# APPENDIX H

## ANALYSES SUPPORTING THE ADDITION OR REVISION OF ENERGY ECONOMY RATIO VALUES FOR THE PROPOSED LCFS AMENDMENTS

# APPENDIX H

## ANALYSES SUPPORTING THE ADDITION OR REVISION OF ENERGY ECONOMY RATIO VALUES FOR THE PROPOSED LOW CARBON FUEL STANDARD AMENDMENTS

## TABLE OF CONTENTS

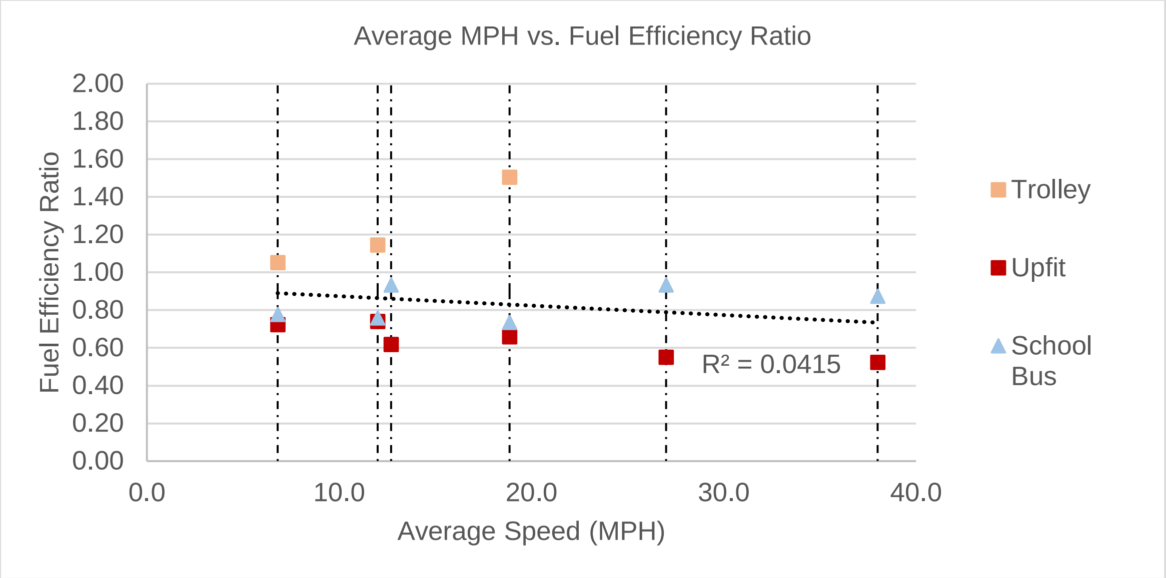
This appendix describes the analyses supporting the addition or revision of Energy Economy Ratio (EER) values for the proposed Low Carbon Fuel Standard (LCFS) Amendments.

## A. Energy Economy Ratio of Liquefied Petroleum Gas Relative to Conventional Diesel Vehicles

This section provides a comparison between energy usage from propane (Liquid Petroleum Gas, LPG) trucks and buses and diesel trucks and buses operated under identical duty cycles. The EER was derived which compares expected energy use and associated greenhouse gas (GHG) emissions between different vehicles technologies and fuel types. This section summarizes updated EER results when comparing 2010 model year or newer propane buses to equivalent diesel buses.

Comparisons between identical models of vehicles using the two fuels was not available. As such, vehicles were grouped into three categories based on size, weight, and purpose. The results are shown in Figure H-1. Based on the available test data, there is not a statistically significant correlation between propane and diesel EER and the average speed the vehicle operates. However, the data does show that propane vehicles are typically less efficient than diesel vehicles.

**Figure H-1: Vehicle Energy Economy Ratio at Different Average Speeds**



## 1. Altoona Test Data

This section describes the data used to compare propane truck and bus fuel consumption to similar diesel-fueled vehicles. The Altoona Bus Research and Testing Center regularly test buses as part of its program to evaluate new bus models.[1] Fuel economy tests are performed by operating the buses at full seated loaded weight (SLW, includes driver, standing, and seated passengers) on an outdoor test course. The fuel economy test includes three test cycles: Central Business District (CBD), Arterial, and Commuter. In addition, vehicle emissions testing and resulting fuel economy (mpg) calculated from the $CO_2$ emissions are performed in an emissions bay on a chassis dynamometer with the vehicle loaded to half-SLW, which is different from the full-SLW used on the outdoor test course. The dynamometer emissions tests include three different test cycles: Manhattan, Orange County, and Urban Dynamometer Driving Schedule (UDDS). These Altoona studies operate test cycles under as identical conditions as possible.

Due to the different SLWs by which these two different tests are conducted, the effects on fuel economy figures may vary between different vehicle types. Altoona assumes a weight of 150 lb. for each passenger and 600 lb. for each wheelchair. A 10,000-lb. curb weight vehicle that has been up-fitted (upfits) with a maximum passenger load of 8 people would be affected by a 600-lb. difference between full-SLW and half-SLW. However, an 18,000-lb. school bus with a 45-max passenger load would see a difference in weight of over 3,000 lb. between full-SLW and half-SLW. From these results, it is apparent that upfits are significantly less impacted than school buses by SLW differences. While these weight differences may affect overall trend relating fuel economy to the average speed of a test cycle, they have no impact on EER as both propane and diesel vehicles are affected by these weight differences during testing.

Five 2010 or newer propane buses and seven comparable 2010 or newer diesel buses have performed emissions and fuel economy testing as a part of Altoona testing. The data for bus fuel economies for the vehicles is shown below in Table H-1. Older models were not included as they do not meet the 2010 NOx standard and may not be representative of current technology engines. Two 2010 buses were excluded from the analysis. The Great American propane trolley, identified with an asterisk in Table H-1, was excluded from data analysis in comparing average fuel economy with the diesel trollies because of its significantly lower GVWR and loaded weight during testing. The Star Trans diesel trolley, also identified with an asterisk, was excluded from data analysis due to its significantly higher loaded weight during testing.

---

[1] Altoona Bus Tests: http://altoonabustest.psu.edu/

**Table H-1: Altoona Testing Data**

| Vehicle Type | Make and Model | Model Year | Vehicle Type - GVWR (lb.) | Length | Fuel Economy (Miles per Diesel Gallon Equivalent) | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | Test Track | | | Chassis Dynamometer | | |
| | | | | | CBD | Arterial | Commuter | Manhattan | OCBC | UDDS |
| | | | | | 12.7 mph | 27.0 mph | 38.0 mph | 6.8 mph | 12.0 mph | 19.1 mph |
| **Propane (LPG) Models** | | | | | | | | | | |
| Trolley | Great American Trolley Company MIDI-Ford* | 2014 | 18,000 | 28’ | 5.36 | 5.19 | 8.97 | 4.72 | 6.71 | 7.66 |
| Trolley | Double K Villager | 2015 | 22,000 | 27' | 4.48 | 4.84 | 7.69 | 4.19 | 5.97 | 8.64 |
| Upfit | Roush ElDorado | 2011 | 14,500 | 25' | 4.45 | 3.79 | 5.93 | 4.98 | 7.20 | 8.49 |
| Upfit | Glaval Titan II | 2013 | 14,200 | 25' | 5.33 | 5.23 | 8.73 | 5.01 | 7.42 | 8.13 |
| School Bus | Blue Bird Propane Vision | 2013 | 31,000 | 39' | 4.17 | 4.59 | 7.99 | 3.15 | 4.43 | 5.49 |
| **Diesel Models** | | | | | | | | | | |
| Trolley | Double K Villager | 2011 | 26,000 | 26' | N/A | N/A | N/A | 3.99 | 5.22 | 5.75 |
| Trolley | Star Trans President* | 2010 | 26,000 | 35' | 4.31 | 4.91 | 8.77 | 3.69 | 5.14 | 6.72 |
| Upfit | Elkhart ECG | 2011 | 14,200 | 26' | 9.02 | 9.41 | 15.3 | 6.95 | 9.85 | 12.03 |
| Upfit | Goshen U.L.F. | 2013 | 14,200 | 26' | 7.11 | 7.17 | 13.07 | 6.85 | 9.89 | 13.24 |
| Upfit | Turtle Top Odyssey | 2010 | 14,200 | 27' | 7.6 | 8.04 | 13.63 | N/A | N/A | N/A |
| School Bus | Blue Bird All American RE | 2013 | 31,350 | 35' | 4.27 | 4.76 | 9.27 | 3.81 | 5.63 | 6.89 |
| School Bus | Blue Bird All American FE | 2013 | 31,350 | 36' | 4.67 | 5.08 | 9.03 | 4.31 | 6.07 | 8.05 |

**Excluded from Analysis*

### a. Altoona Data Analysis

The buses above were separated into three categories dependent on size, weight, and application to promote as appropriate comparisons as possible given the available data. The three groups established are trolleys, passenger-carrying upfits below 30 feet, and large school buses.  The mean propane and diesel fuel economies are shown in Figures H-2 through H-4.

**Figure H-2:  Altoona Trolley Diesel vs. Propane Fuel Economy**

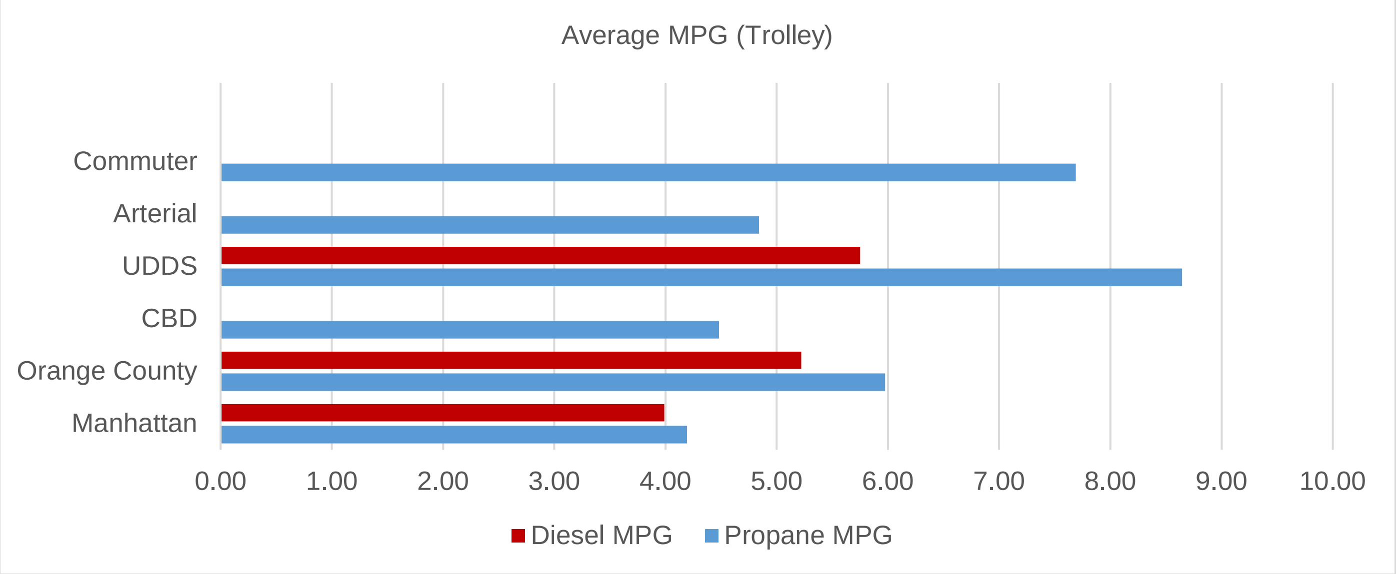
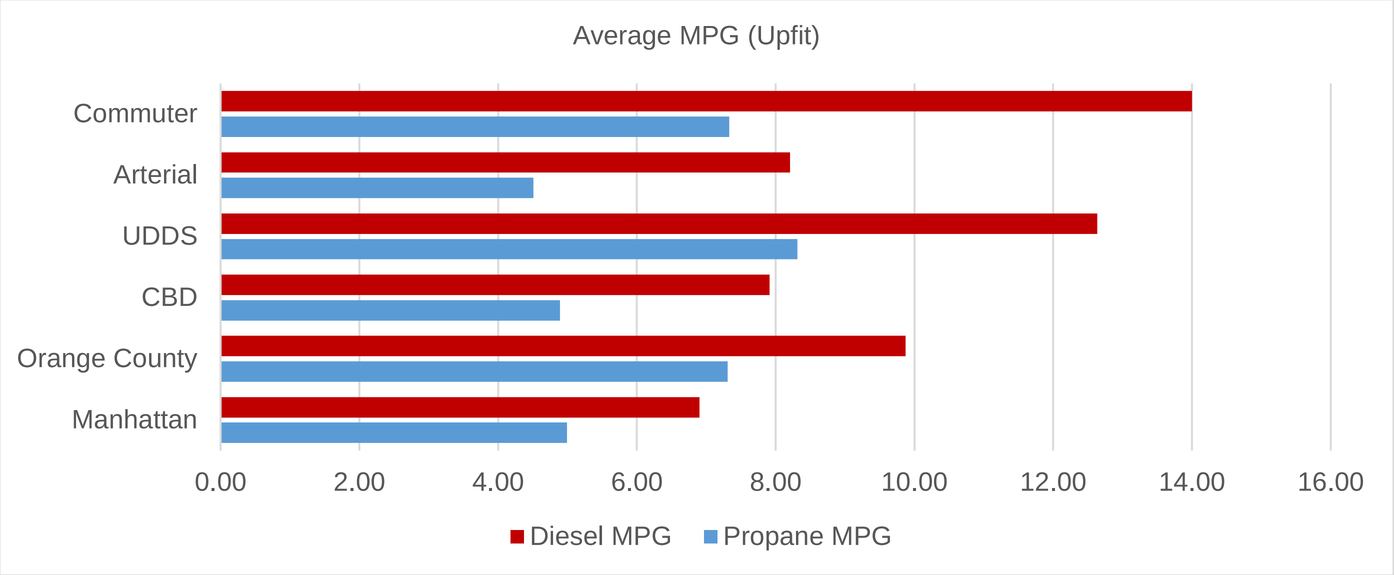
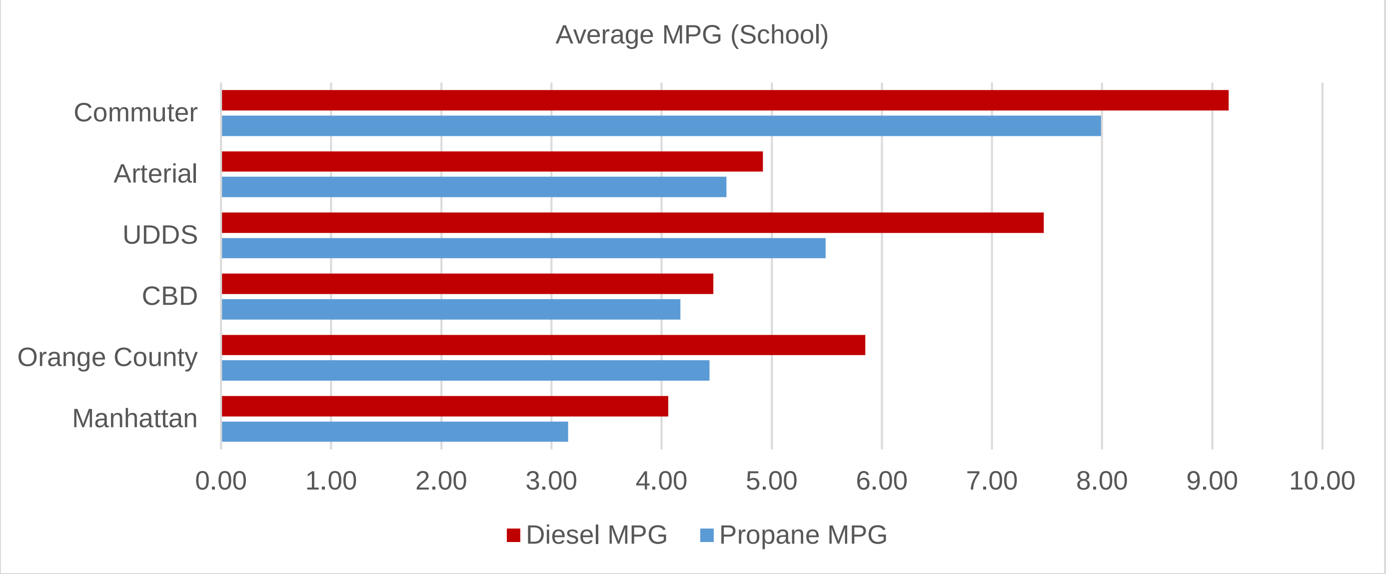


