The energy consumption and cost savings of truck electrification for heavy-duty vehicle applications

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Abstract

This paper evaluates the application of battery electric vehicles (BEVs) and genset plug-in hybrid electric vehicles (PHEVs) to Class-7 local delivery trucks and genset PHEV for Class-8 utility bucket trucks over widely real-world driving data performed by conventional heavy-duty trucks. The genset refers to a PHEV range extension mode in which the PHEV engine is used only to generate electricity and charge battery if the PHEV battery is out of electrical energy. A simulation tool based on vehicle tractive energy methodology and component efficiency for addressing component and system performance was developed to evaluate the energy consumption and performance of the trucks. As part of this analysis, various battery sizes combined with different charging powers on the E-Trucks for local delivery and utility bucket applications were investigated. The results show that the E-Truck applications not only reduce energy consumption but also achieve significant energy cost savings. For delivery E-Trucks, periodic stops at delivery sites enable to provide sufficient time for battery charging, and for this reason, a high-power charger is not necessary. For utility bucket PHEV trucks, energy consumption per mile of bucket truck operation is typically higher because of longer idling times and extra high idling load associated with heavy utility work. The availability of on-route charging is typically lacking at the work sites of bucket trucks; hence, the battery size of these trucks is somewhat larger than that of the delivery trucks studied.
INTRODUCTION

Advanced vehicle electrification technologies, including battery electric vehicles (BEVs) and plug-in hybrid electric vehicles (PHEVs), have the potential to significantly improve air quality, reduce fuel consumption, and cut oil dependence [1]. Medium-duty (MD) and heavy-duty (HD) vehicles represent only 4% of U.S. vehicles but account for nearly 20% of the nation’s transportation fuel consumption [2]. A substantial reduction in fuel consumption and emissions can be achieved using advanced MD and HD vehicle technologies [3–4]. Many nationwide fleets across the United States have shown significant interest and a commitment to electrify part of their fleet even with cost penalty in order to potentially improve society, environment, and economy [3–4]. Thus, considerable growth is expected in the MD and HD E-Truck market in the future [5].

The current major original equipment manufacturers (OEMs) of MD and HD E-Trucks include Balqon, Electric Vehicles International, Motiv Power System, Odyne, TransPower, ZeroTruck, and others [5]. However, their overall E-truck volume in the market is very limited. Navigant Research reported that the global market for MD and HD electric vehicles was less than 16,000 sold in 2014 [6], compared to more than 350,000 MD and HD vehicle sales in the United States alone. Clearly, the E-Truck market is still in its early stages, but research in technologies needed to provide electrical energy to various E-Trucks, including batteries and charging, is being conducted. Also, one truck electrification model cannot fit many diverse truck applications because of their wide range of driving patterns. For example, HD delivery trucks carry cargo from warehouses and make frequent stops at scheduled locations, whereas HD utility trucks typically provide immediate emergency service at unscheduled sites within a wide region [7]. Consequently, different E-Truck battery-range technologies or BEV/PHEV powertrain technologies are required to fit appropriate E-truck applications, as in the case of light-duty vehicles [8]. In addition, an in-depth analysis is necessary to understand the implications of E-trucks charging and battery capacity requirement. Such information is particularly important for designing and optimizing charging infrastructure.

Using real-world and extensive day-to-day drive data performed by conventional trucks, this study aims at evaluating the energy consumption and battery performance of HD E-Trucks operating in real-world conditions. The charging and battery capacity challenges of E-Trucks are investigated in order to expand the E-Truck market. E-Truck applications, including BEV and PHEV powertrain configurations, are studied to determine optimal battery settings during actual transportation. A narrower focus of this research investigates the impact of electrification on Class 7-8 food local delivery and utility bucket trucks. To keep the problem tractable, the analysis of energy consumption was constrained to the vehicle tractive energy methodology and component efficiency for describing truck component and system performance instead of developing detailed component and system models. Appropriate experimental data and commercial software are also employed to validate the methodology. Energy cost savings are also discussed.

METHODOLOGY, DRIVING DATA, AND VEHICLE ASSUMPTIONS

The methodology used in this research compromises of a tractive energy model, truck drive real-world information, truck powertrain configurations, battery size, and charging. In the methodology, the current studies were carried out by (1) selecting a truck and real-world truck drive database; (2) deriving truck speed, road grade, and other information from the selected database; (3) utilizing commercial software to calibrate the simulated trucks and acquire the key parameters and powertrain component efficiencies; (4) analyzing E-truck energy using real-world drive data performed by conventional trucks; and (5) evaluating the battery performance of E-Trucks (including BEV and PHEV trucks) within the given battery charging infrastructure. The details of the truck drive database, vehicle energy model, truck powertrain configurations, and charging assumptions are discussed below.

