2024-01-2812

Exploring Class 8 Long-Haul Truck Electrification: Key Technology Evaluation and Potential Challenges

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Abstract

The phenomena of global warming and climate change are encouraging more and more countries, local communities, and companies to establish carbon neutrality targets, which has very significant implications for the US trucking industry. Truck electrification helps fleets to achieve zero tailpipe emissions and macro-scale decarbonization while allowing continued business growth in response to the rapid expansion of e-commerce and shipping related to increased globalization. This paper presents an analysis of Class 8 long-haul truck electrification using a commercial vehicle electrification evaluation tool and Fleet DNA drive data. The study provides new insight into the impacts of streamlined chassis, battery energy density, and superfast charging on battery capacity needs as well as implications for payload, energy consumption, and greenhouse gas emissions for electric long-haul trucks. The study also identifies a pathway for achieving optimal long-haul truck electrification. The results show that no single technology can simultaneously achieve significant improvements in all these key areas and that a cost-effective approach requires a deliberate combination of all of these technologies. Moreover, the analysis highlights the strong evolution of vehicle and battery technologies and the excellent potential for long-haul truck electrification to achieve 100% year-round service coverage with continued technology advancement.

Introduction

Emerging concerns about global warming and climate change have led more and more countries, local communities, and companies to establish carbon neutrality targets, such as net-zero carbon emissions, by 2050 in an effort to combat the environmental threats. Recent decarbonization trends and policies significantly affect the US trucking industry, which comprises approximately 15.5 million trucks, including 2 million tractor trailers [1]. US trucking transports over 70% of the nation's total freight [2] and is responsible for 7.8 million barrels of petroleum consumption per day [3]. In 2019, medium-duty (MD) and heavy-duty (HD) trucks in the United States generated 444 MMT of CO_2 equivalent, an increase of more than 90% in greenhouse gas (GHG) emissions since 1990 [4]. Because the significant carbon footprint of the trucking industry is strongly driven by e-commerce and other shipping related to increased globalization, expectations for continued future growth suggest that transport-related energy consumption and GHG emissions will continue to rise.

Truck electrification can help MD/HD truck fleets achieve their unique business needs and sustainability goals while realizing zero tailpipe emissions and large-scale decarbonization [5]. In the past, Class 8 long-haul electric trucks (E-trucks) were considered infeasible because of high battery prices and ultralow energy density compared with diesel fuel. However, battery costs have declined significantly over the past 10 years, from more than $1,000/kWh to less than $137/kWh in 2020 [6]. Furthermore, the battery weight penalty has been reduced with improved energy densities and is partially offset by lightweight e-power trains with electric motors replacing the diesel engines, aftertreatments, transmissions, and fuel tanks, etc. Consequently, many truck original equipment manufacturers (OEMs) are responding positively to the emerging opportunity by developing various zero-emission Class 8 long-haul E-trucks. Very few long-haul E-truck models are currently available in the North American market, but at least 19 long-haul E-trucks are expected on the market in the near future [7, 8]. Long-haul E-truck sales are expected to grow exponentially in the coming years. Table 1 summarizes the major long-haul truck electrification technologies and readiness. Currently, all long-haul E-truck models except the Tesla Semi model are designed with ranges of no more than 350 mi., which is quite limited compared with typical trips of conventional long-haul trucks. Tesla claims its Semi model has a range of up to 500 mi. [9]. Little technical information on these zero-emission E-trucks is available, including for the Tesla Semi. Long-haul truck electrification is in very early stages of development. Substantial research studies are needed to understand (1) long-haul truck electrification priority needs for component improvement, (2) superfast charging technology and infrastructure, (3) the impact of long-haul truck electrification on GHG reduction and freight efficiency, and (4) many other factors affecting the market penetration of e-trucks, including payload capacity, cost penalty, policies, financial incentives, etc.

Many studies have been conducted on truck electrification, addressing a broad range of topics such as driving range, charging infrastructure, energy saving potential, as well as economic, environmental, and policy perspectives. Like light-duty battery electric vehicles (BEVs), E-trucks' driving range strongly depends on battery capacity. Recent optimistic studies show that, based on current battery and charging technology, electrification of MD trucks and Class 8 HD regional trucks can be achieved and is economically feasible [10, 11]. The MD and HD regional trucks considered in these studies typically travel to predictable destinations within a primary operating range of less than 100 mi. [12], so electrification requires only limited battery capacity. Other research suggests that long-haul truck electrification is still not generally feasible if the range needs to match that of conventional diesel trucks, which could result in the need for ultrahigh battery energy capacity and cost as well as a significant weight penalty [13, 14]. In fact, 70% of the energy losses of Class 8 E-trucks are due to aerodynamic drag and rolling resistance [15]. This highlights how critical a highly streamlined chassis is to reduce the battery energy capacity requirement and weight penalty because very limited studies have been carried out.

Table 1. Class 8 tractor trailer vehicle electrification technologies.

OEM	Battery (kwh)	Range (mi.)	Charging (kW or h)
BYD 8TT [a]	422–563	—	2.5–3.5 h
Freightliner eCascadia [b]	475	250	80% in 90 min
Kenworth 680E [c]	396	150	120 kW
Lion Lion8 [d]	653	260	>3 h
Mercedes-Benz eActros [e]	336–448	205–248	160 kW
Meritor Tractor [f]	215	100	—
Nikola Tre [g]	750	350	—
Peterbilt 579EV [h]	420	200	3–4 h
Tesla Semi [i]	Up to 900	500	—
Volvo VNR Electric [i]	565	275	80% in 90 min
XOS ET-One [i]	—	300	—

[a] https://en.byd.com/truck/class-8-day-cab/
[c] https://www.kenworth.com/about-us/news/t680e/
[d] https://thelionelectric.com/documents/en/Lion8_all_applications.pdf
[e] https://www.mercedes-benz-trucks.com/en_GB/emobility/world/our-offer/eactros-and-services.html
[f] https://www.meritor.com/applications/electrification
[g] https://nikolamotor.com/tre
[h] https://www.peterbilt.com/trucks/electric-vehicles
[i] https://www.forbes.com/sites/michaelharley/2023/09/24/tesla-isnt-the-only-company-offering-electric-class-8-trucks/?sh=64b955338c24
[j] https://xostrucks.com/

To extend the driving range of BEVs cost effectively, superfast charging technology is rapidly advancing, and charge rates up to 350 kW are currently available; however, it is estimated that 450–800 kW is needed to charge Class 8 long-haul E-trucks in a reasonable period of time [13]. Several results reveal that superfast charging can play a significant role in reducing the battery size requirement, increasing vehicle driving range, and improving the market competitiveness of E-trucks [16, 17]. The results from Phadke et.al. [18] show 30 min of charging using 500 kW and megawatt-scale fast chargers would add sufficient range without impairing the operations or economics of freight movement. However, superfast charging leads to ultrahigh current and voltages, which necessitate complex component designs, system optimization, and additional safety and cooling considerations [19]. For example, in the case of charging power levels of 500 kW, the current and voltage could be up to 500 A and 1,000 V, which would require a liquid cooling circuit in the cables and connectors. It is impossible to operate at 350~400 A with a small-diameter and low-weight cable. Unfortunately, much of the existing literature does not consider the consequences of superfast charging on HD E-trucks and charging infrastructure.

