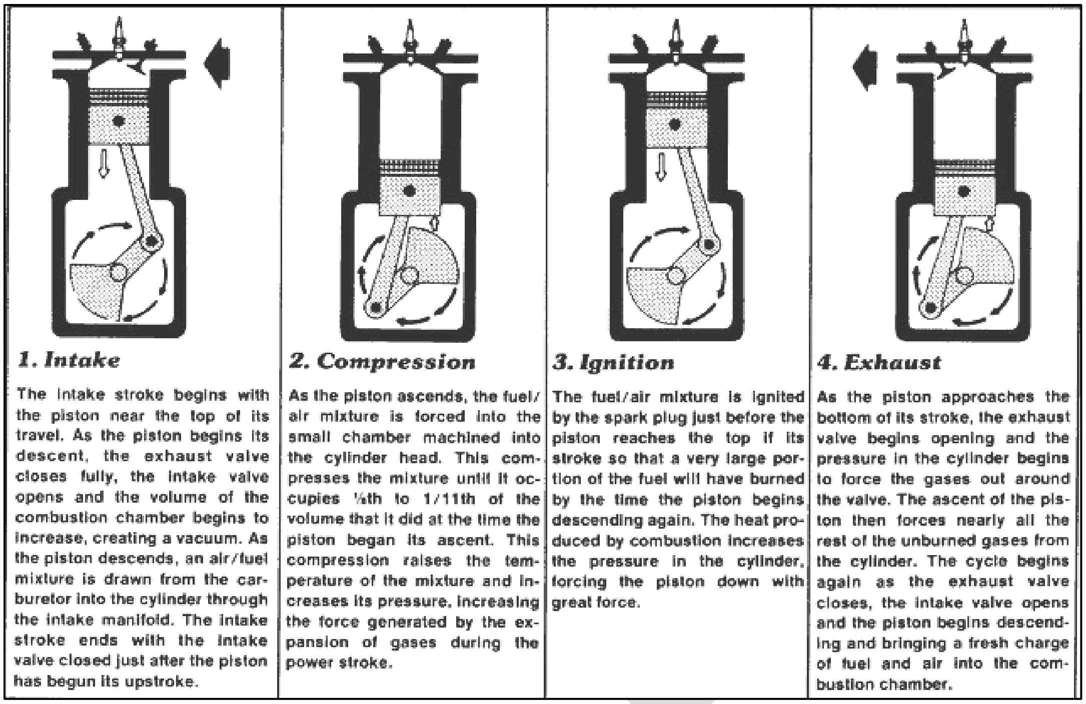
CNG is pipeline natural gas compressed to high pressures in the order of 3,000 to 3,600 psig. At this pressure the volume of the natural gas is 3.5 times the volume of diesel containing the equivalent energy. (AGA, 2013)

LNG is produced by purifying natural gas and super-cooling it to -260°F to turn it into a liquid. Because it must be kept at cold temperatures, LNG is stored in double-walled, vacuum-insulated pressure vessels. LNG is good for trucks needing a longer range because liquid is more dense than gas (CNG) and, therefore, more energy can be stored by volume in a given tank. (AFDC, 2014a)

Propane is a gas that can be turned into a liquid at a moderate pressure, 160 pounds per square inch (psi), and is stored in pressure tanks at about 200 psi at 100°F. When propane is drawn from a tank, it changes to a gas before it is burned in an engine. (CEC, 2014)

<u>Engines</u>

Alternative fueled engines come in three general configurations: dedicated spark ignition, dual fuel pilot injection, and aftermarket conversion kits. Dedicated spark ignition engines function by mixing the fuel vapor with air, before introducing it into the combustion chamber during the intake stroke as shown in Figure III.F-3 (next page). The fuel-air mixture is then compressed (during the compression stroke) and ignited via spark plugs to generate the energy to drive the rotary components (during the power stroke). The cycle resets in the exhaust stroke to expel the exhaust from the cylinders before the next intake stroke draws in a fresh fuel air mixture.


1. Intake

The intake stroke begins with the piston near the top of its travel. As the piston begins its descent, the exhaust valve closes fully, the intake valve opens and the volume of the combustion chamber begins to increase, creating a vacuum. As the piston descends, an air/fuel mixture is drawn from the carburetor into the cylinder through the intake manifold. The intake stroke ends with the intake valve closed just after the piston has begun its upstroke.

2. Compression

As the piston ascends, the fuel/air mixture is forced into the small chamber machined into the cylinder head. This compresses the mixture until it occupies ⅛th to 1/11th of the volume that it did at the time the piston began its ascent. This compression raises the temperature of the mixture and increases its pressure, increasing the force generated by the expansion of gases during the power stroke.

3. Ignition

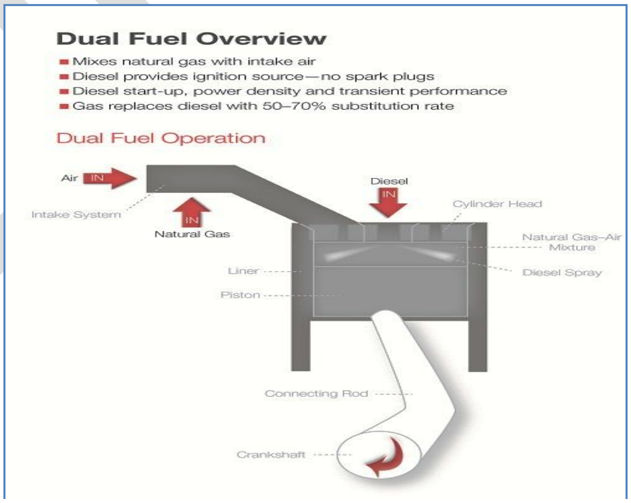
The fuel/air mixture is ignited by the spark plug just before the piston reaches the top if its stroke so that a very large portion of the fuel will have burned by the time the piston begins descending again. The heat produced by combustion increases the pressure in the cylinder, forcing the piston down with great force.

4. Exhaust

As the piston approaches the bottom of its stroke, the exhaust valve begins opening and the pressure in the cylinder begins to force the gases out around the valve. The ascent of the piston then forces nearly all the rest of the unburned gases from the cylinder. The cycle begins again as the exhaust valve closes, the intake valve opens and the piston begins descending and bringing a fresh charge of fuel and air into the combustion chamber.

Figure III.F-3: How Spark Ignition Engines Work (ProCarCare, 2014)

Dual-fuel pilot injection uses a small amount of diesel fuel and high compression to ignite the compressed natural gas that is fumigated into the cylinder during the intake cycle as shown in Figure III.F-4. It has the flexibility to switch between different fuel types by use of a solenoid valve. A critical parameter for dual-fuel operation is the substitution rate, which is defined as the fraction of the total fuel energy that is provided by the natural gas. Substitution rates vary by load. A limitation to dual-fuel systems is the need to carry additional storage tanks for different fuels, which may reduce payload space and increase vehicle/trailer weight, impacting fuel consumption and payload weight capacity.


Dual Fuel Overview

- Mixes natural gas with intake air
- Diesel provides ignition source—no spark plugs
- Diesel start-up, power density and transient performance
- Gas replaces diesel with 50–70% substitution rate

Figure III.F-4: Dual-Fuel Engine Schematic (Cummins Dual Fuel)

Aftermarket conversions are commercially available for in-use engines and their use in TRUs may be near. Aftermarket conversions include more components such as carburetors, vaporizers, and solenoid valves to be able to either switch between fuel types or to accommodate gaseous components in an otherwise liquid fuel based system. Figure III.F-5 shows some of these components.

Figure III.F-5: Diesel to CNG Conversion Kit (CNG United™)

Much data on natural gas combustion comes from heavy duty applications, and may not necessarily translate linearly to smaller engine sizes. There is also a lack of data documenting the ability of alternate fueled engines that could meet the TRU duty cycles.

North American Repower (NAR) has conducted preliminary tests on a 2 liter Yanmar model year 2013 engine (engine family DYDXL2.19NFA >25 hp rating) that was rebuilt to a dedicated CNG platform. They reported significant criteria emissions reductions for NOx, PM, CO, and NMHC, but did not provide any data to confirm these results. NAR plans to conduct further testing in 2015 to measure methane emission reductions, as well as three-way catalyst testing under stoichiometric/lean variable operation to see if further NOx reductions are possible with this engine. (Reed, 2014c)

<u>On-board storage tanks</u>

The discussion on alternative fuels warrants an assessment of the on-board fuel storage considerations due to the gaseous nature of CNG. CNG is typically stored in steel or composite containers at high pressure (3,000 to 4,000 psi) but typically at ambient temperature. There are four types of cylinders, ranging from “Type 1” to “Type 4”, with Type 1 being all steel with no wrappings (the cheapest and heaviest) to Type 4 being made of lighter metals with complete external wrappings and internal liners (also the most expensive and the lightest). (Gambone, 2005)

LNG storage pressures are typically around 50 to 150 psi. Storage temperatures may vary due to varying composition and storage pressure. LNG is far denser than even the highly compressed state of CNG. As a consequence of the low temperatures, vacuum insulated storage tanks, typically made of stainless steel, are used to store LNG.

Fueling Facilities

CNG, LNG, and LPG fueling stations come in several configurations with some components unique to the fuel type. LNG stations come in liquid-to-liquid and liquid-to-gas/CNG configurations.

CNG Fueling Infrastructure

CNG stations come in four types: cascade fast-fill, buffer fast-fill, time-fill, and combination-fill. At this point in time, there is little information available on the actual physical footprint these facilities would occupy. Further research on this topic may be needed.

Cascade fast-fill is the most common type in North America. CNG storage vessels arranged in cascades, or banks, are used to quickly fill vehicles during peak fueling times, when the compressors alone cannot meet demand. Figure III.F-6 shows a fast-fill station schematic.

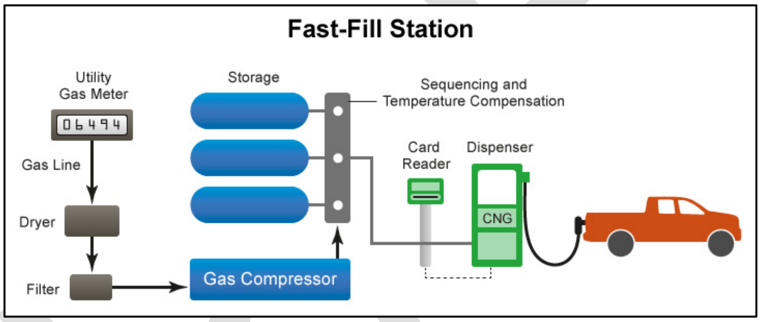


Figure III.F-6: CNG Fast-Fill Station Schematic (AGA, 2013)

Buffer fast-fill is ideal for high fuel use vehicles that require immediate refueling, one after another. Buffer systems primarily fuel directly from the compressor into the vehicle and therefore require a smaller quantity of storage.

Time-fill stations provide fuel to the vehicle directly from the compressor and are ideal for fleets that return to a central location for an extended period of time. They have significantly lower equipment and installation costs because they do not require storage, priority, or sequential refueling components. Figure III.F-7 (next page) shows a time-fill station schematic.

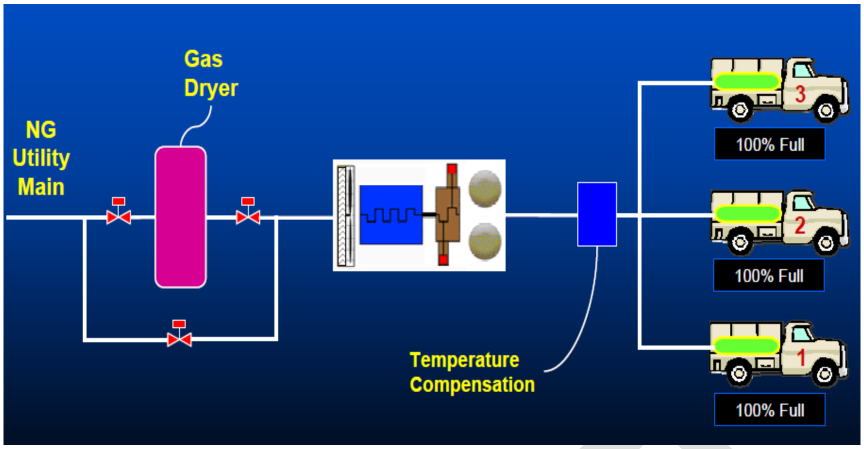


Figure III.F-7: CNG Time-Fill Station Schematic (AGA, 2013)

Combination-fill stations use both fast-fill and time-fill technology to accommodate both fueling types for operational flexibility.

All four station types share key components such as:

- Inlet dryers and filters to remove water vapor and foreign particulates from the gas and dry it to a pressure dew point;
- Compressors to draw natural gas from the utility pipeline and compress it for storage;
- High pressure storage tanks (this differential pressure is used to transfer the gas from the cascade into the vehicle); and
- Sequence priority valves to divert the gas from the compressor to the storage tank.

LNG Infrastructure

LNG stations come in two types, liquid-to-liquid and liquid-to-gas.

Liquid-to-liquid is the typical LNG station design, where the fuel passes through a pump to an ambient air vaporizer that serves as a heat exchanger. In this vaporizer, the temperature of the LNG is increased to approximately 40°F. The pressure also increases, but the fuel remains a liquid. This process is called “conditioning.” After conditioning, LNG is stored in large cryogenic vessels either above or underground. Figure III.F-8 (next page) shows a liquid-to-liquid LNG station schematic.

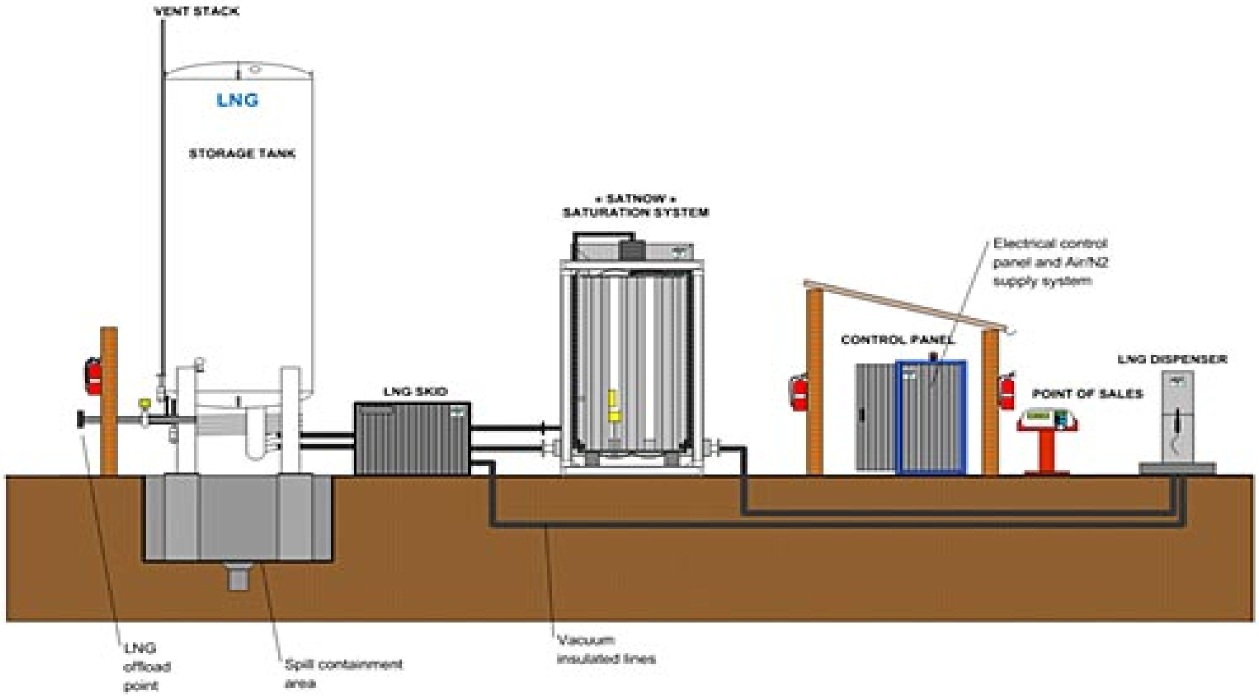


Figure III.F-8: Liquid to Liquid LNG Station Schematic (ANGA, 2013)

Liquid-to-gas is also known as liquid-to-CNG (LCNG) is a variation of the LNG station which uses LNG to make CNG. Some LCNG stations can dispense both CNG and LNG, while others are dedicated LNG dispensers. LCNG stations receive and store truck-delivered LNG, which is pumped to high pressures and vaporized to fuel CNG vehicles. LCNG capability is typically an inexpensive addition to LNG stations. Figure III.F-9 shows a liquid-to-gas station schematic.

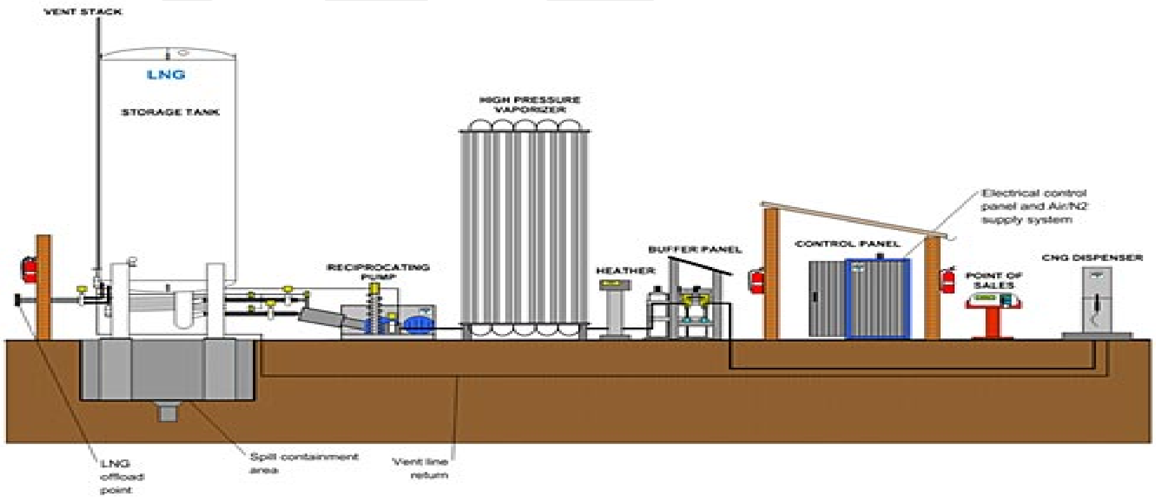


Figure III.F-9: Liquid to Gas Station Schematic (ANGA, 2013)

Both station types share key components such as:

- Cryogenic pumps which transfer the LNG from storage tanks to dispenser;
- Controls for line and buffer pressures, valves, and vaporizer; and
- A cryogenic dispenser, which allows users to choose between cold, saturated, and super saturated fuel at the dispenser as well as possessing total boil-off gas recovery.

LPG Infrastructure

Figure III.F-10 shows a propane station schematic.

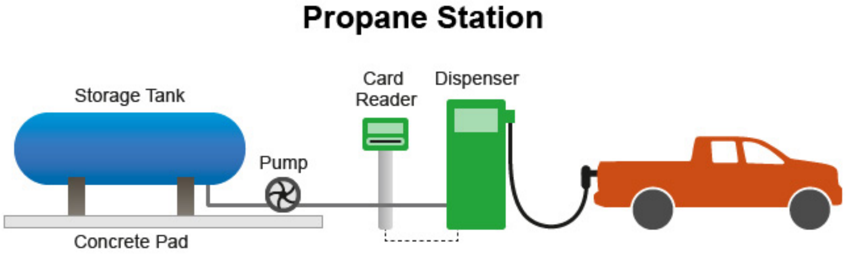


Figure III.F-10: Propane Fueling Station Layout (AFDC, 2014b)

Unlike LNG and CNG, propane fueling infrastructure is very similar to gasoline and diesel refueling equipment. Propane is brought to the site via a transport truck and put into onsite storage, traditionally above ground. The fueling dispenser is similar to a gasoline dispenser. The main difference is that propane is delivered to the vehicle under pressure at 150 to 200 psi so it remains a liquid.

