Renewable and Sustainable Energy Transition 2 (2022) 100038

Contents lists available at ScienceDirect

Renewable and Sustainable Energy Transition

journal homepage: www.journals.elsevier.com/renewable-and-sustainable-energy-transition

Full-length article

Charging needs for electric semi-trailer trucks

Brennan Borlaug [a,*], Matthew Moniot [a], Alicia Birky [a], Marcus Alexander [b], Matteo Muratori [a]

[a] National Renewable Energy Laboratory, 15013 Denver West Parkway, Golden, CO 80401, United States
[b] Electric Power Research Institute, 3420 Hillview Ave., Palo Alto, CA 94304, United States

ARTICLE INFO

Keywords:
Electric vehicle
EV
Heavy-duty vehicle
HDV
Freight
Charging infrastructure
EVSE
Battery
Transportation

ABSTRACT

Battery-electric vehicles provide a pathway to decarbonize heavy-duty trucking, but the market for heavy-duty battery-electric semi-trailer trucks is nascent, and specific charging requirements remain uncertain. We leverage large-scale vehicle telematics data (>205 million miles of driving) to estimate the charging behaviors and infrastructure requirements for U.S. battery-electric semi-trailer trucks within three operating segments: local, regional, and long-haul. We model two types of charging—mid-shift (fast) and off-shift (slow)—and show that off-shift charging at speeds compatible with current light-duty charging infrastructure (i.e., ≤350 kW) can supply 35 to 77% of total energy demand for local and regional trucks with ≥300-mile range. Megawatt-level speeds are required for mid-shift charging, which make up 44 to 57% of energy demand for long-haul trucks with ≥500-mile range. However, demand shifts from mid-shift to off-shift charging as the range for battery-electric trucks increases and when off-shift charging is widely available. Finally, we observe geographic trends in charging demand, finding that local trucks have greater demand within urban areas, whereas long-haul trucks have more demand along rural interstate corridors. As the range for battery-electric trucks increases, we show that charging demand shifts from rural to urban locations due to observed vehicle dwell tendencies.

1. Introduction

In November 2021, the United States updated its long-term strategy, committing to net-zero emissions by no later than 2050, with 50%–52% emissions reduction by 2030 [1]. To achieve these goals, rapid decarbonization is required across all sectors of the economy. Transportation accounts for 29% of U.S. greenhouse gas emissions, the highest share of any end-use sector [2], and in 2020, fossil fuels were responsible for 96% of total U.S. transportation energy use [3]. Despite accounting for <2% of vehicles on the road [4], heavy-duty semi-trailer trucks, with gross vehicle weight >26,000 lbs., are responsible for 15% of U.S. transport energy use and carbon emissions, second only to light-duty vehicles [5]. They are also major contributors of air pollutants (ambient fine particulate matter, $PM_{2.5}$) associated with premature mortalities that disproportionately affect certain communities [6,7]. Despite this, the vast majority (>99%) of new U.S. heavy-duty vehicle sales in 2020 were diesel-powered [8].

Given the urgency needed to meet near-term carbon reduction targets, several states,[1] starting with California, have approved the Advanced Clean Trucks (ACT) rule, mandating an increasing share of all medium-duty (gross vehicle weight >8,500 lbs.) and heavy-duty truck sales be zero-emission vehicles beginning in 2024 [9]. In addition, 16 states[2] (and the District of Columbia) have committed to 100% medium- and heavy-duty zero-emission vehicle sales by 2050 [10]. Today, the U. S. market for zero-emission semi-trailer trucks is nascent. Most current deployments involve battery-electric vehicles (BEVs) in pilot demonstrations. However, the market is set for rapid growth, with 19 models [11] (14 BEVs and 5 hydrogen fuel cell vehicles) becoming available by 2023, many generating large preorders [12]. BEVs, once considered impractical for heavy applications, have experienced significant technology and cost improvements in the previous decade [13], and are now viewed as promising options to decarbonize heavy-duty trucking. In fact, several recent studies show that reduced operating costs, due to highly efficient low-maintenance electric motors, could enable heavy-duty battery-electric semi-trailer trucks (HDBETs) to become a cost-effective near-term option (on a total cost of ownership basis) for

* Corresponding author.
E-mail address: brennan.borlaug@nrel.gov (B. Borlaug).

[1] Includes California, Massachusetts, New Jersey, New York, Oregon, and Washington at the time of writing.

[2] Includes California, Colorado, Connecticut, the District of Columbia, Hawaii, Maine, Maryland, Massachusetts, New Jersey, New York, North Carolina, Oregon, Pennsylvania, Rhode Island, Vermont, Virginia, and Washington at the time of writing.

https://doi.org/10.1016/j.rset.2022.100038
Received 18 March 2022; Received in revised form 10 August 2022; Accepted 7 October 2022
Available online 12 October 2022

many applications, particularly if charging costs are low [14–16].

For HDBETs to replace conventional diesel trucks, large investments in charging infrastructure (i.e., electric vehicle supply equipment [EVSE]) will be required. While previous studies have shown that some heavy-duty trucking applications can already be electrified with minimal impact to existing operations through private EVSE at fleets' depots [17,18], a public high-speed charging network is needed for long-distance applications [19,20]. Recently, multiple U.S. electric utilities and private companies announced their intentions to build such a network over the coming decade [21,22].

Today, most HDBETs in the United States charge using the Combined Charging System (CCS) standard, enabling DC fast charging up to 350 kW (~3 miles [4.8 km] of range added per minute assuming an average energy consumption rate [ECR] of 2 kWh/mile [1.2 kWh/km]). While well-suited for the light-duty BEVs it was designed for (providing up to 20 miles [32 km] of range per minute), it is generally recognized that CCS cannot provide the charging speeds required by many heavy-duty trucks. Thus, a new Megawatt Charging System (MCS) standard is being developed that is capable of charging at ~10 times the rate of CCS, up to 3.75 MW (~30 miles [48 km] of range per minute) [23]. Undoubtedly, MCS represents a significant advancement, but the actual requirements for HDBETs within various operating segments remain uncertain.

Although several studies have shown the effects of light-duty passenger BEV range on vehicle electrification potential [24–26] and charging requirements [27–29], similar studies for HDBETs are absent. A better understanding of the charging requirements for HDBETs is a precursor to developing and deploying the next-generation EVSE required for widespread electrification [30]. There are also fundamental differences in the operating patterns of passenger and commercial vehicles; thus, the geographic distribution of HDBET charging demand can't be assumed to follow that of light-duty passenger BEVs. This has critical implications for electric utilities attempting to plan for new high-power charging loads in the coming years.

Due to a lack of available large-scale semi-trailer truck operating data, previous electrification studies have relied on simplified assumptions to project HDBET charging requirements [19,20,30-33]. While these studies provide insights on aggregate energy demands, detailed telematics data are necessary to understand how conventional semi-trailer trucks operate today and infer the charging behaviors and requirements for HDBETs. Several studies have used high-resolution truck telematics data, but their scope is restricted to an individual fleet or vocation, such as local delivery [17] or drayage [34,35], limiting generalizability. Liimatainen et al. [36] and Çabukoglu et al. [37] leverage unique vehicle-level travel data sources to assess the electrification potential of heavy-duty trucks in two European countries (Finland and Switzerland). However, there is no such analysis for the United States.

In this study, we investigate HDBET range and charging infrastructure jointly, estimating the charging needs for various battery ranges within three separate operating segments: local, regional, and long-haul. We first examine how increased battery range affects HDBET charging behaviors, comparing the relative frequency of mid-shift fast charging to off-shift slow charging. Next, we quantify the charging speed requirements for HDBETs and show how these vary with respect to multiple factors including battery range, operating segment, and the availability of off-shift charging. Finally, we observe the geographic trends in charging demand within three separate region types: urban areas, rural interstate corridors, and rural non-interstate regions. While there has been concern over the impact of high-range HDBET battery sizes on payload capacity [38,32], this is not addressed here. Improvements and breakthroughs in battery technology are highly uncertain, and this study estimates how HDBET charging network design requirements might vary over a span of future HDBET battery ranges.

2. Data and methods

2.1. National semi-trailer truck telematics data

The telematics data set used in this analysis contains hourly location traces, instantaneous speed, and vehicle odometer readings for 55,633 semi-trailer trucks from a single major original equipment manufacturer operating in North America over a 13-day collection period (July 1–13, 2016). In total, the data set covers ~205 million vehicle miles traveled (VMT) (~330 million km) and includes travel in all states within the contiguous United States, as well as some travel in Alaska, Canada, and Mexico (Fig. 1). This data set has been further described in previous publications [39–41].

