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Integrated Testing, Simulation and Analysis of Electric Drive Options for Medium-Duty Parcel Delivery Vehicles

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National Renewable Energy Laboratory

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Integrated Testing, Simulation and Analysis of Electric Drive Options for Medium-Duty Parcel Delivery Vehicles

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Abstract

Medium-duty vehicles consume a significant amount of petroleum and emit a large amount of greenhouse-gases. The National Renewable Energy Laboratory explored pathways to cost effectively reduce that using gasoline and diesel plug-in hybrid electric vehicles. The analysis started by verifying diesel-conventional and diesel-hybrid parcel delivery vehicle models. These plug-in hybrid variants were then run on a field-data-derived design matrix to analyze the effect of drive cycle, distance, battery replacements, battery capacity, and motor power on fuel consumption and lifetime cost. Using two scenarios representing 2011 and 2030 fuel and battery prices, plug-in hybrid lifetime costs are compared with diesel conventional lifetime costs. Under a future cost scenario of $100/kWh battery energy and $5/gal fuel, plug-in hybrids are cost effective. Assuming a current cost treatment of $700/kWh and $3/gal fuel, however, they rarely recoup the additional motor and battery cost with fuel cost savings. The results also highlight the importance of understanding the application's drive cycle, daily driving distance, and kinetic intensity. For those instances in the current cost scenario where the additional plug-in hybrid cost is regained in fuel savings, the combination of kinetic intensity and daily distance travelled does not coincide with the usage patterns observed in the field data. If the usage patterns were adjusted they could possibly become cost effective. This study did not include potential improvements from reduced brake maintenance due to regenerative braking in its cost analysis.

Keywords: Medium-duty, HEV, PHEV, simulation, drive cycles, duty cycles

1 Introduction

Medium-duty vehicles consume a significant amount of petroleum and emit a large amount of greenhouse-gases. Medium-duty vehicles are typically identified as classes 3–6 and weigh between 4,536 and 11,793 kg (10,001–26,000 lbs). Medium-duty vehicles in the parcel-delivery vocation are ideal candidates for electric drive trains because they typically share the following characteristics:

- Route predictability
- Daily drive cycles that return to a central depot, facilitating overnight charging

- Stop-and-go drive cycles that allow for the capture of energy from regenerative braking
- More focus on total cost of ownership as opposed to capital cost

2 Approach

2.1 Fuel Consumption Measurement and Model Verification

Two parcel delivery vehicles owned and operated by the United Parcel Service were transported to the National Renewable Energy Laboratory's (NREL's) Renewable Fuels and Lubricants (ReFUEL) research laboratory for fuel economy and emissions testing on the chassis dynamometer. Both the conventional and hybrid diesel vehicle used the same 149-kW engine. The hybrid-electric van was equipped with a parallel-hybrid system from the Eaton Corporation. The vehicles were tested at the ReFUEL laboratory on three cycles—the New York Composite Cycle (NYComp), the Heavy Heavy-Duty Diesel Truck (HHDDT), and the Hybrid Truck Users Forum (HTUF) 4.

The models were developed in NREL's Future Automotive System Technology Simulator (FASTSim). FASTSim uses vehicle characteristics, basic component specifications, and engine-specific efficiency data to represent a vehicle. It simulates the vehicle as it travels through a time versus speed drive cycle. The model captures key aspects including regenerative braking, energy management strategies, and auxiliary loads.

Table 1: Vehicle and component specifications

	Conventional Diesel	Diesel Hybrid
Test Weight	6,813 kg	7,303 kg
Aerodynamics		
Drag	0.7	0.7
Frontal Area	7.80 m^2	7.80 m^2
Wheels		
Rolling Resistance	0.008	0.008
Radius	0.419 m	0.419 m
Battery		
Energy	N/A	1.8 kWh
Power	N/A	Matched to Motor
Engine		
Power	149 kW	149 kW
Motor		
Peak Continuous Power	N/A	26 kW
Peak Power	N/A	44 kW
Accessory		
Power	3 kW	1.22 kW

The model matched data reasonably well. In Figure 1, the grey error bars represent 10% variability in the ReFUEL laboratory's measured results. Each model result fell within the bars. The simulated hybrid results show more variance than the conventional results, but still fall within 10% of the measured results.

