



Model-Based Analysis of Electric Drive Options for Medium-Duty Parcel Delivery Vehicles

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Abstract—Medium-duty vehicles are used in a broad array of fleet applications, including parcel delivery. These vehicles are excellent candidates for electric drive applications due to their transient-intensive duty cycles, operation in densely populated areas, and relatively high fuel consumption and emissions. The National Renewable Energy Laboratory (NREL) conducted a robust assessment of parcel delivery routes and completed a model-based techno-economic analysis of hybrid electric vehicle (HEV) and plug-in hybrid electric vehicle (PHEV) configurations. First, NREL characterized parcel delivery vehicle usage patterns, most notably daily distance driven and drive-cycle intensity. Second, drive-cycle analysis results framed the selection of drive cycles used to test a parcel delivery HEV on a chassis dynamometer. Next, measured fuel consumption results were used to validate simulated fuel consumption values derived from a dynamic model of the parcel delivery vehicle. Finally, NREL swept a matrix of 120 component size, usage, and cost combinations to assess impacts on fuel consumption and vehicle cost. The results illustrated the dependency of component sizing on drive-cycle intensity and daily distance driven and may allow parcel delivery fleets to match the most appropriate electric drive vehicle (EDV) to their fleet usage profile.

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

1. Introduction

Medium-duty vehicles are typically represented by classes 3 – 6, with a gross vehicle weight range of 10,000 to 26,000 pounds. There has been considerable research on PHEV technology in the light-duty vehicle segment, which, due to its large volume of fuel consumed and well-matched user driving behaviors, makes it an excellent application for PHEV technology. While heavy-duty vehicles are also large fuel consumers, they typically do not exhibit drive cycles that render them appropriate (prohibitively long and/or insufficient transients) for PHEV application. Although it has received less scrutiny for PHEV application, the medium-duty vehicle segment is well suited for the following reasons:

- Drive cycles are transient intensive, for which EDVs equipped with regenerative braking capability are well matched.
- Fleet-based vehicles return to a home base, facilitating overnight charging.
- The potential for significant fuel savings per vehicle multiplies across an entire fleet.
- Plausibly attractive value proposition due to potential for reduced maintenance costs, longer period of vehicle ownership (to realize reduced fuel consumption benefits), and the increasing value of a green corporate image.

2. Approach

This section describes the approach to vehicle and drive cycle selection, model development and validation, battery life calculation, and economic scenarios.

2.1. Drive-Cycle Data Collection and Analysis

Leveraging concurrent U.S. Department of Energy-sponsored parcel delivery fleet evaluation activities with FedEx and UPS, 15 field vehicles were instrumented with

global positioning system-enabled data loggers, and 92 days of spatial speed-time data were collected. These data were used to confirm daily route consistency and to characterize each route according to 58 drive-cycle metrics, including daily distance traveled and kinetic intensity. Kinetic intensity [1], a metric that is derived from the vehicle road load equation, is linked to the magnitude and frequency of accelerations, and, as such, offers insight into the cycle-specific benefits of adding an electric drive.

Although several drive cycle metrics (e.g., average speed, stops/km, and acceleration/decelerations) were used to compare standard drive cycles to those measured in the field, kinetic intensity was the primary comparison metric that framed chassis dynamometer test cycle selection and vehicle simulation activities. The Orange County Bus (OC Bus) cycle was selected as the standard drive cycle that best approximated the routes measured in the field, while the NYCC and HTUF4 cycles were selected as the upper and lower boundaries for vocational kinetic intensity. The kinetic intensity of cataloged stock drive cycles, the average of those measured in the field, and the test cycles selected are presented in Figure 1.

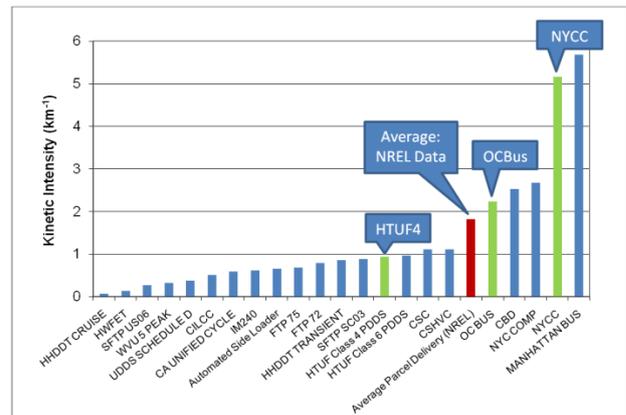


Figure 1: Drive Cycle Kinetic Intensities

2.2. Fuel Consumption Measurement

A parcel delivery charge-sustaining (CS) gasoline hybrid electric vehicle (gHEV) owned and operated by FedEx was transported from California to NREL’s Renewable Fuels and Lubricants (ReFUEL) Research Laboratory chassis dynamometer for emissions and fuel consumption measurement. Fuel consumption values measured over three drive cycles are presented in Table 1 [2].

