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Charging Needs for Battery Electric Semi Trucks

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Executive Summary

Battery-electric vehicles provide a pathway to decarbonize heavy-duty trucking, but the market for electric trucks is nascent, and specific charging requirements remain uncertain. This paper summarizes methods and findings from *Charging Needs for Electric Semi-Trailer Trucks* [1] wherein 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 en-route charging) and off-shift (slow depot charging)—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, the role of off-shift charging increases as the range for battery-electric trucks increases and when off-shift charging is widely available.

Keywords: BEV, heavy-duty, freight transport, electric vehicle supply equipment (EVSE), battery

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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 [2]. Transportation accounts for 29% of U.S. greenhouse gas emissions, the highest share of any end-use sector [3], and in 2020, fossil fuels were responsible for 96% of total U.S. transportation energy use [4]. Despite accounting for <2% of vehicles on the road [5], 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 [6]. They are also major contributors of air pollutants (ambient fine particulate matter, $PM_{2.5}$) associated with premature mortalities that disproportionately affect certain communities [7,8]. Despite this, the vast majority (>99%) of new U.S. heavy-duty vehicle sales in 2020 were diesel-powered [9].

Battery electric vehicles, once considered impractical for heavy applications, have experienced significant technology and cost improvements in the previous decade and are now seen as promising options to decarbonize heavy-duty trucking. For heavy-duty battery electric trucks (HDBETs) to replace conventional diesel trucks, large investments in charging infrastructure (i.e., electric vehicle supply equipment [EVSE]) will be required. 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) [10]. Undoubtedly, MCS represents a significant advancement, but the actual requirements for HDBETs within various operating segments remain uncertain.

This paper summarizes methods and findings from Borlaug *et al.* (2022) [1], which investigated HDBET range and charging infrastructure jointly, estimating the charging needs for various battery ranges within three separate operating segments: local, regional, and long-haul. The study first examines how increased battery range affects HDBET charging behaviors, comparing the relative frequency of mid-shift fast charging to off-shift slow charging. Next, it quantifies 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, geographic trends in charging demand within three separate region types: urban areas, rural interstate corridors, and rural non-interstate regions are observed.

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).

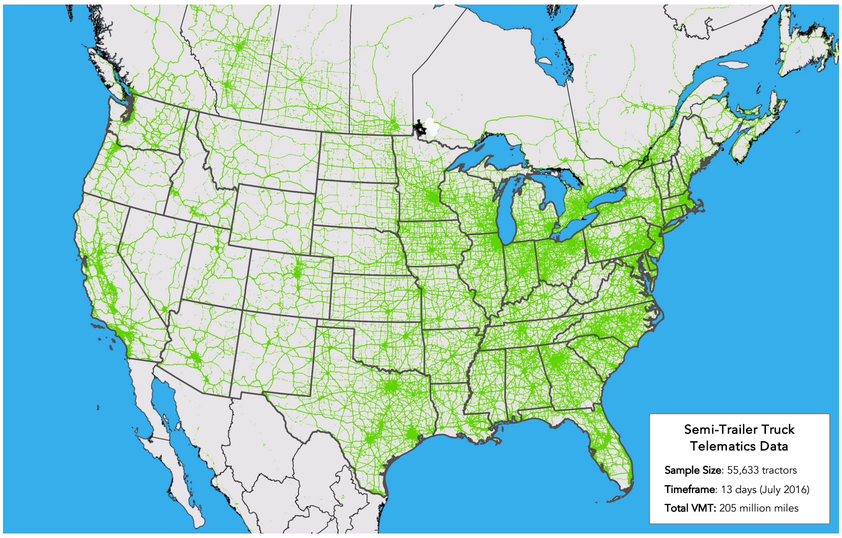

Fig. 1. Geographic coverage of semi-trailer truck telematics data: 205 million miles (330 million km) driven by 55,633 tractors over a 13-day collection period in July 2016. Reprinted from [1] with permission.

2.2 Simulating Heavy-duty Truck Charging

2.2.1 Operating Segment Classification

There is considerable variability in the daily operating requirements of semi-trailer trucks in the United States. 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.

Trucks are classified as either *local*, *regional*, or *long-haul* operations based on their observed operating radius (*OR*), where *local: OR* ≤ 100 miles (161 km); *regional:* 100 miles < *OR* < 300 miles (161–483 km); and *long-haul: OR* ≥ 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.

