Energy Consumption and Cost Savings of Truck Electrification for Heavy-Duty Vehicle Applications

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Energy Consumption and Cost Savings of Truck Electrification for Heavy-Duty Vehicle Applications

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An evaluation was made of 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. GenSet refers to a PHEV range extension mode in which the PHEV engine is used only to generate electricity and charge the 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 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 en route charging is typically lacking at the worksites of bucket trucks; thus, the battery size of these trucks is somewhat larger than that of the delivery trucks studied.

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 have shown significant interest and a commitment to electrify part of their fleet even with cost penalty, 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 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 with 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, while 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-truck 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, 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 consists 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 (*a*) selecting a truck and real-world truck drive database; (*b*) deriving truck speed, road grade, and other

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information from the selected database; (*c*) using commercial software to calibrate the simulated trucks and acquire the key parameters and powertrain component efficiencies; (*d*) analyzing e-truck energy using real-world drive data performed by conventional trucks; and (*e*) 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 as follows.

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-ft pup trailers and provide local and regional food delivery service 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, and so on. For example, compared to the Fleet DNA, a commercial fleet vehicle operating database (*9*), which shows 31.0 mph and 10.9 mpg, respectively, for delivery and utility trucks, their averaged driving speeds recorded in the 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.

(a)

(b)

FIGURE 1 Driving patterns of trucks over 1 year in Knoxville, Tennessee: (*a*) local delivery trucks and (*b*) utility bucket trucks.

These trucks typically carry 3,000 to 10,000 lb of cargo from their warehouses, travel to downtown Knoxville (about 30 mi), and make multiple deliveries with significant stopping times at delivery sites. For example, the average stop time at a delivery site is 0.52 h, 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 mi. 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 6 × 6, a Class-8 2010 International DuraStar, and a Class-8 2004 International 7300. The utility trucks traveled an average of 28 mi 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, indicating 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 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.

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 the following (*10, 11*):

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

where

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

TABLE 1 Key Drive Characteristics of Local Delivery and Utility Trucks

Characteristic	Local Delivery	Utility
Maximum travel mileage per day	127	118
Average travel mileage per day	69	28.5
Average travel time per day	9.1 h (2.5 h at engine on)	4.4 h (3.2 h at engine on)
Average speed	28.3 mph	8.9 mph
Idling time percentage	27	70
Other specifications	Delivery: 27[a], 12[b], 2.8 h[c], 0.56 h[d]	Unscheduled service sites

[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.

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^c_{eng}, can be derived from drivetrain component efficiencies, as follows:

Powered driving:

$$W^c_{\text{eng}} = \frac{W^c_{\text{tract}}}{\eta_{\text{wh}}} \cdot \eta_{\text{fd}} \cdot \eta_{\text{gb}} \cdot \eta_{\text{cl}} + W^c_{\text{acc}} \qquad \forall\left(W^c_{\text{tract}} > 0\right)$$

Braking or idle:

$$W^c_{\text{eng}} = W^c_{\text{acc}} \qquad \forall\left(W^c_{\text{tract}} \le 0\right) \tag{2}$$

where

η_{wh} = wheel efficiency,
η_{fd} = final drive efficiency,
η_{gb} = gearbox efficiency,
η_{cl} = clutch efficiency, and
W^c_{acc} = accessory load of a conventional vehicle.

The conventional truck fuel consumption is given as

$$\dot{m}_{f,\text{conv}} = \frac{W^c_{\text{eng}}}{\eta_{\text{eng}}} \cdot \text{LHV}_f \tag{3a}$$

and

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

where

$\dot{m}_{f,\text{conv}}$ = conventional vehicle fuel consumption,
LHV_f = fuel low heating value (43,500 kJ/kg for diesel),
W^p_{eng} = engine peak power,
η_{eng} = engine efficiency, and
$\eta_{\max}$ = maximum engine efficiency (i.e., $\eta_{\max} = 43\%$).

Equation 3*b* was derived based on an 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 Equation 4. Unlike a conventional vehicle, a 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. It is assumed 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 Equation 4. The constraints are used 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.