Table 1: gHEV Measured Fuel Consumption (Photo credit: Robb Barnitt, NREL)

Drive Cycle	HEV Fuel Consumption (liter / 100km)
HTUF4	22.5
OC Bus	27.3
NYCC	34.9

2.3. Vehicle Model Development and Validation

A model of the FedEx gHEV was developed with assistance from industry partners FedEx and Azure Dynamics. The vehicle model uses vehicle and component specifications to predict fuel consumption on a given cycle. The essential parameters are shown in Table 2.

Table 2: Defining Vehicle-Model Parameters

Parameter	FedEx gHEV
C_d	0.7
Frontal area (m ²)	7.02
Vehicle mass (kg)	4,472
Engine power (kW)	182
Motor power (kW)	100
Battery power (kW)	60
Battery capacity (kWh)	2.5

The model was validated on three drive cycles: the HTUF4, the OC Bus, and the NYCC. The simulated results fell within 10% of the fuel consumption measured on the ReFUEL chassis dynamometer.

Table 3: Model Validation

Drive Cycle	Fuel Consumption (L/100km) Measured	Fuel Consumption (L/100km) Simulated	Error
HTUF 4	22.5	24.5	8.9%
OC Bus	27.3	27.4	0.4%
NYCC	34.9	35.2	0.9%

2.4. Battery Life Model

Battery life was estimated using data from Johnson Controls [3], as shown in Figure 2. The trip distance, battery discharge efficiency, and allowable state of charge (SOC) window was used to estimate the charge-depleting (CD) wear per mile. The wear per mile due to accelerating and braking was based on assumed speed versus time-drive profiles input into vehicle simulations, which was then added to calculate the total wear per mile. The usable SOC was modified until the battery life model predicted that it would last the specified 15 years.

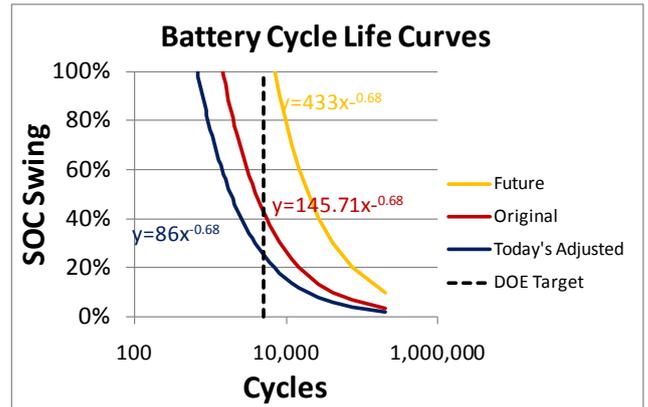


Figure 2: Battery cycle life curves

2.5. Simulation Scenarios

NREL exercised the model by sweeping a matrix of 120 component size, usage, and cost combinations (Table 4 and Table 5) to assess fuel consumption and vehicle cost trade-offs. The effects of increased battery and component mass on fuel consumption, as well as battery wear, are captured and accounted for in the model. Additional assumptions are listed in Table 6.

Table 4: PHEV Analysis Matrix – Drive-Cycle and Component Specifications

Drive cycles	HTUF4, OC Bus, NYCC
Control strategies	All-Electric Range (AER) CD-battery dominant
Daily distance traveled	40, 80, 120, 160 km
Additional battery capacity	20, 40, 60, 80 kWh
Battery power	30, 60 kW

Table 5: PHEV Analysis Matrix - Cost Inputs

Scenario	ESS cost	Fuel cost	Electricity cost
Current	\$700/kWh	\$0.79/L	0.12 \$/kWh
Midterm	\$300/kWh	\$1.32/L	0.12 \$/kWh

Table 6: Additional Assumptions

Vehicle life (years)	15
Battery cost	\$22/kWh + scenario \$/kWh + \$680
Motor and controller cost	\$21.7/kWh + \$425
Markup Factor	1.75
Discount rate	8%
Charger Efficiency	0.9

3. Results

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

3.1 Fuel Consumption

The relationship between fuel consumption and daily distance driven is illustrated in Figure 3 (30-kW case) and Figure 4 (60-kW case).

