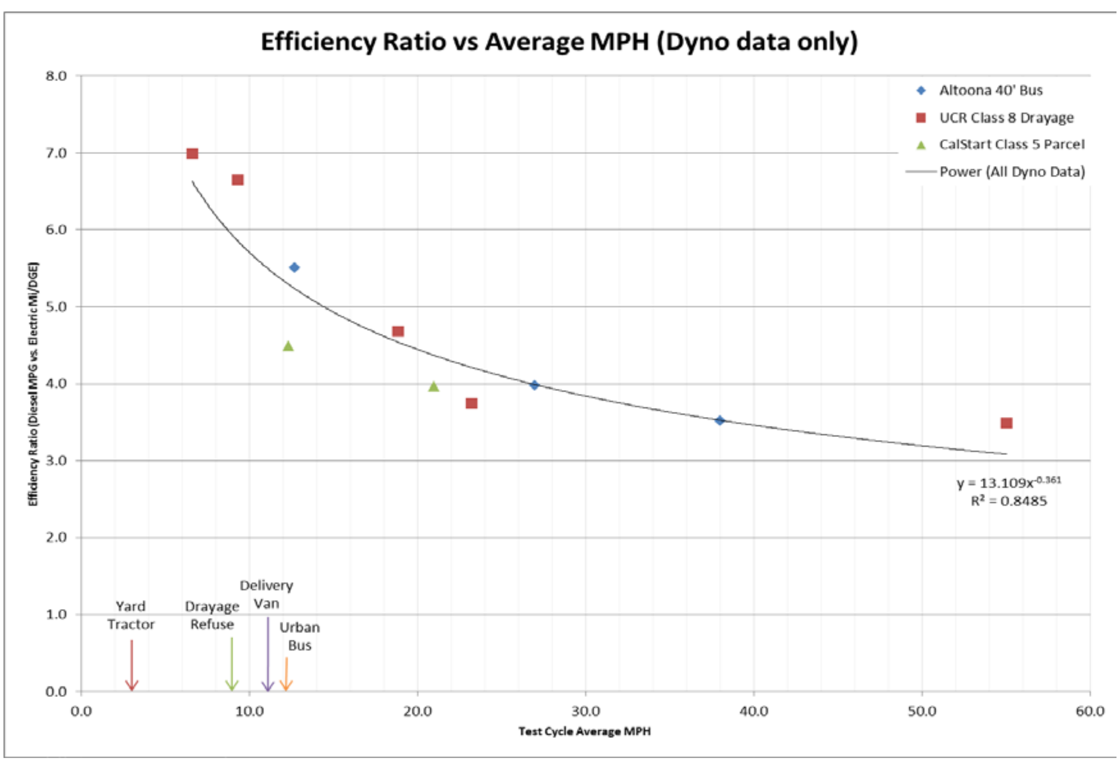
Executive Summary

This paper provides a summary of the efficiency of battery electric vehicles when compared to conventional diesel vehicles operated in the same duty cycle. Several years ago, the California Air Resources Board established an estimated energy efficiency ratio (EER) of 2.7 for battery electric trucks based on limited data from 2007. The EER for buses was set at 4.2 for buses based on more recent test data. The EER is used to determine fuel 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. The EER for trucks did not appear to be consistent with transit bus data nor electricity use and actual fuel savings in recent studies where battery electric truck efficiencies were compared with diesel trucks in local operations that needed to be explained.

We gathered data from available studies where conventional diesel vehicles and equivalent battery electric vehicles were tested on the same dynamometer test cycles to ensure that vehicles were operated under identical conditions for comparison. This ensures that the comparisons are "apples to apples". The primary data sources we used include different fuel economy test cycles for 40' transit buses, a recent study on Class 8 drayage trucks and test data from an evaluation of parcel delivery trucks. The EER for these vehicles were plotted by average speed of the test cycle and results in the best fit curve shown below in Figure 1. Regression analysis confirms statistically significant correlation (P-value <.05 at 95% confidence interval).

Figure 1: Efficiency Ratio at Different Average Speeds (Dynamometer data)



Sources: Altoona Transit Bus Study, UCR Transpower Drayage Study, CalHEAT Parcel Delivery Study

As expected, the results show that the efficiency improvement of battery electric vehicles is considerably higher than conventional vehicles for different weight classes, vehicle types and duty cycles. The data shows a vehicle efficiency improvement of about 3.5 times at high way speeds and efficiencies that are 5 to 6 times higher than conventional diesel vehicles when operated at lower speed duty cycles where idling and coasting loses from conventional engines are highest. We also compared in-use data from Class 3 passenger vans and Class 8 yard trucks to the EER curve and confirmed the efficiency gains were similar in-use and that the relationship holds for different vehicle types and weight classes.

To put these results in context, the average daily speed for a 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 greater than 5 and can be higher than 6 for yard trucks and trash trucks. Several other vehicle categories representative of local vehicle operation average about 13 mph, except line haul operations that is reflective of freeway driving. In the next 10 years, battery electric trucks and buses are most likely to be placed in service in these slower speed operations because of battery range limitations and battery costs.

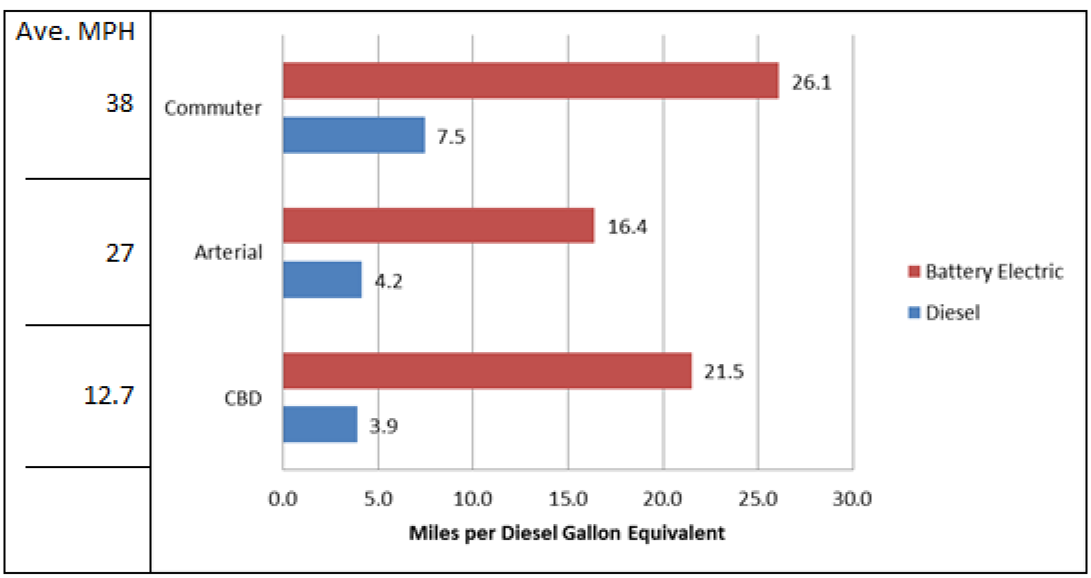
The implication of these results is that the GHG emissions benefits and fuel saving from electrification of trucks and buses are better than previously understood especially for low speed duty cycles. In California, the EER is also used to determine how many credits an electric vehicle owner can receive for using electricity as a motor vehicle fuel. Potential updates to the Low Carbon Fuel Standard (LCFS) program would result in higher credits per kWh used and would improve the total cost of ownership. The EER curve also allows the end user to estimate the electricity usage for a battery electric vehicle that would replace a conventional vehicle if the average speed and fuel economy of the conventional vehicle is known.