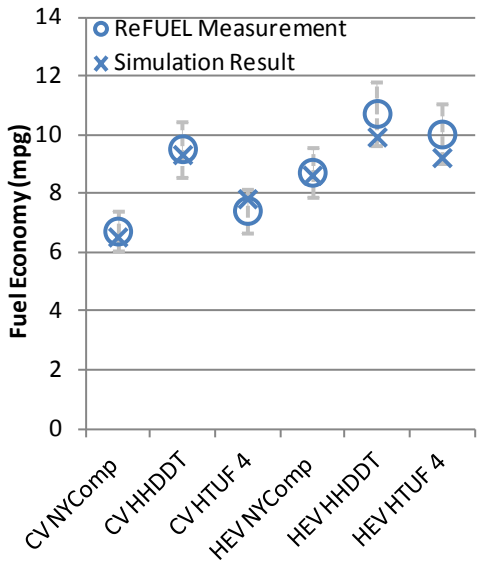

Figure 1: Model verification

The primary source of uncertainty in the hybrid model lies in the motor-efficiency map. Component data for the motor were unavailable. The model uses a motor-efficiency map from another vehicle and assumes a peak efficiency of 93%.

The engine efficiency map for the conventional model was created from ReFUEL laboratory test data and a maximum-torque curve from the engine manufacturer.

2.2 Plug-in Hybrid Model Development

The diesel conventional is used as a point of reference for the other powertrain/fuel combinations in the cost and fuel-use analyses. The diesel hybrid has the same engine as the diesel conventional. A plug-in hybrid version of the model was developed based on the hybrid-diesel template.

To make the plug-in hybrid electric vehicles (PHEV) comparable, the NREL team applied similar vehicle-specific parameters and matched the engine power to that of the diesel hybrid and conventional (149 kW). The engine power was

held constant to ensure enough power for long hill climbs. Acceleration is typically used to identify two vehicles as comparable; however, for the parcel-delivery vocation we assume that fleet managers are primarily concerned with fuel economy and improving their bottom line.

The mass of the diesel and gasoline plug-in hybrid is based on the mass of the diesel hybrid with an appropriate adjustment for the additional battery capacity. No adjustment was made for the gasoline hybrid—the diesel hybrid and gasoline hybrid were assumed to be of the same mass. Battery power was matched to motor power through motor efficiency. To be consistent with a previous study, the NREL team assumed a starting battery capacity of 2.5 kWh [1]. The plug-in hybrid model used the diesel-hybrid accessory load.

2.3 Field Data Framing the Analysis

Field data played an important role in the analysis. The NREL Fleet Test and Evaluation team is building a fleet data center of field drive cycle and performance data. A subset of this data was chosen because it was recorded using ISAAC loggers and appeared to have the best data quality of the group. It is also one of NREL's most recent projects. For this subset, over a month of drive cycle data was collected for 11 vehicles instrumented with Global-Positioning System-enabled data loggers. This field data framed the selection of the design matrix. Although several metrics, including daily distance traveled and kinetic intensity, were measured (e.g., average speed, stops/km, and accelerations/decelerations) and evaluated for consistency, of particular importance was daily vehicle distance traveled and kinetic intensity [2].

The route predictability of parcel delivery fleet vehicles makes them ideal candidates for electrification. The electric drive train can be designed to optimize cost specific to the load and daily distance traveled. A density plot of daily distance traveled illustrates where the design space (40–160 km) falls in relation to the field data collected (Figure 2). The design space envelops the daily distances traveled by these vehicles fairly well.

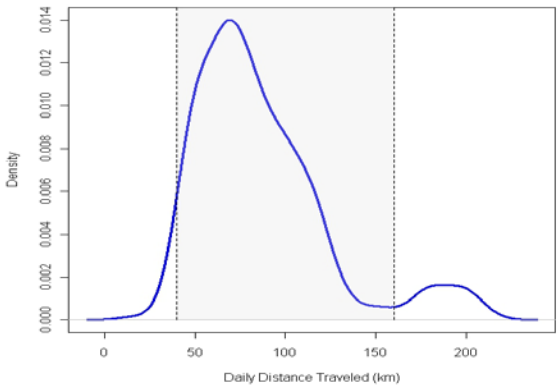

Figure 2: Comparison of daily distance traveled design space with field data

Kinetic intensity, a metric that is derived from the road-load equation for power, is linked to the magnitude and frequency of accelerations, and as such, offers insight into the cycle-specific benefits of adding an electric drive. A kernel density plot of kinetic intensity illustrates where the selected standard cycles fall in relation to the kinetic intensities measured in the field (Figure 3). The HTUF 4 drive cycle was selected as the standard drive cycle that best approximated the routes measured in the field, while the Orange County Bus (OC Bus) and Urban Dynamometer Driving Schedule Heavy-Duty (UDDS HD) cycles were selected as the upper and lower boundaries for vocational kinetic intensity. The density plot of the field data shows a bimodal distribution with the HTUF 4 cycle's kinetic intensity corresponding to the first mode/peak.