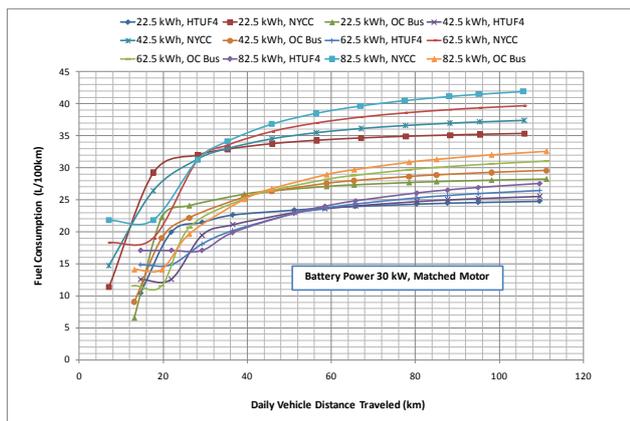


Figure 3: Fuel consumption by daily distance traveled (30 kW)

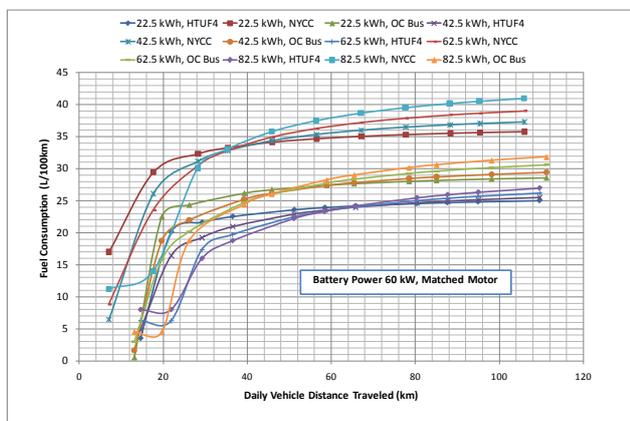


Figure 4: Fuel consumption by daily distance traveled (60 kW)

Several observations can be made for each figure. First, fuel consumption typically begins low while battery energy is available, then trends upward to a plateau, indicating battery depletion and initiation of CS mode. Second, more kinetically intense cycles with higher power demands begin at a higher fuel consumption and reach CS mode within a shorter distance traveled than do less kinetically intense cycles. Third, due to increasing mass with increasing battery capacity, fuel consumption begins higher but CD mode is possible for a longer distance than for a lower-energy capacity.

While the trends for 30-kW and 60-kW battery and motor power are similar in shape, fuel consumption is lower at the same daily distance traveled for the 60-kW case. While the 60-kW motor has a higher mass than the 30 kW motor, its higher power (and matched battery power) allows for greater utilization of battery power, increased capture of regenerative braking energy, and less reliance upon liquid fuel to meet the drive-cycle power requirements.

These results illustrate the importance of understanding both drive-cycle intensity and daily distance traveled in designing, selecting, and deploying the most appropriate technology for a given route.

3.2 Energy Storage System (ESS) Mass and Cost

The relationship between ESS mass and costs (manufacturing and with mark-up) is illustrated in Figure 5. Only the 30-kW scenario is shown as the trend shapes are identical and the mass offset (with the 60-kW scenario) is about 100 kg, and the cost offset (with the 60 kW scenario) is about \$1,000.

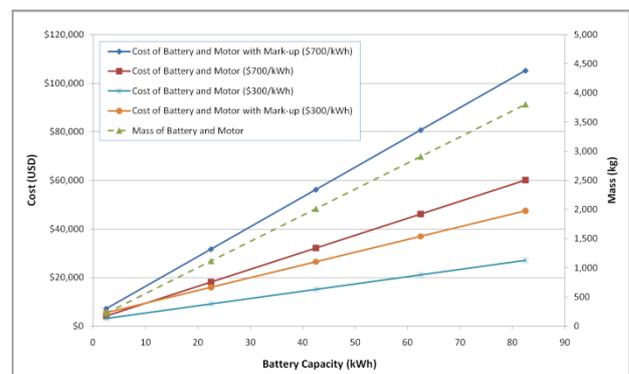


Figure 5: Battery capacity mass and costs

Battery mass and cost increase linearly with capacity. As expected, the cost of a high-capacity battery varies significantly between the two economic scenarios (\$700/kWh and \$300/kWh).

3.3 Lifetime Operating Costs

From the perspective of a fleet manager contemplating the purchase of parcel delivery EDVs, the lifetime cost of operation is the best comparative metric. Currently, parcel delivery vehicles are replaced every 15 years. Thus, in this analysis, the lifetime cost of operation refers to the 15-year cost of liquid fuel, electricity, additional battery

capacity, and electric machine size. For each configuration, the lifetime cost of operation was calculated using current and future economic scenarios. The capital cost of the vehicle is not included, as this cost is negotiated between a seller and buyer and is subject to many more variables than can be captured in broad current and future pricing scenarios. The results presented below compare the lifetime operating cost of the vehicle configurations using the usage and economic scenarios summarized in section 2.5.