TRU Alternative Fuels – Advantages and Disadvantages

Table III.F-1 (next page) summarizes the advantages and disadvantages between the three alternative fuels. The common issues revolve around emissions, operational range, and fueling infrastructure.

Table III.F-1: Advantages and Disadvantages of Each Alternative Fuel Type

Fuel	Advantages	Disadvantages
CNG	Can store in tank indefinitely without boil off concerns (unlike LNG).	CNG tanks take up considerable space and add weight. Low operating range when compared on a volumetric basis with other liquid fuels.
LNG	Liquefied state offers an energy density that extends range and reducing refueling frequency. Faster fills due to liquefied nature.	High cost of cryogenic storage. LNG vaporization in tank is inevitable, resulting in boil-off and fuel loss from the tanks. Active management of boiled off gas needed. Fueling infrastructure not nearly as widespread as CNG and LPG.
LPG	Requires far less compression (20 percent of CNG cost) and is a liquid at room temperature, which lowers tank and compressor costs. Requires no chilling (and thus less energy) and avoids problems associated with extremely cold surfaces, such as thermal injury to unprotected skin (frostbite).	LPG can vary widely in composition, leading to variable engine performance and cold starting performance.

2. Technology Readiness

Although CNG and LNG engines exist in the market, they are typically larger engines built for tractor or facility power applications. Few alternate fueled engines in the 25 horsepower (HP) engine category exist in the market, with Kubota’s DG 23.6 hp natural gas and WG dual fuel engines being the exception. Other manufacturers, such as Lister Petter, have propane-fueled engines in this size range (such as the LPWG series), but have limited experience building engines optimized for TRU applications. (Nunez, 2014)

Engine manufacturers have indicated to staff a willingness to conduct prototype demonstrations sometime in 2015. Anticipated project demonstrations are summarized below in Table III.F-2, as well as efforts by natural gas fueling station operators such as Blu, Amp Trillium, and Clean Energy Fuels Corporation to expand the fueling network.

Table III.F-2: Planned Demonstration Projects and Infrastructure Expansion

Organization	Fuel	Application	Milestones
Amp Trillium	CNG	Infrastructure	Opened a CNG fueling station in Waco, Texas, as the first of seven stations planned as part of an agreement with Dairy Farmers of America and Select Milk Producers to convert part of their diesel fleets to CNG. (Transport Topics, 2014c)
Clean Energy Fuels Corporation	CNG	Infrastructure	Opened fueling stations in New Mexico and Arizona as part of its America's Natural Gas Highway Network. As part of the agreement, Seaboard Transport has deployed 58 HD CNG trucks that will fuel at Clean Energy stations in nine states. (Transport Topics, 2014b)
CR England	LNG	Engines	Field test 10 (potentially up to 60) tractor units by end of 2014
CR England	LNG	Infrastructure	Signed multi-year bulk fueling agreement with Shell in February 2014
Kohler Engines	CNG LPG	Engines	2015 Field Demo Start on TRUs. 2-year period before reevaluating feasibility
Kwik Trip	CNG	Engines	Currently in negotiations with Thermo King and Carrier Transicold advocating demonstrations
NAR	CNG	Engines	There are further plans to begin testing oxidative catalyst testing for methane emission reductions, as well as TWC testing under stoichiometric/lean variable operation to see if they can further reduce NOx in this engine.
Blu	LNG	Infrastructure	Launched first US system to recapture boil-off gas from storage tanks and return it to the pipeline (Transport Topics 2014d)
Raven Transport	LNG	Infrastructure	Expanded fueling agreement by deploying 33 more LNG trucks to serve South East U.S. (Transport Topics, 2014e)

The natural gas fueling station network is already in operation. Currently, LPG and CNG stations are more prevalent than LNG fueling stations. Figure III.F-11 (next page) shows CNG (blue dots) is more prevalent than LNG (red dots) on the map from the Department of Energy's Alternative Fuels Data Center (DOE-AFDC). These are publicly accessible CNG and LNG stations that are accessible to Class 8 heavy duty (HD) vehicles. Updated maps with the most current information were not available at time of publication of this report, but the map shown below does give the reader a sense of the distribution of fueling stations and where the gaps are located.

Figure III.F-11: Department of Energy Alternative Fuels Data Center Public CNG and LNG Fueling Station Infrastructure Nationwide (AFDC, 2014)

Table III.F-3 provides further breakdown of CNG and LNG refueling stations in the U.S. that are accessible to Class 8 HD vehicles. (AFDC, 2015a; AFDC, 2015b)

Table III.F–3: Class 8 HD Vehicle Accessible CNG and LNG Refueling Stations

Heavy-Duty Accessible (Class 1 to 8)		Open stations		Planned Stations	
		Nationwide	California	Nationwide	California
CNG	Total	1039	207	144	15
	Publicly Accessible	591	102	101	6
	Private	448	105	43	9
LNG	Total	109	44	69	2
	Publicly Accessible	73	15	68	1
	Private	37	29	1	1

Table Note: Current as of April 21, 2015.

As Table III.F-3 indicates, there are about 591 CNG and 73 LNG currently open public fueling stations that can accommodate all classes of vehicles, including Class 8 Heavy Duty Vehicles distributed across the US. In California, there are 102 public CNG stations currently open that can accommodate heavy duty vehicles and 15 LNG stations. There are six more planned public CNG stations in California one additional LNG station planned that can accommodate for Class 8 vehicles. (AFDC, 2015a; AFDC, 2015b)

For LPG fueling stations, DOE-AFDC does not have data for LPG that distinguishes whether Class 8 HD vehicles can access the stations in this database. However, it is staffs' understanding that very few, if any, LPG stations are configured for Class 8 HD vehicles. There are 2,818 LPG stations accessible to the public in the U.S., with 233 of these located in California. There are also 263 private LPG stations in the U.S., with 16 of these located in California. An additional 12 publicly accessible LPG stations are planned for the U.S, one of these is in California. (AFDC, 2015c)

Staff believes CNG, LNG, and LPG may apply best to fleets that typically refuel at their home terminals or distribution centers before daily dispatch on local and regional routes. Long-haul carriers need larger tanks (or multiple tanks) or increased numbers of fueling stations distributed between destinations in order to be viable.

3. Economics

Facility Construction and Modification Costs

According to the American Gas Association, the American Natural Gas Alliance, and the Department of Energy, CNG station costs can range from $800,000 to over $1.8 million (AGA, 2013). The estimated cost of a large fleet LNG station with dispensing capacity of 4 to 20 million diesel gallons equivalent (DGE) per year ranges from $2.25 to $7.5 million (ANGA, 2013). LPG station costs run from $37,000 to $175,000 (AFDC, 2014b).

Equipment Costs and Payback Periods

At this time, the capital and operational costs of alternative fueled engines are somewhat uncertain. However, since NAR has participated in small scale testing of rebuilt CNG engines (Reed, 2014a), as well as the proposed demonstrations described above, it seems likely there is still an interest in exploring the potential emissions benefits of alternative fueled TRU engines. There is also a consideration for the economic benefit of harmonizing the maintenance and fueling facilities to accommodate for only one fuel type for both the truck tractor and TRU, if fleets convert their tractors to an alternative fuel. In that case, the cost of fueling infrastructure could be spread across more pieces of equipment, improving the economics.

According to NAR, the cost of converting a diesel TRU engine into a spark ignition CNG-fueled engine ranges from $9,000 to $15,000, including the fuel tank and labor. CNG fuel tanks are a significant portion of the conversion cost (e.g. $6,000 tank cost for trailer conversion, including plumbing and covers). (Reed, 2014b) Other engine manufacturers and fleet operators have been hesitant (or did not have the data) to disclose to staff the natural gas engine capital expenditure and operational costs because they consider this proprietary information. There was consensus that the maintenance and criteria emissions of alternative fueled TRU engines should be less due to the reduction in moving parts (Brown, 2014; Hudak, 2014; Kruse 2014). There should be better clarity on costs after the proposed demonstration projects are completed near the end of 2015.

4. Emissions Reductions Estimates

GHG Emissions

Staff conducted Well-to-Tank (WTT) and Tank-to-Wheels (TTW) emission rate analyses. Combining WTT and TTW emission rates results in the Well-to-Wheels (WTW) emission rate. The methane leakage issue discussed in ARB's *Technology Assessment: Fuels Assessment* creates some uncertainty with respect to WTT emissions for CNG and LNG. ARB used a 1.08 percent methane leakage rate in its carbon intensity (CI) calculations under the Low Carbon fuel Standard (LCFS).

Staff estimated the energy use rates, based on fuel use rates for conventional 2015 diesel-fueled TRUs and TRU gensets. The energy usage rate for CNG engines was increased 8 percent to account for differences in combustion efficiency resulting from lower compression ratio of the CNG engine. (Reed, 2014b) LNG engine energy consumption can be assumed to be similar to CNG since LNG is vaporized into natural gas before fumigation into the engine combustion chamber (Reed 2014d).

Appendix III.F-1 shows the calculations for GHG emission rate estimates for hypothetical CNG and LNG TRs. There are no requirements under the Low Carbon Fuel Standard to reduce the carbon intensity of natural gas used to produce CNG and LNG. Without any renewable natural gas helping to reduce the CI values, the GHG emissions are greater and the GHG reductions compared to conventional diesel-fueled TRUs are smaller. Table III.F-4 (below) displays the WTT, TTW, and WTW GHG emission rates on a per-unit basis for CNG-fueled and LNG-fueled truck and trailer TRs.

Table III.F-4: GHG Emission Rates for CNG and LNG TRs

	CNG		**LNG**	
	Truck TR (kg/hr Co$_2$e)	**Trailer TR (kg/hr Co$_2$e)**	**TruckTR (kg/hr Co$_2$e)**	**Trailer TR (kg/hr Co$_2$e)**
WTT	1.54	2.05	2.06	2.74
TTW	5.28	7.04	5.30	7.04
WTW	**6.82**	**9.09**	**7.36**	**9.81**

Appendix III.A-2 shows the calculations for the GHG emission rates from 2015 conventional diesel truck and trailer TRUs fueled with diesel fuel available in 2015, and 2020 and beyond (as required under ARB's Low Carbon Fuel Standard). Table III.F-5 displays the WTT, TTW, and WTW GHG per-unit emission rates for conventional diesel TRUs fueled with 2015 and 2020 and beyond diesel fuels.

Table III.F-5: GHG Emission Rates for Conventional TRs Fueled with 2015 Fuel and 2020+ Fuel

	Conventional TRU 2015 Fuel		Conventional TRU 2020+ Fuel	
	Truck TR (kg/hr Co_2e)	Trailer TR (kg/hr Co_2e)	TruckTR (kg/hr Co_2e)	Trailer TR (kg/hr Co_2e)
WTT	2.20	2.93	1.37	1.83
TTW	6.06	8.08	6.06	8.08
WTW	**8.26**	**11.01**	**7.43**	**9.91**

The GHG emission rate percent reductions for CNG- and LNG-fueled truck and trailer TRs, compared to appropriate conventional diesel TRUs fueled with 2015 and 2020+ fuels, are displayed in Table III.F-6 (below). For example, the emission reduction for a CNG truck TR compared to a conventional diesel TRU fueled with 2020+ fuel would be 8 percent (((7.43 – 6.82)/7.43)*100 = 8 percent).

Table III.F-6: GHG WTW Emission Rate Reductions - CNG and LNG TRs Fueled with 2020+ Fuels Compared to Conventional TRUs Fueled with 2015 and 2020+ Fuels

TRU Type	2015 Fuel	2020+ Fuel
CNG Truck	17%	8%
CNG Trailer	17%	8%
LNG Truck	11%	<1%
LNG Trailer	11%	1%

LNG appears to be less attractive than CNG for GHG reductions, especially for the truck TR, which was dropped from further consideration. At this point in time, agency-approved carbon intensity factors needed to complete the WTT and TTW analysis for LPG-fueled TRs are unavailable.

Criteria Pollutant Emissions

Appendix III.F-1 includes the detailed assumptions and calculations for criteria pollutant emission rates for CNG- and LNG-fueled TRs. TTW criteria pollutant emission rates for NMHC+NO_x and PM are compared in Table III.F-8.

Table III.F-7: CNG/LNG Fueled TRs -
TTW Criteria Pollutant Emission Rate Comparisons

Equipment Type	NMHC+NO_x (g/hr)	PM (g/hr)	Total CP (g/hr)	Percent Reduction
Conventional Trailer TRU	57.5	1.23	58.73	-
Conventional Truck TRU	37.9	0.79	38.69	-
CNG/LNG Trailer TR	51.67	NA[1]	51.67	12%
CNG/LNG Truck TR	28.99	NA	28.99	25%

Note 1: "NA" means TTW emission factor "Not Available" for PM, but assumed to be small compared to NMHC+NO_x

From the above table, criteria pollutant emission rate reductions for CNG/LNG are 12 percent for the trailer case and 25 percent for the truck case. Again, the methane leakage issue casts some uncertainty on the actual emission rate reductions.

5. Key Performance Parameter Issues and Deployment Challenges

Based on currently available information, staff expects alternative fueled transport refrigerators will be limited to use by return-to-base fleets because of the limited range caused by fuel tank weight and space limitations and lower energy density of alternative fuels compared to diesel. Although CNG and LPG fueling stations are currently more widely available than LNG, they are largely restricted to high population urban centers and many are not configured for use by Class 8 semi-trailers. This may change with time.

As with any fuel, safety and durability are a concern that needs to be managed. All facilities need to meet electrical, ventilation, early detection, and isolation standards that apply to these alternative fuels. The lack of harmonized codes and standards across international jurisdictions may be an additional barrier to market penetration.
(Fortis BC, 2013)

Oxidation and nitration of the lubricating oil may cause durability issues (Pipeline and Gas Journal, 2009; Powermag, 2010).

Alternative fuel engine lab tests and field demonstrations are needed to demonstrate duty cycle compatibility, durability, and reliability with the TRU application before natural gas and propane could be considered for widespread adoption in TRUs. NAR's demonstration of a retrofitted TRU engine to CNG in 2015 (see discussion in Technology Readiness, above) may help address some of the key performance parameter issues.

Finally, the issue of methane leakage is a deployment challenge that must be addressed. More detailed discussion is provided in the *Technology Assessment: Fuels Assessment* document.

G. Advanced Power Plant – Homogeneous Charge Compression Ignition (HCCI)

1. Introduction

As the standards for emissions from off-road diesel become more stringent, alternatives to traditional combustion must be researched to reduce emissions in-cylinder. Current (2014) Tier 4 emissions standards for NO_X+NMHC for off-road compression ignition engines are 7.5 g/kW-hr for less than 19 kW engines, and 4.7 g/kW-hr for engines between 19 and 37 kW. Similarly, particulate emissions standards are 0.40 g/kW-hr and 0.03 g/kW-hr for these power rating ranges, respectively. Advanced combustion cycles using HCCI may offer even further reductions in these criteria pollutants. The primary attraction for diesel HCCI is the potential for low NOx and PM without the need for aftertreatment catalysts.

2. Technology Description

Homogeneous charge compression ignition initiates combustion simultaneously at multiple sites within the combustion chamber (Stanglmaier, 1999) rather than along a flame front. (Epping, 2002) Operation of an HCCI engine is restricted to low engine speeds and torques due to knock and misfire limits. (Shibata, 2012) Methods to control HCCI combustion has been a subject of current research, and is still in the bench phase of research and development. However, HCCI may be well suited to the un-throttled small-scale engines found in TRUs. (Therkelsen, 2014, Therkelsen, 2014a)

Small-scale engine operation does require modification from original engine design in order to be effective. Current conventional engine designs maximize heat loss for thermal efficiency, which is in stark contrast to the requirements for sustained HCCI operation. Benchmark test data was gathered using a spark ignition (SI) engine. Cold start HCCI tests showed poorly timed auto-ignition events. The load-speed range of the engine was limited due to high rates of heat loss through high heat flux aluminum parts. Lean fuel-air mixtures are also problematic with HCCI. A near adiabatic ceramic engine design, coupled with a higher compression ratio, may allow the use of leaner fuel-air ratios to improve energy efficiency in small scale HCCI engines. (Therkelsen, 2011b)

A combination of very lean fuel mixtures and low load conditions are necessary to reduce emissions with HCCI. There is a trade-off with NOx and PM emissions in exchange for much higher hydrocarbon and carbon monoxide emissions. Heated air intake and high cetane diesel fuel helps to ensure a more homogenous charge. (Zhao et al., 2003)

Early studies of HCCI phased fuel injection to 80 degrees before top dead center (TDC) to obtain a premixed lean charge. The results of this phasing obtained a dramatic reduction of NOx from 400 ppm (conventional injection) to 20 ppm at the same excess air ratio. (Takeda et al., 1996)

Noteworthy strategies to extend HCCI speed-load range are explored below. Given the scope of time related to this assessment, not all possibilities for the extension of HCCI to broader loads were explored. Assessments of these findings are summarized in the Key Performance Parameters and Deployment Challenges section (see below) as they are applicable to the TRU application.

Strategies to Control HCCI Using Multi Fuel Mixtures and Additives

Auto-ignition control of the fuel/air mixture is imperative to the successful operation of an HCCI engine. The thermal conditions in-cylinder and composition of the charge at the time of auto-ignition must be correct to control the tendency for misfire and engine knock. One method to control HCCI combustion is through the fuel composition, where the fuel reactivity determines the heat release for auto-ignition. Fuels with high octane ratings require much higher compression ratios for HCCI operation. Therefore, fuel additives used in diesel fuel to increase cetane rating can also be used in gasoline or alternative fuels. (Zhao et al., 2003)

The intrinsic properties of fuel flexibility with HCCI gives a distinct advantage over traditional CI engines, where only the operating characteristics of the engine can be altered to accommodate the fuel used.

Experiments with primary reference fuels (PRFs, iso-octane and n-heptane) suggest it is possible to control HCCI by varying the reactivity. The operating envelopes for higher octane ratings allowed the engine to operate at higher fuel/air ratios and produce more work. Specifically, the range of the PRF60 fuel was extended into a region where a higher reactivity fuel PRF40 could operate. Higher octane fuels operating in HCCI would require additional energy supplied by means of intake heating, but could operate much leaner as a consequence. This could improve fuel economy, while delivering the same amount of power.

Intake air heating has been used to complement the dual fuel approach for HCCI operation at low loads, making leaner mixtures possible over an extended operating range.