**Figure H-3:  Altoona <30 feet Upfits Diesel vs. Propane Fuel Economy**



## Figure H-4: Altoona School Bus Diesel vs. Propane Fuel Economy



### b. Test Data Summary

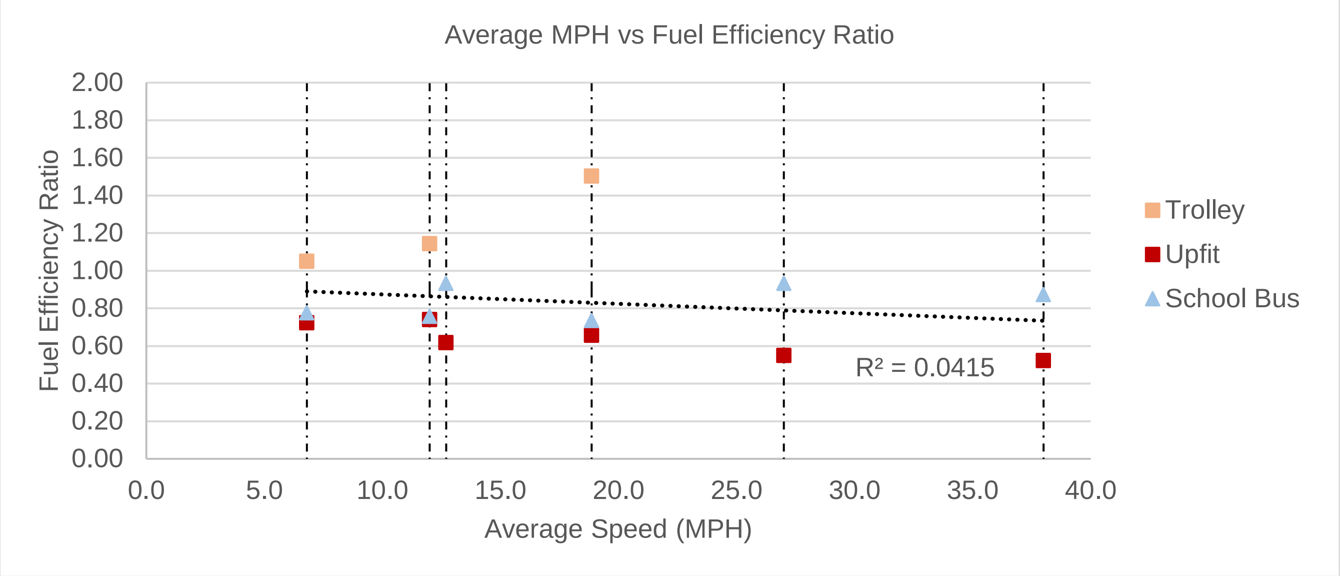
The Altoona tests data results between diesel and propane-fueled comparable vehicles are show in Table H-2 with the average speed of each test cycle. The Calculated EER range from a low of 0.52 to a high of 1.5.

**Table H-2: Summary of Altoona EER Results**

| Test Cycle | Average Speed (mph) | EER (Trolley) | EER (Upfit) | EER (School) |
|---|---|---|---|---|
| Manhattan | 6.8 | 1.05 | 0.72 | 0.78 |
| Orange County | 12.0 | 1.14 | 0.74 | 0.76 |
| CBD | 12.7 | N/A | 0.62 | 0.93 |
| UDDS | 18.9 | 1.50 | 0.66 | 0.74 |
| Arterial | 27.0 | N/A | 0.55 | 0.93 |
| Commuter | 38.0 | N/A | 0.52 | 0.87 |

Note that due to limited data available it was difficult to produce an exact “apples-to-apples” comparison of fuel economies of the vehicles available. All vehicles from the Altoona bus database are tested on identical cycles and were separated into comparable groups to allow for appropriate analysis of EERs. Figure H-5 shows EERs plotted for all Altoona results.

## Figure H-5: Altoona Testing EER Analysis Results



While the trend line for EERs of propane vs. diesel vehicles decrease linearly, the R-squared value implies the trend line is not representative of overall trend. This implies that, given the information available, while it is certain that propane vehicles are typically less energy efficient than their diesel counterparts, the degree of efficiency is most likely not correlated to average speed. With this data, the mean or the median of all data should be regarded as representative of the EER between propane and diesel vehicles. The Altoona test data shows EER values ranging from 0.52 to 1.50, with a mean of 0.83 and a median of 0.76.

Based on the analysis of section B of this Appendix H, the EER of LPG relative to gasoline is about 1.0, which is the same as the EER of CNG relative to gasoline provided in the LCFS regulation. In addition, staff's analysis[2] of certification emissions[3,4] for the same spark-ignited engine operated on LPG and CNG demonstrates EERs differing by only about 1 percent. Also, the LCFS regulation provides an EER of 0.9 for CNG used in spark-ignited engines, relative to diesel fuel used in compression-ignited engines. For these reasons, staff believes that the EER of LPG used in spark-ignited engines, relative to diesel fuel used in compression-ignition engines, should be 0.9.

---

[2] Based on complete combustion, 53.36 Btu/gC for LPG and 60.00 Btu/gC for CNG.

[3] https://www.arb.ca.gov/msprog/onroad/cert/mdehdehdv/2017/roush_hdoe_a3440074r1_6d8_0d05_lpg.pdf

[4] https://www.arb.ca.gov/msprog/onroad/cert/mdehdehdv/2017/roush_hdoe_a3440078_6d8_0d10_cng.pdf

### 2. Conclusion

An “apples-to-apples” comparison was not possible due to limited availability of relevant test data and the generally larger size and weight of diesel vehicles compared to their propane counterparts. However, grouping available vehicles by similar size, weight, and purpose produced somewhat comparable results for the fuel efficiency of propane vs. diesel. Data indicates propane vehicles to be generally less efficient than diesel vehicles.

Based on other analyses, staff believes that the EER of LPG used in spark-ignited engines should be the same as the EER of CNG used in spark-ignited engines. Therefore, staff recommends adopting an EER of 0.9 for LPG used in spark-ignited engines, relative to diesel fuel used in compression-ignition engines.

## B. Energy Economy Ratio of Liquefied Petroleum Gas Relative to Gasoline for a Spark-Ignited-Engine Powered Vehicle

Staff analyzed test data from Altoona Bus Research and Testing Center[5] reports on Blue Bird Body Company’s Propane Vision[6] and Gasoline Vision[7] bus models to determine the EER of liquefied petroleum gas (LPG or propane) relative to gasoline. Both or these bus models were tested for emissions (g/mi) over three different driving cycles on a large-roll chassis dynamometer. Fuel economy (mpg) was calculated from carbon dioxide and carbon monoxide emissions, an average of two runs per cycle, and fuel properties. As can be seen in Table H-3 and Table H-4 below, the two bus models are very similar. There are some differences between the two models, such as weight, which could affect fuel consumption. Some differences may be offsetting, such as tire width and tire pressure, and axel ratio and tire diameter. Although the comparison is not perfect, and the amount of data is very small, the underlying assumption is that the thermal efficiency of a spark-ignited engine operated with two different liquid hydrocarbon fuels should not be vastly different.

**Table H-3: Blue Bird Body Company Test Vehicle Summaries**

| Vehicle Data Type | Propane Vision Bus Model | Gasoline Vision Bus Model |
|---|---|---|
| Number of Seats | 45 | 72 |
| Length (feet, inches) | 39, 8.5 | 39, 1.75 |
| Width (inches) | 96 | 96 |

---

[5] Altoona Bus Tests: http://altoonabustest.psu.edu/.

[6] The Thomas D. Larson Pennsylvania Transportation Institute. Partial STURAA Test 10 Year 350,000 Miles Bus from Blue Bird Body Company Model Propane Vision. July 2013. http://altoonabustest.psu.edu/buses/reports/430.pdf?1377522313.

[7] The Thomas D. Larson Pennsylvania Transportation Institute. Federal Transit Bus Test. Blue Bird Body Company Model Propane Vision. July 2017. http://altoonabustest.psu.edu/buses/reports/478.pdf?1505843250.

| | | |
|---|---|---|
| Height (inches) | 125 | 119 |
| Wheel Base (inches) | 273 | 273.75 |
| Driven Wheels | Rear | Rear |
| Driven Axel Ratio | 5.29 | 6.17 |
| Drive Wheel Track (inches) | 73.4 | 72.6 |
| Driven Axel Weight (lbs.) | 17,940 | 21,020 |
| Seated Load Weight (lbs.) | 24,820 | 28,220 |
| Tire Size | 287 / 11R22.5 | 255 / 70R22.5 |
| Tire Diameter (inches) | 44.5 | 36.6 |
| Cold Tire Pressure (psi) | 120 | 105 |
| Engine | Ford | Ford |
| Displacement (liters) | 6.8 | 6.8 |
| Configuration | V10 (assumed) | V10 |
| Transmission | Ford | Ford |
| Number of Speeds | 6 | 6 |
| Type | Torqshift Automatic | Automatic |

### Table H-4: Vehicle Test Summaries

| Vehicle Test Data | Propane Vision Bus Model | Gasoline Vision Bus Model |
|---|---|---|
| Date Tested | July 10, 2013 | May 2017 |
| CO$_2$ Emissions (g/mi) | | |
| Manhattan Driving Cycle | 2787 | 3207 |
| Orange County Bus Cycle | 1971 | 2270 |
| UDDS Driving Cycle | 1587 | 1474 |
| CO Emissions (g/mi) | | |
| Manhattan Driving Cycle | 4.40 | 5.7 |
| Orange County Bus Cycle | 3.70 | 5.6 |
| UDDS Driving Cycle | 6.52 | 5.4 |
| Carbon Emissions[8] (g/mi) | | |
| Manhattan Driving Cycle | 761.8 | 876.9 |
| Orange County Bus Cycle | 539.0 | 621.3 |
| UDDS Driving Cycle | 435.5 | 404.2 |
| Fuel Economy[9] (mpg) | | |
| Manhattan Driving Cycle | 2.082 | 2.639 |
| Orange County Bus Cycle | 2.942 | 3.724 |
| UDDS Driving Cycle | 3.642 | 5.725 |

---

[8] Calculated as CO$_2$ Emissions x (12/44.011) + CO Emissions x (12/28.011)

[9] [Carbon Content of Fuel (g/gal)]/[Carbon Emissions (g/mi)], where 1586 g/gal is the estimated carbon content of the LPG and 2314 g/gal is the average carbon content of regular Pennsylvania reformulated gasoline from the Alliance of Automobile Manufacturers 2015 Summer Gasoline North American Survey.

| | | |
|---|---|---|
| Fuel Economy[10] (mi/MMBtu) | | |
| Manhattan Driving Cycle | 24.60 | 23.54 |
| Orange County Bus Cycle | 34.76 | 33.22 |
| UDDS Driving Cycle | 43.03 | 51.06 |
| Energy Economy Ratio[11] | | |
| Manhattan Driving Cycle | 1.05 | 1.00 |
| Orange County Bus Cycle | 1.05 | 1.00 |
| UDDS Driving Cycle | 0.84 | 1.00 |
| MEDIAN | 1.05 | 1.00 |
| MEAN | 0.98 | 1.00 |

The specific gravity and lower heating value of the LPG were determined to be 0.5100 and 19,904 Btu per pound, respectively, so the volumetric energy content of the LPG was 84,636 Btu per gallon (89.30 MJ/gal). The gasoline was regular-grade, 10-percent ethanol blend, which staff is assuming had a volumetric energy content of 112,114 Btu/gal[12] (118.29 MJ/gal). Staff is using the lower end of the range for the volumetric energy content of reformulated gasoline. However, the value is higher than the value for CaRFG found in Table 3 of the current LCFS regulation. A higher gasoline volumetric energy content, or a lower LPG volumetric energy content, would increase the EER values calculated for LPG relative to gasoline.