Truck Driving Data
The Oak Ridge National Laboratory (ORNL) HD truck database was selected to reflect the driving complexities and variations of the studied delivery and bucket trucks. The database records 1 year of real-world truck driving from three day-cab tractors, three utility bucket trucks, and many other types of HD and MD vehicles. The tractors are Class-7 2007 International day-cab tractors (model 8600), which regularly haul 28 feet pup trailers and provide local/regional food delivery serving in East Tennessee. The Knoxville Utilities Board provided the three utility vehicles and operates mainly within Knox County, Tennessee. In general, these recorded trucks are representative of the large population of the same trucks in daily drive mileage, average speed etc. For example, compared to the Fleet DNA, a commercial fleet vehicle operating data [9], which shows 31.0 mph and 10.9 mpg respectively for delivery and utility trucks, their averaged driving speeds recorded in ORNL HD truck database show 28.3 mph and 8.9 mph, respectively.

For delivery truck electrification, the study focuses on the local delivery trucks that operate in Knoxville, Tennessee. Knoxville is a typical U.S. medium-sized city with nearly 100,000 residents whose delivery fleets are very similar to those in other areas that want to diversify their vehicles by deploying electric trucks for short-distance deliveries while keeping conventional trucks for long-distance deliveries. Figure 1(a) shows all trips made by the local delivery trucks. These trucks typically carry 3,000 to 10,000 lb of cargo from their warehouses, travel to downtown Knoxville (about 30 miles), and make multiple deliveries with significant stopping times at delivery sites. For example, the average stop time at a delivery site is 0.52 hour, with an average of more than 10 delivery stops per day. A delivery stop is thus a noteworthy time that can be used for E-Truck recharging. The average travel mileage per day is 69 miles. Table 1 summarizes the key drive and delivery characteristics.

Figure 1(b) shows the spatial coverage of the three utility vehicles that were recorded in the database. The trucks include a Class-8 1998 Paystar 5000 6x6, a Class-8 2010 International DuraStar, and a Class-8 2004 International 7300. The utility trucks traveled an average of 28 miles per day, which is much less than the delivery trucks. Table 1 summarizes the key utility vehicle drive characteristics, showing 70% drive time for idling, which indicates a potential opportunity for truck electrification to reduce energy consumptions.

All the recorded data were collected using 73 signals from the deployed sensors and from the available vehicle systems via the SAE vehicle’s J1939 data bus [7]. The key measured data include fuel consumption, vehicle speed and acceleration, engine speed and torque, vehicle weight, and global positioning system (GPS) spatial location information. The data for fuel consumption, speed, weight, and GPS location were used in the evaluation of tractive power and related parameters. For example, the GPS elevation data were used to estimate road grade, θ.

![Fig 1(a) Local delivery truck](image-url)
FIGURE 1: Driving patterns of local delivery and utility bucket trucks over 1 year in Knoxville, TN.

TABLE 1: Key drive characteristics of local delivery and utility trucks.

<table>
<thead>
<tr>
<th>Truck</th>
<th>Local delivery</th>
<th>Utility</th>
</tr>
</thead>
<tbody>
<tr>
<td>Maximum travel mileage per day</td>
<td>127 miles</td>
<td>118 miles</td>
</tr>
<tr>
<td>Average travel mileage per day</td>
<td>69 miles</td>
<td>28.5 miles</td>
</tr>
<tr>
<td>Average travel time per day</td>
<td>9.1 hr (2.5 hr @ engine on)</td>
<td>4.4 hr (3.2 hr @ engine on)</td>
</tr>
<tr>
<td>Average speed</td>
<td>28.3 mph</td>
<td>8.9 mph</td>
</tr>
<tr>
<td>Idling time percentage</td>
<td>27%</td>
<td>70%</td>
</tr>
<tr>
<td>Other specifications</td>
<td>Delivery: 27a, 12b, 2.8 hr,c, 0.56 hr</td>
<td>Unscheduled service sites</td>
</tr>
</tbody>
</table>

a Maximum delivery stops per day; b Average delivery stops per day; c Maximum delivery stop time per delivery; d Average delivery stop time per delivery

Vehicle Energy Methodology

A common tractive power demand is adopted to cover vehicle forward acceleration, rotational inertia, aerodynamic loss, rolling resistance loss, and grade. For any instant in time, tractive power is described as

\[ W_{\text{tract}} = m \cdot V \cdot \frac{dV}{dt} + \frac{1}{2} \rho \cdot C_d \cdot A_f \cdot V^3 + m \cdot g \cdot C_{rr} \cdot V + m \cdot g \cdot V \cdot \sin(\theta), \]  

where \( W_{\text{tract}} \) is vehicle tractive power; \( V \) is velocity; \( \rho \) is air density; \( C_d \) is aerodynamic drag coefficient; \( C_{rr} \) is rolling resistance coefficient; \( A_f \) is frontal area; \( \theta \) is road gradient; \( g \) is gravity; \( t \) is time; and \( m \) is truck weight, including passengers and key components (e.g., engine, clutch/torque, gearbox, final drive, wheel, chassis, generator, battery, mechanical and electrical accessory, as well as motor and high-voltage battery for hybrid powertrain).