Powered driving:

$$W^e_{\text{dis}} = \frac{W^e_{\text{acc}} + W^e_{\text{tract}}}{\eta_{\text{wh}} \cdot \eta_{\text{fd}} \cdot \eta_{\text{mot}} \cdot \eta_{\text{batt}}} \qquad \forall\left(W^e_{\text{tract}} > 0\right)$$

Braking without regen:

$$W^e_{\text{dis}} = W^e_{\text{acc}} \qquad \forall\left(W^e_{\text{tract}} < 0\right) \cap \left\{(a > a_{\text{hb}}) \cup (V < V_{\text{lb}})\right\}$$

Braking with regen:

$$W^e_{\text{chg}} = -W^e_{\text{acc}} + \frac{\left|W^e_{\text{tract}}\right|}{\eta_{\text{wh}}} \cdot \eta_{\text{fd}} \cdot \eta_{\text{mot}} \cdot \eta_{\text{batt}} \qquad \forall\left(W^e_{\text{tract}} < 0\right) \cap (a < a_{\text{hb}}) \cap (V > V_{\text{lb}})$$

Idle:

$$W^e_{\text{dis}} = W^e_{\text{acc}} \qquad \forall\left(W^e_{\text{tract}} = 0\right)$$

Recharging:

$$W^e_{\text{chg}} = W^e_{\text{obc}} \cdot \eta_{\text{chgr}} \qquad \forall\left(W^e_{\text{tract}} = 0\right) \cap \left(\vec{X} \in \vec{C}_i\right) \tag{4}$$

where

W^e_{tract} = electric vehicle tractive power,
regen = regeneration,
η_{mot} = motor efficiency,
η_{batt} = battery efficiency,
η_{chgr} = charger efficiency,
a = acceleration,
a_{hl} (i.e., $a_{\text{hb}} = -3.0\ \text{m/s}^2$) = high boundary for acceleration in converting kinetic energy into electric energy,
V_{lb} (i.e., $V_{\text{lb}} = 5.0$ m/s) = low boundary for speed in converting kinetic energy into electric energy,
W^e_{acc} = accessory load of an electric vehicle,
W^e_{dis} = battery discharge power,
W^e_{chg} = battery charge power from regenerated kinetic energy,
W^e_{obc} = onboard charging power,
$\vec{C}_i$ = ith available charging location, and
$\vec{X}$ = vehicle position.

Therefore, the battery state of charge (SOC) of a BEV truck can be described as Equation 5a.

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 Gao et al. (*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, the researchers considered the engine power running at the maximum engine efficiency condition. Thus, the SOC of a PHEV truck can be described as Equation 5*b*.

BEV mode:

$$\text{SOC} = 1 - \int_0^t \left(W^e_{\text{dis}} - W^e_{\text{chg}}\right) \frac{\text{d}t}{E_{\text{batt}}} \tag{5a}$$

PHEV mode:

$$\text{SOC} = 1 - \int_0^t \left(W^e_{\text{dis}} - W^e_{\text{chg}} - W^{\text{eng}}_{\text{chg}}\right) \frac{\text{d}t}{E_{\text{batt}}} \tag{5b}$$

where

$$W^{\text{eng}}_{\text{chg}} = \delta \cdot W^{\eta_{\max}}_{\text{eng}} \cdot \eta_{\text{gen}} \cdot \eta_{\text{batt}}$$

δ = 1 only if the battery is charged from low threshold (i.e., SOC = 0.25) to high threshold (i.e., SOC = 0.5),
$W^{\text{eng}}_{\text{chg}}$ = engine power for PHEV battery charging,
$W^{\eta_{\max}}_{\text{eng}}$ = engine power operating at the maximum efficiency condition,
η_{gen} = generator efficiency, and
E_{batt} = battery energy capacity.

The fuel consumption for PHEV battery charging is given as

$$\dot{m}_{f,\text{PHEV}} = \frac{W^{\text{eng}}_{\text{chg}}}{\eta_{\text{eng}}} \cdot \text{LHV}_f \tag{6}$$

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. The e-truck weight penalty was considered as

BEV:

$$m_{\text{penalty}} = m_{\text{batt}} + m_{\text{mot}} - m_{\text{eng}} - m_{\text{gb}} \tag{7a}$$