3.3.1 Vehicle Nomenclature

For each drive cycle and daily distance traveled, the battery is sized and controlled to last 15 years. Simulation results indicate that, depending upon drive cycle and daily distance traveled, the CS gHEV with a 2.45-kWh battery capacity may not last 15 years. Thus, the additional battery capacity required for each usage scenario was added, and a new baseline CS gHEV constructed. This new baseline CS gHEV with battery sized for life (BSfL) is referenced as such in subsequent figures. Using the gHEV BSfL reference configuration, a CD control strategy was applied without adding battery capacity (PHEV+0 kWh). This vehicle configuration has the potential to decrease liquid fuel consumption without adding motor and battery costs. However, this configuration was unable to meet the 15-year life with any useful electric range in all drive cycle and daily distance traveled scenarios. Additional PHEV configurations were simulated with additional battery capacity in increments of 20 kWh (PHEV+20kWh, PHEV+40kWh, PHEV+60kWh and PHEV+80kWh).

3.3.2 Motor and Battery Power Levels

As shown in Table 4, two motor and battery power levels (30 and 60 kW) were evaluated. In every scenario, the 60-kW motor and battery have slightly higher capital cost and mass than the 30-kW motor and battery. Depending upon drive-cycle intensity and daily distance traveled, the 60-kW motor and battery is better equipped to power the vehicle using electricity rather than liquid fuel. In some cases, the avoided liquid fuel cost exceeds the higher power cost, resulting in a more cost-effective configuration. In most cases, the daily distance traveled was long enough that all the battery energy was used at both power levels, so similar amounts of liquid fuel were displaced. However, in scenarios with short daily distances and large battery capacity, the lower power levels were not capable of using all the available battery energy before the end of the cycle and thus used more high cost liquid fuel. While the additional power was cost effective for these high battery energy cases, the high cost of battery energy made both power levels less cost-effective than lower energy cases.

3.3.3 Control Strategies

As shown in Table 4, two control strategies (AER and CD battery dominant) were evaluated. The differences between the two cases are motor and battery power. The

AER case uses a higher power 60-kW battery and motor compared to the 30-kW CD battery dominant case. Both use the battery as much as possible during CD mode. The high-power case, however, can provide the full load and prevent the engine from coming on more often. For the simulated drive cycles, the power difference did not have a big impact because most of the time, especially for the less intense HTUF4 and OC Bus cycles, the power level did not exceed 30 kW, and when it did, the battery was still providing a significant portion of the power. The high-power cases also captured more regenerative braking, but in most cases the added power cost more than it saved. The total end cost difference was small, so for each scenario only the most cost-effective one is included.

3.3.4 Lifetime Incremental Fuel and ESS Costs

Lifetime incremental fuel and ESS costs for 40 km driven per day are presented in Figure 6 (current economic scenario) and Figure 7 (future economic scenario). The results for each configuration (gHEV BSfL, PHEV+0kWh, PHEV+20kWh, etc.) are clustered in groups of three. Each column represents the results for each of three drive cycles, consistently presented from left to right: HTUF4, OC Bus, and NYCC. Motor and battery power are referenced in parentheses on the x axis. The gHEV BSfL required additional battery capacities of 0, 0.1, and 0.4 kWh for 15-year life at 40 km/day of HTUF4, OC Bus, and NYCC, respectively. Using these same gHEV BSfL battery capacities, the PHEV+0kWh configuration was simulated. This configuration was only capable of lasting 15 years if driven on the least intense cycle (HTUF4); more intense cycles (OC Bus and NYCC) cycled the battery sufficiently to prevent realization of a 15 year life. While 30- and 60-kW motor and battery power levels were simulated, only the most cost effective is presented. In the 40-km/day scenario, the gHEV BSfL lifetime cost is lowest with a 60-kW power. However, in many PHEV configurations, the 30-kW power results in the lowest lifetime cost; the differences ranged from tens to thousands of dollars.