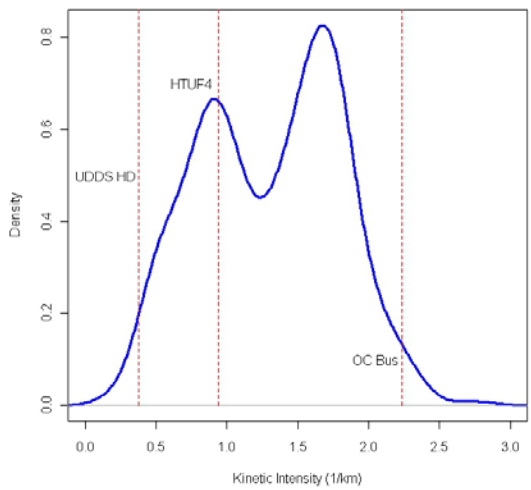

Figure 3: Comparison of kinetic intensities for field and stock drive cycles

2.4 Design and Cost Matrix

Figure 2 and Figure 3 lead to the development of the design matrix in Table 2. To ensure commercial availability of the battery, the power-to-energy ratio was set at a floor of 1.125.[1] The battery power was held constant at 30 kW unless the power-to-energy ratio fell below the 1.125 limit. If the ratio fell below this limit, the battery power was increased to compensate. A set of simulations is run at a motor power matched to the 30-kW battery power. Another set of simulations is run matching the motor power to the varied battery power.

Table 2: Design matrix for PHEVs

Drive cycles	UDDS HD, HTUF 4, OC Bus
Daily distance traveled	40, 80, 120, 160 km
Additional battery capacity	10, 20, 40, 60 kWh
Battery power	MAX (30 kW, Capacity×P/E)
Battery power-to-energy ratio	1.125[2]

Two cost scenarios were developed to represent a fair range of costs. Current and future fuel and electricity costs are yearly highs for 2011 and 2030, respectively [3]. Long-term battery cost per kilowatt-hour is cited from the United States Advanced Battery Consortium (USABC) Goals for Advanced Batteries for EVs [4]. Current battery cost per kilowatt-hour is cited from the U.S. Department of Energy [5].

Table 3: Cost matrix

Reference Key	
	USABC/DOE
	EIA

Cost/Scenario	Current	Future
Battery Cost	$700/kWh	$100/kWh
Fuel Cost		
Gas	$0.81/L ($3.08/gal)	$1.29/L ($4.90/gal)
Diesel	$0.85/L ($3.23/gal)	$1.37/L ($5.19/gal)
Electricity Cost	$0.11/kWh	$0.11/kWh

In addition to this cost matrix, a diesel engine credit was applied to the gasoline plug-in hybrid to compare it with the diesel conventional baseline. Battery replacement, lifetime electricity, and lifetime fuel use were discounted to make costs comparable in present day dollars.

[1] Smith Newton P/E ratio.
[2] Smith Newton battery

Additional assumptions are listed in Table 4. The referenced battery targets were manipulated into a form compatible with FASTSim.

Table 4: Additional assumptions

Vehicle life (years)	15
Motor and controller cost	$21.7/kW + $425
Markup factor	1.75
Discount rate	8%
Charger efficiency	0.9

2.5 Battery-Life Model and Replacements

Battery life and replacements were estimated using cycle-wear data from Johnson Controls, as shown in Figure 4. The curve labeled ―Original‖ represents data published by Johnson Controls. These data were obtained at the cell level and do not capture variations in calendar-life, temperature, or power-level on life. To help account for those impacts, the ―Today's Adjusted‖ curve was created by adjusting the ―Original‖ case to match published data for the Nissan LEAF and the Chevy Volt battery life expectations [6].

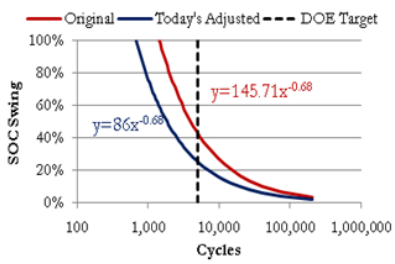

Figure 4: Battery Cycle Life Curves

By solving for the number of cycles (x) and plugging in the state-of-charge (SOC) swing (y) the model can calculate the percent wear for every charge fluctuation.

$$x = \left(\frac{86}{y}\right)^{\frac{1}{0.68}}$$

3 Results

This section presents analytical results for the specified range of vehicle configuration, usage, and economic scenarios.