PHEV:

$$m_{\text{penalty}} = m_{\text{batt}} + m_{\text{mot}} + \gamma m_{\text{gen}} - (1-\gamma)\left(m_{\text{eng}} + m_{\text{gb}}\right) \tag{7b}$$

where m_{batt}, m_{mot}, m_{eng}, and m_{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 $m_{\text{batt}} = 6.67 \cdot E_{\text{batt}}$, $m_{\text{mot}} = 1.20 \cdot W^p_{\text{mot}}$, $m_{\text{gen}} = 1.20 \cdot W^p_{\text{gen}}$, $m_{\text{eng}} = 1.55 \cdot W^p_{\text{gen}}$, and $m_{\text{gb}} = 0.50 \cdot W^p_{\text{gb}}$. The coefficients used were suggested by several sources (*14–16*). The variables W^p_{mot}, W^p_{gen}, W^p_{eng}, and W^p_{gb} represent the peak power for motor, generator, engine, and gearbox, respectively. Here, all of these are defined as 280 kW for BEV trucks; γ 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 that 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 aforementioned 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-ft 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.

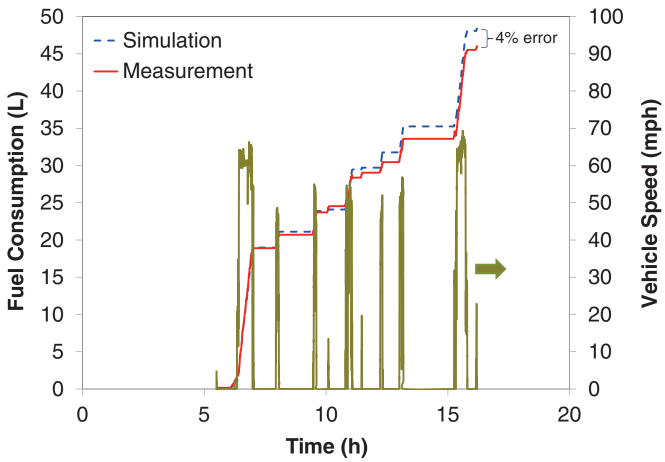
To confirm that the assumptions reasonably reflect the performance of the conventional trucks, the simulations were compared with real-world 2007 International day-cab tractor data and 1998 Paystar 5000 data collected by ORNL. For a delivery travel distance of 98 mi and 11 h including 2.7 h of engine operation, the predicted and measured fuel consumptions were 46.0 and 48.3 L, respectively. The predicted error is less than 4%. For a utility truck travel distance of 15 mi and 7.8 h including 6 h of engine operation, the predicted and measured fuel consumption were 9.7 and 10.13 L, respectively. The predicted error is no more than 5%. Figure 2, *a* and *b*, shows good agreement between the simulations and measurements of fuel consumption, implying that 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.

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 longtime 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

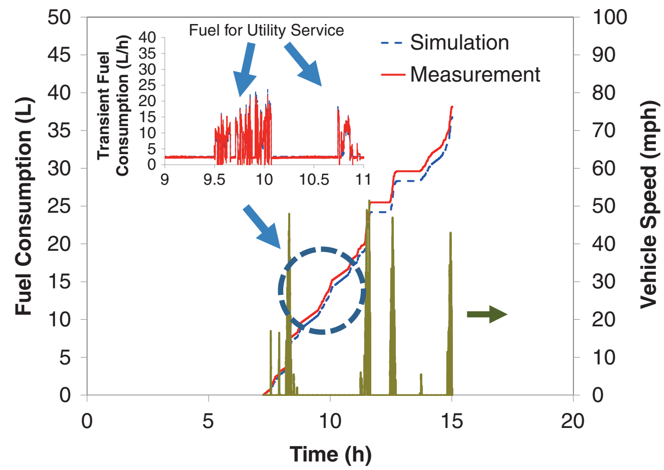
TABLE 2 Parameters Used for Simulating Conventional and e-Trucks