Dimethyl ether (DME) has been shown to combust readily in an HCCI engine. The high cetane rating causes advanced DME ignition, but requires a narrow envelope of operation. (Zhao et al., 2003)

Studies with a methanol-reformed gas (MRG) and DME mixtures have been performed in a HCCI engine to increase thermal efficiency of the engine. Larger ratios of MRG retards the second stage heat release and can control the ignition timing to extend the range of operation. Increases in compression ratio also advance the timing of the heat release. Thermal efficiencies appear to be greater with lower compression ratios. Higher compression ratios cause a smaller value of cumulative apparent heat release per unit of fuel supplied in a cycle. When paired with an optimum compression ratio of

9.7, thermal efficiency is comparable to SI combustion using MRG under lean mixture conditions. (Shudo, 2002)

DME combustion has been shown to extend the HCCI operation range when used with other controls such as EGR. DME is used to broaden the operating range by combining the low temperature heat release (LTHR) intrinsic to DME with that of ethanol, which generates strong LTHR inhibitor effects. EGR is used to promote low temperature combustion over speed-load operational ranges. Using mixtures of fuels to contain the low temperature heat release such as ethanol can extend the range of operation of DME HCCI combustion. Using these mixtures, a thermal efficiency close to SI can be obtained with the complete combustion of both fuels. (Shibata, 2012)

Using gasoline as a pilot fuel for HCCI, CNG can be direct injected to the combustion chamber and provide the benefits of CNG combustion while using gasoline to create the homogeneous charge to produce significant reductions in energy consumption using HCCI as an alternative to SI combustion. The conversion from spark ignition direct injection (SIDI) to HCCI direct injection (HCCIDI) was shown to require minor modifications in a single cylinder test engine and demonstrated improvement for fuel consumption.
Figure III.G-1 shows the indicated specific energy consumption (ISEC) for HCCIDI is roughly 25 to 30 percent less than for SIDI at speeds between 1200 to 2100 rpm. (Noran, 2011)

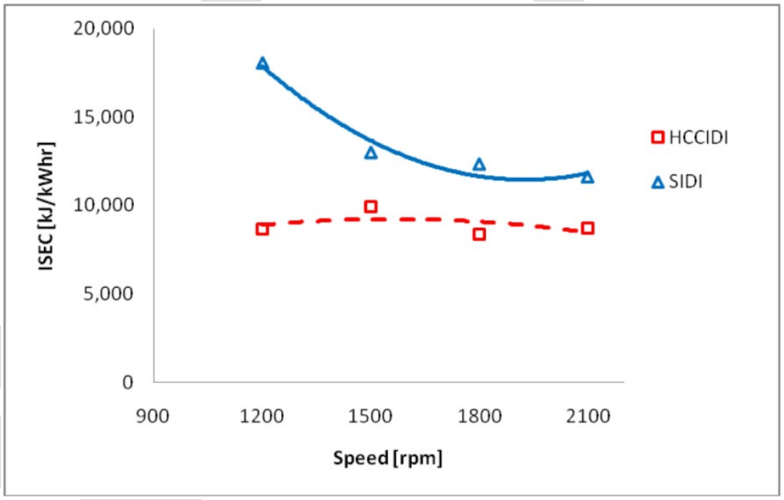


Figure III.G-1: Specific Energy Consumption Savings Using HCCIDI (Noran, 2011)

<u>Range extension of HCCI via SACI</u>

The limited speed-load range of HCCI must be extended for commercial engines to be viable. Combining stoichiometric SI combustion using gasoline at high loads, lean burn spark-assisted compression ignition (SACI) and HCCI at intermediate to low loads maintained efficiency and produced low emissions. SACI was able to bridge engine operation between HCCI to traditional SI operation regimes, but at the cost of increased NOx emissions at high load SACI conditions. (Manofsky, 2011)

3. Technology Readiness

HCCI technology is still very much in the bench phase of research and development. Lawrence Berkeley National Labs (LBNL) is currently working to produce a proof-of-concept for cost-effective HCCI retrofit for TRU engines that meet Tier 4 Final emissions standards. As of September 11, 2014, an R&D project has been awarded an LBNL Lab Directed Research and Development grant. The funds from this grant are to be used to establish a small-scale engine research and development facility to convert a diesel engine from traditional compression ignition to HCCI to serve as a proof-of-concept for HCCI TRU engines. (Therkelsen, 2014c)

4. Emissions Reductions

Emissions from an HCCI engine have been explored in research grade engines (bench scale testing) whose operating conditions do not match commercial engine conditions for certification. Therefore, information from emissions data collected from publications can only offer an indication of the emissions profile of HCCI emissions. Until there is an operational prototype utilizing HCCI under load conditions similar to TRU operation, a comparison cannot be drawn.

5. Key Performance Parameter Issues and Deployment Challenges

Due to the specialized focus on duty cycle and size of TRU engines, outside of the research engine size, research is very sparse with similar power-producing engines. It is well understood that HCCI is a part-load operation strategy, and the steady-operating conditions found in TRUs is suitable for HCCI operation.

As explored above, HCCI allows for large variations in the fuel used for combustion. The combustion of these fuels all depended on a heated air intake to raise in-cylinder temperatures for HCCI operation. To be successful, commercial HCCI will need to overcome the issue with cold starts, as well as address the temperature variation across California.

Future laboratory testing for HCCI using typical operating conditions should be explored at another time as currently there is a lack of information. Such lab testing will confirm or deny the feasibility of HCCI for TRUs and the potential for future demonstrations.

HCCI emissions have been documented to be lower when compared to the standard combustion modes DI and SI. However, research publications that focus specifically on emissions were not extensively found during this technology assessment. A one-to-one comparison with current TRU diesel engines cannot be made as the operating conditions for certification and as found in publications are radically different. Research material is created annually for HCCI, and it can be considered a technology on a path towards pre-commercialization. Further refinement of existing engine design and pre-commercial demonstrations need to be completed before HCCI can be properly compared to current diesel engines. However, HCCI potentially offers a decrease in tailpipe emissions and should continue to be researched as a means of lowering emissions across all horsepower ranges.

H. Well-to-Wheels GHG Emission Rate Comparison

On a per-unit basis, staff evaluated the Well-to-Tank (WTT) and Tank-to-Wheels (TTW) GHG emissions for each technology using 2020+ fuels. Combining WTT and TTW results in Well-to-Wheels (WTW) GHG emissions. The baseline cases (new conventional 2015 truck or trailer TRUs fueled by 2015 fuel) are shown in the first two rows. Select TR technologies are then compared to the baseline cases as a percent reduction (right column). The WTW GHG emissions comparisons are displayed in Table III.H-1.

Table III.H-1:
WTW GHG Emission Rate Comparisons of TR Technologies (2020+ Fuel) to Baseline Conventional 2015 TRUs (2015 Fuel)

	GHG Emission Rate (kg/hr)			WTW Percent Reduction[1]
Equipment Type	WTT	TTW	WTW	
Conventional 2015 Trailer TRU, 2015 Fuel (Baseline)	2.93	8.08	11.01	N.A.
Conventional 2015 Truck TRU, 2015 Fuel (Baseline)	2.20	6.06	8.26	N.A.
All-Electric Plug-in/Battery/Solar Trailer TR	1.24	0	1.24	89%
All-Electric Cold Plate Truck TR	1.73	0	1.73	79%
All-Electric H2 Fuel Cell Trailer TR	4.24	0	4.24	61%
Cryogenic Trailer TR	4.5	0	4.5	59%
All-Electric Plug-in/Battery/Generator Truck TR	0.654	2.89	3.54	57%
CNG Truck TR	1.54	5.28	6.82	17%
CNG Trailer TR	2.05	7.04	9.09	17%
LNG Trailer TR	2.74	7.07	9.81	11%

Note 1. Comparisons are made to conventional truck TRU or conventional trailer TRU, as applicable.

Figure III.H-1 (next page) shows Table III.H-1 WTT and TTW GHG emission rates stacked up for the total WTW GHG emission rate to compare the baseline cases (new conventional 2015 TRUs fueled by 2015 fuel, on the left) to select TR technologies fueled by the fuels available in 2020 and beyond.

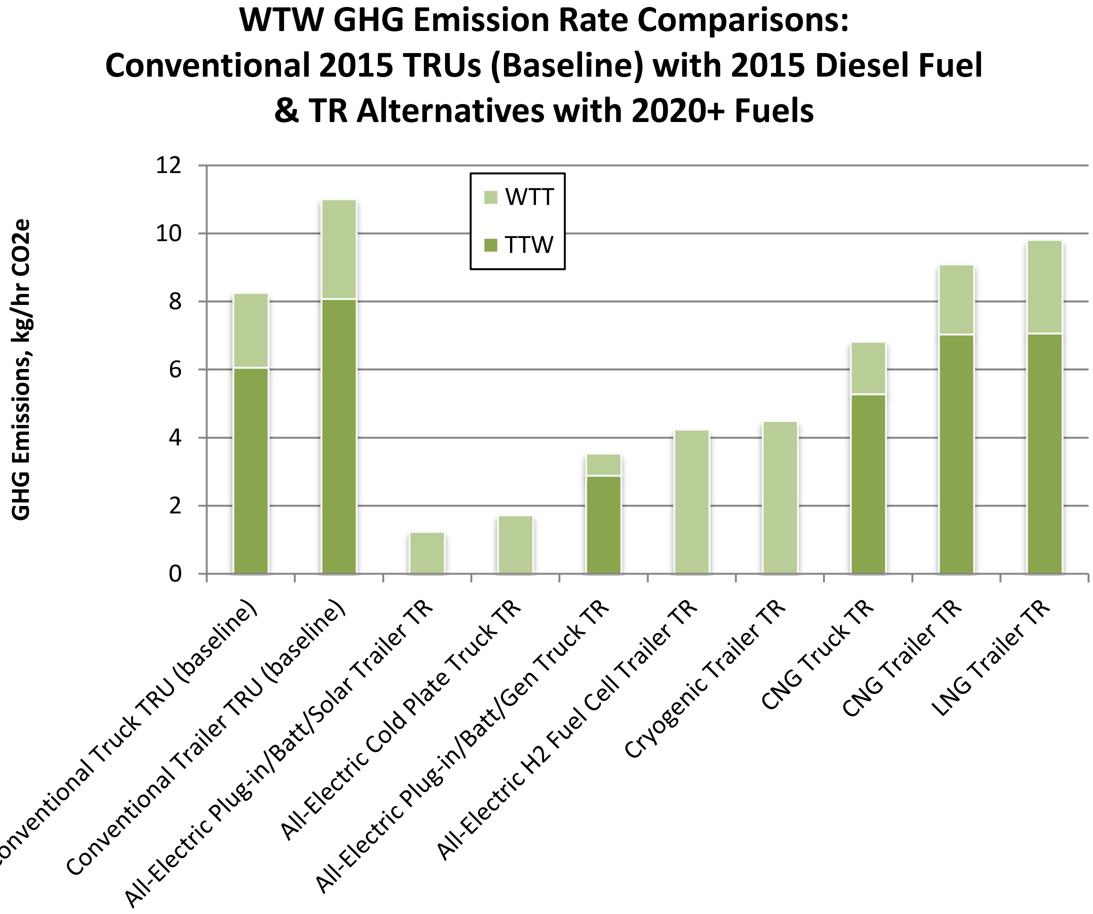


Figure III.H-1: WTW GHG Emission Rate Comparisons

Assumptions and calculations for each of these equipment types are included in the Appendices. All-electric TR variations generally produce significant GHG emissions reductions compared to the conventional TRUs. For example, the all-electric plug-in/battery/vehicle generator technology shown in the fifth bar from the left includes WTT and TTW GHG emissions resulting from the additional drag on the vehicle engine from the generator supplying electric power to an electrically driven transport refrigerator (WTW = WTT+TTW = 0.654 + 2.89 = 3.54 kg/hr CO2e). This value, compared to the conventional truck TRU (2.20 + 6.06 = 8.26 kg/hr CO2e) would amount to about 57 percent reduction in GHG emissions (shown in the right column of Table III.H-1).

Another noteworthy example is the all-electric plug-in/battery/H_2 fuel cell technology in a trailer TR (sixth bar). WTT GHG emission rate shown (4.24 kg/hr CO2e) is for on-site steam methane reformation (SMR) of 66 percent pipeline natural gas and 33 percent renewable natural gas converted to H_2. TTW emissions are zero. So, the emissions reductions for this equipment type would be about 61 percent (shown in Table III.H-1). It is interesting to note that if solar PV electrolysis is used to produce H_2, the WTT emissions would also be zero, so WTW GHG emissions reductions would be 100 percent.

Staff also evaluated the potential GHG emission reductions that would result from using the diesel fuel required by the LCFS in 2020 and beyond in conventional TRUs[4]. At that time, the carbon intensity of diesel fuel is required to be 10 percent less than 2015 diesel fuel. The comparison between conventional TRUs to technologies fueled by 2020+ fuels then becomes more appropriate from an “apples-to-apples” perspective. Table III.H-2 shows these more direct GHG emission rate comparisons. As with the above table, the right column shows the percent reduction of GHG emissions for each technology, compared to conventional TRUs with 2020+ fuel (first two rows).

Table III.H-2: WTW GHG Emission Rate Comparisons, 2020+ Fuel

	GHG Emission Rate (kg/hr)			WTW Percent Reduction[1]
Equipment Type	**WTT**	**TTW**	**WTW**	
Conventional 2015 Trailer TRU, 2020+ Fuel	1.83	8.08	9.91	N.A.
Conventional 2015 Truck TRU, 2020+ Fuel	1.37	6.06	7.43	N.A.
All-Electric Plug-in/Battery/Solar Trailer TR	1.24	0	1.24	87%
All-Electric Cold Plate Truck TR	1.73	0	1.73	77%
All-Electric H2 Fuel Cell Trailer TR	4.24	0	4.24	57%
Cryogenic Trailer TR	4.5	0	4.5	55%
All-Electric Plug-in/Battery/Generator Truck TR	0.654	2.89	3.54	52%
CNG Truck TR	1.54	5.28	6.82	8%
CNG Trailer TR	2.05	7.04	9.09	8%
LNG Trailer TR	2.74	7.07	9.81	1%

Note 1. Comparisons are made to conventional truck TRU or conventional trailer TRU, as applicable.

Although the differences are small, the WTW percent reductions shown in Table III.H-2 are less than those in Table III.H-1 because diesel fuel CI values will be less in 2020 and beyond, compared to today’s baseline 2015 diesel fuel. These differences are especially apparent for CNG and LNG because there are no requirements going forward for CI reductions for CNG and LNG in ARB’s Low Carbon Fuel Standard (LCFS). There are currently no renewable natural gas requirements in LCFS. As a result, WTW GHG reductions for CNG and LNG are shown as less significant.

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[4] Conventional TRU engines in 2020 and beyond are assumed to be similar to current TRU engines because there are no mandated requirements to improve fuel economy for these engines. So, GHG emissions changes would be due to required lower fuel CI values, not engine efficiency.

Figure III.H-2 provides a visual comparison of Table III.H-2 values for WTT, TTW, and (stacked) WTW GHG emissions for conventional TRUs (left two columns) and select TR technologies, with all using 2020+ fuels.

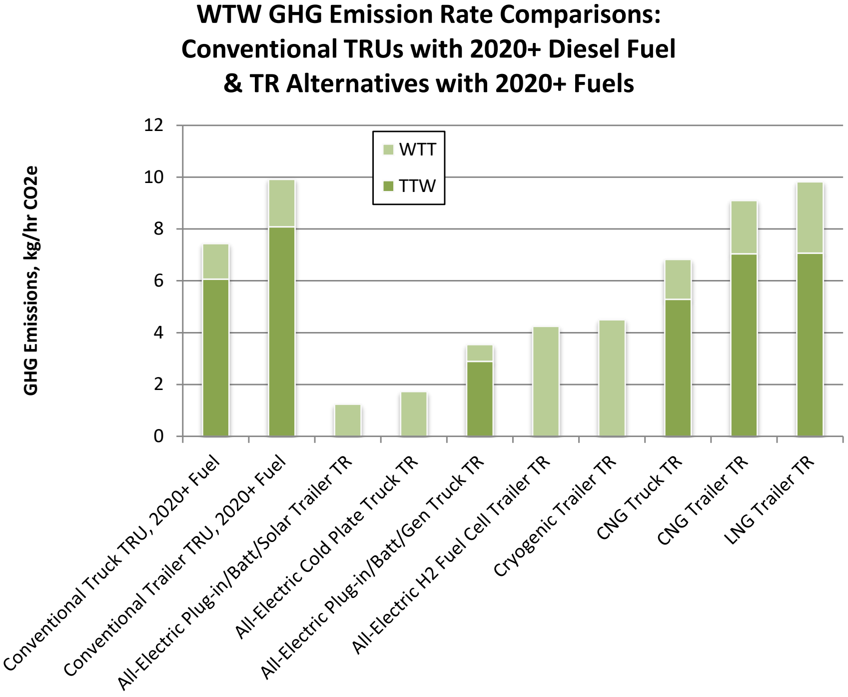


Figure III.H-2:
WTW GHG Emission Rate Comparisons, 2020+ Fuels

I. Tank-to-Wheels Criteria Pollutant Emission Rate Comparison

Staff evaluated the TTW criteria pollutant (CP) “tailpipe” emissions for each TR technology. WTT emissions were not addressed, however they are known to be small compared to TTW emissions and contribute very little to WTW CP emissions. Table III.I-1 (next page) compares CP emission rates of select TR technologies to conventional truck or trailer TRUs. The WTW percent emission reduction for each technology is shown in the right column, as compared to the appropriate type of conventional TRU.

Table III.I-1: TTW Criteria Pollutant Emission Rate Comparisons

Equipment Type	NMHC+NOx (g/hr)	PM (g/hr)	Total CP (g/hr)	TTW Percent Reduction[1]
Conventional Truck TRU	37.9	0.79	38.69	-
Conventional Trailer TRU	57.5	1.23	58.73	-
All-Electric Plug-in/Battery/Solar Trailer TR	0	0	0	100%
All-Electric Cold Plate Truck TR	0	0	0	100%
All-Electric H_2 Fuel Cell Trailer TR	0	0	0	100%
Cryogenic Trailer TR	0	0	0	100%
All-Electric Plug-in/Battery/Generator Truck TR	4.88	0.14	5.02	87%
CNG Truck TR	28.99	NA	28.99	25%
CNG Trailer TR	51.67	NA	51.67	12%

Note 1: Comparisons are made to conventional truck TRU or conventional trailer TRU, as applicable.
Note 2: "NA" means TTW emission factor "Not Available" for PM (but known to be relatively small compared to NMHC+NOx).

Figure III.I-1 shows the TTW criteria pollutant emission rate comparisons between conventional TRUs (left two bars) and select TR technologies.

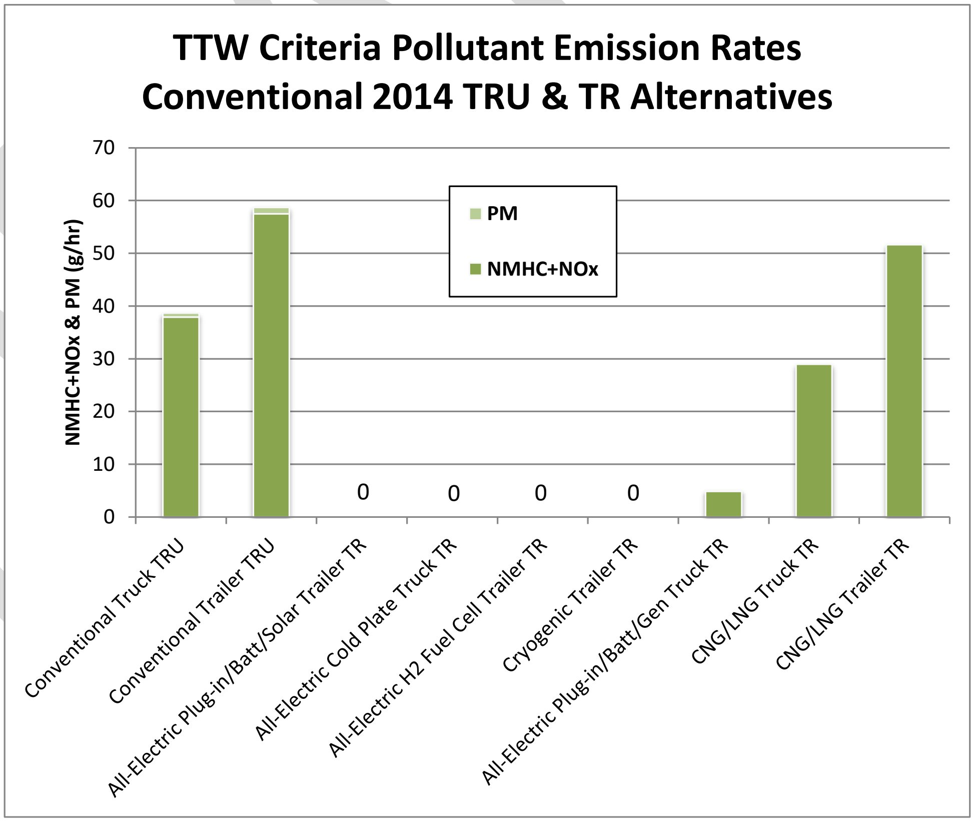


Figure III.I-1:
TTW Criteria Pollutant Emission Rate Comparisons

The above table and chart for TTW criteria pollutant emissions shows that all-electric and cryogenic TRs have zero or very low TTW criteria pollutant emissions compared to conventional truck and trailer TRUs. As discussed with the WTW GHG emission rates, the all-electric plug-in/battery/vehicle generator truck TR emissions (third bar from right) are due to the additional generator drag on the vehicle engine due to the TR electric-drive load. Also, as indicated in Table III.I-1, this technology's total CP emission rate is reduced about 87 percent, when compared to a conventional truck TRU.

