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Medium-Duty Plug-In Electric Delivery Truck Fleet Evaluation

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***Abstract*-In this paper, the authors present an overview of medium-duty electric vehicle (EV) operating behavior based on in-use data collected from Smith Newton electric delivery vehicles and compare their performance and operation to conventional diesel trucks operating in the same fleet. The vehicles' drive cycles and operation are analyzed and compared to demonstrate the importance of matching specific EV technologies to the appropriate operational duty cycle. The results of this analysis show that the Smith Newton EVs demonstrated a 68% reduction in energy consumption over the data reporting period compared to the conventional diesel vehicles, as well as a 46.4% reduction in carbon dioxide equivalent emissions based on the local energy generation source.**

I. INTRODUCTION

In an effort to help commercialize technologies for electric vehicles (EVs) through deployment and demonstration projects, the U.S. Department of Energy's (DOE's) National Renewable Energy Lab (NREL) in Golden, Colorado, is responsible for conducting real-world performance evaluations of advanced medium-duty and heavy-duty vehicle technologies in support of the DOE's Vehicle and Systems Simulation and Testing activities. These evaluations help manufacturers improve their design, test procedures, and ultimately their commercial success while at the same time informing fleet managers to allow them to better select appropriate energy-efficient, low-emission vehicle technologies that fit their operational goals.

II. SMITH ELECTRIC VEHICLES - SMITH NEWTON

NREL recently performed a detailed fleet evaluation project in partnership with Frito-Lay North America (FLNA) to assess and evaluate the real world performance of medium-duty electric delivery vehicles in daily fleet operation at the Frito-Lay distribution center in Federal Way, Washington. The 10 EVs evaluated for this study were all second-generation Smith Electric Newton chassis configured as Class 6 delivery vehicles as seen in Fig. 1 with 80-kWh lithium iron phosphate ($LiFePO_4$) battery packs manufactured by A123 Systems. Additional vehicle specifications are given in Table I. The 10 EVs are charged using Clipper Creek CS-100 electric vehicle supply equipment (EVSE) (Fig. 2). Each vehicle is assigned a specific parking spot, and the vehicles are plugged in to charge by the drivers at the end of each shift (Fig. 3).

Fig. 1. Smith EV charging at Federal Way, Washington, distribution center, operated by FLNA (Robert Prohaska / NREL 34462)

TABLE I
FEDERAL WAY, WASHINGTON, FLNA SMITH NEWTON SPECIFICATIONS [1, 2, 3]

Weight Class	Class 6
GVWR	9,992 kg (22,028 lbs)
Payload Capacity	4,423 kg (9,750 lbs)
Wheel Base (WB)	5.6 m (220 in.)
Overall Length	9.3 m (368 in.)
Turning Radius	14.1 m w/ 3.9 m WB (46.4 ft w/ 154 in. WB)
Charging Standards	J1772
On-board Charger Power	12 kW
Battery Manufacturer	A123 Systems
Battery Model	Nanophosphate®
Battery Chemistry	$LiFePO_4$
Battery Capacity	80 kWh
Inverter Efficiency	94%
Motor Type	Permanent magnet, liquid cooled
Motor Power: Peak | Cont.	150 kW | 80 kW
Motor Torque: Peak | Cont.	600 N-m | 400 N-m (442.5 ft-lbs | 295 ft-lbs)
Motor Efficiency	90% - 93%
Gearbox Ratio	3.4 : 1.0
Advertised Top Speed	80.4 km/h (50 mph)

Fig. 2. Clipper Creek CS-100 EVSEs used for charging Smith Newton delivery vehicles (Mike Simpson / NREL 29589)

Fig. 3. Smith Newton EV parking area at Federal Way, Washington with 10 EVSEs for recharging the vehicles (Mike Simpson / NREL 29586)