	Class-7 Local Delivery Truck			Class-8 Utility Bucket Truck	
Vehicle Parameter	Conventional	BEV	PHEV	Conventional	PHEV
Frontal area (m^2) A_f	10	10	10	9	9
Rolling resistance coefficient C_{rr}	0.008	0.008	0.008	0.009	0.009
Aerodynamic drag coefficient C_d	0.56	0.56	0.56	0.6	0.6
Truck mass (kg) m	12,236–14,545	12,661–15,973	12,702–15,311	14,500[a] 16,500[c] 23,100[d]	15,507–16,107[b] 17,507–18,107[b] 24,107–24,707[b]
Engine efficiency η_{eng}	Equation 3	na	Equation 3	Equation 3	Equation 3
Clutch efficiency η_{cl}	0.99	na	na	0.86	na
Gearbox efficiency η_{gb}	0.98	na	na	0.92	na
Final drive efficiency η_{fd}	0.97	0.97	0.97	0.98	0.98
Wheel drive efficiency η_{wh}	0.99	0.99	0.99	0.99	0.99
Motor efficiency η_{mot}	na	0.92	0.92	na	0.88
Generator η_{gen}	na	na	0.92	na	0.88
Battery efficiency η_{batt}	na	0.98	0.98	na	0.95
Electric vehicle battery (kW-h) E_{batt}	na	100–250	45–90	na	90–180
Charger efficiency η_{chgr}	na	0.97	0.97	na	0.97
Charger power (kW)	na	70–120	45–115	na	na
Accessories (kW) W_{acc}	5.6	2.8	2.8	8.5	4.3

NOTE: na = not applicable.
[a]Conventional truck weight of 2004 Durastar 4400.
[b]Comparable PHEV truck weights.
[c]Conventional truck weight of 2010 International 7300.
[d]Conventional truck weight of 1998 Paystar 5000.



(a)



(b)

FIGURE 2 Validation of fuel consumption for (*a*) conventional delivery trucks and (*b*) utility bucket trucks.

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 foregoing assumptions give reasonable electric truck predictions, 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 the model over the given drive-cycle scenario. Results indicated a less than 5% error, implying that these e-truck assumptions are reasonably accurate.

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

DISCUSSION OF RESULTS

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 min. The predicted battery energy consumption is 1.89 kW-h/mi, which is less than 2.02 kW-h/mi of the conventional truck in engine mechanical energy or 5.24 kW-h/mi 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 kW-h/mi, 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 kW-h-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 kW-h-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 kW-h-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 en route charging power on battery capacity need, the effect 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 160 kW-h-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-h or higher battery capacity. This means that SAE J1772 standard chargers for DC level 2 (i.e., up to 90 kW) 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-h 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 to 90 kW-h with 45 to 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 to 1.97 kW-h/mi. If fuel energy for the engine is considered, battery and fuel energy consumption is around 2.07 to 3.07 kW-h/mi. Battery and engine mechanical energy consumption is slightly higher than BEV electrical energy consumption alone. Figure 5 shows that en route charging is important for the simulated PHEVs in the significant migration from liquid fuel to electric energy. For example, the 90 kW-h-PHEV trucks take nearly 7% and 65% tractive energy from fuel consumption with and without en 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 mi and 0.56 h, respectively, in