Bus Dynamometer

The Altoona Bus Research and Testing Center regularly test buses as part of its program to evaluate new bus models. We evaluated test results for a variety of 40 foot buses from different manufacturers with different fuel types on six dynamometer test cycles for emissions and fuel efficiency comparisons[1]. Hybrid, diesel, compressed natural gas (CNG), and battery electric buses were tested on Central Business District (CBD), Arterial, and Commuter test cycles. Data we evaluated for the buses was for 2011 model year buses and newer diesel and battery electric vehicles. The electric buses compared were a 2013 BYD Motors, Inc. 40 foot battery electric bus, 2013 New Flyer 40 foot battery electric bus, and a 2014 Proterra, Inc. 42 foot battery electric bus. The diesel vehicles were a 2010 New Flyer 40 foot diesel bus, a 2011 North American Bus Industries 41 foot diesel bus, and a 2011 Daimler Buses North America LTD Orion 41 foot diesel bus.

CBD is a test cycle which represents bus operation in dense urban settings. The average speed of this test cycle is 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. Commuter test cycle represents bus operation over even longer distance with no stops, at highway speeds with an average speed of 38 mph. Data reported by transit fleet to the California Air Resources Board shows that 80 percent of buses are urban buses and transit fleet data reported to the National Transit Database (NTD) shows that the average speed for transit buses in California is about 13 miles per hour. The CBD cycle has average speeds that are most representative of typical average transit bus operation than the other two cycles and has an EER of 5.5.

Figure 2: Altoona Buses Diesel vs Electric Fuel Efficiency (Dyno)



Source: Altoona Transit Bus Study

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

Drayage Dynamometer

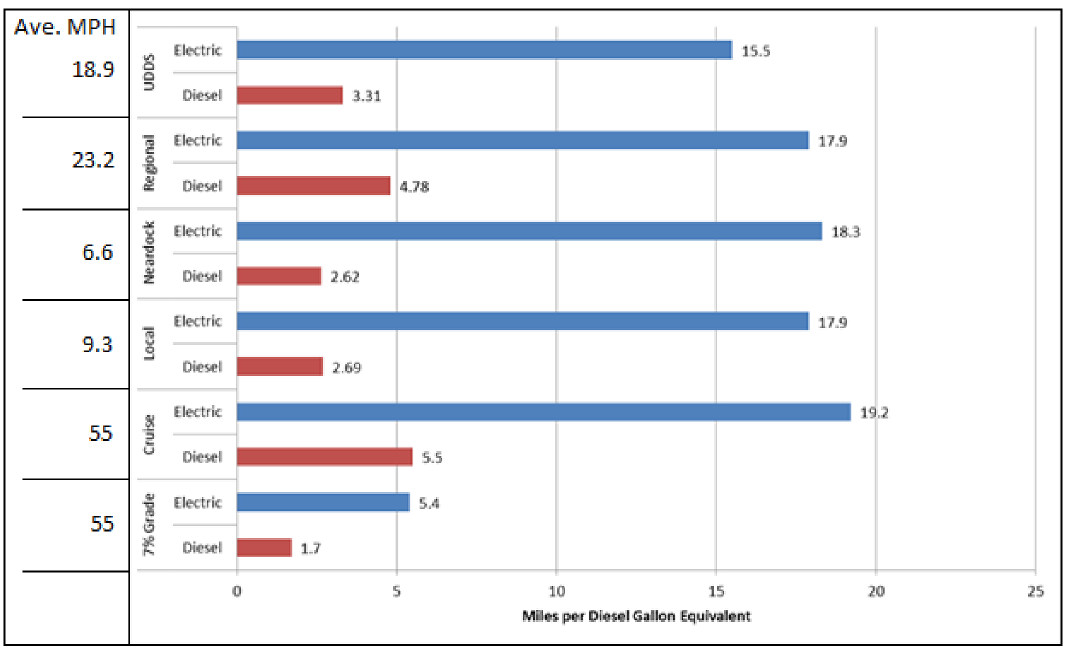
UC Riverside (UCR) undertook a chassis dynamometer and real world study of a 2015 Class 8 TransPower battery electric truck prototype designed for use in drayage operation[2]. Results for the dynamometer portion of the study were published in an April 2015 report.

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 Transpower truck was operated on these cycles and calculated to miles per diesel gallon equivalent, and compared to average data for 2007-2010 conventional diesel heavy duty vehicles tested previously by UCR on the same test cycles.

UDDS is a test cycle which represents truck operations in city settings. The average speed of this test cycle is 18.9 mph. Cruise represents truck operation at steady state and is used for range testing. The average speed of this test cycle is 55 mph. 7% grade represents the unique feature of the Port of LA which has a very long bridge, and was used to determine if the vehicle could surmount this bridge under load. It is also tested at an average 55 mph, with a 7% grade applied. Because this cycle is a unique feature of one port and not representative of ports in general, this data point was not plotted on the EER chart above, but is included in the bar graph below for reference. Drayage cycles of Neardock (6.6pmh), Local (9.3 mph), and Regional (23.2 mph) represent typical drayage trucking routes.

As shown in Figure 3, the data collected support 3 to 6.9 times better fuel efficiency for electric drayage trucks than similar conventional diesel vehicles.

Figure 3: UCR Drayage Diesel vs Electric Fuel Efficiency (Dyno)



Source: UCR Transpower Drayage Study

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

CalStart Parcel Dynamometer

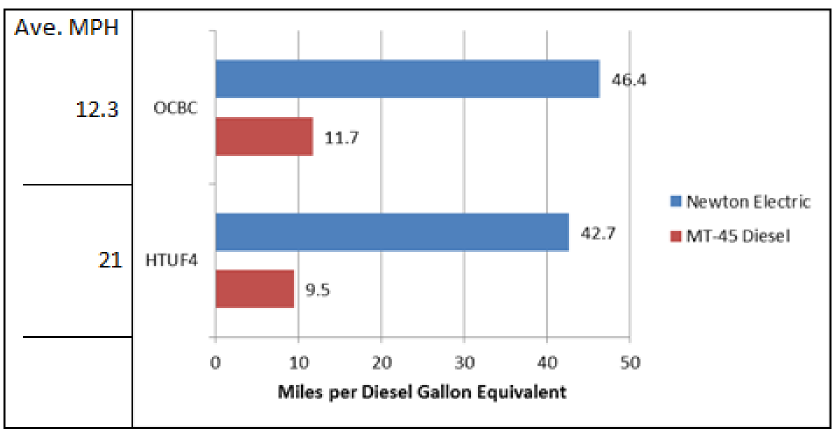
CalStart compared battery electric parcel delivery vans to conventional diesel in an August 2013 test study.[3] The goal of the project was to present data gathering results, findings, and subsequent recommendations of testing and demonstration of battery electric parcel delivery trucks operated by an unnamed large delivery fleet in Los Angeles, CA. Data from in-use data collection, on road testing, and chassis dynamometer testing was used.

