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Field Evaluation of Medium-Duty Plug-in Electric Delivery Trucks

Robert Prohaska, Mike Simpson, Adam Ragatz, Kenneth Kelly, Kandler Smith and Kevin Walkowicz

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Technical Report
NREL/TP-5400-66382
December 2016

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Prepared under Task Nos. VTP2.3102 and VTP2.3103

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This evaluation, which was conducted at FLNA's Federal Way, Washington, distribution center, would not have been possible without the support and cooperation of many people. The authors wish to thank each of the following:

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Matt Myers

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List of Acronyms and Abbreviations

AC	alternating current
ARRA	American Recovery and Reinvestment Act
AVTA	Advanced Vehicle Testing Activity
CARB	California Air Resources Board
CO_2	carbon dioxide
CO_2e	carbon dioxide equivalent
DC	direct current
DOE	U.S. Department of Energy
EV	electric vehicle
EVSE	electric vehicle supply equipment
FLNA	Frito-Lay North America
ft-lb	foot-pounds
GPS	global positioning system
HHDDT	Heavy Heavy-Duty Diesel Truck
kW	kilowatt
kWh	kilowatt-hour
lb.	pound
$LiFePO_4$	lithium iron phosphate
mpg	miles per gallon
mpg_{de}	miles per gallon diesel equivalent
mph	miles per hour
NREL	National Renewable Energy Laboratory
PSE	Puget Sound Energy
Smith	Smith Electric Vehicles Corp.
SOC	state of charge

Executive Summary

This report focuses on medium-duty electric delivery vehicles operated by Frito-Lay North America (FLNA) at its Federal Way, Washington, distribution center. The 100% electric drive system is an alternative to conventional diesel delivery trucks and reduces both energy consumption and carbon dioxide (CO_2) emissions.

Evaluation Design

This in-use evaluation studied Smith Electric Vehicles' (Smith's) Newton electric vehicles (EVs) configured as delivery trucks operating at FLNA's Federal Way distribution center. The EVs were compared to conventional diesel delivery trucks operating at the same location and driving on similar routes. In-use vehicle data were collected for both vehicle types over several weeks.

In addition to characterizing the in-use performance of the EVs compared to the conventional diesels, detailed facility load data were collected at the main building power feed as well as from each of the 10 EV chargers to better understand the broader implications associated with commercial EV deployment.

Evaluation Results

The results and related discussions included here are specific to in-field data collected from the Smith EVs deployed at the Federal Way facility and the comparable conventional diesels.

Vehicle Use and Duty Cycle

Route and drive cycle analysis showed that the Smith EVs were operated on the same routes, performed the same type of work, and were operated in a similar manner as the conventional diesels in and around the Tacoma, Washington, area. The vehicles spend a small proportion of their total day actually driving as the drivers are responsible for stocking their customers' accounts on route as well as delivering product, averaging just over 1.5 hours of driving per day with an average daily distance of less than 40 miles for both the diesel vehicles and the EVs.

Vehicle Performance and Emissions

In-use operation of the EVs demonstrated a 216% (3.15x) improvement in equivalent fuel economy (24.09 MPGe vs 7.63 MPG) over the data reporting period compared to the conventional diesel vehicles as well as a 46% reduction in CO_2 equivalent emissions based on the local energy generation source.

Charging and Infrastructure

FLNA installed 10 chargers at the Federal Way facility, which has the ability to remotely monitor use of each charger. NREL researchers installed a power meter on the main facility power supply line. Together, these data streams allowed researchers to characterize energy use and power requirements. The researchers found a significant increase in the overall facility peak power load (approximately 70kW to 110 kW) and energy requirements with the introduction of the EVs. This additional charging load also increased the peak demand charges of the facility as charging time corresponded with peak facility loads; however, the peak demand charges are comparatively low in the Pacific Northwest and were not found to be high enough to justify the integration of onsite solar and managed EV charging at this location.

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Overview

Advanced Vehicle Testing Activity

This work was sponsored by the Vehicle Systems Program's Advanced Vehicle Testing Activity (AVTA) within the U.S. Department of Energy's (DOE's) Vehicle Technologies Office. The role of the AVTA is to help bridge the gap between research and development and commercial availability for advanced vehicle technologies that reduce petroleum use and meet air-quality standards. AVTA supports the DOE's Vehicle Technologies Office by examining market factors and customer requirements and evaluating the performance and durability of advanced-technology vehicles in commercial fleet applications. The National Renewable Energy Laboratory's (NREL's) Fleet Test and Evaluation team conducts these evaluations with support from AVTA, vehicle manufacturers, and fleet managers.

The main objective of AVTA projects is to conduct comprehensive, unbiased, in-service evaluations of advanced-technology vehicles. Data collected and analyzed can include the operations, maintenance, performance, cost, or emissions characteristics of advanced-technology vehicles and comparable conventional-technology vehicles in fleets operating at the same site. These evaluations help fleet owners and operators make informed operational decisions and vehicle selection decisions. The evaluations also provide valuable data to DOE about the maturity of the technology being assessed and identify key barriers to wide spread commercialization.

The Fleet Test and Evaluation team has been conducting real world evaluations of advanced-propulsion medium- and heavy-duty vehicles for several years. Information on these and other evaluations involving advanced technologies or alternative fuels is available at www.nrel.gov/vehiclesandfuels/fleettest

Project Background

Medium- and heavy-duty vehicles, Classes 3–8, consume 22% of the petroleum-based transportation energy in the United States [1]. The potential energy savings of advanced powertrain technologies and alternative fuels for these vehicles are enticing to fleet owners and operators. High vehicle miles traveled, frequent operation in large population centers, return-to-base fueling regimes, and consistent driving routes of these fleets may further compound these operational cost savings.

Previous testing and analysis conducted by NREL have illustrated the influence of drive cycle and vehicle use on both energy consumption and exhaust emissions [2–5]. Drive cycle has also been shown to influence the all-electric range of battery electric vehicles, the charge depleting range of plug-in hybrid EVs, and the potential fuel economy benefit of hybrid EVs. Accordingly, fleet operators can benefit from a further understanding of advanced vehicle technology deployment to minimize fuel consumption and emissions and maximize return on investment.

Project Objective

This project, which was funded by the DOE's Vehicle Technologies Office and conducted by NREL's Fleet Test and Evaluation group, represents collaboration among NREL, Frito-Lay

North America (FLNA), and Smith Electric Vehicles (Smith) to study the effectiveness of electric vehicles (EVs) in a real-world fleet application. The primary objectives are to:

- **Document experience with electric vehicle supply equipment (EVSE)/charger installation:** Understand what type of infrastructure was installed and what data products are valuable for fleet monitoring
- **Document electricity use:** Obtain data to investigate demand load/charge implications for vehicles charging at a facility and analyze when vehicles could charge and what the costs are.
- **Understand EV versus conventional vehicle use:** Energy use, charging requirements, and route profiles of EVs versus conventional diesel vehicles performing the same function
- **Understand total cost of operation**: Analyze costs of EVs versus conventional diesel delivery trucks
- **Understand drive cycle opportunities:** Examine how well the vehicles are performing and on what routes in the fleet these can be used, and provide FLNA with route indicators that can be used to better match EVs and routes to maximize return on investment
- **Obtain preliminary data to understand battery degradation:** Track battery life performance versus use
- **Obtain overall operational data for modeling and simulation:** Better understand the potential for onsite renewables, energy storage, vehicle-to-grid, and vehicle-to-building opportunities.

NREL designed an in-use vehicle evaluation that included a 3-week capture of conventional vehicle route/drive cycle data, a 12-month fleet operations study, a battery-focused investigation of battery life degradation, and a series of simulations to compare the Smith EVs and conventional diesel trucks.

This project will provide FLNA data and analysis to:

- Evaluate the drive cycles characteristic of their targeted fleet location
- Compare GHG emissions and equivalent fuel economy of the EVs with the conventional diesel vehicles over a range of operation
- Understand range and performance of Smith EVs under various conditions
- Document EV charging costs and EV installation issues.

Frito-Lay North America Advanced Fleet

FLNA, an active member of the National Clean Fleets Partnership, maintains a broad portfolio of conventional and advanced-technology vehicles in its North American fleet, which includes 269 electric delivery trucks and 208 compressed natural gas trucks [6]. In this project, NREL partnered with FLNA to provide a more focused investigation into the implementation and performance of medium-duty EVs at large-scale commercial facilities.

> *"The electric vehicle program builds on a long-standing commitment by Frito-Lay North America and its parent company PepsiCo to environmental sustainability.…With the seventh largest privately owned fleet in the U.S., we have set a goal of becoming the most fuel efficient fleet in the country, and these vehicles give us an opportunity to use the latest advances in transportation technology as a significant way to reduce our environmental impact,"* said Mike O'Connell, senior director of fleet for Frito-Lay North America. [7]

Through this partnership, NREL and FLNA identified a small fleet depot in Federal Way, Washington, as an ideal case for further study. The Federal Way facility is a warehouse and distribution center that serves the greater Tacoma, Washington, area with approximately 50 delivery trucks. The drivers of these delivery trucks go directly to their customer's stores and are responsible for product displays, delivery, and stocking of product as well as general customer account service. Figure 1 shows several of the Smith Newton EVs at FLNA's Federal Way facility. This report details an in-depth examination of the performance and efficiency of 10 Smith EVs operating alongside comparable conventional delivery vehicles at that location as well as the effects that EV implementation has on the overall facility.

Figure 1. FLNA's Smith Newton EVs located at its Federal Way depot (Photo by Mike Simpson / NREL 28804)

Smith Electric Vehicles – Smith Newton

Smith Electric Vehicles, an EV manufacturer based in the United Kingdom, created its U.S. subsidiary, Smith Electric Vehicles–US Corp. in early 2009 with its headquarters in Kansas City, Missouri, to better support the U.S. market. In July 2009, Smith delivered its first Newton vehicles to commercial customers, and in August 2009 the DOE awarded Smith $10M as part of the American Recovery and Reinvestment Act (ARRA). In March 2010, Smith was awarded an additional $22M for vehicle deployments.

NREL was funded by the DOE to collect operational data on Smith vehicles deployed across the country (Figure 2) as part of the ARRA. Data collected from these vehicles is being used to understand overall usage and effectiveness of EVs in medium-duty commercial fleet operations.

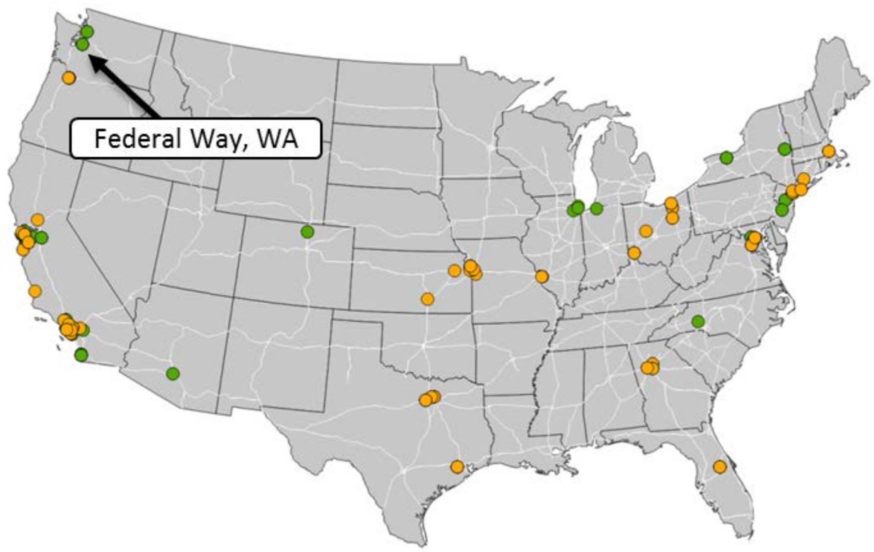

Figure 2. Terminal locations of ARRA-funded Smith Newton vehicles (Generation 1 vehicles: orange, Generation 2 vehicles: green)

NREL was responsible for processing and reporting EV data collected from several manufacturers on a quarterly basis for public use [8]. Additionally, the operational data are being leveraged for research in EV modeling and simulation as well as drive cycle analysis and characterization through NREL's Fleet DNA project [9].

The 10 EVs investigated as part of this report are all second generation Smith Newtons manufactured by Smith Electric Vehicles and were all configured as Class 6 delivery trucks (Figure 3) with an 80-kilowatt-hour (kWh) lithium iron phosphate ($LiFePO_4$) battery pack manufactured by A123 Systems. Figure 4 shows the relative size of the 80-kWh battery pack mounted on the passenger side frame rail with the aerodynamic side skirting removed. $LiFePO_4$ batteries offer a good balance of performance, life span, cost, and safety; they have a very flat discharge curve with good power density, but have lower energy density than other available lithium-ion batteries (Figure 5). Additional vehicle specifications are given in Table 1.

Figure 3. Smith EV operated by FLNA (Photo by Robert Prohaska / NREL 34462)

Figure 4. Smith Newton with passenger-side aerodynamic skirting removed showing 80-kWh $LiFePO_4$ battery pack (Photo: Robert Prohaska / NREL)

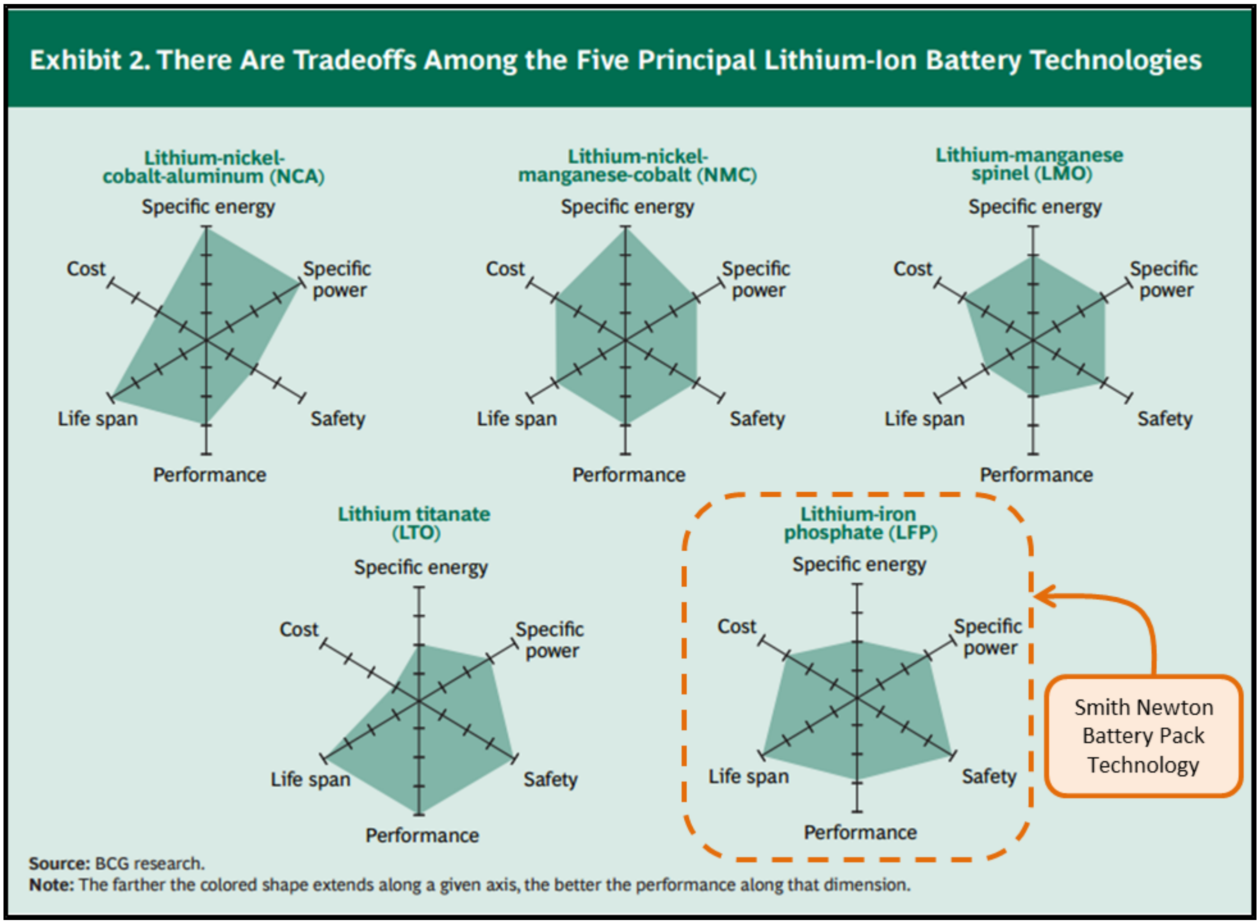

Figure 5. Characteristics of different EV battery chemistries [10]

Table 1. Federal Way, Washington, FLNA Smith Newton Vehicle Specifications [11]

Weight class	Class 6
Gross vehicle weight rating	22,028 lbs.
Payload	9,750 lbs.
Wheelbase	220 in.
Overall length	368 in.
Turning radius	46.4 ft. w/ 154-in. wheelbase
Charging standard	J1772
On-board charger power	12 kW
Battery voltage	346 V_{DC} nominal
Battery capacity	80 kWh (four 20 kWh strings)
Battery manufacturer	A123 Systems
Battery chemistry	Lithium iron phosphate ($LiFePO_4$)
Motor power: peak | cont.	150 kW | 80 kW
Motor torque: peak | cont.	442.5 ft.-lbs. | 295 ft.-lbs.
Gearbox ratio	3.4 : 1.0
Advertised top speed	50 mph

Data Collection

To better understand the real-world performance of the EVs as they compare to conventional diesel delivery vehicles, NREL researchers visited the Federal Way fleet depot, located between Tacoma and Seattle, Washington, to instrument the conventional diesel delivery trucks with Isaac DRU900/908 data loggers (Figure 6) and Garmin 18x-5Hz global positioning system (GPS) modules. (See Appendix A and Appendix B for additional data logger and GPS specifications). The in-use data recording of nine vehicles resulted in 123 total vehicle-days of data. The vehicles were a mix of International and Hino models with varying degrees of age and emissions certifications (Table 2). Due to differing levels of data bus communications available on some of the older vehicles, the SAE J1708 protocol was selected as the best method for data collection on these diesel vehicles.

Figure 6. Diesel vehicle data logger installation (Photos by Adam Ragatz, NREL)

Table 2. Federal Way Vehicles Monitored in Logger Deployment

Manufacturer	Model	Isaac ID	Comm. Protocol	FLNA ID	Model Year
International	4200 SBA 4X2	14	J1708	E06636	2005
International	4200 SBA 4x2	15	J1708	E06644	2003
International	4700 4x2	16	J1708	E04126	2001
International	4200 SBA 4X2	17	J1708	E09471	2005
International	4200 SBA 4x2	25	J1708	E09390	2006
Hino	HINO 238	26	OBD2	E27205	2012
International	4200 SBA 4x2	27	J1708	E09595	2007
International	4200 SBA 4X2	28	J1708	E09392	2005
International	4700 4x2	29	J1708	E04128	2001

Data from the 10 Smith EVs were collected through the use of on-board logging devices connected to the vehicle's controller area network, paired with GPS information (see Appendix C). These data were then transmitted wirelessly over the cellular network to NREL's secure data server for processing. The on-board data logging systems required by the ARRA program and provided by Smith minimized impacts on FLNA's fleet operations while capturing vehicle performance characteristics.

Data collected from the nine diesel vehicles shown in Table 2 provide the baseline against which the Smith EV performance was compared. NREL also gathered data from the 10 Smith EVs stationed at Federal Way during the same 17 days of logging, from April 16 to May 1, 2014, and found correlations between FLNA diesel and EV operations. As shown in Figure 7, the routes for both sets of vehicles span similar ranges across the territory served by the Federal Way depot.