Energy savings potential and GHG emissions reduction are also reported in the literature. Borlaug et.al. [8] showed the average energy consumption of Class 7 and 8 delivery E-trucks varied between 1.5 and 2.8 kWh/mi. for short-haul (<200 mi. operating range) truck electrification, leading to an average of 137–235 kWh/day. Similar results are reported in other studies [11]. Moreover, available results show that, no matter the operating characteristics of the vehicle or electric grid, HD electric vehicles have lower GHG emissions than diesel vehicles [20]. For example, fuel consumption–related GHG emissions (in CO_2 kg/mi.) from E-trucks were reduced as much as 63% [21]. These works focus on MD trucks and HD regional trucks and do not address long-haul trucks. In fact, heavy-duty long-haul truck electrification is key to achieve net-zero on road transport by 2050 [22]. Long-haul truck operations have different driving behaviors and energy requirements because of the significant payload [23]. According to the US Environmental Protection Agency, a typical long-haul truck weight with an empty trailer is about 15.9 tons (35,000 lb.), and payloads average about 18.2 ton (40,000 lb.). Over 90% of long-haul trucks weigh less than 33.2 tons (73,000 lb.) fully loaded, well under the 36.4 ton (i.e., 80,000 lb.) load limit for Class 8 vehicles in the United States. With long-haul truck electrification, the weight penalty imposed by the batteries needed for the extended driving range has to be fully considered because the added weight reduces the payload that can be transported, necessitating additional trucks to deliver the freight and consequently additional costs and energy consumption. Thus, it is vital to understand the freight-based GHG emissions of long-haul truck electrification (i.e., CO_2 kg/ton-mi. instead of CO_2 kg/mi.). Unfortunately, most results in existing literature are based on CO_2 kg/mi.

In addition, many studies have evaluated E-truck economic and policy perspectives [18, 24]. The results reveal that with appropriate technology, economics, and policy, the freight sector can be decarbonized if the electric grid is decarbonized with renewable electricity [24]. Analysis of total cost of ownership (TCO) shows that a Class 8 E-truck with 375 mi. range and operated 300 mi./day can yield an approximately 13% lower TCO per mile compared with a diesel truck, offering an approximately 3-year payback and net present savings of about USD $200,000 over a 15-year lifetime [18]. The economic studies also estimate the cost of a 20 MW charging station to be $6.6–$7.3 million plus $100,000/year, including the costs of electric vehicle supply equipment, grid connection, installation, and operations and maintenance [17]. Higher upfront capital costs of both vehicle and charging infrastructure are major barriers during the initial stages of electric trucking. The key policies accelerating truck electrification include financial incentives, investments in charging infrastructure, and standards that increase the manufacture and purchase of E-trucks [12].

In this study, the Oak Ridge National Laboratory (ORNL) commercial vehicle electrification evaluation tool (CVEET) was used to conduct a comprehensive priority analysis of long-haul truck electrification. The study aimed to understand the impacts of streamlined chassis, battery energy density, and superfast charging technology on long-haul truck electrification, including the effects on battery capacity requirements, payload, energy consumption, and GHG reduction. An objective of this analysis was to identify an optimal technology pathway that will enable full electrification of long-haul trucks. To keep the problem tractable, the energy consumption analysis was based on a vehicle tractive energy methodology. The National Renewable Energy Laboratory's (NREL's) Fleet DNA commercial fleet vehicle operating data and ORNL component efficiency data were used to characterize the performance requirements of conventional and E-trucks.

Data, Methods, and Assumptions

Class 8 Long-Haul Truck Drive Data

Fleet DNA is a database of commercial-fleet vehicle operating data developed and maintained by NREL to provide a wide range of data for real-world routes driven by many Class 3–8 MD and HD vehicles, including long-haul trucks and many other commercial vehicles. [25]. The data available are grouped by vehicle day, which accounts for a 24 h period of operation. The detailed data include extensive vehicle operating behavior statistics, such as route distance, drive duration, average speed, stop duration, stop events exceeding 30 min, deceleration events, deceleration duration, load and grade, as well as many other drive-cycle metrics and travel features. Table 2 summarizes key driving characteristics of Class 8 long-haul trucks.

Table 2. Class 8 long-haul truck driving behavior summary.

Drive characteristics summary	Class 8 long-haul truck
Average driving distance (mi./day)	423.35
Annual travel mileage [a]	154,524
Maximum drive distance (mi./day)	996.30
Average drive duration (h/day)	7.49
Maximum drive duration (h/day)	16.08
Average vehicle-on duration (h/day)	12.22
Maximum vehicle-on duration (h/day)	24.00
Average drive speed (mph) [b]	56.24
Maximum drive speed (mph)	100.22
Average vehicle-on speed (mph) [c]	34.20
Average long-stop events/day [d]	2.2
Maximum long-stop events/day [d]	13.00

[a] 1 year = 365 days
[b] Vehicle speed >0
[c] Vehicle speed ≥0
[d] Stop or idling time >0.5 h

Class 8 long-haul trucks have long daily travel mileages, and their maximum daily travel mileage is much greater than the average daily travel mileage. Table 2 shows that long-haul trucks can travel nearly 1,000 mi. daily, whereas the average daily mileage from the Fleet DNA data is 423 mi. Figure 1(a) displays the details of a complete year for 6 long-haul trucks operating over 1,024 days. Each point represents one day's driving activity. Figure 1(b) shows the distribution of daily driving mileage for Class 8 long-haul trucks. The data show that distances of 250–300 mi./day or less represent only 30% of the year-round service days, whereas 450–500 mi./day represents approximately 50% of year-round service days. Furthermore, 600–650 mi./day represents 80% of year-round service days. Long-haul trucks are driven more than 750 mi./day for 10% of the year-round service days. Also of note, Table 1 shows that long-stop (i.e., at least 30 min) events of long-haul trucks regularly occur. These stop events typically occur at the fleet depot for loading cargo or at destination sites after completing a major operation or a trip. Figure 1(c) indicates that more than 90% of Class 8 long-haul trucks have 2 long-stop events daily. These long-stop events can provide opportunities for daily E-truck en-route charging.

Commercial Vehicle Electrification Evaluation Tool

The CVEET can identify and characterize charging and battery capacity challenges for Class 3–8 commercial vehicle electrification, including various battery-electric and plug in–hybrid trucks, vans, and buses, over a wide range of vehicle operation. The tool can help build an understanding of the impact of commercial vehicle electrification on payload penalty and GHG (i.e., CO_2) emissions. The tool employs a quantitative approach to estimate electric vehicle energy consumption, characterize component performance, and determine appropriate charging assumptions to conduct a comprehensive priority analysis of MD/HD vehicle electrification using Fleet DNA open-source data. Figure 2 shows the general framework of the CVEET.

