CALIFORNIA AIR RESOURCES BOARD

Battery Electric Truck and Bus Energy Efficiency Compared to Conventional Diesel Vehicles

Updated: May 2018

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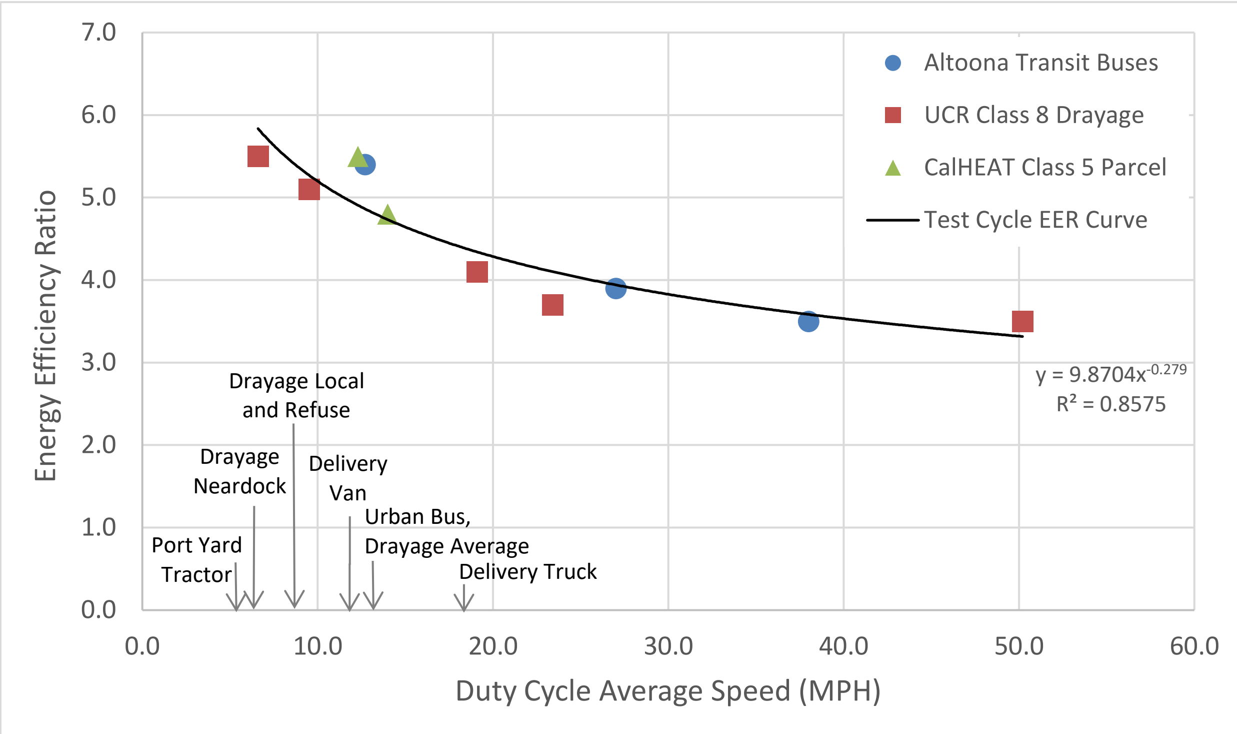
Executive Summary

This paper[1] 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, the California Air Resources Board (CARB) established an estimated energy efficiency ratio (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 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.

We 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 a miles per diesel gallon equivalent (mpdge) basis. 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, we 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 1. 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.

[1] This paper supersedes the version originally posted in September 2017.

Figure 1: Vehicle Energy Efficiency Ratio at Different Average Speeds



*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 energy efficiency ratio 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.

We 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 Appendix 1.

This paper 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. We 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[2]. Diesel and battery electric buses were tested on the Central Business District (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.

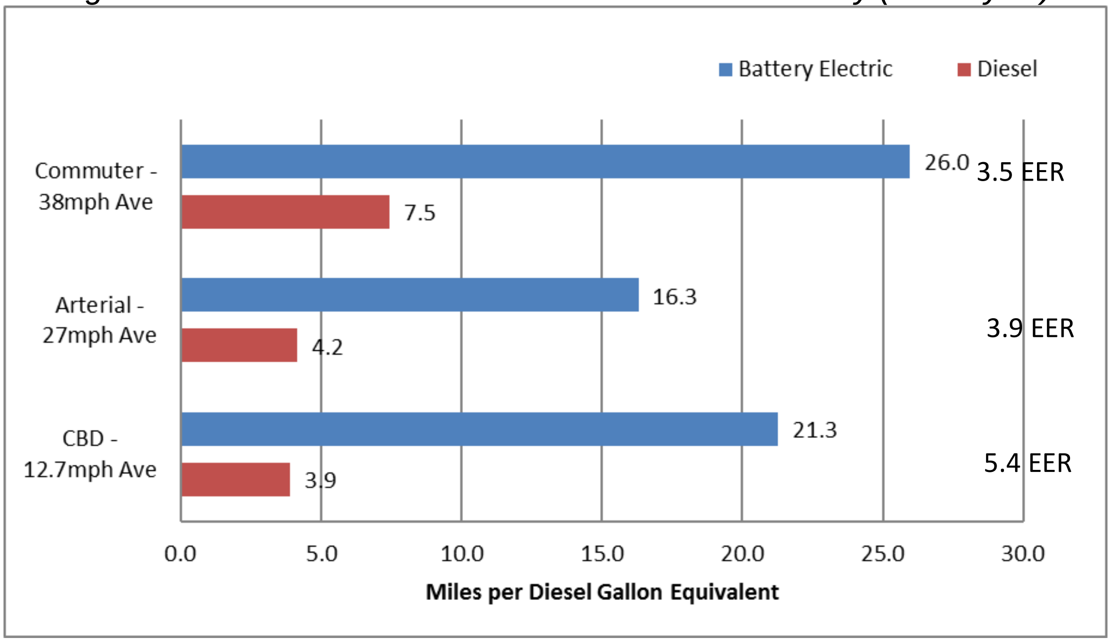
The CBD is a test cycle which represents bus operation in urban settings and has an average speed of 12.7 mph. The Arterial test cycle represents bus operation over longer distances with higher average speed of 27 mph, and fewer starts and stops than the CBD cycle. The Commuter test cycle represents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