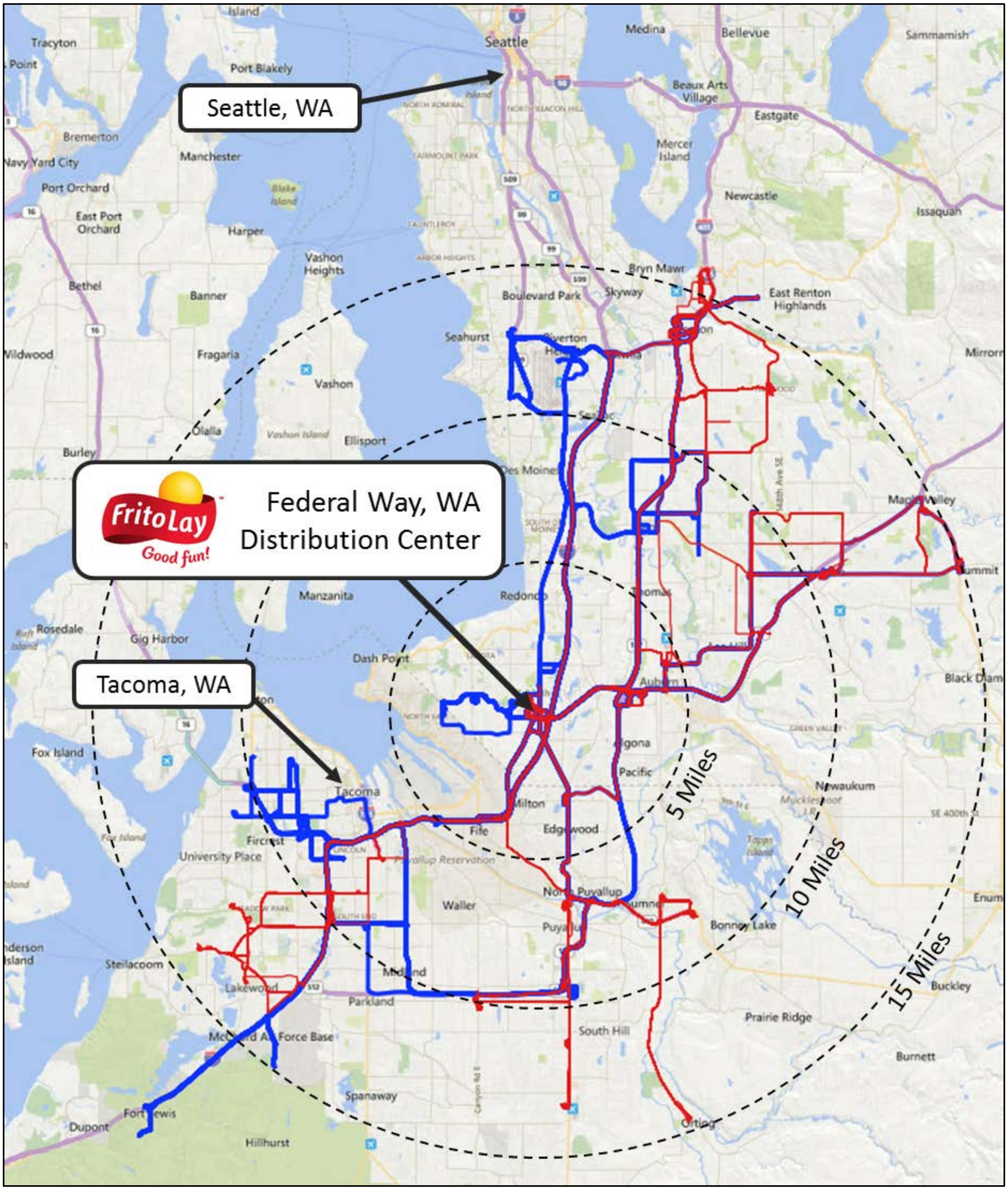

Figure 7. Comparison of diesel (blue) and EV (red) routes

Drive Cycle Analysis and Performance

In Federal Way, the Smith EVs run regular delivery routes similar to conventional diesels, often leaving early in the morning, between 2 a.m. and 4 a.m., and returning late morning or early afternoon, between 10 a.m. and 1 p.m., as seen in Figure 8.

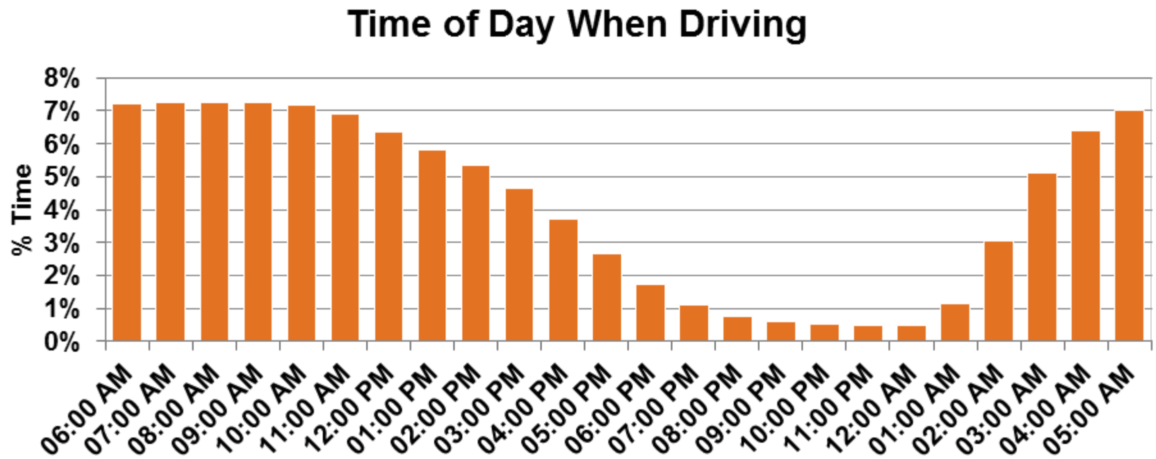

Figure 8. Federal Way Smith Newton EV average time of day when driving

The average driving time per day during this study was found to be just 1.5 hours for both the EVs and diesels, as the FLNA employees spend a considerable amount of time at each stop handling customer accounts and other non-driving tasks. The daily driving distance distribution is shown in Figure 9. This daily distance is the total distance traveled in a 24-hour period starting at 12 a.m. local time. The small number of short trips (less than 5 miles in length) can be attributed to vehicle movement for loading, unloading, and maintenance on days where the typical full route was not serviced.

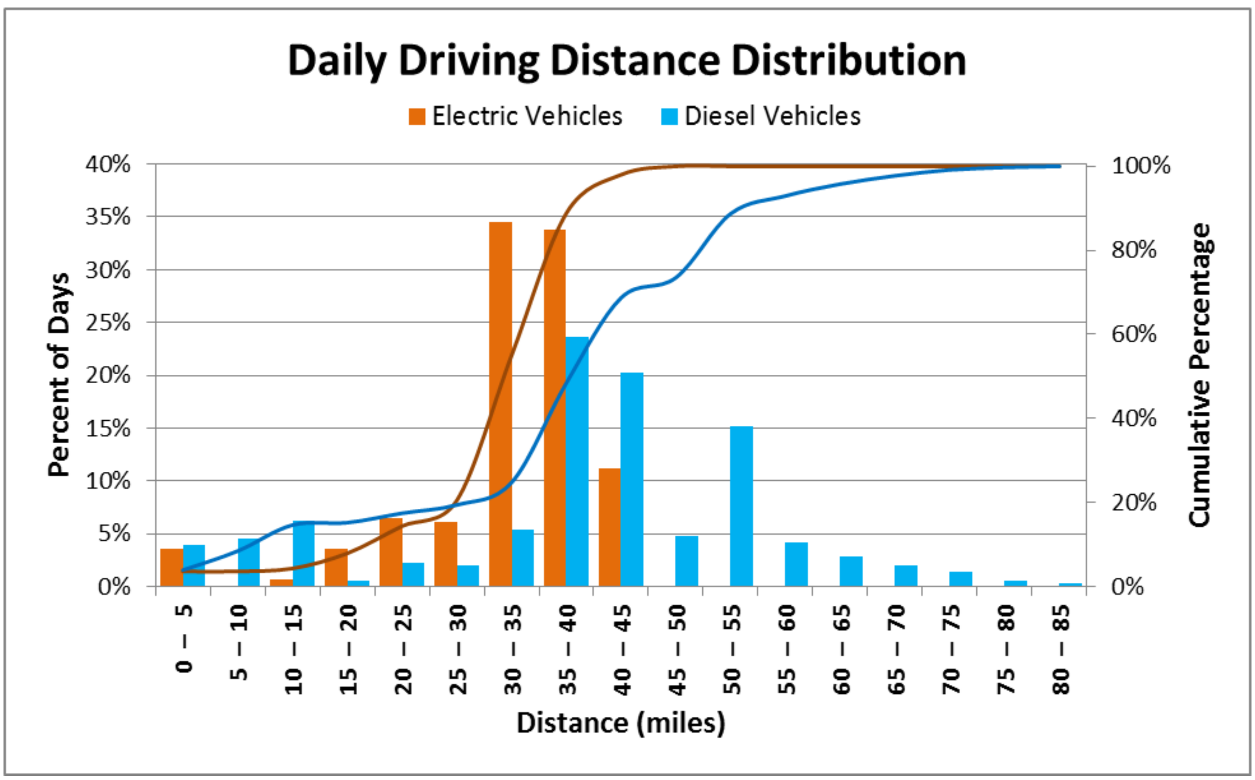

Figure 9. Federal Way Smith Newton EV and conventional diesel daily driving distance distribution

Daily average kinetic intensity (see equation 1), a relative measure of driving aggressiveness, represents the ratio of a drive cycle's characteristic acceleration (see equation 2) to its aerodynamic speed (see equation 3), was used to compare the vehicle's operation along with average speed. Kinetic intensity is often used as a metric to determine how a specific drive cycle may benefit from energy recapture through regenerative braking. For example, drive cycles with very few decelerations and extended cruising sections, such as the cruise portion of California Air Resources Board (CARB) Heavy Heavy-Duty Diesel Truck (HHDDT) cycle,[1] have a low kinetic intensity when compared to drive cycles with more stop-and-go type driving like the CARB HHDDT Transient cycle.

$$Kinetic\ Intensity = \frac{\alpha_{ch}}{v_{aero}^2} \quad \text{(Eq. 1)}$$

$$\text{Characteristic Acceleration} = \alpha_{ch} = \frac{1}{2} * \frac{\sum v_{j+1}^2 - v_j^2}{\Delta\, Distance} + g * \frac{h_{j+1} - h_j}{\Delta\, Distance} \quad \text{(Eq. 2)}$$

$v = vehicle\ speed$
$g = gravitational\ acceleration$
$h = elevation$

$$\text{Aerodynamic Speed} = v_{aero} = \sqrt{\frac{\sum \overline{v_{j,j+1}^3} * \Delta time_{j,j+1}}{Distance}} \quad \text{(Eq. 3)}$$

The CARB HHDDT Composite [12] test cycle is shown in Figure 10 for reference. This drive cycle was developed to represent heavy-duty commercial vehicle operation. This test cycle is used for emissions regulations and for the U.S. Environmental Protection Agency medium- and heavy-duty greenhouse gas regulations. The cycle consists of four segments: an initial idle segment (600 sec); a creep segment (253 sec); a transient segment (668 sec); and finally, a highway cruise segment (2,083 sec), with much of this segment representing a 55-mph highway cruise driving profile with slight dithering in cruise speed. The total cycle lasts approximately 3,600 seconds, reaches a top speed of 59.3 mph, and travels a distance of 26 mi with an average speed of 26 mph and a kinetic intensity of 0.17 1/mi. This cycle represents the lower end of kinetic intensity for the FLNA vehicles and demonstrates how standard chassis dynamometer test cycles compare to real-world data.

The relationship between kinetic intensity and average speed for the FLNA vehicles can be seen in Figure 11. In this plot, the circles represent each vehicle-day of data from the diesel trucks (blue) and the EVs (orange), and the squares represent the average for each truck throughout the sample period. In addition to the field data, three standard chassis dynamometer test cycles are also shown for comparison. These standard cycles, which are often used for modeling, simulation, and testing validation, were selected as comparisons for this evaluation as their range of values is representative of the range in operation observed in field data as the majority of points fall between the HHDDT Transient and HHDDT Cruise, indicating a mix of stop-and-go driving with some cruise type behavior.

[1] The HHDDT is a chassis dynamometer test developed by the California Air Resources Board with the cooperation of West Virginia University.

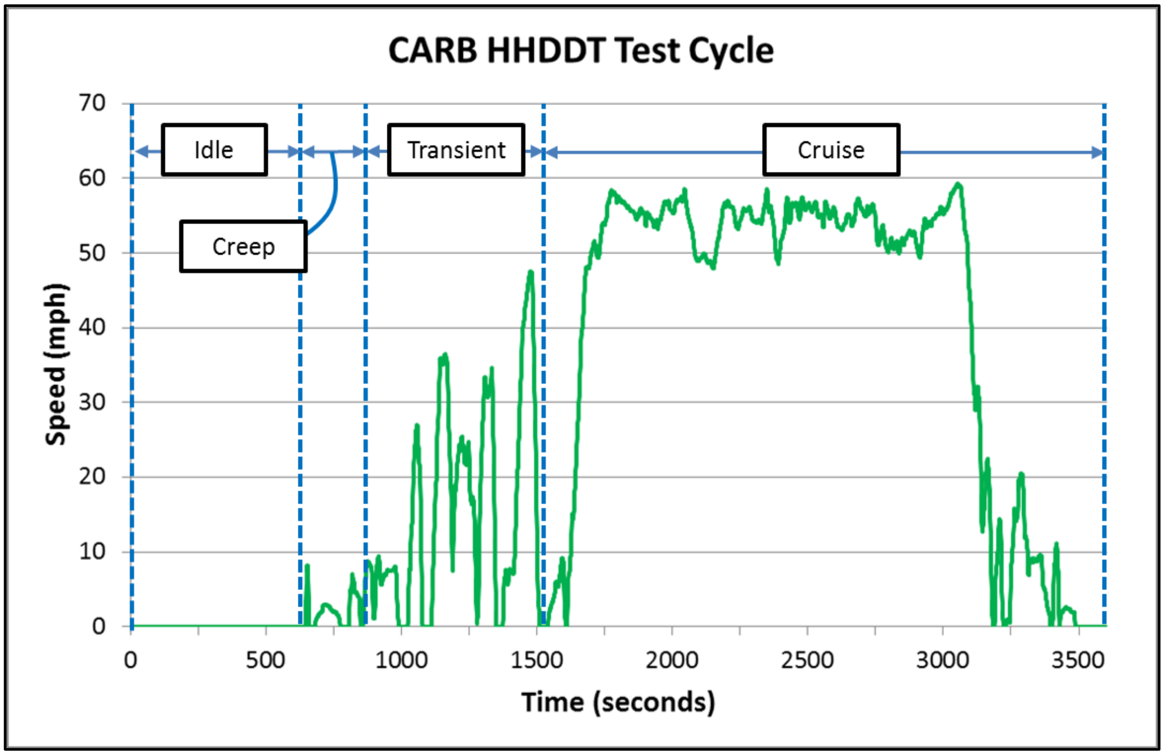

Figure 10. CARB HHDDT chassis dynamometer test cycle

The FLNA delivery duty cycle closely matched the capabilities of Smith EVs. The kinetic intensity of the EVs is slightly more aggressive than that of the diesels relative to daily average speed, but is still very comparable with a homoscedastic t-test yielding a very small p-value of 2.914×10^{-5} at a 99% confidence interval for kinetic intensity and a p-value of 2.261×10^{-7} for average speed (includes speed equal to zero).

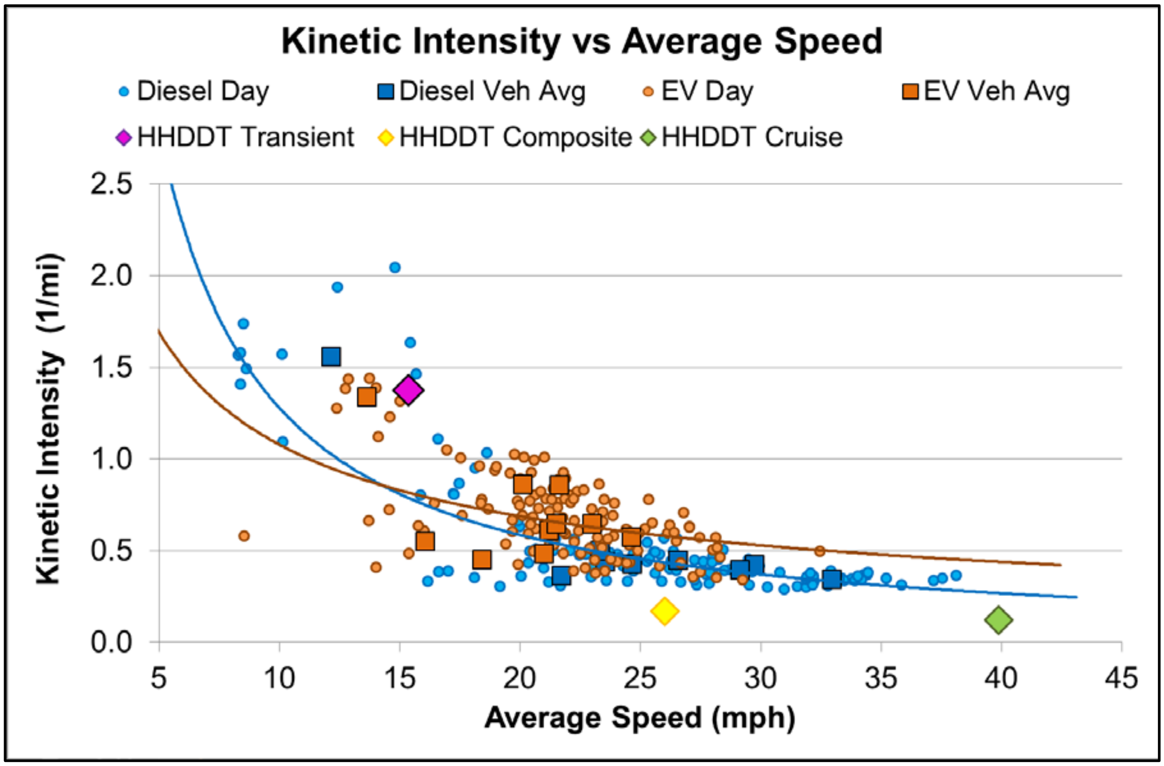

Figure 11. Baseline route comparison using kinetic intensity vs. average speed for Federal Way depot delivery vehicles

Investigation of the average daily driving distance as a function of daily average driving speed, as seen in Figure 12, shows a high level of overlap between the two vehicle types and with a homoscedastic t-test and an α of 0.01 yields a p-value of 6.048×10^{-5}. This reinforces the match between conventional vehicle and EV uses at the Federal Way depot. Additional metrics comparing the usage of each vehicle type are shown in Table 3.

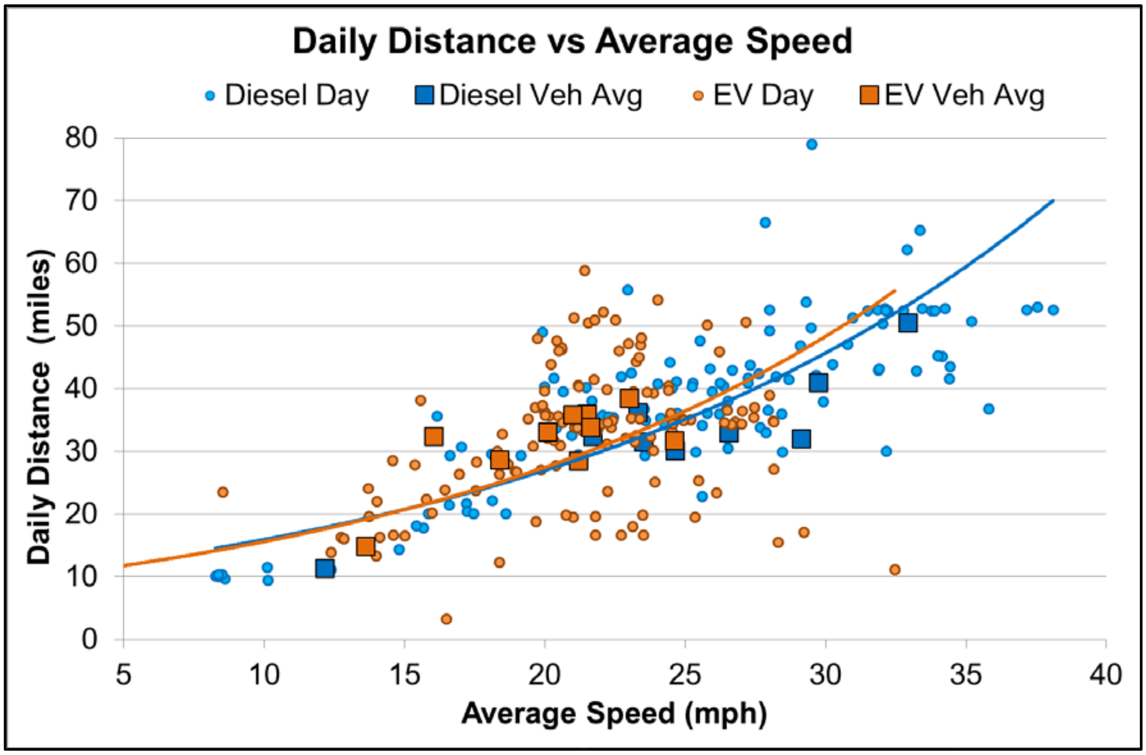

Figure 12. Daily driving distance vs. average speed for Federal Way depot diesels and EVs

Table 3. Federal Way Vehicle Daily Performance Metrics Shown with Standard Deviations (σ)

Daily Averages	Diesels	σ	EVs	σ
Average driving time (hours)	1.51	0.31	1.54	0.45
Average total distance (miles)	38.23	12.76	32.50	10.40
Average speed (mph)	25.18	6.84	21.48	4.23
Average fuel consumed (gallons)	4.97	1.58	1.21[a]	0.35[a]
Gallons / 100 miles	13.11	1.08	3.81[a]	0.53[a]
Average energy consumed (kWh)	187.24[a]	59.49[a]	45.66	13.12
kWh / mile	4.99[a]	0.33[a]	1.40	0.20
Average fuel economy (mpge)	7.63	0.59	24.09[b]	2.85[b]
Average number of stops	44.25	13.74	43.28	14.47
Average number of stops / mile	1.35	0.76	1.38	0.41
Average kinetic intensity (1 / mile)	0.54	0.37	0.70	0.23

[a]37.656 kWh per gallon of diesel fuel

[b]Miles per gallon equivalent (mpge) assumes 90% charger efficiency.