Despite its scale and coverage, there are several limitations of the data used in this study. First, operating patterns are observed over a 2-week period that includes a national holiday (July 4) and may therefore not be representative of annual or seasonal travel patterns. For example, the limited collection period does not enable us to observe travel trends or model charging demands in the winter when colder temperatures reduce the effective range of EVs, potentially impacting seasonal charging requirements. Additionally, the data were collected in 2016, so observed operating patterns may not be reflective of current (2022) or future operations. Despite these limitations, to the authors' knowledge, this data set provides the most complete picture of large-scale semi-trailer truck operations in the United States to date.

2.2. Operating segment classification

There is considerable variability in the daily operating requirements of semi-trailer trucks in the United States [17,42]. In this study, truck segments are characterized by their maximum operating radius observed over the collection period. Specifically, the vehicle's *operating radius* refers to the maximum distance traveled from a central location (e.g., a home base or depot) over time. It is a measure of the geographic extent of a truck's operations. For vehicle v, its operating radius (OR) is calculated as:

$$OR_v = \frac{\max(d(C(P_v,\ 2)))}{2} \tag{1}$$

where $C(P_v,\ 2)$ are the combinations of all pairs of n GPS points, $P_v = \{p_{v,1},\ p_{v,2},\ \ldots,\ p_{v,n}\}$, registered for vehicle v. The haversine formula is used to calculate the great-circle distance, d, an approximation of the shortest path distance between two points on the Earth's surface [43].

Trucks are classified as either *local, regional*, or *long-haul* operations based on their observed operating radius (OR), where *local:* $OR \leq 100$ miles (161 km); *regional:* 100 miles $< OR <$ 300 miles (161–483 km); and *long-haul:* $OR \geq 300$ miles (483 km). Fig. 2 shows the distribution of trucks by inferred operating segment in the data set. Note that this distribution may not be nationally representative, as the trucks are all from a single manufacturer without guarantee that systematic bias was avoided during sampling. However, given large within-segment sample sizes, we assume that segment-level groupings are representative of the population of trucks within each operating segment.

2.3. Shift segmentation

Truck operations are segmented into "on-shift" and "off-shift" periods based on observed vehicle activity patterns. A truck's activity is classified as either driving or not (i.e., dwelling) on an hourly basis (data set resolution), where a "driving hour" is one where a truck drives $\geq$5 miles ($\geq$8 km) and a "dwell hour" is one where a truck drives <5 miles. Once an activity is assigned for each hour and all trucks in the data set, a simple heuristic is applied to infer whether a truck is on-shift or off-shift at any time. The rule assumes that trucks are on-shift until a certain number of consecutive "dwell hours" are observed. At that time, a truck

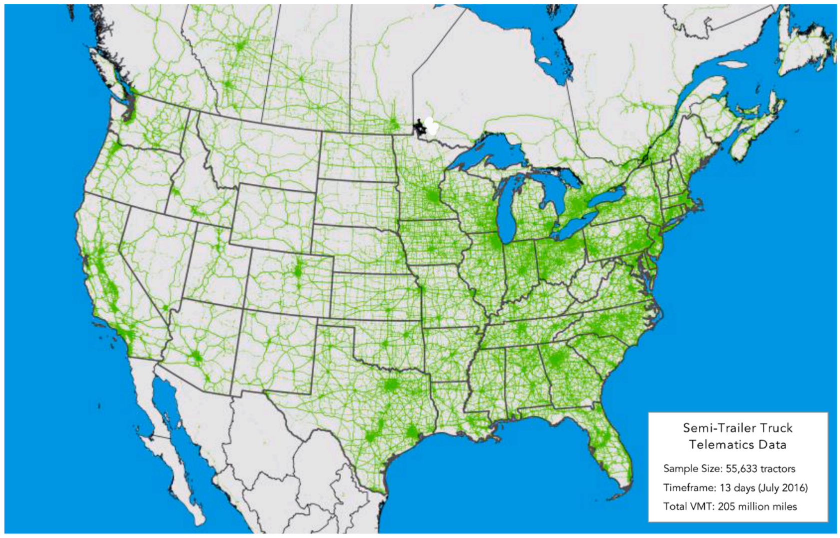

Fig. 1. Geographic coverage of semi-trailer truck telematics data: 205 million miles (330 million km) driven by 55,633 tractors over a 13-day collection period in July 2016.

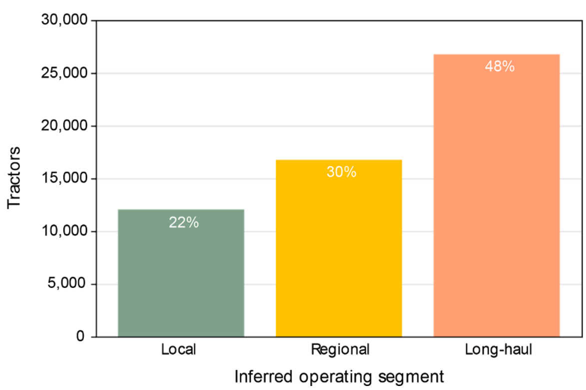

Fig. 2. Distribution of semi-trailer trucks in the data set by operating segment: local (OR ≤ 100 miles), regional (100 miles < OR < 300 miles), and long-haul (OR ≥ 300 miles). A truck's operating radius (OR) represents the maximum distance traveled from a central location such as a home base or depot.

is determined to be off-shift (and potentially available to charge) from the first "dwell hour" in the sequence until the next "driving hour" is observed, indicating the start of a subsequent shift. In the baseline scenario, 8 hours of inactivity is chosen as the threshold for classifying trucks as on-shift or off-shift for its parallel to the 10-h off-duty requirement mandated by the U.S. Federal Motor Carrier Safety Administration [44]. This assumption is conservative from an HDBET charging perspective, in that it limits off-shift charging opportunities to periods of extended inactivity rather than assuming frequent, shorter opportunities to "top off" are available. A sensitivity where this parameter is reduced to 4 hours, reflecting greater opportunity for off-shift charging, is also presented (Table 1).

Fig. 3 shows the cumulative distributions of average daily VMT and average daily off-shift hours, an indication of the opportunity for HDBET charging without disrupting existing operations, for all vehicles in the data set, partitioned by operating segment. These plots enable the observation of within-segment variations and between-segment differences in operating patterns. The average VMT/veh/day and average off-shift hours/veh/day for all trucks in the data set are 283 miles (455 km) and 14.8 hours, respectively, with local trucks driving the least, both in terms of mileage (145 miles [233 km]/veh/day) and duration (16.9 off-shift hours/veh/day), followed by regional trucks (260 miles [418 km]/veh/day and 15.2 off-shift hours/veh/day) and long-haul (360 miles [579 km]/veh/day and 13.6 off-shift hours/veh/day).

Fig. 4 shows the distributions of average shift VMT and maximum shift VMT (i.e., each vehicle's longest shift, with respect to VMT, observed throughout the collection period) within each operating segment assuming 8-hour dwell segmentation (see Fig. S1 for these same distributions with 4-hour dwell segmentation). Note that maximum shift VMT is a proxy for the range required for trucks to be electrified without any operational changes or mid-shift charging. Average shift VMT often exceeds average daily VMT for several reasons. First, trucks are not driven every day. In fact, we find that local, regional, and long-haul tractors are driven on average just 8, 9, and 10 of the 13 days in the collection period, respectively. Second, shift VMT distributions contain a long tail due to slip seating (where multiple drivers share one truck) or team driving (where two drivers ride together and take turns driving during long-haul). In fact, nearly 8% of shifts exceed 1,000 miles in the baseline scenario (8-hour dwell segmentation). The median average shift VMT and median maximum shift VMT (i.e., the median per-vehicle maximum shift length observed over the collection period—indicative of the range required for 50% of trucks to be electrified without any operational changes or mid-shift charging) for local trucks is 229 miles (369 km)/shift/veh and 331 miles (533 km)/shift/veh, respectively; for regional trucks it is 431 miles (694 km)/shift/veh and 603 miles (970 km)/shift/veh, and for long-haul trucks it is 520 miles (837 km)/shift/veh and 791 miles (1,273 km)/shift/veh, respectively.

Table 1
Off-shift "slow" charging availability scenarios.