Based on the test data, the EERs calculated for the three driving cycles, a median EER of 1.05 and a mean EER of 0.98, staff recommends adopting an EER of 1.0 for LPG relative to gasoline in spark-ignited-engine powered vehicles.

## C. Calculation of Proposed Energy Economy Ratio for Electric Transport Refrigeration Units under the Low Carbon Fuel Standard

A preliminary EER value of 3.4 is proposed for grid-connected electric transport refrigeration units (eTRU) to establish an initial category for eTRU in the LCFS.

Electric refrigeration units (TRUs) are currently defined as refrigeration systems that are powered by internal combustion engines (inside the unit housing). TRUs control the environment of temperature-sensitive products transported in refrigerated trucks, trailers, railcars and shipping containers. They may be capable of cooling or heating. TRUs are used to transport and store many products, including, but not limited to food,

---

[10] Based on complete combustion, 53.36 Btu/gC for LPG and 48.45 Btu/gC for gasoline.

[11] The Energy Economy Ratio (EER) is [Fuel Economy (mi/mmBtu)]/[Fuel Economy (mi/mmBtu)]$_{\text{Gasoline}}$.

[12] U.S Department of Energy. Alternative Fuels Data Center. Fuel Properties Comparison. https://www.afdc.energy.gov/fuels/fuel_properties.php.

pharmaceuticals, plants, medicines, blood, chemicals, photographic film, art work, and explosives.[13]

Certain TRUs have dual fuel capability; powered from diesel-fueled internal combustion engines while mobile and capable of being powered by the electric grid whenever parked at electrified parking spaces with an appropriate TRU electric outlet, known as eTRU. The preliminary EER value proposed applies to commercially available eTRU connected to the electric grid while stationary.

This initial data is from a technical assistance project “Pollution Prevention and Technical Assistance for Idle Reduction and Electrification in Transport Refrigeration Units”[14] supported by EPA Region 10 to provide technical assistance to reduce idling in stationary TRU. The referenced technical assistance and data collection project was a collaboration between TREC, the Transportation Research and Education Center for Portland State University, Forth Mobility, and CleanFuture.

Further research on transport refrigeration units is being conducted by CARB in a project “Data Collection and Business Case Study for eTRUs”[15] and other organizations are also conducting research on transport refrigeration units which will continue to add to the body of knowledge for grid-connected electric standby and hybrid electric TRUs.[16] Once results of these other studies become available there will likely be refinements to the Energy Economy Ratio(s) for TRUs to better encompass the variety of TRU use-cases. In the meantime, the EER of 3.4 is proposed as a conservative value based on field data collection.

Data presented in Table H-5 and Figure H-6 are from a single fleet, collected during a technical study of refrigerated fleet operations in multi-temperature trailers. The purpose was to develop a business case for TRU idle reduction. While the sample size

---

[13] CARB, (2017). ”Transition to Zero-Emission Technologies for TRUs.” https://www.arb.ca.gov/cc/coldstorage/cold-storage.htm. Accessed September 1, 2017

[14] EPA, (2016) “Fiscal Year 2015 Pollution Prevention Grant Summaries.” Collections and Lists. U.S. Environmental Protection Agency. Office of Chemical Safety and Pollution Prevention. https://www.epa.gov/p2/fiscal-year-2015-pollution-prevention-grant-summaries#region10. Accessed August 15, 2017

[15] CARB, (2017). “Request for Proposal (RFP) No. 16TTD008 titled "Data Collection and Business Case Study for eTRUs." This RFP can be found at the California State Contracts Register at:

https://caleprocure.ca.gov/pages/index.aspx.

[16] An “Electric Standby TRU” has a refrigeration system that may be selectively powered by either a diesel-fueled internal-combustion engine or an integrated electric motor. A “Hybrid Electric TRU” is powered by a diesel fueled internal-combustion engine coupled with an electric generator that provides electricity to an electric-motor driven refrigeration system within the same housing. Both are capable of being powered via an external source, such as the electric power grid. CARB, “Regulatory Guidance: Transport Refrigeration Units Alternative Technology Compliance Strategies – Electric Standby and Hybrid Electric Systems.” June 2013,

https://www.arb.ca.gov/diesel/tru/documents/guidance_electricstandby_ets.pdf, accessed July 8, 2017.

is small, the data is valid data, presents conservative figures, and is a conservative representation of TRU diesel and electricity consumption.

The diesel fuel usage of 1.01 gallon per engine operating hour is averaged from four trailers; this value is consistent with an industry rule of thumb of 1 gallon of diesel per engine hour, and with similar values measured in other studies. The electricity consumption is measured in one of the four trailers in the sample. Details of the transport refrigeration equipment are as follows:

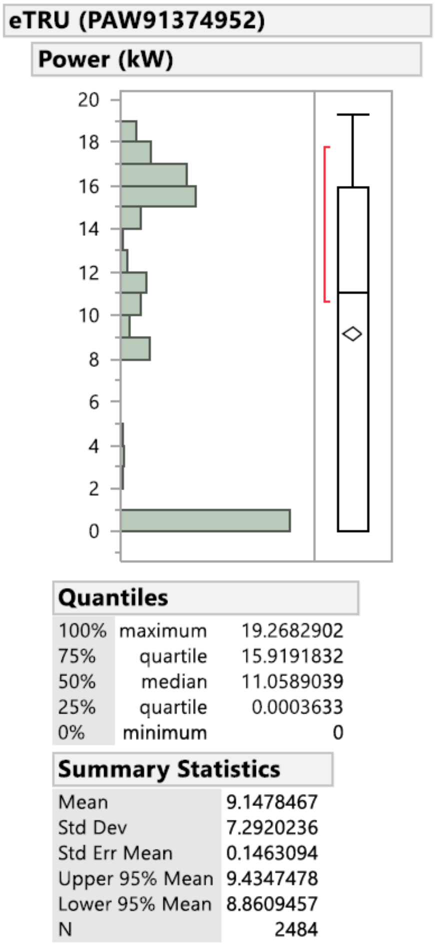
- TRU make/model: Carrier Transicold / Vector 8600 MT
- Temperature set point, compartment 1: -9.9 (°F)
- Temperature set point, compartment 2: 34.0 (°F)
- Diesel fuel consumption: 1.01 gallons / hour averaged from 4 TRUs during June 2016 in Table H-5.

**Table H-5: TRU Average Fuel Consumption (June 2016)**

| Trailer # | Diesel (gallons) | Engine hours | Fuel Consumption (gal/hr.) |
|---|---|---|---|
| 5057 | 389.50 | 248 | 1.57 |
| 5058 | 121.26 | 300 | 0.4 |
| 5059 | 153.08 | 190 | 0.81 |
| 5060 | 351.09 | 269 | 1.31 |
| **Total** | **1014.9** | **1007** | |
| Average | | | 1.01 |

Median electricity consumption: 11.05 kWh from a sample TRU is shown in Figure H-6.

**Figure H-6: eTRU Electricity Use**



**Quantiles**

| | | |
|---|---|---|
| 100% | maximum | 19.2682902 |
| 75% | quartile | 15.9191832 |
| 50% | median | 11.0589039 |
| 25% | quartile | 0.0003633 |
| 0% | minimum | 0 |

**Summary Statistics**

| | |
|---|---|
| Mean | 9.1478467 |
| Std Dev | 7.2920236 |
| Std Err Mean | 0.1463094 |
| Upper 95% Mean | 9.4347478 |
| Lower 95% Mean | 8.8609457 |
| N | 2484 |

The EER of 3.4 is proposed as a preliminary value for eTRUs. The proposed EER is calculated as follows:

$$EER^{XD} = \frac{E^{XD}_{displaced}}{E_i}$$

where:

$E_i$ is the energy density of electricity in MJ for these fuels:

| Symbol | Fuel (units) | Energy Density |
|---|---|---|
| $E^{XD}_{displaced}$ | Diesel fuel (gal) | 134.47 MJ/gal |
| $E_i$ | Electricity (kWh) | 3.60 MJ/kWh |

$$EER^{XD} = \frac{1.01\,\frac{gal}{hr} \times 134.47\,\frac{MJ}{gal}}{11.05\,\frac{kWh}{hr} \times 3.60\,\frac{MJ}{kWh}}$$

$$EER^{XD} = \frac{135.81\ MJ}{39.79\ MJ}$$
$$EER^{XD} = 3.4$$

The TRU example data is from a technical study in a refrigerated fleet to evaluate the business case to invest in TRU electric infrastructure for idle reduction of hybrid eTRUs. The example provided to establish preliminary EER is a conservative example, for instance, the energy consumption in a multi-temperature TRU is typically greater due to separate temperature zones and more frequent door openings inherent with multi-temperature applications. A typical energy consumption in a single temperature TRU may be closer to 9 kWh/hr, which would indicate a higher EER value. It is expected that ongoing studies by CARB and other organizations will contribute more data to refine the EER value(s) for eTRUs as larger samples are examined, both by application and manufacturer.

## D. Estimate for Energy Economy Ratios for Consideration of On-Road Electric Motorcycles in the Low Carbon Fuels Standard Program

CARB staff conducted this analysis to determine the EER for on-road electric motorcycles for use in the LCFS program. Due to limited availability of data, staff was only able to make a conservative EER estimate of 4.4 for on-road electric motorcycles.

### 1. Data Sources

Manufacturers of electric on-road and dual sport motorcycles submitted miles per gallon-equivalent (MPGe) data generated using the Urban Dynamometer Driving Schedule (UDDS). To determine the fuel economy for comparable on-road and dual sport motorcycles, staff referred to the United States Environmental Agency's (U.S. EPA) on-road motorcycle emissions certification data generated using the UDDS.[17]

### 2. Methodology

Staff calculated UDDS fuel economy (mpg) for comparable internal combustion engine (ICE) motorcycles from the U.S. EPA emissions data set. Comparable ICE motorcycles were defined as those having a power rating within approximately ± 10 percent of the electric motorcycle being considered. EERs were determined for each electric motorcycle by taking the ratio of UDDS generated MPGe over mpg. An average EER was then calculated for electric motorcycles. Table H-6 lists the MPGe, mpg of comparable ICE motorcycles, and EER for each of the electric motorcycles included in this evaluation.

---

[17] U.S. EPA motorcycle emissions data. https://www.epa.gov/sites/production/files/2017-03/2018-mc-ctrr.xls.

**Table H-6: Motorcycle Data for Calculating EERs**

| | Power (kW) | MPGe UDDS | MPGe Highway | Avg. MPG UDDS (comparable ICE) | EER |
|---|---|---|---|---|---|
| Bike A | 20 | 485 | 205 | 68.8 | 7.05 |
| Bike B* | 25 | 475 | 225 | 61.0 | 7.79 |
| Bike C | 33 | 485 | 205 | 53.6 | 9.04 |
| Bike D* | 40 | 453 | 225 | 54.5 | 8.32 |
| Bike E* | 45 | 457 | 225 | 53.6 | 8.51 |
| Bike F | 50 | 476 | 240 | 44.0 | 10.81 |
| Bike G | 52 | 476 | 240 | 44.5 | 10.69 |

* Composite MPGe of multiple bikes with the same power rating.

Staff's initial estimate of the average EER for On-Road Electric Motorcycles is 8.89. However, a truly representative EER would be based on data collected over multiple drive cycles representing real world operating conditions. Only emissions data derived from the UDDS was available to staff to calculate ICE motorcycle fuel economy. Data presented in Table H-6 shows that Highway MPGe is approximately one-half of the UDDS MPGe, meaning staff's estimated EERs may be higher than a truly representative EER that is based on real world usage. To account for the difference between UDDS MPGe and the actual MPGe that is likely to be achieved in real world usage, staff multiplied the initial EERs by a factor of 0.5. This results in more conservative EER values, which staff recommends should be used until such time that a more comprehensive data set of motorcycle fuel economy data under various operating conditions can be collected and analyzed.