One way to quantify the energy efficiency of EVs is to look at their daily average DC energy consumption per mile on a kilowatt-hour basis. The distribution of kilowatt-hours per mile shows energy used to drive the vehicle and power any auxiliary loads, such as lights and climate control, but does not necessarily represent the total energy consumed by the system. Losses occur in the EVSE, the onboard AC-DC charger, and the onboard DC-DC converter during charging. In this study, the researchers used a combined 90% efficiency to account for losses between the AC supply and end-use driving, which means that for each 1.11 kWh of energy from the AC charging station that is plugged into the vehicle, only 1.0 kWh of energy is converted into usable DC energy on the vehicle. Figure 13 shows the distribution over a multi-week period of the daily driving kilowatt-hour per mile energy consumption of the 10 Federal Way EVs. The average DC energy consumption for the Federal Way EV fleet, including the use of accessory loads during operation, was found to be 1.40 kWh/mi, and the average daily energy consumption for this study was found to be 45.7 kWh, with an average daily driving distance of 32.5 miles.

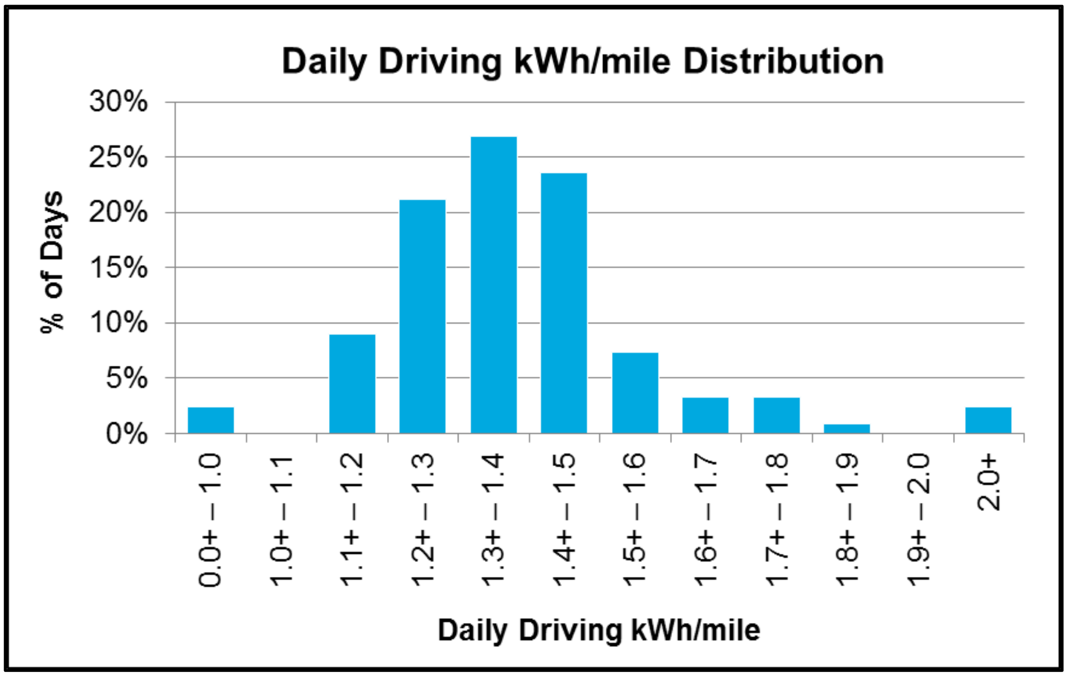

Figure 13. Federal Way Smith Newton EV DC energy consumption per mile, data collected 4/14–5/14

Traveling on similar routes as the diesel trucks, FLNA's Federal Way EVs operated at much higher fuel economies. As shown in Figure 14, the EVs at times exceed 25 miles per diesel gallon equivalent (mpg_{de}), resulting in nearly three times the distance traveled of the diesels on an energy basis. The diesel equivalence was calculated using the Alternative Fuels Data Center [13] energy density for a gallon of low-sulfur diesel fuel. With the diesel trucks averaging 7.63 mpg_{de} at $3.85/gal, the average diesel price in Seattle at the time of data collection, and the EVs averaging 23.3 mpg_{de} at $0.102/kWh, the average delivered price per kilowatt-hour FLNA paid in 2013, the same ratio in fuel economy applies to fuel savings for EVs. FLNA spent $0.507 for every mile driven with diesel trucks versus $0.159 for every EV mile. As fuel prices continue to fluctuate, the relative per-mile cost savings of the EVs over the diesels varies. Assuming the same AC energy cost of $0.102/kWh and the same vehicle and charger efficiencies, the break-even cost per mile fuel price was found to be $1.212/gallon. At this price per gallon of diesel fuel, the energy cost to operate the diesels and the EVs would be the same. This metric can be useful for fleet managers as they try to optimize their operations with widely varying fuel prices.

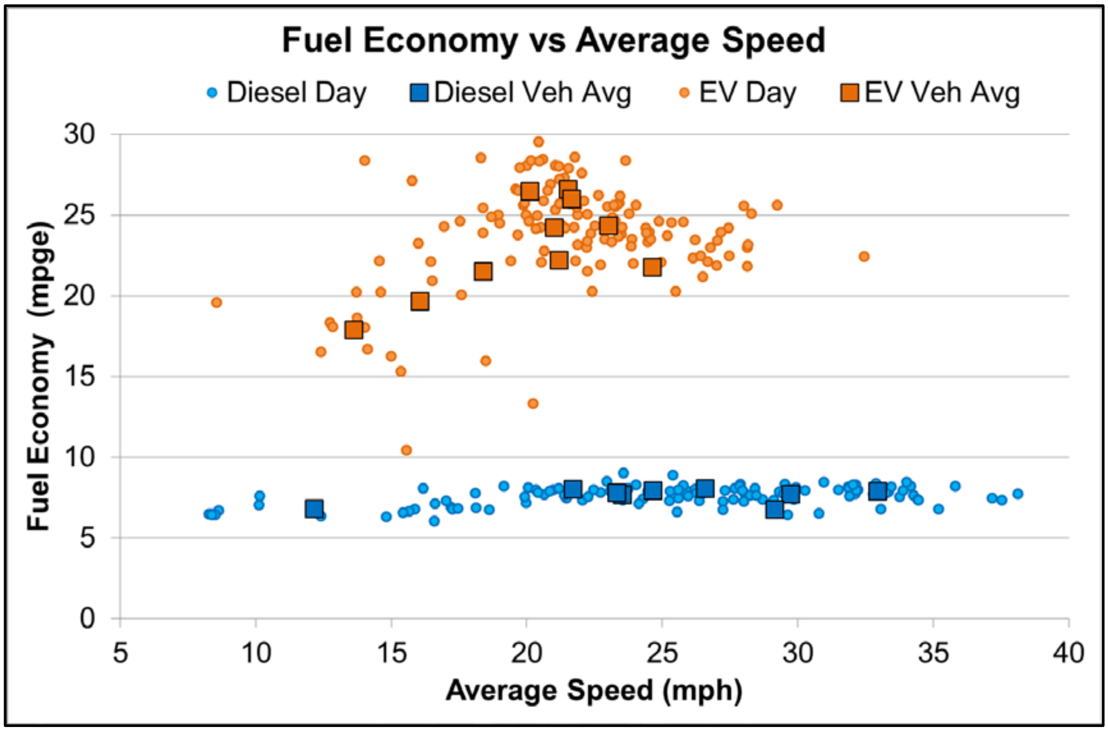

Figure 14. Fuel economy vs. average speed for Federal Way depot diesels and EVs

Further examination of average energy efficiency as a function of kinetic intensity shows that in this application, kinetic intensity is not a strong indicator of fuel economy for either the conventional diesels or the EVs as there is a wide range of kinetic intensity levels for a given level of equivalent fuel economy. The relationship between energy efficiency and kinetic intensity is shown in Figure 15.

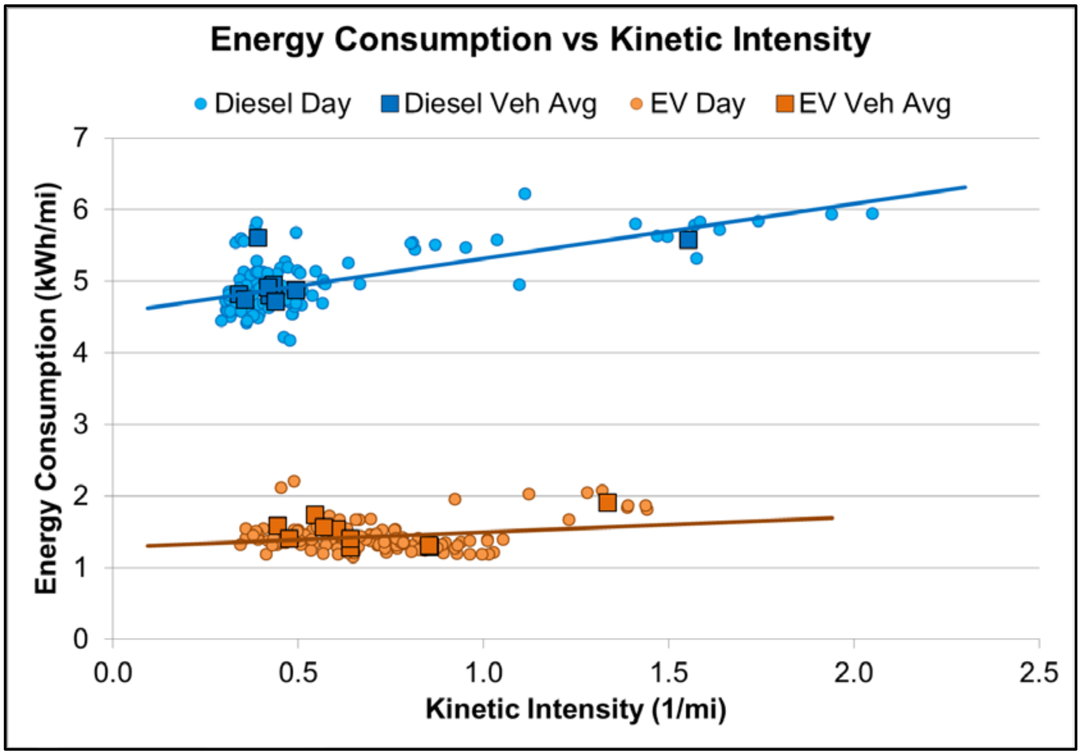

Figure 15. Energy efficiency vs. kinetic intensity for Federal Way depot diesels and EVs

While the level of kinetic intensity alone may not be a strong predictor of overall energy consumption for this fleet, daily driving distance is correlated to energy consumption for both the EVs and the diesel vehicles. As seen in Figure 16, a strong correlation exists between the daily distance traveled and the total amount of energy each vehicle consumed with neither vehicle type varying significantly in efficiency as a function of distance. Just as shown in Figure 14 and Figure 15, the EVs demonstrate a higher efficiency across the spectrum of operation. With such a strong correlation between energy consumption and distance travelled, fleet managers can use this type of information to forecast energy use over longer periods of time based on projected mileage. This simple relationship is key to understanding the benefits a fleet can recognize through electrification. In this specific operation, the more an EV is driven within the limits of its battery capacity, the more energy saved as compared to the diesel, thereby increasing the cost benefit of electrification.

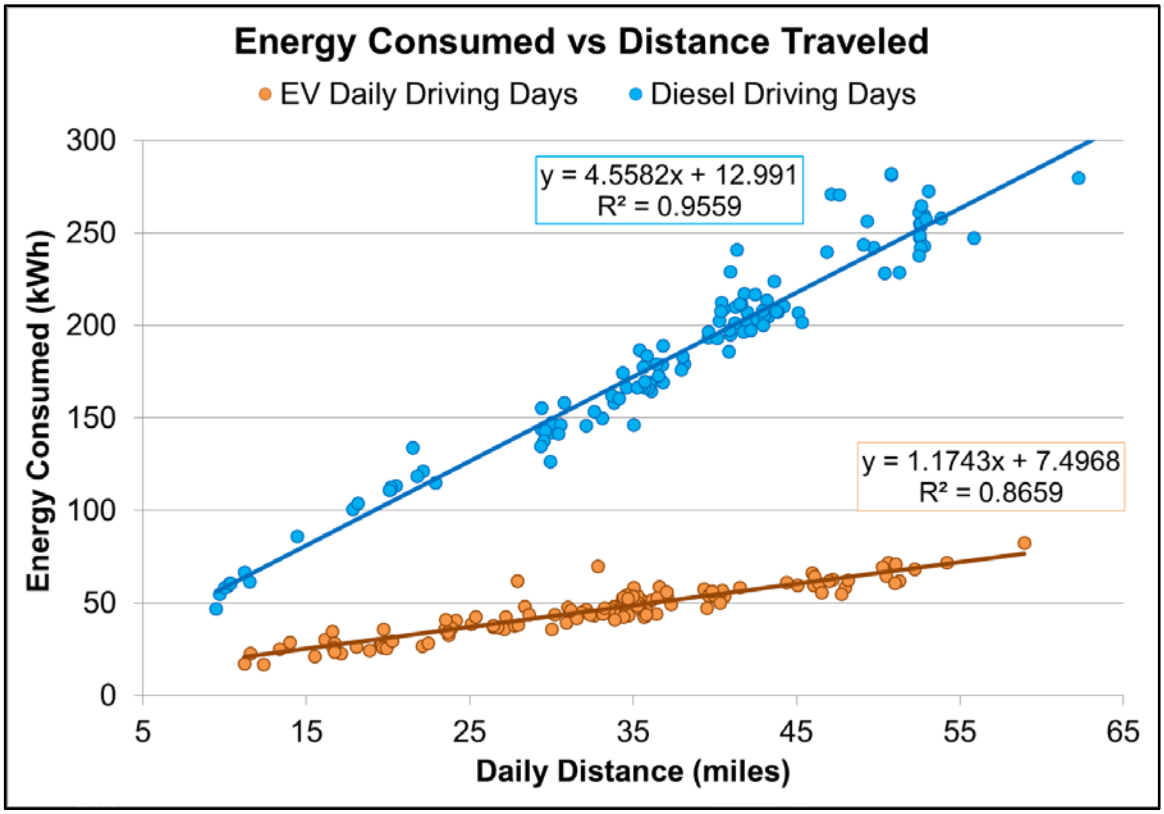

Figure 16. Energy consumption as a function of daily distance traveled

FLNA fleet managers could improve their operational efficiency by dispatching the EVs on routes closer to their maximum range to maximize the electrification advantage. As seen in Figure 17, 79% of EV trips required less than 55 kWh of the available 80 kWh. However, fleet managers are aware that longer routes may increase the driver's range anxiety and will increase the possibilities for incomplete trips. Figure 18 shows the average savings per EV based on distance travelled and average diesel fuel price. Using the annual distance traveled of 8,488 miles as a baseline, fleet operators could save on average an additional $750 per year per vehicle with an average fuel price of $3.79 per gallon by increasing the annual distance driven of the EVs by just 25%, to 10,610 mi. This increased use would result in an average daily energy consumption of approximately 57 kWh. At a diesel fuel price of just $2.25 per gallon, this 25% additional mileage would result in an average annual per vehicle savings of $322. The average savings per EV assumes a cost of $0.102/kWh, which was the average electricity charge from FLNA's utility bill during this evaluation, and the vehicle efficiencies outlined in Table 3.

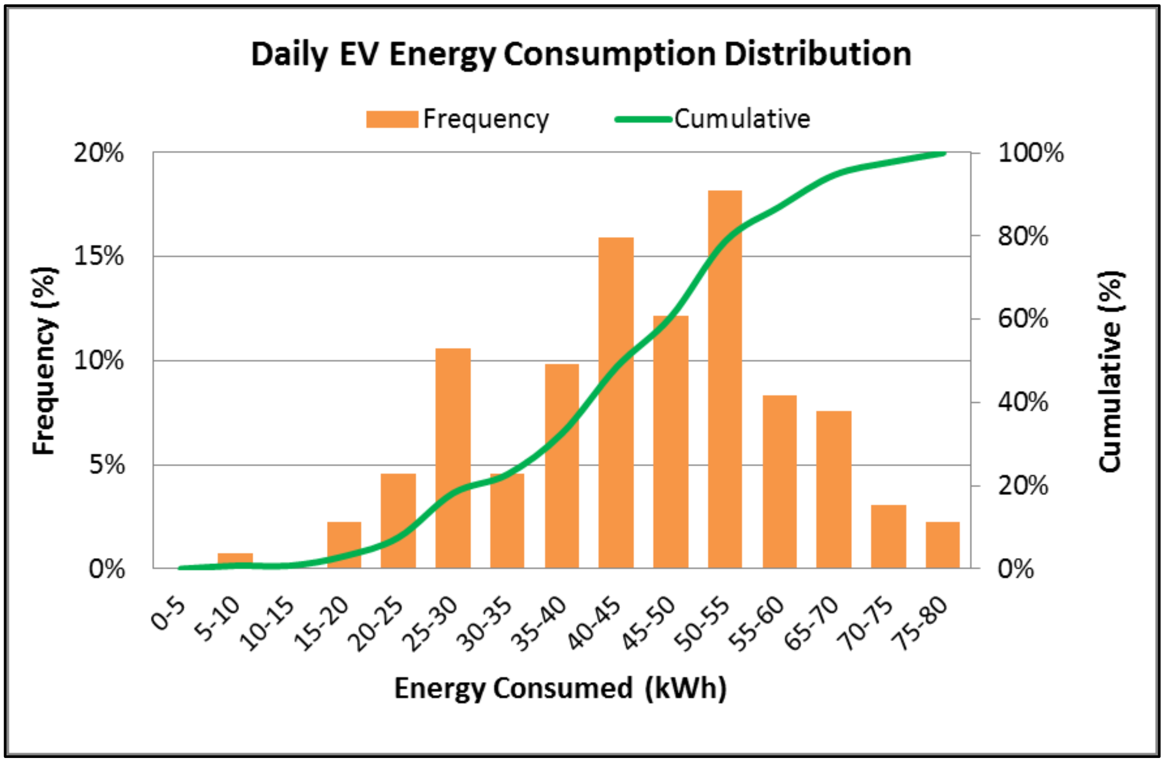

Figure 17. Distribution of daily EV energy consumption

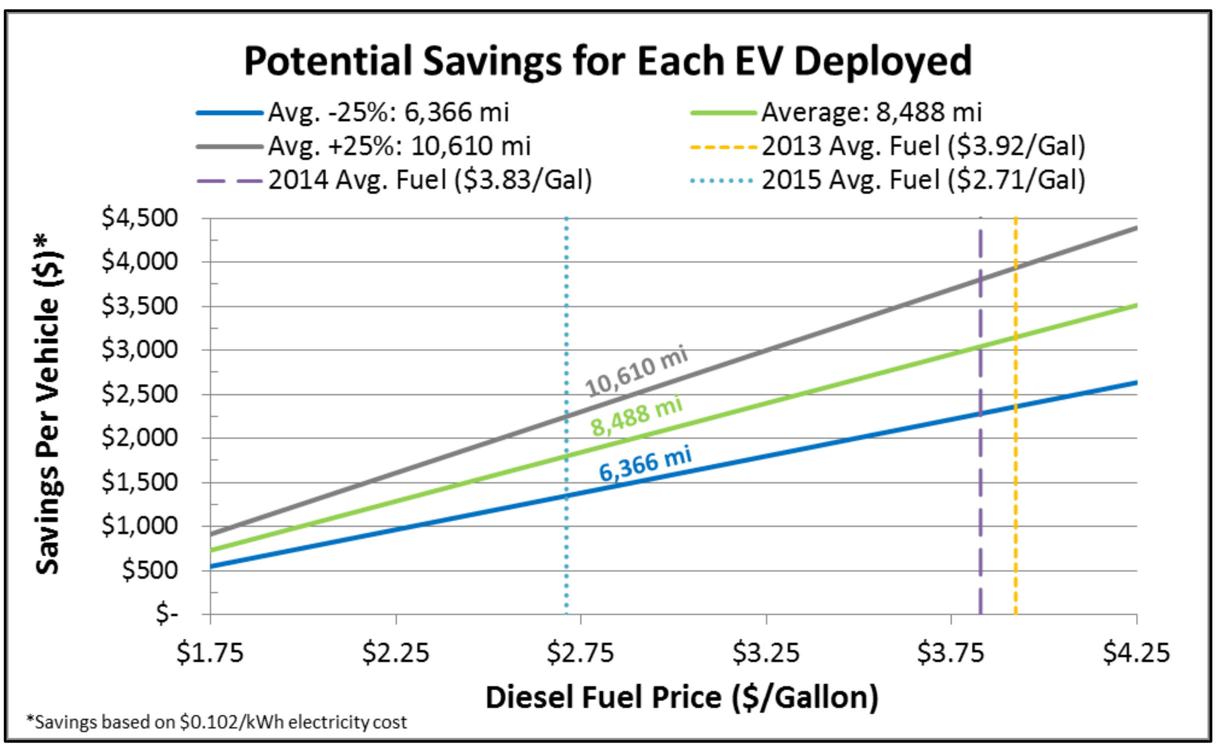

Figure 18. Cost savings of EVs over conventional diesels based on average annual mileage and fuel price [14], assuming electricity cost of $0.102/kWh

While EVs show a significant savings on a per-mile basis, their incremental cost over conventional diesels is a significant barrier for most fleets. For example, New York State's EV voucher incentive program [15] lists the incremental cost of an 80-kWh Smith Newton at $86,791 over the cost of a comparable conventional vehicle. While they do offer a $60,000 voucher, there is a significant up-front cost to consider when purchasing EVs.