SC Availability Scenario	Description
Baseline	SC available at 75% of ≥8-h dwells
Low SC	SC available at 50% of ≥8-h dwells
High SC	SC available at 100% of ≥4-h dwells

SC: slow charging

2.4. Simulating HDBET charging

A BEV's range depends on its usable battery capacity (kWh) and ECR (kWh/mi); however, the ECR for real-world operations is variable due to multiple factors, including driving style [45], tractor/trailer aerodynamics [46,47], vehicle weight (including payload) [48], ambient temperature [49], road grade [50], and traffic conditions [51,52]. To highlight the association between HDBET range and charging infrastructure in this study, range is assumed and analyzed without

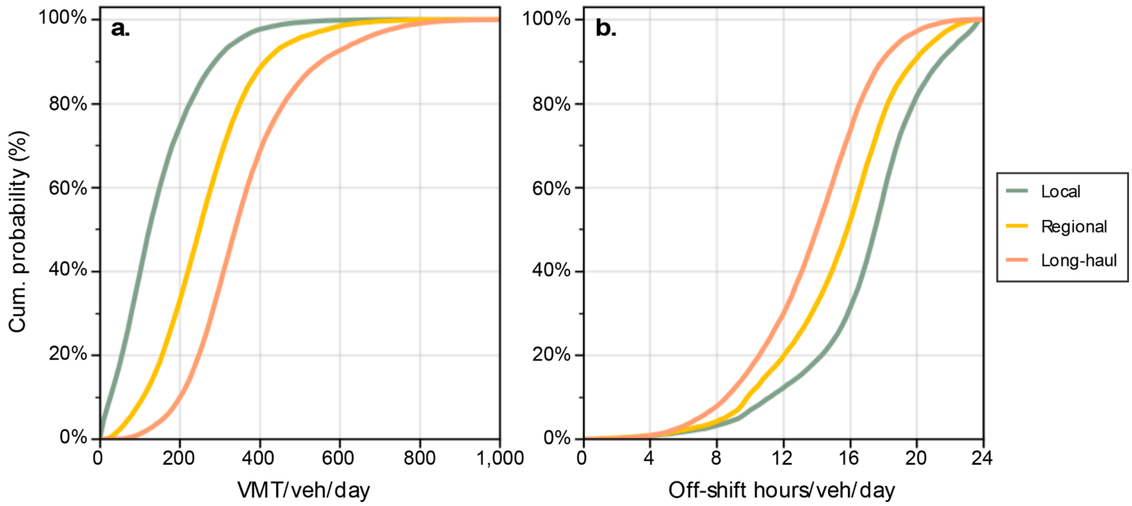

Fig. 3. Cumulative distributions of (a) VMT/veh/day and (b) off-shift hours/veh/day (an indication of available time for electric semi-trailer truck charging without modifying existing operations) by operating segment: local (OR ≤ 100 miles), regional (100 miles < OR < 300 miles), and long-haul (OR ≥ 300 miles). A truck's operating radius (OR) represents the maximum distance traveled from a central location such as a home base or depot.

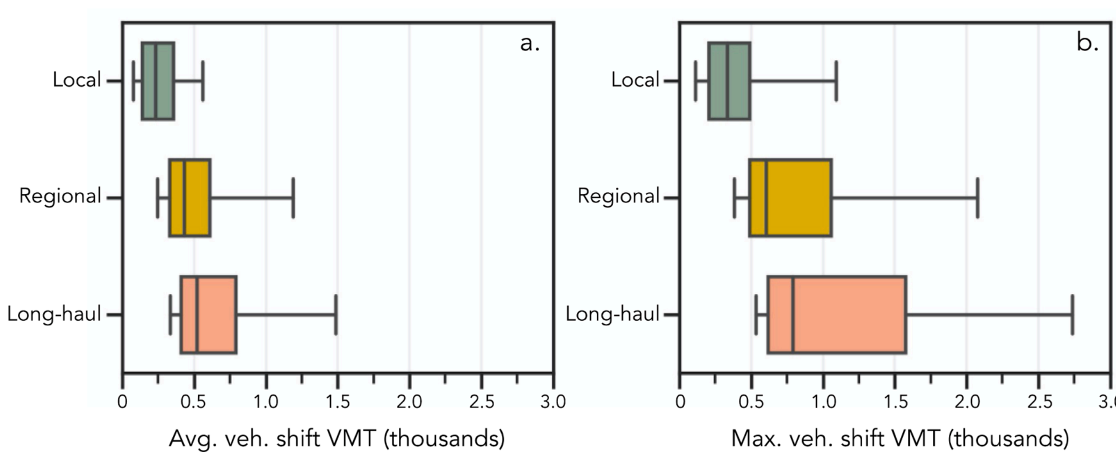

Fig. 4. Boxplot distributions of (a) average VMT/shift/veh and (b) maximum VMT/shift/veh (indicative of the range required for semi-trailer trucks to be electrified without any operational changes or mid-shift charging) by operating segment: local (OR ≤ 100 miles), regional (100 miles < OR < 300 miles), and long-haul (OR ≥ 300 miles). Results are for the baseline scenario (see Table 1). Whiskers denote 10th and 90th percentile values. A truck's operating radius (OR) represents the maximum distance traveled from a central location such as a home base or depot.

speculation for how it is achieved (i.e., usable battery capacity and ECR are not assumed in this analysis). Multiple HDBET ranges are studied: 150, 300, 500, and 750 miles (241, 483, 805, and 1,207 km). These correlate with HDBETs available today (first-generation Volvo VNR Electric, 150-mile range [53], and Freightliner eCascadia, 250-mile range [54]), those announced and coming to market (second-generation Volvo VNR Electric, 275-mi range [53]; Tesla Semi, 300- and 500-mile range [55]; and Nikola Tre BEV, 350-mile range [56]), and a future technology improvement case (750-mile range).

Two types of HDBET charging are modeled in this study: off-shift and mid-shift charging. Off-shift charging is opportunistic, occurring when a truck is not being driven and causing no disruption to existing operations. In the baseline scenario, we assume that 75% of off-shift dwells are eligible for off-shift charging, assigning these opportunities at random to off-shift dwell periods in the data set. This assumption, however, is uncertain and depends on both the future availability of EVSE at common dwell locations and the driver's willingness to seek these locations. Thus, additional high (100% of ≥4-h dwells) and low (50% of ≥8-h dwells) off-shift charging availability sensitivities are considered in response to this uncertainty. The three off-shift charge availability scenarios modeled in this study are presented in Table 1.

Mid-shift charging occurs during a shift when an HDBET's battery state of charge drops to 10%. Since it is less convenient, mid-shift charging speeds are faster than off-shift charging to limit shipment delay due to electrification. To minimize the effect of charge power tapering when charging at high C-rates (i.e., charging rate relative to battery capacity), mid-shift "fast" charging events conclude when the battery's state of charge reaches 80% [57]. Additionally, it is assumed that HDBET drivers prioritize off-shift charging to mid-shift charging, such that a shift's last mid-shift charging event will only charge enough to reach the next off-shift dwell location (preserving a 10% state of charge buffer). Long (e.g., ≥8-h) dwell durations enable slower charging speeds for off-shift charging. With lower C-rates, the vehicle's battery management system allows charging to higher states of charge without significant power tapering [58]; thus, we assume that off-shift "slow" charging events fully charge an HDBET's battery if time allows. A 10-min buffer is added to each off-shift charging event to account for the time taken to prepare for and conclude charging. For mid-shift charging, this buffer is reduced to 5 min given the increased time sensitivity.

2.5. Determining charging speed requirements

HDBET charging speeds must enable trucks to continue to operate efficiently without significant delay from slower refueling times compared to conventional diesel trucks. In this study, we introduce the concept of an allowable charging time margin and use it to estimate charging speed requirements for mid-shift fast HDBET charging. The allowable time margin is the maximum delay (as a percentage of total shift duration) that a fleet operator will endure to accommodate HDBETs. We compare allowable time margins of 5% and 10%, meaning that all shifts driven by an HDBET are completed within (at most) an additional 5% and 10% of the time taken for diesel trucks to complete them. To demonstrate, a 5% margin ensures that an 8-h shift in a diesel truck can be completed within 8 h and 24 min or less in an HDBET, while a 10% margin ensures that the same shift is completed within 8 h and 48 min or less.

The allowable time margin determines the total time available for charging during each shift. This is used to calculate the charging speed (in miles of range added per minute) required to finish the shift within the allowable time margin. Specifically, the charging speed required to complete shift i within the allowable time margin μ is calculated as:

$$CS_{mid-shift_i} = \frac{\sum_{j=1}^{n} CM_{i,j}}{t_i\mu - 5n} \tag{2}$$

where $CM_{i,j}$ are the miles of range added for charge event j of n total in shift i, and t_i is the total duration (in minutes) of shift i. Once the required charging speeds are calculated for all shifts with at least one mid-shift charging event ($n \geq 1$), the recommended mid-shift charging speed is taken as the 90th percentile charging speed value within the set. This ensures, with >90% likelihood, that the recommended charging speed will keep HDBETs on schedule (within a 5% or 10% time margin compared to diesel) assuming no queuing for charging ports. In actuality, the time penalty for HDBETs will be less than the allowable time margin, since we assume that all on-shift dwells for conventional trucks (including breaks for diesel refueling) are replicated by HDBETs but that they do not charge during these periods. This assumption is required because the low (hourly) temporal resolution of the data obfuscates subhourly activities.