Staff's final estimate of the average EER for On-Road Electric Motorcycles is 4.4.

Staff encourages industry stakeholders to use their expertise and resources to generate and submit additional data for electric motorcycles and comparable ICE motorcycles operated under a wide variety of real-world conditions. Staff will evaluate additional data when it becomes available, and will consider proposing to amend to the on-road motorcycle EER, and including off-road applications, if such action is supported by a more robust data set than what was available in the above analysis.

## E. Battery Electric Truck and Bus Energy Economy Compared to Conventional Diesel Vehicles

This section[18] provides a comparison of energy usage from battery electric trucks and buses when compared to energy usage from similar conventional diesel vehicles operated in the same duty cycle. Several years ago, CARB established an estimated EER of 2.7 for battery electric trucks compared to diesel trucks based on limited data from 2007. The EER for buses was set at 4.2 for buses based on test data on several

---

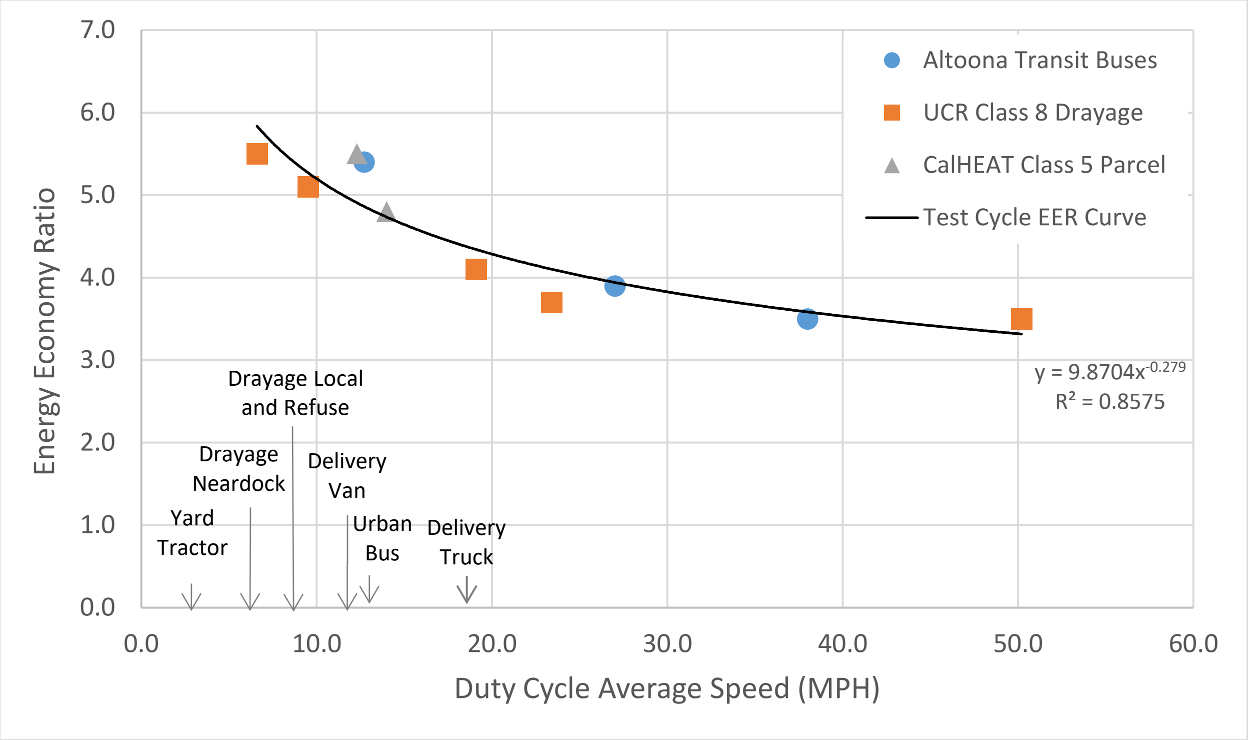
[18] This section supersedes the version originally posted in September 2017 (https://www.arb.ca.gov/msprog/actruck/docs/HDBEVefficiency.pdf)

buses that was more recent. The EER is used to compare expected energy use and associated greenhouse gas emissions for different vehicle technologies and fuel types. As more zero emission trucks and buses have come to market additional information has become available for comparison.

Staff found that the combined data from different studies show a statistically significant correlation between the EER and average driving speed for battery electric trucks and buses when compared to equivalent conventional diesel trucks and buses for a wide range of vehicle types and weight classes. Most fuel economy comparisons for electricity or other fuel types are made on the basis of miles per diesel gallon equivalent (mpdge). The primary data sources used in this analysis was from three studies that measured diesel fuel and electricity use for 40-foot transit buses, Class 8 drayage trucks and parcel delivery trucks.

These studies were performed with comparable vehicles and loads on the same test cycles. This ensures that the comparisons are as "apples-to-apples" as possible. Although fuel economy varies for different vehicles and duty cycles, staff found that the EER has a statistically significant correlation (P-value <.05 at 95 percent confidence interval) to test cycle average speed as shown in Figure H-7. Also displayed on the bottom left of the figure is the average speed of several vehicle categories where electric vehicles are commercially available or are being demonstrated.

**Figure H-7: Vehicle Energy Economy Ratio at Different Average Speeds**[19]



---

[19] Vehicle energy use excludes charger-battery system efficiency losses.

The results show that the efficiency improvement of battery electric vehicles is considerably higher than conventional diesel vehicles for different weight classes, vehicle types, and duty cycles.  The vehicle EER is about 3.5 at highway speeds and 5 to 7 times the efficiency of conventional diesel vehicles when operated at lower speed duty cycles where idling and coasting loses from conventional engines are highest.

Staff also compared the results to available in-use data for additional vehicle types.  The in-use data is from an extensive one-year study of a transit bus fleet operation, data from an airport shuttle business using Class 3 passenger vans, a report of in-use Class 3 and 4 delivery vans, and a report on Class 8 yard trucks.  By its nature, in-use data has more variables and is not as robust as data collected on the same test cycle; however, the in-use data from these additional vehicles showed that the efficiency gains were largely consistent in-use as the test data.

To put these results in context, the average daily speed for near dock drayage trucks, delivery vans, urban buses, and yard tractors are commonly below 13 miles per hour (mph).  For a typical delivery van or urban bus, the EER is about 5 and can be higher than 6 for yard trucks and trash trucks that tend to operate at the lowest speeds. Several other vehicle categories representing local vehicle operation average less than 13 mph.  In the next decade, battery electric trucks and buses are more likely to be placed in service in these slower speed operations because of battery range limitations, battery costs, and the expectation that the early battery electric truck and bus market is more likely to be supported by centrally operated and maintained fleets that are expected to primarily be charged in the yard.

These results show that the expected efficiency gains from electrification of trucks and buses are better than previously estimated, especially for low speed duty cycles.  The resulting greenhouse gas emissions benefits and fuel saving would also be higher than previously estimated.  The EER is also used to determine how many credits an electric vehicle owner can receive for using electricity as a motor vehicle fuel.  Potential updates to the Low Carbon Fuel Standard program would result in higher credits per kWh used and would lower the total cost of ownership of a given electric vehicle.  The EER curve also allows the end user to estimate the electricity usage for a battery electric vehicle that would replace a conventional vehicle operated in the same conditions if the average speed and fuel economy of the conventional vehicle is known.  When doing emissions analysis or total cost of ownership analysis, charger and battery system inefficiencies must also be taken into consideration as discussed in Attachment 1.

This section is organized as follows:

- Section 1 describes the information that was used from individual studies where conventional diesel vehicles and equivalent battery electric vehicles were tested for vehicle energy used.

- Section 2 describes available in-use data that was used to compare to the test cycle results.
- Section 3 provides an overview of typical average driving speeds for different vehicle types and uses.

## 1. Test Data Comparison

This section describes the studies that were used to compare heavy-duty battery electric vehicle energy use to equivalent diesel-fueled vehicles. These studies compared the vehicles on the same test cycles to ensure that vehicles were operated under identical conditions. This ensures that the comparisons are “apples-to-apples”. The data sources used in this paper include fuel economy test results for 40-foot transit buses, a recent study on Class 8 drayage trucks and an evaluation of Class 5 parcel delivery trucks. The resulting EERs are plotted on the best fit curve at the end of this section.

### a. Bus Track Test Cycles

The Altoona Bus Research and Testing Center regularly test buses as part of its program to evaluate new bus models. For the tests, the buses are loaded to full capacity and operated on different cycles. Staff evaluated test results for a variety of late model 40-foot buses from different manufacturers on three track test cycles that included fuel or energy consumption.[20] Diesel and battery electric buses were tested on the CBD, Arterial, and Commuter test cycles and loaded to maximum capacity. Data for the electric buses included a 2013 BYD Motors, Inc. 40-foot long battery electric bus (BEB), 2013 New Flyer 40-foot BEB, and a 2014 Proterra, Inc. 42-foot BEB. The diesel vehicles used for comparison were a 2010 New Flyer 40-foot bus, a 2011 North American Bus Industries 41-foot bus, and a 2011 Daimler Buses North America LTD Orion 41-foot bus.

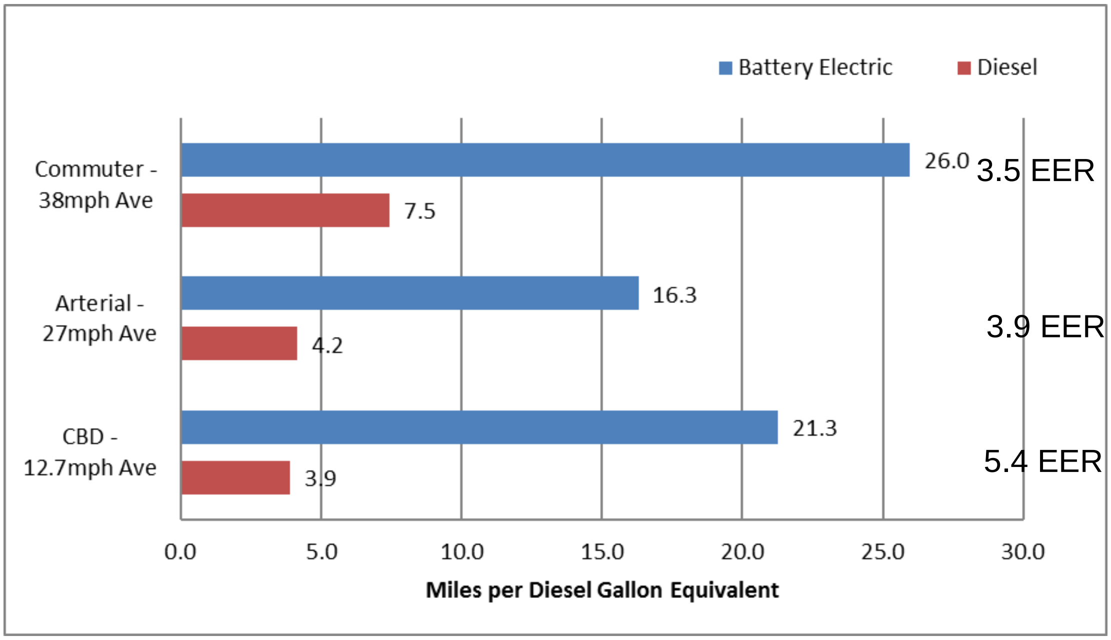
The CBD is a test cycle which represents bus operation in urban settings and has an average speed of 12.7 mph. The Arterial test cycle represents bus operation over longer distances with higher average speed of 27 mph, and fewer starts and stops than the CBD cycle. The Commuter test cycle represents bus operation primarily on the freeway at an average speed of 38 mph.

Figure H-8 shows the comparison of the average diesel fuel economy to the BEBs’ average energy use for each of the cycles. The average speed for each cycle is shown in the legend and the calculated EER is shown on the right. The diesel bus fuel economies generally increase with average speed. They are lowest on the CBD test cycle at 3.9 miles per gallon (mpg), and nearly double to 7.5 mpg on the Commuter test cycle. The energy use for the battery electric buses do not show a pattern related to average speed and is highest on the Arterial cycle and lowest for the Commuter test cycle. However, the calculated EER increases as the average speed decreases. The CBD cycle (12.7 mph) is representative of average speeds for urban bus operation and has an EER of 5.4. The Arterial cycle has an average speed of 27 mph, which is more typical for commuter bus cycle with few stops and has an EER of 3.9. The Commuter test cycle (38 mph) provides an indication of energy use on the freeway and has an EER of 3.5.

---

[20] Altoona Bus Tests (2010 and newer buses): http://altoonabustest.psu.edu/buses/

**Figure H-8: Altoona Buses Diesel versus Electric Fuel Economy (Test Cycle)**



### b. Drayage Dynamometer Test Cycles

UC Riverside (UCR) undertook a chassis dynamometer and in-use study of a 2015 Class 8 TransPower battery electric truck prototype designed for use in drayage operation. The results were compared to a Cummins 11.9 liter (L) diesel engine that was evaluated in a previous 2013 UCR study that included several conventional heavy-duty vehicles.[21,22] Results for the dynamometer portion of the study were published in an April 2015 report. In this paper, the battery electric truck is compared against three representative diesel engines from the 2013 UCR study drayage trucks that met the 2010 NOx engine certification standard: a Cummins 8.3L, a Cummins 11.9L, and a Mack 12.8L.

UCR simulated loading the test vehicles to 72,000 lbs. to represent the average fully loaded weight of drayage trucks operating in the Ports of Long Beach and Los Angeles and to provide comparable results across different test cycles designed to mimic port operation.