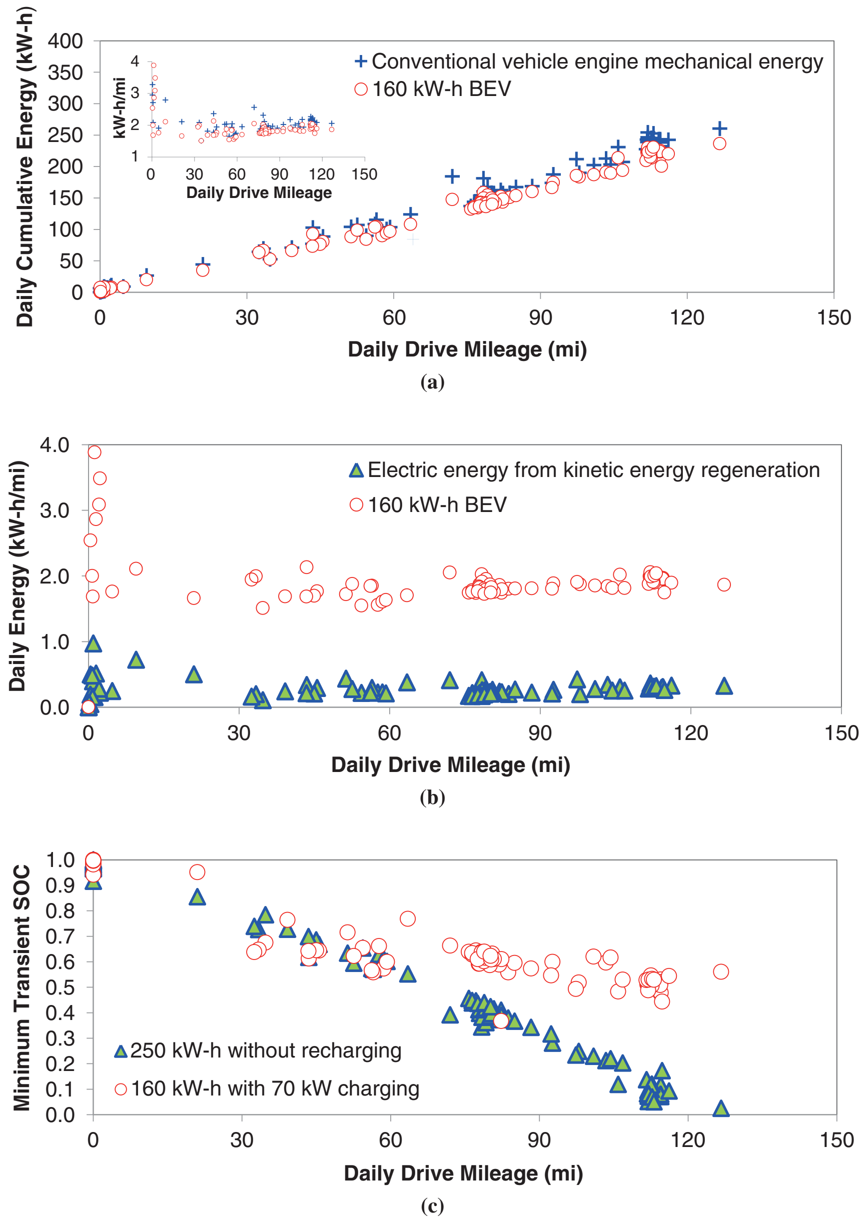


FIGURE 3 Energy consumption of conventional and electric delivery trucks as a function of daily drive mileage based on real-world driving data of local delivery activities for 1 year: (*a*) cumulative energy, (*b*) energy consumption per mile, and (*c*) minimum SOC per day (BEV delivery truck simulation was conducted with a 160 kW-h battery and 70 kW charging power at each delivery stop).

the studied delivery trucks. Thus, 20 to 30 kW charging power and a half-hour charging provide sufficient electrical energy to travel 6 mi 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. 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 en 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.

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 en route recharging was considered. Figure 6*a* compares the cumulative energy of the conventional bucket truck with the GenSet PHEV equipped with a 135 kW-h-battery. The battery and engine mechanical energy consumed in the PHEVs is 3.0 kW-h/mi compared with

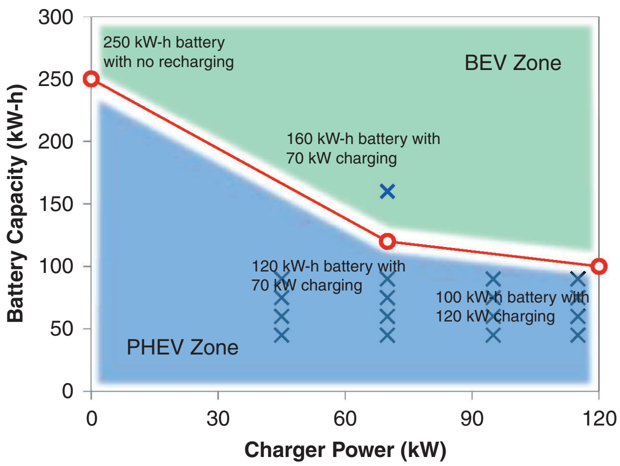


FIGURE 4 Battery capacity need for satisfying local delivery service with various charging power at delivery stops (0 kW charging power represents no en route charging).

4.1 kW-h/mi 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 kW-h/mi compared with 11.1 kW-h/mi of fuel energy in the conventional truck. The simulated PHEV braking energy recovered is nearly 0.57 kW-h/mi, 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 kW-h per day. Figure 6*c* compares fuel consumption of the simulated PHEV and conventional trucks. The results show that the 135 kW-h-battery PHEV allows running in EV mode on most days with a driving distance of less than 50 mi. Otherwise, engine operation needs to supply power. Still, the overall fuel consumption of the PHEV is much less than that of 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 in Figure 7*a*. The 180 kW-h-PHEV bucket truck enables EV mode with 83% of service days, compared with only 44% of service days with the 90 kW-h-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 with 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 owing to longer idling, extra-higher idling load associated with occasional heavy utility work operation, and unscheduled utility sites, which typically make no en route recharging available. Delivery PHEVs with moderately larger batteries are essential to minimize liquid fuel consumption.