For off-shift slow HDBET charging, we determine charging speed requirements for off-shift dwell periods observed in the data set under the assumption that the battery is fully recharged prior to the start of the next shift. For dwell i, the required off-shift charging speed is calculated as:

$$CS_{off-shift_i} = \frac{CM_i}{t_i - 10} \tag{3}$$

where CM_i are the miles of range that must be added during dwell i to fully recharge the vehicle's battery within dwell time t_i (in minutes) minus a 10-min buffer to prepare for and conclude charging. The recommended off-shift charging speed is taken as the 90th percentile charging speed value from the set of all off-shift dwells in the data.

2.6. Geographic assignment

Each simulated charging event is located geographically through linear interpolation of the most immediate preceding and succeeding geographic coordinates in the hourly data. Events are assigned as either urban, rural interstate, or rural non-interstate based on their location and proximity to the U.S. interstate highway system. Specifically, urban events refer to those that take place within a U.S. Census urbanized area (densely developed regions with population ≥50,000), rural interstate events are outside of an urbanized area but within 5 miles (8 km) of an interstate highway, and rural non-interstate events are outside of an urbanized area and not within 5 miles of the interstate network. Fig. 5 shows the full extent of these regions throughout the contiguous United States.

3. Results and discussion

3.1. Energy by charging type

There are multiple benefits to charging HDBETs while off-shift, including greater convenience, reduced charging speeds, lower charging costs [59], and higher operating efficiency. In this study, we show that off-shift charging has increased potential to serve energy demands for trucks operating within a limited distance (i.e., local versus regional or national operations) and as HDBET range increases (Fig. 6). Specifically, the share of total HDBET energy from off-shift slow charging increases (displacing mid-shift fast charging) by 36%, 33%, and 28% for local, regional, and long-haul HDBETs, respectively, as range is increased from 150 to 500 miles in the baseline scenario. For 750-mile-range HDBETs, off-shift charging is the primary means of acquiring energy within all operating segments, representing 77%, 65%, and 56% of total energy demand by local, regional, and long-haul trucks, respectively (baseline scenario). Additionally, the average number of mid-shift fast charging events per shift decreases exponentially across all operating segments, from 2, 4, and 5.1 events per shift with 150-mile range to 0.1, 0.4, and 0.6 events per shift with 750-mile range for

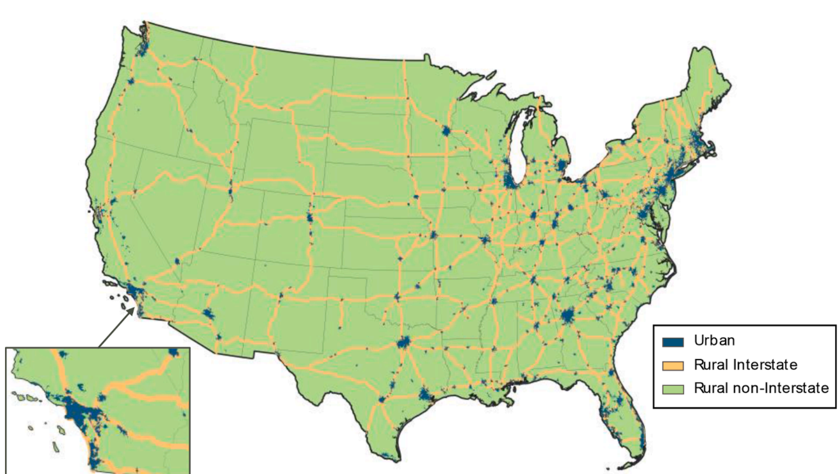

Fig. 5. Geographies used to classify electric semi-trailer truck charging demand as urban, rural interstate, or rural non-interstate within the contiguous United States.

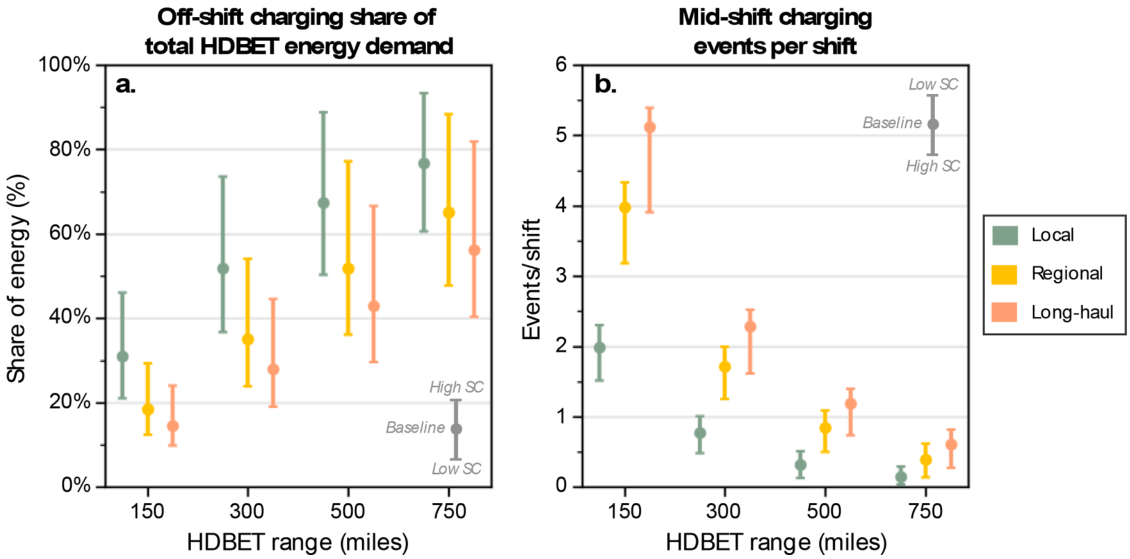

Fig. 6. (a) Share of electric semi-trailer truck (HDBET) charging demand via off-shift slow charging and (b) number of mid-shift fast charging events per shift, by operating segment: local (OR ≤ 100 miles), regional (100 miles < OR < 300 miles), and long-haul (OR ≥ 300 miles) and for multiple HDBET ranges: 150, 300, 500, and 750 miles. Points show results for the baseline off-shift slow charging availability scenario, whereas ticks show results for high and low off-shift slow charging availability sensitivities. A truck's operating radius (OR) represents the maximum distance traveled from a central location such as a home base or depot.

local, regional, and long-haul HDBETs, respectively (baseline scenario).

In addition to increased HDBET range, greater availability of off-shift charging reduces the demand for mid-shift fast charging considerably. In the "High SC" scenario (where slow charging is available for all ≥4-hour dwells), the share of off-shift charging increases by 9–25% depending on range and operating segment. In fact, we see that for a given HDBET range above 150 miles, high use of slow charging when the vehicle is not driving decreases the requirement for mid-shift fast charging more than an incremental upgrade in HDBET range (e.g., long-haul HDBET with 500-mile range can perform 67% of charging off-shift with high slow charge availability, whereas only 56% of charging is off-shift for a long-haul HDBET with 750-mile range and baseline slow charge availability). This finding is important given the current (2022) state of the U.S. HDBET and HDBET EVSE markets, where low-range HDBETs (150- to 300-mile range) and low-power (≤350-kW) EVSE (better suited for off-shift slow charging) are available today, and high-range HDBETs (≥500-mile range) and high-power EVSE for mid-shift fast charging (i.e., MCS standard) are under development and unlikely to be widely deployed for some time. Lower availability of off-shift slow charging ("Low SC" scenario), on the other hand, increases dependence on mid-shift fast charging, potentially delaying electrification.

Given the present lack of HDBET-compatible mid-shift charging stations in the United States, our results suggest that only certain short-distance applications may be electrified with HDBETs available today (150- to 300-mile range) without modifying operations. For local trucks—the most compatible segment for present-day HDBETs—off-shift slow charging provides 31% of total energy demand when trucks have 150-mile range and 52% of energy demand with 300-mile range (baseline scenario). This increases to 46% and 74%, respectively, when off-shift slow charging is widely available, emphasizing the importance of installing EVSE at locations where trucks typically dwell.