Figure 2 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

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

test cycle (38 mph) provides an indication of energy use on the freeway and has an EER of 3.5.

Figure 2: Altoona Buses Diesel vs Electric Fuel Efficiency (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[3][4]. 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; urban dynamometer driving (UDDS) cycle; and steady state cruise cycles. The report provided the average speeds of the vehicles performing

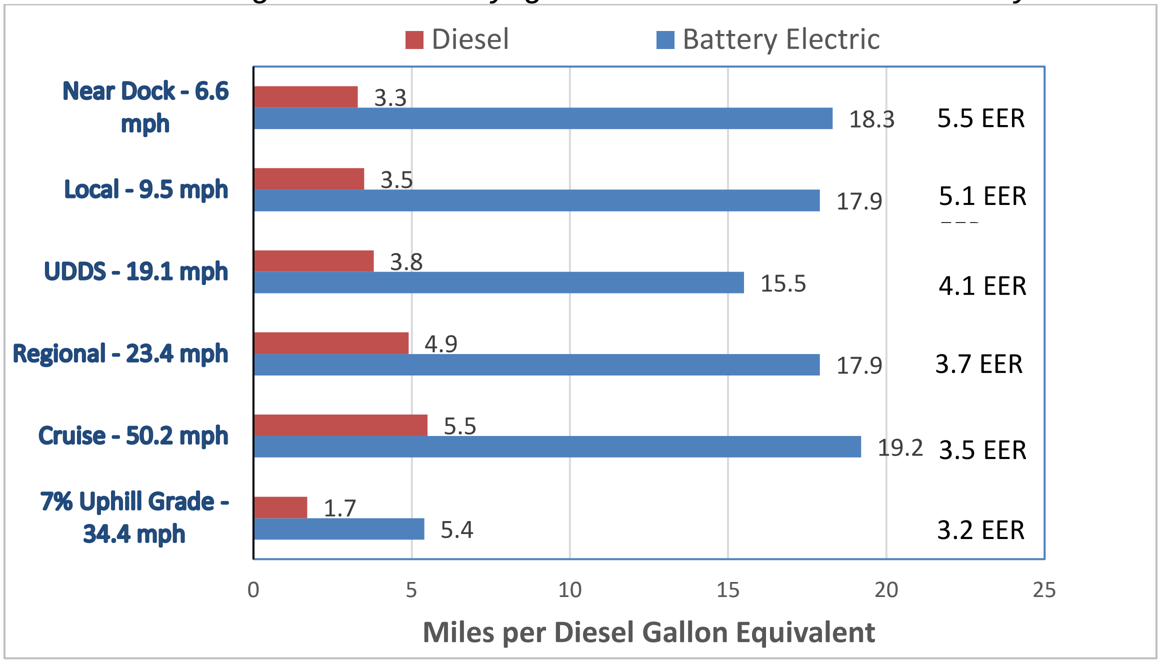
[3] Performance Evaluation of TransPower All-Electric Class 8 On-Road Truck. Johnson. Kent; Miller, J. Wavne; Xiao, Jiang Yu.

[4] 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.

the test cycles. UDDS is a test cycle which represents truck operations in city settings. The average speed of the 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 3 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 3: UCR Drayage Diesel vs Electric Fuel Efficiency



c. Parcel Delivery Dynamometer Test Cycles

CalHEAT compared battery electric parcel delivery vans to conventional diesel in an August 2013 study.[5] 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 we are only using the test cycle data to ensure the efficiency comparison is as comparable as possible. As seen in Figure 4, the data collected support 4.8 to 5.5 times better fuel efficiency for electric class 5 parcel delivery trucks than similar