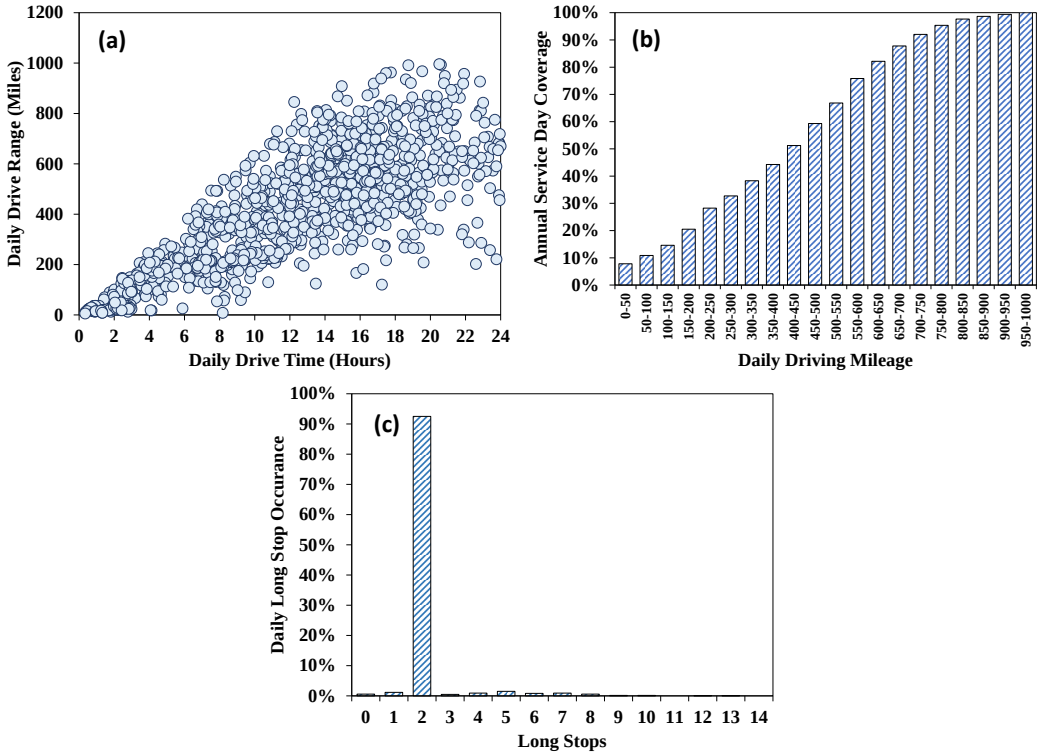


Figure 1. (a) Daily drive range vs. time, (b) driving statistics, and (c) ≥30 min-stop statistics of Class 8 long-haul trucks.

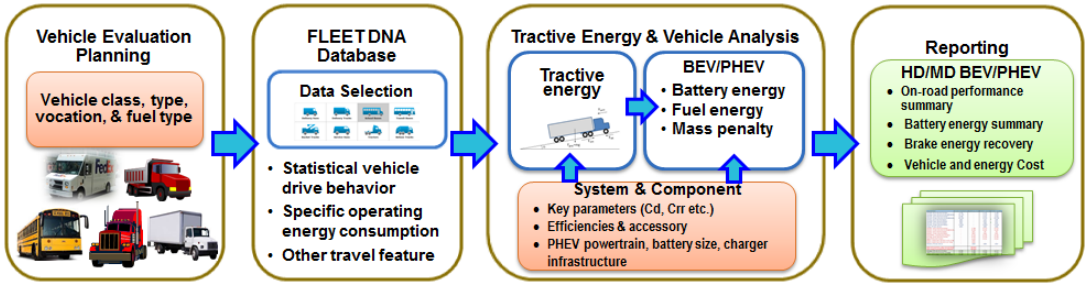


Figure 2. General structure of the commercial vehicle electrification evaluation tool. PHEV stands for plug-in hybrid electric vehicle.

In CVEET, the tractive power demands are used to account for vehicle acceleration, aerodynamic loss, rolling resistance loss, and road grade conditions. The power demand is described as [15, 26, 27]

$$\dot{E}_{tract} = m \cdot v \cdot dv/dt + \frac{1}{2}\rho \cdot c_d \cdot A_f \cdot v^3 + m \cdot g \cdot c_{rr} \cdot v + m \cdot g \cdot v \cdot \sin(\theta), \quad (1)$$

where $\dot{E}_{tract}$ is tractive power; v is velocity; ρ is air density; c_d is the aerodynamic drag coefficient; A_f is the projected frontal area; c_{rr} is the rolling resistance coefficient; θ is road gradient; g is gravity; t is time; and m is gross vehicle weight, including payload.

The tractive power is positive if the vehicle is being actively propelled, whereas the tractive power becomes negative during braking. Braking represents a dissipative force that depletes vehicle kinetic and potential energy. The propulsive energy of a given vehicle over a daily operating time of ΔT is calculated by Equation 2.

$$E_{prop} = \int_{\Delta T} \dot{E}_{tract}\, dt, \forall \dot{E}_{tract} > 0 \quad (2)$$

In conventional vehicles, the engine supplies power to propel the wheels and satisfy accessory loads during idling or braking. Fuel energy consumption and CO_2 emissions of conventional vehicles are calculated based on power train component efficiencies, described in Equation 3a and 3b:

$$E^c_{fuel} = \left[E^c_{acc} + E^c_{prop}/\left(\eta_{wh} \cdot \eta_{fd} \cdot \eta_{gb} \cdot \eta_{cl}\right)\right]/\eta_{eng}, \quad (3a)$$

$$f^c_{CO2} = \frac{E^c_{fuel}\delta_{carbon} \cdot M_{CO2}/M_{Carbon}/LHV_{fuel}}{mileage}, \quad (3b)$$

where η_{wh}, η_{fd}, η_{gb} η_{cl}, and η_{eng} are the efficiencies of the wheel, final drive, transmission, clutch, and engine, respectively; E^c_{acc} is the accessory load in a given conventional vehicle; M_{Carbon} and M_{CO2} are the molecular weights of carbon and CO_2, respectively; δ_{carbon} is fuel carbon content; LHV_{fuel} is fuel lower heating value; and the superscript c indicates a conventional vehicle. The current study assumes long-haul trucks use diesel fuel so that δ_{carbon} and LHV_{fuel} are 0.862 and 42.6 MJ/kg [15].

In electric vehicles, electric energy from the battery is based on the efficiencies of the motor and battery, drivetrain components (including final drive and wheel), and electric accessory load, as described in Equation 4:

$$E^e_{batt} = E^e_{acc} + E^e_{prop}/\left(\eta_{wh} \cdot \eta_{fd} \cdot \eta_{mot} \cdot \eta_{batt}\right) - E^e_{regen}, \quad (4)$$

where $E^e_{regen} = \eta_{regen} \cdot \int_{\Delta T} \dot{E}_{tract}\, dt, \forall\left(\dot{E}_{tract} < 0\right)$ is the electrical energy generated from braking energy regeneration and is very limited in long-haul trucks typically driving on highways, η_{regen} is the efficiency of the regenerator; η_{mot}, η_{batt}, and η_{chg} are the efficiencies of the motor, battery, and charger, respectively; E^e_{acc} is overall electrical energy for accessory load; and the superscript e represents electric vehicle.

Although electric vehicles have zero tailpipe emissions, the used electric energy is generated by the electric power industry using fossil fuels and renewable clean energy. Thus, the GHG emissions of E-trucks are estimated based on the consumed electric energy, CO_2 produced per kilowatt-hour of US electricity generation, and battery charging efficiency and electricity loss during transmission and distribution, as described in Equation 5:

$$f^e_{CO2} = \frac{E^e_{batt}\alpha_{CO2}/(1-\Delta\delta_{dist}) \cdot \eta_{chg}}{mileage}, \quad (5)$$

where α_{CO2} is the averaged CO_2 produced per kilowatt-hour of US electricity generation, which is 417.3 g/kWh estimated based on the 2019 US total electricity generation by the electric power industry [28]; $\Delta\delta_{dist}$ is an electricity loss factor during transmission and distribution, which is 0.05 [29]; and η_{chg} is battery charger efficiency, which is assumed to be 0.96 [19].