Longer-distance applications are more dependent on mid-shift fast charging, especially with low-range (150-mile to 300-mile) HDBETs. With 500-mile HDBETs, 48% (High SC: 23%) and 57% (High SC: 33%) of energy demands for regional and long-haul trucks, respectively, are supplied by mid-shift fast charging. Increasing HDBET range to 750 miles reduces the share of total charging demand from mid-shift fast charging to 35% (High SC: 12%) and 44% (High SC: 18%) for regional and long-haul trucks, respectively.

3.2. Charging speed requirements

It is widely acknowledged that the power levels required to rapidly recharge HDBETs while on-shift will exceed those used by light-duty BEVs. However, empirical studies that estimate the charging speeds necessary to avoid significant disruption to existing freight operations are limited. Here, we show that mid-shift charging speed requirements vary depending on (1) HDBET range, (2) truck operating segment, (3) availability of off-shift charging, and (4) shipment time flexibility (Fig. 7). In general, we find that greater charging speeds are required for longer-distance applications (e.g., long-haul) and for low-range HDBETs, since more mid-shift charging events are needed to complete shifts under these conditions. We also observe that greater availability of off-shift slow charging opportunities reduces fast charging speed requirements and that increased time flexibility (i.e., higher allowable time margin) can significantly decrease these requirements. Due to significant uncertainties around assumptions for the in-use energy consumption of HDBETs, which vary with respect to multiple factors including the gross vehicle weight (a function of the battery's weight and average payload), road conditions, drive cycles, temperature, and drivetrain efficiencies, we present charging speed requirements in units of miles of range added per minute rather than the more familiar units of power (e.g., MW). This decision is made so that findings may be generalizable beyond a single set of assumptions, however Fig. S2 is also provided for translating between miles of range added per minute and charging power (in kW) for several assumed truck average energy consumption rates.

Low-range HDBETs (150- to 300-mile range) have significantly higher mid-shift fast charging speed requirements than high-range HDBETs (≥500-mile range). This is especially true for 150-mile HDBETs, where fast charging speed requirements are 21.9, 44.5, and 67.5 miles (35.2, 71.6, and 108.6 km) of range added per minute for local, regional, and long-haul, respectively (5% time margin, baseline scenario). For context, light-duty BEV manufacturers today report peak charging speeds of up to 350 kW, ~20 miles (32 km) of range added per minute [60], though peak speeds are not maintained throughout the entire charge duration and most vehicles can only charge at 10 miles (16 km) of range added per minute or less. In the baseline scenario with 5% time margin, operating segment-level charging speeds vary from 21.9 to 67.5 miles (35.2–108.6 km) of range added per minute for 150-mile

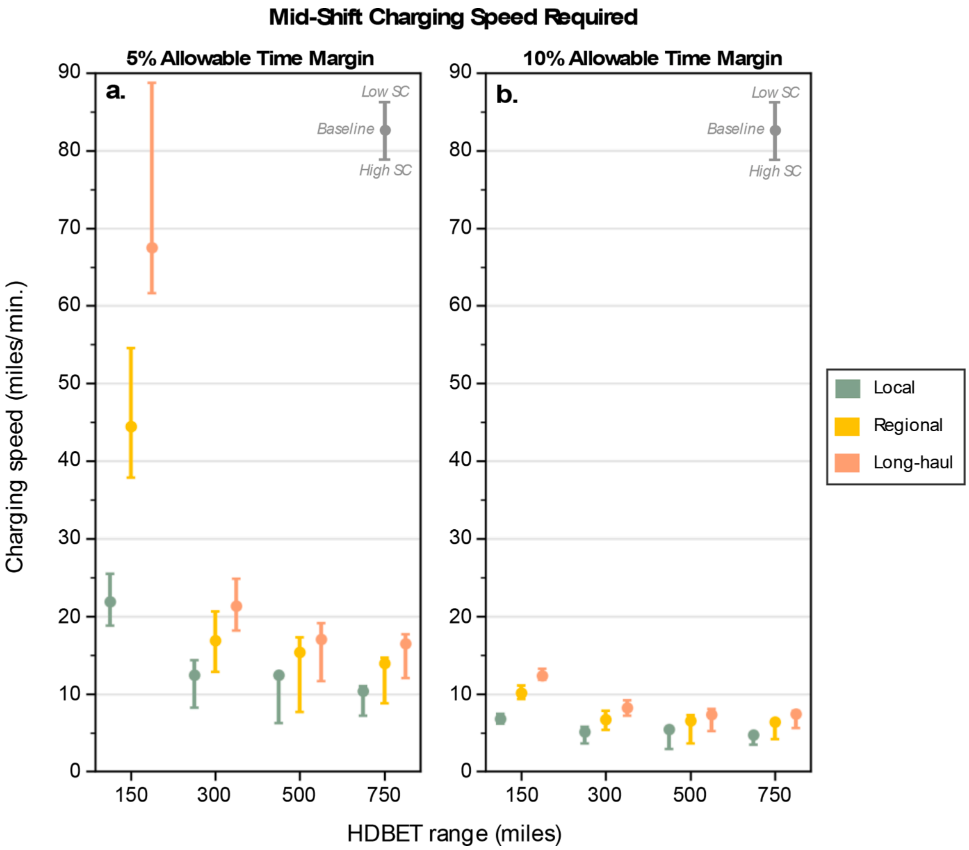

Fig. 7. Mid-shift fast charging speeds (in miles of range added per minute) required to complete shifts within a time margin of (a) 5% and (b) 10% by operating segment: local (OR ≤ 100 miles), regional (100 miles < *OR* < 300 miles), and long-haul (*OR* ≥ 300 miles) and electric semi-trailer truck (HDBET) ranges: 150, 300, 500, and 750 miles. Points show results for the baseline off-shift slow charging availability scenario, whereas ticks show results for high and low off-shift slow charging availability sensitivities. A truck's operating radius (OR) represents the maximum distance traveled from a central location such as a home base or depot.

HDBETs (2.6 MW to 8.1 MW average, assuming 2 kWh/mile); 12.4 to 21.4 miles (20–34.4 km) of range per minute (1.5 MW to 2.6 MW) for 300-mile HDBETs; 12.4 to 17.1 miles (20–27.5 km) of range per minute (1.5 MW to 2.1 MW) for 500-mile HDBETs; and 10.4 to 16.5 miles (16.7–26.6 km) of range per minute (1.2 MW to 2 MW) for 750-mile HDBETs. A plot showing the relationship of charging speed (in miles of range added per minute) and ECR (kWh/mile) to charging power (kW) is provided as Supplementary Information.

If fleet operators can accommodate up to 10% time delay per shift, fast charging speeds are reduced 54% to 82% depending on HDBET range and operating segment. This operational flexibility enables the electrification of longer-distance applications (e.g., long-haul) with lower-range HDBETs (e.g., 300-mile range) and fast charging speeds of 8 miles (~13 km) of range added per minute (1 MW average, assuming 2 kWh/mile).

Long dwell periods (≥8 hours) enable HDBETs to charge at much slower speeds while off-shift; however, there is an approximately linear relationship between HDBET range and off-shift charging speeds (Fig. 8). This is because with greater HDBET range, trucks can forego mid-shift charging, resulting in higher energy demands during dwell periods. We also find that, like with mid-shift charging, local trucks require the slowest charging speeds, followed by regional and long-haul. This can be explained through lower shift VMT (i.e., less energy required) and longer typical off-shift dwell periods (local: 15 h, regional: 14 h, long-haul: 12 h).

In the baseline scenario, off-shift slow charging speed requirements vary from 0.2 miles (0.3 km) of range added per minute (local, 150-mile HDBET) to 1.2 miles (1.9 km) of range added per minute (long-haul, 750-mile HDBET). Assuming an ECR of 2 kWh/mile, this equates to 24–144 kW. Greater off-shift charging availability (i.e., charging during shorter dwell periods) increases the off-shift charging speed requirements to between 0.3 and 1.4 miles (0.5–2.3 km) of range added per minute (36–168 kW, assuming 2 kWh/mile). The only exception is for local 750-mile HDBETs, where charging speeds are reduced with high off-shift charging availability due to distributional differences in energy requirements of events (high availability of off-shift charging introduces additional short off-shift charging events with low energy requirements for local trucks). These charging power levels are well within the range of the current CCS standard (and future MCS standard) and are in line with EVSE for light-duty BEVs deployed today (≤350 kW).