Data from two Freightliner Custom Chassis Corp (FCCC) MT E-Cell Class 4 battery electric delivery vans, four Navistar eStar Class 3 battery electric delivery vans, and one Smith Electric Newton Class 5 battery electric step van were gathered in the report. One MT E-Cell was tested in-use, and one was tested with several on-road test cycles on different routes. All four eStars were tested in-use, and the Newton was tested on the chassis dynamometer.

Test data were compared to 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 FCCC MT-45 Class 5 diesel walk-in van. The Newton and FCCC MT-45 were tested on HTUF4 cycle (21 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.

As seen in Figure 4, the data collected support 3.96 to 4.5 times better fuel efficiency for electric class 5 parcel delivery trucks than similar conventional diesel vehicles for two different test cycles. In-Use data from this study is presented in subsequent sections.

Figure 4: CalHEAT Parcel Van Diesel vs Electric Fuel Efficiency (Dyno)



Source: CalHEAT Parcel Delivery Study

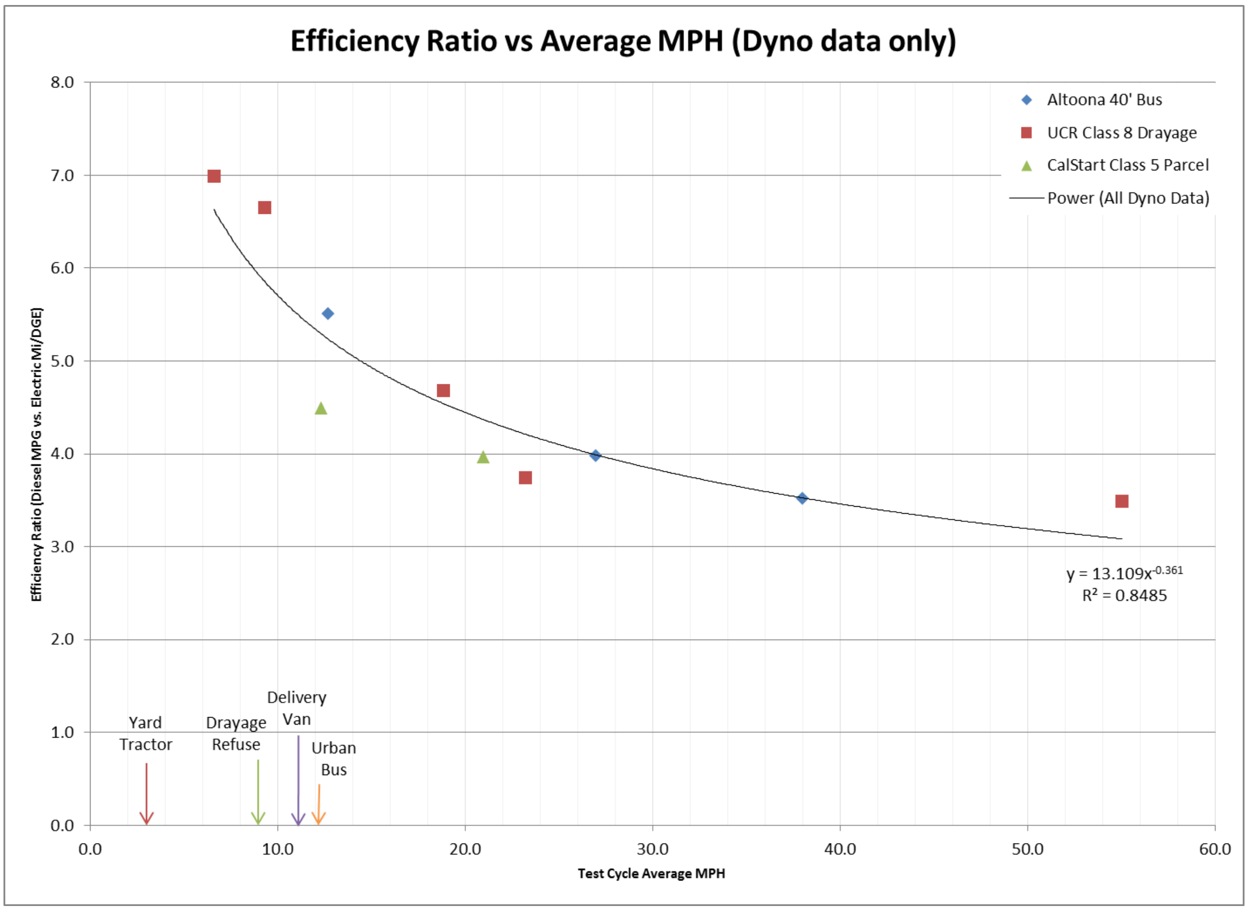
[3] Battery Electric Parcel Delivery Truck Testing and Demonstration. California Energy Commission. Gallo, Jean-Baptiste, Jasna Tomic. (CalHEAT). 2013

Dynamometer Data Summary

The EER values for the dynamometer tested vehicles were plotted against the average speed of the test cycle, resulting in the curve shown below in Figure 5. Regression analysis confirms statistically significant correlation (P-value <.05 at 95% confidence interval).

Also denoted on the chart are several vehicle types that, according to the NREL Fleet DNA database[4] and in-use port yard tractor studies by Transpower[5], have low average operating speed across a variety of vocations. These were marked to illustrate the current prime target market for electrification

Figure 5: Efficiency Ratio at Different Average Speeds (Dynamometer data)



Sources: Altoona Transit Bus Study, UCR Transpower Drayage Study, CalHEAT Parcel Delivery Study

The curve shows that EER ratios increase exponentially with lower speeds. The equation 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 graph indicates vehicle types with lower average speeds to illustrate the prime target market for electrification.

[4] NREL Fleet DNA Fleet Operations Database

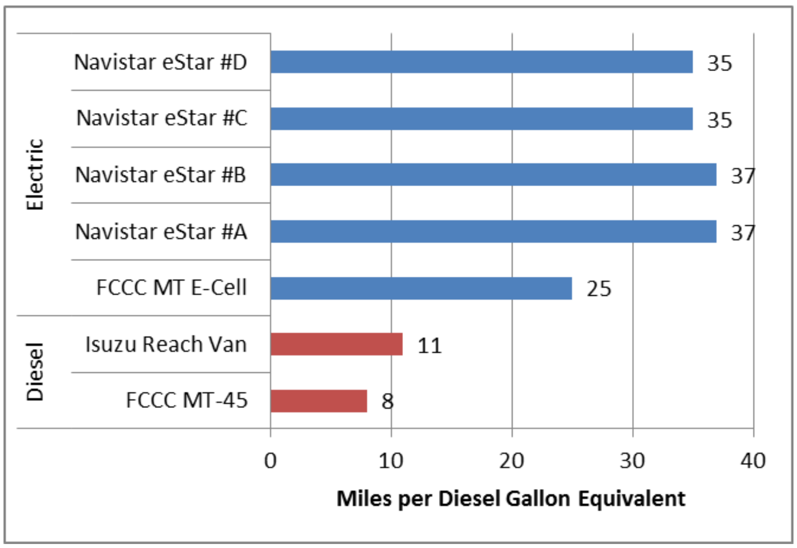
[5] *TransPower Electric Yard Tractor Demonstration Project for City of Los Angeles Harbor Department*. May 2015.