3.1 Cumulative Fuel Consumption vs. Daily Vehicle Miles Traveled

The effects of battery capacity, motor power, fuel energy density, and battery replacement on fuel consumption for plug-in hybrids are illustrated in Figure 5 – Figure 8.

Effect of increasing battery capacity (Figure 5**).** Increasing battery capacity increases the distance traveled in charge depleting mode. In Figure 5 increasing color intensity corresponds to increasing battery energy. The higher the battery capacity, the greater the distance traveled in charge depleting mode.

The charge-depleting and charge-sustaining mode of vehicle operation can be identified from the fuel consumption vs. daily distance traveled plots. The vehicle starts off in charge-depleting mode, only using the engine if the battery alone cannot meet the power demand. Once the battery depletes, the upward slope indicates charge-sustaining mode. It plateaus as greater amounts of travel are done in charge sustaining mode.
An expanded matrix of daily distances traveled is plotted in the cumulative fuel consumption plots. The grayed-out portions of the plot illustrate those areas that were not included in the cost design matrix.

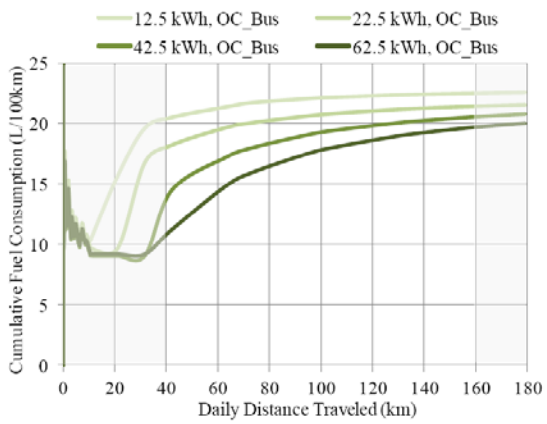

Figure 5: Effect of increasing battery capacity

Effect of increasing motor power to match battery power (Figure 6**).** Two sets of simulations were run. One set of simulations was run with a motor power matched to the 30-kW battery power. Another set of simulations was run matching the motor power to the varied battery power. A higher-power motor can provide the excess power that would have otherwise been supplied by the engine.

Increasing the motor power on the 42.5-kWh (power 47.8 kW) and 62.5-kWh (power 70.3 kW) batteries—where the battery power-to-energy ratio is fixed at 1.125—results in significantly lower fuel consumption in charge-depleting and slightly lower fuel consumption in charge-sustaining mode.

In Figure 6, Figure 7, and Figure 8 the text box corresponds to the change illustrated by the dotted lines. In Figure 6 dotted lines represent those simulations run with the motor power matched to the varied battery power while solid lines represent the motor power matched to the 30-kW battery power.

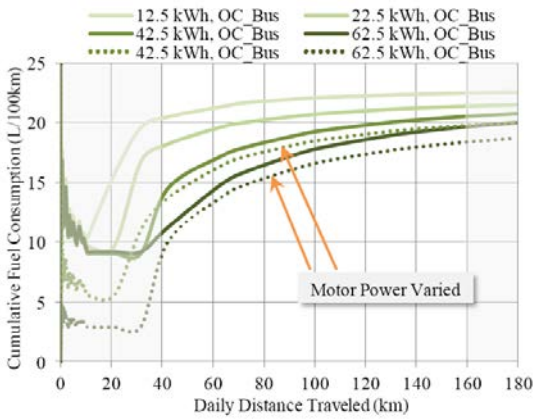

Figure 6: Effect of increasing motor power to match battery power

Effect of decreasing energy density (Figure 7**).** Dotted lines represent the gasoline-fueled plug-in hybrid while solid lines represent the diesel-fueled plug-in hybrid. The gasoline plug-in vehicle has slightly higher fuel consumption in charge-depleting mode and significantly higher fuel consumption in charge-sustaining mode.