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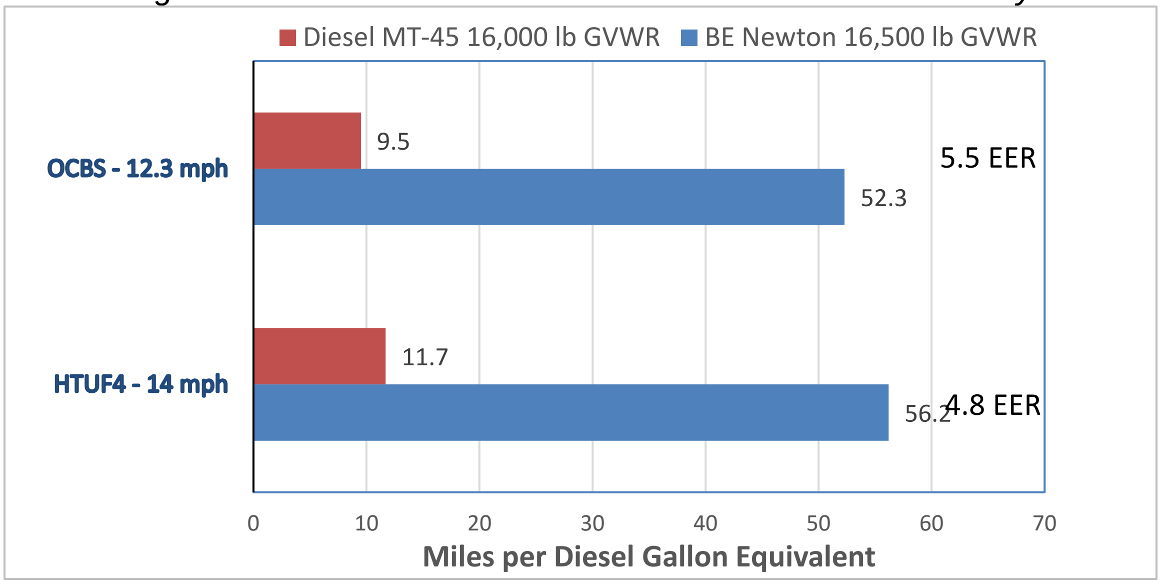
[5] Battery Electric Parcel Delivery Truck Testing and Demonstration. California Energy Commission. Gallo, Jean-Baptiste, Jasna Tomic. (CalHEAT). 2013

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

Figure 4: CalHEAT Parcel Van Diesel vs Electric Fuel Efficiency

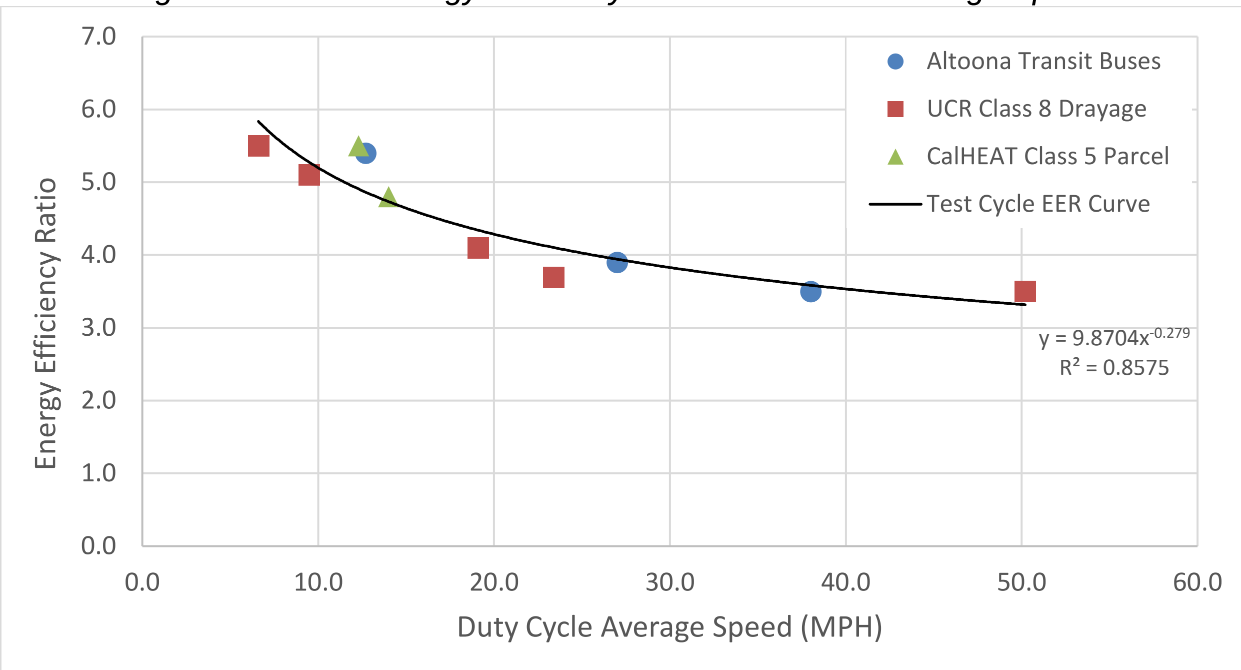


d. Test Cycle Comparison Summary

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 5. 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 Table 1 below.

Figure 5: Vehicle Energy Efficiency Ratio at Different Average Speeds



*Vehicle energy use excludes charger-battery system efficiency losses.