The dynamometer tests included six test cycles: sustained grade; regional, local and near dock drayage port cycles; UDDS cycle; and steady state cruise cycles. The report provided the average speeds of the vehicles performing the test cycles. UDDS is a test cycle which represents truck operations in city settings. The average speed of the

---

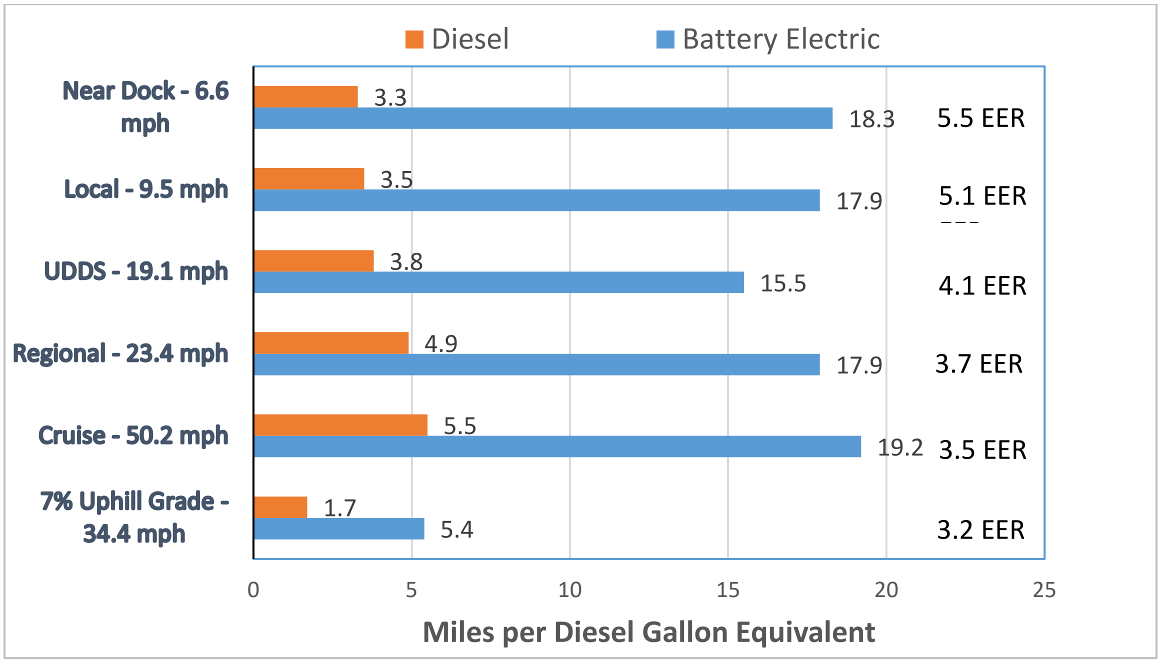
[21] Performance Evaluation of TransPower All-Electric Class 8 On-Road Truck. Johnson. Kent; Miller, J. Wavne; Xiao, Jiang Yu.

[22] In-Use Emissions Testing and Demonstration of Retrofit Technology for Control of On-Road Heavy-Duty Vehicles. Miller, Wayne; Johnson, Kent; Durban, Thomas; Dixit, Poornima.

UDDS cycle was 19.1 mph. Cruise represents truck operation at steady state and is used for range testing. The cruise cycle was measured for the diesel drayage trucks in the 2013 study by using a portion of the regional drayage cycle. The average speed of the cruise test cycle was 50.2 mph. The 7 percent grade test was used to represent a unique feature of the Port of LA, which has a very long bridge with a steep grade, and was used to determine how the electric vehicle system would compare with the conventional truck under this maximum load condition. The 7 percent grade test was calculated for diesel drayage trucks in the study by using logged data from in-use drayage trucks to create a correction factor. The grade test cycle was performed at both a fast approach and dead stop approach resulting in an average speed of 34.4 mph. Because this cycle is a unique feature of one segment of a truck trip for this port and is performed under maximum load conditions, it is not representative of a daily operating cycle (The test also excludes the downhill segment of a trip that would result in some energy recovery for the battery electric truck from regenerative brakes). The Near Dock (6.6 mph), Local (9.5 mph), and Regional (23.4 mph) drayage test cycles were designed to represent typical drayage trucking operation in congested urban areas near the Ports of Los Angeles, Long Beach and Oakland.

Figure H-9 shows the results of the study for different test cycles. The data shows that the diesel drayage truck fuel economy ranges from 3.3 mpg when operated on the near dock cycle with the slowest average speed and more than doubles to 5.5 mpg when operated on a cruise cycle at 50 mph. The energy use for the electric drayage truck remained in a relatively narrow range from 15.5 mpdge to 19.2 mpdge when excluding the 7 percent uphill grade test. The EER ranged from 3.5 to 5.5 for the electric drayage trucks when compared to similar diesel vehicles operated under the same conditions. The 7 percent grade test was not considered to be representative of normal daily operation because the test was performed under maximum load conditions going uphill only, and had an EER of 3.2 and does not include any energy recapture associated with regenerative braking.

**Figure H-9: UCR Drayage Diesel vs. Electric Fuel Economy**



### c. Parcel Delivery Dynamometer Test Cycles

California Hybrid, Efficient and Advanced Truck Research Center (CalHEAT) compared battery electric parcel delivery vans to conventional diesel in an August 2013 study.[23] The goal of the project was to present data gathering results, findings, and subsequent recommendations of testing and demonstration of battery electric parcel delivery trucks operated by an unnamed large delivery fleet in Los Angeles, California. Data from in-use data collection, on road testing, and chassis dynamometer testing was used. Data from four Navistar eStar Class 3 battery electric delivery vans and one Smith Electric Newton Class 5 (16,500 lb.) battery electric step van were included in the report. All four eStars were tested in-use, and the Newton was tested on the chassis dynamometer. The report compared results to previous tests performed on conventional walk-in vans: two diesel Isuzu Reach Class 3 walk-in vans tested in-use on similar routes from the same facility as the E-Trucks, and a National Renewable Energy Laboratory (NREL) study of an FCCC MT-45 Class 4 (16,000 lb.) diesel walk-in van. The Newton and FCCC MT-45 were both tested on dynamometer cycles HTUF4 (14 mph average) which represents a city package delivery route and Orange County Bus Cycle (12.3 mph) which represents a bus cycle for Orange County.

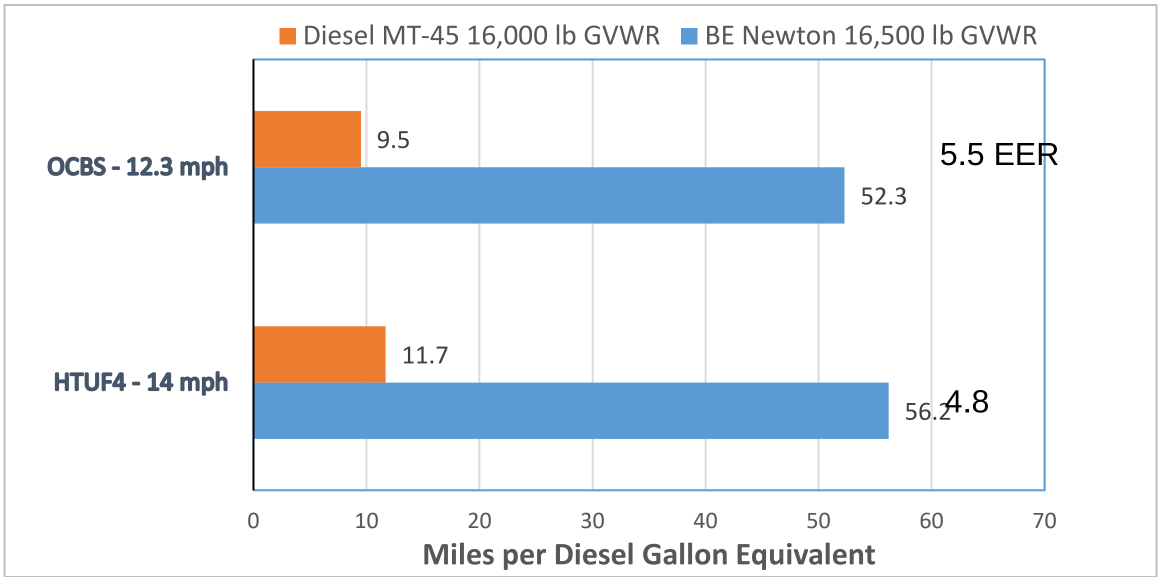
In this section, staff are only using the test cycle data to ensure the efficiency comparison is as comparable as possible. As seen in Figure H-10, the data collected support 4.8 to 5.5 times better fuel efficiency for electric class 5 parcel delivery trucks

---

[23] Battery Electric Parcel Delivery Truck Testing and Demonstration. California Energy Commission. Gallo, Jean-Baptiste, Jasna Tomic. (CalHEAT). 2013

than similar conventional diesel vehicles for two different test cycles.  In-use data from this study is also presented in the next section.

**Figure H-10: CalHEAT Parcel Van Diesel vs. Electric Fuel Efficiency**



### d. Test Cycle Comparison Summary

The data from the Altoona bus tests, the CalHEAT parcel delivery study and the UCR TransPower drayage truck study show lower diesel fuel economy in slower speed cycles for the same vehicle, where the load remains constant (excluding the uphill segment test).  The energy consumption for battery electric vehicles also fluctuated with test cycle, but there is no obvious trend in energy use with average speed.  As expected, the battery electric energy use and diesel vehicle fuel use for the lighter parcel delivery trucks was substantially lower than it was for heavier trucks and buses. The drayage truck results for the 7 percent grade uphill test also show that the battery electric vehicle and diesel fuel vehicle fuel economy drops substantially when going uphill under a heavy drivetrain load at a constant speed.  There insufficient information to establish a relationship for fuel economy or energy consumption by vehicle type and weight; however, EERs from all the tests showed a consistent pattern with average speed despite differences in vehicle types and loads.

Combined, the studies showed that the vehicle EERs for battery electric vehicles compared to similar diesel vehicles ranged from 3.5 to 5.5 for parcel delivery Class 5 vehicles, Class 8 tractor, and transit buses when operating under different speeds and conditions.  The drayage truck 7 percent grade EER of 3.2 is not used because it represents an uncommon event under maximum load conditions without considering the downhill portion of the bridge, and therefore is not representative of daily operation. The EERs were highest in lower speed cycles regardless of the vehicle size, type, or weight class and are plotted against the average speed of the test cycle as shown in Figure H-11.  The best fit curve shows that the EER ratio increases exponentially with lower speeds. Regression analysis confirms there is a statistically significant correlation (P-value <.05 at 95 percent confidence interval). The equation is displayed on the graph and can be used to reasonably predict the likely energy consumption of an electric vehicle if the average speed of a given test cycle and the fuel economy of the conventional diesel vehicle is known. The data that is used on the chart is also shown in H-7 below.

**Figure H-11: Vehicle Energy Economy Ratio at Different Average Speeds[24]**

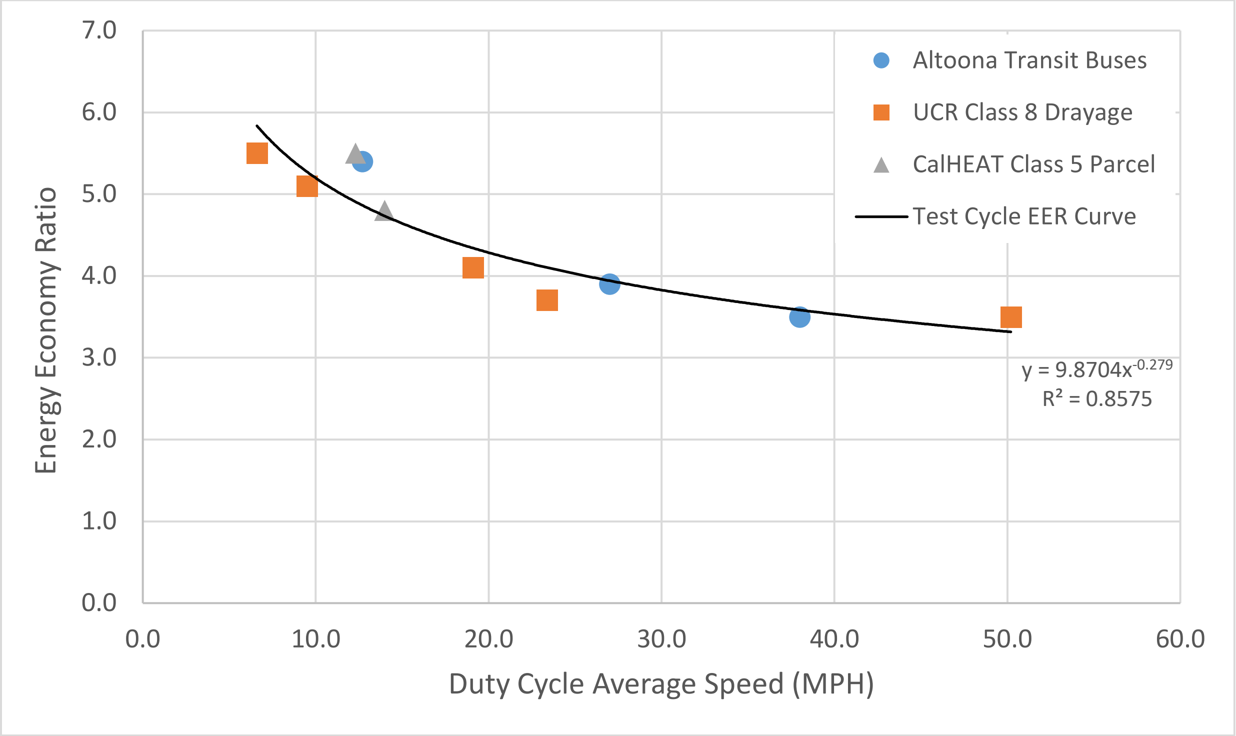


**Table H-7: Test Cycle Vehicle Energy Economy Ratio[25] at Different Average Speeds**

| Data Source | Route/Test Cycle Name | Average Speed (mph) | Diesel (mpdge) | Elec (kWhr/mi) | Elec (mpdge) | EER Ratio (Calculated) |
|---|---|---|---|---|---|---|
| UC Riverside - Class 8 Drayage Tractor | Drayage Neardock | 6.6 | 3.3 | 2.1 | 18.3 | 5.5 |
| UC Riverside - Class 8 Drayage Tractor | Drayage Local | 9.5 | 3.5 | 2.1 | 18.0 | 5.1 |
| CalStart - Class 5 Step Van | OCBC | 12.3 | 9.5 | 0.7 | 52.3 | 5.5 |

---

[24] Vehicle energy use excludes charger-battery system efficiency losses.