These results demonstrate how charging speed requirements are dependent on HDBET range and vary by multiple factors including the truck operating segment, availability of off-shift charging, and shipment time flexibility. It emphasizes the challenge that low-range (e.g., 150-mile) HDBETs present from an EVSE network design perspective, requiring extremely fast mid-shift charging speeds, even exceeding the capabilities of MCS, to remain on schedule. For ≥300-mile HDBETs, however, MCS can deliver the megawatt-level mid-shift charging speeds needed, with requirements decreasing as HDBET range increases and more off-shift charging opportunities become available, and for shorter-distance operations (e.g., local). Off-shift charging speed requirements, on the other hand, are well within the capabilities of today's EVSE used for light-duty BEVs.

3.3. Geographic distribution of charging demand

The spatial implications of freight movement and logistics lead to geographic trends in simulated charging demand. Fig. 9 shows the share of HDBET charging demand by operating segment and charging type (mid-shift fast vs. off-shift slow) within each of the regions described in Section 2.6 (i.e., urban, rural interstate, and rural non-interstate). These results represent the baseline scenario, though additional results for the high and low slow charging availability scenarios are available as Supplementary Information.

In all truck operating segments, when HDBET range increases,

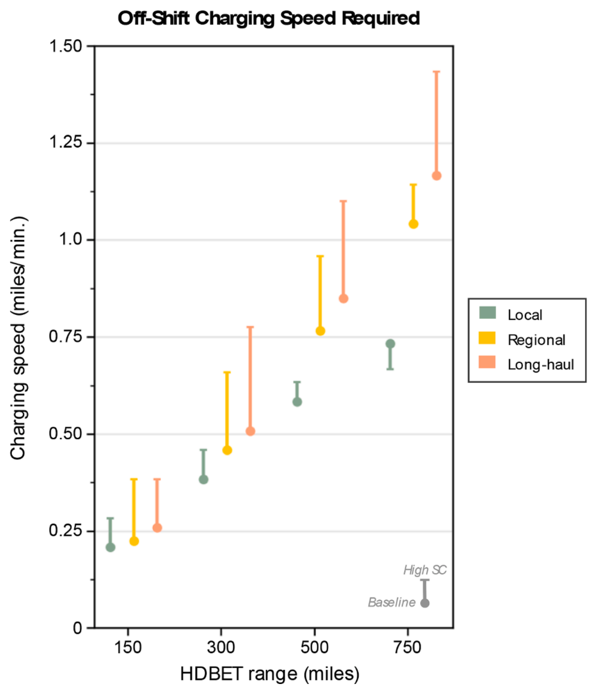

Fig. 8. Off-shift slow charging speeds (in miles of range added per minute) required to fully recharge electric semi-trailer trucks (HDBETs) during off-shift dwell periods, by operating segment: local (OR ≤ 100 miles), regional (100 miles < *OR* < 300 miles), and long-haul (*OR* ≥ 300 miles) and HDBET range: 150, 300, 500, and 750 miles. Points show results for the baseline off-shift slow charging availability scenario, whereas ticks show results for high off-shift slow charging availability sensitivity. A truck's operating radius (OR) represents the maximum distance traveled from a central location such as a home base or depot.

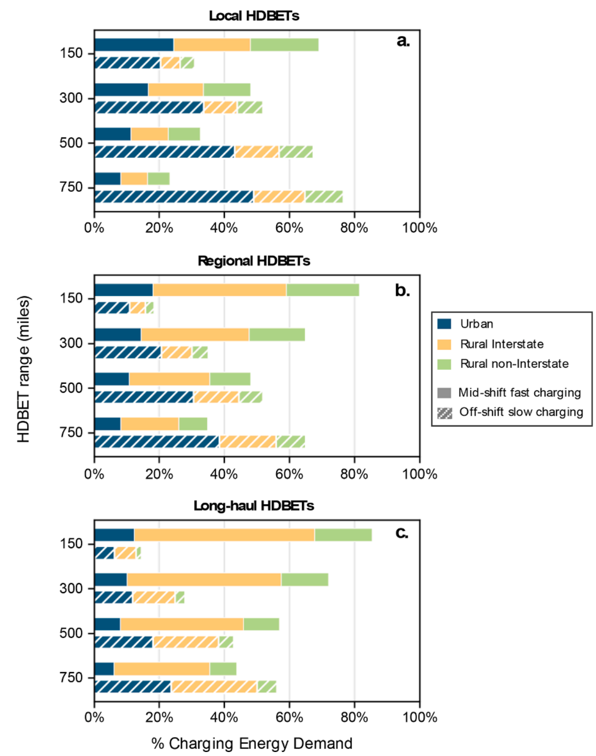

Fig. 9. Share of electric semi-trailer truck (HDBET) energy demand by operating segment: local (OR ≤ 100 miles), regional (100 miles < *OR* < 300 miles), and long-haul (*OR* ≥ 300 miles); HDBET: 150, 300, 500, and 750 miles; and for various location types: urban, rural interstate, and rural non-interstate. Results are for the baseline scenario. A truck's operating radius (OR) represents the maximum distance traveled from a central location such as a home base or depot.

charging demand shifts from rural to urban locations. This trend can be attributed to the increase in off-shift slow charging due to higher HDBET range and the fact that off-shift dwells are more frequently in urban areas. From the data, we find that 53% of all ≥8-hour dwells are in urban areas compared to 34% and 13% for rural interstate and rural non-interstate, respectively.

While all segments experience a shift in demand from fast to slow charging as HDBET range increases, local operations have greater demand in urban areas than longer-distance operations. Conversely, long-haul HDBETs have higher energy demands along rural interstate corridors (especially for mid-shift fast charging) than in urban areas, in contrast to light-duty passenger BEVs, which have higher energy demands near where people live and work [61,62]. These trends are important for power system planning, as they indicate where HDBET charging might occur on the network and how charging patterns may interact with the operational characteristics of the freight system.

4. Conclusions

In this study, telematics data from 55,633 semi-trailer trucks operating in the United States are used to infer the charging behaviors and requirements for electric semi-trailer trucks (HDBETs) within multiple operating segments: local (≤100 miles), regional (100–300 miles), and long-haul (≥300 miles). Specifically, we model two types of charging—mid-shift (fast) and off-shift (slow)—and show that off-shift charging at speeds compatible with current light-duty charging infrastructure (i.e., <350 kW) can provide a significant share of total energy demand within all operating segments. Megawatt-level speeds are required for mid-shift charging, which make up a greater share of energy demand for longer-distance applications (e.g., long-haul). However, demand shifts from mid-shift to off-shift charging as HDBET range increases and when off-shift charging is widely available. Finally, we observe the geographic trends in charging demand, finding that shorter-distance applications have greater demand within urban areas, whereas longer-distance applications have more demand along rural interstate corridors. We show that as HDBET range increases, charging demand shifts from rural to urban locations due to increased slow charging demand and observed vehicle dwell tendencies.

These findings have implications for heavy-duty fleet operators, original equipment manufacturers, electric utilities, EVSE developers, policymakers, and infrastructure planners in preparing for the electrification of heavy-duty trucks and its ramifications. Further modeling and research are required to estimate the geographic variations in HDBET charging demand at a more granular level (e.g., grid region or highway corridor) that would enable the study of projected requirements and potential impacts of HDBET charging at various stages of the power system. Additionally, the trade-offs between differing HDBET charging network design strategies, comparing, for example, a network comprised of highly distributed and relatively low-power (i.e., off-shift slow) EVSE to a network that is centralized with high-power (i.e., mid-shift fast) EVSE, should be assessed in future studies.

Funding

Funding provided by the U.S. Department of Energy Office of Energy Efficiency and Renewable Energy Vehicle Technologies Office.

Data and code availability

Results generated in this study are available through the NREL Data Catalog at https://data.nrel.gov/submissions/198.

CRediT authorship contribution statement

Brennan Borlaug: Conceptualization, Methodology, Software, Formal analysis, Data curation, Writing – original draft, Writing – review & editing, Visualization, Project administration. **Matthew Moniot:** Formal analysis, Data curation, Writing – review & editing. **Alicia Birky:** Writing – review & editing. **Marcus Alexander:** Writing – review & editing, Funding acquisition. **Matteo Muratori:** Writing – review & editing, Funding acquisition.

Declaration of Competing Interest

The authors declare no competing interests.