III. DATA COLLECTION AND ANALYSIS

As part of the funding requirements for an American Recovery and Reinvestment Act vehicle voucher program, NREL was responsible for summarizing data collected from all 459 participating Smith Electric vehicles nationwide for more than two years [4]. In-use data were provided by onboard telematics installed by Smith Electric, and the data were uploaded to NREL for processing and secure storage. The 10 FLNA EVs operating in Federal Way, Washington were all part of the American Recovery and Reinvestment Act voucher program, and their data were transmitted to NREL. To perform a comparative analysis on the in-use performance of the Smith EVs, NREL researchers installed nine vehicle data loggers on conventional diesel vehicles operating in the same fleet performing the same service as the EVs. For a period of 17 days, global positioning system and either SAE J1939 Controller Area Network or SAE J1708 serial data were collected from the diesel vehicles depending on their data bus messaging protocol. The class 6 diesel delivery vehicles were a mix of International and Hino models with varying degrees of age and emission certifications. Examples of these diesel vehicles can be seen in Fig. 4.

A sample route comparison between the EVs and the diesel vehicles using the collected global positioning system data is shown in Fig. 5. The red lines show the EV routes and the blue lines show the diesel routes around the Tacoma, Washington area.

Fig. 4. Diesel vehicles parked at Federal Way, Washington distribution center (Adam Ragatz / NREL)

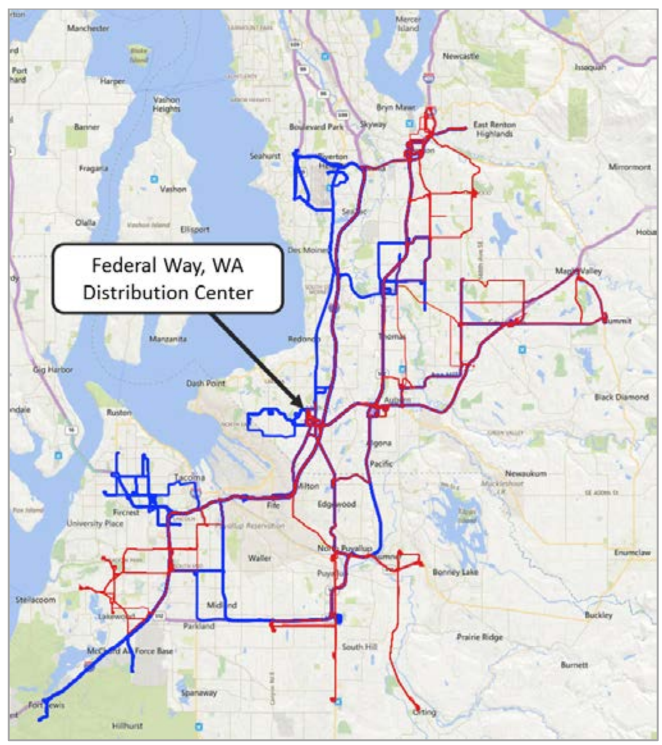

Fig. 5. Sample comparison of diesel (blue) and EV (red) routes based out of the Federal Way, Washington FLNA distribution center.

After verifying that the vehicles were being dispatched in a similar manner and in the same geographic area, their duty cycle kinematics were analyzed to confirm the two vehicle types were being operated in a comparable way. The first metrics compared were daily distance travelled and average speed. While both vehicle types operate across a range of speeds and average distances, Fig. 6 shows that there is a considerable amount of overlap between the two clusters as both vehicle types were driven similar distances with similar average speeds. In this plot, each circle represents a day of driving, and each square represents the average for a specific truck throughout the sample period. Statistically with a homoscedastic t-test assuming equal variances and an α of 0.01, we see a p-value of 6.048×10^{-5} for daily distance travelled between the two vehicle sets and a p-value of 2.261×10^{-7} for average speed, indicating at a 99% confidence level that these two data sets are not statistically different.