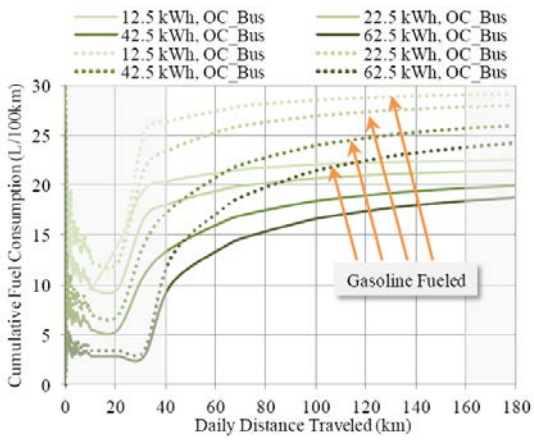

Figure 7: Effect of decreasing energy density of fuel

Effect of battery replacement (Figure 8**).** Sets of simulations were also run with and without battery replacement. Adding a battery replacement results in a larger useable capacity/SOC window—illustrated in the plots by an extension of the charge-depleting operating mode. Expanding the usable SOC window allows the powertrain to use the battery more which saves fuel and increases wear.

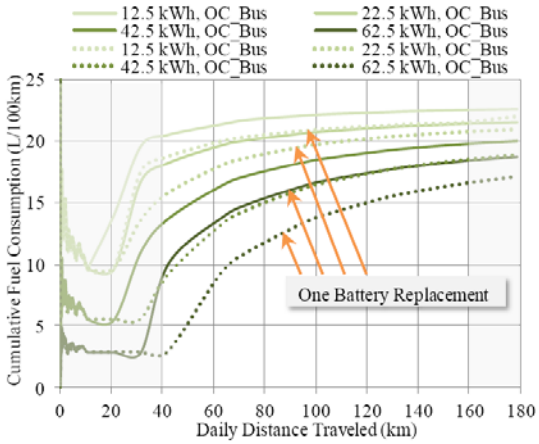

Figure 8: Effect of battery replacement

3.2 Lifetime Cost Analysis

Three different methods compare costs: a relative comparison with the baseline diesel conventional, a component-level comparison, and a fuel savings comparison. The relative comparison subtracts the cost of the baseline diesel conventional (fuel) from the cost of the plug-in hybrid version (battery and motor, fuel, and electricity). The component-level comparison charts allow for easy identification of the cost makeup in terms of traction battery and motor, liquid fuel, electricity, and replacement battery. Lastly, the fuel savings comparison enables determination of how many liters of diesel fuel were saved by the plug-in hybrid gasoline or diesel vehicle when compared to the diesel conventional as well as the amount spent or saved to save one liter of diesel fuel.

3.2.1 Vehicle Nomenclature

Column charts (Figure 10 - Figure 16**)** are organized by daily distance traveled, vehicle configuration and battery capacity, kinetic intensity of drive cycle, battery replacement, and motor power, in that order as applicable.

The labels represent the configuration. The first set of labels—UDDS HD, HTUF 4, and OC Bus—show results for the conventional diesel vehicle. The subsequent sets of labels are in order of increasing battery capacity for the plug-in hybrid configurations; i.e., UDDS HD + 10, HTUF 4 + 10, and OC Bus + 10 represent the plug-in hybrid configuration with a 12.5-kWh battery capacity.

It should be noted that the +40 and +60 kWh scenarios resulted in a battery power-to-energy ratio of less than 1.125. For these cases the battery power was increased and two sets of motor power simulations were run: one with a motor power matched to the original 30-kW battery power and another with the motor power matched to the varied battery power. In the column charts this is shown in two instances of each cycle. The first instance corresponds to the constant-power scenario while the second corresponds to the varied motor power scenario.

3.2.2 When Are Plug-In Hybrids Cost Effective?

Figure 10 - Figure 13 represent the difference between the plug-in hybrid lifetime cost and the diesel conventional lifetime cost. The plug-in hybrid lifetime cost is composed of upfront battery and motor costs, liquid fuel cost, electricity cost, and a battery replacement cost as applicable. The diesel conventional lifetime cost is composed of the cost of liquid fuel. A positive value indicates that the plug-in hybrid is more expensive.

Assuming $700/kWh battery costs and $3/gal fuel costs, there were very few usage patterns in which the plug-in hybrid paid off. Several observations can be made from these graphs. For each battery capacity the cycle with the highest kinetic intensity paid off first. Figure 10 and Figure 11 show the scenarios that paid off for the plug-in hybrid diesel, with and without replacements. For most battery sizes, the costs were not recouped with current-scenario cost assumptions. There were a few cases, however, where the plug-in hybrid costs were recouped. When a vehicle exceeded 160 km/day the 12.5-kWh battery paid back on all cycles. For those vehicles that travel distances greater than 160 km/day (Figure 2) on a cycle with high kinetic intensity, there is a potential for $10,000 in savings. In general, the higher motor power was advantageous on those usage scenarios that exceeded 80 km daily distance traveled and ran on drive cycles of higher kinetic intensity (i.e., HTUF 4 and OC Bus). The higher motor power

was not advantageous in the columns marked with an "X."