Acknowledgments

This work was authored in part by the National Renewable Energy Laboratory, operated by Alliance for Sustainable Energy, LLC, for the U. S. Department of Energy (DOE) under Contract No. DE-AC36-08GO28308. The authors would like to thank Raphael Isaac (DOE) and Jacob Ward (DOE) for their guidance and support and acknowledge Eric Wood (NREL) for reviewing the manuscript, Ian Sutherland (GM) for verifying the approach, and Michael Deneen (NREL) for editing assistance. The views expressed in the article do not necessarily represent the views of the DOE or the U.S. Government. The U.S. Government retains and the publisher, by accepting the article for publication, acknowledges that the U.S. Government retains a nonexclusive, paid-up, irrevocable, worldwide license to publish or reproduce the published form of this work, or allow others to do so, for U.S. Government purposes.

Supplementary material

Supplementary material associated with this article can be found, in the online version, at doi:10.1016/j.rset.2022.100038.

References

[1] U.S. Department of State & U.S. Executive Office of the President, The long-term strategy of the United States: pathways to net-zero greenhouse gas emissions by 2050, U.S. Department of State & U.S. Executive Office of the President, Washington DC, 2021. https://www.whitehouse.gov/wp-content/uploads/2021/10/US-Long-Term-Strategy.pdf (accessed December 6, 2021).
[2] U.S. Environmental Protection Agency, Inventory of U.S. greenhouse gas emissions and sinks, U.S. Environmental Protection Agency, 2021. https://www.epa.gov/sites/default/files/2021-04/documents/us-ghg-inventory-2021-main-text.pdf?VersionId=uuA7i8WoMDBOc0M4ln8WVXMgn1GkujvD (accessed December 6, 2021).
[3] U.S. Energy Information Administration, Use of energy explained: energy use for transportation, (2021). https://www.eia.gov/energyexplained/use-of-energy/transportation.php (accessed December 6, 2021).
[4] D. Lowell, J. Culkin, Medium- and Heavy-Duty Vehicles: Market Structure, Environmental Impact, and EV Readiness, M.J. Bradley & Associates, LLC, 2021. https://www.edf.org/sites/default/files/documents/EDFMHDVEVFeasibilityReport22jul21.pdf. accessed February 1, 2022.
[5] U.S. Energy Information Administration, Annual energy outlook 2021: transportation sector energy use by mode and type, (n.d.). https://www.eia.gov/outlooks/aeo/data/browser/#/?id=45-AEO2021&cases=ref2021&sourcekey=0 (accessed February 1, 2022).
[6] C.A. Arter, J. Buonocore, C. Chang, S. Arunachalam, Mortality-based damages per ton due to the on-road mobile sector in the Northeastern and Mid-Atlantic U.S. by region, vehicle class and precursor, Environ. Res. Lett. 16 (2021), 065008, https://doi.org/10.1088/1748-9326/abf60b.
[7] A. Vodonos, Y.A. Awad, J. Schwartz, The concentration-response between long-term PM2.5 exposure and mortality; a meta-regression approach, Environ. Res. 166 (2018) 677–689, https://doi.org/10.1016/j.envres.2018.06.021.
[8] U.S. Energy Information Administration, Annual energy outlook 2021: freight transportation energy use, (n.d.). https://www.eia.gov/outlooks/aeo/data/browser/#/?id=58-AEO2021&cases=ref2021&sourcekey=0 (accessed February 1, 2022).
[9] Medium- and heavy-duty zero emission vehicle (ZEV) requirement, alternative fuels data center. (n.d.). https://afdc.energy.gov/laws/12473 (accessed February 23, 2022).
[10] Multi-state medium- and heavy-duty zero emission vehicle memorandum of understanding, (n.d.). https://www.nescaum.org/documents/mhdv-zev-mou_12-14-2021.pdf (accessed February 23, 2022).
[11] CALSTART, Drive to zero's zero-emission technology inventory (ZETI) tool, 2020. https://globaldrivetozero.org/tools/zero-emission-technology-inventory/ (accessed February 23, 2022).
[12] B.M. Al-Alawi, O. MacDonnell, R. McLane, K. Walkowicz, Zeroing in on zero-emission trucks, (2022). https://calstart.org/wp-content/uploads/2022/02/ZIO-ZETs-Report_Updated-Final-II.pdf (accessed February 23, 2022).
[13] The rise of electric vehicles—2020 status and future expectations - IOPscience, (n. d.). https://iopscience.iop.org/article/10.1088/2516-1083/abe0ad/meta (accessed February 1, 2022).
[14] C. Hunter, M. Penev, E. Reznicek, J. Lustbader, A. Birky, C. Zhang, Spatial and temporal analysis of the total cost of ownership for class 8 tractors and class 4 parcel delivery trucks, 2021. doi:10.2172/1821615.
[15] A. Burnham, D. Gohlke, L. Rush, T. Stephens, Y. Zhou, M. Delucchi, A. Birky, C. Hunter, Z. Lin, S. Ou, F. Xie, C. Proctor, S. Wiryadinata, N. Liu, M. Boloor, Comprehensive total cost of ownership quantification for vehicles with different size classes and powertrains, 2021. doi:10.2172/1780970.
[16] California Air Resources Board, Advanced clean trucks: total cost of ownership discussion document, (2019) 46.
[17] B. Borlaug, M. Muratori, M. Gilleran, D. Woody, W. Muston, T. Canada, A. Ingram, H. Gresham, C. McQueen, Heavy-duty truck electrification and the impacts of depot charging on electricity distribution systems, Nat. Energy 6 (2021) 673–682, https://doi.org/10.1038/s41560-021-00855-0.
[18] Gladstein Neandross & Associates, California heavy-duty fleet electrification, 2021. https://www.gladstein.org/research/california-heavy-duty-fleet-electrification/(accessed December 3, 2021).
[19] L. McKenzie, J. Di Filippo, J. Rosenberg, N. Nigro, U.S. vehicle electrification infrastructure assessment: medium- and heavy-duty truck charging, (2021). https://atlaspolicy.com/wp-content/uploads/2021/11/2021-11-12_Atlas_US_Electrification_Infrastructure_Assessment_MD-HD-trucks.pdf (accessed February 1, 2022).
[20] R. Minjares, F. Rodríguez, A. Sen, C. Braun, Infrastructure to support a 100% zero-emission tractor-trailer fleet in the United States by 2040, international council on clean transportation, 2021. https://theicct.org/wp-content/uploads/2021/12/ze-tractor-trailer-fleet-us-hdvs-sept21.pdf (accessed February 1, 2022).
[21] Daimler Truck AG, Daimler Truck North America, NextEra energy resources and blackrock renewable power announce plans to accelerate public charging infrastructure for commercial vehicles across the U.S., Daimler Truck. (2022). https://media.daimlertruck.com/marsMediaSite/en/instance/ko/Daimler-Truck-North-America-NextEra-Energy-Resources-and-BlackRock-Renewable-Power-Announce-Plans-To-Accelerate-Public-Charging-Infrastructure-For-Commercial-Vehicles-Across-The-US.xhtml?oid=51874160 (accessed February 1, 2022).
[22] West coast clean transit corridor initiative, Interstate 5 Corridor: California, Oregon, Washington, 2020. https://westcoastcleantransit.com/.
[23] National Renewable Energy Laboratory, Industry experts, researchers put charging systems for electric trucks to the test, (2021). https://www.nrel.gov/news/program/2021/industry-experts-researchers-put-charging-systems-for-electric-trucks-to-test.html (accessed February 1, 2022).
[24] W. Wei, S. Ramakrishnan, Z.A. Needell, J.E. Trancik, Personal vehicle electrification and charging solutions for high-energy days, Nat. Energy 6 (2021) 105–114, https://doi.org/10.1038/s41560-020-00752-y.
[25] N.S. Pearre, W. Kempton, R.L. Guensler, V.V. Elango, Electric vehicles: how much range is required for a day's driving? Transp. Res. Part C Emerg. Technol. 19 (2011) 1171–1184, https://doi.org/10.1016/j.trc.2010.12.010.
[26] Z.A. Needell, J. McNerney, M.T. Chang, J.E. Trancik, Potential for widespread electrification of personal vehicle travel in the United States, Nat. Energy 1 (2016) 1–7, https://doi.org/10.1038/nenergy.2016.112.
[27] J. Wenig, M. Sodenkamp, T. Staake, Battery versus infrastructure: tradeoffs between battery capacity and charging infrastructure for plug-in hybrid electric vehicles, Appl. Energy 255 (2019), 113787, https://doi.org/10.1016/j.apenergy.2019.113787.
[28] D.L. Greene, E. Kontou, B. Borlaug, A. Brooker, M. Muratori, Public charging infrastructure for plug-in electric vehicles: what is it worth? Transp. Res. Part D Transp. Environ. 78 (2020), 102182 https://doi.org/10.1016/j.trd.2019.11.011.
[29] M.A. Tamor, Examining the case for long-range battery electric vehicles with a generalized description of driving patterns, Transp. Res. Part C Emerg. Technol. 108 (2019) 1–11, https://doi.org/10.1016/j.trc.2019.09.003.
[30] B. Nykvist, O. Olsson, The feasibility of heavy battery electric trucks, Joule 5 (2021) 901–913, https://doi.org/10.1016/j.joule.2021.03.007.
[31] S. Sripad, V. Viswanathan, Quantifying the economic case for electric semi-trucks, ACS Energy Lett. 4 (2019) 149–155, https://doi.org/10.1021/acsenergylett.8b02146.
[32] A. Phadke, A. Khandekar, N. Abhyankar, D. Wooley, D. Rajagopal, Why regional and long-haul trucks are primed for electrification now, 2021. https://escholarship.org/uc/item/3kj8s12f (accessed February 1, 2022).
[33] F. Tong, D. Wolfson, A. Jenn, C.D. Scown, M. Auffhammer, Energy consumption and charging load profiles from long-haul truck electrification in the United States, Environ. Res. Infrastruct. Sustain. 1 (2021), 025007, https://doi.org/10.1088/2634-4505/ac186a.
[34] Port of Oakland, Zero-emissions drayage truck feasibility study, 2019. https://www.portofoakland.com/files/PDF/Zero%20Emissions%20Truck%20Feasibility%20Study%20Final.pdf.
[35] R. Prohaska, A. Konan, K. Kelly, M. Lammert, Heavy-duty vehicle port drayage drive cycle characterization and development, SAE Int. J. Commer. Veh. 9 (2016) 331–338, https://doi.org/10.4271/2016-01-8135.