In-Use Data – Parcel Delivery

Data including mileage and fuel use for the eStar in-use routes were collected over approximately nine months, from March 2012 through December 2012. Data including mileage and fuel use for one MT E-Cell in-use route were collected over approximately six months, from June 2012 through December 2012. The four eStars travelled almost 9500 miles combined, and the E-Cell travelled over 1300 miles for the duration of the data gathering periods, averaging 220-330 miles per month. The baseline data from the Isuzu Reach vans amounted to 844 miles over 3 weeks. The in-use routes were described as typical for a parcel delivery company in downtown Los Angeles. Speed of the in-use vehicle routes was not provided in the report. The fuel consumption rates for the vehicles in-use were available and are charted below.

As seen in Figure 5, the data collected support 2.2 to 4.65 times better fuel efficiency for E-Trucks than similar conventional diesel vehicles.

Figure 5: CalHEAT Parcel Van Diesel vs Electric Fuel Efficiency (In-Use Data)



Source: CalHEAT Parcel Delivery Study

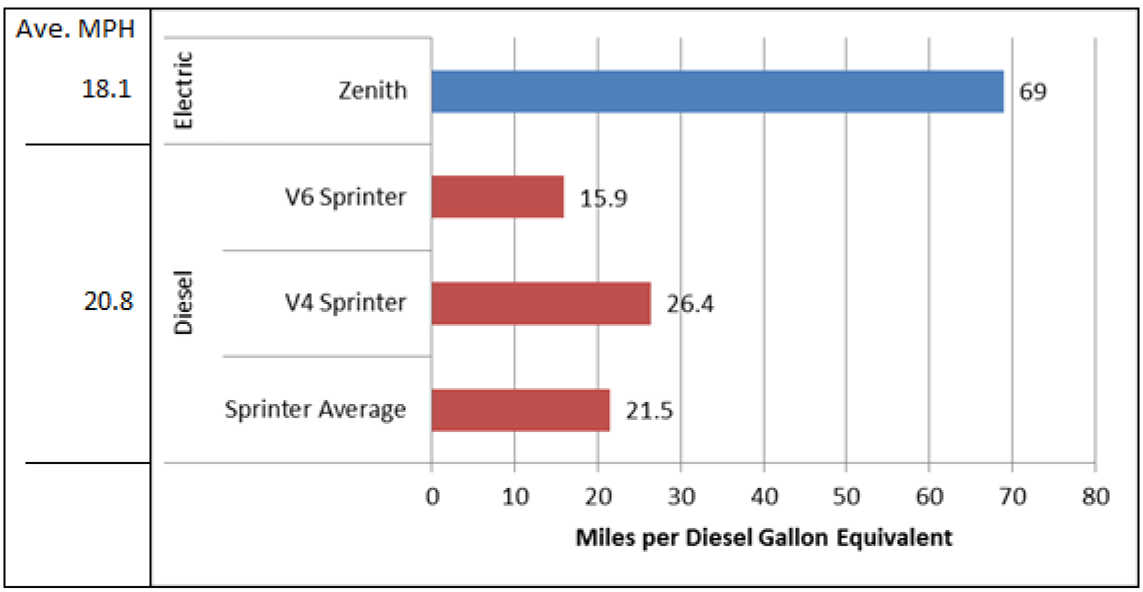
In-Use Data - Shuttle Vans

The San Diego Airport Parking Company provided data from her fleet for three conventional diesel Mercedes-Benz Sprinter Class 2b-3 van shuttles and three Dodge Ram Class 3 shuttle vans converted into battery electric vehicles by Zenith Motors. Mileage and fuel use data were collected over several periods of real world operation, averaging one month of data collection per vehicle, from December 2015 through September 2016. The Dodge Ram electric conversions travelled just over a combined 29000 miles, and the conventional diesel Sprinters travelled almost 18000 miles over the course of the study.

The raw in-use data for the typical in-use route were analyzed in-house by staff. Average speed for the conventional diesel vehicles was 20.8 mph, while the electrics averaged 18.1 mph. The speeds are fairly close but are not the same.

As seen in Figure 6, the data collected support 2.6 to 4.3 times better fuel efficiency for E-Shuttle buses than similar conventional diesel vehicles.[6]

Figure 6: San Diego Airport Shuttle Bus Diesel vs Electric Fuel Efficiency (In-Use Data)



Source: SD Airport Parking Company

[6] San Diego Airport Parking Company In-Use Shuttle Dataset provided by Lisa McGee

In-Use Data – Yard Tractors

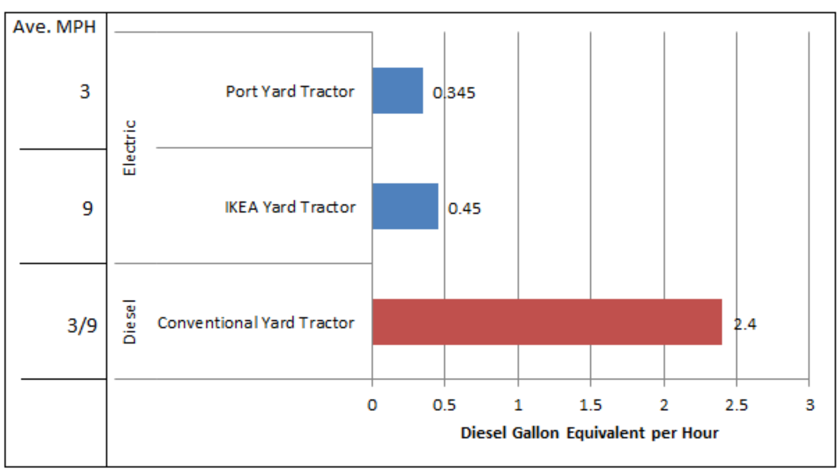
Transpower demonstrated three class 8 battery electric yard tractors. Two were demonstrated in conjunction with the Port of Los Angeles[7] and one at an IKEA warehouse in conjunction with the San Joaquin Valley Air Pollution Control District[8]. The yard tractor demo projects covered a total period from September 2014 through May 2015. Because no diesel vehicle baseline was measured in these reports, another CalStart report[9] detailing hybrid yard truck demo project with the Port of LA was used to get an average diesel baseline fuel economy, which the report mentions is industry standard for the port type operations.

It is important to note that yard truck fuel economy is typically reported in gallons per hour, rather than mile per gallon. Many of these vehicles do not have odometers due to the off-road nature of their use and run solely on hour meters. Additionally, the IKEA tractor was a first prototype, the experience and demonstration of which Transpower used to improve the port yard tractors efficiency.