CNG/LNG-powered TRs do not appear to have nearly as significant criteria pollutant emission rate reductions compared to the estimated emission rate reductions for all-electric and cryogenic TR technologies. For example, emission rate reductions were 25 and 12 percent for CNG/LNG-powered truck and trailer TRs, respectively, compared to 87 to 100 percent reductions for the all-electric and cryogenic TR technologies.

J. Energy Efficiency

GHG emissions reductions can be achieved with improved thermal efficiency of insulated vans, and the improved energy efficiency of refrigeration systems and the engines or electric motors driving them. This starts with the thermal efficiency of the cargo van because reducing the heat load on the refrigeration system results in reduced engine load, run time and fuel consumption, with operating cost savings and extended cooling unit life. This can be accomplished a number of ways:

- Use of high R-value insulation;
- Elimination of ambient air leakage;
- Incorporation of structural features into the walls, ceiling, floors, and doors that eliminate thermal short-circuits; and
- Use of “cool” exterior paints/coatings or films (all discussed further below).

Moreover, as the efficiency (or coefficient of performance) of the refrigeration system improves, less power is demanded from the engine or electric motor to reject the heat load and maintain the cargo space set point temperature. More efficient engines or electric motors also require less fuel/electric energy to meet the refrigeration system’s power demand, which translates to reduced GHG emissions rates. Each of these factors is discussed below.

<u>Refrigerated Van Insulation</u>

Improved thermal efficiency of refrigerated vans reduces the energy requirements and related GHG emissions from fossil-fueled TRUs, and has the added effect of extending the range (hours of operation between refueling) of all of the technologies that are being assessed herein. Thermal efficiency and durability of refrigerated vans can be improved by:

- Using thicker, or more effective and durable insulation in the walls, ceiling, floors, and doors;
- Incorporating low permeability film layers into floors, walls, ceiling, and doors to prevent outgassing and moisture intrusion that leads to insulation degradation; and
- Incorporating scuff guards on interior walls to prevent forklift damage to walls and insulation, which causes air leakage and allows moisture intrusion and accelerated insulation degradation (all discussed further below).

Polyurethane foam insulation is used almost exclusively in refrigerated vans. Chlorofluorocarbons (CFC), hydrofluorocarbons (HFC), hydrochlorofluorocarbons (HCFC), hydrocarbons, and liquid CO_2 are used as blowing agents in closed-cell polyurethane insulating foams. The blowing agent is used to propel two liquid polymer resin components, with catalyst, flame retardants, and other additives, to mix and form polyurethane as it is injected between two metal or plastic sheets creating a composite panel. The blowing agent changes from liquid to gaseous phase, producing millions of tiny bubbles in the polymer. As the bubbles expand, the polymer fills the space between metal or plastic sheets. The resin hardens very quickly into a ridged solid. The blowing agent then functions as a low-conductivity insulating gas. The composite panel includes spaced structural ribs that serve to reinforce the wall or ceiling in what is called sheet and post construction. (Parker, 2015; Bennett, 2015)

As indicated above, the thicker the insulation, the greater the overall R-value of a composite wall. There are three broad practical considerations regarding insulation thickness.

1. Weight: Thicker insulation adds to the tare weight of a truck or trailer, which can impact the amount of cargo that can be hauled if the load “grosses-out” (cargo loading stops before all of the cargo space is used because of the gross vehicle weight rating would be exceeded).

2. Cargo space: The maximum overall width of a trailer is limited to 102 inches by Department of Transportation Federal Highway Administration and state Vehicle Codes. So, the thickness of side-wall insulation may be limited by the pallet size used and the clearance space between pallets needed by the forklift operator to maneuver pallets into two rows across the width. As a result, the insulation thickness can range from 1.5 inches to 5 inches, and R-value ranges from R-11 to R-28 insulation values. (Navarro, 2015; Parker, 2015)

3. Forklift maneuvering space: As indicated above, thicker insulation also reduces the space for forklifts maneuvering pallets. With less space, there is a greater rate of wall surface punctures and pallet impacts during loading, followed by moisture intrusion, which rapidly degrades thermal performance. (Bennett, 2015) Metal film or polymer layers within the composite walls and thermoplastic interior liners or “rub rails” on the lower cargo space interior surfaces can be used to provide protection against punctures caused by careless forklift operators.

Conventional polyurethane foam insulation R-values are about R-6 per inch of thickness at the beginning of the van life, but then R-value degrades to R-5.5 per inch within several years due to outgassing of the blowing agent and moisture intrusion. Road-induced vibration and panel flexing, forklift/pallet impacts and other normal wear effects also break down the insulation, which leads to moisture intrusion, air leakage, and accelerated outgassing, all of which contribute to thermal performance degradation. (TMC, 2013) Low permeability barriers are typically used to slow down outgassing, including the aluminum or stainless steel exterior skin sheet and various types of polymeric films, laminated foil/plastic films, metalized films, fiberglass, glass, glass mat, and various composite liners. Thicker and crystalline barriers tend to have lower permeability. (Fetz, 2015; Navarro, 2015; US Liner, 2013)

Figure II.J-1 (next page) shows the measured thermal degradation of insulation in refrigerated trailers over time. UA is the conductance of the composite reefer walls and is the reciprocal, or inverse of the R-value. As UA increases, heat loss increases. The bottom dashed curve illustrates very low degradation rates with an impermeable skin that stops outgassing. The top dashed curve shows much more rapid degradation with permeable skins that allow outgassing. The curves in between represent a level of outgassing control offered by Great Dane Trailer's ThermoGuard liner product.

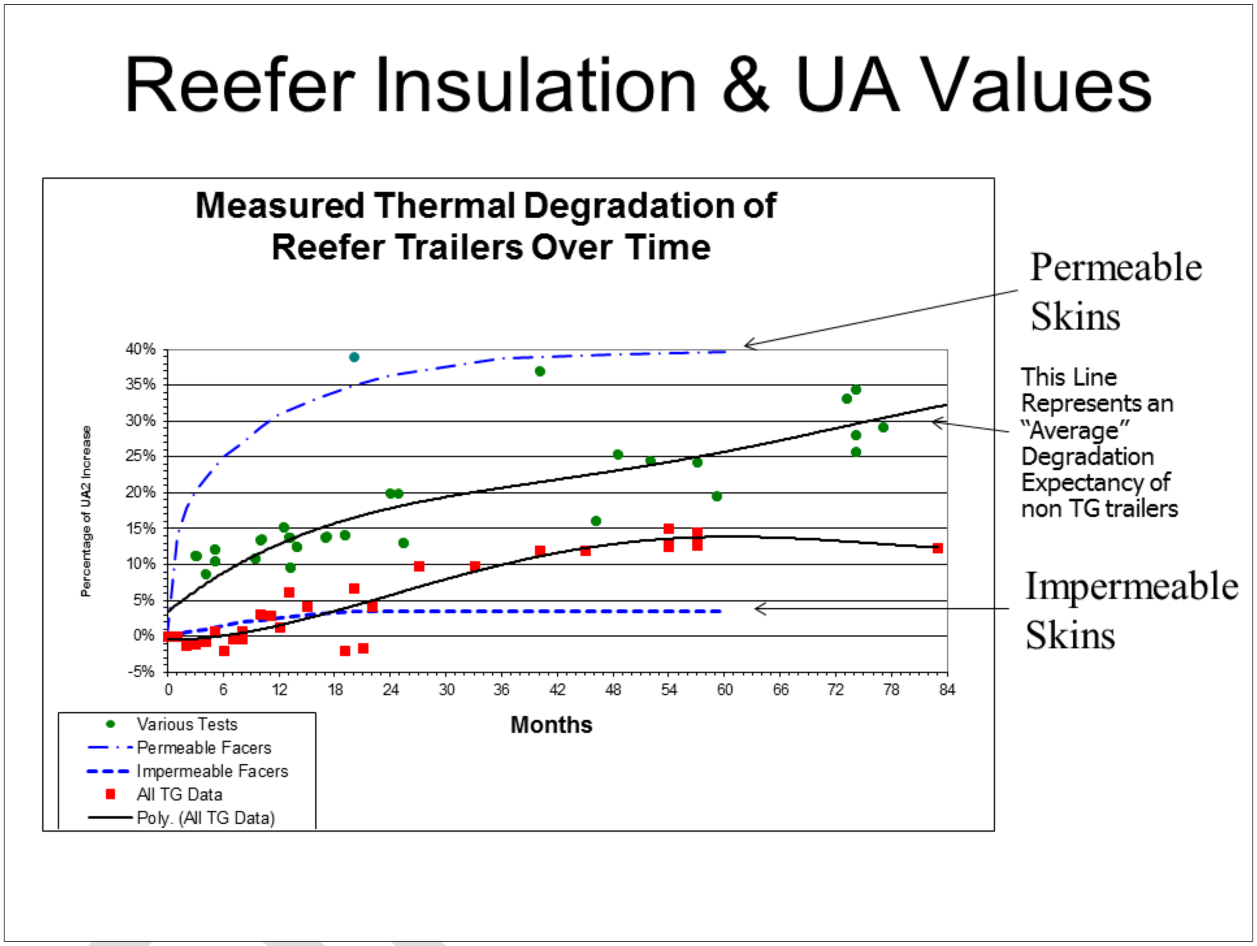


Figure III.J-1: Measured Thermal Degradation of Reefer Insulation UA Values (Great Dane, 2015)

Some blowing agents have high GWP. Use of low GWP blowing agents in insulation would reduce the climate change impact that result from outgassing of the blowing agent as the insulation deteriorates. This could be at the expense of some R-value, however, if the thermal conductivity of the replacement blowing agent is greater than the original blowing agent being replaced. As an example, the blowing agent R134a is scheduled to be replaced soon as a result of its ozone depletion potential and high GWP. Hydrofluoroolefin (HFO) blowing agents are likely replacements. HFO blowing agents would have about 350 times lower GWP, but they cost three-to-five times more than the R134a being replaced. HFO blowing agents also have a somewhat lower thermal conductivity compared to R134a. (Parker, 2015)

Embedded vacuum panel insulation (currently in development at the bench-scale testing phase) may eventually provide insulating values approaching R-50. (Bergeron, 2001; Feinerman, 2014) These are rather delicate structures that would require strategies to protect the vacuum panel from abuse by forklifts, road vibration, wall flexing, tree abrasion, and internal jams that anchor insulated bulkheads used to create multiple temperature zones within the cargo space.

Aerogels are another type of insulating material that has been considered by trailer manufacturers. Aerogels have about 50 percent greater R-values compared to polyurethane foam insulation and much lower density. The insulating value is due to being composed mostly of air. Aerogels start out as sol-gel polymerizations - a structure of macromolecules with liquid gel solution in between. The structure is heated to evaporate off the liquid gel, leaving the porous polymer structure behind. Many modern aerogel formulations are very durable. However, their high cost makes aerogels' use hard to justify, so they may have a limited role in certain areas where higher R-values are needed. (Ehrlich, 2015) For example, aerogel strips can be used between the aluminum post and inner skin of a composite sidewall to create a thermal break, significantly increasing the R-value. (Kosny, 2007; Thermablok, 2009))

U.S. semi-trailer manufacturers may use Truck Trailer Manufacturers Association Recommended Practice *R.P. No. 38 Method for Testing and Rating Heat Transmission of Controlled Temperature Vehicles/Domestic Containers* and/or *Recommended Practice, RP 718A Refrigerated Transportation Foundation Method for Classification of Controlled Temperature Vehicles* including domestic containers, in the American Trucking Associations Technology and Maintenance Council's *2014-2015 Recommended Practices Manual*. (TMC, 2013)

In addition to the practical considerations listed earlier for insulation thickness, economics and market forces influence how much insulation is built into refrigerated truck and trailer vans. U.S. trailer manufacturers build what their customers demand, which tends to be less insulation when fuel prices are low. Thinner insulation means more cargo space because the overall width of the van is limited by law. More cargo space means more revenue per load, if the truck or trailer's weight limit is not reached first. But, as the insulation thickness becomes thinner, the cooling load on the TRU increases, increasing the operating cost of TRU fuel to the point where lifecycle costs tilt back in favor of more insulation. Likewise, when fuel costs are higher, more insulation can improve the economics of refrigerated transport. The most typical sidewall insulation thicknesses in the U.S. are two inches and two and one-half inches, but insulation thickness ranges from one inch to 5 inches. The front wall is typically four inches thick. Floors are typically two and a half inches to three inches. Roofs are typically two to two and a half inches thick.

In contrast, refrigerated van insulation thickness tends to be thicker in Europe due to regulatory requirements and economics. The 26 members of the European Union (EU), and 23 other European, former Soviet Union, North African and Middle Eastern countries have signed on as contracting parties to the United Nations Economic

Commission for Europe's (UNECE) standards under the *Agreement on the International Carriage of Perishable Foodstuffs and on Special Equipment to be Used on Such Carriage (ATP).* ATP requires testing and certification of the insulation and cooling capacity of refrigerated transport equipment, and provides for separate testing of TRUs. France, Italy, Russia, and Spain apply ATP standards to domestic transportation within their borders. Although the United States is a contracting party to ATP, the United States made a declaration under article 10 of the International Carriage of Perishable Foodstuffs Act of 1982 and the implementing regulations at title 7 CFR 3300, resulting in ATP standards being voluntary in the United States. (UNECE-ATP, 2014; McGregor, 2015)

Under the ATP, samples of new-model insulated vans are tested to ensure they meet the appropriate overall heat transfer coefficient standard (K-value). Passing models are certified for six years. Certification of insulated vans may be renewed at six year intervals by inspecting and/or testing a sample of aged insulated vans to determine if they still meet the ATP K-value standard.

In addition, market forces are at work in Europe, because diesel fuel typically costs two to three times more than U.S. fuel due to differences in government subsidies, taxes, and other influences. (Fuel Prices-Europe, 2015; Currency Converter, 2015; Transport Topics, 2015b) Greater thermal efficiency in truck and trailer vans makes legal and economic sense in the Europe, so insulation is generally thicker there (side walls are typically about four inches thick) (Fetz, 2015).

Although the U.S. signed the UN's ATP agreement in 1983, international transportation of perishables, between the United States, and Canada and Mexico (which are not contracting parties) is exempt from the provisions of the agreement under a declaration the United States made under article 10, on January 17, 1983. International maritime container transportation of perishables between the United States and contracting parties is exempt under articles 3 and 5, as these movements are more than 150 kilometers by sea. United States does not apply ATP standards to domestic transportation as is done in France, Italy, Russia, and Spain.

Several U.S. trailer manufacturers tested their refrigerated trailers at two U.S. ATP test stations approved by the U.S. Department of Agriculture, which issued U.S. ATP certificates based on the test reports at the request of the manufacturers. This enabled 250 trailers to be exported to Turkey, Denmark, and Greece, from 1986 through 1998. (McGregor, 2015) Great Dane Trailer Manufacturing operates the only remaining U.S. ATP test facility in the North America. (Fetz, 2015)

The high cost of diesel fuel, the above-mentioned thermal efficiency standards, and greater prevalence of noise ordinances have also made European refrigerated fleets more open to trying new or alternative transport refrigeration technologies. For example, there is greater use of cryogenic TRs, all-electric, and hybrid electric TRs with various range extender strategies in the EU (see discussions in Sections III.A and III.E, above).

Air Leakage Prevention

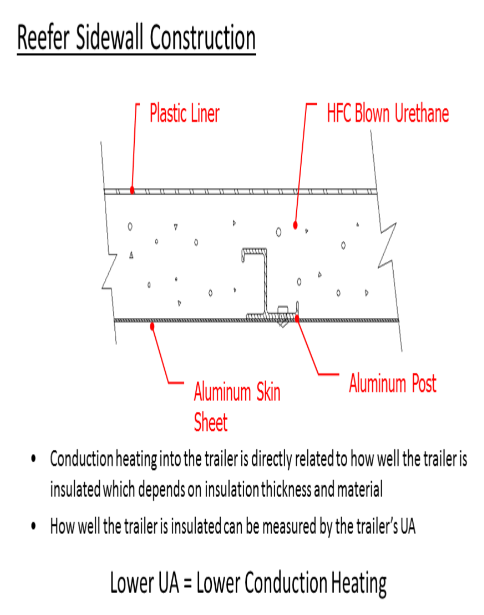
Door design choices also impact heat load on the cooling unit. Roll-up overhead doors are more convenient for foodservice refrigerated vans that go through frequent door openings at multiple delivery points along their daily routes, but they leak more air at the hinge lines and therefore may not be as thermally efficient as vertically hinged swing doors. There may be trade-offs if the operator can more quickly close the roll-up door and is diligent about doing that and not leaving the door open for extended periods.

Door seals are also a source of air leakage. They require durable yet compliant materials that perform over a wide temperature range (-20 °F to 120 °F) with good insulating properties. Door seals require close monitoring for damage and wear, and easy maintenance, repair, and replacement. Proper alignment of door hinges and latches can also affect door seal performance and air leakage. Wabash has a patent pending on an inflatable door seal that is designed to avoid the abrasion wear and damage that are common on sliding lip door seals for roll-up (overhead) doors. (Ehrlich, 2015)

Construction techniques and how effectively the insulation fills the void space between inner and outer skin layers also affect air leakage. The connections between walls, floor, roof, and header (front wall) are potential air leak paths that need to be sealed and insulated. These are also areas that are exposed to damage from tree side-swiping and wear from road-induced flexing; so monitoring, maintenance, and repair are necessary to prevent degradation and air leakage.

Structural Design Features

Refrigerated vans must be structurally designed with thermal breaks to cut the routes of high thermal conduction. Figure III.J-2 shows a cross-section of a sheet and post composite construction that is typical for insulated vans. Polyurethane foam insulation is sandwiched between the inner plastic liner (top) and the outer aluminum skin sheet (bottom). An aluminum structural "J" post is embedded in the foam, between the sheets. The outer flange of each post is typically riveted to the outer aluminum sheet. To create a thermal break, the inner (upper) flange is not connected to the inner skin, leaving space for foam insulation. To reduce thermal conduction, the post flanges closest to the inner plastic liner are as narrow as possible to minimize heat transfer area.



- Conduction heating into the trailer is directly related to how well the trailer is insulated which depends on insulation thickness and material
- How well the trailer is insulated can be measured by the trailer's UA

Lower UA = Lower Conduction Heating

**Figure III.J-2:
Sheet and Post Construction
with Thermal Break
(Great Dane, 2015)**

Greater numbers of wall posts, floor cross-members, and roof bows, cause increased heat conduction. Anchor points along walls, meat rails in the roof, and other load tie-off strategies also present challenges for managing thermal conduction routes. The structures around doors and floor drains are also a challenge. Nonmetallic composite materials or layers can be used to create a thermal barrier or low conductivity connection (see aerogel discussion, above). Sometimes metallic connections can be configured with longer, thinner thermal routes with less cross-sectional heat flow area to increase thermal resistance. Poor designs are exposed by the presence of moisture condensation or ice on exterior surfaces, which indicate thermal short circuits. Infrared thermal imaging tools positioned outside with heaters positioned inside can reveal thermal conduction areas during the prototype design phase so that design adjustment can be made if necessary.