The CO_2 emissions described in Equations 3 and 5 do not account for payload. Although the current battery technology has been substantially improved, it still leads to a significant weight penalty, particularly in the case of long-haul truck electrification. Thus, payload-based CO_2 emission, referred to as freight CO_2 emission, was evaluated for conventional and E-trucks, respectively, given as Equation 6a and 6b:

$$f^c_{CO2/payload} = \frac{f^c_{CO2}}{m^c_{payload}}, \quad (6a)$$

$$f^e_{CO2/payload} = \frac{f^e_{CO2}}{m^e_{payload}}, \quad (6b)$$

$$m^c_{payload} = m^c_{GVW} - m^c_{tare}, \quad (6c)$$

$$m^e_{payload} = \begin{cases} m^e_{GVW} - m^e_{tare} & \forall\, m^e_{GVW} < m_{GVW,thre} \\ m_{GVW,thre} - m^e_{tare} & \forall\, m^e_{GVW} \geq m_{GVW,thre} \end{cases}, \quad (6d)$$

$$m^e_{tare} = m^c_{tare} + \left(m_{batt} + m_{mot} + m_{cov/inv} - m_{eng} - m_{cpl} - m_{gb} - m_{at}\right), \quad (6e)$$

where m_{batt}, m_{mot}, $m_{cov/inv}$, m_{eng}, m_{cpl}, m_{gb}, and m_{at} are the weights of the battery, motor, converter/inverter, engine, clutch, gearbox, and aftertreatment system, respectively. These component weights are estimated based on their peak powers, except for the battery. Battery weight is determined based on battery energy capacity. The detailed mass estimations have been addressed in our previous works [5, 11]. In Equation 6d, $m_{GVW,thre}$ is the maximum standard weight for a Class 8 truck allowed in the United States, given as 36.4 ton (80,000 lb.). In Equation 6c, m^c_{GVW} and m^c_{tare} represent the typical conventional long-haul truck loaded weight and tare weight (i.e., with an empty trailer), respectively, which are given as 34.1 tons (75,000 lb.) and 15.9 tons (35,000 lb.), respectively. This indicates the simulated conventional truck payload is about 18.2 tons (40,000 lb.). The E-truck payload, $m^e_{payload}$, is estimated based on Equation 6d and 6e, where the payload penalty depends on battery properties (i.e., battery capacity and energy density) and is partially offset by the lightweight electric power train because of the removal of the engine, among other factors.

In addition, en-route charging activities were considered for electric vehicles to reduce battery capacity need and extend driving range. The charging process is substantially related to charger power level, charging time, and battery capacity. Battery capacity, charging events, and charger infrastructure need are identified using Equation 7 together with Equation 4:

$$E^e_{batt} = n_{chg} \cdot \eta_{chg} \cdot \int_{\Delta t_{chg}} W^e_{chg} dt + (1 - SOC_{lb}) \cdot C_{batt} \qquad (7)$$

where C_{batt} is battery capacity; n_{chg} is the number of charging events (the charging events are assumed to be distributed evenly during the daily driving energy consumption); η_{chg} is charger efficiency; W^e_{chg} is charging power; Δt_{chg} is charging time; and SOC_{lb} is the low-boundary state of charge for battery protection, which is assumed to be 10%. In addition, E-trucks are assumed to be fully charged before starting daily service.

The method has been well validated with MD/HD conventional and electric vehicles and is reported in Gao et al. [11]. To avoid a lengthy description, the details are not provided here.

Vehicle Parameters and Assumptions

The studied baseline conventional long-haul truck was established based on an ORNL in-house database and open literature. The key components considered included the engine, clutch, gearbox, final drive, wheel, and chassis. The key parameters of the long-haul truck are listed in Table 3, in which the frontal area, rolling resistance, and drag coefficient were estimated based on the ORNL MD/HD vehicle database. Also, average efficiencies for each power train and drivetrain component were assumed [11]. Constant average values for the accessory power were therefore used. The considered gross vehicle weight of the conventional long-haul truck was based on the statistical data provided in Fleet DNA.

For Class 8 long-haul E-trucks, the major components considered were the battery, motor, final drive, wheel, and chassis. Similarly, constant average efficiencies for motor and battery components were assumed [5, 11]. The key parameters of the long-haul E-truck are shown in Table 3. Other drivetrain components and chassis parameters were considered as the same as those used in the conventional vehicle. A constant average value of accessory load was considered in the modeled electric vehicle, but the accessory load in the electric vehicle was assumed to be 50% less than that in a conventional vehicle. An identical assumption has been widely used in open literature because of lower accessory energy consumption in electric vehicles [14, 30, 31]. The E-truck weight was estimated based on the comparable conventional vehicle weight plus the E-truck weight penalty predicted using Equation 6e under a given battery capacity. Three representative battery energy densities were considered to address current technology and future technology. In addition, electric vehicles usually use a streamlined body/chassis design that achieves a low drag coefficient, and low–rolling resistance tires are normally employed. Thus, two sets of chassis parameters were considered in the simulations to identify their potential benefits on long-haul truck electrification.

Table 3. Key parameters used for modeled conventional and battery electric vehicles.

Key parameters		Baseline conventional truck	E-truck
Regular chassis	Regular aerod. drag ($c_d \cdot A_f$)	5.22	5.22
	Regular c_{rr}	0.007	0.007
Streamlined chassis	Ultralow aerod. drag ($c_d \cdot A_f$)	—	3.24
	Ultralow c_{rr}	—	0.004
Engine efficiency		40.5%	—
Clutch efficiency		86%	—
Transmission efficiency		92%	—
Final drive efficiency		98%	98%
Wheel efficiency		99%	99%
Motor efficiency		—	88%
Battery	Battery efficiency	—	98%
	Energy density (Wh/kg)	—	150, 275, or 400
Conv_acc (kW)		8	—
BEV_acc (kW)		—	4
Gross vehicle weight (kg)		34,068	See Eq. 6d
Superfast charging	Charging power (kW)	—	250, 500, or 750
	Charging efficiency	—	96%

En-route charging is necessary during an E-truck's daily route operation. As shown in Figure 1(b), more than 90% of Class 8 long-haul trucks have two or more daily stop events of at least 30 min. The long-stop events were considered here as opportunities for E-truck daily en-route charging. To simplify the current electrification studies and analyses, a superfast recharging technology was considered which enables 250, 500, and 750 kW and conducts 1 h of en-route charging per day. The charger efficiency was assumed to be 96%, accounting for the entire charging procedure from grid electricity to E-truck battery. In the studies, the study doesn't consider battery aging related to fast charging and high charging powers and currents.

RESULTS AND DISCUSSIONS

To understand the challenges of long-haul truck electrification and identify potential cost-effective pathways, energy consumption, CO_2

emissions, battery capacity needs, and payload penalty were simulated as functions of year-round service coverage**,** streamlined chassis, battery energy density, superfast charging, and their combination.