Average speed of the IKEA yard tractor was 9 mph. The port yard trucks travelled on average 3 mph. Because no conventional diesel baseline was provided in the report for comparison, staff assumed the conventional truck would travel the same speed as the electric yard tractors in their conventional operations while operating at the industry standard efficiency reported by CalStart at 2.4 diesel gallons per hour.

Figure 7 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 suggests an EER above 5, which is not inconsistent with the in use data gathered from the Transpower studies.

Figure 7: Transpower Yard Truck- Port and Warehouse Diesel vs Electric Fuel Efficiency (In-Use Data)



Sources: Transpower Electric Yard Truck Demos, CalStart Hybrid Yard Hostler Demo

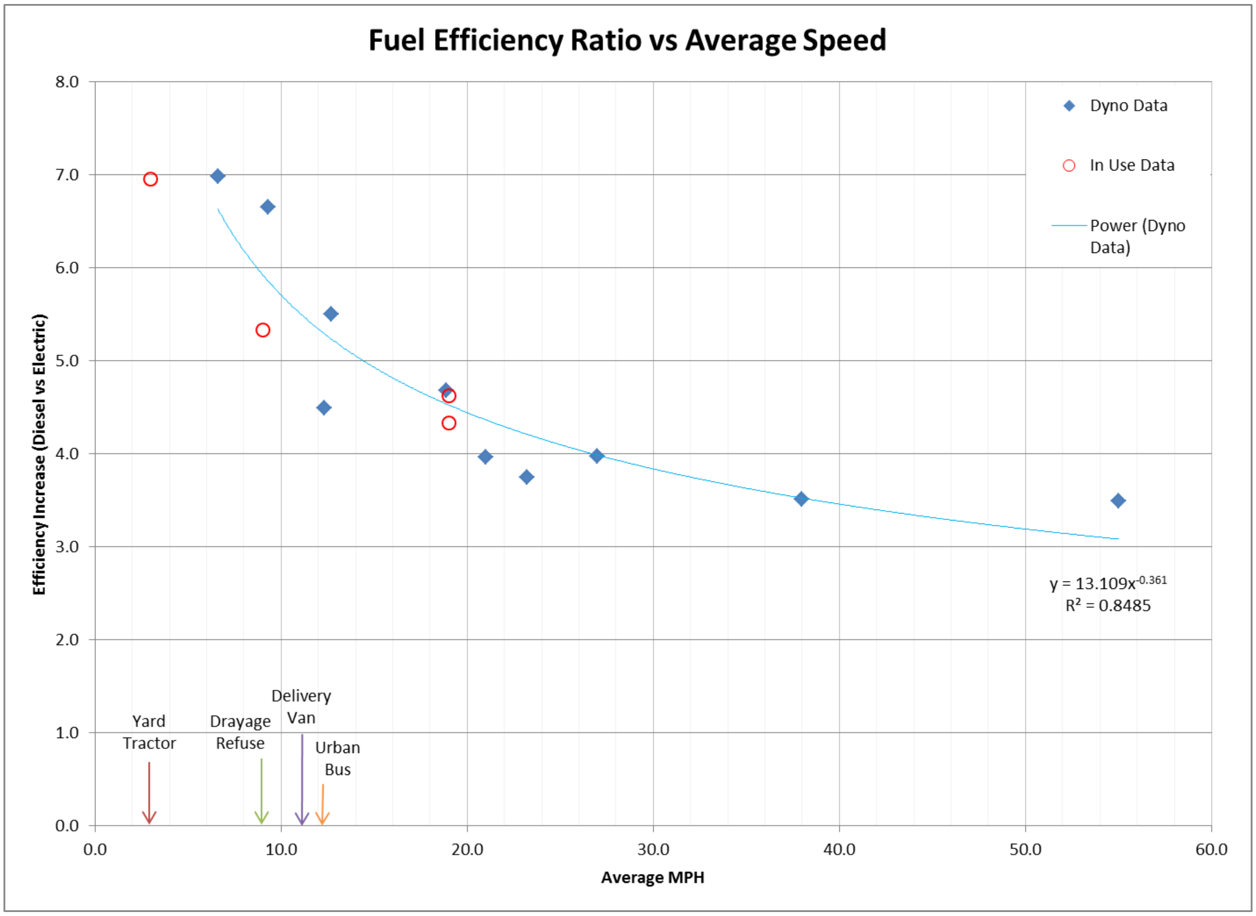
---

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

In-Use Data Summary

After gathering the in-use data, staff wanted to plot the EER points to see if they fit the curve. Even though the in-use data are not perfect "apples-to-apples" comparisons, they still fit the EER curve of the dynamometer data well.

Figure 8: Efficiency Ratio at Different Average Speeds (In-Use and Dynamometer data)



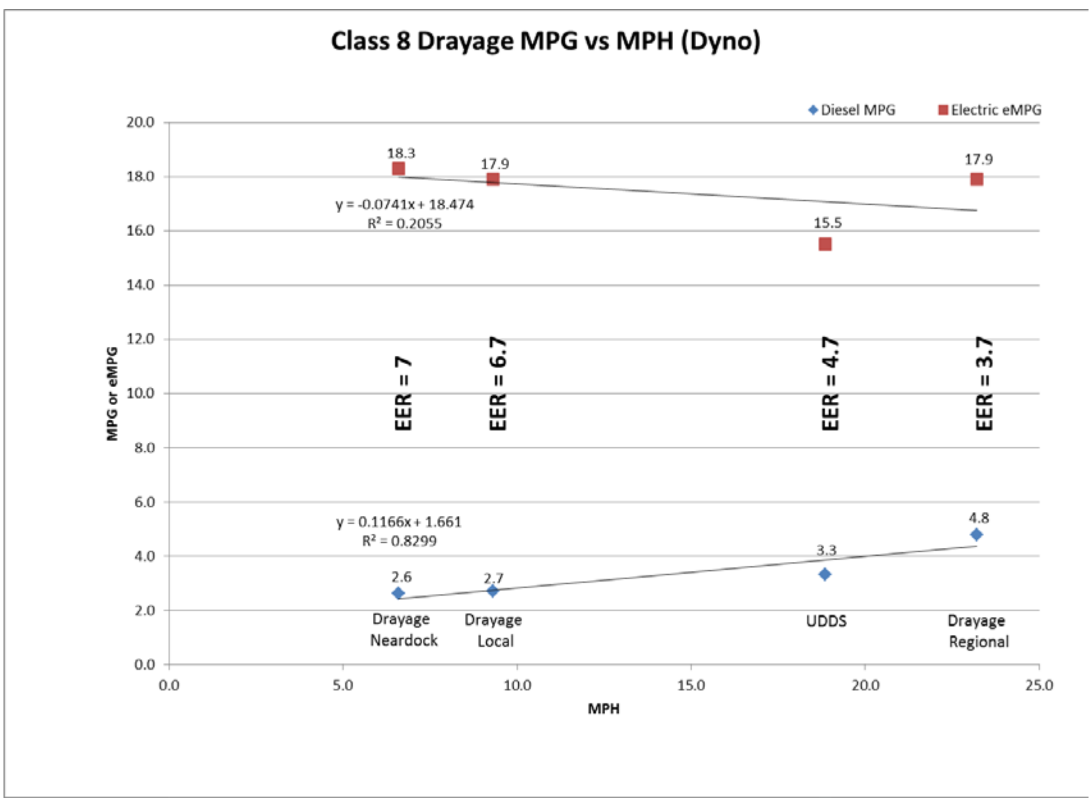
Sources: Altoona Transit Bus Study, UCR Transpower Drayage Study, CalHEAT Parcel Delivery Study, SD Airport Parking Company, Transpower Electric Yard Truck Demos