Vehicle Emissions

One of the potential benefits of EV adoption is a reduction in greenhouse gas emissions compared to conventionally powered diesel vehicles, as EVs emit no tailpipe greenhouse gases. However, significant emissions can be produced upstream depending on the local energy source distribution; this is sometimes referred to as the "extended tailpipe." The power is supplied to the Federal Way facility by Puget Sound Energy (PSE), which reported a 2014 carbon dioxide equivalent (CO_2e) emissions intensity of 450.58 g/kWh [16]. This emissions intensity includes all PSE-generated and purchased power measured at the generation source (non-distributed). The 2014 generation source distribution is shown in Figure 19. Once electric energy is generated, it must be moved to areas where it will be used through transmission and distribution. The National Electrical Manufacturers Association considers normal transmission and distribution losses to be between 6% and 8% from the power generation source to the end user's site [17]. Using the Energy Information Administration's 2013 transmission and distribution loss of 7.2% [18], we arrive at a CO_2e emissions intensity level of 485.54 g/kWh for energy at the FLNA facility from PSE. Factoring in the charging efficiency losses discussed earlier, the Smith EVs average 759.06 grams of CO_2e emissions per mile traveled.

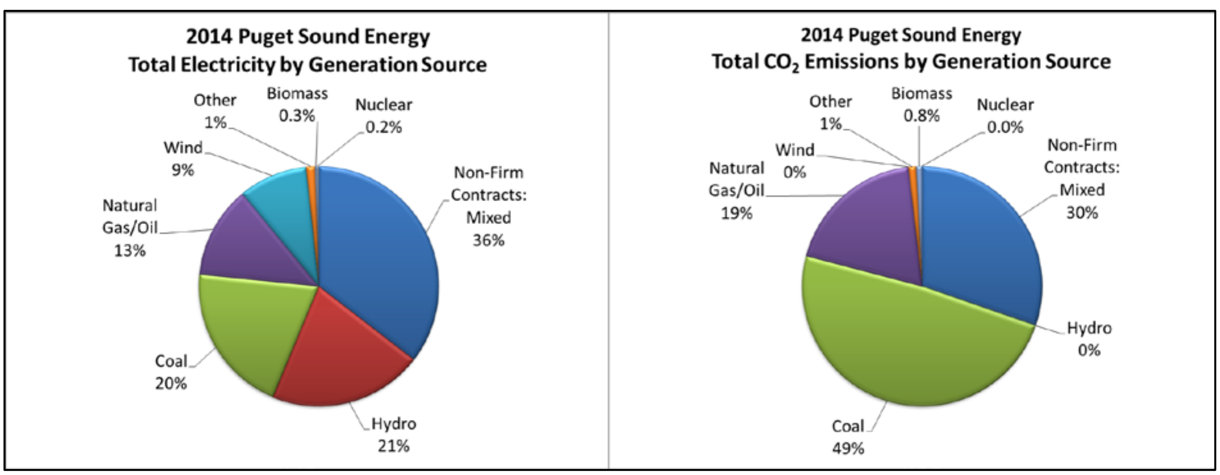

Figure 19. 2014 PSE total electricity (kWh) by generation source and CO_2 emissions (metric ton)

Using Argonne National Laboratory's Greenhouse Gases, Regulated Emissions, and Energy Use in Transportation (GREET) Model's [19] CO_2e emissions for the delivered, national energy generation source distribution, we find the CO_2e emissions are 613.12 g/kWh, which equates to 958.51 g CO_2e/mi using the Smith EV average energy efficiency including the charger and inverter efficiency losses. The average CO_2e emissions from the EVs can then be compared to the conventional diesels operating in Federal Way using the using GREET's well-to-wheels analysis tool. Using the national low-sulfur diesel values and the diesel vehicle energy efficiency from GREET, the emissions are 1,414.93 g CO_2e/mi. The EVs, using PSE's source distribution, emit 46.4% less CO_2e emissions per mile travelled than the diesel vehicles, and using the national energy source distribution, the EVs emit 32.3% less CO_2e per mile. With an average annual distance travelled of approximately 8,488 miles, each EV deployed at the Federal Way site saves approximately 6.136 tons per year of CO_2e emissions compared to a conventional diesel vehicle (see Figure 20).

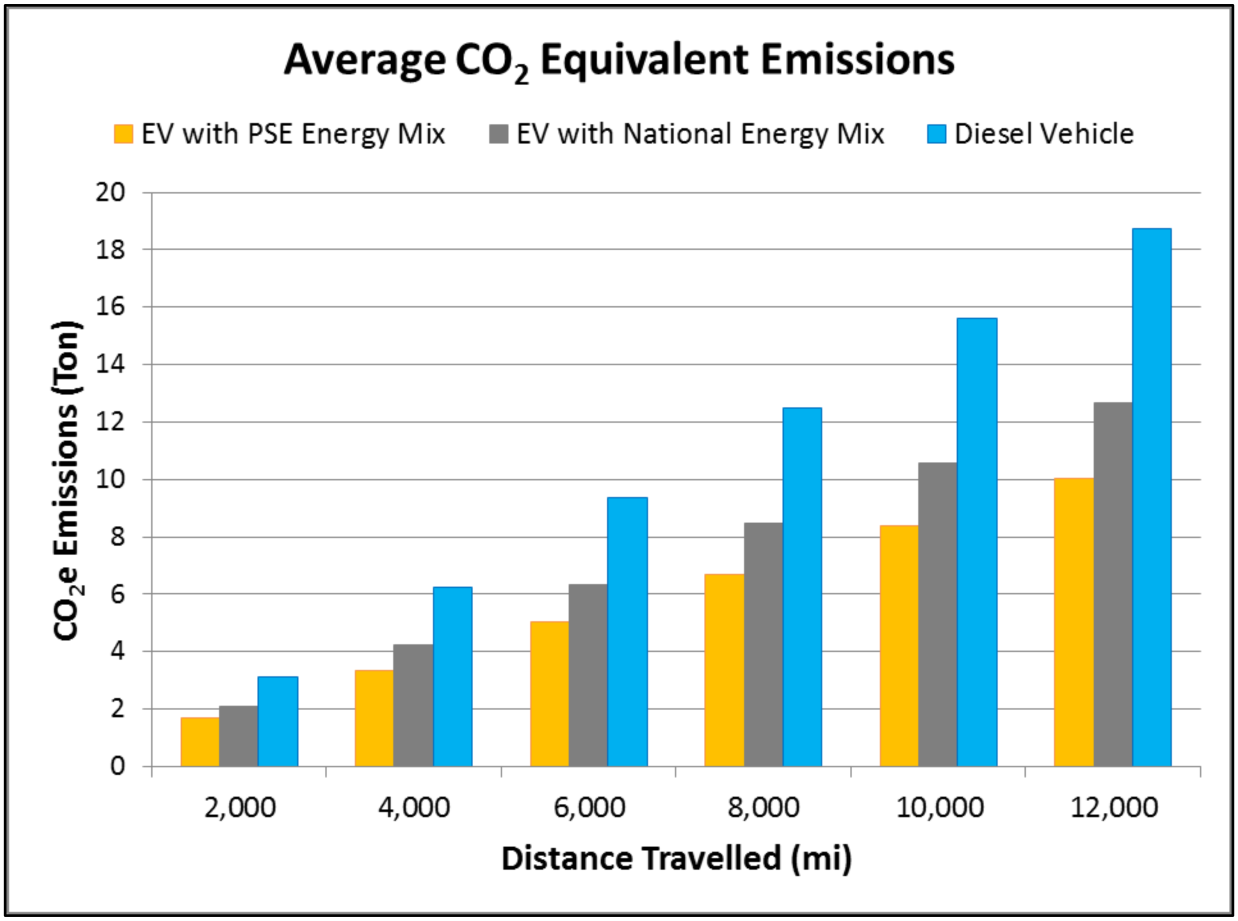

Figure 20. Average CO_2 equivalent emissions by energy source and distance travelled based on Federal Way delivery vehicle operation

Charging Infrastructure

At the Federal Way depot, FLNA installed 10 ClipperCreek CS-100 charging stations (see Figure 21 and Figure 22). Each parking spot is assigned to a specific vehicle, which is in turn assigned to a specific driver (except when vehicles are taken out of service for repair). NREL utilized this correlation to align EVSE energy consumption with individual vehicle usage and ultimately vehicle availability for grid services while each vehicle is plugged in at each EVSE (see Appendix E for list of data channels).

Figure 21. ClipperCreek CS-100 at the Federal Way fleet depot (Photo by Mike Simpson / NREL 29589)

Figure 22. Federal Way EV parking section with 10 EVSEs while most vehicles are in-service (Photo by Mike Simpson / NREL 29586)

Each charging station provides up to 75 amps at 208 volts as specified in Table 4, although each vehicle's on-board charger only draws closer to 50 amps maximum (nearly 10 kW per vehicle). The EVSEs were installed near the maintenance shop, but separate from the diesel vehicle parking spots. Each station is close to the other nine, but all 10 are a significant distance from the building, and thus the main facility electrical room (see Figure 23).

Table 4. ClipperCreek CS-100 EVSE Charger Specifications [20, 21]

Voltage & Wiring	220/240 VAC single-phase 208 VAC 3-Phase, Why-Connected 240 VAC 3-Phase, Delta Connected
Current	100 A
Frequency	50/60 Hz
Continuous current rating	16 to 80 A
Continuous output power rating	3.8 kW to 19.2 kW
Cable length	22 ft.
Dimensions (H x W x L)	12 in. x 18 in. x 8 in.
Operating temperature range	-40°F to 122°F
NEMA rating	NEMA 4 – Outdoor use, watertight
Agency approvals	UL Listed, FCC, CUL, ETL, cETL
Codes and Standards	UL 2594 UL 2231 UL 1998 UL 991 NEC 625 SAE-J1772

°F = degrees Fahrenheit
A = amps
cETL = Electrical Testing Laboratory of Canada
CUL = Underwriters' Laboratories of Canada
ETL = Electrical Testing Laboratory
FCC = Federal Communications Commission
Hz = hertz (cycles per second)
NEC = National Electric Code
NEMA = National Electrical Manufacturers Association
VAC = volts alternating current

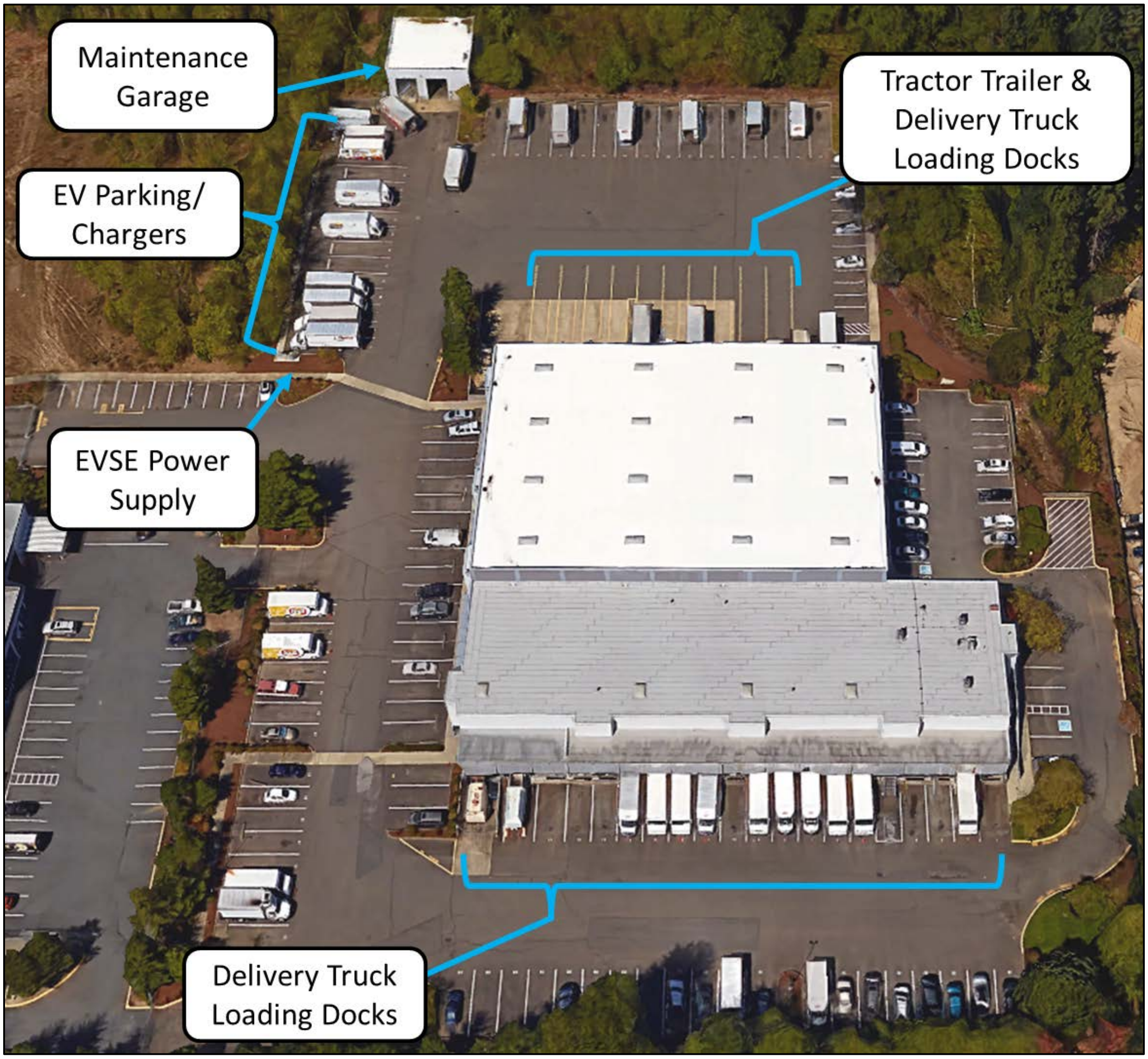

Figure 23. Aerial view of Federal Way FLNA distribution center (Base map: Google Earth)

EVSE Cost

FLNA's fleet management approximated the average cost of installing each charging station (across several U.S. depot facilities) at $22,000, dominated by construction fees that include trenching, conduit installation, and concrete mounting pads.

The Federal Way site incurred additional expense to support installation of a new transformer as well as control and data acquisition system (Figure 24). FLNA used Federal Way as one of three pilot sites for the Chateau Energy Solutions energy monitoring system described below.

Figure 24. EVSE power supply. From left to right: main disconnect, new transformer, load panel, and Chateau Energy Solutions monitoring equipment panel (Photo by Mike Simpson / NREL 29590)

EVSE Use

When an EV returns from its daily route, it is plugged into one of 10 charging stations for the night. At this point, the battery pack state of charge (SOC) for this 10-vehicle EV fleet is on average 42%, requiring an average of 6.1 hours of charging to recharge the battery to 100% SOC. SOC is a relative measure (0%–100%) of the remaining energy in the battery pack, similar to a fuel gauge on a conventional diesel vehicle. Figure 25 shows a typical 24-hour charging profile for a single vehicle with current and cumulative energy shown. The 24-hour period starts with the vehicle out on the route making deliveries, then around 11:30 a.m. (#1 on Figure 25), the vehicle returns to the depot and is plugged in for recharging. At some point before the vehicle leaves for the next day of deliveries, it is moved a short distance to the main facility's loading dock for loading of the next day's goods (#2 on Figure 25). After the vehicle is loaded, it is returned to the charging station and plugged in again (#3 on Figure 25) where it remains until the next morning. Due to this unique loading procedure at Federal Way, the average number of total plug-in events per day is 2.1.

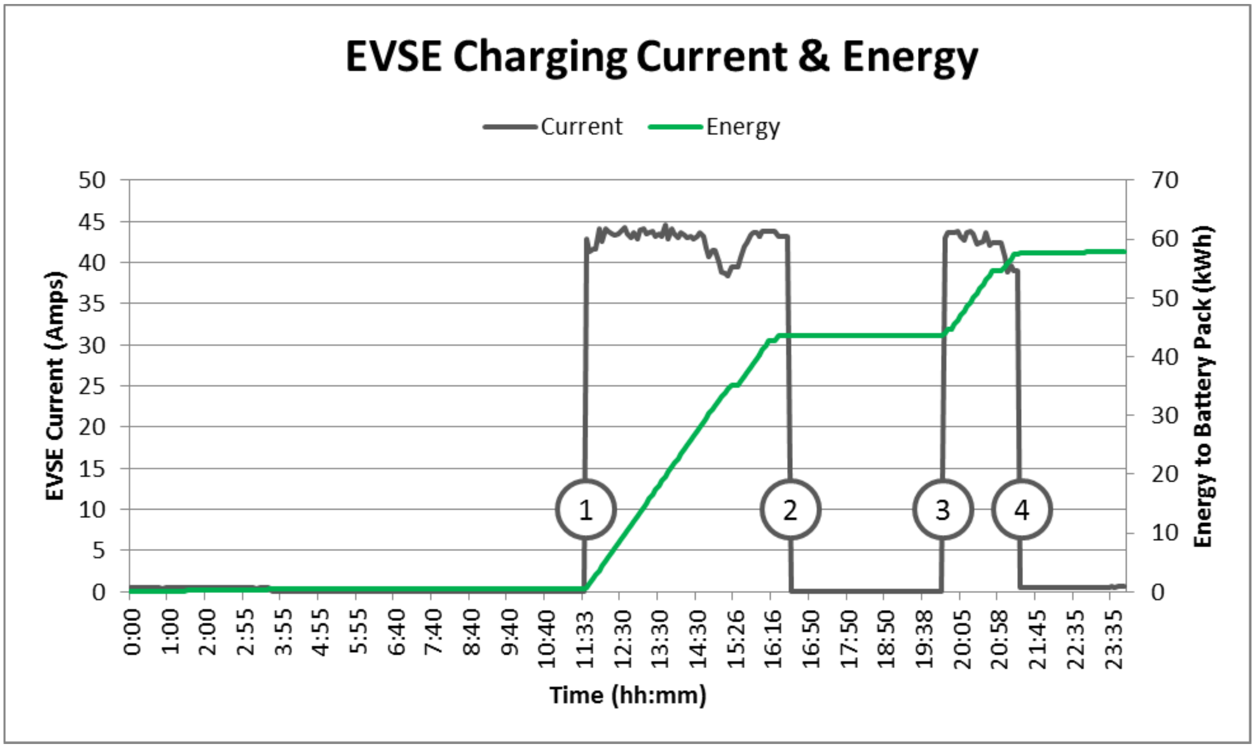

Figure 25. EVSE charging profile for EVSE 7 on 11/8/2015. (1) Vehicle returns from route and is plugged in. (2) Vehicle is unplugged and moved to loading dock to be reloaded for following day's route. (3) Vehicle is returned to original parking spot and plugged back in. (4) Vehicle reaches full SOC and stops charging.

EVSE Monitoring and Control

FLNA recently deployed EVSE monitoring and control networks at several sites in different regions of the United States. Chateau Energy Solutions installed and continues to monitor the charging station power consumption and quality, hosting a server for FLNA to view EV utilization and correlate with its overall energy costs.

The system currently installed at several FLNA Smith charging sites uses open building automation protocols and enables near real-time measurement and control via a Java browser-based user interface, as seen in Figure 26. These systems enable possible future testing of charge strategies presented in this report that may enable FLNA to reduce bills and improve electrical infrastructure reliability.