For a conventional vehicle, the tractive power is positive when a vehicle is being actively propelled by engine power. The tractive force becomes negative during periods of braking. Braking represents a dissipative force that depletes the energy that is effectively stored as vehicle kinetic and potential energy. Tractive power becomes zero when a vehicle is idling, but the engine still has to run to fulfill accessory loads. Thus, mechanical power output from the engine, \( W_{\text{eng}} \), can be derived from drivetrain component efficiencies, as described below.

\[
\text{Powered driving: } W_{\text{eng}} = W_{\text{tract}} \ell_{\text{wh}} \cdot \ell_{\text{fd}} \cdot \ell_{\text{gb}} \cdot \ell_{\text{el}} + W_{\text{acc}} \\
\text{Braking or idle: } W_{\text{eng}} = W_{\text{acc}} \\
\text{forall } (W_{\text{tract}} > 0).
\]  

(2)
where $\eta_{wh}$ is wheel efficiency; $\eta_{fd}$ is final drive efficiency; $\eta_{gb}$ is gearbox efficiency; $\eta_{cl}$ is clutch efficiency; and $W'_{acc}$ is accessory load of a conventional vehicle. The conventional truck fuel consumption is given as

$$m_{f,conv} = \frac{W^c_{eng}}{\eta_{eng}} \cdot LHV_f$$

and

$$\eta_{eng} = \eta_{max} \left\{ 2.790338 \cdot \left( \frac{W^p_{eng}}{W^p_{eng}} \right)^{0.5} - 2.394271 \cdot \left( \frac{W^p_{eng}}{W^p_{eng}} \right)^2 + 0.550695 \cdot \left( \frac{W^p_{eng}}{W^p_{eng}} \right)^2 \right\}. \quad (3b)$$

where $m_{f,conv}$ is conventional vehicle fuel consumption; $LHV_f$ is fuel low heating value (43,500kJ/kg for diesel); $W^p_{eng}$ is engine peak power; $\eta_{eng}$ is engine efficiency; and $\eta_{max}$ is maximum engine efficiency (i.e., $\eta_{max}=43\%$). Equation 3(b) was derived based on a MD engine map [12].

For BEV and PHEV vehicles, electric power output from the battery is estimated based on the efficiencies of the electric components (i.e., motor and battery) and related drivetrain components (e.g., final drive and wheel), as shown in Eq. (4). Unlike a conventional vehicle, an BEV or PHEV is capable of converting vehicle kinetic energy into a storable form of battery energy during braking if the thresholds of vehicle speed and acceleration are satisfied. We assume that energy regeneration from braking occurs once the vehicle acceleration has not exceeded the threshold and the vehicle speed has not fallen below the given value, as is described in Eq. (4). The constraints are used in order to distinguish vehicle emergency braking from regenerative kinetic energy and avoid very low kinetic energy regeneration.

Further charging activities are important to consider. To understand their charging impacts, different charging power levels are used to service on-route charging in the model. The charging efficiency is also assumed to be constant.

$$\begin{align*}
\text{Powered driving:} & \quad W^e_{dis} = W^e_{acc} + W^e_{tract}/\eta_{wh} \cdot \eta_{fd} \cdot \eta_{mot} \cdot \eta_{batt} \quad \forall (W^c_{tract} > 0), \\
\text{Braking w/o regen:} & \quad W^e_{dis} = W^p_{acc} \quad \forall (W^c_{tract} < 0) \cap \{b>a_{th}\} \cup (V<V_{th}), \\
\text{Braking w/ regen:} & \quad W^e_{chrg} = W^e_{acc} + |W^e_{tract}|/\eta_{wh} \cdot \eta_{fd} \cdot \eta_{mot} \cdot \eta_{batt} \quad \forall (W^c_{tract} < 0) \cap \{b<a_{th}\} \cup (V>V_{th}), \\
\text{Idle:} & \quad W^e_{dis} = W^e_{eng} \quad \forall (W^c_{tract} = 0), \\
\text{Recharging:} & \quad W^e_{chg} = W^e_{acc} \cdot \eta_{chgr} \quad \forall (W^c_{tract} = 0) \cap \left( \vec{x} \in \bar{C}_i \right).
\end{align*}$$

(4)

where $\eta_{mot}$ is motor efficiency; $\eta_{batt}$ is battery efficiency; $\eta_{chgr}$ is charger efficiency; $a$ is acceleration; $a_{hi}$ (i.e., $a_{hh} = -3.0 \text{ m/s}^2$) is high boundary for acceleration in converting kinetic energy into electric energy; $V_{th}$ (i.e., $V_{th} = 5.0 \text{ m/s}$) is low boundary for speed in converting kinetic energy into electric energy; $W^e_{acc}$ is accessory load of an electric vehicle; $W^e_{dis}$ is battery discharge power; $W^e_{chrg}$ is battery charge power from regenerated kinetic energy; $W^e_{eng}$ is engine power for PHEV battery charging; $W^e_{batt}$ is final drive efficiency; $\eta_{cl}$ is clutch efficiency; and $\vec{x}$ is vehicle position. Therefore, the battery state of charge (SOC) of an BEV truck can be described as Eq. 5(a).