Figure 9 focuses on the cost effectiveness of a 12.5-kWh diesel plug-in hybrid with no battery replacement under the current cost scenario. Under the current cost scenario of $700/kWh and $3/gal fuel, diesel plug-in hybrids seldom recoup the additional motor and battery cost. In those instances where the additional cost is regained in fuel savings (the region of the figure marked with a transparent white overlay), the kinetic intensity and daily distance traveled do not coincide with the usage patterns observed in the field data. If the usage patterns were adjusted, there is a potential for the plug-in hybrids to become cost effective.

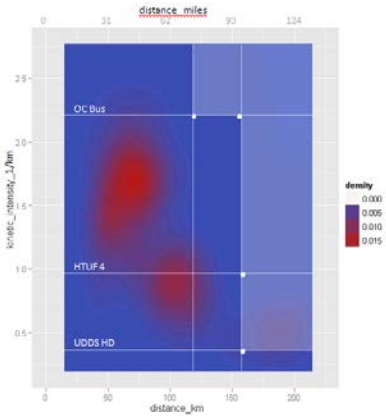

Figure 9: Usage patterns and cost effectiveness of a 12.5 kWh diesel plug-in hybrid with no battery replacement under the current cost treatment

The gasoline plug-in hybrid vehicle did not pay off with or without battery replacements in the current scenario.

Figure 12 and Figure 13 show the cases that paid off for the plug-in hybrid diesel, with and without replacements, in the future scenario. All were cost effective except the 62.5 kWh battery case with the lower motor power and battery replacement when going 40 km per day on the least kinetically intense cycle.

3.2.3 Cost Breakdown

A stacked column chart aids in understanding how these costs add up. In the stacked column charts, battery replacements are easily identifiable by the battery replacement cost. Figure 14 illustrates the cost breakdown for the diesel plug-in hybrid vehicle operated 160 km/day under the current scenario. It agrees with the results in Figure 10 and Figure 11. For the 12.5-kWh battery, all the scenarios without a battery replacement paid back (relative to the lifetime fuel cost for the conventional vehicle over the corresponding cycle). For scenarios with a battery replacement, only the OC Bus paid back.

3.2.4 Cost Effectiveness

One of the benefits of adding an electric drive train is fuel savings. In Figure 15 and Figure 16, fuel savings and cost effectiveness are plotted for the above scenarios. The scenarios where the PHEV was less expensive than the diesel conventional are identified by a negative cost per liter saved. As expected, the longer the distance traveled, the greater the fuel savings and the lower the cost per liter saved.

4 Conclusion

This study evaluated a gasoline and a diesel plug-in hybrid vehicle to determine when a plug-in is a good value in comparison to a conventional diesel parcel delivery vehicle. The future scenario shows that plug-in hybrids become cost effective when battery costs meet USABC's long-term goals for advanced batteries for electric vehicles ($100/kWh) and fuel reaches $5/gal. Under the current cost scenario with an assumption of $700/kWh battery energy and $3/gal fuel, PHEVs are generally not cost effective.

This study also evaluated battery replacements and higher motor power in terms of cost. Replacing the battery was not cost effective unless battery costs go down. A higher motor power was cost effective in those scenarios that included a battery replacement, or in those cases with no replacement where the drive cycle was kinetically intense and traveled enough miles to recoup the extra cost through hybridization fuel savings (from regenerative braking, etc.).

The results show that kinetic intensity and distance traveled are important considerations when trying to evaluate if a plug-in hybrid vehicle is a good investment. Under the current scenario with no battery replacement, the plug-in hybrids that were cost effective traveled distances exceeding 160 km per day to pay off the additional 12.5-kWh battery cost on the UDDS HD, HTUF 4, and OC Bus cycles. For these simulations, the cost savings is greatest on the most kinetically intense cycle, the OC Bus cycle.

There are several possible directions for future work. They include evaluating the threshold of where PHEVs become cost effective, incorporating thermal and calendar battery wear into the model, and evaluating total cost of ownership. This study does not include a hybrid discount for brake maintenance costs. The Fleet Testing and Evaluation Team observed roughly a doubling of brake life on most fleets. These modifications could change the results of this study.