Exterior surfaces

Exterior van surfaces that use lighter paint colors, reflective paints, reflective surface films, and polished aluminum or stainless steel exterior sheets can reduce heat load and fuel use significantly, as demonstrated by several studies. (SAE, 2007; SAE, 2012; SAE, 2014). These strategies reduce the heat load absorbed by the trailer from direct sunlight and long-wave infra-red heat energy emitted by solar-heated surfaces, such as roadways. Many refrigerated trailers use polished stainless steel skins on the rear doors to reflect thermal heat load. Wabash offers their *Solarguard Roof System* as an option, which reflects direct solar radiation. Wabash data suggests SolarGuard may reduce engine run time as much as 17 percent when the trailer is stationary (Wabash-SolarGuard, 2011).

Miscellaneous and Operating Procedures

Refrigeration strip door curtains and other operating procedure modifications also help to reduce the loss of cold air from the cargo space, and by extension, reduces heat load on the refrigeration system. An example of operating procedures is turning off the TRU during deliveries when the van doors are open, which prevents the evaporator fans from blowing the cold cargo space air out of the open door. Warmer, humid ambient air replaces the cold air, which must be cooled and causes the TRU to initiate more frequent, high-load defrost cycles.

Empty pallets and bins get loaded into the van at delivery locations for return to distribution centers. If these items have been sitting outside in the sun just prior to loading, they can add significantly to the heat load on the cooling unit. Staging these items in the shade or under a cover reduces this unnecessary fuel expense and GHG emissions.

Refrigeration System Efficiency

In the U.S., the American National Standards Institute (ANSI) and the Air Conditioning Heating and Refrigeration Institute (AHRI) have established standards for testing and determining the performance rating of mechanical TRUs. These standards also include minimum data requirements for published ratings, operating requirements, marking and nameplate data and conformance conditions. (ANSI/AHRI, 2013) However, these standards are only intended as guidance to industry, including manufacturers, engineers, installers, contractors, and end users. These standards do not set minimum requirements for efficiency or coefficient of performance of the refrigeration system. TRU OEMs build what their U.S. customers demand, meaning that refrigeration system efficiency in the U.S. is effectively set by market forces.

As described above, the United Nations' ATP contains minimum performance standards and test protocols for the separate testing of TRUs and refrigerated and mechanical refrigerated equipment used for the transport of refrigerated foods. Testing determines which performance class is met. A sample of each model is tested initially (before the equipment enters into service) and also periodically (aged equipment is again tested at least once every six years) to check conformity with the performance standards. If the aged equipment fails to meet the initial performance class, it may be de-rated to a less demanding class.

In advance of the more stringent Tier 4 final new diesel engine emissions standards for the 25-50 hp category that went into effect January 1, 2013, both major TRU OEMs redesigned their trailer TRU refrigeration system platforms to improve efficiency and reduce the power demand on engines. For most cases, this allowed them to "de-rate" their engine specification and use engines in the less-than 25 hp category, which is subject to less stringent emissions standards. Reduced engine power demand resulted in fossil fuel savings (up to 20 percent), which translates into reduced GHG emissions. These efficiency improvements were achieved a number of ways using various combinations of the following: (Carrier Transicold, 2012a; Thermo King, 2012a; Thermo King, 2012b; Griffin, 2011))

- Scroll refrigerant compressors;
- Electronic expansion valves;
- Microchannel heat exchangers (i.e. condensers and evaporators);
- Improved air management systems; and
- Additional sensors, new electronic control modules, CAN bus communications, and new temperature control and power management algorithms;

In addition to reduced fuel use, the redesigned refrigeration systems also had several other advantages:

- Reduced weight, which can increase payload capacity or reduce the load on the truck tractor, producing additional vehicle fuel savings and thus GHG emissions;
- Less refrigerant charge, which reduces the potential climate change impact of a high GWP refrigerant leak; and
- Improved durability and longevity of the refrigeration system components, resulting from lower operating speeds and loads.

In the last several years, the two major TRU OEMs have applied many of these design improvements to more of their transport refrigeration system platforms. More detailed discussion of component and subsystem efficiency improvements that may be available for transport refrigeration systems is provided below.

Refrigeration Compressors

Hermetically-sealed refrigeration compressors are now available for transport refrigeration, wherein the electric motor is sealed inside a brazed canister with the refrigeration compressor. This construction eliminates the shaft seal on the compressor that previous open-drive transport refrigeration systems have used. The input shaft seals on open-drive systems eventually leak refrigerant, which is a potent GHG. The most common refrigerant currently used in TRUs is R404a, which has a GWP of 3,922. (Rajendran, 2011) Some TRU models still use open-drive systems. Hermetically-sealed scroll compressors are used in home refrigeration systems, residential air conditioners, and refrigerated shipping containers. Figure III.J-3 shows the refrigerated shipping container hermetically sealed refrigeration compressor offered by Daikin.

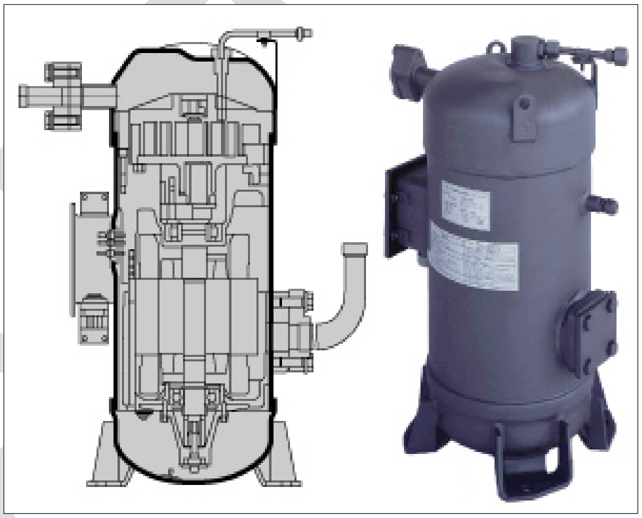


Figure III.J-3: Hermetically Sealed Scroll Compressor

In recent years, more scroll-type compressors are being used in truck and trailer TRUs because they are more efficient, more reliable, smaller, lighter, quieter, and require less maintenance due to 70 percent fewer moving parts. Scroll compressor use in trailer TRUs has resulted in a 200 pound weight savings compared to a traditional reciprocating compressor. (Carrier Transicold, 2014a; Daikin, 2014b; Emerson, 2014a; Emerson, 2014b; Gerken, 2000; Purdue, 2002b) Scroll compressors have allowed the use of economizer refrigeration circuits under light cooling load conditions, which use less energy. (Griffin, 2011) Figure III.J-4 shows Daikin's schematic representation of a scroll compressor.

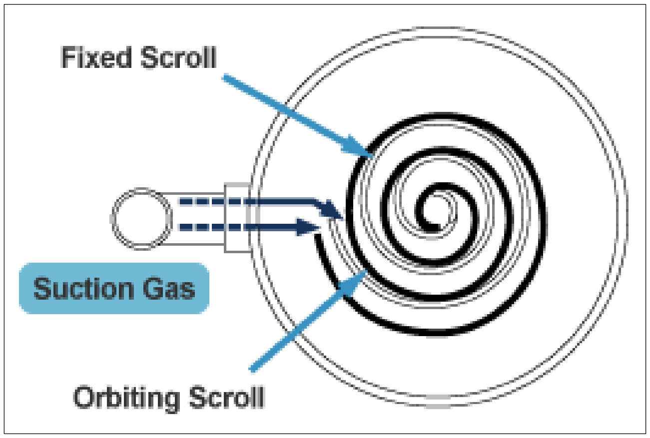


Figure III.J-4: Scroll Compressor

Microchannel Condensers and Evaporators

Microchannel condensers and evaporators provide superior thermal performance over the round-tube and fin, multi-pass heat exchangers that have been used in the past. Microchannel heat exchangers have better heat transfer, require about 20 percent less refrigerant charge, and result in reduced fan and compressor load (due to reduced refrigerant-side pressure drop), all of which lead to improved coefficient of performance (Purdue, 2002a). Microchannel coils used in TRUs are typically made of aluminum with multiple flat tubes containing small channels (microchannels) connected on each end to manifolds, with numerous fins located between the flat microchannel tubes. Figure III.J-5 shows a cut-out sample to illustrate the construction. Improved efficiency results in more compact design, material cost savings, and opportunities for lighter heat exchangers. (STSL, 2014) Additional efficiency improvements may be possible with enhanced cooling fin profiles. (Griffin, 2011)

Figure III.J-5:
Microchannel Coil Construction
(Heatcraft Refrigeration Products)

Air Management Systems

Electric motor-driven condenser and evaporator fans or blowers have also been optimized for high-efficiency, further reducing the load demand on the engine or electric motor. Fan blade and shroud geometries benefited from finite element computer modeling. Die casting and composite molding is used to achieve high efficiency fan blade profiles that are coupled with velocity recovery vane stators that maximize air flow. Variable electric motor speed controls have replaced engine belt-drive systems, providing optimized air flow for multiple operating modes at minimum power, independent of the engine speed. Fan motor suppliers are using new materials and design tools to optimize motor designs so that motor power more closely meets fan requirements, resulting in better efficiency, reduced horsepower ratings, and reduced motor weight. Compared to conventional fans with stamped metal fan blades, the state-of-the-art fans can reduce component energy needs by more than 30 percent. (Griffin, 2011)

Sensors, Communications, Controls, and Control Logic Software

In 2013 TRU models, controller area network (CAN) bus communications came into use, enabling the integration of higher tech engines, additional sensors, upgraded microprocessor controllers, and programming to manage components better and provide more precise temperature control. Defrost cycle initiation can be based on smart controls, using sensor inputs and advanced control logic instead of the less-effective, energy-wasting timed cycles. Electronic expansion valves allow more precise temperature control than older mechanical expansion valves. From a full-system perspective, the result was a step-change in efficiency (about 20 percent). More optimization is possible. Next generation communication protocol systems may provide promise for further efficiency improvements. (Carrier Transicold, 2014a; Griffin, 2011)

<u>Refrigerants</u>

As discussed previously, the refrigerants that have historically been used in transport refrigeration units have been compounds with high GWPs. The chlorofluorocarbon (CFC) refrigerant R-12, which has a GWP of 10,900, was phased out under the Montreal Protocol in 1994 because the stratospheric ozone potential was too high. R-12 and R-502 refrigerants were used temporarily before being replaced by the hydrofluorocarbon (HFC) refrigerant R-134a, which eliminated the ozone layer problem, but was found to contribute to global warming with a GWP of 1,430. The HFC R-404a has been used in TRUs since 1994, but a GWP of 3,922 is problematic. (SNAP, 2014)

Lower GWP refrigerants are being evaluated, looking for a balance between competing goals. Environmental impacts (e.g. stratospheric ozone and GWP) are balanced against safety (e.g. toxicity, flammability, corrosiveness), performance (e.g. physical properties, energy capacity, and system energy efficiency), and economics (e.g. cost of incorporating a technology change and total costs). (U.S. DOE-EERE, 2014) Roadmaps and goals have been announced by U.S. DOE-EERE for the phase-down of HFCs and the transition to low-GWP refrigerants across the entire HVAC and refrigeration industry. The left side of Figure III.J-6 shows the HCF phase-down schedules for North American Montreal Protocol along with the European F-gas Regulation. The right side shows the U.S. HFC phasedown proposal against the business-as-usual scenario.

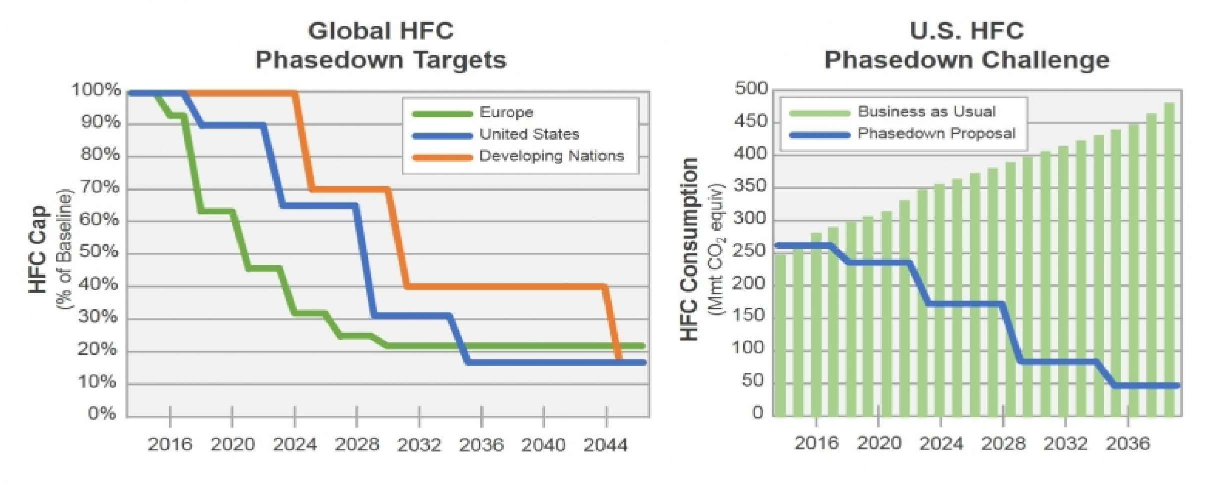


Figure III.J-6: HFC Phasedown Targets (U.S. DOE-EERE)

Currently available “drop-in” refrigerants, which would replace one refrigerant for another without the need to convert or re-design the refrigeration system, do not provide the degree of GWP reduction needed. As an example, Thermo King announced in 2014 that it had adopted a hydrofluoroolefin (HFO) refrigerant R-452a (Dupont/Chemours’ Opteon XP44) because it has a lower GWP of 2,141, is nonflammable and is a close performance match for R-404a. (Thermo King, 2014; Trucking Info, 2015) However, R-452a had not been approved by U.S. EPA as of late July 2015. R-452a’s GWP reduction of only 45 percent may be necessary for the short-term; but, that reduction may not be enough for a long-term solution.

Other HFOs may be more attractive from a GWP perspective, such as HFO-1234yf (GWP of <1), which was developed for automotive air conditioners. (DuPont, 2013) However, this refrigerant may not be a drop-in replacement because TRUs must perform over a much wider temperature range (-20 to 95 °F) than an automotive air conditioner. HFO-1234yf is also mildly flammable; however, SAE testing determined ignition is not possible under “normal” vehicle operating conditions. Nonetheless, potential safety concerns may need to be managed if a leak is directed at a hot exhaust manifold creating a potentially explosive situation under the right conditions. Significant re-design of the refrigeration system may be necessary to work with HFO-1234yf, a process that would take the TRU OEMs and their component suppliers years to complete, test and demonstrate to generate customer confidence (driven by food safety concerns).

Use of natural refrigerants, such as propane, ammonia, and CO_2 (R-744) may help to diminish a TR’s environmental impact, with their inherent zero ozone depletion potential (ODP) and very low GWP. Since propane is a common fuel, it has an obvious explosive potential, so propane leaks inside the cargo van would need to be managed.

Although ammonia’s ODP and GWP are both zero, it is not used in the mechanical vapor compression refrigerators used for transport refrigeration. Ammonia is used in absorption type refrigeration systems, which work well for large industrial refrigeration systems where there is usually more space available for the bulkier (and heavier) components (e.g. pressure vessels). Ammonia is corrosive and at high concentrations can cause respiratory failure and even death, so leak management would be an issue.

CO_2 has been used as a refrigerant in the past, but was surpassed by CFC refrigerants in the early 1930s. (UNEP, 2014) Refrigeration with CO_2 requires multi-stage compressors, which are now available and capable of higher pressure sub-critical and trans-critical operation that is necessary; but this is at the expense of higher energy consumption, especially in hotter climates, which may reduce the overall benefit. CO_2 has advantages – GWP of one, zero ozone depletion potential, nonflammable, and non-toxic classifications – but there are significant challenges that must be resolved at all component levels to achieve a system design that meets transport refrigeration system needs.

Carrier Transicold and Thermo King have announced successful testing of CO_2 refrigeration technologies. (Griffin, 2011; Thermo King, 2012c) Staff was unable to locate any reports or technical papers on the Thermo King field demonstrations to learn about their performance.

Carrier Transicold began marketing their *NaturaLine* refrigerated shipping container in 2012, which uses CO2 refrigerant in a marine application. (Carrier Transicold, 2012b) Carrier is now developing that system into a trailer hybrid-electric TRU version that was successfully demonstrated in the UK at Sainsbury grocery distribution. The hybrid electric drive system used in this demonstration is similar to Carrier's Vector e-TRU in that they used an under-slung TRU generator set to provide electric power to the CO2 refrigeration system. This new system includes many design improvements to reduce diesel fuel consumption and GHG emissions. When stationary, the NaturaLine trailer TRU can be plugged into shore power and when mobile it is powered by the genset. Carrier Transicold claims the marine shipping container version has 28 percent less overall GHG emissions compared to a conventional Carrier PowerLine version, taking into account diesel and refrigerant leaks. (Carrier, 2014b) Efficiency testing of the trailer version still needs to take place in a number of operational applications, including warmer ambient conditions where efficiency and GHG emissions could be more of a challenge.

Engine and Electric Motor Efficiency

The efficiency of diesel engines used in TRUs ranges between 26 percent and 33 percent. (Kubota, 2015a) Efficiency of these engines has not improved over the last 10 years and there are no plans to make improvements over the next 10 years. (Kubota, 2015b)

Electric motor efficiency has improved significantly, driven by the Energy Independence and Security Act of 2007 (EISA), the National Electrical Manufacturers Association's "NEMA Premium" Program (NEMA Premium, 2015), and the International Electrotechnical Commission efficiency standards (IEC, 2015). U.S. DOE-EERE has also recently announced a $20 million funding program to develop advanced components to increase efficiency using high power density designs and integrated power electronics. (U.S. DOE-EERE, 2015)

Refrigerated shipping container manufacturers are using digital frequency modulation to provide variable electric motor speed control, along with advanced temperature control algorithms. Efficiency improvements of 20 percent have been reported, along with significant weight reduction, smaller space, and more precise temperature control. (Emerson, 2014b; Emerson, 2014c; Emerson, 2014d; Daikin, 2015) These technologies may prove to be beneficial to all-electric truck and trailer plug-in/battery technologies.

E-Circuit Motors has made significant advances in brushless air-gap winding, axial flux permanent magnet synchronous motors, which are capable of variable speeds, at efficiencies greater than 91 percent, as shown in Figure III.J-7 (next page). (E-Circuit Motors, 2015) E-Circuit Motors technology uses an interconnected, multi-layered printed circuit board as the stator for an electric motor/generator, resulting in high power density (based on weight) and specific power (based on volume). This technology has been used in hand-held power tools, such as weed eaters, trimmers, and leaf blowers since 2011. The technology is scalable and could be optimized for any of the all-electric plug—in battery TR applications. Such efficiency improvements would reduce the power demand on the batteries, resulting in greater range or reduced battery costs. E-Circuit Motors estimates the cost for these advanced designs would be about 10 percent greater than the conventional motors currently being used.