Table 1: Test Cycle Vehicle Energy Efficiency Ratio[6] at Different Average Speeds

Data Source	Route/Test Cycle Name	Average Speed (mph)	Diesel (mpdge)	Electric (kWhr/mi)	Electric (mpdge)	EER Ratio (Calculated)
UC Riverside - Class 8 Drayage Tractor	Drayage Near Dock	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
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

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

2. In-Use Data Evaluation

We 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[7]. The latest report provides information about twelve battery electric 35 foot Proterra fast charging buses and compares them to eight 42' 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. 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.

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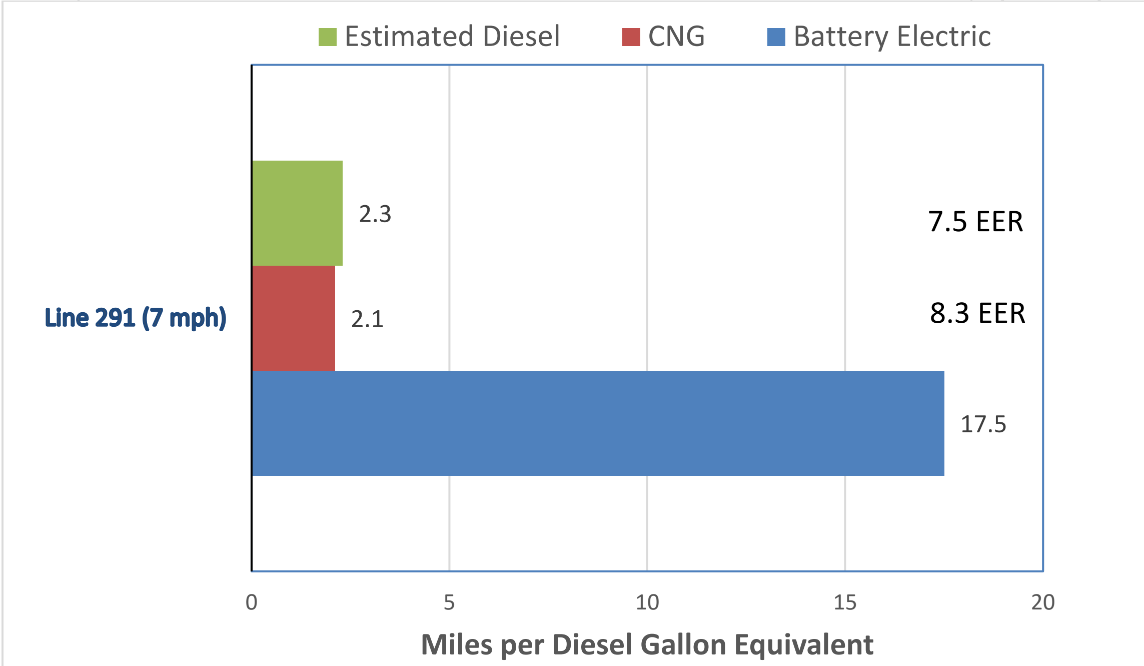
[7] Foothill Transit Battery Electric Bus Demonstration Results: Second Report. Eudy and Jeffers. NREL. June 2017.

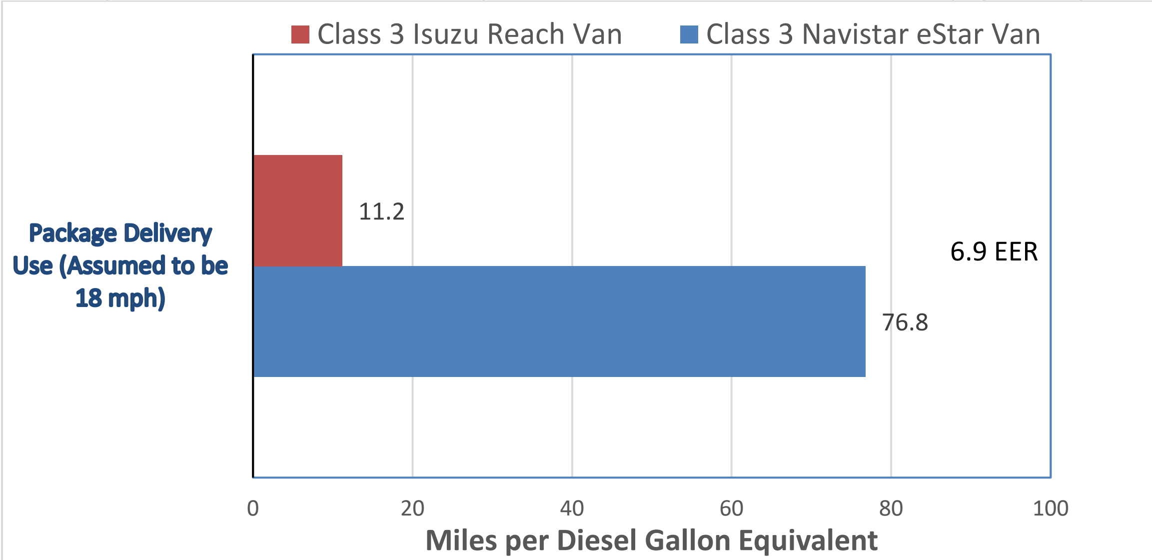
Figure 6: Foothill Transit Bus Fleet CNG vs Electric Fuel Efficiency (In-Use)



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. We 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 7. The EER is calculates to 6.9 for the Class 3 electric delivery vans when compared to similar conventional diesel vans.