Challenge of Long-Haul Truck Electrification

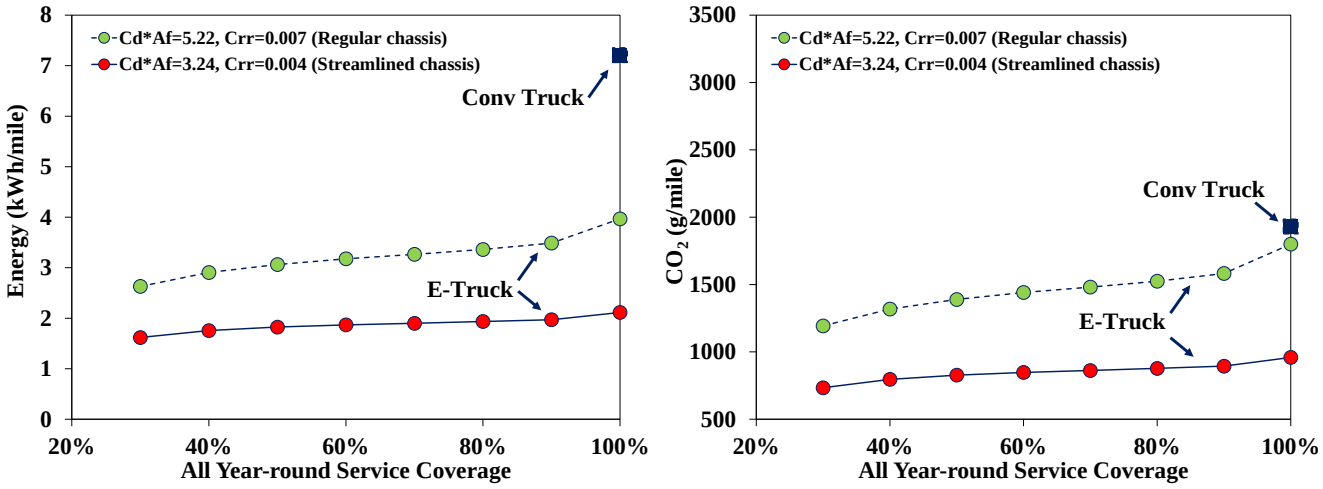
Figure 3 compares the energy consumption and CO_2 emissions of the baseline conventional long-haul truck with those of the comparable E-truck at various levels of year-round service coverage. The comparable E-truck adopts the regular chassis design (i.e., $c_d \cdot A_f = 5.22$) and 150 Wh/kg battery energy density, both of which reflect current technologies available for the long-haul truck application. To identify the challenges of long-haul truck electrification, en-route charging was not considered in these cases. Without considering payload issues, the comparable E-truck achieves substantial energy savings. Figure 3(a) shows that the comparable E-truck achieves energy savings of 53% at 80% of year-round service coverage and 64% at 30% of year-round service coverage. However, the energy consumption of conventional long-haul trucks is based on diesel fuel consumption, and the energy consumption of the long-haul E-truck is based on grid energy, which also emits CO_2 during power generation. Thus, unbiased CO_2 emissions (i.e., CO_2 g/mi.) were compared (Figure 3[b]). The detailed data show that the comparable E-truck achieves a CO_2 emissions reduction of 21% at 80% of year-round service coverage and 38% at 30% of year-round service coverage, considerably less than the energy saving shown in Figure 3(a).

Figure 4 indicates that the challenges of long-haul truck electrification are tremendous battery capacity need, substantial mass penalty, and payload reduction for the scenario without vehicle chassis optimization, battery energy density enhancement, and innovative charging technology. For example, the required battery capacities are 903 and 2,094 kWh for 30% year-round service coverage (~250–300 mi./day) and 80% year-round service coverage (~600–650 mi./day), respectively, leading to 18% and 74% payload penalties compared with the baseline conventional long-haul truck. Figure 5 shows that freight-based CO_2 emissions of the comparable E-truck are comparable to those of the baseline conventional long-haul truck only at very low year-round service coverage. Thus, understanding the impact of E-truck chassis optimization, battery energy density, and superfast charging technology is vital in the pursuit of optimal truck electrification.

Impact of Streamlined Chassis

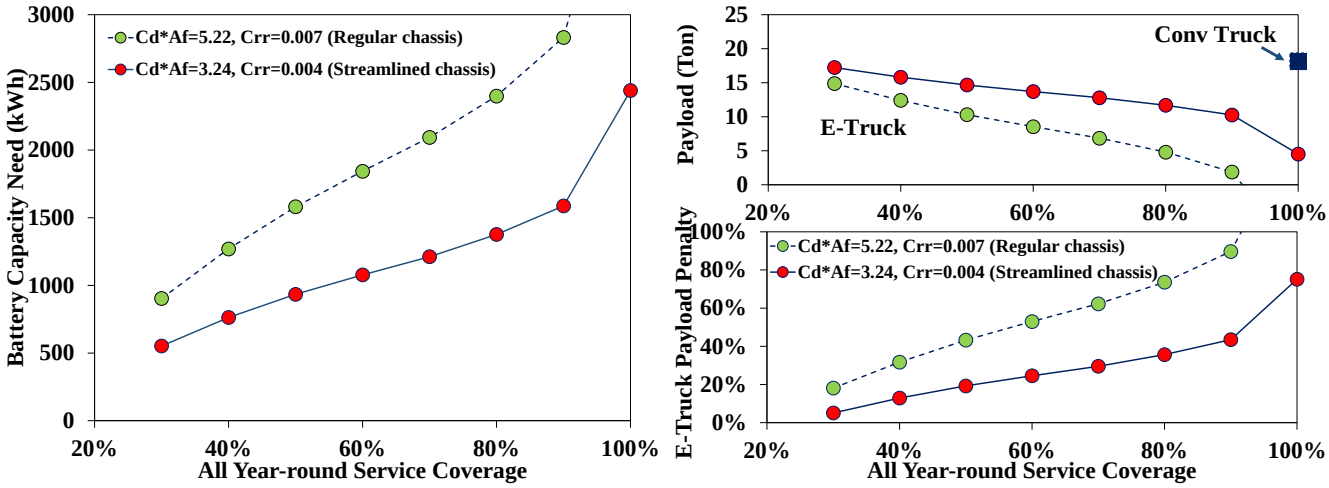
The impacts of a regular chassis and a streamlined chassis in the E-trucks were evaluated and compared. In Figures 3 and 4, the streamlined chassis design substantially reduces the E-truck energy consumption, battery capacity need, and payload penalty. For example, compared with the regular chassis, the streamlined chassis design (i.e., $c_d \cdot A_f = 3.24$) enables truck electrification energy savings of around 38%–42%, corresponding to approximately 30%–80% of year-round service coverages (Figure 3[a]). Subsequently, the battery capacity is reduced from 903~2,094 kWh to 552~1,376 kWh. The payload penalty is correspondingly reduced from 18%~74% to 5%~36%. Compared with the regular chassis, the streamlined chassis substantially reduces CO_2 emissions (by 39% and 42% at 30% and 80% of year-round service coverages, respectively). In particular, the study reveals that the streamlined chassis of the E-truck yields freight CO_2 emissions that are 46.9%~76% less than those of the baseline conventional truck for 30%~80% year-round service coverage cases. This is significant decarbonization based on freight efficiency.

Although the streamlined chassis has significant benefits in energy savings, freight CO_2 emissions reduction, and payload capacity improvement, it is still not sufficient to achieve a driving range that covers 90% or more of year-round service without intolerable battery capacity, poor payload, and significant cost penalties. This state of affairs suggests that optimal long-haul E-trucks require innovative batteries and superfast charging technologies.



(a) Energy consumption (b) CO_2 emissions

Figure 3. Comparison of energy consumption and CO_2 emissions between conventional and electric long-haul trucks for regular and streamlined chassis designs as a function of year-round service coverage. En-route charging was not considered for this case. Battery energy density is 150 Wh/kg.



(a) Battery capacity need (b) Payload

Figure 4. Impact of long-haul truck electrification on (a) battery capacity need and (b) payload for regular and streamlined chassis designs as a function of year-round service coverage. En-route charging was not considered. Battery energy density is 150 Wh/kg.