Moreover, for PHEV trucks, a charge depletion control strategy is specified to maximize electric energy usage when the battery charge is high, as described in [13]. The charge depletion mode allows the PHEV to primarily use electrical energy, minimizes engine operation, and reduces fuel consumption. When the battery SOC hits its low threshold, the developed strategy turns on the engine to charge the battery until the SOC returns to the high threshold. For PHEV battery charging, we considered the engine power running at the maximum engine efficiency condition. Hence, the SOC of an PHEV truck can be described as Eq. 5(b).

$$\begin{align*}
\text{BEV mode:} \quad SOC = 1 - \int_0^t (W^e_{dis} - W^e_{chrg}) \, dt / E_{batt}. \\
\text{PHEV mode:} \quad SOC = 1 - \int_0^t (W^e_{dis} - W^e_{chrg} - W^e_{eng}) \, dt / E_{batt}. \quad (5a)
\end{align*}$$

where $W^e_{eng} = \delta \cdot W^e_{eng} \cdot \eta_{eng} \cdot \eta_{batt}$; $\delta=1$ only if the battery is charged from low threshold (i.e., SOC=0.25) to high threshold (i.e., SOC=0.5); $W^e_{chrg}$ is engine power for PHEV battery charging; $W^e_{eng}$...
is engine power operating at the maximum efficiency condition; and \( \eta_{\text{gen}} \) is generator efficiency. \( E_{\text{batt}} \) is battery energy capacity. The fuel consumption for PHEV battery charging is given as

\[
m_{f_{\text{PHEV}}} = \frac{W_{\text{eng}}}{\eta_{\text{eng}} \cdot \text{LHV}_f}.
\]

In addition, battery and related electronic components used in E-Trucks typically lead to a significant weight penalty due to the low energy density of the battery. We considered the E-Truck weight penalty as

\[
\begin{align*}
\text{BEV: } m_{\text{penalty}} &= m_{\text{batt}} + m_{\text{mot}} - m_{\text{eng}} - m_{\text{gb}}, \\
\text{PHEV: } m_{\text{penalty}} &= m_{\text{batt}} + m_{\text{mot}} + \gamma m_{\text{gen}} - (1 - \gamma)(m_{\text{eng}} + m_{\text{gb}}),
\end{align*}
\]

where \( m_{\text{batt}}, m_{\text{mot}}, m_{\text{eng}}, \) and \( m_{\text{gb}} \) are the weight of battery, motor, engine, and gearbox, respectively. Their values are estimated based on the component peak powers except for the battery, which is estimated based on the battery capacity. The detailed mass estimations are considered as \( m_{\text{batt}} = 6.67 \cdot E_{\text{batt}} \), \( m_{\text{mot}} = 1.20 \cdot W_{\text{mot}}^P \), \( m_{\text{gen}} = 1.20 \cdot W_{\text{gen}}^P \), \( m_{\text{eng}} = 1.55 \cdot W_{\text{eng}}^P \), and \( m_{\text{gb}} = 0.50 \cdot W_{\text{gb}}^P \). The coefficients used were suggested by [14–16]. The variables, \( W_{\text{mot}}^P, W_{\text{gen}}^P, W_{\text{eng}}^P, \) and \( W_{\text{gb}}^P \), represent the peak power for motor, generator, engine, and gearbox, respectively. Here, all of these are defined as 280 kW for BEV trucks; \( \gamma \) is the fraction of engine downsizing for PHEV trucks. It is assumed that \( \gamma = 0.7 \). Also, the peak engine power in the PHEV is 70% of the comparable conventional trucks, while the PHEV generator power is assumed to be the same as that of the PHEV engine power.

Finally, a simulation tool based on the above tractive energy methodology and component efficiency for addressing component and system performance was developed using Matlab. By incorporating driving data, vehicle component efficiency, vehicle weight, charging power, and infrastructure into the designated excel format, the impact of the battery and charger on energy consumption and transportation service can be forecast.