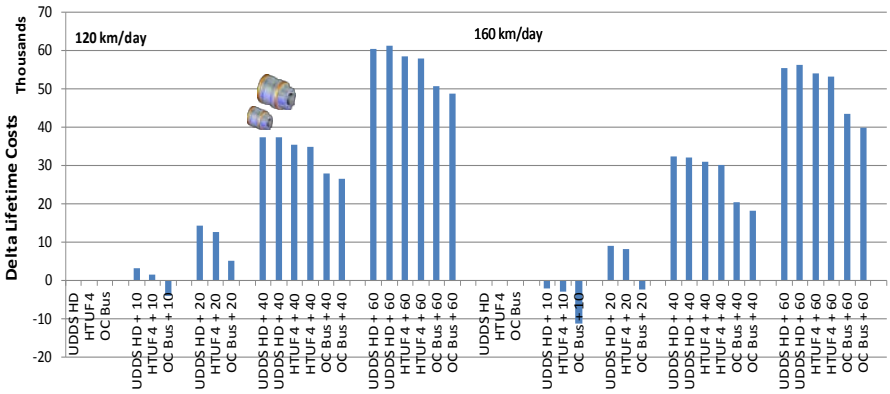

Figure 10: Current scenario, no replacement, diesel PHEV

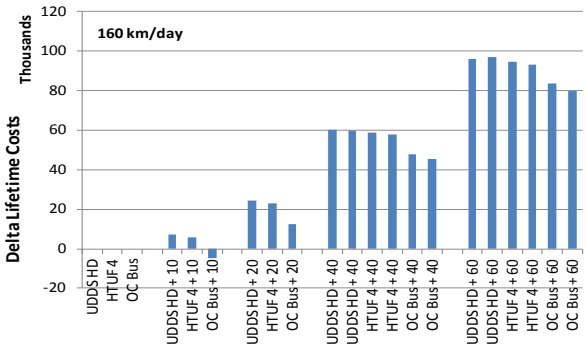

Figure 11: Current scenario, replacement, diesel PHEV

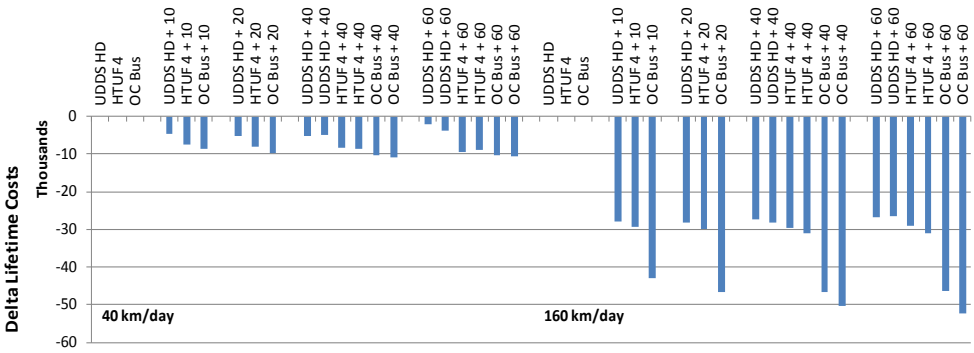

Figure 12: Diesel PHEV, future scenario, no replacement

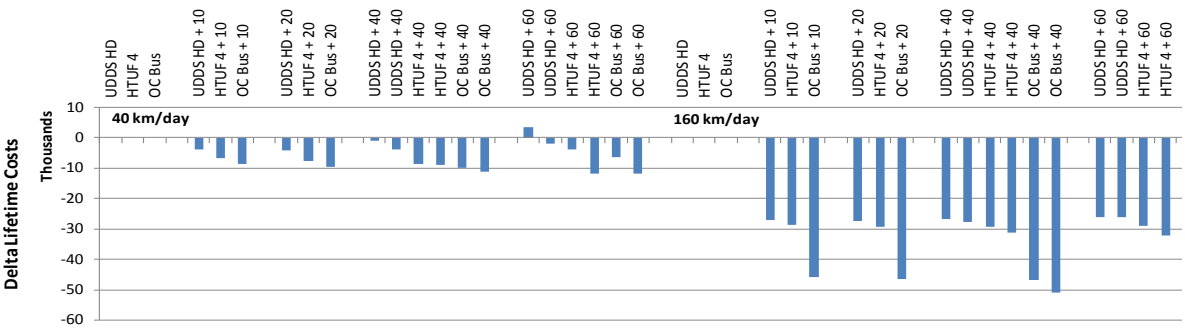