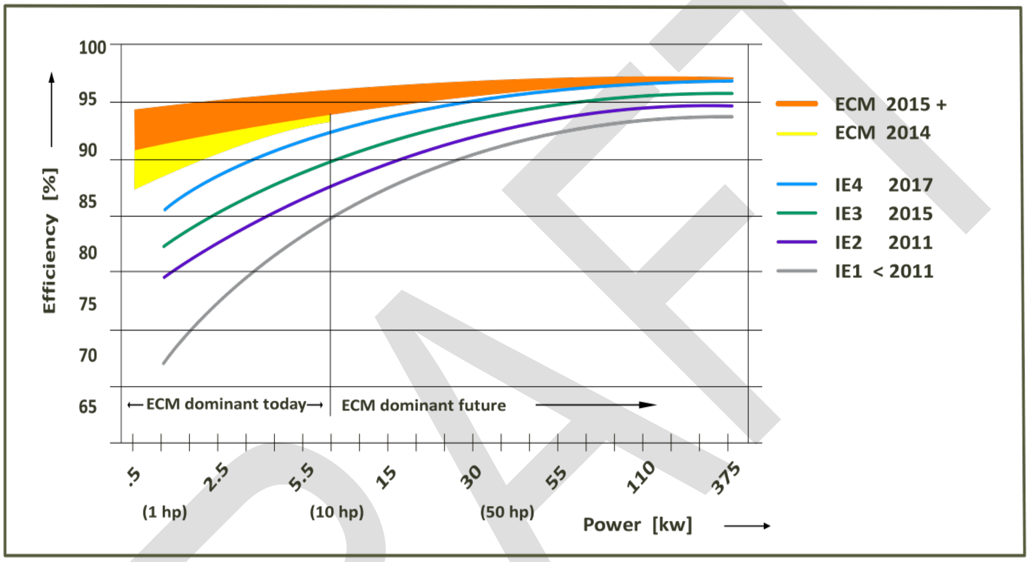


Figure III.J-7: IEC Efficiency Standards Compared to E-Circuit Motors

Staff believes that overall energy efficiency of refrigerated vans and refrigeration systems can be improved by at least 20 percent with the next five years. References discussing the above potential energy efficiency improvements were absent cost information. But, reduced fossil fuel use would result in fuel cost savings, and GHG and CP emissions reductions. Higher efficiency refrigeration systems would reduce the power demand on any TR and would therefore make it easier for all of the transport refrigeration technologies assessed herein to be viable. All-electric TRs with batteries would need less power from various range extender strategies such as vehicle-mounted generator, H_2 FC, or solar-assist. Similarly, refrigeration systems that use natural refrigerants, such as CO_2, may provide the GWP advantage discussed above without a net increase in fuel use, compared to the conventional refrigeration systems.

IV. CONCLUSIONS

A. Summary of Most Promising Technologies

As discussed in Chapter I, staff gathered information to provide an assessment of the current state and projected development over the next 5 to 10 years for technologies that could be used for transport refrigerators. These technologies are needed to support ARB's long-term objective of transforming transport refrigeration equipment into one utilizing zero and near-zero emission technologies to meet air quality and climate change goals. Given limited resources and time, the technologies discussed do not represent the universe of applicable technologies.

Key performance parameters were identified and discussed in Chapter II, Section D. Each technology was assessed against these performance parameters in Chapter III. The following questions were considered.

- Could it be commercially available in the 5- to 10-year window we need?
- Could it provide zero or near-zero emissions by 2050? Or, could it provide significant enough emissions reductions, if optimized, such that it could accelerate the transition toward near-zero emissions?
- Does a technology meet the key performance parameters? Could deployment challenges realistically be resolved in the 5- to 10-year window?

Based on the technical assessment described above, staff compiled a list of the "most promising" TR emission reduction technologies:

- Energy efficiency improvements;
- Cryogenic TRs;
- All-electric plug-in/battery/vehicle generator and cold plate TRs; and
- Hydrogen fuel cell-powered TRs.

Staff's reasoning for considering these technologies as "most promising" is discussed below.

Hybrid-electric TRUs and TRUs that are equipped with electric standby can be driven by a diesel engine when on the road and an electric motor, when stationary and plugged into the grid. These hybrids have been called "eTRUs", but they are not considered zero or near-zero emission technologies and were not covered in this technology assessment. They have been commercially available for years and can serve a role, along with cryogenic TRs, for near-term strategies that reduce the stationary operation of fossil-fueled TRUs. This near-term strategy is discussed in sub-section B, below, under "Staff Recommendations and Next Steps."

Efficiency Improvements

As discussed in Section J, the U.N. ATP program's equipment standards have resulted in more thermally efficient insulated bodies, more efficient refrigeration systems, and more use of zero and near-zero emission transport refrigeration technologies in countries that have implemented ATP standards, as compared to the United States. TRU OEMs and trailer manufacturers with international markets in ATP-implementing countries are already aware of the technologies that are needed to meet the ATP standards.

Staff believes further improvements in the thermal efficiency of refrigerated vans and the mechanical efficiency of refrigeration systems are possible -- another 15 to 20 percent improvement is possible within the next five years.

More research will be necessary to provide an estimate of the potential improvements to efficiency, energy use, and emissions reductions (both GHG and criteria pollutants). Energy efficiency improvements could produce energy cost savings that result in acceptable payback periods and would help the other technologies evaluated herein to meet the key performance parameters and achieve better viability.

Cryogenic TRs

Staff believes cryogenic TRs are promising because WTW GHG and TTW CP emission reductions are significant at 59 and 100 percent, respectively. Cryogenic TRs provide much faster initial chill-down and temperature recovery after a delivery door opening. Also, initial capital equipment costs for a cryogenic TR are close to the cost of a conventional diesel TRU and maintenance cost savings are significant enough to at least partially offset the significant cryogenic fueling infrastructure costs. Cryogenic TRs are commercially available and hundreds of them are in use in Europe.

Range is an issue for cryogenic TRs due to extremely limited cryogenic refueling infrastructure and on-board storage tank capacity. Europeans conserve cryogenic fuel by using more thermally efficient cargo vans. Operating procedures can also be modified to conserve fuel, but operator safety procedures can limit the effectiveness of some of these efforts because the cargo space needs to be thoroughly ventilated prior to entry for the direct-cooling type cryogenic TR (not an issue for the indirect-cooling type).

All-Electric/ Plug-In/Battery/Vehicle Generator and Cold Plate TRs

Staff believes all-electric/plug-in/ battery transport refrigerators have potential for being a promising technology for several reasons. First, emission reductions are significant for an all-electric truck Auragen system. WTW GHG and criteria pollutant emission rate reductions are about 57 and 87 percent, respectively. For an all-electric plug-in cold plate system, WTW GHG and TTW CP emission rate reductions are about 79 and 100 percent, respectively.

All-electric plug-in trailer transport refrigerators are commercially available and have historically been used for stationary cold storage applications that plug into shore power. Their use as on-road trailer TRs has not been attempted because lead-acid batteries are so heavy they sacrifice too much payload capacity. Advanced vehicle generator systems may serve as a range extender. Advanced battery systems have been developed for other applications, such as electric vehicles, and could be adapted for use with all-electric TRs. Combining advanced batteries and vehicle generator system hybrids could facilitate on-road operation with acceptable operating range.

Small truck and delivery van all-electric TRs are already in use to some extent in Europe. Several companies are in the process of integrating all-electric transport refrigerators (conversions from conventional diesel TRUs to all-electric) with advanced batteries, inverters, and power control units to provide electric power systems that are compatible with the rigors of on-road operations. Staff believes such integrated designs are between the pilot scale deployment and early commercialization phases for truck transport refrigerators (currently about 50 have been installed) and the design/prototype demonstration phase for trailer transport refrigerators. The truck application appears to be somewhat further along than the trailer version. Further optimization and field demonstrations are needed for both types; but, staff believes there is a very good chance that both versions may be commercially available in the next five to ten years.

Range is an issue, but several strategies for extending range are available, such as cold plates (available for decades) and high-efficiency vehicle engine-mounted generators (such as the Auragen System). All-electric transport refrigerators do not appear to be a viable option for long-haul or for-hire carriers because:

1) They may not have ready access to power plugs at the distribution centers they pick up and deliver goods to, and
2) Plug-in infrastructure for all-electric TRs at publicly accessible stations configured for Class 8 semi-trailers is not widespread (currently only 29 spread across the U.S. and six in California).

Private fleets that return to base every day may be good candidates for all-electric transport refrigerators, provided they can afford to install power plugs at their home base.

Staff believes that duty cycle demands, payload impacts, energy and maintenance costs, and safety issues are readily addressable. All-electric transport refrigerators should be able to meet the duty cycle demands by plugging into the shore power for the initial chill-down, during loading, and while parked, waiting for dispatch. Payload impacts are not expected to be an issue if Li-ion advanced battery costs continue to drop, making their use a reasonable, economic choice. Energy and maintenance savings may be significant enough that all-electric TRs will have an acceptable payback period. Finally, safety issues related to working with high voltage 3-phase power are manageable with standardized connectors, switches, and safety procedures.

Hydrogen Fuel Cell-Powered TRs

Although it is still in the demonstration phase and it is not yet commercially available, staff considers H_2 FC-powered transport refrigerators to be one of the most promising technologies for a number of reasons. First, WTW GHG and TTW CP emission rate reductions are significant at 62 and 100 percent, respectively. It is worth noting that GHG emissions reductions could be 100 percent if solar PV is used to produce hydrogen with electrolysis because the WTT GHG emissions related to SMR would be eliminated.

Also, there is a very good chance that H_2 FC systems for trailers will be in the early commercialization phase within the next five to 10 years, after further demonstrations of next generation designs, if costs decrease. H_2 FC systems were developed for material handling forklifts at distribution centers (DC) several years ago. They worked so well that there are now between 6,000 and 10,000 H_2 FC forklifts at distribution centers around the U.S., including refrigerated distribution centers (e.g. Sysco Foodservice, Walmart, Associated Wholesale Grocers, Central Grocers, Winco Foods, Krogers, Wegmans, Whole Foods, and H-E-B Groceries). The apparent success of H_2 FC forklifts at Sysco Foodservice and H-E-B Groceries may be why they are now involved in demonstration projects with H_2 FC-powered transport refrigerators. If both forklifts and transport refrigerators are using refueling infrastructure, the costs of the H_2 refueling infrastructure are spread across more pieces of equipment. Such leverage improves the return on investment and payback period.

Duty cycle, noise, and payload impacts are not issues with H_2 FC-powered TRs. Range is problematic for long-haul carriers because public refueling infrastructure for Class 8 semi-trailers is insufficient. But return-to-base fleets, such as those listed above, may be a good match and their use of H_2 FCs may help reduce barriers for long-haul fleets.

Safety features, such as flame and H_2 detectors have been incorporated into these systems in accordance with national standards. The experience fleets have with H_2 FC forklifts and their interest in FC transport refrigerators indicates they have gained some level of comfort with safety issues related to handling H_2.

When the previously mentioned H_2 FC-powered transport refrigerator demonstration projects are completed in mid- to late 2016, more information should be available about durability, reliability, and cost so that ROI and payback period can be evaluated. The demonstration project reports will be helpful in determining the path forward.

B. Staff Recommendations and Next Steps

In the near-term, staff recommends a regulation to limit stationary operation of fossil-fueled TRUs for cold storage and incentives to install infrastructure at affected locations to facilitate compliance strategies. Compliance options would include, but not be limited to, plugging hybrid electric TRUs and TRUs equipped with electric standby into the electric power grid or using cryogenic transport refrigeration systems (e.g. using liquid nitrogen, liquid carbon dioxide, or liquid air to cool the cargo space). In addition to producing near-term GHG emission reductions, the proposed regulatory measure could help to advance zero and near-zero emission transport refrigeration system commercialization by increasing the earlier penetration of infrastructure that will be needed for those technologies. The same infrastructure that is used to comply with the near-term GHG control measure could be used as zero and near-zero emission technologies become commercially ready.

Staff also recommends monitoring all of the planned and in-progress demonstration projects that were discussed for each of the technologies evaluated in Chapter III. The results of these demonstrations are needed to better-understand the strengths and weaknesses of each technology and how well they meet the key performance parameters. A continuing effort is needed to fill the data gaps staff has identified with regards to reliability, capital costs, operating savings, ROI, and payback period. When the results of these demonstrations are available, staff will have a better understanding of the commercial viability of the technologies discussed in this report and how they can help meet ARB's emission reduction goals.

If the pilot demonstration phase (one or two units per demonstration) results continue to show promise, additional funding is needed to conduct pre-commercial scale demonstrations of these technologies with ten to 20-units. Further component optimization and second generation demonstrations may be needed for some of these technologies before they can be considered for early commercialization. Incentive programs are needed to reduce economic barriers and accelerate deployment. Without these demonstration projects, it is highly unlikely the TRU industry would risk their loads and/or compromise on food safety with technology they would consider unreliable and unproven. Encouraging necessary energy/fueling infrastructure development would also address one of the key barriers to deployment.

Advanced battery systems also need to be designed and tested to provide electric power for all-electric trailer TRs while they are operating on the road. Lead-acid batteries are too heavy, reducing payload capacity. Partners and funding are needed to adapt electric vehicle battery technology to all-electric trailer TRs for on-road operation with adequate range.

Staff is coordinating with U.S. EPA's SmartWay Technology Program staff to explore opportunities to consider energy saving technologies for TRUs and TRs in that program. Staff believes there are significant opportunities for energy-saving innovations with conventional TRUs and insulated trailers, which should translate into improved economics and reduced emissions. State incentive programs must be more inclusive of TRUs and TRs. Partnerships with U.S. EPA and U.S. DOE are needed to establish regulatory insulation and refrigeration unit standards.

Staff also believes it should continue to monitor other technologies that were not evaluated during the current assessment.

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VI. ACRONYMS AND ABBREVIATIONS USED IN THIS REPORT

13 CCR	Title 13 California Code of Regulations
40 CFR	Title 40 Code of Federal Regulations
AC	Alternating Current
AGM	Absorbed Glass Mat (battery)
ARB	Air Resources Board
ARPA-E	Advanced Research Projects Agency – Energy
ATCM	Airborne Toxic Control Measure
°C	Degrees Centigrade
CAA	Clean Air Act
CNG	Compressed Natural Gas
CO	Carbon Monoxide
CO_2	Carbon Dioxide
CO2e	Carbon Dioxide Equivalent
COP	Coefficient of Performance
Cryo	Cryogenic
DC	Direct Current
DGE	Diesel Gallon Equivalent
DOE	U.S. Department of Energy
DOT	U.S. Department of Transportation
EPA	U.S. Environmental Protection Agency
EERE	Office of Energy Efficiency and Renewable Energy (DOE)
°F	Degrees Fahrenheit
FC	Fuel Cell
FDA	U.S. Food and Drug Administration
gal	Gallon
GHG	Greenhouse Gas
GREET	Greenhouse gases, Regulatory Emissions, and Energy use in Transportation
GVWR	Gross Vehicle Weight Rating
H_2	Hydrogen
HCCI	Homogenous Charge Compression Ignition
HNEI	Hawaii Natural Energy Institute
HP	Horse Power
hr	Hour
HSC	Health and Safety Code (California)
ICE	Internal Combustion Engine
ITC	Business Energy Investment Tax Credit
kg	Kilogram
kW	Kilowatt
LCNG	Liquid-to-CNG
LCO_2	Liquid Carbon Dioxide
LHV	Lower Heating Value
Li-Ion	Lithium-ion (battery)
LN_2	Liquid Nitrogen

LNG	Liquefied Natural Gas
LPG	Liquefied Petroleum Gas (propane)
m^3	Cubic Meters
MARAD	Maritime Administration (U.S. DOT)
NAR	North American Repower
NM^3	Normalized Cubic Meters
NMHC	Non-Methane Hydrocarbons
NMHC+NOx	Non-Methane Hydrocarbons Plus Nitrogen Oxides
NOx	Nitrogen Oxides
NPV	Net Present Value
NREL	National Renewable Energy Laboratory (DOE)
LTL	Less-Than-Load
OEM	Original Equipment Manufacturer
PCCI	Premixed Charge Compression Ignition
PCM	Phase Change Material
PEM	Proton Exchange Membrane (Fuel Cell)
PM	Particulate Matter
PNNL	Pacific Northwest National Laboratories (DOE)
PV	Photovoltaic
R&D	Research and Development
ROI	Return on Investment
SCAQMD	South Coast Air Quality Management District
SMR	Steam Methane Reformer
SRP	Scientific Review Panel
STEP	Shorepower Truck Electrification Program
TAC	Toxic Air Contaminant
TL	Truck-Load
TR	Transport Refrigerator
TRU	Transport Refrigeration Unit
TTW	Tank-To-Wheels
WTT	Well-To-Tank
WTW	Well-To-Wheels
U.S.	United States

APPENDICES

TECHNOLOGY ASSESSMENT: TRANSPORT REFRIGERATORS

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APPENDIX III.A-1:
WTW Assumptions and Calculations –
All-Electric Plug-In/Battery/Vehicle Generator TR (Auragen TR)

Average power output of the Auragen generator is 3.225 KW[5]

To determine the energy input rate to the vehicle engine, we must account for the inefficiencies of the belt, engine, and Auragen.

Engine – 45 percent
Auragen – 70 percent
Belt – 96 percent

$$\frac{3.225\ kW}{0.45 \times 0.70 \times 0.96} = 10.7\ kW$$

To determine fuel use rate, we first need to convert the Lower Heating Value for ULSD, which is equal to 127,464 BTU/gal[6]

$$\left(127{,}464 \frac{BTU}{gal}\right) * \frac{1{,}055J}{BTU} * \frac{1W}{\left(\frac{J}{s}\right)} * \frac{1kW}{1{,}000W} * 1\frac{hr}{3{,}600s} = 37.3 \frac{kW - hr}{gal}$$

Vehicle engine fuel use rate due to the parasitic load is then:

$$Diesel\ fuel\ use\ rate = 10.7\ kW * \frac{1\ gal}{37.3\ kw - hr} = \ \ 0.287\ gal/hr$$

Conversion factors:
948 BTU/MJ

$$Energy\ Use\ Rate, Truck\ TR = 0.287 \frac{gal}{hr} * 127{,}464 \frac{BTU}{gal} / 948\ \frac{BTU}{MJ} = 38.6\ MJ/hr$$

GHG Emission Rates (Auragen Truck TR)

Well-to-Tank (WTT) GHG Emission Rate (Auragen Truck TR)

WTT carbon intensity (CI) for 2020+ ULSD fuel is: 16.95 gCO_2e/MJ[7]

$$WTT\ GHG\ Emission\ Rate = 38.6 \frac{MJ}{hr} * 0.01695 \frac{kgCO2e}{MJ} = 0.654 \frac{kg}{hr} CO2e$$

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[5] (Auragen, 2012) See References, Chapter III-A.

[6] "Detailed California Modified GREET Pathway for Ultra Low Sulfur Diesel (ULSD) from Average Crude Refined in California," February 2009, Section 5: Carbon Emissions from ULSD Combustion, Table 5.01.

[7] Technology Assessment: Fuels Assessment, Table V-6, 2020 Fuel Blend Assumptions for Diesel, 10% Low CI (2020+). April 2015.

Tank-to-Wheels (TTW) GHG Emission Rate (Auragen Truck TR)

TTW CI for 2020+ ULSD is: 74.86 gCO2e/MJ[8]

$$TTW\ GHG\ Emission\ Rate = 38.6 \frac{MJ}{hr} * 0.07486\ \frac{kgCO2e}{MJ} = 2.89 \frac{kg}{hr} CO2e$$

Well-to-Wheels (WTW) GHG Emission Rate (Auragen Truck TR, 2020+ fuel)

$$WTW\ GHG\ Emission\ Rate = WTT + TTW = 0.654 + 2.89 = 3.54 \frac{kg}{hr} CO2e$$

Criteria Pollutant (CP) Emission Rates (Auragen TR)

Emission rates use the parasitic generator load on the vehicle engine due to the TR: 10.7 kW (see above). CP emissions are only evaluated for TTW emissions (not WTT).

TTW CP Emission Rates (vehicle Engine):

The vehicle engine used by Auragen's mid-sized truck was a 150 kW (200 hp) diesel engine. Federal and State emissions standards for this power category are used as emission factors: [9]

NOx = 0.20 g/kW-hr; NMHC = 0.14 g/hp-hr; NMHC+NOx = 0.34 g/hp-hr
PM = 0.01 g/hp-hr

TTW NMHC+NOx = 10.7 kW * 0.34 g/hp-hr * 1.341 hp/kW = 4.88 g/hr

TTW PM = 10.7 kW * 0.01 g/hp-hr * 1.341 hp/kW = 0.14 g/hr

These emission calculations do not account for the electricity used for chill-down, battery re-charging, and refrigerator operation when the TR is parked, plugged in, and waiting for dispatch because they can vary based on use of this technology.

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[8] Technology Assessment: Fuels Assessment, Table V-6, 2020 Fuel Blend Assumptions for Diesel, 10% Low CI (2020+). April 2015.