### Vehicle and Charging Assumptions

A conventional Class-7 delivery truck model was first constructed based on a 2007 International day-cab tractor that hauls 28 feet pup trailers. Table 2 lists the major specifications of the modeled delivery truck, where the frontal area, rolling resistance, and aerodynamic drag coefficients were estimated and corrected using a tractive energy analysis of fuel consumption and engine power measurements from the ORNL HD conventional truck database. The appropriate constant average efficiencies for each component were assumed, and a constant average value was also adopted for power consumption relative to all accessories.

Similarly, a conventional Class-8 utility bucket truck model was also created. Table 2 lists its specifications. Because three different trucks were measured, their estimated truck weights are given separately.

To confirm that the assumptions reasonably reflect the performance of the conventional trucks, the simulations were compared with real-world 2007 International day-cab tractor data and 1998 Paystar 5000 data collected by ORNL. For a delivery travel distance of 98 miles and 11 hours including 2.7 hours of engine operation, the predicted and measured fuel consumptions were 46.0 and 48.3 liters, respectively. The predicted error is less than 4%. For a utility truck travel distance of 15 miles and 7.8 hours including 6 hours of engine operation, the predicted and measured fuel consumption were 9.7 and 10.13 liters, respectively. The predicted error is no more than 5%. Figures 2(a) and 2(b) show good agreement between the simulations and measurements of fuel consumption, implying the basic simulation assumptions for the conventional powertrain were indeed reasonable. In Figure 2(b), the circled area is utility service time when the truck is idle and fuel consumption is significant. The implemented figure clearly shows the transient fuel consumption.

### TABLE 2: Parameters used for simulating conventional and E-Trucks.
### Table 2: Vehicle parameters

<table>
<thead>
<tr>
<th>Component</th>
<th>Class-7 Local delivery truck</th>
<th>Class-8 Utility bucket truck</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Conv</td>
<td>BEV</td>
</tr>
<tr>
<td>Frontal area (m^2) A_f</td>
<td>10</td>
<td>10</td>
</tr>
<tr>
<td>Rolling resistance coefficient C_rr</td>
<td>0.008</td>
<td>0.008</td>
</tr>
<tr>
<td>Aerodynamic drag coefficient C_d</td>
<td>0.56</td>
<td>0.56</td>
</tr>
<tr>
<td>Truck mass (kg) m</td>
<td>12,236-14,545</td>
<td>12,661-15,973</td>
</tr>
<tr>
<td>Engine efficiency η_{eng}</td>
<td>Eq. (3)</td>
<td>-</td>
</tr>
<tr>
<td>Clutch efficiency η_{cl}</td>
<td>0.99</td>
<td>-</td>
</tr>
<tr>
<td>Gearbox efficiency η_{gb}</td>
<td>0.98</td>
<td>-</td>
</tr>
<tr>
<td>Final Drive efficiency η_{fd}</td>
<td>0.97</td>
<td>0.97</td>
</tr>
<tr>
<td>Wheel drive efficiency η_{wh}</td>
<td>0.99</td>
<td>0.99</td>
</tr>
<tr>
<td>Motor efficiency η_{mot}</td>
<td>-</td>
<td>0.92</td>
</tr>
<tr>
<td>Generator η_{gen}</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Battery efficiency η_{batt}</td>
<td>-</td>
<td>0.98</td>
</tr>
<tr>
<td>EV Battery (kWh) E_{batt}</td>
<td>-</td>
<td>100-250</td>
</tr>
<tr>
<td>Charger efficiency η_{char}</td>
<td>-</td>
<td>0.97</td>
</tr>
<tr>
<td>Charger power (kW) W_{acc}</td>
<td>-</td>
<td>70-120</td>
</tr>
<tr>
<td>Accessories (kW) W_{acc}</td>
<td>5.6</td>
<td>2.8</td>
</tr>
</tbody>
</table>

1, 2, 3 The conventional truck weights of 2004 Durastar 4400, 2010 International 7300, 1998 Paystar 5000, respectively; a, b, c The comparable PHEV truck weights.

---

**FIGURE 2:** Validation of fuel consumption for conventional delivery and utility bucket trucks.

For the E-Truck simulations, both BEVs and power-genset PHEVs were considered for local delivery trucks, but only power-genset PHEVs were considered for utility bucket trucks. A backup power source is typically necessary for utility bucket trucks because these vehicles are usually involved in unexpected long-time service and distance. In these power-genset PHEVs, the downsized engine is used to generate electricity and charge the battery if the PHEV battery is out of electrical energy. The major E-powertrain components studied were the battery, motor, final drive, wheel, and chassis, as well as adding an engine and generator in PHEVs. Again, constant average efficiencies for motor and battery components were assumed. Table 2 summarizes the features of the main electric vehicle systems. Other
drivetrain components and chassis parameters remained the same as those used in the conventional trucks. Similarly, the E-Truck simulation used a constant value for the accessory load. Because there are fewer accessory components in an E-Truck, the accessory load for the E-Truck was assumed to be 50% less than that used in a conventional vehicle based on widely published literature [17–19].