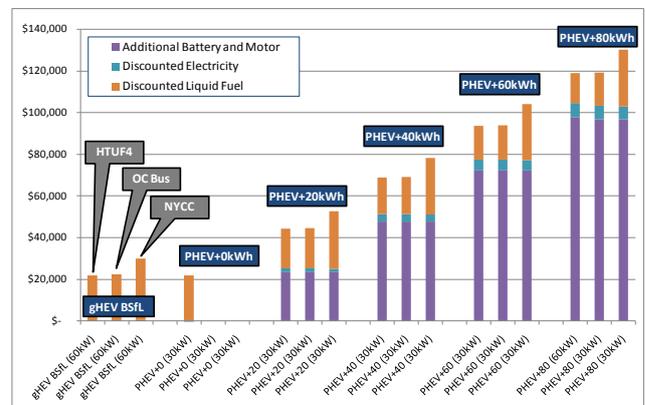


Figure 6: 40 km per day, current economic scenario

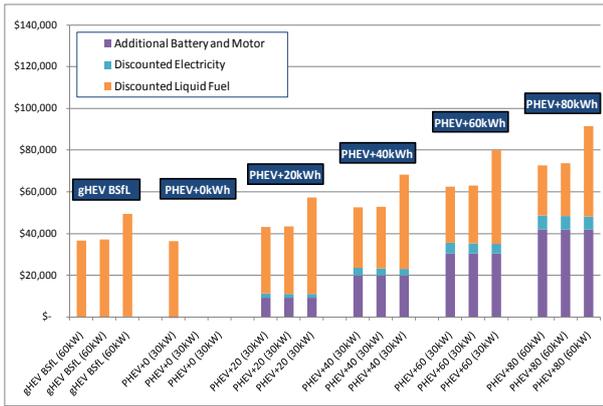


Figure 7: 40 km/day, future economic scenario

For the relatively small daily distance (40 km/day) usage scenario, the PHEV+0kWh (30-kW) configuration is feasible, and at slightly lower cost than the comparable gHEV BSfL (60 kW) configuration. This is driven primarily by the lower motor and battery costs (\$1,219 less), as well as by lower fuel costs (\$162 and \$269 less for the current and future scenarios, respectively).

Lifetime fuel and incremental ESS costs for 80 km driven per day are presented in Figure 8 (current economic scenario) and Figure 9 (future economic scenario). As in Figures 6 and 7, the results for each configuration (gHEV BSfL, PHEV+20kWh, PHEV+40kWh, etc.) are clustered in groups of three. Each column represents results for each of three drive cycles, consistently presented from left to right: HTUF4, OC Bus, and NYCC. Motor and battery power are referenced in parentheses on the x axis. The gHEV BSfL required additional battery capacities of 0.5, 1.6, and 2.1 kWh for a 15-year life at 80 km/day for the HTUF4, OC Bus, and NYCC, respectively. At this longer daily distance traveled, the PHEV+0kWh configuration was not feasible in that it could not last 15 years.

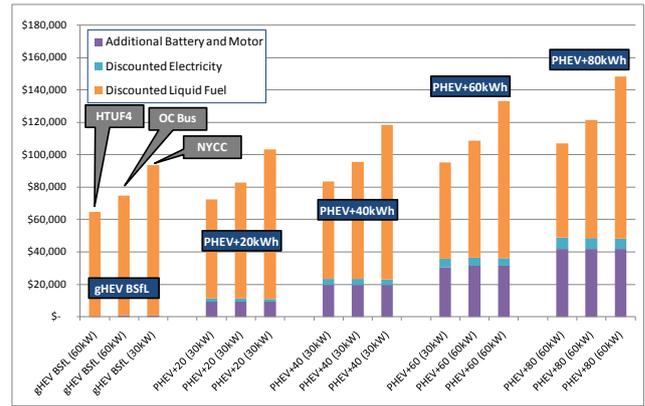


Figure 9: 80 km/day, future economic scenario

3.3.5 Delta Lifetime Costs

The most intuitive way to compare PHEV configurations to the gHEV BSfL baseline configuration is by delta lifetime cost. The lifetime cost for the gHEV BSfL configuration simulated for each drive cycle, motor and battery power level, and daily distance traveled was subtracted from the lifetime cost for each comparative PHEV configuration. This metric of comparison can aid fleet managers in understanding the lifetime cost implications of purchasing a particular PHEV configuration and balance that value against available purchase incentives, tax rebates, or other “green” strategic value propositions. The delta lifetime cost values are presented in Figure 10 (current economic scenario) and Figure 11 (future economic scenario). Individual columns represent daily distance traveled for a given configuration. The four configurations (PHEV+20kWh, PHEV+40kWh, PHEV+60kWh, and PHEV+80kWh) are clustered and separated by spaces. As indicated by the callouts over the PHEV+20kWh group, every two sequential columns represent results for each of three drive cycles, consistently presented from left to right: HTUF4, OC Bus, and NYCC. Motor and battery power are referenced in parentheses on the x axis.