[25] Reflects battery electric vehicle energy usage, and does not include any other battery or charging losses.

| | | | | | | |
|---|---|---|---|---|---|---|
| Altoona - Class 8 40' Bus | Bus CBD | 12.7 | 3.9 | 1.8 | 21.3 | 5.4 |
| CalStart - Class 5 Step Van | HTUF4 | 14.0 | 11.7 | 0.7 | 56.2 | 4.8 |
| UC Riverside - Class 8 Drayage Tractor | UDDS | 19.1 | 3.8 | 2.4 | 15.5 | 4.1 |
| UC Riverside - Class 8 Drayage Tractor | Drayage Regional | 23.4 | 4.9 | 2.1 | 17.9 | 3.7 |
| Altoona - Class 8 40' Bus | Arterial | 27.0 | 4.2 | 2.3 | 16.3 | 3.9 |
| Altoona - Class 8 40' Bus | Commuter | 38.0 | 7.5 | 1.5 | 26.0 | 3.5 |
| UC Riverside - Class 8 Drayage Tractor | Drayage Cruise | 50.2 | 5.5 | 2.0 | 19.2 | 3.5 |
| UC Riverside - Class 8 Drayage Tractor | 7% Grade Test | 34.4 | 1.7 | 7.0 | 5.4 | 3.2 |

## 2. In-Use Data Evaluation

Staff also evaluated in use data to confirm whether the EER relationship to average speed was applicable to other vehicle types, and whether the test data is representative of results from normal in-use operation. Although, there are more variables with in use operation including how vehicles are operated, how they are loaded and fluctuations with driver habits, some of the data in-use data is available for multiple vehicles and several months of data. The data sources are described below and how the in-use EER's compare to the test data is shown at the end of this section.

### a. NREL Foothill Transit Study

NREL has been collecting information in partnership with Foothill Transit comparing battery electric buses to CNG baseline buses that are operating in Los Angeles County in regular revenue service.[26] The latest report provides information about twelve battery electric 35-foot Proterra fast charging buses and compares them to eight 42-foot NABI CNG buses of the same model year. This study has two phases; the initial testing period was between April 2014 and July 2015, and the most recent test period was from August 2015 to December 2016 for a total of over two years. The most recent report contained information comparing battery electric bus energy use to conventional CNG buses. Through the data collection period ending December 2016, the electric buses have travelled combined over 902,000 miles.

The Proterra electric buses were exclusively driven on Foothill's Line 291, which is a short route that has a Proterra overhead fast charging station installed for on-route charging. The battery electric buses on this route had an average total speed of 7.0 mph (and an average driving speed of about 18 mph when idle time and time stopped is excluded). The baseline CNG buses were randomly dispatched to all of Foothill Transit routes for most of the test period and operate at substantially higher average speeds.

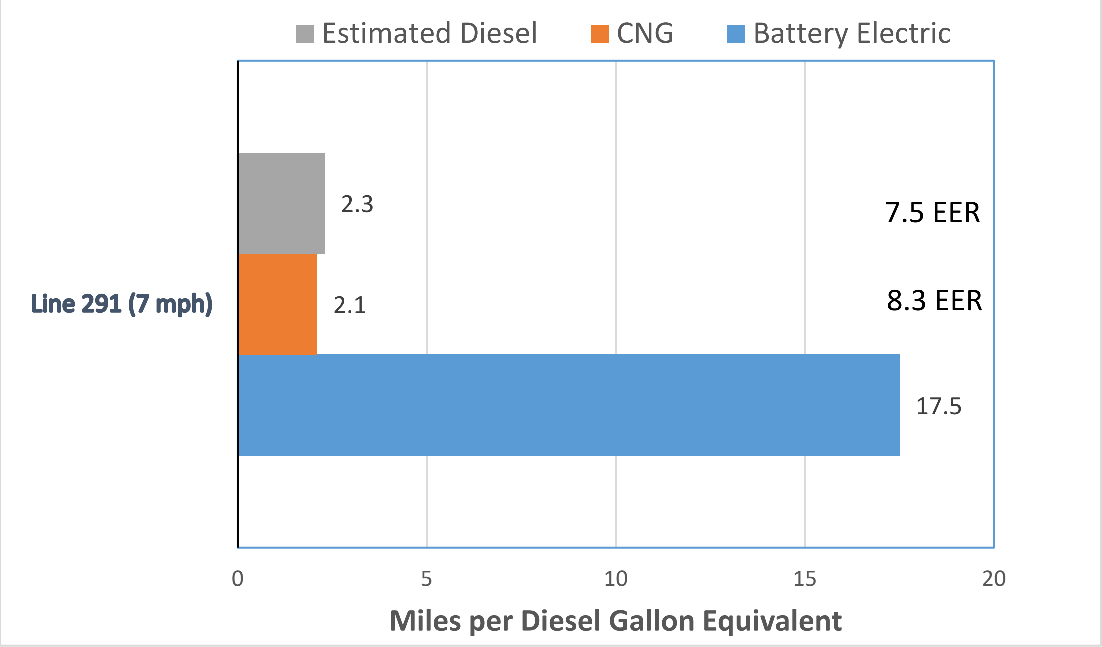
---

[26] Foothill Transit Battery Electric Bus Demonstration Results: Second Report. Eudy and Jeffers. NREL. June 2017.

However, to make a valid comparison of energy use on an “apples-to-apples” basis, fuel consumption data was collected for CNG buses operated for two days on Line 291 with an average total speed of 9.5 mph (and average driving speed of 18.1 mph). The NREL report suggests that the on-route charging period contributed to the difference between the electric and CNG difference in total average speed.

The measured fuel economy of the electric buses was 17.5 mpdge, which included a full year of in-use data in real world conditions including varying auxiliary loads such as air conditioning and varying environmental and seasonal conditions. The fuel economy of the CNG buses on the same route was 2.1 mpdge, data-logged over 2 days on the same route. The EER of the battery electric bus compared to the CNG bus equates to a ratio of 8.3 on this type of route. If the CNG engine has a 10 percent lower fuel efficiency compared to diesel, the EER would be about 7.5 compared to a diesel bus on the same route.

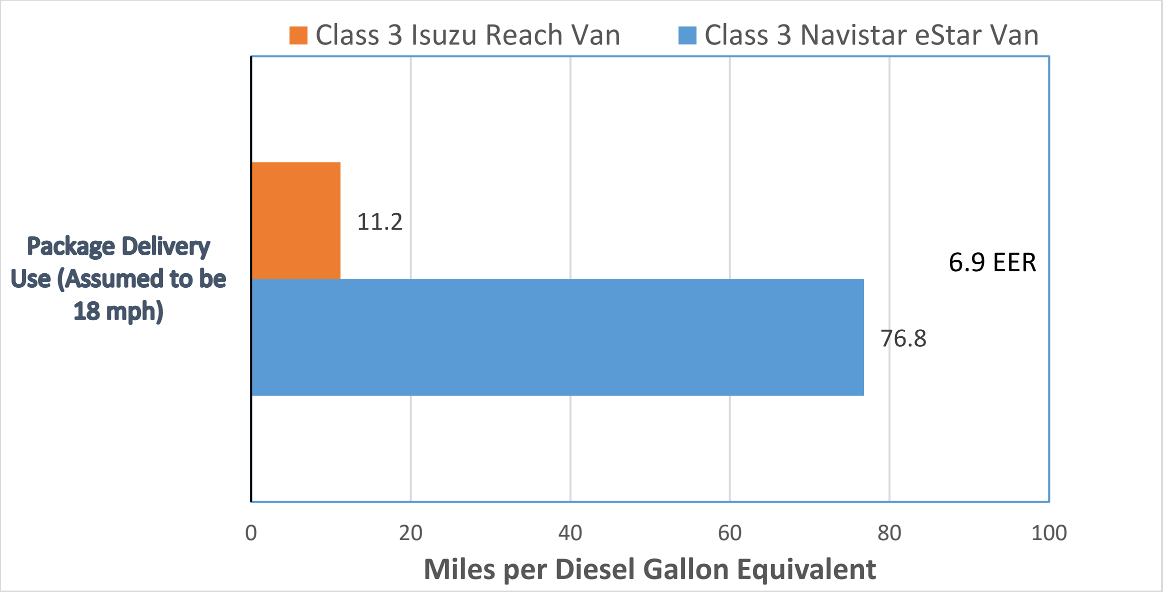
**Figure H-12: Foothill Transit Bus Fleet CNG vs. Electric Fuel Efficiency (In-Use)**



### b. CalHEAT Parcel Delivery Study

Data including mileage and fuel use for the eStar in-use routes were collected over approximately nine months in regular service, from March 2012 through December 2012. The four eStars travelled almost 9500 miles combined for the duration of the data gathering periods, averaging 220-330 miles per month. The baseline data from two Isuzu Reach vans were operated 844 miles over 3 weeks. The in-use routes were described as typical for a parcel delivery company in downtown Los Angeles. Average speed of the in-use electric vehicle routes was not provided in the report. However, the Reach vans operating on “routes similar to the routes the E-Trucks were operating on” averaged 18.2 mph. Staff used 18.2 mph as representative for these vehicles although there is some uncertainty with this assumption. The fuel consumption rates for the vehicles in-use were available and are shown below in Figure H-13. The EER is calculates to 6.9 for the Class 3 electric delivery vans when compared to similar conventional diesel vans.

**Figure H-13: Parcel Van Delivery Diesel vs. Electric Fuel Efficiency (In-Use)**



### c. San Diego Airport Parking Company Shuttle Vans

The San Diego Airport Parking Company provided several months of data[27] for three conventional diesel Mercedes-Benz Sprinter vans and one Ford Transit Class 2b-3 shuttle van, and three Dodge Ram Class 3 shuttle vans converted into battery electric vehicles by Zenith Motors. Mileage and fuel use data were collected over different periods of operation in regular service. The in-use data were analyzed by staff.

The data for the diesel vehicles included about 24,000 miles in the fall and winter (the data for the V6 diesel vans was collected in September, data for one V4 diesel van was collected in November and the other from December to January). The data for the three battery electric vans included about 29,000 miles of operation in the summer from May 30 to July 24. Data for the battery electric conversions included daily mileage and daily electricity used from the electric utility bill. Staff applied a power efficiency conversion of 85 percent to get the energy used by the vehicle to calculate the EER.