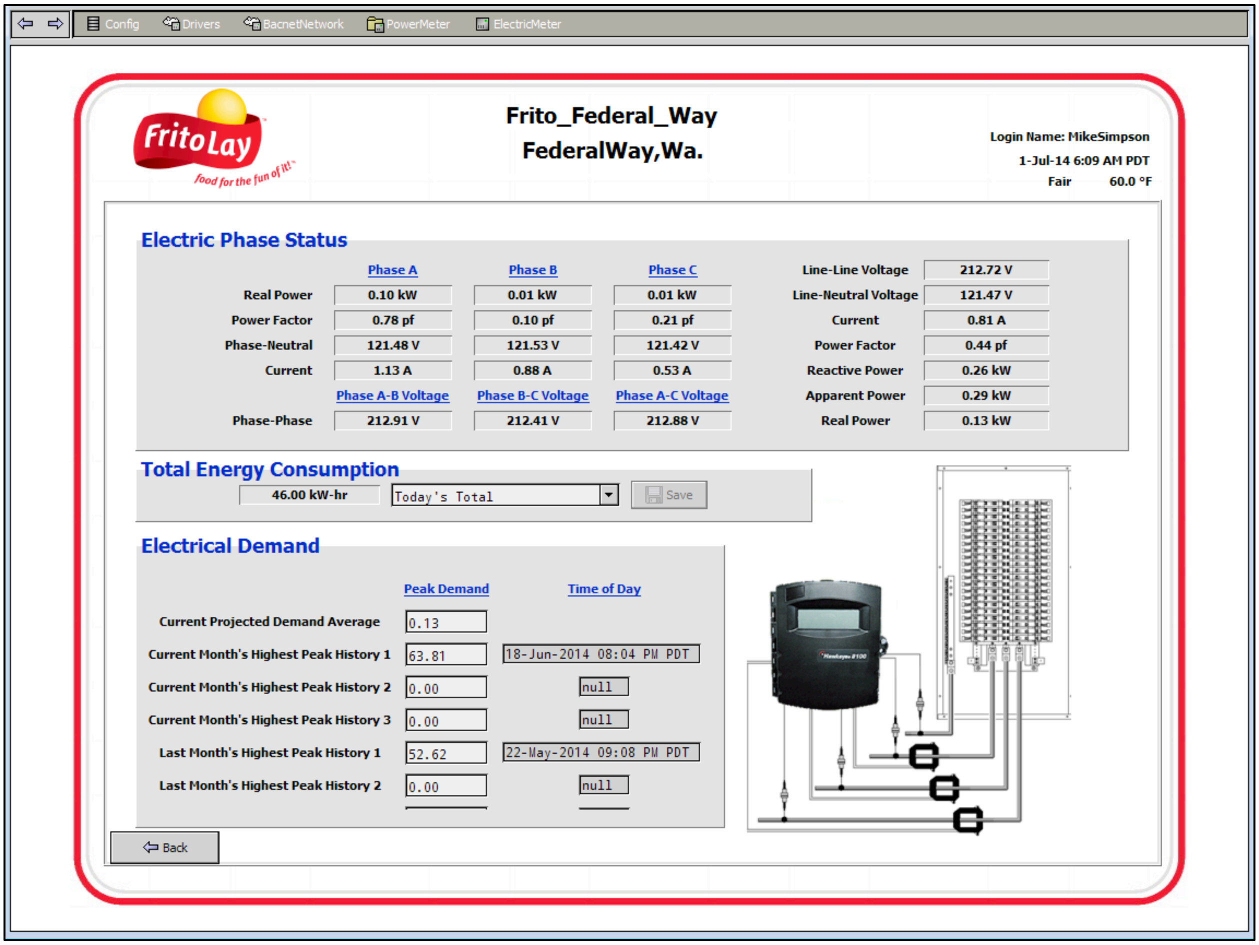

Figure 26. Chateau Energy Solutions online interface for EVSEs

Figure 27 shows an example of the data recorded by the Federal Way charging station energy management system. Each stacked color represents the power recorded over time (energy) delivered by a single charging station. When looking at each EVSE individually, there is some variation in the average and peak power delivered by each EVSE over a 3-month period of time as seen in Figure 28. This variation is to be expected due to the variety of routes serviced from this facility. Using these data, NREL found that each of the Federal Way EVs charged an average of 52.6 kWh AC per day.

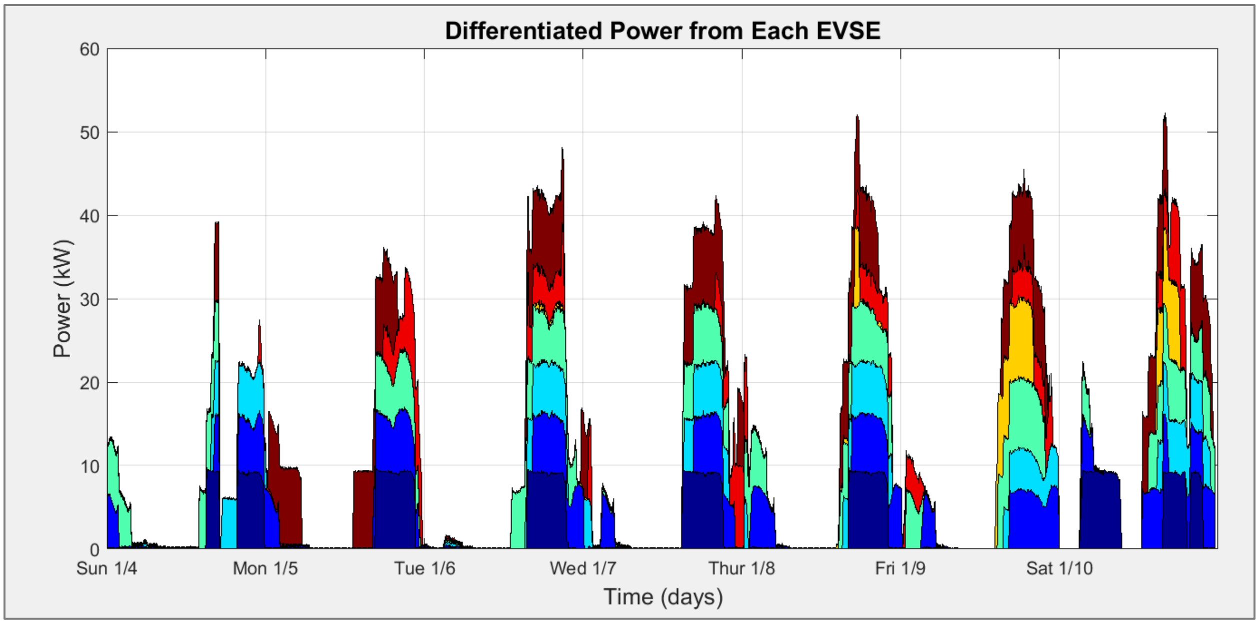

Figure 27. Data from Chateau Energy management system showing differentiated power from each EVSE as a different color

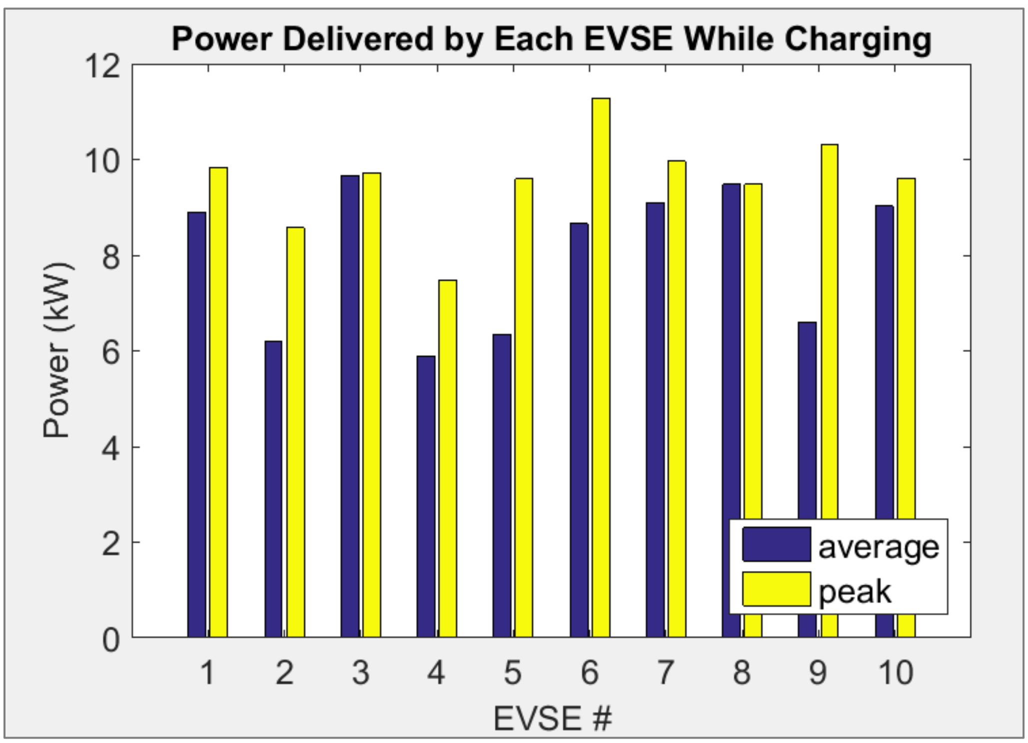

Figure 28. Average and peak EVSE power delivered while charging over a 3-month period

EV Facility Integration

EV deployments generally create new requirements for and impacts to depot facilities of commercial fleets, such as installation of electric infrastructure, new maintenance, training, and safety protocols, but they also increase the utility bill.

As shown in Figure 29 and Figure 30, the EVs charge overnight until early morning when the delivery shifts begin. Adding load throughout the afternoon and into the early evening coincides with many facility loads and has nearly doubled the Federal Way FLNA depot's demand.

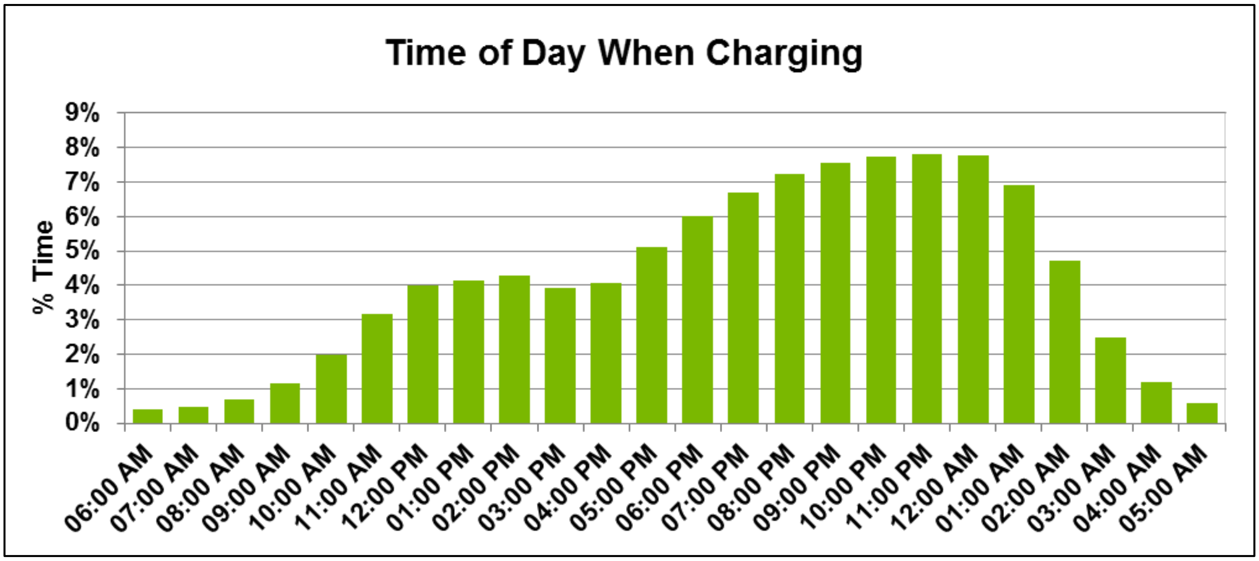

Figure 29. Federal Way Smith EV time of day when vehicle is charging

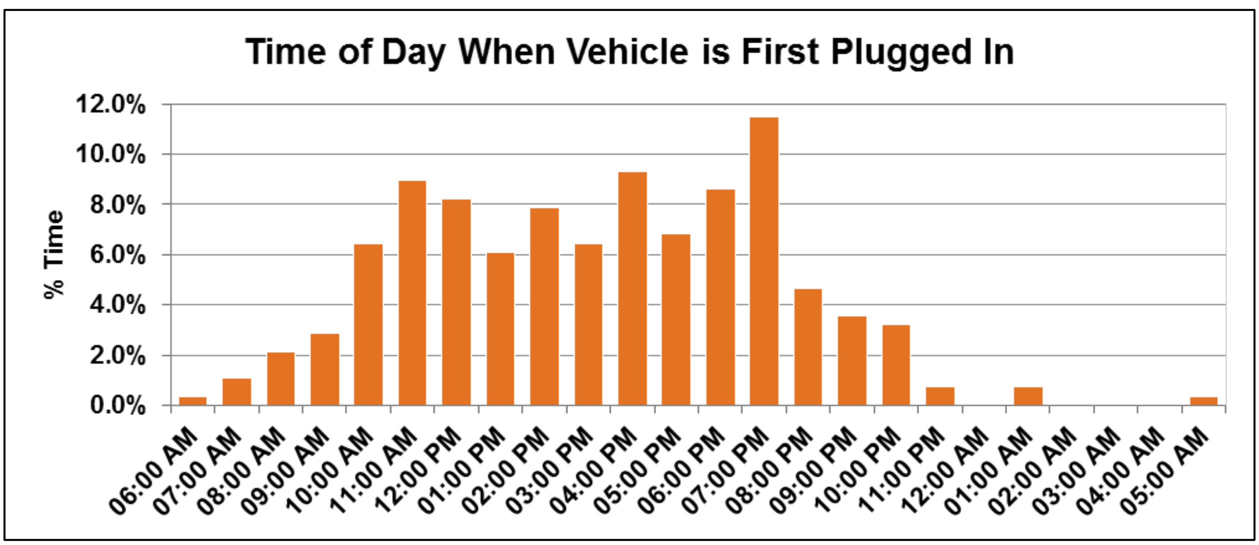

Figure 30. Federal Way Smith Newton EV time of day when vehicle is first plugged into EVSE for the day

As seen in Figure 31, the addition of plug-in EVs to the Federal Way facility in January 2013 had a direct impact on the overall facility peak demand requirements as Federal Way's 2013 rate schedule from PSE charged an additional "demand charge" fee, which is based on the highest power required over 50 kW for any given 15-minute interval for the billing period. While the Federal Way facility is not subject to exorbitant peak demand charges in comparison to other metropolitan cities, with a 2013 demand charge equal to $6.01/kW in April through September and $9.01/kW in October through March, peak demand charges still play a critical role in the overall cost effectiveness of EV operations. For example, in November 2013, the Federal Way facility's peak demand was 149 kW, and FLNA was charged an additional $9.01/kW or $1,342.49 on top of the base energy consumption charges. In the future, as more EVSEs are put into service, delivery fleets such as FLNA's may be able to offset their peak demand charges and increase their available driving range through opportunity charging at delivery locations by coordinating with their customers. Sample peak demand charges from select metropolitan areas across the country are shown in Figure 32.

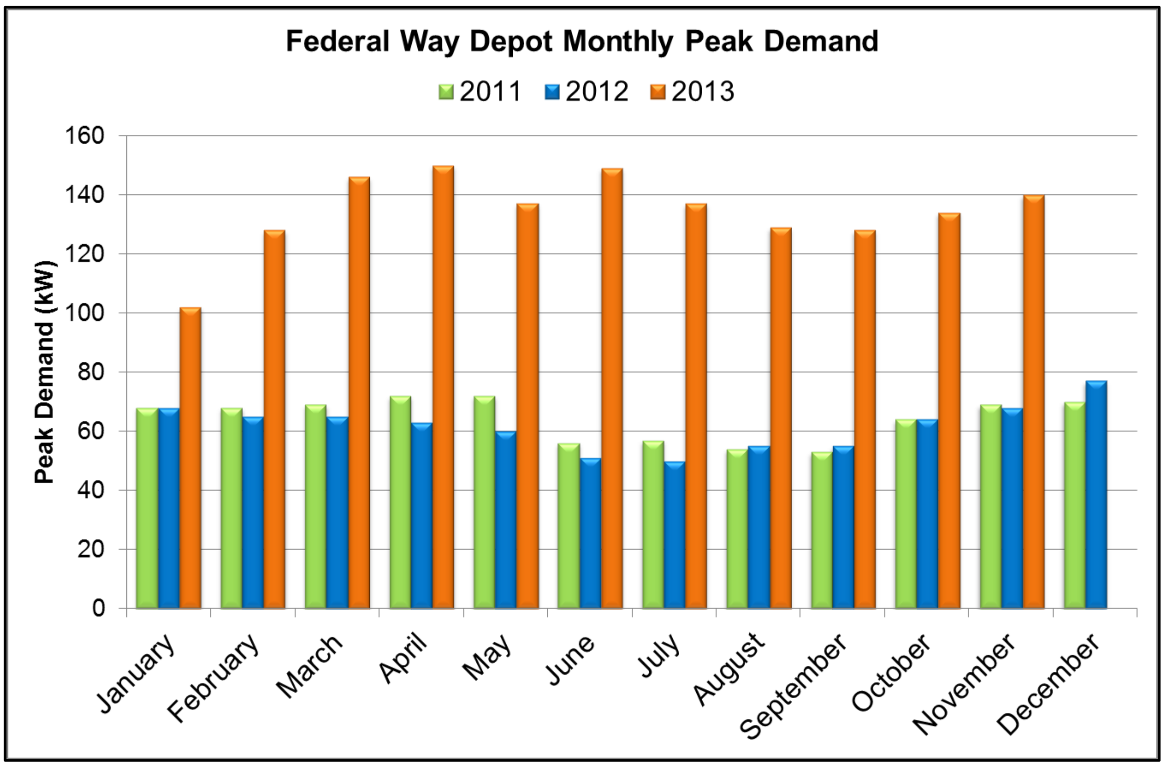

Figure 31. Federal Way depot monthly peak demand. EVs were introduced in January 2013.

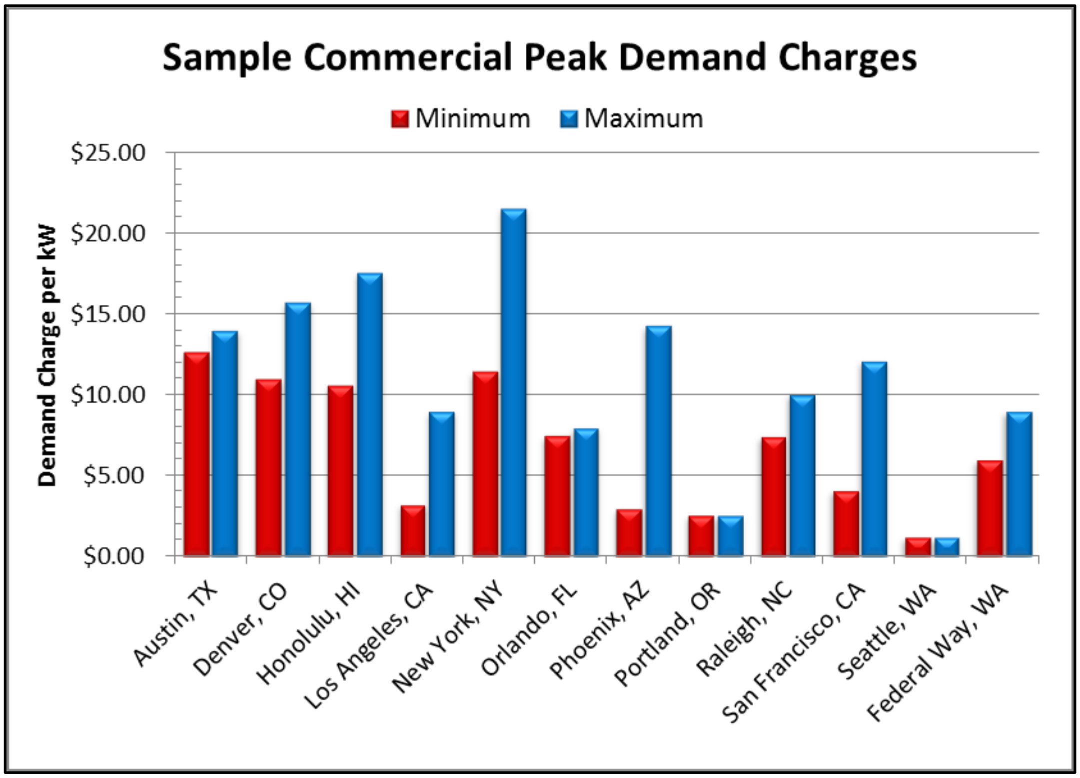

Figure 32. Sample monthly peak demand charges from across the United States. Historical data sourced from local energy companies.