Figure 7: 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[8] 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 CARB staff.

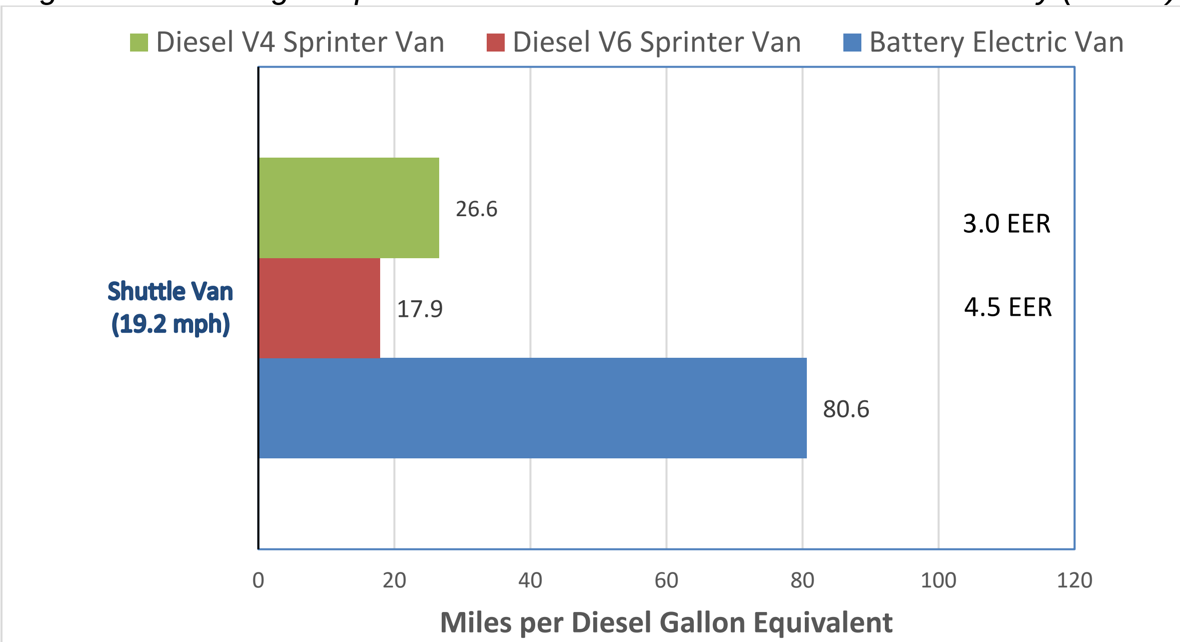
The data for the diesel vehicles included about 24,000 miles in the fall and winter (the data for the V6 diesel vans was collected in September, data for one V4 diesel van was collected in November and the other from December to January). The data for the three battery electric vans included about 29,000 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. We 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, we averaged the speeds from all 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, we 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 8. 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

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

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 8: 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[9] and one at an IKEA warehouse in conjunction with the San Joaquin Valley Air Pollution Control District[10]. 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, we referenced a different CalStart report[11] 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 we 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.

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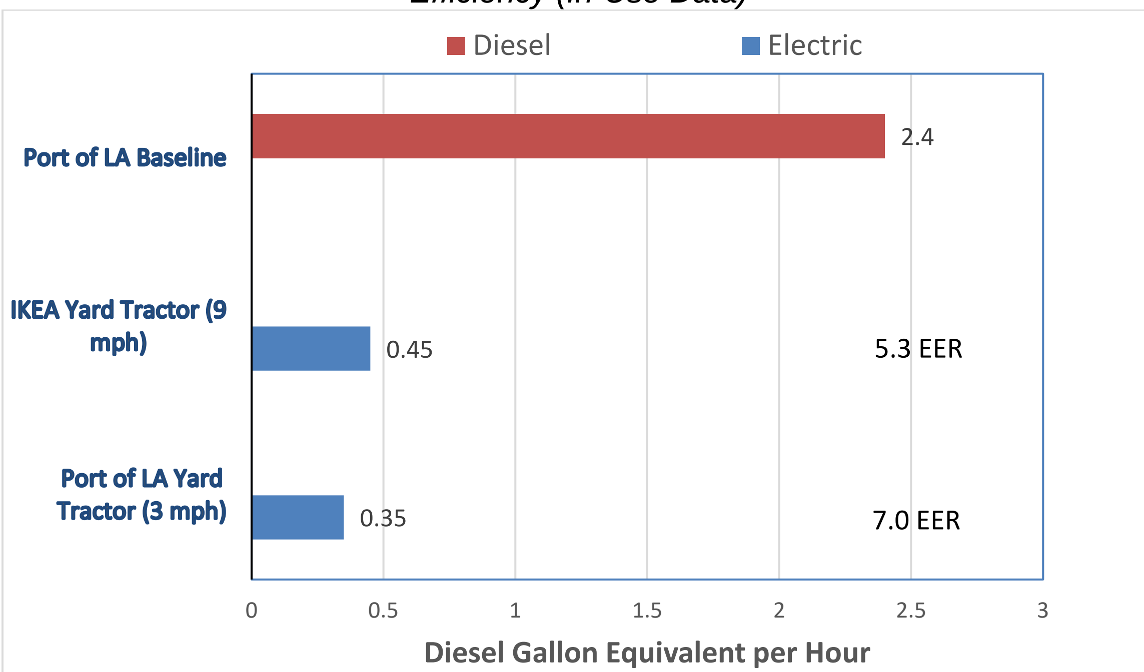
[9] *TransPower Electric Yard Tractor Demonstration Project for City of Los Angeles Harbor Department*. May 2015.
[10] *TransPower Electric Yard Tractor Demonstration Project for San Joaquin Valley Air Pollution Control District*. July 2015.
[11] CalStart Hybrid Yard Hostler Demo- Port of LA