[9] MHDD Engine Certification Executive Order A-021-0604 for 2014 Cummins Engine Family ECEXH0408BAP.
http://www.arb.ca.gov/msprog/onroad/cert/mdehdehdv/2014/cummins_mhdd_a0210604_6d7_0d20-0d01.pdf

APPENDIX III.A-2:
WTW Assumptions and Calculations – Conventional (Diesel) TRUs

Energy Use Rate (New Conventional Diesel Trailer TRU):

TRU original equipment manufacturers (OEM) have published marketing brochures for 2013 and later model year trailer TRUs that claim a 20 percent reduction in fuel consumption compared to previous designs. TRU OEMs have redesigned their refrigeration systems in the last several years to be more efficient, demanding less power from the engine. The previous average fuel use rate[10] for trailer TRUs was about 1.0 gallon (gal) per hour for all of the trailer TRU applications. Applying a 20 percent reduction means the new average diesel fuel use rate after redesign would be about 0.80 gal/hr.

Energy Use Rate (New Conventional Diesel Truck TRU):

The industry-accepted average fuel use rate for truck TRUs is about 0.6 gal/hour for all of the truck TRU applications.

Conversion factors:

Lower Heating Value, ULSD = 127,464 BTU/gal[11]
948 BTU/MJ

$$Energy\ Use\ Rate, Trailer\ TRU = 0.8\frac{gal}{hr} * 127{,}464\frac{BTU}{gal} / 948\ \frac{BTU}{MJ} = 108\ MJ/hr$$

$$Energy\ Use\ Rate, Truck\ TRU = 0.6\frac{gal}{hr} * 127{,}464\frac{BTU}{gal} / 948\ \frac{BTU}{MJ} = 81\ MJ/hr$$

GHG Emission Rates

Well-to-Tank (WTT) GHG Emission Rates for 2015 Baseline Diesel Fuel

WTT carbon intensity (CI) for 2015 ULSD fuel is: 27.15 gCO2e/MJ[12]

New Conventional Trailer TRU:

$$WTT\ GHG\ Emissions = 108\frac{MJ}{hr} * 0.02715\frac{kgCO2e}{MJ} = 2.93\frac{kg}{hr}CO2e$$

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[10] Industry-accepted average fuel use rates. TRU OEMs consider this information to be proprietary.

[11] "Detailed California Modified GREET Pathway for Ultra Low Sulfur Diesel (ULSD) from Average Crude Refined in California," 2/2009, Section 5: Carbon Emissions from ULSD Combustion, Table 5.01.

[12] Technology Assessment: Fuels Assessment, Table V-6, LCFS 2015 Proposed CI (baseline), Diesel LCFS CI. (April 2015 proposed).

New Conventional Truck TRU:

$$WTT\ GHG\ Emissions = 81\frac{MJ}{hr} * 0.02715\frac{kgCO2e}{MJ} = 2.20\frac{kg}{hr}CO2e$$

Tank-to-Wheels (TTW) GHG Emission Rates for 2015 Baseline Diesel Fuel

TTW CI for ULSD fuel is: 74.86 gCO2e/MJ[9]

New Conventional Trailer TRU:

$$TTW\ GHG\ Emissions = 108\frac{MJ}{hr} * 0.07486\ \frac{kgCO2e}{MJ} = 8.08\frac{kg}{hr}CO2e$$

New Conventional Truck TRU:

$$TTW\ GHG\ Emissions = 81\frac{MJ}{hr} * 0.07486\ \frac{kgCO2e}{MJ} = 6.06\frac{kg}{hr}CO2e$$

WTW GHG Emission Rates for 2015 Baseline Diesel Fuel

New Conventional Trailer TRU:

WTW = WTT + TTW = 2.93 + 8.08 = 11.01 kg/hr CO2e

New Conventional Truck TRU:

WTW = WTT + TTW = 2.20 + 6.06 = 8.26 kg/hr CO2e

Well-to-Tank (WTT) GHG Emission Rates for 2020+ Diesel Fuel

WTT carbon intensity (CI) for 2020+ Diesel fuel is: 16.95 gCO2e/MJ[13]

New Conventional Trailer TRU:

$$WTT\ GHG\ Emissions = 108\frac{MJ}{hr} * 0.01695\frac{kgCO2e}{MJ} = 1.83\frac{kg}{hr}CO2e$$

New Conventional Truck TRU:

$$WTT\ GHG\ Emissions = 81\frac{MJ}{hr} * 0.01695\frac{kgCO2e}{MJ} = 1.37\frac{kg}{hr}CO2e$$

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[13] Technology Assessment: Fuels Assessment, Table V-6, 2020 Fuel Blend Assumptions. Diesel, 10% Low CI (2020+) April 2015.

Tank-to-Wheels (TTW) GHG Emission Rates for 2020+ Diesel Fuel

TTW CI for 2020+ Diesel fuel is: 74.86 gCO2e/MJ[10]

New Conventional Trailer TRU:

$$TTW\ GHG\ Emissions = 108 \frac{MJ}{hr} * 0.07486\ \frac{kgCO2e}{MJ} = 8.08 \frac{kg}{hr} CO2e$$

New Conventional Truck TRU:

$$TTW\ GHG\ Emissions = 81 \frac{MJ}{hr} * 0.07486\ \frac{kgCO2e}{MJ} = 6.06 \frac{kg}{hr} CO2e$$

WTW GHG Emission Rates for 2020+ Diesel Fuel

New Conventional Trailer TRU:

WTW = WTT + TTW = 1.83 + 8.08 = 9.91 kg/hr CO2e

New Conventional Truck TRU:

WTW = WTT + TTW = 1.37 + 6.06 =7.43 kg/hr CO2e

Criteria Pollutant (CP) Emission Rates

CP emissions are only evaluated for TTW emissions (not WTT).

TTW CP Emission Rates:

Staff conducted a study using Prior Production data submitted by TRU OEMs for the first half of 2014, in accordance with the requirements of title 13, California Code of Regulations, section 2477.13(b)(2). Actual TRU production numbers for each model, with the certification values of the installed TRU engines were used to calculate weighted average emissions rates for each equipment type. Production numbers are confidential, so only the weighted averages can be presented below.

Equipment Type	**NMHC+NOx (g/hr)**	**PM (g/hr)**
Conventional Trailer TRU	57.5	1.23
Conventional Truck TRU	37.9	0.79

APPENDIX III.B-1
WTW Assumptions and Calculations – All-Electric/Cold Plate TR

Average energy use to freeze cold plates is 6.0 kW-hr/hr[14]

Greenhouse Gas (GHG) Emissions:

$$Energy\ Use\ Rate, Cold\ Plate\ TR = 6.0\ \frac{kW-hr}{hr} * 3{,}412\frac{BTU}{kW-hr}/948\ \frac{BTU}{MJ}$$
$$= 21.6\ MJ/hr$$

Well-to-Tank (WTT) GHG Emissions (All-electric, cold plate)

WTT carbon intensity (CI) for 2020+ electricity is: 79.95 gCO2e/MJ[15]

$$WTT\ GHG\ Emissions = 21.6\frac{MJ}{hr} * 0.07995\frac{kgCO2e}{MJ} = 1.73\frac{kg}{hr}CO2e$$

Tank-to-Wheels (TTW) GHG Emissions (All-electric, cold plate)

TTW GHG emissions are zero for all-electric TR.

Well-to-Wheels (WTW) GHG Emissions (All-electric, cold plate)

$$WTW\ GHG = WTT + TTW = 1.73 + 0 = 1.73\frac{kg}{hr}CO2e$$

Criteria Pollutant (CP) Emissions:

CP emissions are only evaluated for TTW emissions (not WTT).

TTW CP Emission Rates (All-electric, cold plate)

TTW CP emission rates for all-electric cold plate TRs are zero.

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[14] (Johnson, 2014) See References, Chapter III-B.

[15] Technology Assessment: Fuels Assessment, Table V-6, 2020 Fuel Blend Assumptions for Electricity Marginal, 33% renewables to meet RPS (2020+). April 2015.

APPENDIX III.C-1:
WTW Assumptions and Calculations – Hydrogen Fuel Cell TRs

Energy Use Rate (All-Electric Trailer Transport Refrigerator, H_2 Fuel Cell):

Pacific Northwest National Laboratories (PNNL) is sponsoring a demonstration project with Nuvera Fuel Cell and Thermo King. Nuvera's estimated H_2 fuel use for their trailer TR FC is 0.40 kg/hr when it has been optimized for the production unit.

The Lower Heating Value of H_2 is 119.99 MJ/kg.[16]

Conversion to MJ per hour allows GHG emissions calculations:

$$Energy\ Rate = 0.40\frac{kg}{hr} * 119.99\frac{MJ}{kg} = 48.0\ MJ/hr$$

Better actual fuel use rate data may be available after the demonstration projects are completed in late 2015.

The demonstration unit is not using a battery for load leveling, so there will be no need to re-charge the battery at the distribution center by plugging into the grid.

GHG Emissions Rates (All-electric H_2 FC Trailer TR)

Well-to-Tank (WTT) GHG Emissions (H2 FC Trailer TR)

The WTT carbon intensity (CI) of 2020+ H_2 is 88.33 g CO2e/MJ[17]

$$WTT\ GHG\ Emissions = 48.0\frac{MJ}{hr} * 0.08833\frac{kgCO2e}{MJ} = 4.24\ kg/hr\ CO2e$$

Tank-to-Wheels (TTW) GHG Emissions (H_2 FC Trailer TR)

The TTW CI of H_2 is 0 (Only heat and water are produced by a fuel cell).

Well-to-Wheels (WTW) GHG Emissions (H_2 FC Trailer TR)

$$WTW\ GHG = WTT + TTW = 4.24 + 0 = 4.24\frac{kg}{hr}CO2e$$

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[16] "LCFS Initial Statement of Reasons December 2014, Appendix C, Table 10, CA-GREET 2.0.

[17] Technology Assessment: Fuels Assessment, Table V-6, 2020 Fuel Blend Assumptions for G.H2, onsite 2/3 NA-NG and 1/3 (33%) Renewable NG (2020+). April 2015

Criteria Pollutant (CP) Emissions (H_2 FC Trailer TR)

CP emissions are only evaluated for TTW emissions (not WTT).

TTW CP Emission Rates

Fuel cells emit only water and heat. Therefore TTW criteria pollutant emissions are zero.

APPENDIX III.D-1:
WTW Assumptions and Calculations – All-Electric/Solar Assist TRs

Energy Use Rate (All-Electric Trailer Transport Refrigerator, Battery Plug-in, Solar Assist):

A solar trailer demonstration project was designed and built in the UK by University of Southampton, sponsored by J. Sainsbury plc between 1997 and 2002.[18] Staff were able to procure three published reference documents on this project. Many of the assumptions are based on those reports.

An all-electric transport refrigerator (no diesel engine) is used. A battery/inverter system provides AC electric power to the hermetically-sealed refrigeration compressor. The battery is re-charged at the grocery distribution center before being dispatched for store deliveries.[19]

The demonstration project reports indicated battery back-up daily usage was heaviest in August at 28 kW-hr/day (delivered from the inverter) and lightest during December at 2.1 kW-hr/day. Daily delivery activity was 6 hr/day.[20]

Assumptions:

Average inverter output over 12 months = 15 kW-hr/day
Battery charge/discharge efficiency = 85 percent[21]
Inverter average efficiency = 80 percent[22]
Battery charge time = 6 hours
Battery charger efficiency = 85 percent[23]

$$Power\ Input = 15\ kW\frac{hr}{day}/(6\ \mathrm{hr/day} * 0.85 * 0.80 * 0.85)\ =\ 4.3\ \mathrm{kW}$$

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[18] (Bahaj, 1998) See References, Chapter III-D.
[19] (Bahaj, 2000) See References, Chapter III-D.
[20] (Bahaj, 2002) See References, Chapter III-D.
[21] Wholesaler, 2014a) See References, Chapter III-D.
[22] (Solar-Facts, 2014) See References, Chapter III-D.
[23] (Wholesaler, 2014b) See References, Chapter III-D.

GHG Emission Rates (All-Electric, Solar Assist)

Well-to-Tank (WTT) GHG Emission Rates

Emissions would be due to plugging a battery charger into the electric power grid for 6 hours each day.

Assumptions:

Conversion factor: 3.6 MJ/kW-hr
Carbon intensity factor (CI) for 2020+ electricity[24] = 79.95 gCO2e/MJ

$$WTT\ GHG\ Emissions = 4.3\ kW * 3.6 \frac{MJ}{kW - hr} * 0.07995 \frac{kgCO2e}{MJ} = 1.24\ kg\ CO2e/hr$$

Tank-to-Wheels (TTW) GHG Emissions (All-electric, solar assist)

TTW GHG emissions are zero for all-electric TR.

Well-to-Wheels (WTW) GHG Emissions (All-electric, solar assist)

$$WTW\ GHG = WTT + TTW = 1.24 + 0 = 1.24 \frac{kg}{hr} CO2e$$

Criteria Pollutant (CP) Emissions (All-Electric, Solar Assist)

CP emissions are only evaluated for TTW emissions (not WTT).

TTW CP Emission Rates (All-electric, solar assist*)*

TTW CP emissions rates for all-electric solar assist *TRs are zero.*

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[24] Technology Assessment: Fuels Assessment, Table V-6, 2020 Fuel Blend Assumptions for Electricity Marginal, 33% renewables to meet RPS (2020+). April 2015.

APPENDIX III.E-1:
WTW Assumptions and Calculations – Cryogenic TRs

There was no CA-Greet pathway for Liquid Nitrogen (LN_2) production, so TRU staff created a draft CA-GREET pathway document, which is included in Appendix III.E-2. Staff is requesting comments on that document.

Fuel Use Rate (Pure Cryogenic Trailer Transport Refrigerator, LN_2):

For the trailer transport refrigerator LN_2 technology, staff averaged the LN_2 fuel use rate estimate published for the CO_2 comparison in the Pedolsky paper with data provided by Linde for a use of 32.5 liters/hour (8.6 gallons/hour). (Ewig, 2014b; Pedolsky, 2010)

GHG Emissions Rates (Cryogenic TR)

Well-to-Tank (WTT) GHG Emissions (Cryogenic TR)

Fleets will most likely be supplied by a specialty gas company that produces LN_2 fuel by air liquefaction and cryogenic distillation at a central facility and transports it to the fleets’ on-site dispenser.

The LN_2 “fuel” is not a traditional fuel and is used for the cooling value rather than the heating value for combustion. Therefore, the “fuel” carbon intensity value is presented in gCO_2 per gallon rather than per mmBTU of heating value. This is different than the source of carbon intensity values that were used for all of the other WTT calculations herein, so it may be less comparable.. A similar pathway analysis is presented in Appendix III.E-2 Draft California Modified GREET 1.8b Pathways for Liquid Nitrogen from California Marginal Electricity. The GHG emissions factor for the manufacture, and transport and storage is calculated to be 524 gCO_2e/gal LN_2.

$$WTT\ GHG\ Emissions = 8.6\frac{gal}{hr} * 0.524\frac{kgCO2e}{gal\ LN2} = 4.5\ kg/hr\ \text{CO2e}$$

Tank-to-Wheels (TTW) GHG and Criteria Emissions Rates

Pure cryogenic LN_2 systems only emit nitrogen gas. Therefore TTW GHG and criteria pollutant emissions are zero.

Well-to-Wheels (WTW)

Since the TTW emissions are zero, the WTW emissions would equal the WTT emissions.

$$WTW\ (GHG) = WTT + TTW = 4.5\frac{kg}{hr}CO2e + 0 = 4.5\frac{kg}{hr}CO2e$$

Criteria Pollutant (CP) Emissions (Cryogenic TR)

CP emissions are only evaluated for TTW emissions (not WTT).

TTW CP Emissions Rates

Cryogenic TRs have no tailpipe emissions, so TTW CP emissions are zero.

APPENDIX III.E-2
DRAFT California Modified GREET Pathway For Liquid Nitrogen from California Marginal Electricity

SUMMARY

The Well-To-Tank (WTT) life cycle analysis of liquid nitrogen (LN_2) for use in cryogenic transport refrigerators (TR) pathway includes all steps from feedstock production to dispenser storage at the fueling location. Tank-To-Wheel (TTW) analysis includes the use of LN_2 for cooling. WTT and TTW analysis are combined together to provide a total Well-To-Wheel (WTW) analysis.

A life cycle analysis model called the Greenhouse gases, Regulated Emissions, and Energy use in Transportation (GREET)[25] developed by Argonne National Laboratory and updated in September 2008 has been used to estimate the energy use and greenhouse gas (GHG) emissions and attendant GHG emissions generated during the entire process required to produce electricity. The model however, was modified by TIAX under contract to the California Energy Commission during the AB 1007 process.[26] Changes were restricted to mostly input factors (electricity generation factors, transportation distances, etc.) with no changes in methodology inherent in the original GREET model. This California-modified GREET model formed the basis for all the fuel pathways published by staff in mid-2008. Subsequent to this, the Argonne Model was updated in September 2008. To reflect the update and to incorporate other changes, staff contracted with Life Cycle Associates to update the CA-GREET model. This updated California modified GREET model (v1.8b)[27] (released February 2009) formed the basis of the original electricity document

CA-GREET 2.0[28] is an update to CA-GREET 1.8b which was released in December 2014 and will be considered for adoption at the July 2015 ARB Board Meeting. The carbon intensity of California electricity is calculated in CA-GREET 2.0 using the 2010 average California generation resource mix from the U.S. Environmental Protection Agency's Emissions and Generation Resource Integrated Database (eGRID) database. The carbon intensities and heating values used in this document to calculate the energy use and greenhouse gas (GHG) emissions associated with a WTW analysis of LN_2 production for use in TRs are derived from CA GREET 2.0 and are available in the LCFS December 2014 Staff Report: Initial statement of Reasons, Appendix C: Comparison of CA-GREET 1.8b, GREET1 2013, AND CA-GREET 2.0[29]. and Proposed Updates as presented in the

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[25] GREET Model: Argonne National Laboratory: http://www.transportation.anl.gov/modeling_simulation/GREET/index.html

[26] California Assembly Bill AB 1007 Study: http://www.energy.ca.gov/ab1007

[27] CA_GREET Model (modified by Lifecycle Associates) released February 2009 (http://www.arb.ca.gov/fuels/lcfs/lcfs.htm)

[28] CA_GREET Model 2.0 released December 2014 (http://www.arb.ca.gov/fuels/lcfs/ca-greet/ca-greet.htm)

[29] LCFS December 2014 Staff Report: Initial Statement of Reasons, Appendix C: Comparison of CA-GREET 1.8b, GREET1 2013, AND CA-GREET 2.0 http://www.arb.ca.gov/react/2015/lcfs2015/lcfs15appc.pdf (Table 10, page C-24)

LCFS April 3, 2015 Workshop: Low Carbon Fuel Standard Re-adoption: Natural Gas Carbon Intensity and other CA-GREET Model Adjustments[30]

This document first details the WTT energy and inputs required to produce liquid nitrogen starting with the electricity required in the production of liquid nitrogen in California (section 1), then distribution to the dispensing facility (section 2). The electricity mix assumed is the *California average mix with 33 percent renewables*. Well-To-Tank energy and greenhouse gas emissions are calculated based on a volume basis as nitrogen is not used as a fuel – instead, it is used for cooling. The TTW part includes the use of liquid nitrogen in a cryogenic TR.

Several general descriptions and clarification of terminology used throughout this appendix are:

- Btu/mmBtu is the energy input necessary in Btu to produce one million Btu of a finished (or intermediate) product. This description is used consistently in CA- GREET for all energy calculations. There are 1,055 MJ per 1 mmBtu. As LN_2 is not a true fuel and does not have a heat value, energy use and emissions will be reported on a volume basis.
- gCO_2e/MJ provides the total greenhouse gas emissions on a CO_2 equivalent basis per unit of energy (MJ) for a given fuel. Methane (CH_4) and nitrous oxide (N_2O) are converted to a CO_2 equivalent basis using IPCC global warming potential values and included in the total. For the LN_2 pathway, gCO_2e will be reported on the volume basis of gCO_2e/gal LN_2.
- CA-GREET assumes that VOC and CO are converted to CO_2 in the atmosphere and includes these pollutants in the total CO_2 value using ratios of their molecular weights.
- Note that rounding of values has not been performed in several tables in this document. This is to allow stakeholders executing runs with the CA-GREET model to compare actual output values from the CA-modified model with values in this document.