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 (*20, 21*). Thus, it is important to understand how much energy cost savings could be gained from the e-truck applications.

Table 3 summarizes the analyses for the energy cost of the 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 gal, the average U.S. market price of diesel as of July 2016 (*20*). The price selected for electricity is 9.81 cents per kW-h, the average U.S. market cost of electricity for April 2016 (*21*). In general, whether they are 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 do, as expected, because bucket trucks consume 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

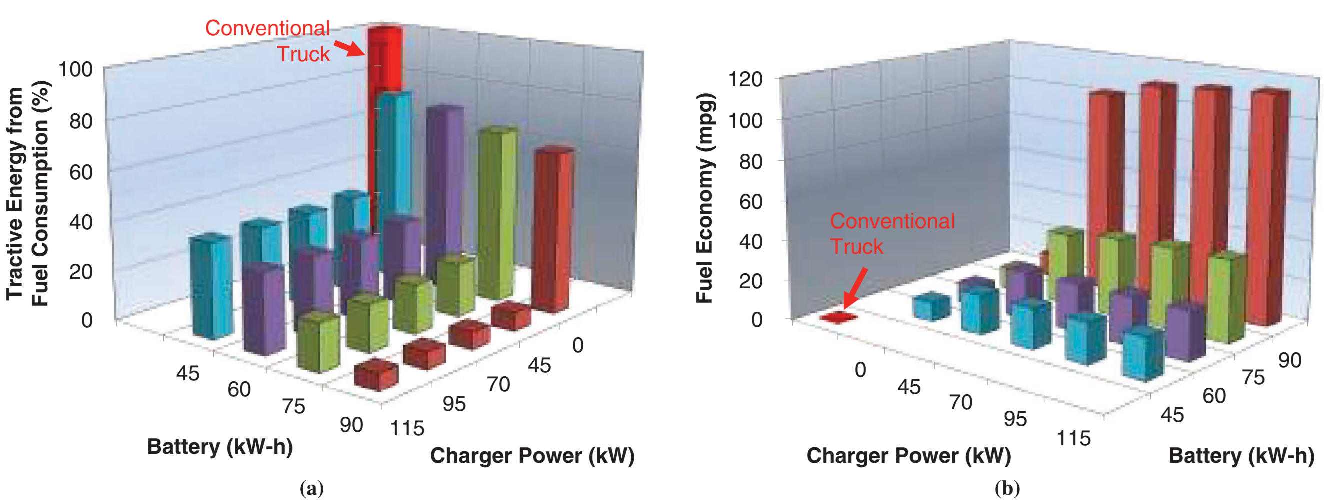
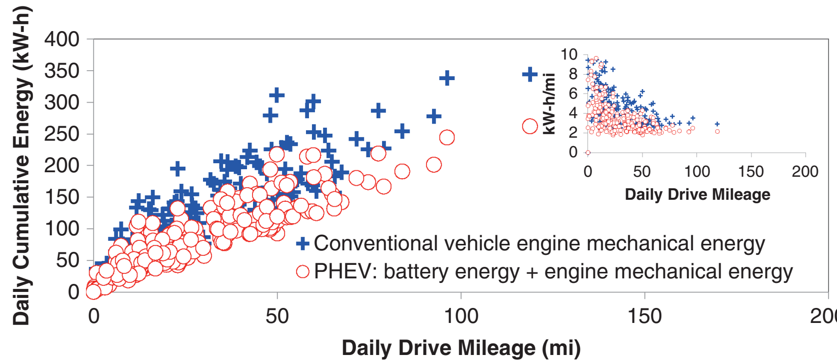
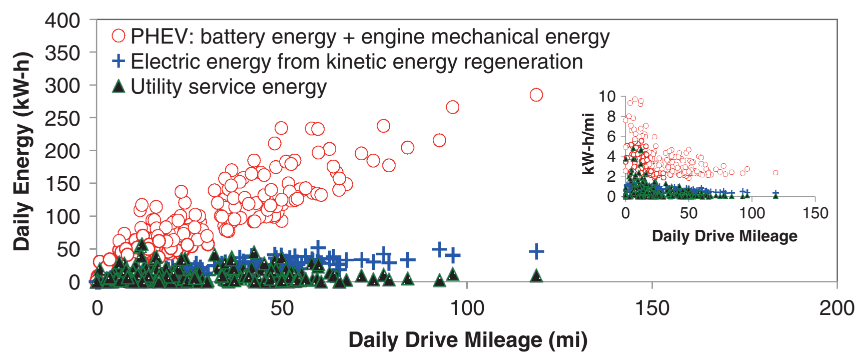