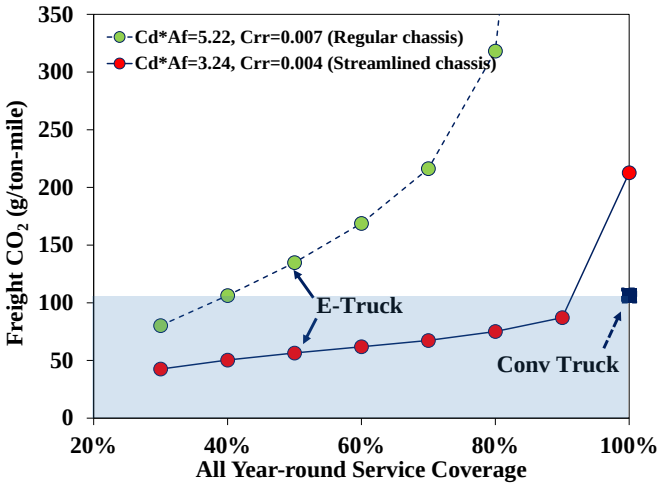
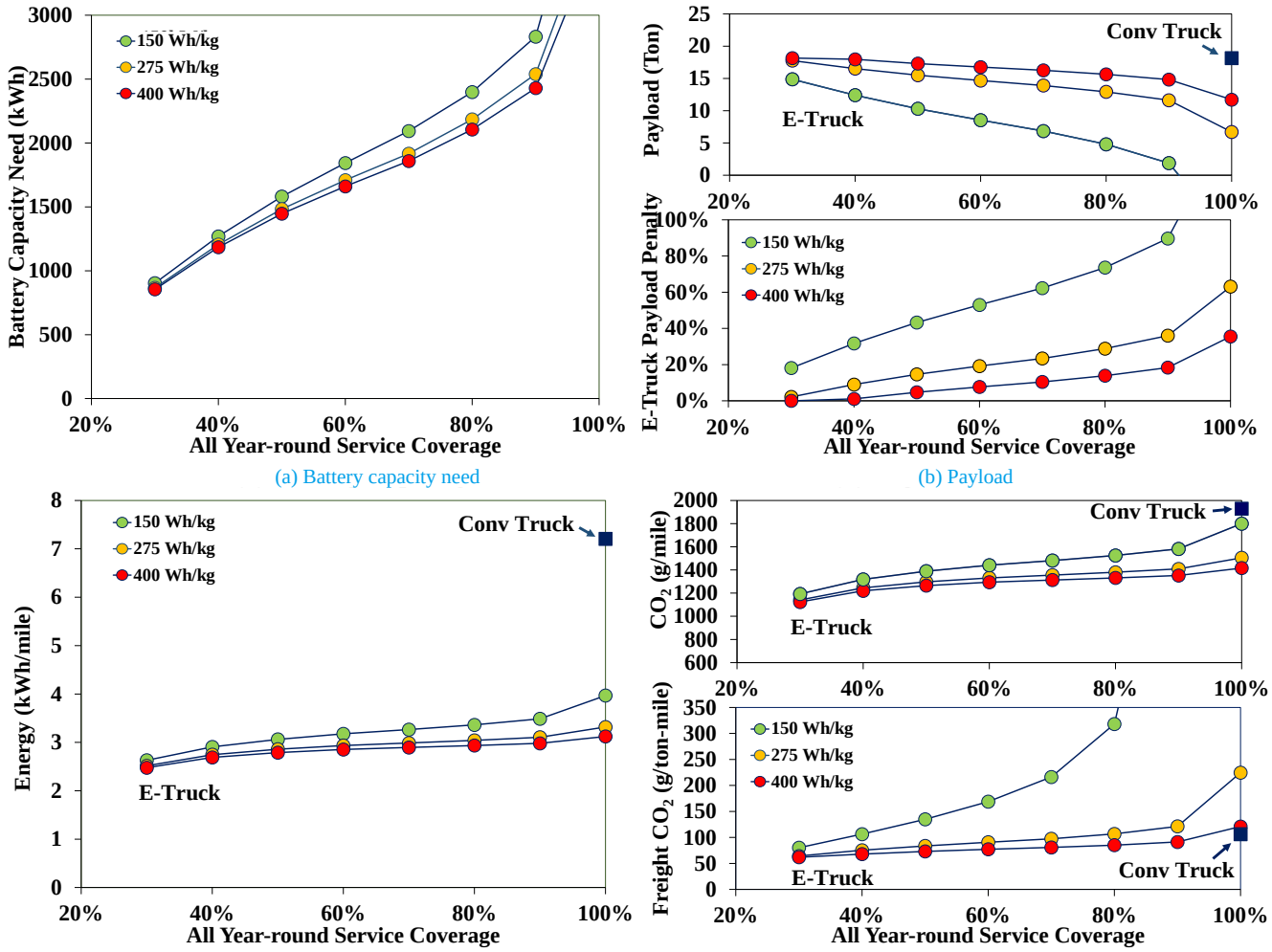


Figure 5. Freight CO_2 emissions of long-haul truck electrification for regular and streamlined chassis designs as a function of year-round service coverage. En-route charging was not considered. Battery energy density is 150 Wh/kg.

Impact of Future Battery Energy Density

A higher specific battery energy decreases the amount of material needed for the same total battery energy, thus reducing mass and possibly cost. The current energy density of a lithium-ion commercial battery cell is around 90~190 Wh/kg, depending on the manufacturer and what the cell is optimized for [32]. Tesla has stated that a 400 Wh/kg cell with high cycle life is not far away [33]. Therefore, it is important to understand the impact on truck electrification of increasing the energy density beyond that of today's battery. Results are shown in Figure 6, where en-route charging was not considered and a regular chassis design was used in the simulated E-truck. In the parametric analysis, 150 Wh/kg was used as a representative energy density of the commercial lithium-ion battery cells currently on the market, and 275 and 400 Wh/kg were assumed as future battery energy densities.

The results (Figure 6[a]) show that the 275 and 400Wh/kg densities only slightly alter the battery capacity need because various battery energy densities do not alter the tractive energy consumption under the maximum weight (i.e., 36.4 tons or 80,000 lb.) for a long-haul E-truck in the United States. Accordingly, the energy savings are minor (Figure 6[c]). The key benefit of 275 and 400 Wh/kg densities is the significant payload penalty reduction, which is important to fleets. As shown in Figure 6(b), a 275 Wh/kg density results in 2% and 29% payload penalties for 30% and 80% of year-round service coverage, respectively, compared with 18% and 74% payload penalties for an energy density of 150 Wh/kg. The 400 Wh/kg density results in 0% and 13% payload penalties for the 30% and 80% of year-round service coverage scenarios, respectively. Compared with the case of the streamlined chassis and 150 Wh/kg density (shown in Figure 4), the 275 and 400 Wh/kg cases with a regular chassis design can reduce payload loss. Significant payload improvements with 275 and 400 Wh/kg densities leads to improved freight CO_2 emissions as well, as shown in Figure 6(d).