Figure 1 shows the discrete components that form the production of liquid nitrogen via air separation pathway.

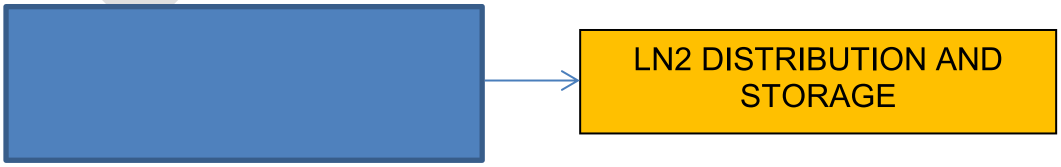

Figure 1: Discrete Components of the Nitrogen Pathway

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[30] Proposed Updates as Presented in the LCFS April 3, 2015 Workshop: Low Carbon Fuel Standard Re-Adoption: Natural Gas Carbon Intensity and other CA-GREET Model Adjustments http://www.arb.ca.gov/fuels/lcfs/lcfs_meetings/040315presentation.pdf

Table A provides a summary of the results for this liquid nitrogen pathway. The WTW analysis for liquid nitrogen results in **6146** Btu of energy required to produce 1 (one) gallon of liquid nitrogen. From a GHG perspective, **524** g CO_2e/gal of greenhouse gas emissions are generated during the production and distribution for the use of liquid nitrogen in a cryogenic TR. *Note that this pathway assumes California average 33 percent renewables electricity use.*

Table A: Summary of Energy Consumption and GHG Emissions for Liquid Nitrogen

	Energy Required (Btu/gal LN_2)	% Energy Contribution	GHG Emissions (gCO_2e/gal LN_2)	% Emissions Contribution
Well to Tank				
LN_2 Production	5738	93%	484	92%
Distribution and Storage	408	7%	40	8%
Total WTT	6146	100%	524	100%
Tank to Wheels				
Total TTW	0	0	0	0
Well to Wheels				
Total WTW	6146	100%	524	100%

Table A details the relative contribution of each discrete component of this pathway to the total energy use and total GHG emissions. From both an energy viewpoint and a GHG emissions perspective, the nitrogen production step (93 percent and 92 percent, respectively) comprises the largest part of the energy contributions to both the WTT and the WTW pathway.

The following sections provide summaries of each of the WTW components of these pathways for only the case of LN_2 gas from electricity. Expanded details are provided in Attachment A. A table of all input values and assumptions is provided in Attachment B.

For detailed calculations regarding electricity used here as an energy source for LN_2 production, please refer to another companion document "*Detailed California-Modified GREET Pathway for California Average and Marginal Electricity, Version 3*" (referred to as Electricity Document in sections to follow). For detailed calculations regarding the diesel fuel used in the transport of LN_2 to the dispensing site via heavy duty diesel tube trailers, please refer to another companion document "*Detailed California-Modified GREET Pathway for Ultra Low Sulfur Diesel (ULSD) from Average Crude Refined in California, Version 2.1*" (referred to as Diesel Document in sections to follow). All the companion documents listed here are available on

ARB's Low Carbon Fuel Standard website at http://www.arb.ca.gov/fuels/lcfs/workgroups/workgroups.htm#pathways .

Liquid Nitrogen Production:

Tables B and C provide a summary of the energy consumption and associated GHG emissions from liquid nitrogen production. Calculation details are provided in Attachment A.

Table B: Total Energy Consumption for Liquid Nitrogen Production, Btu/gal LN_2

Energy Type	Btu/gal LN_2
Total Energy	**5738**

Table C: Total GHG Emissions from Liquid Nitrogen Production, g/gal LN_2

Emission Type	gCO_2e/gal LN_2
Total GHG Emissions	**484**

Liquid Nitrogen Distribution and Storage

Tables D and E summarize energy consumption and GHG emissions from liquid nitrogen distribution and storage loss. Calculation details are provided in Attachment A.

Table D: Energy Use for Liquid Nitrogen Distribution and Storage Loss, Btu/gal LN_2

Energy Type	Btu/gal LN_2
Distribution Truck Energy	405.7
Distribution Storage Loss	2.6
Total Energy	408

Table E: GHG Emissions from Liquid Nitrogen Distribution and Storage Loss, g CO_2e/gal LN_2

Emission Type	g CO_2e/gal
Distribution Truck Emissions	39.3
Storage Loss Emissions	0.3
Total GHG Emissions	40

Cryogenic TR TTW Emissions

Since cryogenic TRs have no energy input, and only the cryogenic fuel emits to atmosphere, the TTW emissions of CO_2, CO, VOC, CH_4, and N_2O emissions are assumed to be zero.

ATTACHMENT A

SECTION 1. LIQUID NITROGEN PRODUCTION

1.1. Energy Use for Liquid Nitrogen Production

Liquid nitrogen is produced through air liquefaction and separation of the liquid air. Atmospheric air is used as the raw material and is filtered to remove particulates, moisture and contaminants. The air is then compressed in a centrifugal compressor from atmospheric (101.3 kPa) to 520 kPa. Impurities (primarily water vapor and carbon dioxide) are removed via molecular sieves or reversing heat exchangers. After cooling of the liquid air by a refrigeration process that includes expansion (to about -300 degrees F), the liquid air is then separated into liquid nitrogen and oxygen via distillation. These processes use equipment powered by electricity.

The LN_2 production process is assumed to use the most efficient available technologies based on the position paper published by the European Industrial Gases Association - Indirect CO_2 emissions compensation: Benchmark Proposal for Air Separation Plants[31]. The value in the reference is 549 kWh/tonne, which has been converted to Btu/gal for use in the model. The results of this energy calculation are provided in Table 1.1.

Table 1.1: Calculation of Total Energy Used to Produce Liquid Nitrogen, Btu/gal LN_2

Process Fuel Type	Conversion from kWh/tonne to Btu/gal LN_2	Direct Energy Use Btu/gal LN_2
Electricity	(Energy for LN_2 Production)*(3412.14Btu/kWh)*(0.454 kg/lb)(6.747 lb/gal)/(1000 kg/tonne)	5738

1.2. GHG Emissions from Liquid Nitrogen Production

The emission calculation methodology is analogous to the energy calculations. Emissions of GHG due to electricity generation are quantified using the carbon intensity factor of 80 g/MJ for Average CA electricity using 33 percent renewables and are shown in Table 1.2.

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[31] European Industrial Gases Association, Position Paper PP-33- Indirect CO_2 emissions compensation: Benchmark proposal for Air Separation Plants, December 2010 Retrieved from http://eiga.web1.apollo-com.be/fileadmin/docs_pubs/PP-33-Indirect_CO2_emissions_compensation_Benchmark_proposal_for_Air_Separation_Plants.pdf

Table 1.2: Calculation of GHG Emissions from Liquid Nitrogen Production, g/gal LN_2

Process Fuel Type	Calculation of GHG emissions	GHG emissions gCO_2e/gal LN_2
Electricity	(Energy for LN_2 Production, Btu/gal LN_2) *(1055 MJ/mmBtu)*(80 g/MJ) /(10^6 Btu/mmBtu)	484

SECTION 2. NITROGEN DISTRIBUTION AND STORAGE

2.1. Energy Use for Liquid Nitrogen Distribution and Storage

The final step in this nitrogen pathway is delivery by truck to the dispensing station. For the delivery component, it is assumed that liquid nitrogen is delivered by heavy duty diesel trucks over a one-way distance of 50 miles directly to dispensing stations (no intermediate stops at fuel terminals). Liquid nitrogen is stored briefly at the dispensing station, but generally the dispensing process to the on-board storage tank is performed via gravity or vaporization and does not use pumps or process that requires energy input.

In addition to truck fuel consumption, there are energy losses associated with nitrogen boil-off during truck transport and storage at the dispensing station. Emissions associated with these losses are accounted for in the net dispensed product. Table 2.1 provides the input values utilized in the energy consumption calculations while Table 2.2 illustrates the formulas used in the energy consumption calculations.

Table 2.1: Input Values Used to Calculate Distribution and Storage Energy Use

	Units	Value	Source
Diesel LHV	Btu/gal	127,464	CA-GREET Default
Truck Fuel Economy	Mi/gal	5.3	CA-GREET Default
Truck Liquid N_2 Payload	Tons	20	CA-GREET Default
Distance (roundtrip)	Miles	100	CA-GREET Default
LN_2 Density	lb/gal	6.747	Air Products Chart[32]
Truck Transit Time	Days	0.1	CA-GREET Default
Truck Boil-off rate	%/day	0.3%	Linde Brochure[33]
Truck Boil-off Recovery	%	80%	CA-GREET Default
Storage Time	Days	3	CA-GREET Default
Storage Boil-off rate	%/day	0.21%	Linde Brochure[34]
Storage Boil-off recovery	%	80%	CA-GREET Default

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[32] Air Products Chart: Nitrogen-Weight and Volume Equivalents retrieved from http://www.airproducts.com/products/Gases/gas-facts/conversion-formulas/weight-and-volume-equivalents/nitrogen.aspx

[33] Linde Cryogenic Standard Tanks LITS 2 retrieved from http://www.lindeus-engineering.com/internet.le.le.usa/en/images/P_3_3_e_12_150dpi136_5774.pdf

[34] Linde Cryogenic Standard Tanks LITS 2 retrieved from http://www.lindeus-engineering.com/internet.le.le.usa/en/images/P_3_3_e_12_150dpi136_5774.pdf

Table 2.2: Liquid Nitrogen Distribution and Storage Energy Calculations

Parameter	Units	Formula	Value
Truck Energy Intensity	Btu/ton-mile	(Diesel LHV, Btu/gal) / (Truck Fuel Economy, mi/gal) / (Truck LN_2 Payload, tons)	1202
Truck Energy Use	Btu/gal LN_2	(Truck energy intensity, Btu/ton-mile) * (roundtrip miles) * (LN_2 Density, lb/gal)/ (2000 lb LN_2/ton)	406
Truck Loss (Boil-off)	Btu/gal LN_2	(Truck Energy Use, Btu/gal LN_2) * ((Transit time, days) * (Boil-off rate, %/day)) / (1 – (transit time) * (Boil-off rate)) * (1 – recovery rate)	0.12
Storage Loss (Boil-off)	Btu/gal LN_2	(Truck Energy Use, Btu/gal LN_2) * ((Storage time, days) * (Boil-off rate, %/day)) / (1 – (storage time) * (Boil-off rate)) * 10^6 Btu/mmBtu * (1 – recovery rate)	2.56
Total Distribution and Storage Energy	Btu/gal LN_2	Truck Energy + Distribution Loss + Storage Loss	408

2.2. GHG Emissions from Liquid Nitrogen Distribution

The GHG emissions from distribution consist of emissions from the diesel truck over the 100 mile roundtrip distance plus storage boil-off losses. The GHG emissions are calculated using the carbon intensity factor of 91.8 g/MJ for Diesel, 10 percent Low CI (2020+) April 2015 and are shown in Table 2.3.

Table 2.3: Calculation of GHG Emissions from Distribution and Storage, g/gal LN_2

Process Fuel Type	Calculation of GHG emissions	GHG emissions gCO_2e/gal LN_2
Diesel	(Energy for LN_2 Distribution, Btu/gal LN_2) * (1055 MJ/mmBtu) * (91.8 g/MJ) / (10^6 Btu/mmBtu)	39.3
Diesel	(Energy for LN_2 Storage, Btu/gal LN_2) * (1055 MJ/mmBtu) * (91.8 g/MJ) / (10^6 Btu/mmBtu)	0.3
Total		39.6

SECTION 3. GHG EMISSIONS FROM CRYOGENIC TR

3.1. GHG Emission from a Cryogenic TR

If nitrogen is utilized in a cryogenic TR, it is assumed that there are no CO_2, CO, VOC, CH_4 and N_2O emissions. Hence for this pathway, there are no GHG emissions from the TTW portion of the analysis. All emissions are from the WTT part of the analysis.

ATTACHMENT B

LIQUID NITROGEN PATHWAY INPUT VALUES

Scenario: Liquid Nitrogen using California Electricity Marginal Mix

Parameters	Units	Values	Note
GHG Equivalent			
CO_2		1	CA-GREET Default
CH_4		25	CA-GREET Default
N_2O		296	CA-GREET Default
VOC		3.1	CA-GREET Default
CO		1.6	CA-GREET Default
Liquid Nitrogen Production			
Process Direct Energy Use	kWh/tonne LN2	549	EIGA Paper
Process Fuel Shares			
Electricity		100%	CA-GREET Default
Liquid Nitrogen Transport			
Heavy Duty Truck		100%	CA-GREET Default
Miles		50	CA-GREET Default
Boil Off Losses			
Loss Rate	%/day	0.3%	Linde Cryogenic Standard Tanks Brochure
Number of Days Stored	Days	0.1	CA-GREET Default
Liquid Nitrogen Storage at Refueling Station			
Boil Off Losses			
Loss Rate	%/day	0.21%	Linde Cryogenic Standard Tanks Brochure
Number of Days Stored	Days	3	CA-GREET Default
Recovery Rate		80%	CA-GREET Default

APPENDIX III.F-1:
WTW Assumptions and Calculations – Alternative Fuel (CNG, LNG) TRs

<u>Energy Use Rate (CNG Rebuild TR):</u>

According to North American Repower's preliminary tests on a 25 hp TRU engine, the fuel consumption was higher on a Diesel Gallon Equivalent basis, but less than 8 percent due to the lower compression ratio of the CNG engine.[35] No specific data with units were given. ARB staff assumes that the CNG fuel consumption will be 8 percent higher than the energy use rate of ultra-low sulfur diesel numbers presented in Appendix III.C-2.

Based on Appendix III.C-2, ARB staff used an average diesel use rate of 0.80 gal/hr for trailer TRUs and 0.6 gal/hr for truck TRUs.

Energy use for CNG TRs, with the 8 percent adjustment:

$$CNG\ Energy\ Use\ Rate, Trailer\ TR = 0.8\frac{gal}{hr} * \frac{127{,}464\frac{BTU}{gal}}{947.47\ BTU/MJ} * 1.08 = 116\ MJ/hr$$

$$CNG\ Energy\ Use\ Rate, Truck\ TR = 0.6\frac{gal}{hr} * \frac{127{,}464\frac{BTU}{gal}}{947.47\ BTU/MJ} * 1.08 = 87\ MJ/hr$$

<u>Energy Use Rate (LNG TR):</u>

Although LNG is a liquid in storage, it is vaporized and injected as a gas into the engine combustion chamber. The assumption is that the energy use of LNG engines will be very similar to CNG engines.

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[35] (Reed, 2014b) See References, Chapter III-F.

GHG Emission Rates:

Well-to-Tank (WTT) GHG Emissions (Alternative Fueled Engines)

WTT carbon intensity (CI) for 2020+ CNG fuel is: 17.67 gCO2e/MJ[36]

WTT CNG Trailer TR GHG Emissions:

$$WTT\ GHG\ Emissions = 116\frac{MJ}{hr} * 0.01767\frac{kgCO2e}{MJ} = 2.05\frac{kg}{hr}CO2e$$

WTT CNG Truck TR GHG Emissions:

$$WTT\ GHG\ Emissions = 87\frac{MJ}{hr} * 0.01767\frac{kgCO2e}{MJ} = 1.54\frac{kg}{hr}CO2e$$

WTT CI for 2020+ LNG fuel is: 23.63 gCO2e/MJ[37]

WTT LNG Trailer TR GHG Emissions:

$$WTT\ GHG\ Emissions = 116\frac{MJ}{hr} * 0.02363\frac{kgCO2e}{MJ} = 2.74\frac{kg}{hr}CO2e$$

WTT LNG Truck TR GHG Emissions:

$$WTT\ GHG\ Emissions = 87\frac{MJ}{hr} * 0.02363\frac{kgCO2e}{MJ} = 2.06\frac{kg}{hr}CO2e$$

Tank-to-Wheels (TTW) GHG Emissions

TTW CI for 2020+ CNG = 60.69 g CO2e/MJ[35]

TTW CNG Trailer TR GHG Emissions:

$$TTW\ GHG\ Emissions = 116\frac{MJ}{hr} * 0.06069\ \frac{kgCO2e}{MJ} = 7.04\frac{kg}{hr}CO2e$$

TTW CNG Truck TR GHG Emissions:

$$TTW\ GHG\ Emissions = 87\frac{MJ}{hr} * 0.06069\ \frac{kgCO2e}{MJ} = 5.28\frac{kg}{hr}CO2e$$

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[36] Technology Assessment: Fuels Assessment, Table V-6, 2020 Fuel Blend Assumptions for CNG, no renewable NG (2020+). April 2015. (There are currently no LCFS requirements for NG CI reductions.)

[37] Technology Assessment: Fuels Assessment, Table V-6, 2020 Fuel Blend Assumptions for LNG, no renewable NG (2020+). April 2015. (There are currently no LCFS requirements for NG CI reductions.)

TTW CI for 2020+ LNG = 60.92 g CO2e/MJ[36]

TTW LNG Trailer TR GHG Emissions:

$$GHG\ Emissions = 116\frac{MJ}{hr} * 0.06092\ \frac{kgCO2e}{MJ} = 7.07\frac{kg}{hr}CO2e$$

TTW LNG Truck TR GHG Emissions:

$$GHG\ Emissions = 87\frac{MJ}{hr} * 0.06092\ \frac{kgCO2e}{MJ} = 5.30\frac{kg}{hr}CO2e$$

Well-To-Wheels (WTW) GHG Emissions for 2020+ CNG and LNG

Combining (WTW = WTT + TTW):

CNG Trailer TR:	WTW = 2.05 + 7.04 = 9.09 kg/hr CO2e
CNG Truck TR:	WTW = 1.54 + 5.28 = 6.82 kg/hr CO2e
LNG Trailer TR:	WTW =2.74 + 7.07 = 9.81 kg/hr CO2e
LNG Truck TR:	WTW = 2.06 + 5.30 = 7.36kg/hr CO2e

Criteria Pollutant (CP) Emission Rates (2014)

CP emissions are only evaluated for TTW emissions (not WTT).

TTW CP Emission Rates

Certification values and inputs for alternative-fueled engines of comparable horsepower ratings were chosen from the ARB Engine Certification Page[38] as listed below. The emission standard for PM was listed in the Executive Order (EO) as “not applicable”.

TR Type	Fuel Type	Engine Example	Engine Power (HP)	HC + NOx Certification (g/kW-hr)	Load Factor	HC + NOx (g/hr)
Trailer	Nat Gas	Briggs & Stratton DBXS.9932HS EO: U-U-002-0763	24.67	5.4	52%	51.67
Truck	Nat Gas	Cummins EN5XS.7202BC EO: U-U-008-0254	14.77	4.7	56%	28.99

The calculations below are for the values shown in the right column of the table, above.

Trailer TR, natural gas-fueled:

$$TTW\ HC + NOx = \ 5.4\frac{g}{kW.hr} \times \frac{1kW}{1.341HP} \times 24.67HP \times 0.52 = 51.67\frac{g}{hr}$$

Truck TR, natural gas-fueled:

$$TTW\ HC + NOx = \ 4.7\frac{g}{kW.hr} \times \frac{1kW}{1.341HP} \times 14.77HP \times 0.56 = 28.99\frac{g}{hr}$$

PM emissions could not be calculated due to lack of emission factors.

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[38] ARB Engine Certification Data, Small Spark-Ignited Engines, 2013 and 2014, respectively. Retrieved October 7, 2014. http://www.arb.ca.gov/msprog/offroad/cert/cert_mfr.php

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