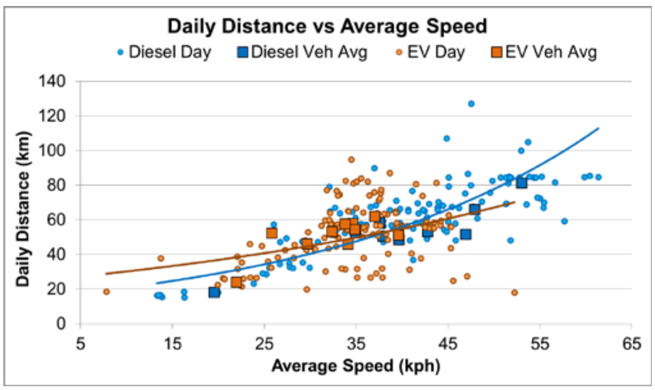

Fig. 6. Daily distance vs. average speed for Federal Way depot delivery vehicles

Daily average kinetic intensity [5], a relative measure of driving aggressiveness, represents the ratio of a drive cycle's characteristic acceleration to its aerodynamic speed, 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, have a low kinetic intensity when compared to drive cycles with more stop-and-go type driving like the HHDDT Transient cycle.

The relationship between kinetic intensity and average speed for the FLNA vehicles can be seen in Fig. 7. In addition to the field data, three standard chassis dynamometer test cycles are also shown for comparison. These standard cycles that 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.

The CARB HHDDT Composite [6] test cycle is shown below in Fig. 8 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 US 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 an 88.5-km/h highway cruise driving profile with slight variations in cruise speed. The total cycle lasts approximately 3,600 seconds, reaches a top speed of 95.4 kph, and travels a distance of 41.8 km with an average speed of 41.9 km/h and a kinetic intensity of 0.10 1/km. 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.

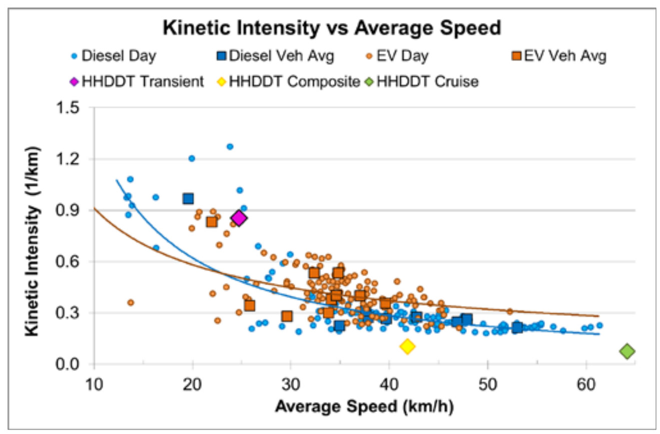

Fig. 7. Baseline route comparison using kinetic intensity vs. average speed for Federal Way depot delivery vehicles

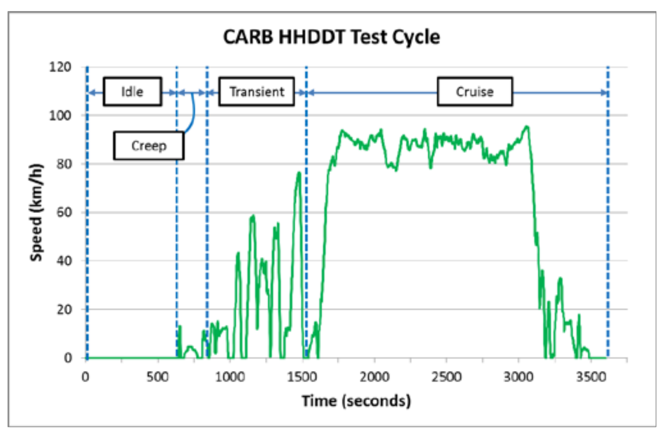

Fig. 8. CARB HHDDT test cycle

After the duty cycles were analyzed and it was determined that the two data sets were good comparisons of the similar operation with a homoscedastic t-test with α equal to 0.01 yielding a very small p-value of 2.914×10^{-5} for kinetic intensity, the overall energy efficiency was investigated. Table II shows daily average statistics for all the vehicles in this study separated by vehicle type.