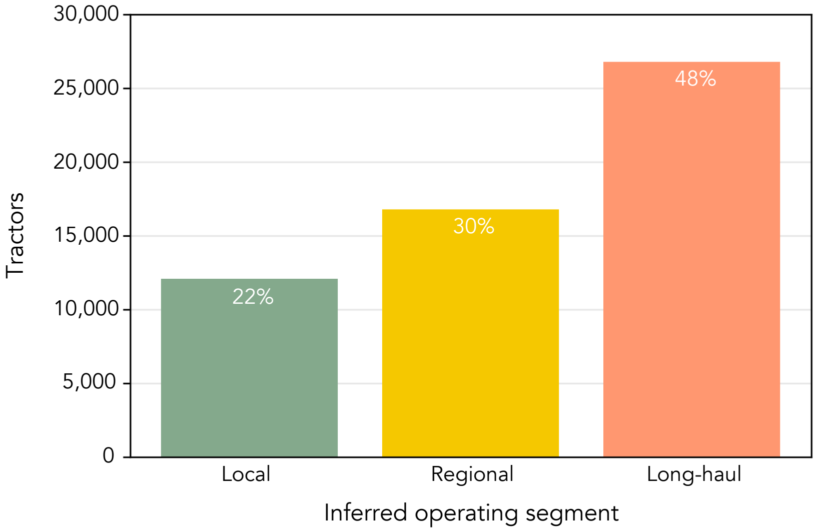

Fig. 2. Distribution of semi-trailer trucks in the data st by operating segment. Reprinted from [1] with permission.

2.2.2 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 ≥5 miles (≥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 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. 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.

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).

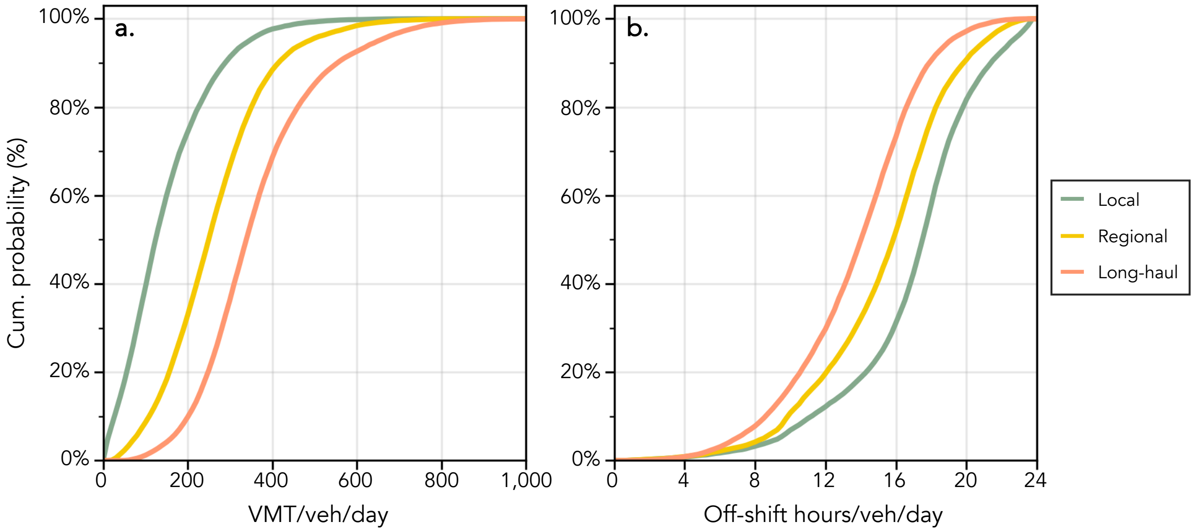

Fig. 3. Cumulative distributions of (a) VMT/veh/day and (b) off-shift hours/veh/day (an indication of opportunities for charging). Reprinted from [1] with permission.

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. 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.