[36] H. Liimatainen, O. van Vliet, D. Aplyn, The potential of electric trucks – an international commodity-level analysis, Appl. Energy 236 (2019) 804–814, https://doi.org/10.1016/j.apenergy.2018.12.017.
[37] E. Çabukoglu, G. Georges, L. Küng, G. Pareschi, K. Boulouchos, Battery electric propulsion: an option for heavy-duty vehicles? Results from a Swiss case-study, Transp. Res. Part C Emerg. Technol. 88 (2018) 107–123, https://doi.org/10.1016/j.trc.2018.01.013.
[38] S. Sripad, V. Viswanathan, Performance metrics required of next-generation batteries to make a practical electric semi truck, ACS Energy Lett. 2 (2017) 1669–1673, https://doi.org/10.1021/acsenergylett.7b00432.
[39] M.P. Lammert, B. Bugbee, Y. Hou, A. Mack, M. Muratori, J. Holden, A. Duran, E. Swaney, Exploring Telematics Big Data for Truck Platooning Opportunities, SAE International, Warrendale, PA, 2018, https://doi.org/10.4271/2018-01-1083.
[40] X. Zhu, B. Mather, P. Mishra, Grid impact analysis of heavy-duty electric vehicle charging stations, in: Proceedings of the IEEE Power Energy Society Innovative Smart Grid Technologies Conference (ISGT), 2020, pp. 1–5, https://doi.org/10.1109/ISGT45199.2020.9087651.
[41] X. Zhu, R. Mahmud, B. Mather, P. Mishra, A. Meintz, Grid voltage control analysis for heavy-duty electric vehicle charging stations, in: Proceedings of the IEEE Power & Energy Society Innovative Smart Grid Technologies Conference (ISGT), IEEE, Washington, DC, USA, 2021, pp. 1–5, https://doi.org/10.1109/ISGT49243.2021.9372213.
[42] A. Leslie, D. Murray, An Analysis of the Operational Costs of Trucking: 2021 Update, American Transportation Research Institute, 2021. https://truckingresearch.org/atri-research/operational-costs-of-trucking/.
[43] Shortest path calculation: a comparative study for location-based recommender system | IEEE conference publication | IEEE Xplore, (n.d.). https://ieeexplore.ieee.org/document/7791971 (accessed February 1, 2022).
[44] Federal motor carrier safety administration, hours of service of drivers, 2011. https://www.govinfo.gov/content/pkg/FR-2011-12-27/pdf/2011-32696.pdf (accessed February 1, 2022).
[45] National Highway Traffic Safety Administration, Factors and Considerations for Establishing a Fuel Efficiency Regulatory Program for Commercial Medium- and Heavy-Duty Vehicles, U.S. Department of Transportation, 2010. https://www.nhtsa.gov/sites/nhtsa.gov/files/nhtsa_study_trucks.pdf. accessed February 1, 2022.
[46] K. Salari, DOE's effort to improve heavy vehicle aerodynamics through joint experiments and computations, (2013). https://www.energy.gov/sites/prod/files/2014/03/f13/vss006_salari_2013_o.pdf (accessed February 1, 2022).
[47] H. Chowdhury, H. Moria, A. Ali, I. Khan, F. Alam, S. Watkins, A study on aerodynamic drag of a semi-trailer truck, Procedia Eng. 56 (2013) 201–205, https://doi.org/10.1016/j.proeng.2013.03.108.
[48] Navistar, Inc., Fuel economy weight, international. (n.d.). https://www.internationaltrucks.com/blog/fuel-economy-weight (accessed February 1, 2022).
[49] S. Ma, M. Jiang, P. Tao, C. Song, J. Wu, J. Wang, T. Deng, W. Shang, Temperature effect and thermal impact in lithium-ion batteries: a review, Prog. Nat. Sci. Mater. Int. 28 (2018) 653–666, https://doi.org/10.1016/j.pnsc.2018.11.002.
[50] S. Lopp, E. Wood, A. Duran, Evaluating the Impact of Road Grade on Simulated Commercial Vehicle Fuel Economy Using Real-World Drive Cycles, National Renewable Energy Lab. (NREL), Golden, CO (United States), 2015, https://doi.org/10.4271/2015-01-2739.
[51] J. Zhang, P.A. Ioannou, Longitudinal control of heavy trucks in mixed traffic: environmental and fuel economy considerations, IEEE Trans. Intell. Transp. Syst. 7 (2006) 92–104, https://doi.org/10.1109/TITS.2006.869597.
[52] B. Borlaug, J. Holden, E. Wood, B. Lee, J. Fink, S. Agnew, J. Lustbader, Estimating region-specific fuel economy in the United States from real-world driving cycles, Transp. Res. Part D Transp. Environ. 86 (2020), 102448, https://doi.org/10.1016/j.trd.2020.102448.
[53] Volvo trucks launches electric truck with longer range, Volvo. (2022). https://www.volvogroup.com/en/news-and-media/news/2022/jan/news-4158927.html (accessed February 1, 2022).
[54] Daimler Trucks North America, Freightliner eCascadia, (n.d.). https://freightliner.com/trucks/ecascadia/(accessed February 1, 2022).
[55] Tesla, Tesla Semi, Tesla. (n.d.). https://www.tesla.com/semi (accessed February 1, 2022).
[56] Nikola Corp., Nikola Tre BEV, Nikola Motor Company. (n.d.). https://www.nikolamotor.com/tre-bev (accessed February 1, 2022).
[57] E.D. Kostopoulos, G.C. Spyropoulos, J.K. Kaldellis, Real-world study for the optimal charging of electric vehicles, Energy Rep. 6 (2020) 418–426, https://doi.org/10.1016/j.egyr.2019.12.008.
[58] Y. Gao, J. Jiang, C. Zhang, W. Zhang, Z. Ma, Y. Jiang, Lithium-ion battery aging mechanisms and life model under different charging stresses, J. Power Sources 356 (2017) 103–114, https://doi.org/10.1016/j.jpowsour.2017.04.084.
[59] J. Bennett, P. Mishra, E. Miller, B. Borlaug, A. Meintz, A. Birky, Estimating the breakeven cost of delivered electricity to charge class 8 electric tractors, forthcoming, n.d (2022).
[60] Lucid, Press release: August 19, 2020, Lucid. (2020). https://www.lucidmotors.com/media-room/lucid-air-fastest-charging-ev (accessed February 1, 2022).
[61] J.H. Lee, D. Chakraborty, S.J. Hardman, G. Tal, Exploring electric vehicle charging patterns: mixed usage of charging infrastructure, Transp. Res. Part D Transp. Environ. 79 (2020), 102249, https://doi.org/10.1016/j.trd.2020.102249.
[62] S.Á. Funke, F. Sprei, T. Gnann, P. Plötz, How much charging infrastructure do electric vehicles need? A review of the evidence and international comparison, Transp. Res. Part D Transp. Environ. 77 (2019) 224–242, https://doi.org/10.1016/j.trd.2019.10.024.