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 the fuel economy of the electric tractor equated to .45 diesel gallon equivalents per hour. There was no data available to determine the average diesel yard truck fuel economy operating in warehouse operation. The Port of LA yard tractor consumed about .35 diesel gallon equivalents per hour. We used the conventional 2.4 diesel gallons per hour estimate to compare with the energy used in the battery electric prototypes. While it may not be the best comparison, the results provide some insight into the efficiency comparison for yard truck operations.

Figure 9 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 suggests that an EER above 5 is likely for yard truck operations.

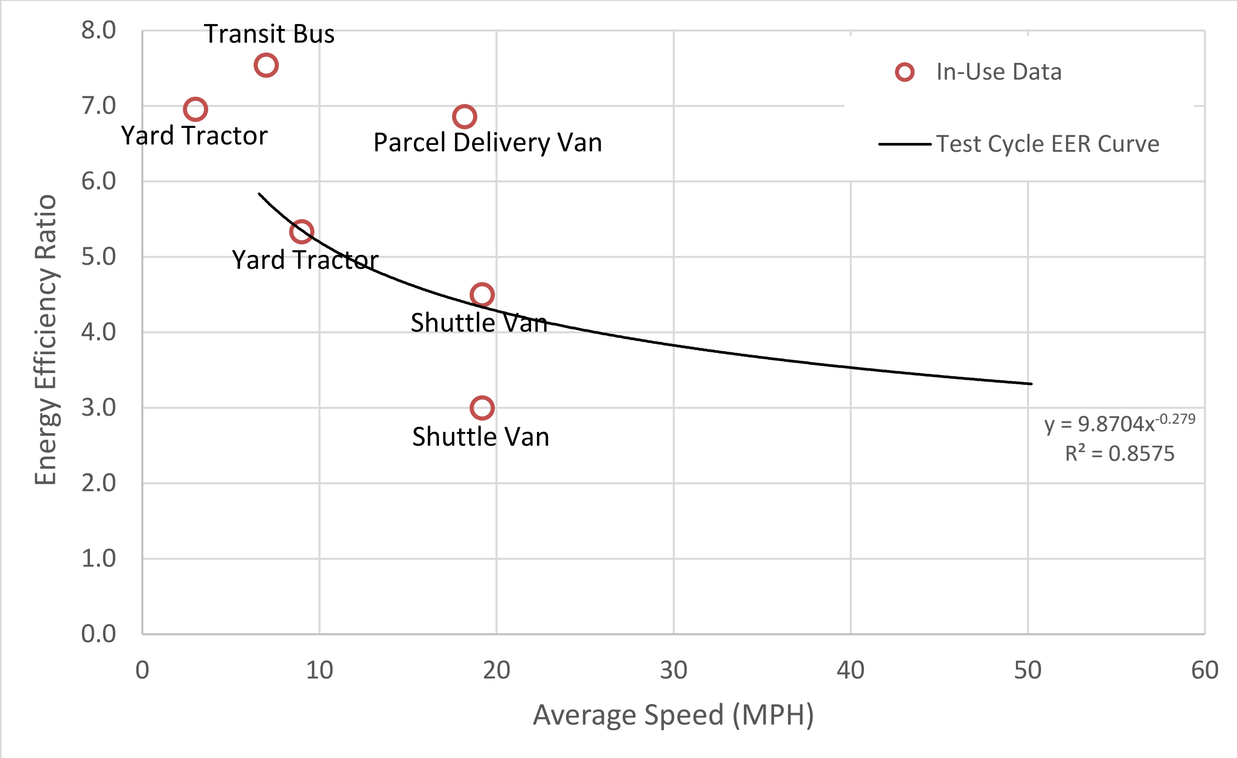
Figure 9: TransPower Yard Truck- Port and Warehouse Diesel vs Electric Fuel Efficiency (In-Use Data)



e. In-Use Data Summary

The in-use data was primarily collected from applications 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 was collected over an extended period of time with normal daily variations like traffic, weather, auxiliary loads and driver behavior that are generally not included in the test cycle comparisons. We 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 10. The in-use data is shown with red circles.

Figure 10: Vehicle Energy Efficiency Ratio at Different Average Speeds (Test Cycle and In-Use)



*Vehicle energy use excludes charger-battery system efficiency losses.

Although there is some uncertainty with the in-use data, we 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 2 shows the diesel and electric fuel economy data used in the above graph.