Looking more closely at the facility power requirements, as seen in Figure 33, one can compare the load duration curves for the Federal Way facility with the load duration curve of the EVSEs as well as with the load duration curve of the combination of the building and EVs during a period of slightly more than 3 months.

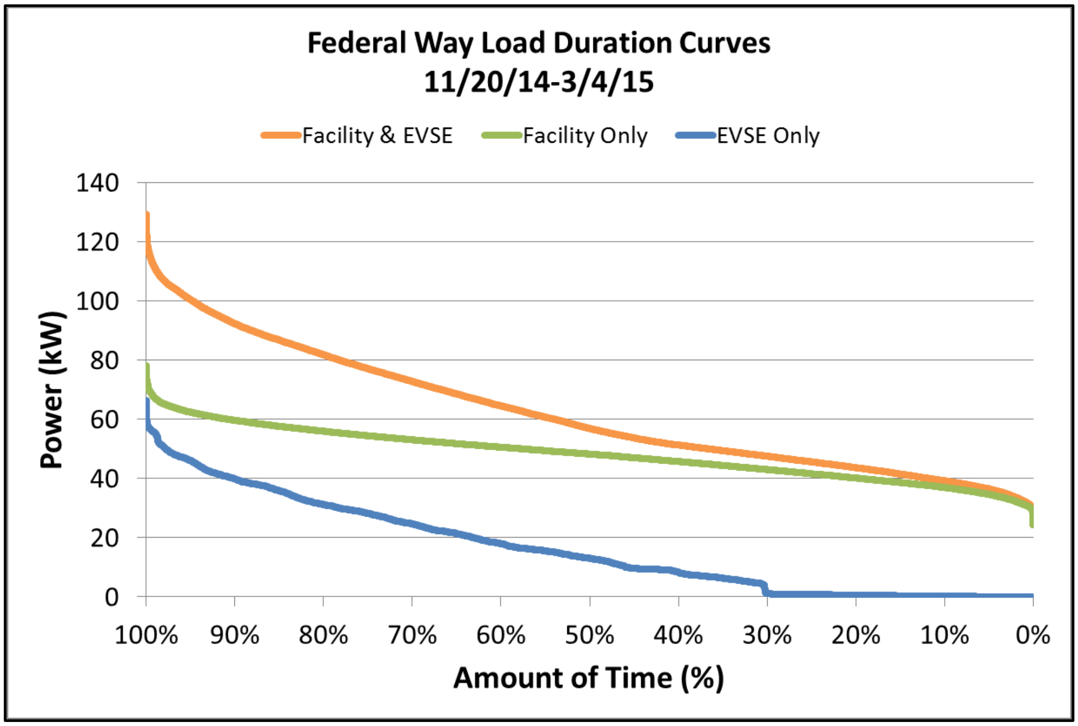

Figure 33. Load duration curves for Federal Way with and without EVSEs

On a more granular level, NREL also installed a high-speed, transient power quality monitor on the main utility feed at the Federal Way depot to better understand the overall facility power consumption behaviors. When examining the power requirements of the Federal Way facility at a daily level, one can see a direct correlation between EVSE use and an increase in total facility power requirements (including EVSEs), as seen in Figure 34.

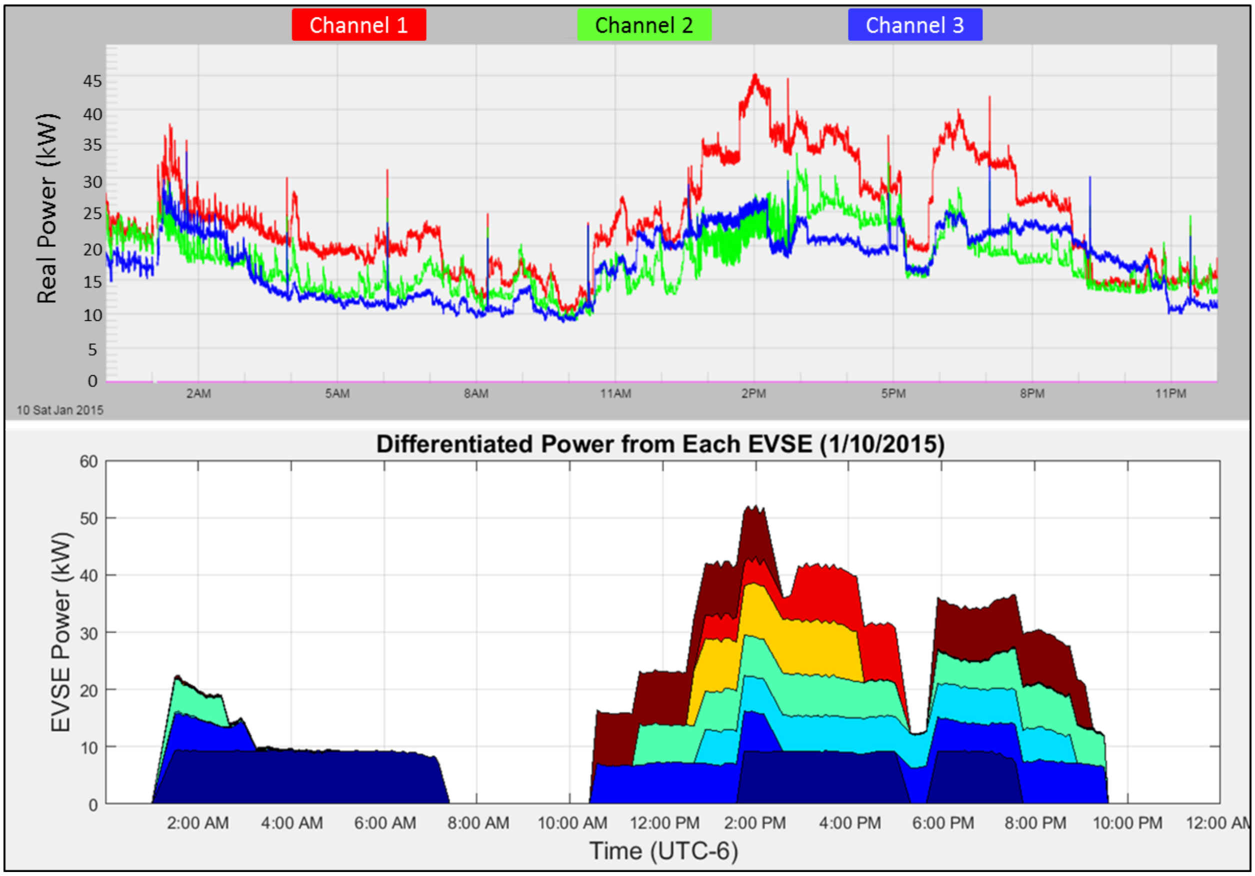

Figure 34. Comparison of Federal Way facility power consumption and EVSE usage. Data from 1/10/2015.

Another way to visualize the impact EV integration can have on a facility's power requirements is to look at the continuous power load requirements with and without the additional EVSE loads. Several days of power load data collected from the Federal Way facility and the EVSEs are shown in Figure 35. The difference between these two lines represents the additional power required for the EVSEs. When looking at the additional energy requirements on a monthly basis, Figure 36 shows the monthly facility energy consumption with the EVs introduced in January 2013.

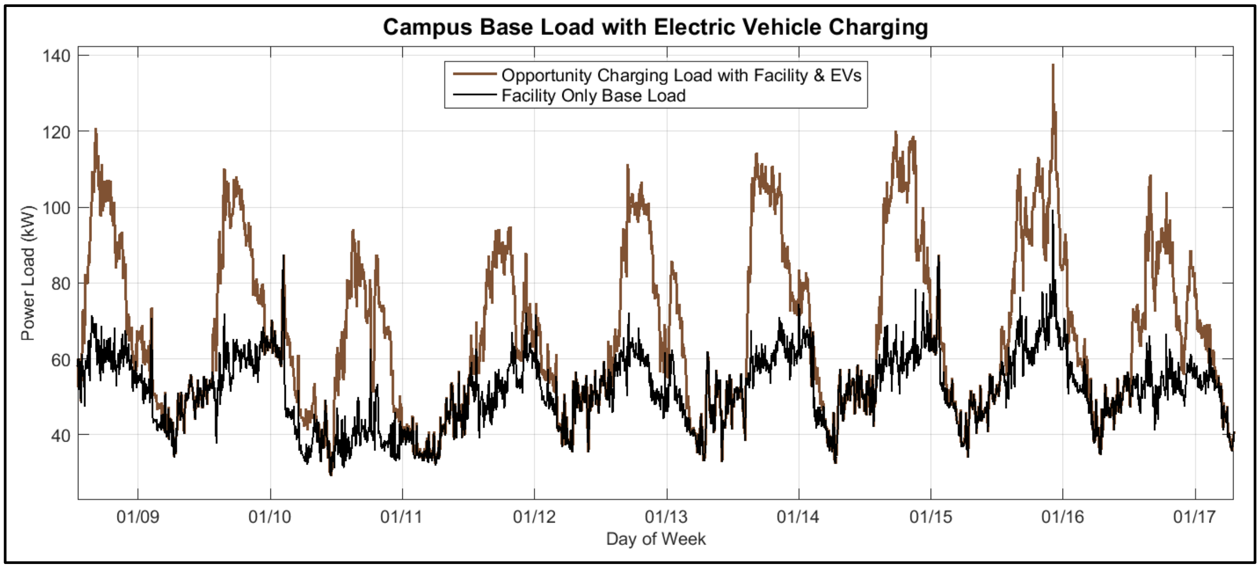

Figure 35. Federal Way load profile with facility base load and EVs, January 9 – 17, 2013

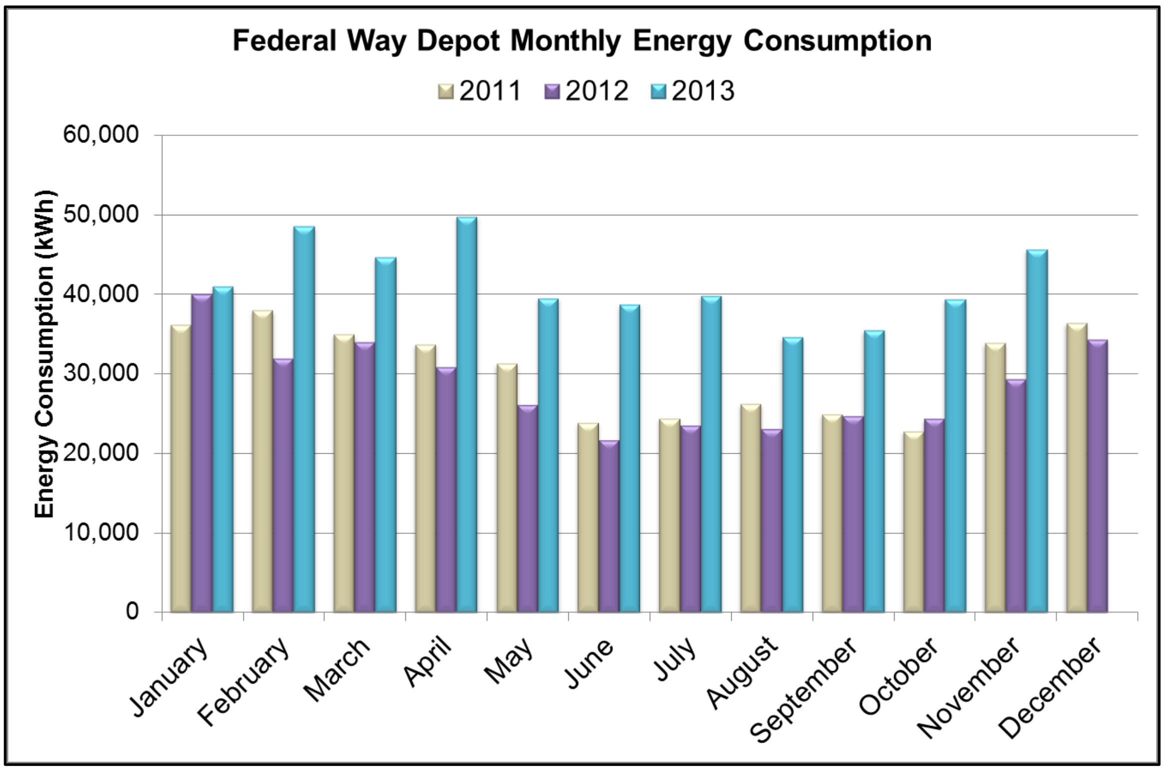

Figure 36. Federal Way depot monthly energy consumption. EVs were introduced in January 2013.

In addition to total energy consumption and time of day usage, there are other important power considerations to be aware of with the integration of onsite vehicle charging. One of these is the influence the charging loads have on a facility's power factor. In a general sense, the power factor is the ratio of real power used for work and apparent power that is supplied to the circuit. The power factor of the charger supply circuit falls while vehicles charge, with assumed contributions to reactive power from both the charging stations and the vehicle on-board chargers. As shown in Figure 37 and Figure 38, the power factor dips below 75% during periods with several coinciding charge events. The reactive power profile strongly correlates to the real power consumption, indicating the relationship of power quality to the power electronics design of these systems.

Although PSE does not penalize this facility for reactive power, several utilities across the United States do bill their customers for power factor correction. In fact, this can constitute a significant portion of a site's utility expense at even relatively high power factors (upwards of 95%). At other installations where vehicle demand may dominate the facility load profile and where a power factor correction charge is applied, charger design and installation (and thus vehicle choice) will require consideration for proper balancing.

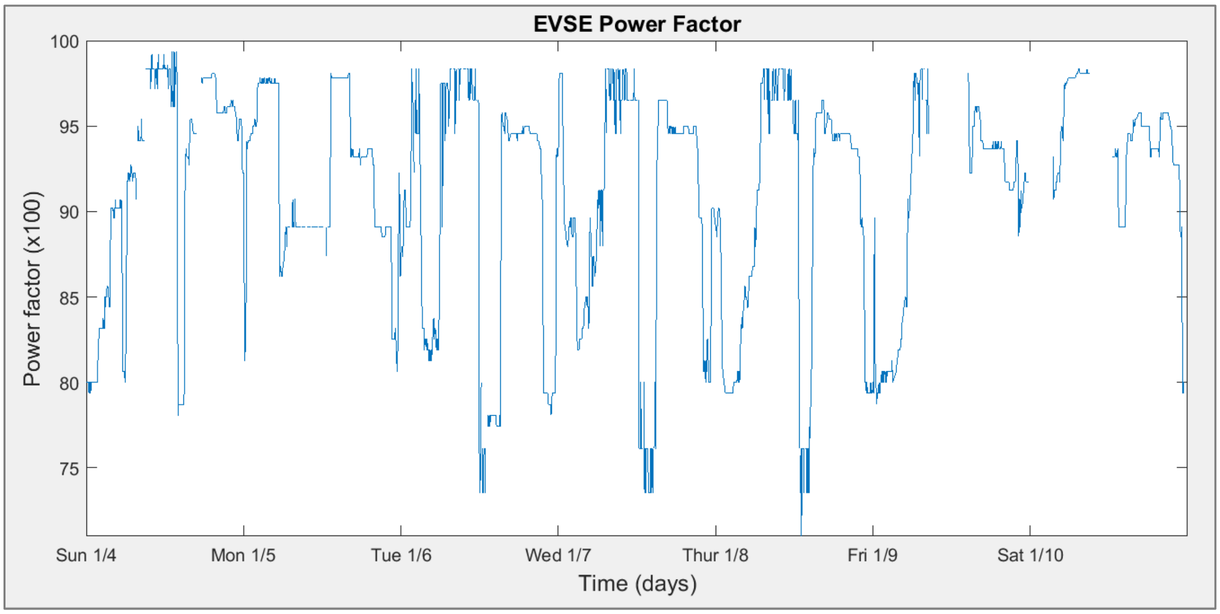

Figure 37. EVSE power factor

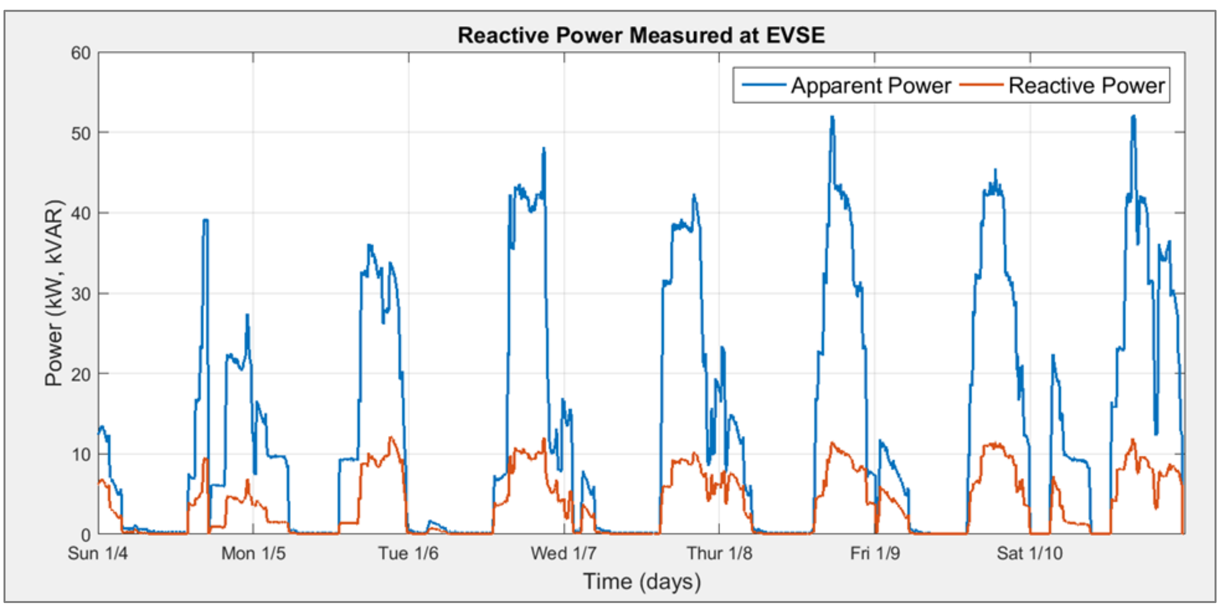

Figure 38. EVSE apparent and reactive power

Facility Power Model

Using this detailed facility load data, a facility energy model was created to demonstrate the opportunity for managed plug-in EV charging. The differences between opportunity charging, delayed charging, and managed charging are shown in Figure 39.

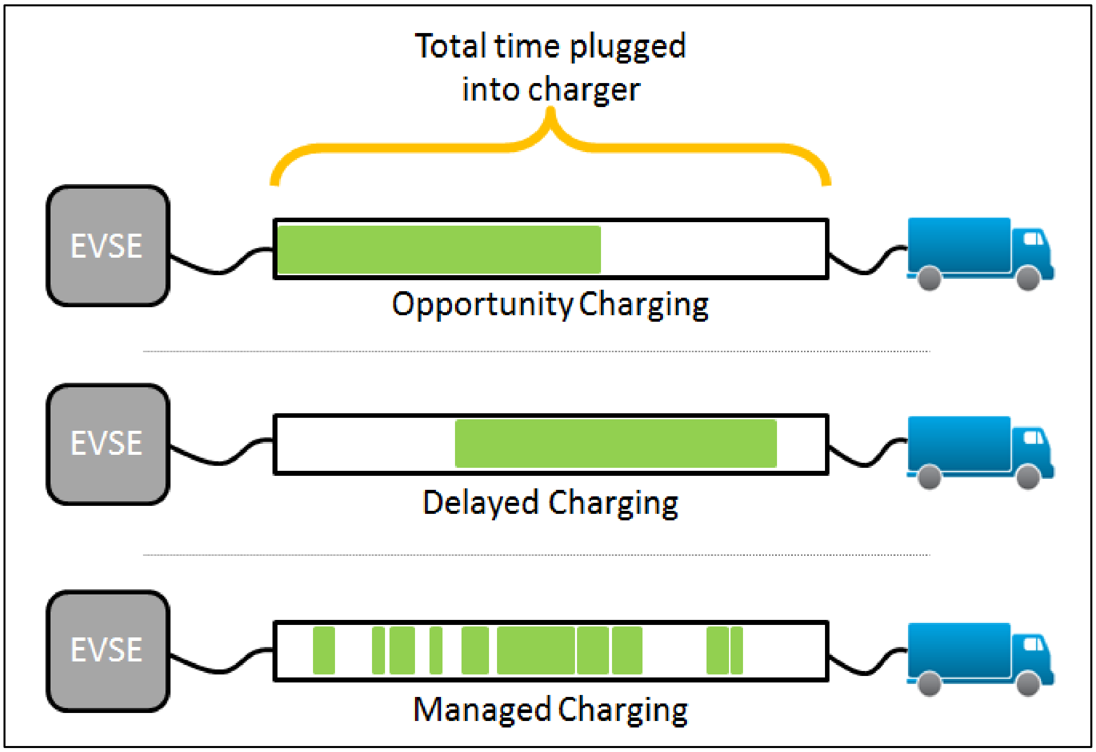

Figure 39. Opportunity charging, delayed charging, and managed charging.