TABLE II
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 (km)	61.52	20.54	52.31	16.74
Average Speed (km/h)	40.52	11.01	34.57	6.80
Average Fuel Consumed (l)	18.82	5.98	N/A	N/A
Average Energy Consumed (kWh)	187.24[a]	N/A	45.66	13.12
Energy Consumed per km (kWh/km)	3.07[a]	0.25	0.87	0.12
Average Fuel Economy (km/L_{de})	3.24	0.25	10.24[b]	1.21
Avg. Fuel Consumption (L_{de}/100 km)	30.84	2.54	9.77[b]	1.39
Average Number of Stops per day	44.25	13.74	43.28	14.47
Average Number of Stops/km	0.72	0.67	0.83	0.86
Average Kinetic Intensity (1 / km)	0.34	0.23	0.44	0.14

[a] 9.9477 kWh/L of diesel fuel
[b] Assumes 90% charger/inverter net efficiency

The distribution of the Federal Way EVs' daily average energy consumption (direct current kilowatt-hours consumed from the vehicle battery pack for every kilometer driven) can be seen in Fig.9.

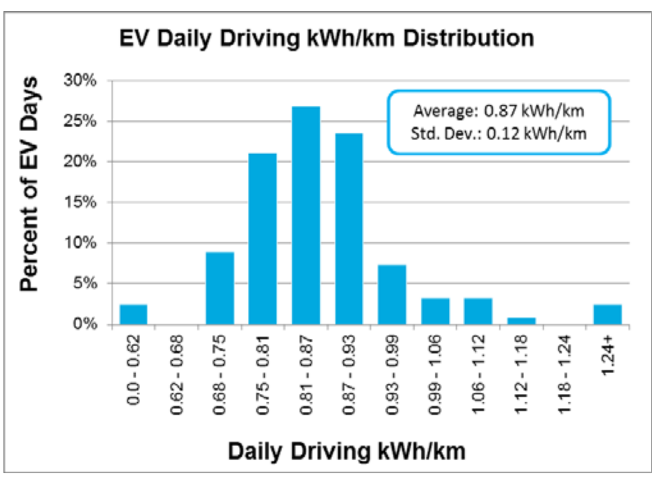

Fig. 9. Federal Way Smith Newton EV dc energy consumption per mile over the 17-day sample period

The distribution of kilowatt-hours per kilometer 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. In this study, we 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.

The EVs in operation averaged a daily energy consumption of 0.87 kWh/km, or 11.34 km per liter diesel equivalent (l_{de}) over the course of this study. When adjusted for charger and inverter efficiencies, their average equivalent diesel fuel economy was 10.24 km/l_{de}. The diesel equivalence was calculated using the Alternative Fuels Data Center [7] energy density for a gallon of low sulfur diesel fuel (35.81 MJ/l or 9.95 kWh/l of diesel). Meanwhile, the diesel vehicles operating on the same routes averaged 3.24 km/l_{de} or 3.07 kWh/km.

Fig. 10 shows the average daily fuel consumption as well as the average equivalent fuel consumption for the vehicles over the reporting period as a function of average total vehicle speed. The EVs show the lowest level of equivalent fuel consumption at an average daily speed of approximately 35 km/h while the diesels see their lowest fuel consumption at a slightly higher average daily speed. This difference is likely attributed to the regeneration capabilities of the EVs as lower average speeds typically coincide with more average stops per km thereby yielding more opportunities for regenerative braking.