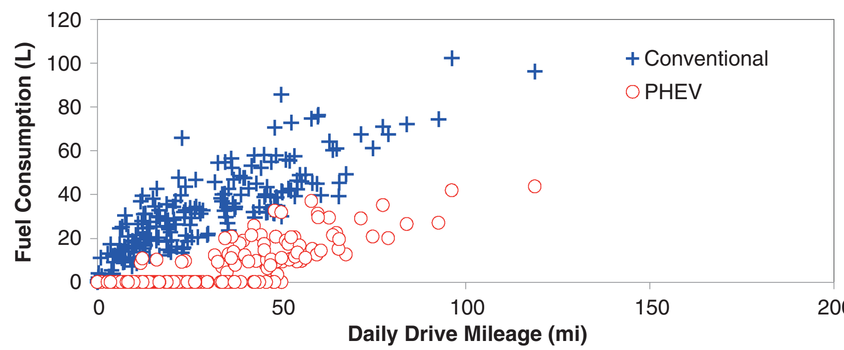
FIGURE 5 Impact of PHEV battery capacity and charging power on electrical and fuel energy consumption: (*a*) tractive energy provided from fuel and (*b*) fuel economy (0 kW charging power represents no en route charging).



(a)



(b)



(c)

FIGURE 6 Energy consumption of conventional and GenSet PHEV bucket trucks as a function of daily drive mileage based on real-world driving data of utility bucket trucks for 1 year: (*a*) comparison of cumulative energy, (*b*) detailed energy consumption in PHEVs, and (*c*) comparison of fuel consumptions (PHEV truck simulation conducted with 135 kW-h battery without any en route charging).

technologies to offer significant energy cost savings by maximizing electric energy consumption and reducing fossil fuel consumption, in addition to reducing energy consumption.

Also, the estimation based on the weight data available from Table 2 shows that the Class-7 delivery BEVs with 100 to 250 kW-h-battery size could make the full-payload BEV weight around 14,969 to 15,973 kg. Similarly, the full-payload delivery PHEV weight with 45 to 90 kW-h-battery size is about 15,012 to 5,311 kg. Therefore, a larger battery could lead to the e-truck weight slightly beyond the weight limitation of Class 7 HD truck (i.e., 33,000 lb or 15,000 kg), 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.