Some of the key assumptions driving this energy model include the following: the SOC when the vehicle is plugged in, the time the vehicle will be used next, and the base facility load as a function of time. With the addition of a tuning parameter based on the historical peak loads, a peak demand reduction of up to 23% was demonstrated for the Federal Way facility, bringing the opportunity charging peak load down from 138 kW to 106 kW through managed charging. Opportunity charging is the typical charging pattern for these vehicles, where they are plugged in and charged whenever they are not in use. When combined with the relatively low peak demand charges in the Federal Way area, this 23% reduction equates to only a 6%–12% bill reduction. The modeled power load for nine days can be seen in Figure 40 along with the opportunity charging profile for comparison.

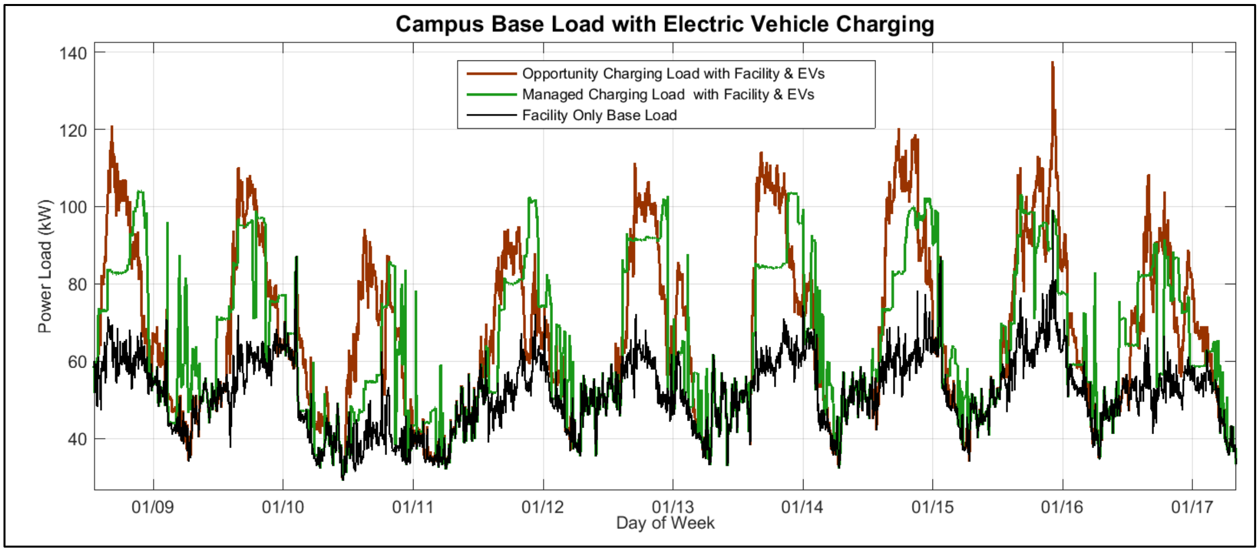

Figure 40. Plug-in EV charging load profiles for opportunity charging and managed charging with facility base load shown

When considering managed EV charging at a facility, it is important to understand the timing of different loads. For example, at the Federal Way facility there is a significant overlap in peak facility loads and peak charging loads, which combine to increase the peak demand charge. This overlap allows for the reduction of peak demand charges by shifting the vehicle charging to later in the day with an active charge management system. The amount of time the vehicle is charging can be shifted depending on the current SOC and the amount of time before the vehicle is dispatched again. While the model shows what is theoretically possible, there are limitations in terms of real-world implementation as the managed charging model relies on an up-to-date dispatch schedule and, more importantly, communication of the vehicle's SOC when it returns to the depot. This feature is not currently available on the Smith Newton vehicles. While there are industry working groups developing standard protocols to transmit this SOC information between the EVSE and the EV, there have been no wide-spread field deployments of this technology.

Modeling Integration of On-site Renewables

Taking the EV integration analysis one step further, one can consider the potential benefits of the integration of onsite renewables. Using the same base facility model, an onsite 100-kW solar array was modeled using NREL's PVWatts® Calculator [22]. This web-based application estimates the electricity production of a grid-connected roof- or ground-mounted photovoltaic system for a specific geographic location. The calculator estimates the monthly and annual electricity production of a photovoltaic system using an hour-by-hour simulation over a period of one year.

Evaluating the hour-by-hour electricity production on an annual basis as a function of solar array orientation, the PVWatts model shows a total annual output at 111,396 kWh for a southern-facing array and an annual output of 97,203 kWh for a western-facing array. While the southern-facing array has a greater total annual output, using the facility power and charging data with the facility power model, it was found that the generation from a western-facing solar array would actually align slightly better with late afternoon/evening charging of this EV fleet. Figure 41 shows the annual hourly power distribution as a function of solar array orientation and can be compared to the charging times shown in Figure 29.

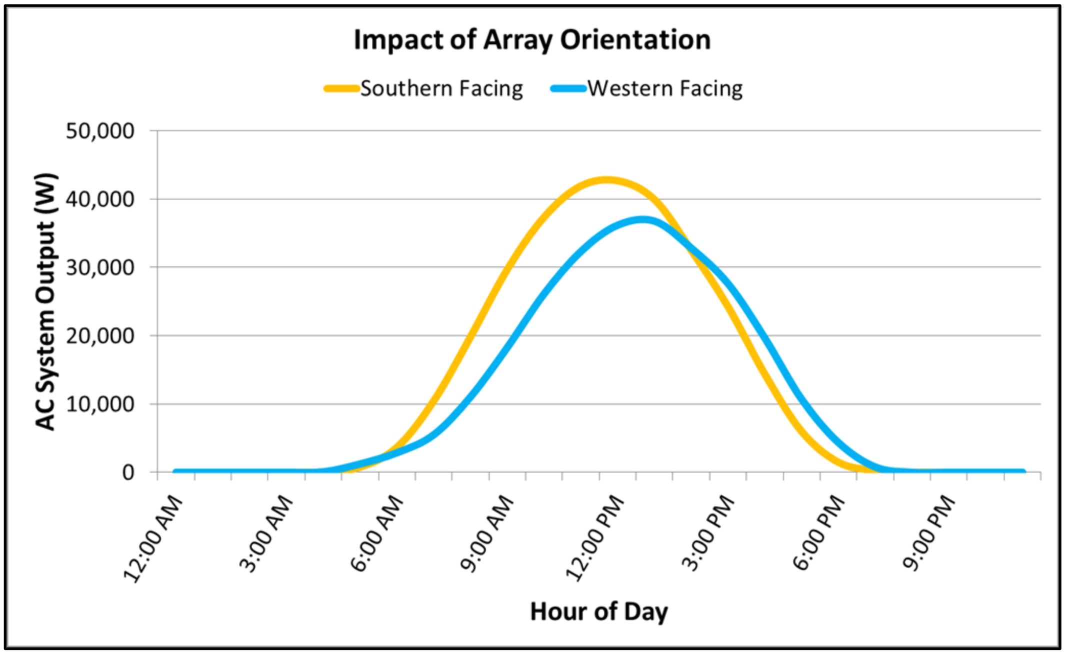

Figure 41. Average hourly output of 100-kW AC system based on array orientation at Federal Way facility

Integrating this PVWatts solar profile into the facility power model, the offset between daily peak solar and daily peak demand loads can be seen in Figure 42. In this 3-day period, the difference between the dashed blue line and the solid green line shows the benefit of integrating a 100-kW solar array into the Federal Way facility with a managed charging routine. The black line indicates the power load requirements of the facility only, not including the EVSEs. Even when the western-facing array is modeled, it is evident from Figure 42 that the facility peak demand loads are offset by several hours from the solar peak loads, thereby minimizing the benefit in reducing peak loads as seen in the direct overlap of the blue and green lines for the majority of the day.

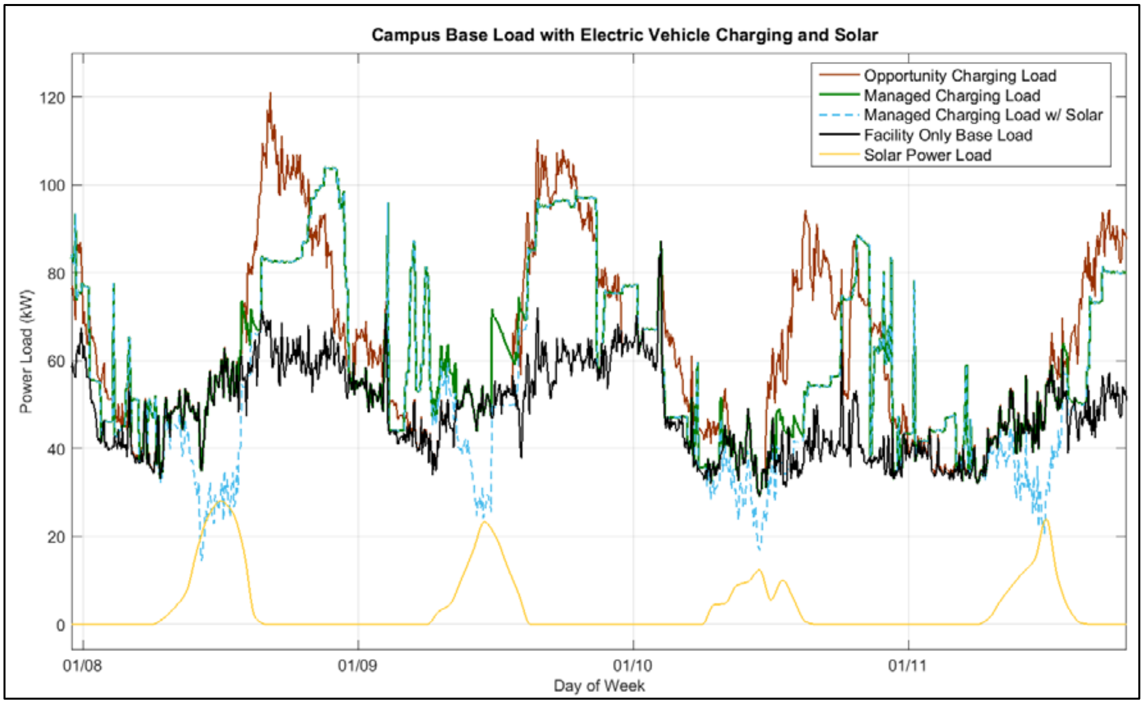

Figure 42. Campus net load with simulated 100-kW PV array and managed EV charging

Considering the operational characteristics of the EV fleet at Federal Way, the relatively low peak demand charges in the Seattle area, and the low average solar potential in the Pacific Northwest as shown in Figure 43, our analysis showed that from a financial perspective, the Federal Way facility is not a strong candidate for integration of onsite solar. For locations with greater solar resource potential and a different EV dispatch schedule, there could be better opportunities to offset vehicle charging loads through the use of onsite solar. To demonstrate the impact of greater solar resources, a western-facing 100-kW solar array was modeled using the solar resource profile of a FLNA location in Casa Grande, Arizona, in conjunction with the same Federal Way facility model. The results are shown in Figure 44. This simulated solar profile for Casa Grande equates to 149,246 kWh of annual output. As before, the difference between the solid green line and the dashed blue line indicates the added benefit of the solar array. Values less than zero, as seen on day 1/10, indicate opportunities to sell back power to the grid. While the solar resource potential is much greater in Arizona, without large-scale onsite energy storage capacity, there is very little impact on the overall peak power loads due to the offset between EV charging times and peak solar loads.

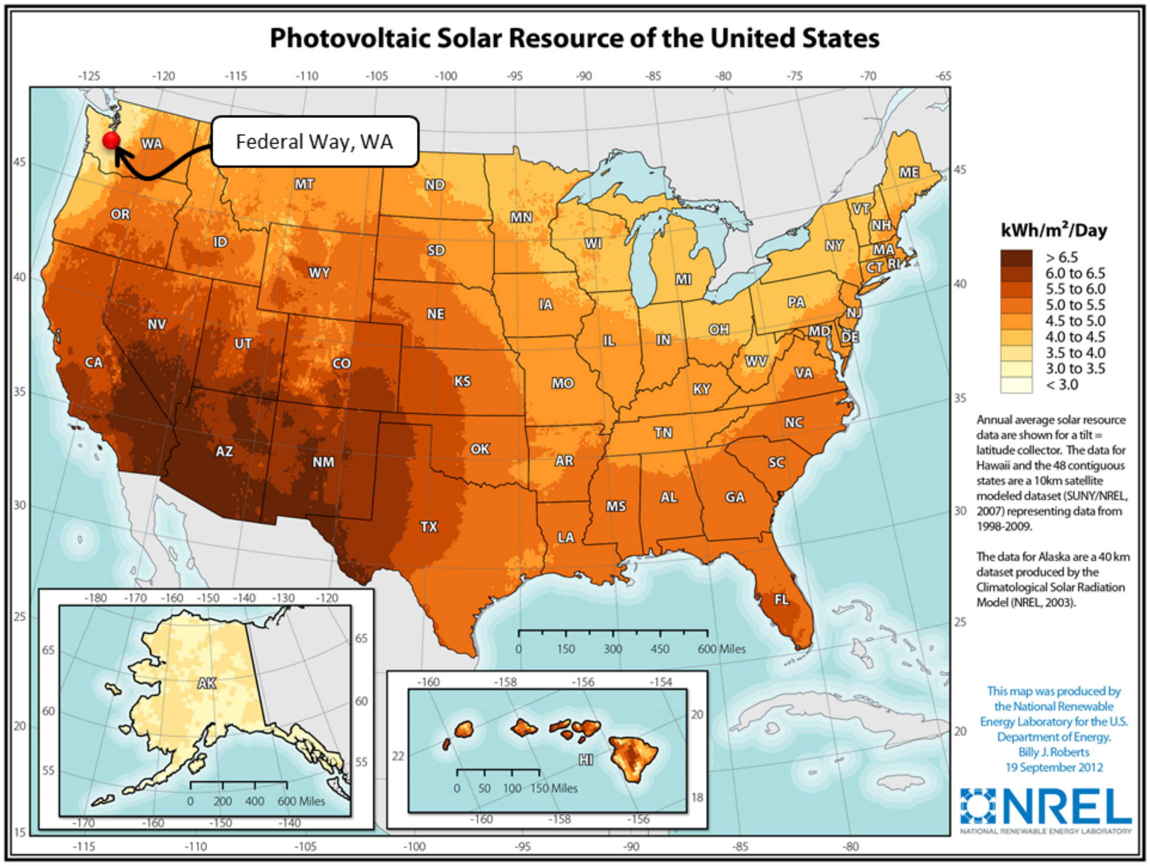

Figure 43. Solar energy potential. National map shows low solar resource potential near Federal Way [23]

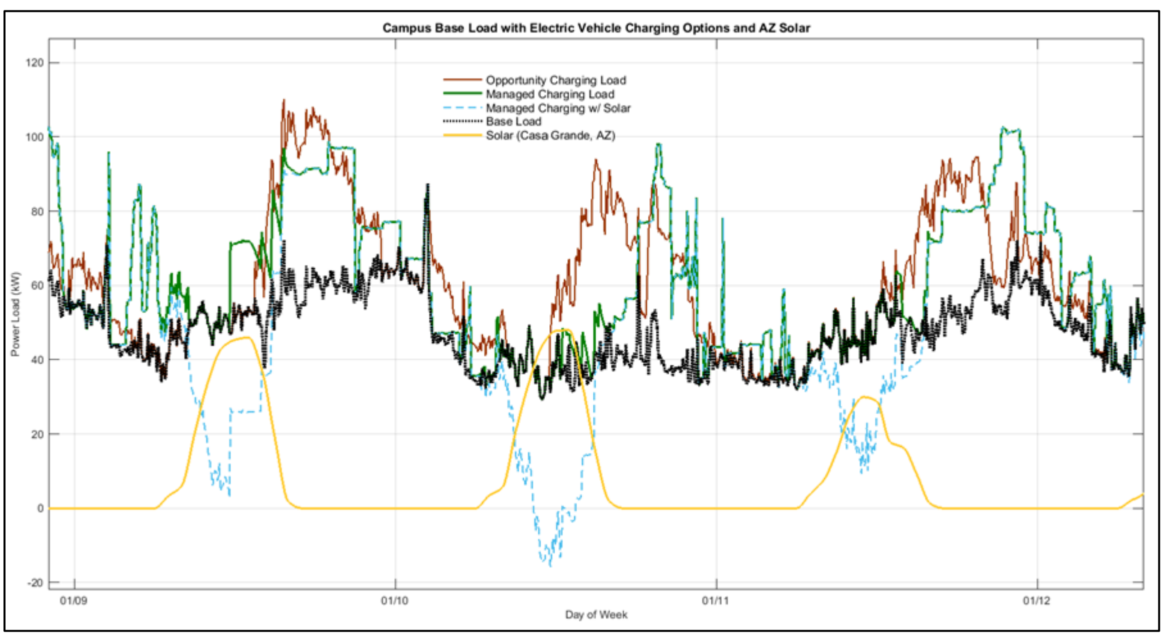

Figure 44. Campus net load with simulated 100-kW PV array using Casa Grande solar resource profile and managed EV charging

Therefore, to truly maximize the benefit of onsite solar to reduce peak power loads, the solar peaks must align with the demand peaks. To demonstrate the benefit of aligning peak solar times with peak power demand times, the western-facing Casa Grande solar profile used in Figure 44 was shifted 6 hours ahead. This simulated 6-hour time shift puts the facility peak loads and the solar output in better alignment. As seen in Figure 45, the “Managed Charging w/ Solar” power load line (shown in red) has much lower values when compared to the “Managed Charging Load” line (without solar) (shown in green).

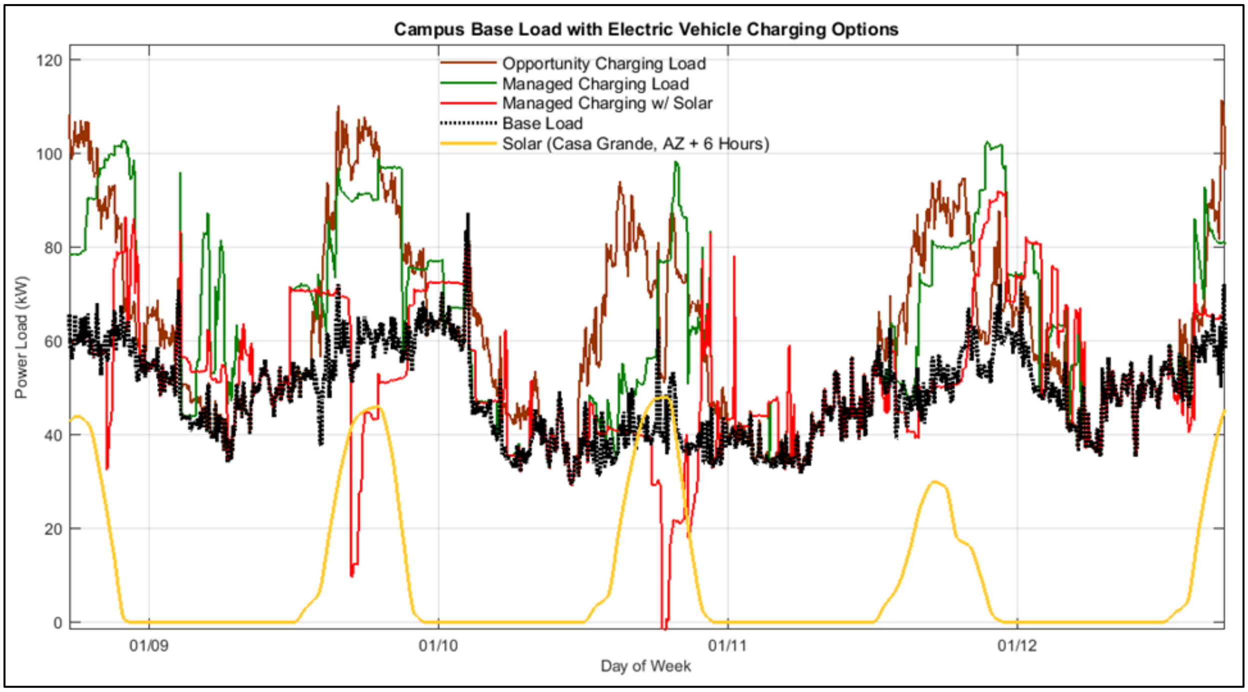

Figure 45. Campus net load with managed EV charging and simulated 100-kW PV array using a 6-hour time shifted Casa Grande solar resource profile

This modeling exercise, while not representative of the Federal Way FLNA operation, demonstrates the potential benefits of integrating onsite renewables in the right application. With flexible vehicle dispatching, managed charging, and high solar resources, it is possible to offset a substantial amount of the demand charges that would otherwise be incurred with the integration of EVs into a facility.