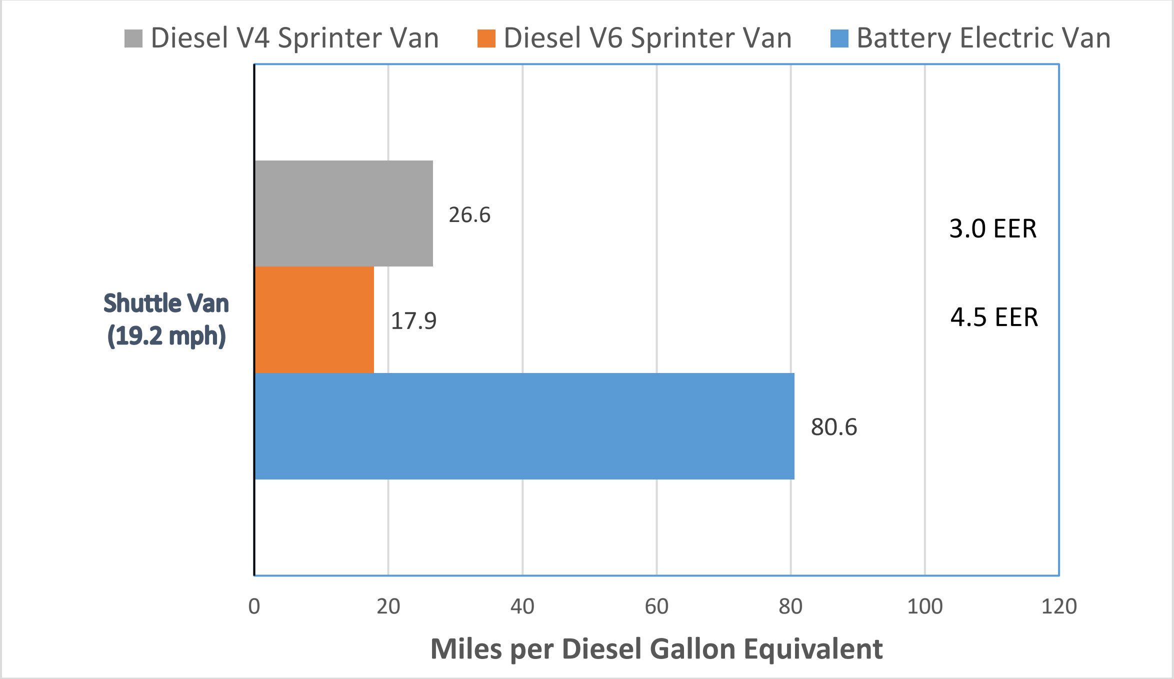
The average speed for the conventional diesel vehicles was 20.3 mph, while for the battery electric vans the average was about 17.9 mph. The speeds are fairly close but are not the same. For purposes of plotting data, staff averaged the speeds from all

---

[27] San Diego Airport Parking Company In-Use Shuttle Dataset provided by Lisa McGhee

vehicles in use to get an average fleet speed of 19.2 mph. The average fuel economy and total (AC) electricity consumption equates to 69 mpdge and includes all battery and charging losses measured at the electric utility meter. However, to remain consistent with the other study results in this paper, staff estimate the vehicle efficiency without charging loses (about 15 percent battery and charging losses) would be closer to 80.6 mpdge as show in Figure H-14. These in-use results indicate the vehicle EER is close to 4.5 for the Class 2b-3 electric shuttle buses when compared to similar conventional V6 diesel vehicles and close to 3.0 when compared to conventional V4 diesel vehicles used in this type of parking shuttle application. It is unclear whether the performance characteristics of the battery electric van conversions are more similar to the V6 configuration or to the V4 so both are shown.

**Figure H-14: San Diego Airport Shuttle Bus Diesel vs. Electric Fuel Efficiency (In-Use)**



### d. Port of Los Angeles and IKEA Yard Tractors

TransPower demonstrated three class 8 battery electric yard tractors at the port of Los Angeles and IKEA. Two were demonstrated in conjunction with the Port of Los Angeles[28] and one at an IKEA warehouse in conjunction with the San Joaquin Valley Air

---

[28] TransPower Electric Yard Tractor Demonstration Project for City of Los Angeles Harbor Department. May 2015.

Pollution Control District.[29] The yard tractor demo projects covered a total period of 9 months from September 2014 through May 2015.

Because no diesel vehicle baseline was measured in these reports, staff referenced a different CalStart report[30] detailing a hybrid yard truck demo project with the Port of Los Angeles where the operation was deemed to be representative of the industry standard for port type operations and the measured average speed was 3 mph. The CalStart report also indicated that the industry standard efficiency for yard trucks in port operations is 2.4 diesel gallons per hour and staff used this as a representative diesel yard truck fuel economy. It is important to note that yard truck fuel economy is typically reported in gallons per hour, rather than miles per gallon. Many yard truck only use hour meters and do not have odometers due to the high hours of operation and few miles driven.

The IKEA tractor was a first prototype that TransPower was using to learn from the in-use experience and demonstration to improve future yard tractor designs. The average speed of the IKEA battery electric yard tractor was 9 mph, and there was no data available to determine the average diesel yard truck fuel economy operating in warehouse operation. Staff used the 2.4 diesel gallons per hour estimate to compare with the energy used in the battery electric prototype. While it may not be the best comparison, the results provide some insight into the efficiency comparison for yard truck operations.

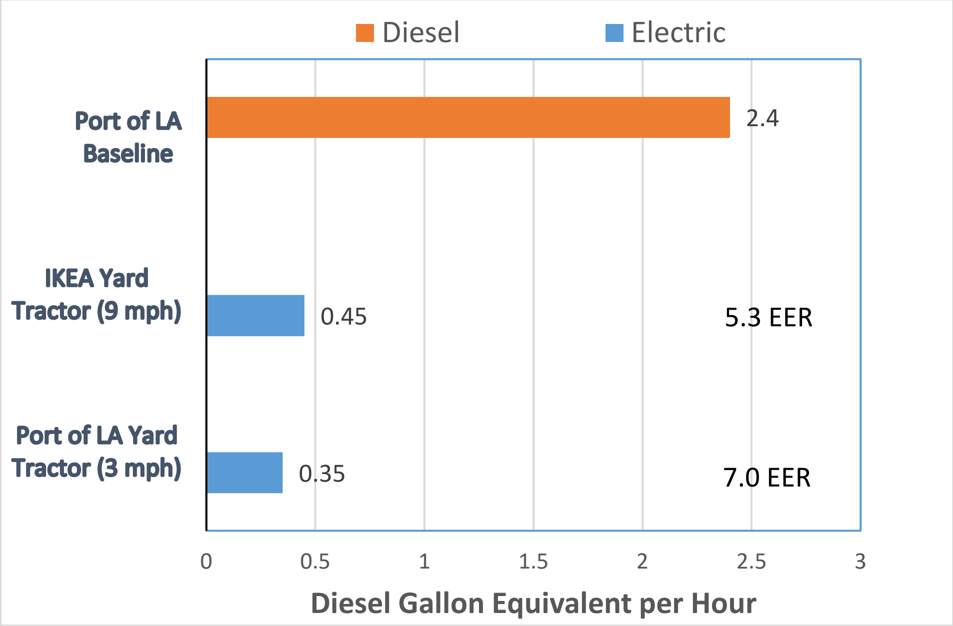
Figure H-15 shows the EER potential range from 5.3 to 7.0 for electric yard tractors compared to similar conventional diesel vehicles. Although not a direct comparison, the data does suggest that an EER above 5 is likely for yard truck operations.

**Figure H-15: TransPower Yard Truck- Port and Warehouse Diesel vs. Electric Fuel Efficiency (In-Use Data)**

---

[29] TransPower Electric Yard Tractor Demonstration Project for San Joaquin Valley Air Pollution Control District. July 2015.

[30] CalStart Hybrid Yard Hostler Demo- Port of LA



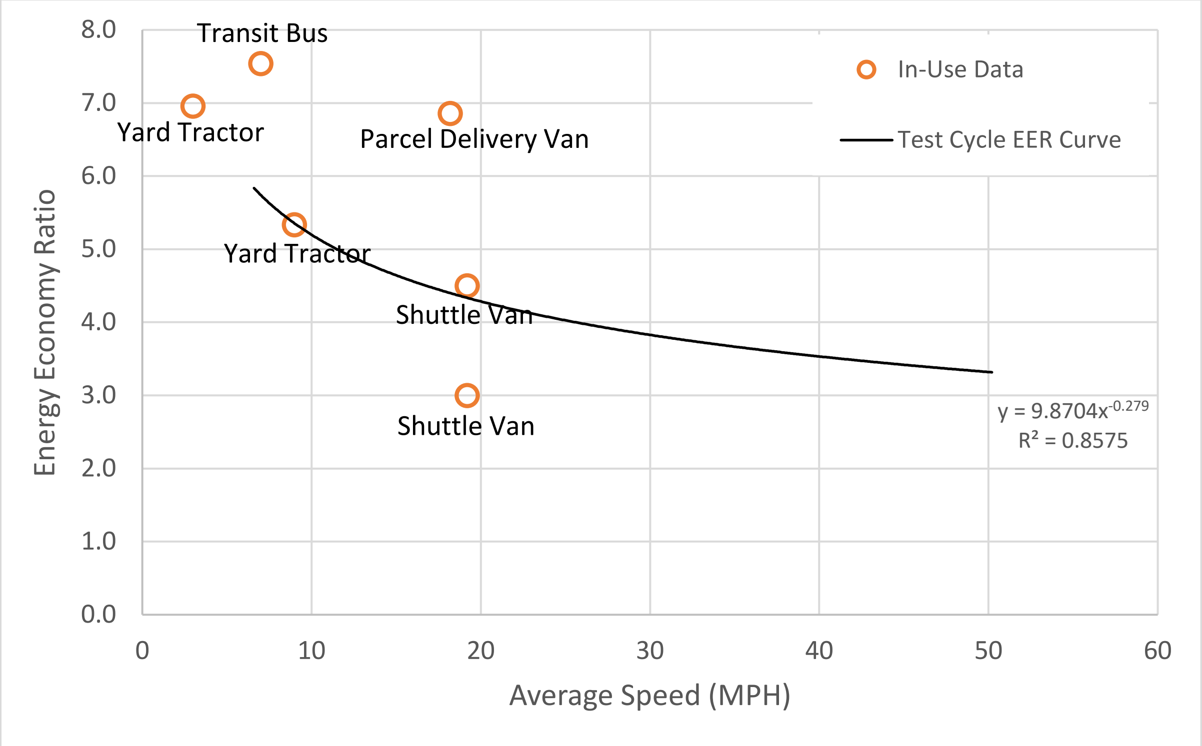
### e. In-Use Data Summary

The in-use data was primarily collected from uses where electric vehicles were either being used in normal revenue service or to evaluate early models to assess their viability for the particular application. Even though the in-use data EER comparisons are somewhat variable the data collection periods were for extended periods of time with normal daily variations like traffic, weather, auxiliary loads and driver behavior that are generally not included in the test cycle comparisons. Staff compared the in-use results to the EER curve previously derived from the test cycle data (described in the Test Data Comparison Section) as shown in Figure H-16. The in-use data is shown with red circles.

**Figure H-16: Vehicle Energy Economy Ratio at Different Average Speeds (Test Cycle and In-Use)**[31]

---

[31] Vehicle energy use excludes charger-battery system efficiency losses.



Although there is some uncertainty with the in-use data, staff can derive a few conclusions from these results. First, the in-use data shows the same trend of increasing EER with lower average speeds and is consistent with the test cycle data. Second, all of the in-use data was collected for vehicles with an average operating speed of less than 20 mph confirming that battery electric vehicles are being evaluated and demonstrated for use in stop and go applications with lower average speeds. Third, the in-use results confirm that the EER relationship from “apples-to-apples” test data for a wide range of medium and heavy-duty vehicles (Class 8 drayage trucks, Class 8 transit buses, and Class 5 parcel delivery trucks) is also representative for in-use operation of other vehicle types including Class 2B-3 passenger vans, transit buses and Class 8 yard tractors. Table H-8 shows the diesel and electric fuel economy data used in the above graph.

**Table H-8: Vehicle Energy Economy Ratio at Different Average Speeds**

| Data Source | Route/Test Cycle Name | Average Speed (mph) | Fuel Economy (mpdge) | Elec Fuel Economy (kWhr/mi) | Elec Fuel Economy (mpdge) | EER Ratio (Calculated) |
|---|---|---|---|---|---|---|
| TransPower - Class 8 Yard Tractor | Port of LA In-Use Route | 3.0 | 2.4 gal/hr | NA | .345 DGE/hr | 7.0 |
| UC Riverside - Class 8 Drayage Tractor | Drayage Near dock - Test Cycle | 6.6 | 3.3 | 2.1 | 18.3 | 5.5 |
| NREL - Class 8 Proterra 35' Transit Bus | Foothill Transit Line 291 | 7.0 | 2.1 | 2.2 | 17.5 | 8.4 |

| | | | | | | |
|---|---|---|---|---|---|---|
| TransPower - Class 8 Yard Tractor | IKEA Warehouse In-Use Route | 9.0 | 2.4 gal/hr | NA | .45 DGE/hr | 5.3 |
| UC Riverside - Class 8 Drayage Tractor | Drayage Local - Test Cycle | 9.5 | 3.5 | 2.1 | 18.0 | 5.1 |
| CalHEAT - Class 5 Step Van | OCBC - Test Cycle | 12.3 | 9.5 | 0.7 | 52.3 | 5.5 |
| Altoona - Class 8 40' Bus | Bus CBD - Test Cycle | 12.7 | 3.9 | 1.8 | 21.3 | 5.4 |
| CalHEAT - Class 5 Step Van | HTUF4 - Test Cycle | 14.0 | 11.7 | 0.7 | 56.2 | 4.8 |
| CalHEAT - Class 3 Sprinter Van | Navistar eStar In-Use Route | 18.2 | 11.2 | 0.5 | 76.8 | 6.9 |
| UC Riverside - Class 8 Drayage Tractor | UDDS - Test Cycle | 19.1 | 3.8 | 2.4 | 15.5 | 4.1 |
| SD Airport - Class 3 V6 Shuttle Van | SD Airport Shuttle In-Use Route | 19.2 | 17.9 | 0.5 | 80.6 | 4.5 |
| SD Airport - Class 3 V4 Shuttle Van | SD Airport Shuttle In-Use Route | 19.2 | 26.6 | 0.5 | 80.6 | 3.0 |
| UC Riverside - Class 8 Drayage Tractor | Drayage Regional - Test Cycle | 23.4 | 4.9 | 2.1 | 17.9 | 3.7 |
| Altoona - Class 8 40' Bus | Arterial - Test Cycle | 27.0 | 4.2 | 2.3 | 16.3 | 3.9 |
| Altoona - Class 8 40' Bus | Commuter - Test Cycle | 38.0 | 7.5 | 1.5 | 26.0 | 3.5 |
| UC Riverside - Class 8 Drayage Tractor | Drayage Cruise - Test Cycle | 50.2 | 5.5 | 2.0 | 19.2 | 3.5 |
| UC Riverside - Class 8 Drayage Tractor | 7% Grade - Test Cycle | 34.4 | 1.7 | 7.0 | 5.4 | 3.2 |

### 3. Vehicle Average Speeds

Staff have determined that the EER of a battery electric vehicle is closely associated with the average speed of the cycle in which it is operated when all other factors are equal (vehicle weight class, type, size, terrain, and load). The total vehicle average speed is an indicator of stopping frequency, idling, time spent in line or at traffic lights, and coasting. Vehicle average speed is key to determining the expected EER for a battery electric vehicle that would replace a given conventional diesel vehicle. The EER for battery electric vehicles provides an understanding of how to compare energy use, fuel/energy costs, daily range (or hours of service), and air quality benefits for a given use or application. This section describes available information that identifies typical average speed by vehicle or use type.