CONCLUSIONS

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

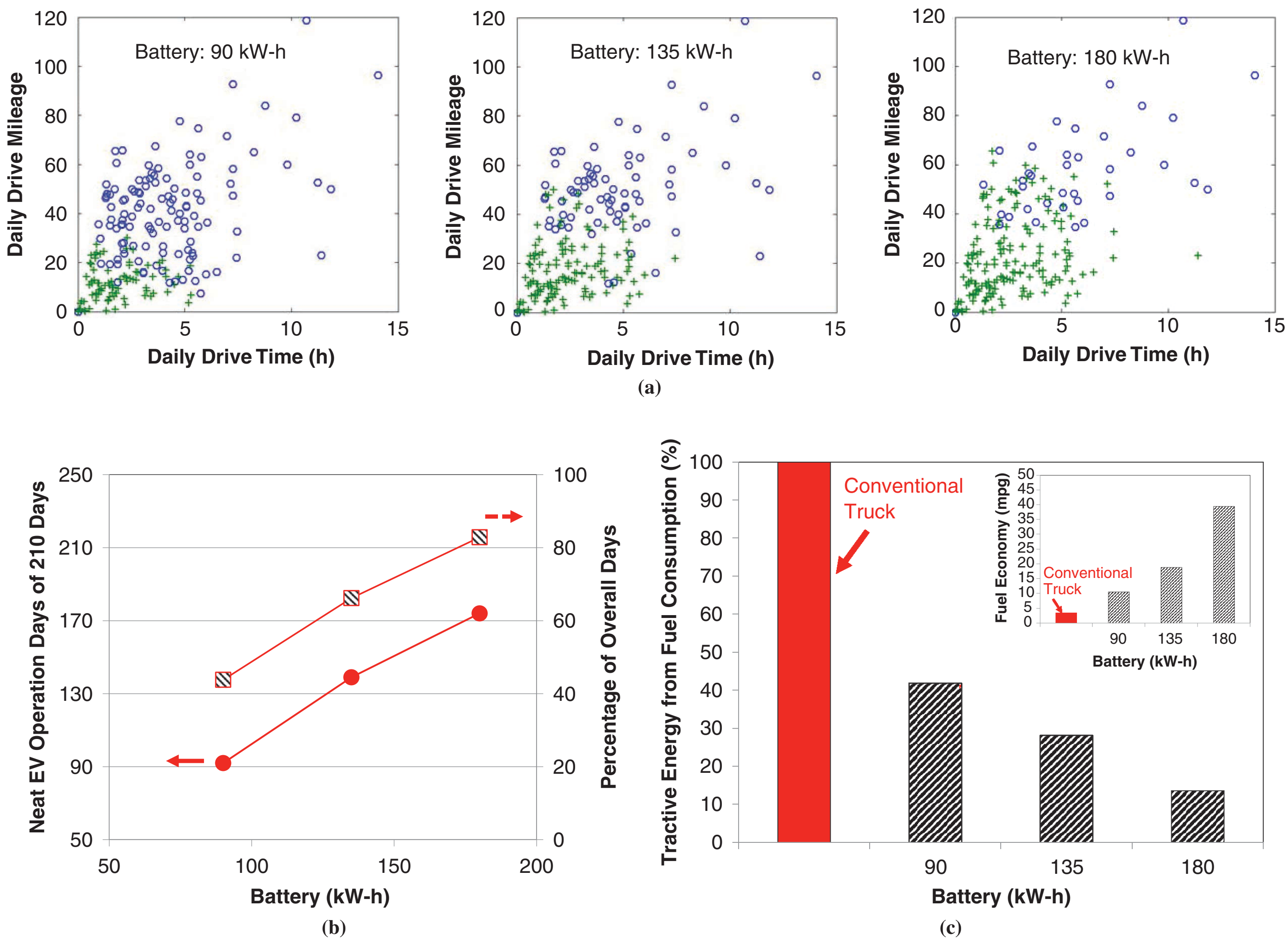


FIGURE 7 Impact of various battery capacities on utility bucket PHEV performance and fuel consumption: (*a*) impact on engine power need (each spot representing a day; blue circle representing engine power need; and green cross representing running EV only), (*b*) EV operation days, and (*c*) tractive energy provided from fuel (EV = electric vehicle).

TABLE 3 Economic Analyses for Energy Cost of e-Trucks

Truck	Diesel Fuel (gal/mi)	Electricity (kW-h/mi)	Energy Cost (cents/mi)	Cost Saving (%)
Delivery				
Conventional	0.137	na	33.0	na
45 kW-h PHEV[a]	0.050	1.152	23.3	29.5[b]
60 kW-h PHEV[a]	0.042	1.270	22.6	31.6[b]
75 kW-h PHEV[a]	0.026	1.511	21.0	36.3[b]
90 kW-h PHEV[a]	0.009	1.755	19.4	41.0[b]
135 kW-h BEV[a]	na	1.889	18.6	43.6[b]
Bucket				
Conventional	0.294	na	70.7	na
90 kW-h PHEV[c]	0.095	1.601	38.7	45.3[d]
135 kW-h PHEV[c]	0.053	2.233	34.8	50.9[d]
180 kW-h PHEV[c]	0.025	2.659	32.3	54.4[d]

[a]70 kW en route charging power.
[b]Based on conventional delivery truck.
[c]No en route charging.
[d]Based on conventional bucket truck.

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 en route charging, the e-trucks maximize electricity usage and reduce liquid fuel, thus reducing the overall cost of energy by 29% to 44%. Delivery stops are critical to e-truck battery charging, but high-power chargers are not necessary. In the Knoxville area, 100 kW-h 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 future research.

The bucket PHEVs also achieve energy savings. Compared with 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 with 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 owing 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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