Figure 13: Diesel PHEV, future scenario, replacement

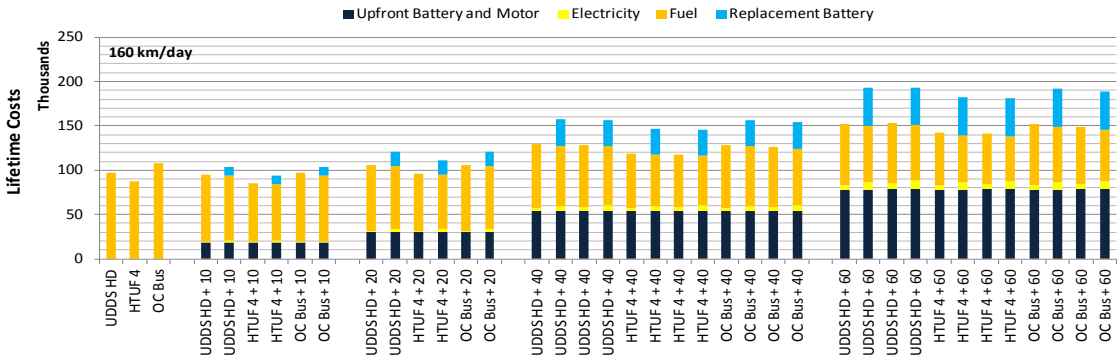

Figure 14: Diesel PHEV, current scenario

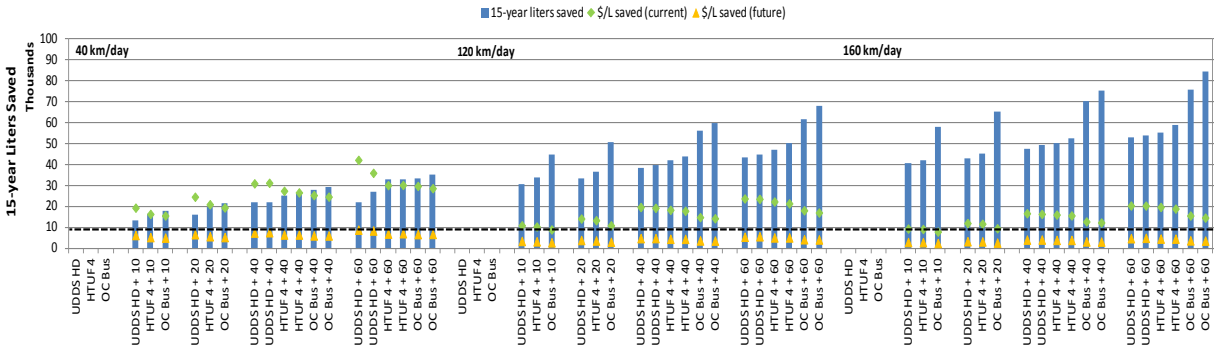

Figure 15: Diesel PHEV, no replacement

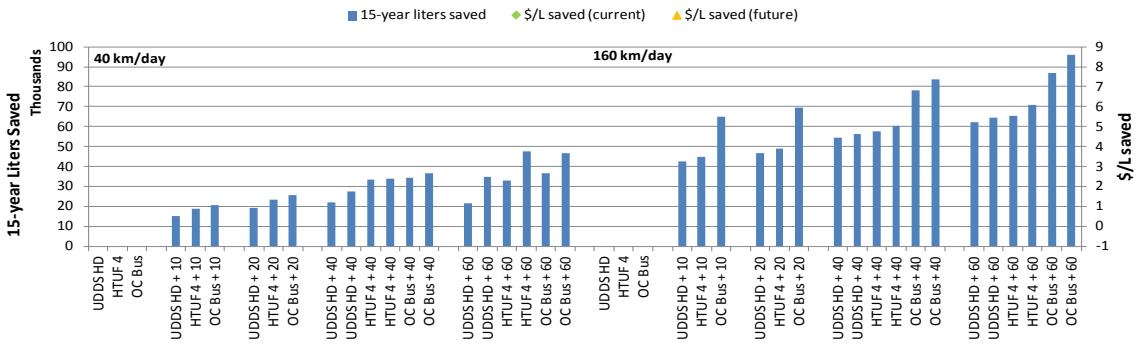

Figure 16: Diesel PHEV, replacement

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