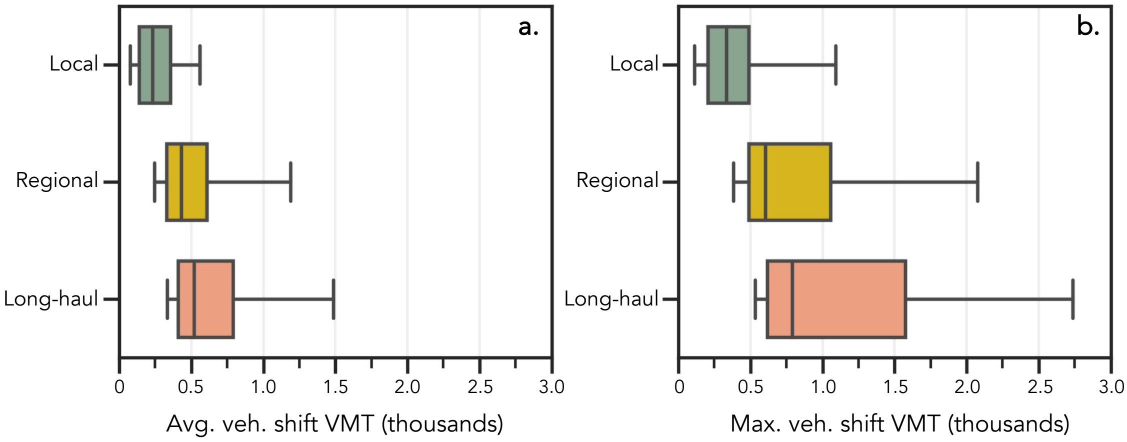

Fig. 4. Boxplot distributions of (a) average VMT/shift/veh and (b) maximum VMT/shift/veh (indicative of the range required for semi-trailer trucks to be electrified without any operational changes or mid-shift charging). Reprinted from [1] with permission.

2.2.3 Charging Simulation

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-hour dwells) and low (50% of ≥8-hour dwells) off-shift charging availability sensitivities are considered in response to this uncertainty.

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%. 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-hour) 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; thus, we assume that off-shift "slow" charging events fully charge an HDBET's battery if time allows. A 10-minute 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 minutes given the increased time sensitivity.

2.2.4 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-hour shift in a diesel truck can be completed within 8 hours and 24 minutes or less in an HDBET, while a 10% margin ensures that the same shift is completed within 8 hours and 48 minutes 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:

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

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-minute 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.

2.3 Geolocating Charging Demands

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.

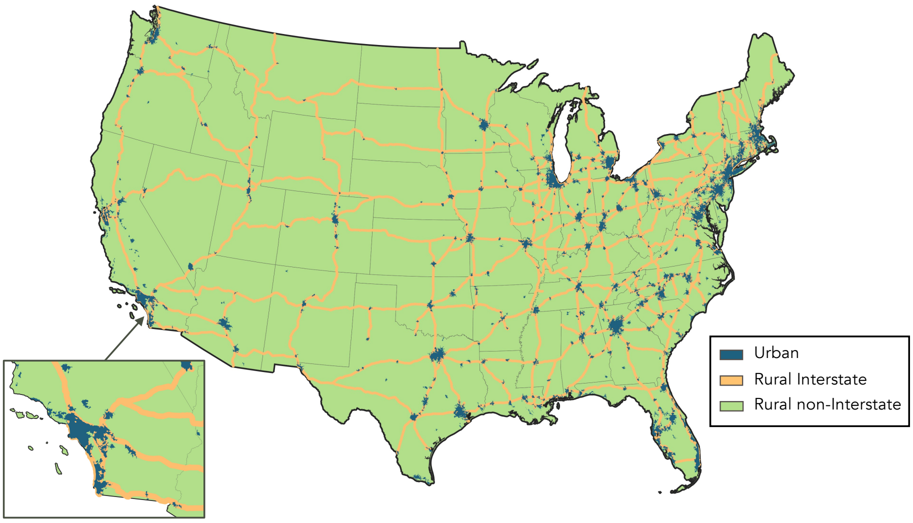

Fig. 5. Geographies used to classify electric semi-trailer truck charging demand as urban, rural interstate, or rural non-interstate within the contiguous United States. Reprinted from [1] with permission.

3 Results and Discussion

3.1 Energy Demands by Charger Type

There are multiple benefits to charging HDBETs while off-shift, including greater convenience, reduced charging speeds, lower charging costs, 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 significantly 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 local, regional, and long-haul HDBETs, respectively (baseline scenario).