It is difficult to calibrate the E-Truck model directly in the absence of available experimental data. To confirm that the above assumptions give reasonable electric truck predictions, the Autonomie software was used to construct a virtual E-truck based on the specifications listed in Table 2. The battery energy consumption predicted by Autonomie was then compared with our model over the given drive-cycle scenario. Results indicated a less than 5% error, implying that these E-Truck assumptions are reasonably accurate.

For on-route charging, a delivery truck stop of more than 10 minutes is considered to be a charging event. As shown in Table 1, delivery trucks make frequently stops with an average stop time of more than 30 minutes, providing a good opportunity for recharging. Compared to delivery trucks, utility bucket trucks demonstrate a different driving pattern that usually requires immediate travel to any unscheduled site for emergency service. Thus, on-route recharging for PHEV utility trucks during their travel was not included.

RESULTS AND DISCUSSIONS

Delivery E-Truck

Figure 3(a) compares the cumulative battery energy consumed by the delivery BEV truck against the engine mechanical energy of the conventional delivery truck in the Knoxville area. The battery truck was assumed to be charged with 70 kW at each delivery stop lasting more than 10 minutes. The predicted battery energy consumption is 1.89 kWh/mile, which is less than 2.02 kWh/mile of the conventional truck in engine mechanical energy or 5.24 kWh/mile of the conventional truck fuel energy. Apparently, delivery truck electrification improves truck energy savings. This energy savings is mainly due to BEV braking energy recovery. In the simulated electric truck, braking energy recovered is nearly 0.28 kWh/mile, which is about 15% of battery energy consumption. Figure 3(b) details the level of braking energy recovery.

The minimum transient SOC of the 160 kWh battery each delivery day is shown in Figure 3(c), indicating 37% of the minimum transient SOC over the overall local delivery data. Thus the 160 kWh battery with 70 kW charging at delivery stops is sufficient to meet the target of local delivery service in Knoxville. Figure 3(c) also shows a 250 kWh battery is required if no battery recharging is available. Clearly, battery recharging at delivery stops is vital to reducing the size of batteries.

To determine the impact of on-route charging power on battery capacity need, the impact of 70 kW and 120 kW charging power was compared in Figure 4. In the Knoxville region, the area above the line is the BEV application zone, and the other is the PHEV application zone where engine power is needed to charge the battery. The case of the above, the 160 kWh battery is located well within the BEV application zone (Figure 4). In the BEV zone, greater charging power reduces battery capacity needed; however, charging power greater than 70 kW is not necessary, particularly in the case of 120 kW or higher battery capacity. This means that SAE J1772 standard chargers for DC level 2 (i.e., up to 90 kW) [20] would be adequate to meet the BEV delivery truck charging demand. The figure also indicates it is impossible to reduce the local delivery BEV battery to less than 100 kW even with an extra-fast and higher power charger. Such information would be more relevant to the design of a charging infrastructure and the choice of E-Truck battery.

The impact of battery size and charging power on delivery genset PHEV trucks was further investigated. The batteries considered were in the range of 45–90 kWh with 45–115 kW charging power, as shown in the PHEV zone of Figure 5. The SOC of the PHEV is fully charged at the beginning of each operating day. The battery and engine mechanical energy consumption is around 1.90–1.97 kWh/mile. If fuel energy for the engine is considered, battery and fuel energy consumption is around 2.07–3.07 kWh/mile. Battery and engine mechanical energy consumption is slightly higher than BEV electrical...
energy consumption alone. Figure 5 shows that on-route charging is important for the simulated PHEVs in the significant migration from liquid fuel to electric energy. For example, the 90 kWh PHEV trucks take nearly 7% and 65% tractive energy from fuel consumption with and without on-route charging, respectively. This impact becomes more significant with increasing battery size. Figure 5 also indicates that the PHEV fuel consumption is not sensitive to the power level of the charger. The main reasons are that the averaged delivery distance and stop time are 6 miles and 0.56 hour, respectively, in the studied delivery trucks. Thus, 20–30 kW charging power and a half-hour charging provide sufficient electrical energy to travel 6 miles between two delivery sites. Consequently, SAE J1772 standard chargers, such as AC level 2 (up to 19.2 kW) or DC level 1 (up to 36 kW), would be acceptable [20]. It is not necessary for the genset PHEVs to adopt expensive extra-fast charger technologies.

Therefore, BEVs achieve a better energy savings and completely eliminate liquid fuel consumption, while genset PHEVs provide the option of less battery size and a lower power charger. The larger battery and on-route charging in delivery PHEVs allow significant mitigation from liquid fuel to electrical energy. Delivery stops serve as good opportunities for the truck battery charging, but significant high-power chargers are not necessary, particularly for PHEVs.