Battery Degradation

Battery lifetime uncertainty is a major barrier to fleet manager decisions regarding the adoption of plug-in EVs. To reduce life uncertainty, NREL, Smith, and FLNA have developed a study in parallel to the Federal Way fleet evaluation to perform benchmarking tests of EV batteries at regular stages throughout their life to better quantify battery pack health and track battery performance changes. This research will also serve to validate battery life prediction models to help fleet managers better forecast their vehicle purchasing and deployment strategies.

In 2013, NREL designed and built an integrated load bank test apparatus, as shown in Figure 46. This equipment was used at Smith’s U.S. headquarters in Kansas City, Missouri, to validate proper operation and obtain a reference point for an unused battery pack. NREL and Smith developed a test to perform a controlled discharge every 6 to 12 months of Smith EV batteries without removing them from the truck. Prior to testing, the truck was fully charged overnight using the normal charge protocol. NREL test engineers electrically disconnected the battery from the truck and routed the electrical leads through the test equipment. The test equipment discharged the battery at a C/6 rate with periodic rests to measure open circuit voltage and resistance. Data were recorded both from the vehicle's controller area network and using an independent data-logger. Following the 6-hour discharge, the truck was returned to its original condition and placed on the charger to resume normal service the following day. This one-day test was minimally invasive to fleet operations. Data collected at Smith's headquarters on a factory-new truck will serve as a benchmark for comparison of beginning-of-life performance of Smith EV battery packs.

Figure 46. Battery load test conducted at Frito Lay (Photo by Mike Simpson / NREL 29612)

To date, NREL has collected 17 battery degradation data points from eight separate vehicles located in four different regions (Table 5).

Table 5. Smith EV Subjects of Battery Degradation Testing

Location	Vehicle ID	Test Date
Casa Grande, AZ	FLNAR42175	9/11/13
		5/6/14
		Moved Terminal
	FLNAR42176	9/10/13
		5/7/14
		7/7/2015
Federal Way, WA	FLNAE27123	9/24/13
		4/16/14
		7/21/2015
	FLNAE27124	9/25/13
		4/15/14
		7/22/2015
Clifton Park, NY	FLNAE27144	6/3/14
		11/5/14
	FLNAE27148	6/4/14
		11/4/14
Manteca, CA	FLNAE27157	6/18/14
	FLNAE27159	6/17/14

Unfortunately, due to vehicle availability and mechanical failures, vehicle testing intervals are varied; however, it is expected that a minimum of two to three years of testing may be required to discern any actionable trends in degradation from the eight vehicles under test, so this gap in data collection is not anticipated to be problematic. NREL has strong support from Smith and FLNA to continue the testing for several years as battery duty cycles harvested from large data sets of in-use operation provide an excellent opportunity to monitor and better understand the real-world aging process in EV battery packs. For this effort, the ARRA Smith data set is being used to identify combinations of drive cycles and climates that result in accelerated degradation.

The EV battery life model employs time series histories of pack current and voltage that are applied to an electrical model of the pack that considers zero order current-resistance dynamics and a single-particle model of electrode concentration gradients (used to describe transient voltage relaxation). The modeled pack voltage is compared to the historical data, and a constrained non-linear optimization algorithm is used to minimize the root mean square of model error (usually achieving values of tens of millivolts per cell).

Error is minimized by updating model parameters such as pack capacity, bulk resistance, initial thermodynamic SOC, and multiple diffusion coefficients. Following optimization of the model over each individual drive cycle, estimated parameters used to describe pack available energy and power are reported through time and compared to controlled performance tests conducted by NREL engineers in the field.

As of the date of this report, the results are still preliminary because most vehicles tested have relatively low mileage and few data measurements. Data will be presented as more in-field measurements are collected in the coming years, averaging out any errors. A successful outcome of the project is targeted to be the dissemination of credible multi-year battery performance data to support increased adoption of EVs in commercial fleets.

Battery degradation testing is currently planned to continue through 2016 on the vehicles shown in Table 5 in hopes of better understanding the trends in battery performance over time based on geographic location and/or duty cycle.

Going forward, battery state of health will be estimated for the Smith ARRA data set through time and will potentially be used to construct a life model of the pack based on in-use field data similar to the graph shown in Figure 47. Such a model would be of great value in better understanding long-term value of EVs for fleet managers interested in pairing EVs with appropriate vocations in their fleet.

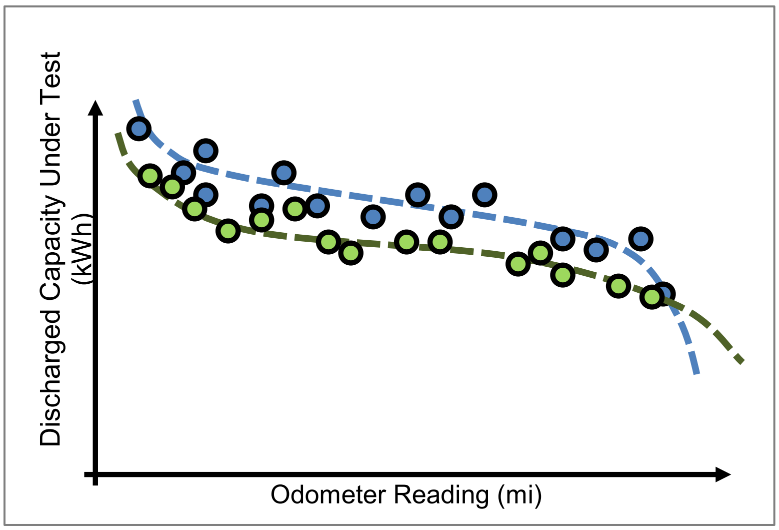

Figure 47. Intended data collection: Collecting several data points over a period of years will help to validate life models.

Summary

This fleet evaluation of FLNA's Federal Way Smith electric delivery vehicles shows that the success of advanced vehicle technologies for medium- and heavy-duty vehicles is highly dependent on the drive cycle characteristics as well as the general operation of the vehicles. The way in which vehicles are dispatched and operated on the road will dictate how well a specific technology, such as electrification or hybridization, can perform in a fleet setting. As discussed, the route characteristics and requirements of the observed fleet made electrification a viable choice to reduce fleet energy consumption and emissions. Just as energy efficiency is highly dependent on a vehicle's duty cycle, emissions savings with electrification is highly dependent on the power generation source.

Specific to plug-in EVs, considerations for peak demand charges and charging infrastructure requirements as well as the time required for charging between shifts must be taken into account for successful deployment of electric delivery vehicles. It is imperative for fleet managers to collect and analyze real-world data describing how their vehicles are operated before attempting to adopt a new technology into their fleet.

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Appendix A. Data Logger Specifications

Vehicle Data Logger	
Manufacturer	Isaac
Model	DRU 900/908
Data Storage	Internal Memory
Input Voltage	10 Vdc – 30 Vdc
Input Current	75 mA at 12 Vdc
Vehicle Communication Ports	CAN 2.0 a/b, SAE J1708, SAE J1587
Serial Ports	RS-232
Operating Temperature	-40°F to +185°F
Ingress Protection	IP 65 (dust & waterproof)

°F degrees Fahrenheit
Vdc volt-direct current

Appendix B. GPS Specifications

Global Positioning System	
Manufacturer	Garmin
Model	18x-5Hz
Input Voltage	4.0 – 5.
Input Current	100 mA at 5 Vdc
Operating Temperature	-22°F to +176°F
Update Rate	5 Hz
Position Accuracy (WAAS)	< 3m, 95% typical
Interface	TIA-232-F (RS-232)

Hz hertz
m meter
mA milliamp
Vdc volt – direct current

Appendix C. FLNA Smith Electric Vehicle Field Data Channel List

Channel Name	Description	Frequency
Timestamp	Time stamp	1 Hz
BMU_Mode_SYS	Battery Management Mode	1 Hz
GPS_Speed	GPS Speed	1 Hz
VS_DCMD	Accelerator pedal position.	1 Hz
vs_bcmd	Brake pedal position.	1 Hz
Battery_Current_SYS	Battery System Current	1 Hz
Battery_Voltage_SYS	Battery System Voltage	1 Hz
Lowest_Cell_Voltage_SBS1	Battery Cell Voltage	1 Hz
Lowest_Cell_Voltage_SBS2	Battery Cell Voltage	1 Hz
Lowest_Cell_Voltage_SBS3	Battery Cell Voltage	1 Hz
Lowest_Cell_Voltage_SBS4	Battery Cell Voltage	1 Hz
Highest_Cell_Voltage_SBS1	Battery Cell Voltage	1 Hz
Highest_Cell_Voltage_SBS2	Battery Cell Voltage	1 Hz
Highest_Cell_Voltage_SBS3	Battery Cell Voltage	1 Hz
Highest_Cell_Voltage_SBS4	Battery Cell Voltage	1 Hz
GPS_Latitude	GPS Latitude	1 Hz
GPS_Longitude	GPS Longitude	1 Hz
GPS_Altitude	GPS Altitude	1 Hz
Lowest_Cell_Temperature_SBS1	Battery Cell Temperature	1 Hz
Lowest_Cell_Temperature_SBS2	Battery Cell Temperature	1 Hz
Lowest_Cell_Temperature_SBS3	Battery Cell Temperature	1 Hz
Lowest_Cell_Temperature_SBS4	Battery Cell Temperature	1 Hz
Highest_Cell_Temperature_SBS1	Battery Cell Temperature	1 Hz
Highest_Cell_Temperature_SBS2	Battery Cell Temperature	1 Hz
Highest_Cell_Temperature_SBS3	Battery Cell Temperature	1 Hz
Highest_Cell_Temperature_SBS4	Battery Cell Temperature	1 Hz
ms_tmf1	Motor temperature sensor 1	1 Hz
ms_tmc1	Motor temperature sensor 2	1 Hz
ms_ths1	Motor temperature sensor 3	1 Hz
ms_ths2	Motor temperature sensor 4	1 Hz
ms_ths3	Motor temperature sensor 5	1 Hz
ms_ths4	Motor temperature sensor 6	1 Hz
ms_ths5	Motor temperature sensor 7	1 Hz

Channel Name	Description	Frequency
ms_nmot	Motor Speed	1 Hz
CT_Heater_Current_RD	Cabin Heater Current	1 Hz
vs_24vbat	24V system voltage	1 Hz
CT_Air_Con_Current_RD	An indication of if the AC is in use	1 Hz
RD_Ambient_Temp_degC	Ambient Temperature	1 Hz
RD_Cab_Temp_degC	Cabin Temperature	1 Hz
SOC_SYS	State of Charge	1 Hz

Appendix D. FLNA Conventional Diesel Field Data Channel List

Data Channel Name	Data Channel Name	Acronym	PGN#	SAE SPN#	Units
Transmission Output Shaft Speed	TransOutputShaftSpeed_1	ETC1	61442	191	rpm
Transmission Input Shaft Speed	TransInputShaftSpeed_1	ETC1	61442	161	rpm
Accelerator Pedal Position 1	AccelPedalPos1	EEC2	61443	91	%
Engine Percent Load At Current Speed	EngPercentLoadAtCurrentSpeed	EEC2	61443	92	%
Actual Maximum Available Engine - Percent Torque	ActMaxAvailEngPercentTorque	EEC2	61443	3357	%
Driver's Demand Engine - Percent Torque	DriversDemandEngPercentTorque	EEC1	61444	512	%
Actual Engine - Percent Torque	ActualEngPercentTorque	EEC1	61444	513	%
Engine Speed	EngSpeed	EEC1	61444	190	rpm
Transmission Selected Gear	TransSelectedGear_1	ETC2	61445	524	Gear
Transmission Current Gear	TransCurrentGear_1	ETC2	61445	523	Gear
Engine Exhaust Gas Recirculation 1 (EGR1) Mass Flow Rate	EngExhstGsRcrcltionMassFlowRate	EGF1	61450	2659	kg/hr.
Engine Intake Air Mass Flow Rate	EngInletAirMassFlowRate	EGF1	61450	132	kg/hr.
Diesel Particulate Filter Lamp Command	DieselParticulateFilterLampCmd	DPFC1	64892	3697	-
Diesel Particulate Filter Passive Regeneration Status	DslPrtclPssvRgnrtionStatus	DPFC1	64892	3699	-
Diesel Particulate Filter Active Regeneration Status	DslPrtclActvRgnrtionStatus	DPFC1	64892	3700	-
Diesel Particulate Filter Status	DieselParticulateFilterStatus	DPFC1	64892	3701	-
Exhaust System High Temperature Lamp Command	ExhaustSystemHighTempLampCmd	DPFC1	64892	3698	-

Data Channel Name	Data Channel Name	Acronym	PGN#	SAE SPN#	Units
Diesel Particulate Filter Active Regeneration Forced Status	DslPrtclActvRgnrtionFrcdStatus	DPFC1	64892	4175	-
Aftertreatment 1 Diesel Particulate Filter Outlet Gas Temperature	Aftrtrtmnt1PrtcltTrpOtltGasTemp	AT1OG2	64947	3246	deg C
Aftertreatment Exhaust Gas Temp	Aftertreatment1ExhaustGasTemp1	AT1IG2	64948	3241	deg C
Referenced Torque	ReferenceEngineTorque	EC1	65251	544	Nm
Red Stop Lamp (engine)	EngRedStopLampData	DLCD1	64773	5095	-
Amber Warning Lamp (engine)	EngAmberWarningLampData	DLCD1	64773	5094	-
Protect Lamp (engine)	EngProtectLampData	DLCD1	64773	5093	-
Nominal Friction - Percent Torque	NominalFrictionPercentTorque	EEC3	65247	514	%
Engine Coolant Temperature	EngCoolantTemp	ET1	65262	110	deg C
Engine Fuel Temperature 1	EngFuelTemp	ET1	65262	174	deg C
Engine Oil Temperature 1	EngOilTemp1	ET1	65262	175	deg C
Engine Intercooler Temperature	EngIntercoolerTemp	ET1	65262	52	deg C
Engine Fuel Delivery Pressure	EngFuelDeliveryPress	EFL_P1	65263	94	kPa
Engine Oil Pressure	EngOilPress	EFL_P1	65263	100	kPa
Wheel-Based Vehicle Speed	WheelBasedVehicleSpeed	CCVS	65265	84	km/h
Brake Switch	BrakeSwitch	CCVS	65265	597	-
Engine Fuel Rate	EngFuelRate	LFE	65266	183	L/h
Barometric Pressure	BarometricPress	AMB	65269	108	kPa
Ambient Air Temperature	AmbientAirTemp	AMB	65269	171	deg C
Engine Air Intake Temperature	EngAirInletTemp	AMB	65269	172	deg C
Engine Intake Manifold 1 Pressure	EngTurboBoostPress	IC1	65270	102	kPa
Engine Intake Manifold 1 Temperature	EngIntakeManifold1Temp	IC1	65270	105	deg C

Data Channel Name	Data Channel Name	Acronym	PGN#	SAE SPN#	Units
Engine Air Intake Pressure	EngAirInletPress	IC1	65270	106	kPa
Engine Exhaust Gas Temperature	EngExhaustGasTemp	IC1	65270	173	deg C
Engine Oil Temperature 2	EngOilTemp2	ET2	65188	1135	deg C
Engine Exhaust Gas Temperature - Left Manifold	EngExhaustGasTempLeftManifold	ET	65031	2434	deg C
Engine Exhaust Gas Temperature - Right Manifold	EngExhaustGasTempRightManifold	ET	65031	2433	deg C
Engine Exhaust Gas Average Temperature	EngExhaustGasTempAverage	EAI	64851	4151	deg C
Diesel Oxidation Catalyst Intake Gas Temperature 1	Aftrtrtmnt1DslOxdtnCtlystDffPrss	A1DOC	64800	4765	deg C
Diesel Oxidation Catalyst Exhaust Gas Temperature 1	Aftrtrtmnt1DslOxdtnCtlystIntkGsT	A1DOC	64800	4766	deg C
Diesel Oxidation Catalyst Differential Pressure 1	Aftrtrtmnt1DslOxdtnCtlystOutlGsT	A1DOC	64800	4767	kPa
Diesel Oxidation Catalyst Intake Gas Temperature 2	Aftrtrtmnt2DslOxdtnCtlystIntkGsT	A2DOC	64799	4771	deg C
Diesel Oxidation Catalyst Exhaust Gas Temperature 2	Aftrtrtmnt2DslOxdtnCtlystOutlGsT	A2DOC	64799	4772	deg C
Diesel Oxidation Catalyst Differential Pressure 2	Aftrtrtmnt2DslOxdtnCtlystDffPrss	A2DOC	64799	4773	kPa
SCR Catalyst Intake Gas Temperature 1	Aftrtrtmnt1SCRCtlystIntkGasTemp	A1SCREGT	64830	4360	deg C
SCR Catalyst Exhaust Gas Temperature 1	Aftrtrtmnt1SCRCtlysOutlGasTemp	A1SCREGT	64830	4363	deg C
SCR Exhaust Gas Differential Pressure 1	Aftrtrtmnt1SCRCtlysExhstGsDffPr	A1DCREGP	64831	4358	kPa
SCR System State 1	Aftertreatment1SCRSystemState	A1SCRDS1	61475	4332	-
SCR Diesel Exhaust Fluid Dosing Requested Quantity 1	Aftrtrtmnt1SCRRqdDsngRgntQntity	A1SCRDSR1	61476	4348	g/hr.

Data Channel Name	Data Channel Name	Acronym	PGN#	SAE SPN#	Units
SCR 1 Diesel Exhaust Fluid Average Consumption	Aftrtrtmnt1SCRAvrgCtlystRgntCnsm	SCR1	64878	3826	L/hr.
SCR Conversion Efficiency	Aftrtrtmnt1SCRCtlystCnvrsnEffcnc	SCR1	64878	4364	%
Diesel Exhaust Fluid Actual Dosing Quantity 1	Aftrtrtmnt1SCRActlDsngRgntQntty	A1SCRDSI1	61475	4331	g/hr.
Diesel Particulate Filter Differential Pressure	Aftrtrtmnt1DsPrtcltFltrDffPrss	AT1IMG	64946	3251	kPa
Diesel Particulate Filter Intermediate Gas Temperature	Aftrtrtmnt1DslPrtcltFltrInt_0001	AT1IMG	64946	3252	deg C
Engine Exhaust Gas Recirculation Temperature 1	EngExhaustGasRecirculation1Temp	ET2	65188	4750	deg C
Aftertreatment 1 Outlet NH3	Aftertreatment1OutletNH3	A1SCRAI	61477	4377	ppm
Aftertreatment 1 Outlet NOx	Aftertreatment1OutletNOx	AT1OF1	61455	3226	ppm
Aftertreatment 1 Intake NOx	Aftertreatment1IntakeNOx	AT1IG1	61454	3216	ppm

deg C degrees Celsius
g gram
h hour
kg kilogram
km kilometer
kPa kilopascal
L liter
Nm newton-meter
ppm parts per million
rpm revolution per minute

Appendix E. EVSE Data Channels

Data Channel	Frequency
Timestamp	1/5 Hz
Apparent_Power	1/5 Hz
Average_Current	1/5 Hz
Average_Line_Line_Voltage	1/5 Hz
EV_1Amps	1/5 Hz
EV_1Charger_Status	1/5 Hz
EV_1kWh	1/5 Hz
EV_2Amps	1/5 Hz
EV_2Charger_Status	1/5 Hz
EV_2kWh	1/5 Hz
EV_3Amps	1/5 Hz
EV_3Charger_Status	1/5 Hz
EV_3kWh	1/5 Hz
EV_4Amps	1/5 Hz
EV_4Charger_Status	1/5 Hz
EV_4kWh	1/5 Hz
EV_5Amps	1/5 Hz
EV_5Charger_Status	1/5 Hz
EV_5kWh	1/5 Hz
EV_6Amps	1/5 Hz
EV_6Charger_Status	1/5 Hz
EV_6kWh	1/5 Hz
EV_7Amps	1/5 Hz
EV_7Charger_Status	1/5 Hz
EV_7kWh	1/5 Hz
EV_8Amps	1/5 Hz
EV_8Charger_Status	1/5 Hz
EV_8kWh	1/5 Hz
EV_9Amps	1/5 Hz
EV_9Charger_Status	1/5 Hz
EV_9kWh	1/5 Hz
EV_10Amps	1/5 Hz
EV_10Charger_Status	1/5 Hz
EV_10kWh	1/5 Hz

Data Channel	Frequency
EV_Main_kwH	1/5 Hz
Phase_A_N_Voltage	1/5 Hz
Phase_B_N_Voltage	1/5 Hz
Phase_C_N_Voltage	1/5 Hz
Power_Factor	1/5 Hz