Comparing Fuel Efficiency

The lower speed data points for the class 8 drayage vehicles from the Transpower study were plotted against the MPG and eMPG in Figure 8. The figure shows the drayage truck fuel economy is 4.8 mpg at about 23 mph and declines to 2.6 mpg when operated in a duty cycle with an average speed of below 8 mph. The electric trucks tend to operate at about 18 eMPG for 3 of the 4 data points over the same range. We can see that the EER ratios increase as the diesel efficiency decreases. This relationship holds even when the drive cycle causes a dip in the fuel economy for both vehicles, as seen in the UDDS cycle when compared to the trend line. The EER still increases as speed decreases. This suggests that the fuel economy for either a diesel or electric vehicle (with the same operating conditions) may be reasonably predicted independent of other variables like load terrain and vehicle loading if the fuel consumption is known for either vehicle. Figure 9 can be used to draw the same conclusions using the transit bus data. Fleet owners should be able to use the equation of the EER curve to input the average speed of a conventional diesel vehicle and its average fuel economy to closely approximate the energy usage of an electric vehicle used in the same capacity.

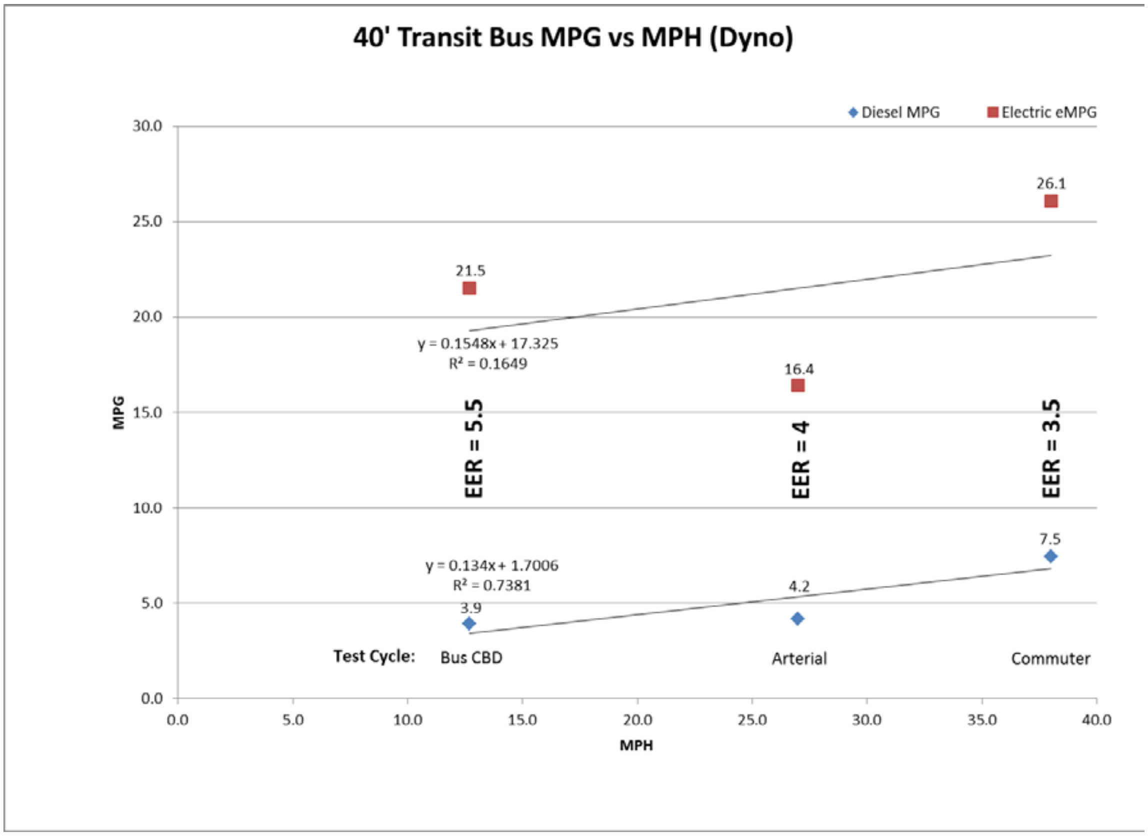
For example, a diesel vehicle travelling at 10 mph average would have an EER of 5.7. If we know that diesel vehicle gets on average about 2.8 mpg (such as a drayage truck), we can multiply the diesel mpg by the EER to find the approximate electric eMPG, which would be about 16.0 eMPG. The eMPG can be converted to kilowatt hours per mile (kWh/mi) to estimate a variety of costs associated with operating the vehicle and assist in making business decisions related to fuel consumption and costs.

Figure 9: Class 8 Drayage MPG vs MPH (Dynamometer)



Source: UCR Transpower Drayage Study

Figure 10: 40' Transit Bus MPG vs MPH (Dyno)



Source: Altoona Transit Bus Study

Table 1: Drive Cycle Fuel Efficiency, EER and Average Speed (In-use and Dyno)

Data Source	Cycle Name	Average Speed (MPH)	EER Ratio	Diesel MPG	Electric eMPG
Transpower - Class 8 Yard Tractor	Port of LA In-Use Route	3.0	7.0	2.4 gal/hr	.345 DGE/hr
UC Riverside - Class 8 Drayage Tractor	Drayage Neardock	6.6	7.0	2.6	18.3
Transpower - Class 8 Yard Tractor	IKEA Warehouse In-Use Route	9.0	5.3	2.4 gal/hr	.45 DGE/hr
UC Riverside - Class 8 Drayage Tractor	Drayage Local	9.3	6.7	2.7	17.9
CalStart - Class 5 Step Van	OCBC	12.3	4.5	9.5	42.7
Altoona - Class 8 40' Bus	Bus CBD	12.7	5.5	3.9	21.5
UC Riverside - Class 8 Drayage Tractor	UDDS	18.9	4.7	3.3	15.5
CalStart - Class 3 Sprinter Van	Navistar eStar In-Use Route	19.0	4.6	8	37
SD Airport - Class 3 Shuttle Van	SD Airport Shuttle In-Use Route	19.0	4.3	15.9	69.0
CalStart - Class 5 Step Van	HTUF4	21.0	4.0	11.7	46.4
UC Riverside - Class 8 Drayage Tractor	Drayage Regional	23.2	3.7	4.8	17.9
Altoona - Class 8 40' Bus	Arterial	27.0	4.0	4.2	16.4
Altoona - Class 8 40' Bus	Commuter	38.0	3.5	7.5	26.1
UC Riverside - Class 8 Drayage Tractor	Drayage Cruise	55.0	3.5	5.5	19.2

Table 1 shows diesel MPG and electric eMPG for a variety of vehicles across different drive cycles, and includes in-use data. This shows that even in real world situations, the EER relationship holds well to average speed, and thus should be a good predictor of energy use or diesel fuel economy using the EER curve line equation.