![Cumulative energy](image1)
![Energy consumption per mile](image2)
![Minimum SOC per day](image3)

**FIGURE 3:** Energy consumption of conventional and electric delivery trucks as a function of daily drive mileage based on real-world driving data of local delivery activities for 1 year. The BEV...
delivery truck simulation was conducted with a 160 kWh battery and 70 kW charging power at each delivery stop.

![Battery capacity need for satisfying local delivery service with various charging power at delivery stops; 0 kW charging power represents no on-route charging.](image)

**FIGURE 4:** Battery capacity need for satisfying local delivery service with various charging power at delivery stops; 0 kW charging power represents no on-route charging.

![Impact of PHEV battery capacity and charging power on electrical and fuel energy consumption; 0 kW charging power represents no on-route charging.](image)

**FIGURE 5:** Impact of PHEV battery capacity and charging power on electrical and fuel energy consumption; 0 kW charging power represents no on-route charging.

**Utility Bucket E-Truck**

In the study, the SOC of the PHEV bucket trucks is assumed to have a full charge at the beginning of each operating day, but no on-route recharging was considered. Figure 6(a) compares the cumulative energy of the conventional bucket truck with the genset PHEV equipped with a 135 kWh battery. The battery and engine mechanical energy consumed in the PHEVs is 3.0 kWh/mile compared to 4.1 kWh/mile of the engine mechanical energy used in the conventional truck. If fuel energy for the engine is considered, the battery and fuel energy consumption in the PHEVs is 4.3 kWh/mile compared to 11.1 kWh/mile of fuel energy in the conventional truck. The simulated PHEV braking energy recovered is nearly 0.57 kWh/mile, which is about 19% of the overall engine mechanical and battery electrical energy. The bucket truck electrification definitely improves vehicle energy savings. Figure 6(b) details braking energy recovery and utility work energy consumption and indicates a maximum utility work energy consumption of up to 50 kWh per day. Figure 6(c) compares fuel consumption of the simulated PHEV and
conventional trucks. The results show that the 135 kWh battery PHEV allows running in EV mode on most days with a driving distance of less than 50 miles. Otherwise, engine operation needs to supply power. Still, the overall fuel consumption of the PHEV is much less than the comparable conventional truck.

Figure 7 shows the impact of various battery capacities on PHEV performance and fuel consumption. As expected, the larger battery better supports the PHEV EV mode over longer distances and work time, as shown Figure 7(a). The 180 kWh PHEV bucket truck enables EV mode with 83% of service days, compared to only 44% of service days with the 90 kWh PHEV bucket truck, as shown in Figure 7(b). As a result, the energy consumption from diesel fuel is significantly reduced when larger batteries are used, as shown in Figure 7(c). Compared to delivery PHEVs, the batteries used in the simulated bucket PHEV are somewhat larger. In particular, the energy consumption per mile of bucket truck is typically higher due to longer idling, extra-higher idling load associated with occasional heavy utility work operation, and unscheduled utility sites, which typically make no on-route recharging available. Delivery PHEVs with moderately larger batteries are essential in order to minimize liquid fuel consumption.
FIGURE 6: Energy consumption of conventional and genet PHEV bucket trucks as a function of daily drive mileage based on real-world driving data of utility bucket trucks for 1 year. The PHEV truck simulation was conducted with a 135 kWh battery without any on-route charging.

(a) Impact of battery size on engine power need; each spot represents a day; blue circle represents engine power need; green cross represents running EV only.

(b) EV operation days

(c) Tractive energy provided from fuel consumption

FIGURE 7: Impact of various battery capacities on utility bucket PHEV performance and fuel consumption.

Discussions on Energy Cost Saving and Payload Limit

The foregoing simulations show that local delivery and utility bucket E-Trucks lead to energy savings, in particular the significant migration from liquid fuel to electric energy. Electrical energy is much cheaper than power energy generated by liquid fuel and engines [21–22]. Thus, it is important to understand how much energy cost savings could be gained from the E-Truck applications.

Table 3 summarizes our analyses for the energy cost of E-Truck. The estimated energy cost is the sum of both diesel fuel and electricity. In the calculations, the price used for diesel fuel is $2.403 per gallon, which is the average U.S. market price of diesel as of July 2016 [21]. The price selected for electricity is 9.81 cents per kWh, which is the average U.S market cost of electricity for April 2016 [22]. In general, whether delivery or bucket trucks, E-Trucks provide significant cost savings. Larger batteries lead to more cost savings. In the case of delivery trucks, the delivery BEV truck achieves greater cost savings than the PHEVs because the BEV maximizes electric energy consumption and eliminates fossil fuel consumption, which is more expensive.