Battery electric transit buses are already widely commercially available for use in transit service. Most transit agencies replace existing buses with funding from the Federal

Transit Administration (FTA) Section 5307 or Section 5311 programs. Participating agencies are required to submit data to the National Transit Database[32] (NTD) about their fleets and operating characteristics. For California transit agencies, the data reported for calendar year 2015 shows that 94 percent of all buses average about 13.0 mph and the remaining 6 percent are primarily commuter buses operate at an average speed of about 25 mph.

For trucks, NREL hosts a database of fleet operational data called the Fleet DNA database.[33] This database is intended to assist in characterizing the operations of certain types of vehicles. Staff analyzed the data from each category to identify the average category speed and included these in the Table H-9. The average speed of long haul tractors was obtained from a 2011 industry study.[34] Staff also included data from the UCR Drayage report for local haul drayage and CalStart yard hostler report for port yard tractor use to cover those types of operations.

**Table H-9: Average Speed by Vehicle Category**

| Vehicle Category | Class | Vocation | Total Average Speed (mph) | Source |
|---|---|---|---|---|
| **Refuse** | 8 | Refuse | 9.5 | NREL FleetDNA |
| **Service Van** | 2 to 3 | Utility/Telecomm | 14.7 | NREL FleetDNA |
| **Delivery Van** | 3 to 6 | Food, Parcel, Linen, Beverage | 11.7 | NREL FleetDNA |
| **Delivery Truck** | 3 to 7 | Delivery, straight, stake, furniture, rack, beverage | 18.4 | NREL FleetDNA |
| **Bucket Truck** | 3 to 7 | Utility/Telecomm- Boom with Bucket only | 11.0 | NREL FleetDNA |
| **Vocational Tractor** | 7 to 8 | Delivery, Beverage, Semi, Refrigerated, Fuel, Regional | 20.1 | NREL FleetDNA |
| **Class 8 Long Haul Tractor** | 8 | Long Haul | 48.0 | Duleep |
| **Transit Bus** | 8 | Public transit (urban buses) | 13.0 | NTD |
| **Yard Tractor** | 8 | Port/Yard Hostler | 3.0 | TransPower |

---

[32] National Transit Database. https://www.transit.dot.gov/ntd (accessed 0219/2018).

[33] NREL Fleet DNA Fleet Operations Database. https://www.nrel.gov/transportation/fleettest-fleet-dna.html (accessed 0219/2018).

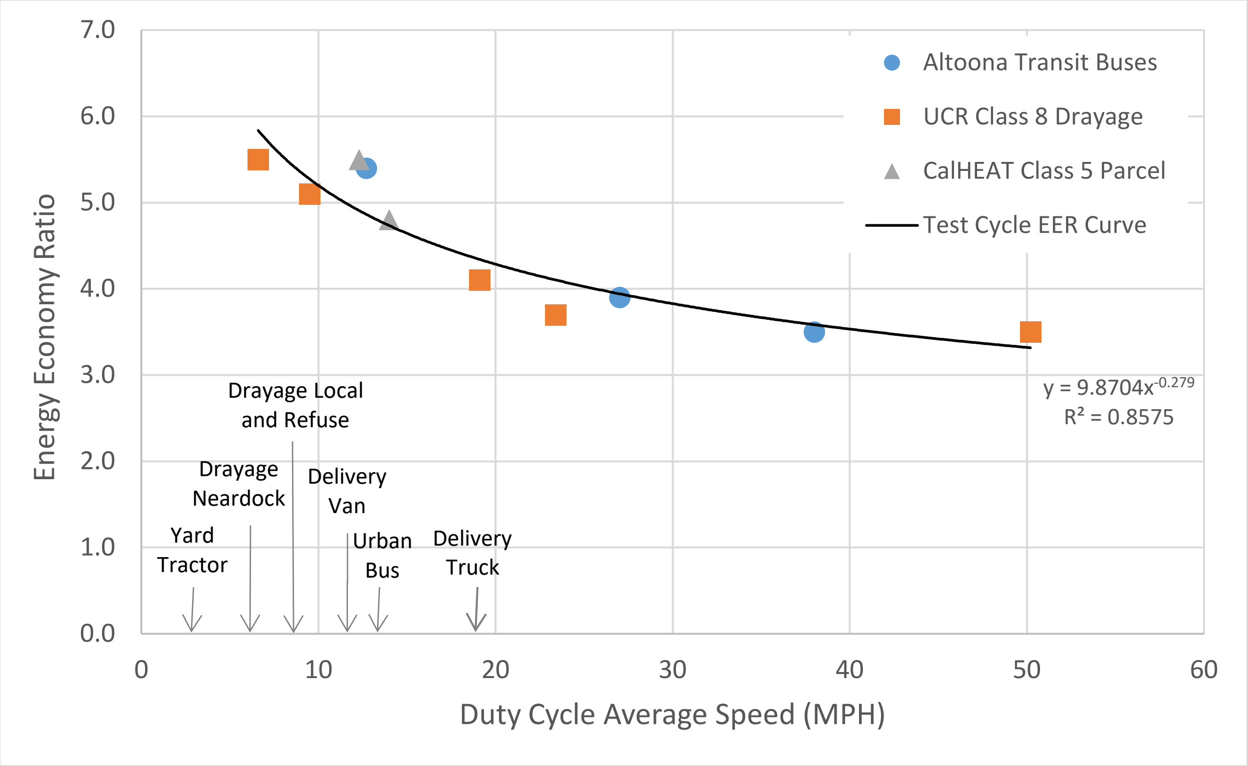
[34] Dupleep, K.G. Presentation to International Energy Agency workshop. May 2011. Available at: http://www.iea.org/workshop/work/hdv/duleep.pdf

|  |  |  |  |  |
|---|---|---|---|---|
| **Drayage Local Tractor** | 8 | Port/Intermodal Container Haul | 9.5 | UC Riverside |

## 4. Conclusions

The combined data from the studies with comparable test data shows a statistical correlation between heavy-duty conventional diesel fuel efficiency and comparable heavy-duty electric fuel efficiency based on the vehicle's average operating speed. The test cycle "apples-to-apples" comparisons resulted in the EER relationship as shown in the best fit curve on Figure H-17 in below. Heavy-duty electric vehicles in on-road applications across multiple vocations, weight classes, and drive cycles have energy economy ratios ranging from 3.5 for highway speed duty cycles to greater than 7 for slow speed duty cycles when compared to similar conventional vehicles. The in-use data is consistent with these findings when plotted along the curve and provides assurance that this relationship holds over a wide variety of vehicle types, payloads and duty cycles in real world operation.

**Figure H-17: Vehicle Energy Economy Ratio at Different Average Speeds**



In the next decade, battery electric trucks and buses are more likely to be placed in service in these slower speed operations because of battery range limitations, battery costs, and energy recovery advantages associated with regenerative braking. Commercial sales of battery electric vehicles are targeting uses with shorter range needs.  Electric models exist today for several truck categories operating at lower speeds with almost all being under 20 mph.  Our expectation that the early battery electric truck and bus market is more likely to be supported by centrally operated and maintained fleets that are expected to primarily be charged in the yard.  Shorter range applications present less operational risk, have lower upfront cost with smaller battery packs and have a better near term potential for a payback period more attractive for fleets.

The EER can be used to estimate total energy used by a battery electric vehicle when the average speed and fuel consumption of the conventional diesel vehicle is known. This information allows for a more accurate comparison of costs and emissions benefit calculations.  When doing emissions analysis or total cost of ownership analysis, charger-battery system inefficiencies must also be taken into consideration.  More detail on battery system and charging efficiencies is provided in Attachment 1.

## Attachment 1: Battery System and Charging Efficiency

The vehicle EER can be used to compare the energy used by an alternative fueled vehicle to a comparable conventional diesel vehicle. However, to understand the total energy needed to charge a battery electric vehicle also requires information about the total energy used in charging the battery in a vehicle and any energy losses that may occur in the battery. We evaluated available vehicle charging data from the battery electric vehicle studies to estimate battery and charging loses. This information can be used to estimate total energy needed when evaluating total fuel costs or in determining emissions as part of a life cycle analysis of different fuel types.

In the Foothill Transit Study, NREL measured the energy used (DC) by the buses, and the total energy used to charge the buses from the utility bills for the entire fleet of Foothill Transit's battery electric buses over the course of one year. The buses are charged on-route and often charge at a rate greater than 300 kW. The resulting total battery system charging efficiency was 90 percent and represents real world operation in varying conditions for a fleet of electric fast charging Proterra buses and is the most robust data set available.

Staff also evaluated the Altoona bus results. Altoona measured the total energy used by the vehicles over the course of its tests until the battery was depleted and the total amount of energy used to return the batteries to a full state of charge (SOC). The data available on the charging systems is limited, and generally includes one or two charging events per bus. The results of four charging events for three battery electric buses evaluated are summarized in Table 1.

**Table 1: Altoona Charger-Battery System Efficiencies**

| Transit Bus on Test Cycle | Test kWh(DC) | Test kWh(AC) | System Efficiency |
|---|---|---|---|
| Proterra Day 1 | 65.0 | 80.6 | 81% |
| Proterra Day 2 | 66.4 | 73.9 | 90% |
| BYD Day 1 | 256.7 | 281.3 | 91% |
| New Flyer Day 1 | 158.0 | 208.7 | 76% |
| New Flyer Day 2 | Only Partial Charge, Cannot Use Data | | |

Of these Altoona test results, BYD, Inc.'s bus with an on-board PEU had the highest efficiency, and New Flyer had the lowest charging efficiency where each report only had data for one charging event. BYD, Inc.'s bus was charged at 40kW (half the manufacturer rated 80kW charger) for about 6.9 hours to return to full SOC. According to the Altoona report regarding the New Flyer bus charging, "The bulk charge mode consumed power at a rate of about 80 kW and returned the bus to a relatively high SOC in about 2.5 hours. During the remaining 15 hours a relatively low power of 2.5 kW was consumed in a 'top off' mode."[35] This relatively "low-and-slow" charge during the "top off" mode may have affected the results. The charging strategy used at Altoona for the Proterra bus, which has an on-route configuration, was to charge it 3 times at about 200 kW and disconnecting between charging events for a total charge time of 40 minutes.

CalHEAT also measured the DC energy used and AC recharge energy used for the Smith Newton parcel delivery van for each drive cycle tested on the chassis dynamometer. The results are summarized in Table 2 below. CalHEAT points out that they were unable to charge at the manufacturer recommended 220 volt/63 amperage (13.8 kW) due to site infrastructure limitations at the test site and used 32 amps instead which resulted in longer charge times. They also state that using different charge rate may affect the charger efficiency and AC consumption may be higher than if the vehicle were charged at the higher manufacturer recommendations.

**Table 2: CalHEAT Charger-Battery System Efficiencies**

| Class 5 Delivery Van on Test Cycle | Test kWh(DC) | Test kWh(AC) | System Efficiency | Vehicle System Efficiency Average |
|---|---|---|---|---|
| Smith Newton HTUF4 | 0.7 | 0.8 | 83% | 82.3% |
| Newton OCBC | 0.7 | 0.9 | 82% | |
| Newton Steady State | 0.8 | 1.0 | 82% | |

A recent study by the University of Delaware[36] found that overall vehicle charging efficiencies are higher with higher electrical current. The study included information about efficiencies of building side components such as the building transformer which steps down the utility supplied voltage to the distribution panel voltage for consumption, the breaker panel, and the electric vehicle supply equipment (EVSE), known commonly as the charging station. Additionally, the study included vehicle components including the power electronics unit (PEU) which converts AC to DC power for use in the battery, and the battery pack itself. Some manufacturers such as BYD, Inc. include the PEU on the vehicle, while others may include it as part of the EVSE. The study found that total energy losses were most affected by the charging rate or electrical current (higher current on average produced higher efficiency) and the battery's SOC (higher SOC on average produced higher efficiency).

The median of the charger-battery system efficiency for the Altoona reports, the three charging events for the CalHEAT report, and the Foothill Transit report is 85.5 percent

---

[35] Federal Transit Bus Test. New Flyer XE40. Thomas D Larson Pennsylvania Transportation Institute. July 2015.

[36] Apostolaki-Iosifidou, Codani, Kempton. Measurement of Power Loss during Electric Vehicle Charging and Discharging. Energy. March 7, 2017.

efficiency. Staff believe that using an 85 percent overall battery and charging system efficiency is a conservative estimate based on the information that is available for the following reasons:

- The Foothill data showed a 90 percent overall charging efficiency and was far more robust than the limited dynamometer tests and included a full year of real world operating conditions over varying states of charge and other conditions.
- Two of the charging results were at power levels well below the manufacturer recommended rating due to limitations at the test sites which is likely to show lower efficiencies.

As the heavy-duty ZEV market grows technology improvements will likely make improvements.