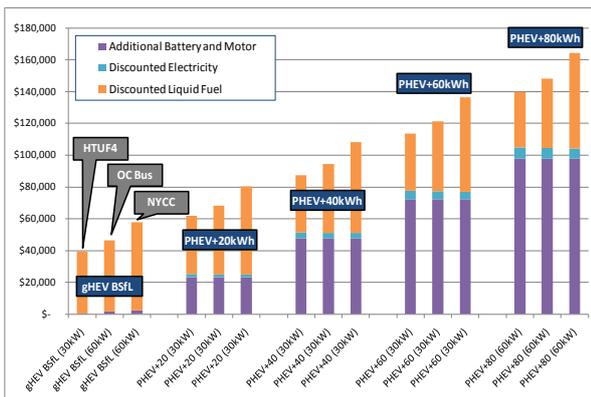


Figure 8: 80 km per day, current economic scenario

The trends for 120 km/day and 160/day usage scenarios are similar to those presented above, but are more pronounced. In general, lifetime costs increase with battery size. However, in the future economic scenario (high liquid fuel cost and lower battery cost), the lifetime cost difference between the gHEV BSfL and PHEV configurations decreases.

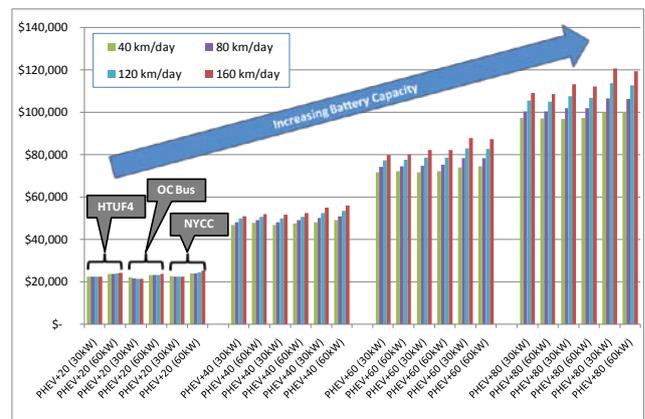


Figure 10: Delta lifetime costs, current economic scenario

Under the current economic scenario, the most cost-effective vehicle configuration is the PHEV+20kWh, with an incremental lifetime cost of over \$20,000. Incremental costs vary according to drive cycle and daily distance traveled.

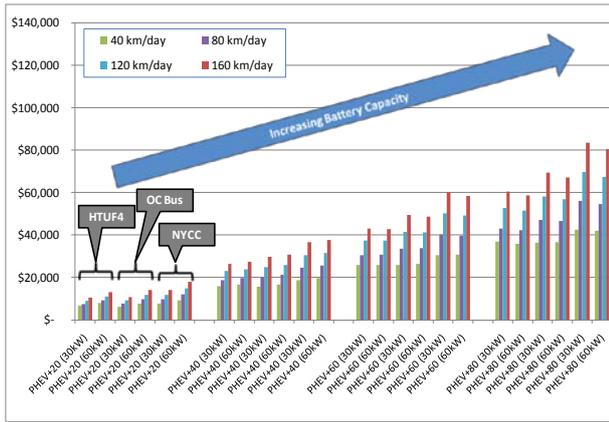


Figure 11: Delta lifetime costs, future economic scenario

Under the future economic scenario, the incremental lifetime cost of the PHEV+20kWh configuration ranges from \$6,154 to \$17,927, depending upon drive cycle and daily distance traveled (Table 7).

Table 7: PHEV+20kWh Incremental Lifetime Costs, future economic scenario

Vehicle	Drive Cycle	40 km/day	80 km/day	120 km/day	160 km/day
PHEV+20 (30kW)	HTUF4	\$6,568	\$7,525	\$9,018	\$10,473
PHEV+20 (60kW)	HTUF4	\$7,944	\$9,247	\$11,150	\$13,029
PHEV+20 (30kW)	OC Bus	\$6,154	\$7,600	\$9,200	\$10,854
PHEV+20 (60kW)	OC Bus	\$7,661	\$9,719	\$11,880	\$14,149
PHEV+20 (30kW)	NYCC	\$7,620	\$9,678	\$11,838	\$14,049
PHEV+20 (60kW)	NYCC	\$9,311	\$12,040	\$14,924	\$17,927

As evidenced in Table 7, large lifetime incremental cost differences are possible, depending upon drive cycle and daily distance traveled. With a relatively small battery capacity, longer daily distances can deplete the battery, thus requiring the vehicle to use more expensive liquid fuel.