Bucket utility E-trucks achieve even greater cost saving than delivery E-trucks, as expected, because bucket trucks consumed much more energy than delivery trucks. E-Truck technologies allow bucket trucks to use more electrical energy to increase the energy cost savings percentage. These results
indicate the potential of E-Truck technologies to offer significant energy cost savings by maximizing electric energy consumption and reducing fossil fuel consumption, in addition to reducing energy consumption.

**TABLE 3: Economic analyses for the energy cost of E-Trucks.**

<table>
<thead>
<tr>
<th>Truck</th>
<th>Diesel Fuel (gal/mile)</th>
<th>Electricity (kWh/mile)</th>
<th>Energy cost (cents/mile)</th>
<th>Cost saving</th>
</tr>
</thead>
<tbody>
<tr>
<td>Delivery</td>
<td>Conventional</td>
<td>0.137</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td></td>
<td>45kWh PHEV</td>
<td>0.050</td>
<td>1.152</td>
<td>23.3</td>
</tr>
<tr>
<td></td>
<td>60kWh PHEV</td>
<td>0.042</td>
<td>1.270</td>
<td>22.6</td>
</tr>
<tr>
<td></td>
<td>75kWh PHEV</td>
<td>0.026</td>
<td>1.511</td>
<td>21.0</td>
</tr>
<tr>
<td></td>
<td>90kWh PHEV</td>
<td>0.009</td>
<td>1.755</td>
<td>19.4</td>
</tr>
<tr>
<td></td>
<td>135kWh BEV</td>
<td>-</td>
<td>1.889</td>
<td>18.6</td>
</tr>
<tr>
<td>Bucket</td>
<td>Conventional</td>
<td>0.294</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td></td>
<td>90kWh PHEV</td>
<td>0.095</td>
<td>1.601</td>
<td>38.7</td>
</tr>
<tr>
<td></td>
<td>135kWh PHEV</td>
<td>0.053</td>
<td>2.233</td>
<td>34.8</td>
</tr>
<tr>
<td></td>
<td>180kWh PHEV</td>
<td>0.025</td>
<td>2.659</td>
<td>32.3</td>
</tr>
</tbody>
</table>

* 70 kW on-route charging power;  
* no on-route charging;  
* based on conventional delivery truck;  
* based on conventional bucket truck.

Also, the estimation based on the weight data available from Table 2 shows that the Class-7 delivery BEVs with 100-250kWh battery size could make the full-payload BEV weight around 14,969 - 15,973 kg. Similarly, the full-payload delivery PHEV weight with 45-90kWh battery size is about 15,012 - 15,311 kg. Therefore, a larger battery could lead to the E-truck weight slightly beyond the weight limitation of Class 7 HD truck (i.e. 33,000lb or 15,000kg), thus requiring a slight payload reduction in the real operation to comply with weight regulations. How to optimize the balance among battery size, payload reduction and energy saving for the delivery E-trucks is particularly important. It deserves future studies, but is not considered here. Unlike Class-7 E-trucks, the Class-8 utility bucket E-trucks is still within the weight limitation and without any payload reduction problems.

**CONCLUSION**

A simulation tool based on the vehicle tractive energy methodology and component efficiency for addressing component and system performance was developed to evaluate energy consumption and battery performance of HD delivery and utility E-Trucks. The simulations were carried out to identify the advantages of BEV and genset PHEV for local delivery trucks, as well as genset PHEV for utility bucket trucks, using a wide range of real-world driving data obtained from conventional diesel trucks.

The results demonstrate that both BEV and PHEV delivery trucks can achieve energy savings. With appropriate on-route charging, the E-Trucks maximize electricity usage and reduce liquid fuel, thus reducing the overall cost of energy by 29%–44%. Delivery stops are critical to E-Truck battery charging, but high-power chargers are not necessary. In the Knoxville area, 100 kWh is the minimum size battery required in local delivery BEVs. However, genset PHEVs provide more flexibility, allowing a smaller size battery and lower power charger. For both delivery BEVs and PHEVs, a larger battery could lead to slight payload reduction. How to optimize the balance among battery size, payload reduction and energy saving for the delivery E-trucks is particularly important in the future research.

The bucket PHEVs also achieve energy savings. Compared to delivery trucks, the battery size used in bucket PHEVs is somewhat larger, allowing bucket E-Trucks to achieve greater energy cost savings through energy consumption reduction and the mitigation from liquid fuel to electricity. Unlike Class-7 delivery trucks, a large battery size does not cause any payload problems to Class-8 utility bucket E-trucks.
Although the E-Truck applications show significant energy cost savings, it is important to also consider the considerable cost associated with electric powertrain systems (i.e., battery cost). Because large battery packs can be typically expensive and thus energy cost savings due to E-Truck applications are not sufficient to yield satisfactory payback times, a more detailed cost-benefit analysis is necessary to best understand the trade-offs associated with vehicle price, battery cost, operational cost savings, and E-Truck benefits from society, air quality and U.S. importing oil dependence and economy policy.

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