(a) Battery capacity need (b) Payload

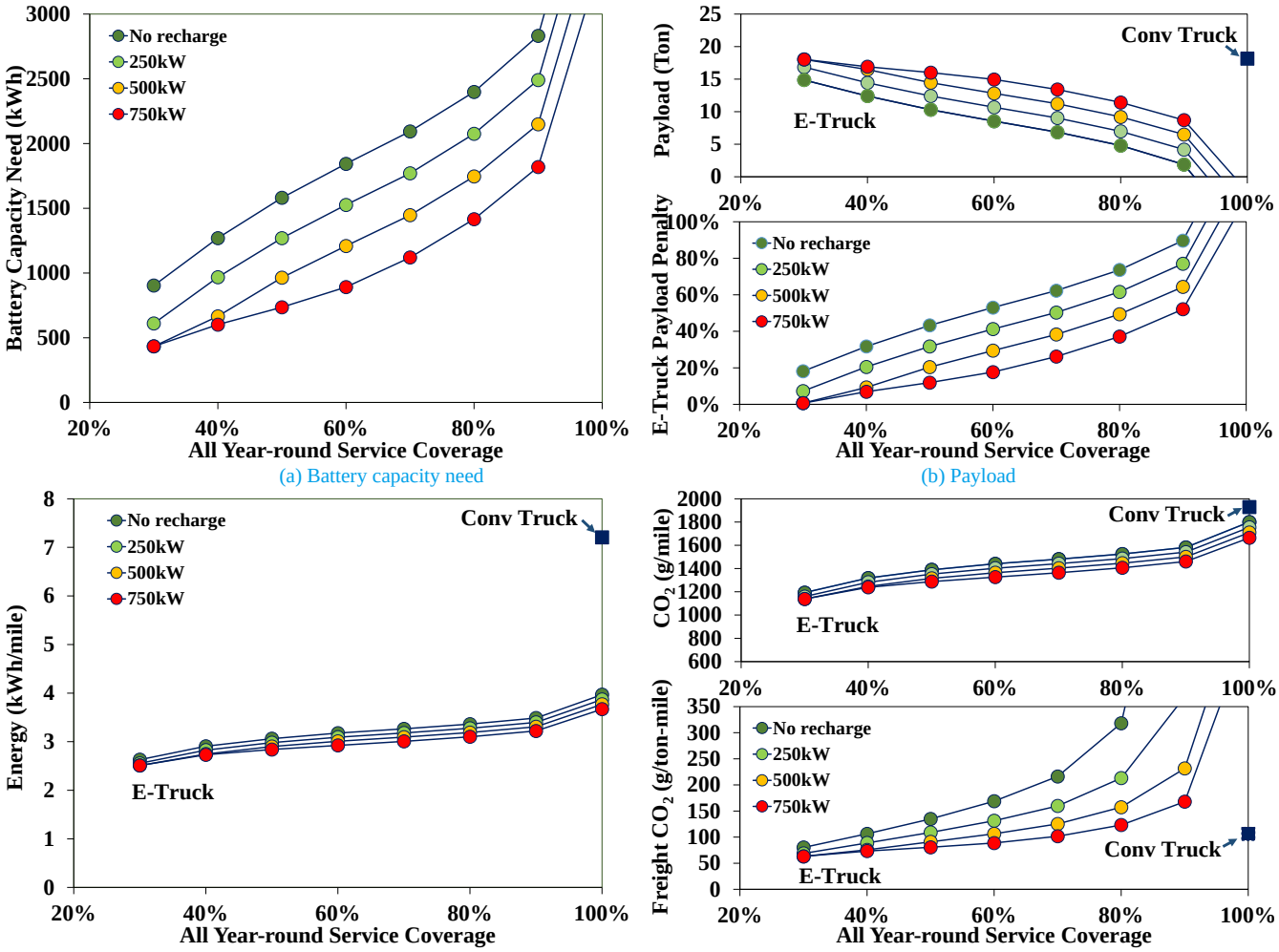
(c) Energy consumption (d) CO_2 emissions

Figure 6. Comparison of battery capacities, payloads, energy consumption, and CO_2 emissions between conventional and electric long-haul trucks with various battery energy densities as functions of year-round service coverage. En-route charging was not considered. The E-truck was simulated with a regular chassis design (i.e., $c_d \cdot A_f = 5.22$ and $c_{rr} = 0.007$).

Impact of En-Route Charging and Charger Power

En-route charging is widely considered a practical approach for extending E-truck driving range and reducing battery capacity [34]. Scenarios with 1 h en-route daily charging with various charging powers were evaluated. The results are plotted in Figure 7, in which the simulated E-truck is considered with a regular chassis. Higher superfast charging power reduces the battery capacity need as well as payload loss. Figure 7(a) and 7(b) reveal that, for 80% year-round service coverage, a 1 h, 250 kW charging event results in a battery capacity requirement of approximately 2,075 kWh with a payload penalty of 62%. On the other hand, 1 h charging at 500 and 750 kW reduces the battery capacity need to approximately 1,746 and 1,416 kW, respectively, with payload penalties of 49% and 37%. Figure 7(a) and 7(b) indicates that it is difficult to cover 100% year-round service even with the 750 kW charging without E-truck chassis optimization and battery energy density improvement.

Like battery energy density**,** superfast charging improves payload, but it does not benefit E-truck energy savings (Figure 7[c]). Superfast charging also does not alter E-truck tractive energy. So, CO_2 emissions vary slightly, but freight CO_2 emissions are reduced significantly with higher superfast charging power, as shown in Figure 7(d). This is because of payload improvement due to superfast charging.



(a) Battery capacity need (b) Payload

(c) Energy consumption (d) CO_2 emissions

Figure 7. Comparison of battery capacities, payloads, energy consumption, and CO_2 emissions between conventional and electric long-haul trucks with various 1 h en-route charging powers as functions of year-round service coverage. Battery energy density is 150 Wh/kg. The E-truck was simulated with a regular chassis design (i.e., $c_d \cdot A_f = 5.22$ and $c_{rr} = 0.007$).

Optimal Truck Electrification with the Combined Technologies

Figures 4–7 show that no single technology can provide significant, simultaneous improvements in energy savings, freight CO_2 emissions, battery capacity need, and payload penalty. Table 4 summarizes the individual benefits, based on an E-truck with a regular chassis, 150 Wh/kg battery energy density, and no en-route charging so that it is comparable to the conventional power train long-haul truck. The streamlined chassis is the top approach, enabling energy savings, freight CO_2 emissions reduction, and battery capacity reduction, and it can also significantly reduce payload penalty. Increasing the battery energy density causes the E-truck to achieve its greatest payload improvement. Also, superfast en-route charging reduces the battery capacity needs and improves payload capacity significantly. However, higher battery energy density and superfast en-route charging do not enhance energy savings. Therefore, the combination of these approaches will probably yield the most cost-effective solution for optimal truck electrification.

Table 4. Summary of benefits for advanced individual technologies on long-haul truck electrification for 80% year-round service coverage. [a]

Technology	Parameters	Battery capacity reduction [a]	Payload improvement [a]	Energy savings [a]	Freight CO_2 reduction [a]
Streamlined chassis	$c_d \cdot A_f = 3.24$ and $c_{rr} = 0.004$	42.6%	38%	42.2%	76.4%
Battery energy density (Wh/kg)	275	8.9%	45%	9.5%	66.4%
	400	12.2%	60%	12.8%	73.2%
Superfast charging (kW)	250	13.5%	12%	2.3%	33.0%
	500	27.2%	25%	5.1%	50.6%
	750	41.0%	37%	7.7%	61.3%

[a] This is compared with a baseline E-truck which has a regular chassis, 150 Wh/kg battery energy density, and no en-route charging.