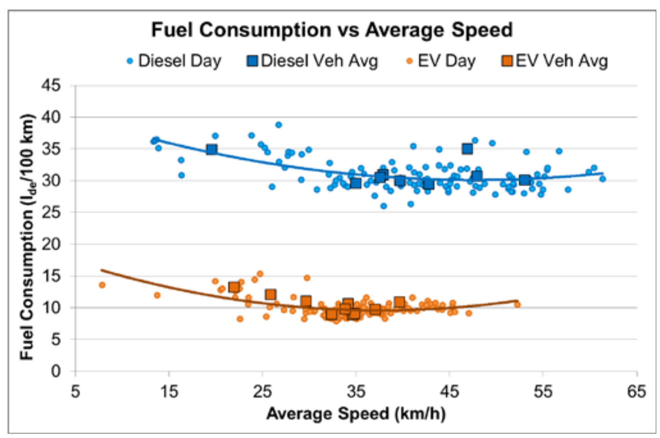

Fig. 10. Fuel Consumption vs Average Speed for Federal Way depot Diesels and EVs. EV fuel consumption shown as diesel equivalent liters per 100 km with an assumed 90% net (charger and inverter) efficiency

In a broader sense, we can look at the total energy consumed in kilowatt-hours as a function of daily distance travelled as shown in Fig. 11 and see that both vehicle types demonstrate a strong correlation between energy consumption and total distance travelled. 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 battery capacity, the more energy is saved as compared to the diesel, thereby increasing the cost benefit of electrification. 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 Fig. 12, 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. Fig. 13 shows the average savings per EV based on distance travelled and average diesel fuel price. Using the annual distance traveled of 13,660 km as a baseline, fleet operators could save on average $750 per year per vehicle with an average fuel price of $1.00/l ($3.79 per gallon) by increasing the annual distance driven of the EVs by just 25%, to 17,705 km. This increased usage would result in an average daily energy consumption of approximately 57 kWh. 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 II.