3.3.6 Lifetime Liquid Fuel Displacement

For some fleets, lifetime operating cost may not be the only factor influencing the purchase of PHEVs. Lifetime liquid fuel reductions and subsequent reductions in tailpipe emissions may also figure into the purchase decision. The volume of liquid fuel saved over a 15-year vehicle lifetime was calculated. In addition, the cost per liter (\$/L) was calculated for current and future economic scenarios. This \$/L metric is calculated by dividing the delta lifetime cost for each vehicle configuration (gHEV BSfL is the reference) by the lifetime liquid fuel volume saved.

Figure 12 presents these results for the 40 km/day case. Individual columns represent lifetime liquid fuel saved for a given configuration. The five configurations (PHEV+0kWh, PHEV+20kWh, PHEV+40kWh, PHEV+60kWh, and PHEV+80kWh) are clustered and separated by spaces. As indicated by the callouts over the PHEV+20kWh group, each sequential column represents

results for each of three drive cycles, presented from left to right: HTUF4, OC Bus, and NYCC. The motor and battery power resulting in the largest liquid fuel savings (and lowest lifetime operating cost) are referenced in parentheses on the x axis. Lifetime liquid fuel saved is represented by blue bars, while the cost-effectiveness results are represented by red and green points.

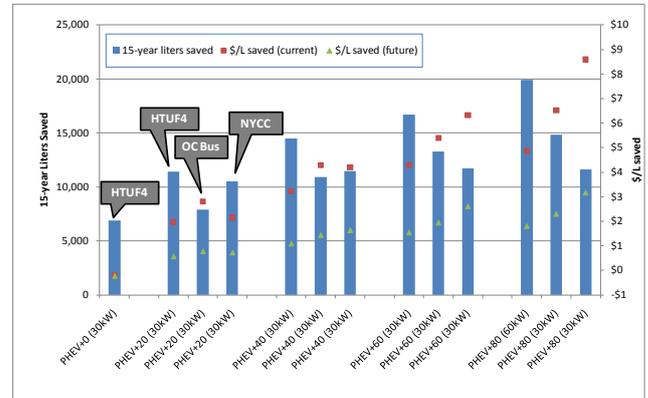


Figure 12: Lifetime liquid fuel displacement and cost effectiveness, 40 km/day

As discussed previously and as evidenced in Figure 12, the PHEV+0kWh is feasible for this low daily distance (40 km/day) and low intensity drive cycle (HTUF4) case. All PHEV configurations represent significant lifetime liquid fuel savings. This is true especially for PHEV configurations with larger battery capacity, as a shorter daily distance does not succeed in fully depleting the battery, resulting in less liquid fuel consumption and larger lifetime liquid fuel savings. The cost effectiveness of obtaining lifetime liquid fuel savings decreases with increasing battery capacity.

Figure 13 presents the results for the 80 km/day case. The chart format is the same as Figure 12, except that the PHEV+0kWh case is not feasible.

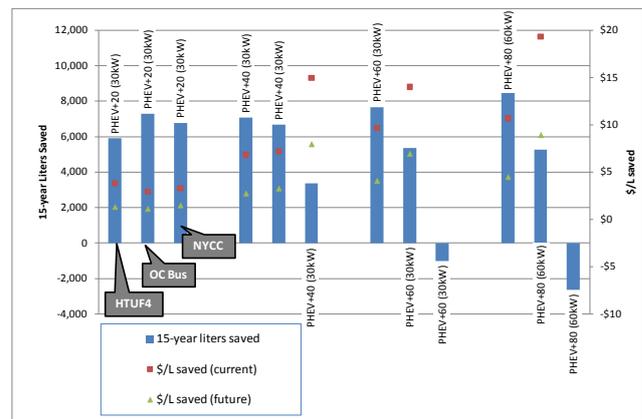


Figure 13: Lifetime liquid fuel displacement and cost effectiveness, 80 km/day

The lifetime liquid fuel savings for these PHEV configurations with longer daily distances are less than those realized in the 40-km/day case. Longer distances result in more battery depletion and eventually a transition from CD to CS operation. For the OC Bus and NYCC drive cycles, liquid fuel savings go down with increasing

battery capacity. These more intense drive cycles deplete the battery more quickly, leading to an earlier transition to CS operation and a fuel consumption penalty due to the larger mass of the battery. In fact, on the NYCC drive cycle, the PHEV+60kWh and PHEV+80kWh configurations consume more lifetime fuel than the gHEV BSfL reference case. The cost effectiveness of obtaining lifetime liquid fuel savings decreases with increasing battery capacity, and the \$/L saved values are higher than those in the 40-km/day case.

Figure 14 presents the results for the 120 km/day case.