Table 2: Vehicle Energy Efficiency Ratio at Different Average Speeds

Data Source	Route/Cycle Name	Average Speed (MPH)	Conventional Fuel Economy (mpdge)	Electric Fuel Economy (kWhr/mi)	Electric Fuel Economy (mpdge)	Vehicle 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

We 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.

a. Transit Buses

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[12] (NTD) about their fleets and operating characteristics. For California transit agencies, the data

[12] National Transit Database

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.

b. Drayage Trucks

Staff analyzed drayage fleet activity data collected by TIAX, LLC, the same data set used by UC Riverside to develop the drayage port truck test cycles used in the dynamometer report. These data were used to develop representative chassis dynamometer drayage truck duty cycles that have been widely used to characterize in-use emissions from drayage trucks by the South Coast Air Quality Management District, CARB, and other agencies. To date, this study is believed to be the most comprehensive evaluation of drayage truck activity within California.[13] Therefore, we used the summary statistics of the raw activity data to determine a single activity-weighted average speed for drayage trucks operating across California.

The TIAX report classified truck driving patterns from 1258 trips into several modes, including the following: very low speed in truck queues (Creep), low speed operation during on-dock movement (Low Speed Transient), operation on regional roads and briefly on highways (Short/Long High Speed Transient), and sustained operation at high speeds (High Speed Cruise). The average truck speed was calculated for each mode and summarized in Table 3.

Table 3: Average speed associated with various "modes" of drayage truck operation from the Ports of Los Angeles and Long Beach to locations throughout California.

Metrics	Creep	Low Speed Transient	Short High Speed Transient	Long High Speed Transient	High Speed Cruise
Average Speed [υ_{Mean}] (mph)	2.7	7.6	17.1	18.7	37.9
Fraction of Total Trips	0.193	0.376	0.200	0.118	0.113

[13] TIAX, LLC. March 2011. Characterization of Drayage Truck Duty Cycles at the Port of Long Beach and Los Angeles.

Using the weight fraction (f) of trips and average speeds (υ) a mean speed can be estimated using Equation 1:

Equation 1: Drayage Truck Average Speed

$$\upsilon_{Mean} = \upsilon_{Creep}*(f_{Creep}) + \upsilon_{LST}*(f_{LST}) + \upsilon_{SHST}*(f_{SHST}) + \upsilon_{LHST}*(f_{LHST}) + \upsilon_{HSC}*(f_{HSC}) \quad (1)$$

$$\upsilon_{Mean} = 2.7*(0.193) + 7.6*(0.376) + 17.1*(0.200) + 18.7*(0.118) + 37.9*(0.113)$$

$$\boxed{\upsilon_{Mean} = 13.3 \text{ mph}}$$

c. Port Yard Tractors

The University of California, Riverside, College of Engineering-Center for Environmental Research and Technology (CE-CERT) prepared a report on the evaluation of electric yard tractors operating with Medium-Heavy-Duty (MHD) and Heavy-Heavy-Duty (HHD) loads.[14] In this report, CE-CERT provided yard truck operational data for the Long Beach Container Terminal (LBCT) within the Port of Long Beach. CARB has reviewed this data and is assuming this data reasonably represents yard truck operational characteristics at other port applications within California.

Based on information provided in CE-CERT's report, the following assumptions are made for the analysis presented:

- Ship and Rail work comprises 95% of yard truck activities.
- Measured gross combined vehicle weights (i.e., combined vehicle, trailer, and container weights) of yard trucks less than 44,181 lbs are referred to as Medium-Heavy-Duty (MHD) loads. The MHD load classification likely includes operation of yard tractors with a trailer but no container, and no trailer or container at all.
- Similarly, measured gross combined vehicle weights greater than 44,181 lbs are referred to as Heavy-Heavy-Duty (HHD) loads.
- The average of binned MHD and HHD loads are 26,209 and 72,393 lbs, respectively. Here, MHD and HHD are classifications of actual combined weights of a tractor, trailer, and/or container, not the capacity or weight rating of the tractor being used.
- Yard trucks spend 64.1 and 35.9 percent of their time carrying MHD and HHD loads, respectively.

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[14] College of Engineering-Center for Environmental Research and Technology (CECERT). Accessed January 2017. Performance Evaluation of Transpower All-Electric Yard Tractor.

- Yard trucks spend 25 and 75 percent of their time performing rail and ship work, respectively.

Accounting for "creep and idle", the average speeds for MHD and HHD loads are 5.3 and 7.1 mph, respectively. This information is stratified further into specific duty sub-cycles in Table 4.

Table 4: Average speed associated with duty "sub-cycles" for yard trucks operating at LBCT.

Metrics	Rail-MHD	Ship-MHD	Rail-HHD	Ship-HHD
Average Speed [υ_{Mean}] (mph)	6.1	5.0	7.1	7.1

We used data collected by CE-CERT to derive an activity-weighted average speed according to Equation 2, where υ represents the average speed for the associated duty cycle and work activity, *f* represents the weight fraction of time performing ship or rail work, and *f'* represents the weight fraction of time spent carrying MHD or HHD loads.