Vehicle Operating Characteristics

The NREL hosts a database of fleet operational data called the Fleet DNA database[10]. This database is intended to assist in characterizing the operations of certain types of vehicles. 8 main categories exist, and staff analyzed the data from each to identify potential targets for electrification. Refuse trucks (9.5 mph average), delivery vans (11.7 mph average), service vans (14.7 mph average), delivery trucks (18.4 mph average), and service vans (14.7 mph average) fall well within the 20 mph average target for potential electrification. Class 8 tractors have an average speed of 20.1 mph, which includes local and regional delivery. Line haul tractors (48 mph average)[11] would not be a target in class 8, but very short haul operations such as drayage and yard trucks would be a good target, averaging 9[12] and 3[13] mph respectively. Urban buses, according to the National Transit Database[14], average 12 mph.

Table 2: Average Speed by Vehicle Category

Vehicle Category	Class	Vocation	Total Average Speed (mph)
Refuse	8	Refuse	9.5
Service Van	2 to 3	Utility/Telecomms	14.7
Delivery Van	3 to 6	Food, Parcel, Linen, Beverage	11.7
Delivery Truck	3 to 7	Delivery, straight, stake, furniture, rack, beverage	18.4
Bucket Truck	3 to 7	Utility/Telecomms- Boom with Bucket only	11.0
Tractor	7 to 8	Delivery, Beverage, Semi, Refridgerated, Fuel, Regional, Long Haul	20.1
Class 8 Long Haul Tractor	8	Long Haul	48.0
Transit Bus	8	Public Transit	12.0
Yard Tractor	8	Port/Warehouse/Yard Hostler	3.0
Drayage Tractor	8	Port/Intermodal Container Haul	9.0

Sources: NREL Fleet DNA, International Energy Agency, UCR Transpower Drayage Truck Study, Transpower Electric Yard Truck Demo, National Transit Database

[10] NREL Fleet DNA Fleet Operations Database
[11] International Energy Agency Presentation
[12] Performance Evaluation of TransPower All-Electric Class 8 On-Road Truck. Johnson. Kent. J. Wavne Miller. And Jiang Yu Xiao.
[13] *TransPower Electric Yard Tractor Demonstration Project for City of Los Angeles Harbor Department*. May 2015.
[14] National Transit Database

Conclusion

The combined data from the above studies suggests that heavy duty electric vehicles in on-road applications across multiple vocations, weight classes, and drive cycles have energy efficiency ratios ranging from 3 for high speed duty cycles to greater than 6 for slow speed duty cycles when compared to similar conventional vehicles.

The early market for electric trucks and buses is expected to be in applications with average speeds around 12 miles per hour with many start/stop events on a typical route. About 50 percent of transit buses travel at average speeds below 13 mph and are the most likely buses to go to zero emissions because of lower battery costs, lower operational risks, and slower speeds are most common in densely populated area where noise concerns are higher. The data supports increasing the EER to 5.5 for heavy duty full electric vehicles that are likely to be deployed in the next ten years. and vehicles with over 100 miles all electric range.

For trucks the early market is most likely to be served by duty cycles with average daily trips of less than 100 miles per day. Part of the reason is that truck upfront costs are lower with smaller battery packs that can be used to fit the existing need. Manufacturers are currently producing vehicles that meet these short range needs. Plug-in range extended trucks are also being produced and operated. These trucks are more likely to displace both high and lower mileage vehicles, and may have an EER that is lower than for battery electric trucks simply because the vehicles displaced are more likely to operate at higher daily average speeds than short range trucks.

Figure 11: Efficiency Ratio at Different Average Speeds (Dynamometer data) (Identical to Figures 1 and 5)

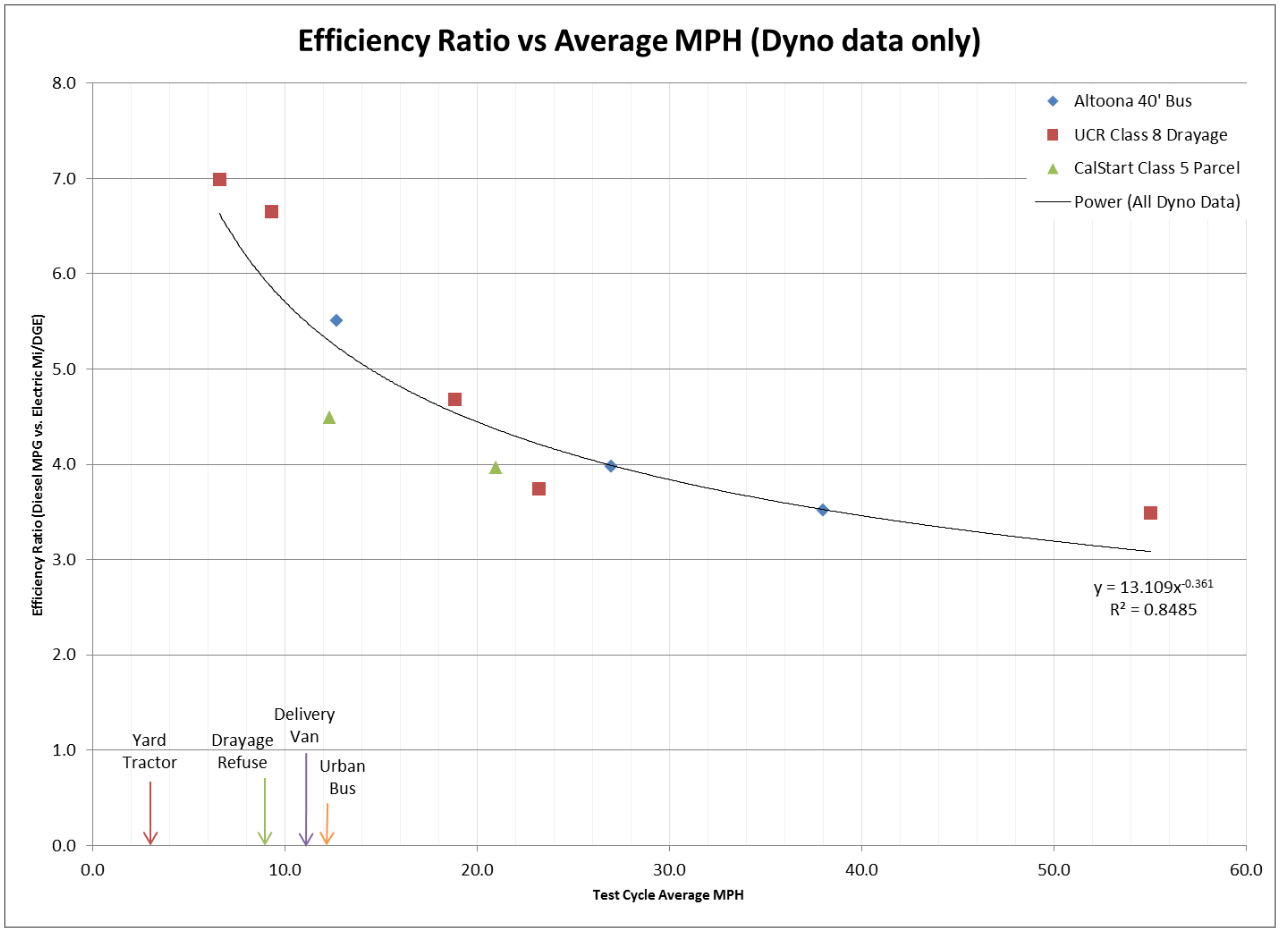


Table 3: Efficiency Ratio at Different Average Speeds (Dynamometer data)