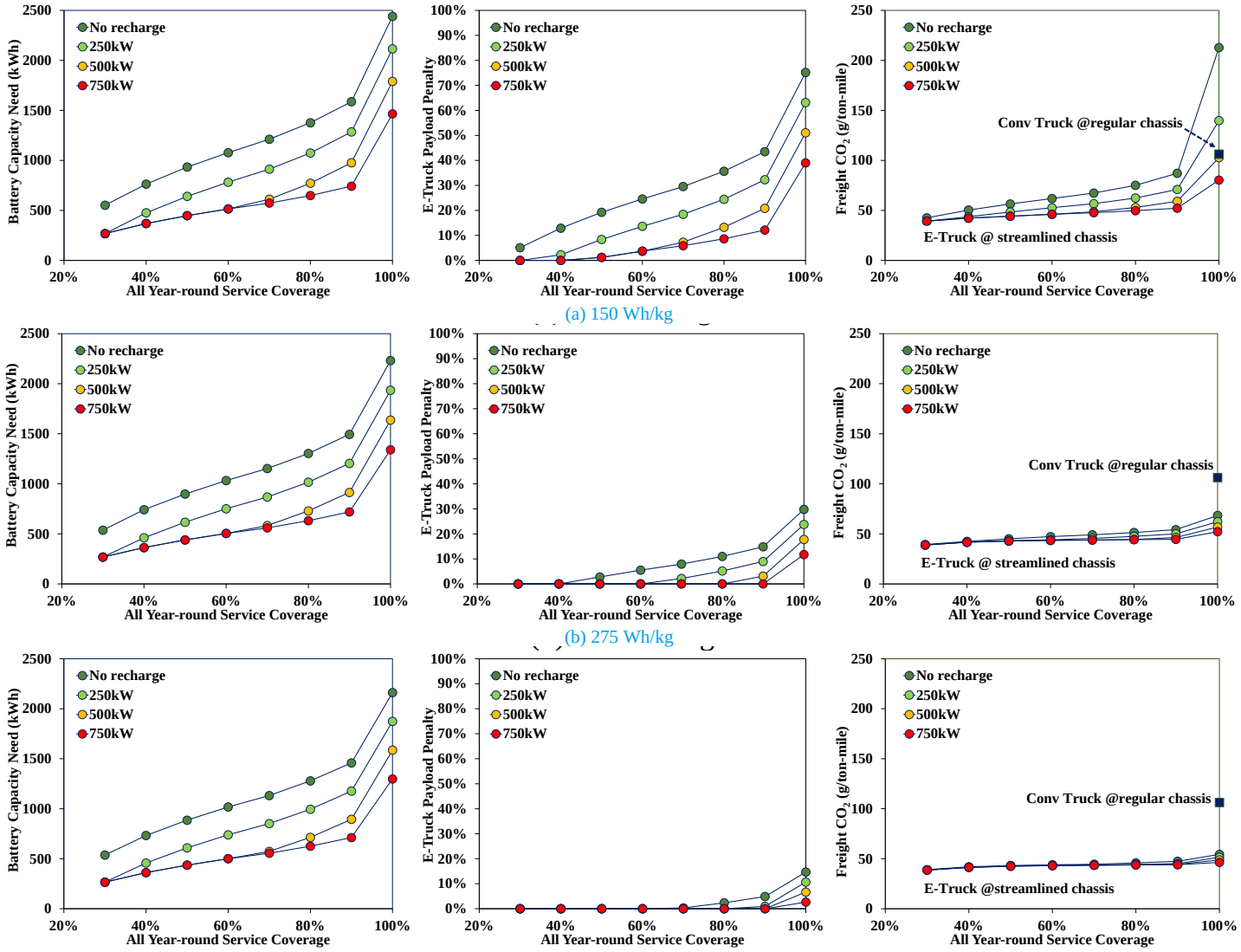


Figure 8. Comparison of battery capacities, payloads, and freight CO_2 emissions between the baseline conventional truck and the electric long-haul truck with a streamlined chassis design (i.e., $c_d \cdot A_f = 3.24$ and $c_{rr} = 0.004$) with various 1 h en-route charging powers and battery energy densities as a function of year-round service coverage.

Figure 8 displays results for combinations of streamlined chassis, battery energy density, and en-route superfast charging. The combination of 275 Wh/kg battery energy density and 1 h en-route charging of 500 kW requires 729 kWh battery capacity to satisfy up to 80% of year-round service coverage (up to 700–750 mi./day), which is very close to the combination of 400 Wh/kg battery energy density and 750 kW charging power. Meanwhile, the payload penalty in the combination of 275 Wh/kg battery energy density and 500 kW charging is nearly zero. Freight CO_2 emissions are 44.4 g/ton-mi., which are 58.2% less than those of the baseline conventional truck. Even for 100% of year-round service coverage (up to ~1,000 mi./day), the battery capacity need is 1,637 kWh, but the payload penalty is just 18%. The freight CO_2 emissions are 56.8g/ton-mi., which are 46.6% less than those of the baseline conventional truck. Considering payload, energy consumption, and decarbonization, it is practicable to achieve long-haul electrification with the combination of future advanced streamlined chassis, battery, and charging technology while achieving significant freight decarbonization.

The results in Figure 8 indicate that cost-effective long-haul truck electrification requires a comprehensive integration of optimal technologies. The extreme improvement of battery energy density or superfast charging alone does not have a linear benefit for truck electrification enhancement because the benefit degrades after hitting a threshold. For example, when battery energy density is increased to 275 Wh/kg, charging technology of more than 500 kW is no longer attractive, and the added benefits from 750 kW charging are very limited compared with 500 kW, whereas the cost and technology challenges grow exponentially. These insights may help guide and balance the development of optimal E-truck technologies.

In addition, from Figure 8, with a streamlined chassis, 275~400 Wh/kg battery energy density, and 500–750 kW superfast charging, the E-truck can achieve 100% year-round service coverage (~1,000 mi./day). In this case, the payload penalty is no more than 18%, and the battery capacity need is no more than 1,600 kWh. The 18% payload loss is acceptable because the freight CO_2 emissions are still reduced by more than 46.5%. Although the battery capacity need is higher, the E-truck's

battery cost actually may be reduced because of less material consumption with higher–energy density technology.

CONCLUSION

The paper presents an analysis of Class 8 long-haul truck electrification using ORNL's CVEET and NREL Fleet DNA drive data. The work focused on understanding the impact of streamlined chassis, battery energy density, and superfast charging technology on battery capacity need, payload, energy consumption, and GHG emissions in long-haul truck electrification. An optimal combination of the key technologies needed for E-trucks to conduct all conventional long-haul operations was identified.

The results show that the streamlined chassis is the best option for reducing energy consumption, freight CO_2 emissions, and battery energy capacity needs as well as for decreasing payload loss significantly, although higher battery energy densities improve payload the most. En-route superfast charging can reduce both the battery capacity need and payload loss significantly. However, higher battery energy density and superfast charging do not enhance energy savings. The outstanding gains from battery energy density or superfast charging without energy savings do not have a linear benefit for truck electrification enhancement because the benefit degrades after hitting a threshold. The results reveal that a single technology cannot simultaneously achieve significant improvement in all these key results for E-trucks. Consequently, to realize optimal truck electrification while providing energy savings, lower battery capacity, small payload loss, and significant CO_2 reduction, a optimal combination of all three technologies is required for a cost-effective approach.

Vehicle technologies are continuously evolving to create innovative vehicle designs, new battery materials, and improved superfast charging, and battery cost is continuously decreased. Although electric vehicle technology has demonstrated early promise for the electrification of HD trucks, continued innovations are necessary to enable a long-haul E-truck that cost-effectively achieves the same service coverage as conventional diesel trucks. In particular, fuel cell powertrain may provide substantial potential to increase the overall system energy density and allow for downsized battery packs in the future electrification of HD trucks.

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Acknowledgments

This work was sponsored by the US Department of Energy’s Vehicle Technologies Office, Advanced Research Projects Agency–Energy, and ORNL Building Technologies Research and Integration Center. The author appreciates ORNL colleagues’ help with technical editing the manuscript. The thanks also go to SAE paper reviewers’ time and suggestions and comments that make the paper better.

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