Equation 2: Yard Tractor Average Speed

$$\upsilon_{\text{Yard Trucks}} = (\upsilon_{\text{Rail-MHD}})*(f_{\text{Rail}})*(f'_{\text{MHD}}) + (\upsilon_{\text{Ship-MHD}})*(f_{\text{Ship}})*(f'_{\text{MHD}}) \quad \textbf{(2)}$$

$$+ (\upsilon_{\text{Rail-HHD}})*(f_{\text{Rail}})*(f'_{\text{HHD}}) + (\upsilon_{\text{Ship-HHD}})*(f_{\text{Ship}})*(f'_{\text{HHD}})$$

$$\upsilon_{\text{Yard Trucks}} = 6.1*0.25*0.641 + 5.0*0.75*0.641 + 7.1*0.25*0.359 + 7.1*0.75*0.359$$

$$\upsilon_{\text{Yard Trucks}} = 5.9 \text{ mph}$$

Thus, we assume that the average speed of yard trucks in California is 5.9 mph.

d. Other Trucks

For trucks, NREL hosts a database of fleet operational data called the Fleet DNA database[15]. 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 5. Additionally, the International Energy Agency recently presented a paper which characterized the average speed of long haul tractors, which was included in the table[16]. We also included data from the UCR Drayage report and TIAX, LLC for local haul drayage, total average drayage, and CalStart yard hostler report for port yard tractor use to cover those types of operations.

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[15] NREL Fleet DNA Fleet Operations Database
[16] International Energy Agency Presentation

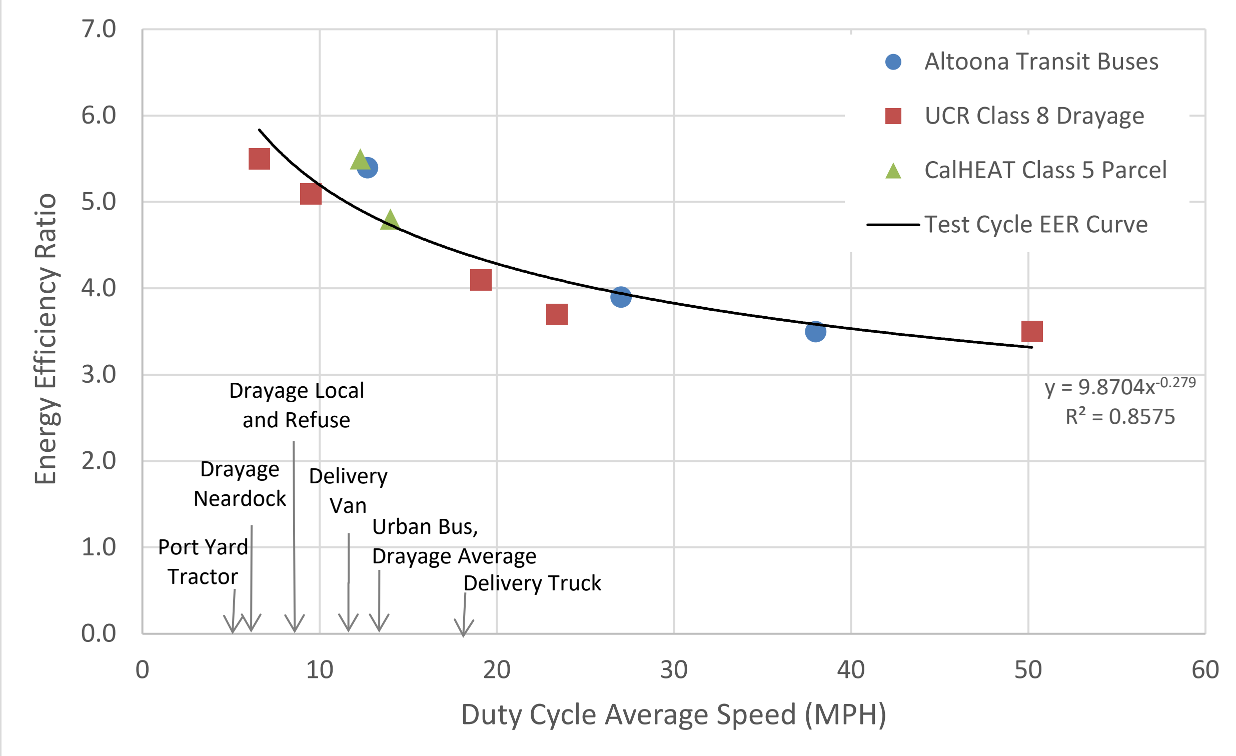
Table 2: Average Speed by Vehicle Category

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	International Energy Agency
Transit Bus	8	Public transit (urban buses)	13.0	NTD
Yard Tractor	8	Port/Yard Hostler	5.9	CE-CERT LBCT
Drayage Local Tractor	8	Port/Intermodal Container Haul	9.5	UC Riverside
Drayage Average	8	Port/Intermodal Container Haul	13.3	TIAX, LLC

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 11, below. Heavy duty electric vehicles in on-road applications across multiple vocations, weight classes, and drive cycles have energy efficiency 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 11: Vehicle Energy Efficiency 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 are described in more detail in Appendix 1.

Appendix 1: Battery System and Charging Efficiency

The vehicle energy efficiency ratio (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.

We 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 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 6.

Table 3: 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."[17] 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 7 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 4: 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[18] 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 state of charge (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 efficiency. We believe that using an 85 percent overall battery and charging system

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

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

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.