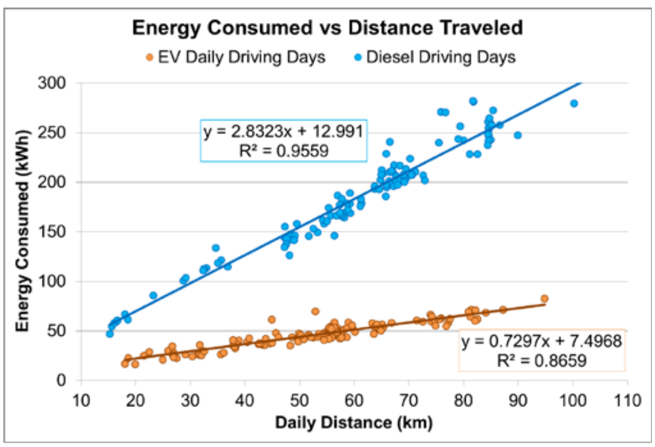

Fig. 11. Daily energy consumption as a function of daily distance travelled

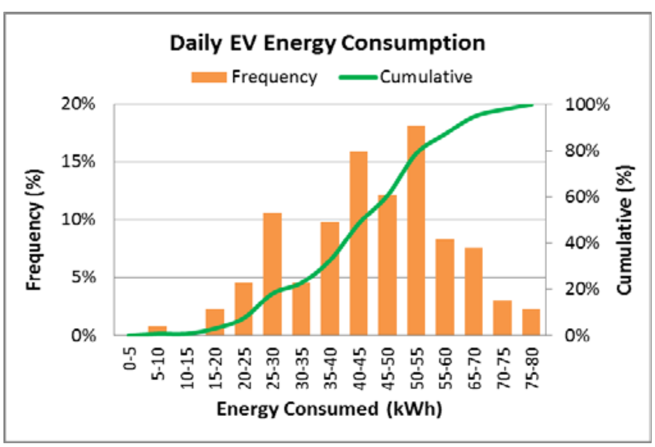

Fig. 12. Distribution of daily EV energy consumption

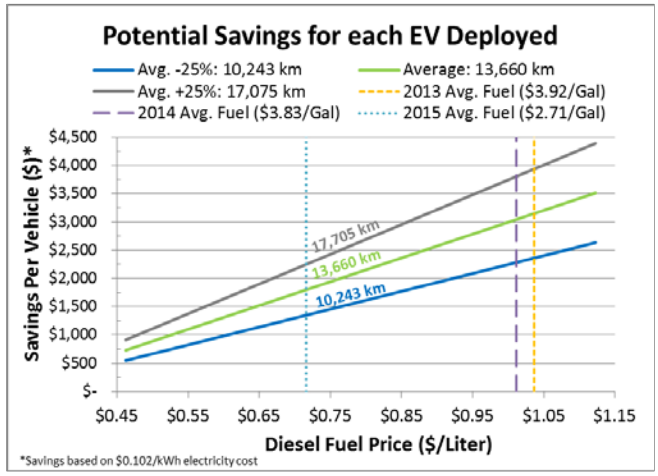

Fig. 13. Cost savings of EVs over conventional diesels based on average annual mileage and fuel price [8], assuming electricity cost of $0.102/kWh

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." When looking at the Federal Way facility, its power is supplied by Puget Sound Energy (PSE), which reported a 2014 carbon dioxide equivalent (CO_2e) emissions intensity of 450.58 g/kWh [9]. This emissions intensity includes all PSE generated and purchased power measured at the generation source (non-distributed). 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% - 8% from the power generation source to the end user's site [10]. Using the Energy Information Administration's 2013 transmission and distribution loss of 7.2% [11], 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 471.66 grams of CO_2e emissions per kilometer traveled.

Using Argonne National Lab's Greenhouse Gases, Regulated Emissions, and Energy Use in Transportation (GREET) Model's [12] 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 595.59 g CO_2e/km using the Smith EV average energy efficiency including the charger and inverter efficiency losses. We can then compare the average CO_2e emissions from the EVs to the conventional diesels using the GREET model. Using GREET's well-to-wheels analysis tool, we can calculated the CO_2e emissions of the conventional diesels operating in Federal Way. Using the national low-sulfur diesel values and the diesel vehicle energy efficiency from Table II, we see that the emissions are 879.20 g CO_2e/km. The EVs, using PSE's source distribution emit 46.4% less CO_2e emissions per kilometer travelled than the diesel vehicles. Using the national energy source distribution, the EVs emit 32.3% less CO_2e per kilometer. With an average annual distance travelled of approximately 13,660 km, each EV deployed saves approximately 5.57 metric tons per year of CO_2e emissions compared to a conventional diesel vehicle (see Fig. 14).

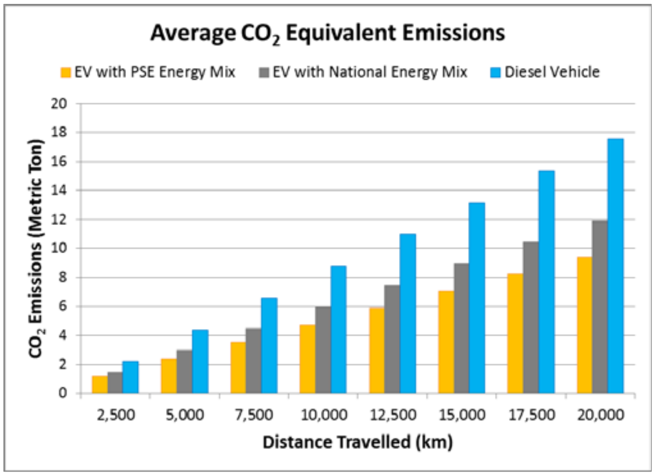

Fig. 14. Average CO_2 equivalent emissions by energy source and distance travelled based on Federal Way, Washington, duty cycle.

IV. Conclusion

As seen in this fleet evaluation of the Federal Way, Washington FLNA delivery vehicles, 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 in this paper, the route characteristics and requirements of the observed fleet made electrification a viable choice to reduce fleet fuel 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 charging infrastructure requirements as well as the time required for charging between shifts must be taken into account for a successful deployment. 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. Additional research has been conducted on this fleet deployment encompassing the on-road performance discussed in this paper, the charging infrastructure required, the facility impacts of EV adoption, and the potential benefits of integrating onsite renewable energy sources through modeling and simulation. This additional research will be presented in a comprehensive technical report to be published at a later date.

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