Data Source	Cycle Name	Average Speed (MPH)	EER Ratio
UC Riverside - Class 8 Drayage Tractor	Drayage Neardock	6.6	7.0
UC Riverside - Class 8 Drayage Tractor	Drayage Local	9.3	6.7
CalStart - Class 5 Step Van	OCBC	12.3	4.5
Altoona - Class 8 40' Bus	Bus CBD	12.7	5.5
UC Riverside - Class 8 Drayage Tractor	UDDS	18.9	4.7
CalStart - Class 5 Step Van	HTUF4	21.0	4.0
UC Riverside - Class 8 Drayage Tractor	Drayage Regional	23.2	3.7
Altoona - Class 8 40' Bus	Arterial	27.0	4.0
Altoona - Class 8 40' Bus	Commuter	38.0	3.5
UC Riverside - Class 8 Drayage Tractor	Drayage Cruise	55.0	3.5

Figure 12: Efficiency Ratio at Different Average Speeds (Dynamometer and In-Use data) (Identical to Figure7)

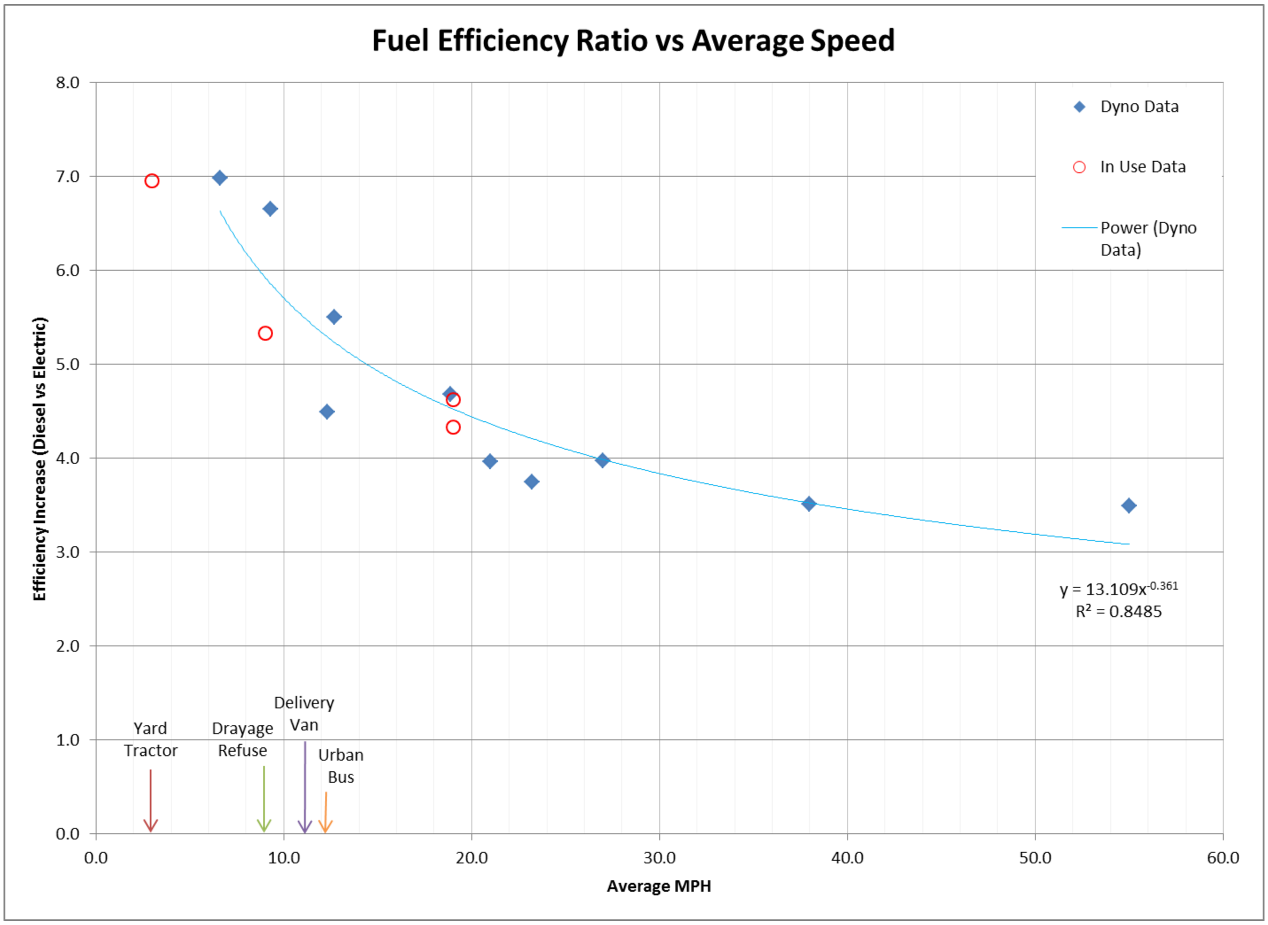


Table 4: Efficiency Ratio at Different Average Speeds (Dynamometer and In-Use data)

Data Source	Cycle Name	Average Speed (MPH)	EER Ratio
Transpower - Class 8 Yard Tractor	Port of LA In-Use Route	3.0	7.0
UC Riverside - Class 8 Drayage Tractor	Drayage Neardock	6.6	7.0
Transpower - Class 8 Yard Tractor	IKEA Warehouse In-Use Route	9.0	5.3
UC Riverside - Class 8 Drayage Tractor	Drayage Local	9.3	6.7
CalStart - Class 5 Step Van	OCBC	12.3	4.5
Altoona - Class 8 40' Bus	Bus CBD	12.7	5.5
UC Riverside - Class 8 Drayage Tractor	UDDS	18.9	4.7
CalStart - Class 3 Sprinter Van	Navistar eStar In-Use Route	19.0	4.6
SD Airport - Class 3 Shuttle Van	SD Airport Shuttle In-Use Route	19.0	4.3
CalStart - Class 5 Step Van	HTUF4	21.0	4.0
UC Riverside - Class 8 Drayage Tractor	Drayage Regional	23.2	3.7
Altoona - Class 8 40' Bus	Arterial	27.0	4.0
Altoona - Class 8 40' Bus	Commuter	38.0	3.5
UC Riverside - Class 8 Drayage Tractor	Drayage Cruise	55.0	3.5