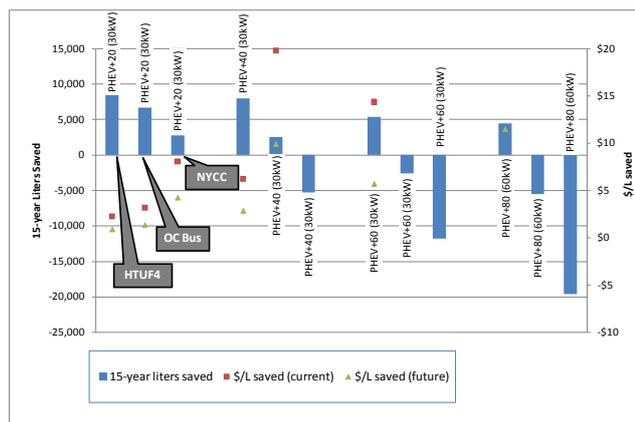


Figure 14: Lifetime liquid fuel displacement and cost effectiveness, 120 km/day

The lifetime liquid fuel savings for these PHEV configurations with longer daily distances are less than those realized in the 80 km/day case. As seen in Figure 13, liquid fuel savings decrease with added battery capacity due to longer daily distances, an earlier transition to CS operation, and a battery mass penalty. On the NYCC and OC Bus drive cycles, the PHEV+60kWh and PHEV+80kWh configurations consume more lifetime fuel than the gHEV BSfL reference case. The same is true for the NYCC drive cycle and PHEV+40kWh configuration. The cost effectiveness of obtaining lifetime liquid fuel savings decreases with increasing battery capacity, and the \$/L saved values are higher than those in the 80 km/day case.

4. Conclusion

Electric drive is well suited to medium duty parcel delivery vehicles. CS gHEV vehicles have already been successfully deployed by FedEx. The results of this analysis underscore the importance of targeted design and strategic deployment of EDVs to maximize reductions in fuel consumption and lifetime operating cost.

The results of this analysis show that the 60-kW power version of the gHEV BSfL configuration has lower lifetime costs, by virtue of lower fuel consumption but despite higher capital cost, than the 30 kW power configuration. In this analysis, for one drive cycle and daily distance combination (HTUF4, 40 km/day), fuel consumption and hardware costs were below those for a gHEV BSfL baseline with a low cost control strategy adjustment (PHEV+0kWh, 30 kW). For less kinetically

intense, relatively short daily routes, lower power and smaller battery capacity PHEV configurations may provide lower lifetime costs due to reduced component costs and fuel consumption. In most smaller battery capacity cases, the 30 kW power level was the most cost effective. This is due primarily to lower mass associated with a relatively smaller battery.

Even in an optimistic future economic scenario, battery costs remain the primary driver in lifetime incremental cost. With the exception of the specific case referenced above, the PHEV configurations analyzed are currently (\$3/gallon fuel and \$700/kWh battery) and forecasted (\$5/gallon fuel and \$300/kWh battery) to be more expensive than the CS gHEV reference vehicle. PHEV configurations with smaller battery capacities (PHEV+20kWh) represent the lowest lifetime incremental cost option. However, minimizing the incremental lifetime cost, even for this lowest cost PHEV option, depends upon strategic route deployment. When extended over tens to hundreds of vehicles or more, large incremental costs should motivate fleet managers to assign EDVs to routes best suited for this technology.

The largest PHEV lifetime fuel savings are realized on shorter daily distances, where they are also the most cost effective. As daily distance driven increases, CD PHEV configurations, especially those with large batteries, can consume more lifetime fuel than a CS reference vehicle.

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14. ABSTRACT (Maximum 200 Words) Medium-duty vehicles are used in a broad array of fleet applications, including parcel delivery. These vehicles are excellent candidates for electric drive applications due to their transient-intensive duty cycles, operation in densely populated areas, and relatively high fuel consumption and emissions. The National Renewable Energy Laboratory (NREL) conducted a robust assessment of parcel delivery routes and completed a model-based techno-economic analysis of hybrid electric vehicle (HEV) and plug-in hybrid electric vehicle configurations. First, NREL characterized parcel delivery vehicle usage patterns, most notably daily distance driven and drive cycle intensity. Second, drive-cycle analysis results framed the selection of drive cycles used to test a parcel delivery HEV on a chassis dynamometer. Next, measured fuel consumption results were used to validate simulated fuel consumption values derived from a dynamic model of the parcel delivery vehicle. Finally, NREL swept a matrix of 120 component size, usage, and cost combinations to assess impacts on fuel consumption and vehicle cost. The results illustrated the dependency of component sizing on drive-cycle intensity and daily distance driven and may allow parcel delivery fleets to match the most appropriate electric drive vehicle to their fleet usage profile.						
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