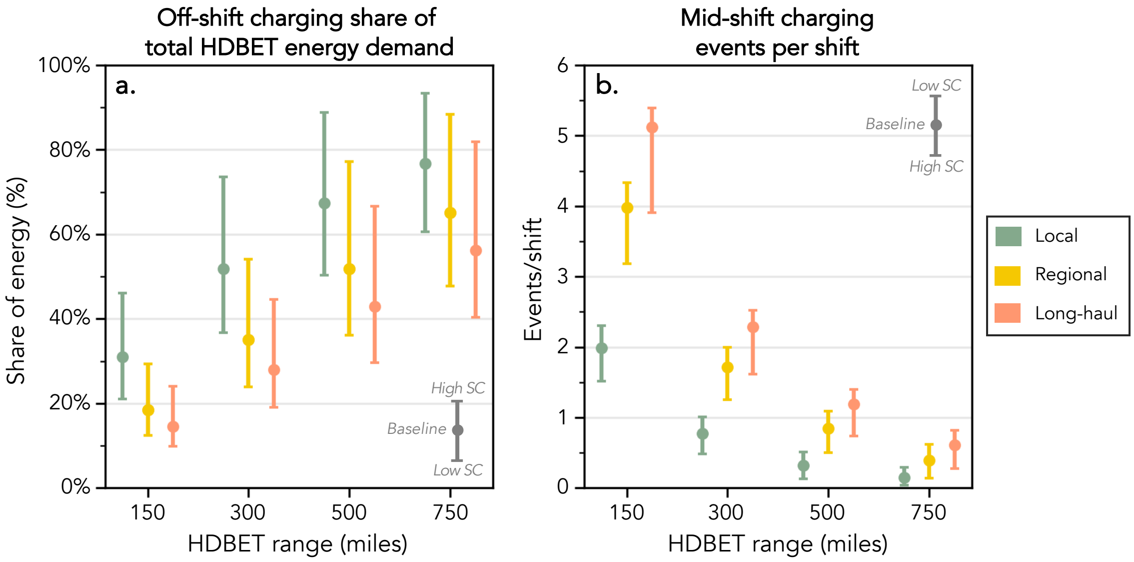

Fig. 6. (a) Share of electric semi-trailer truck (HDBET) charging demand via off-shift slow charging and (b) number of mid-shift fast charging events per shift by operating segment. Reprinted from [1] with permission.

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).

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.

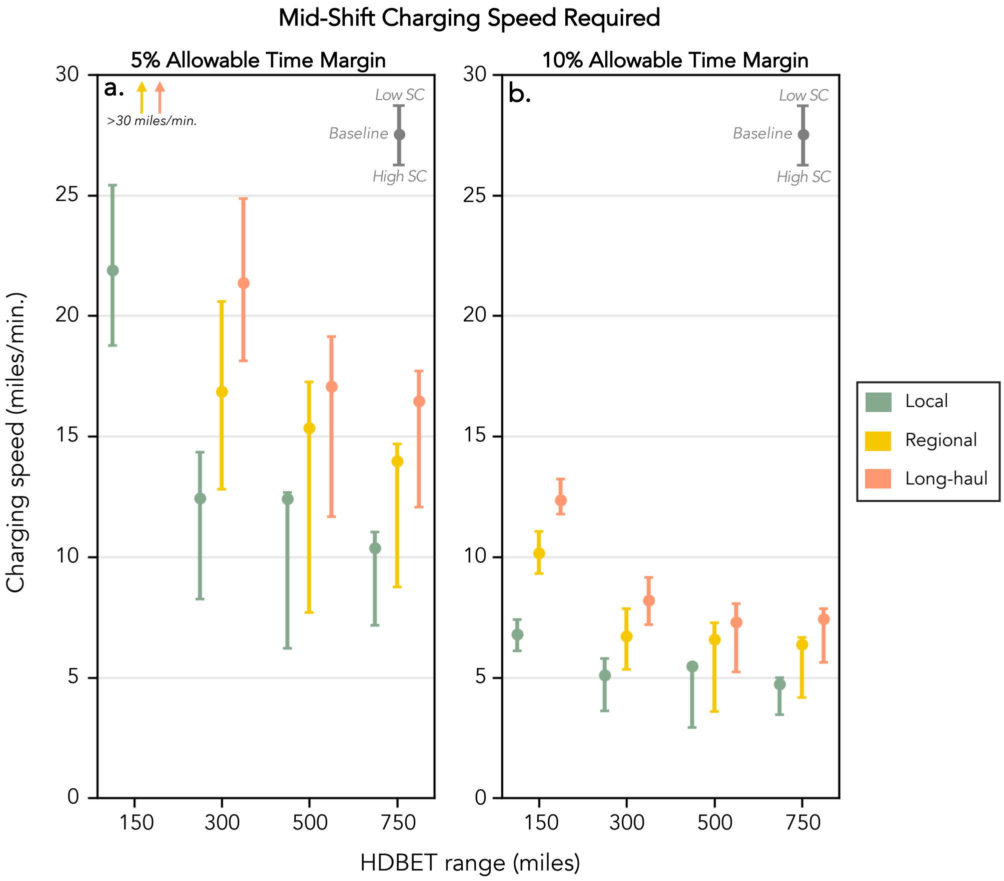

Fig. 7. Mid-shift fast charging speeds (in miles of range added per minute) required to complete shifts within a time margin of (a) 5% and (b) 10% by electric semi-trailer truck (HDBET) range and operating segment. Adapted from [1] with permission.

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). 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 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. 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 hours, regional: 14 hours, long-haul: 12 hours).

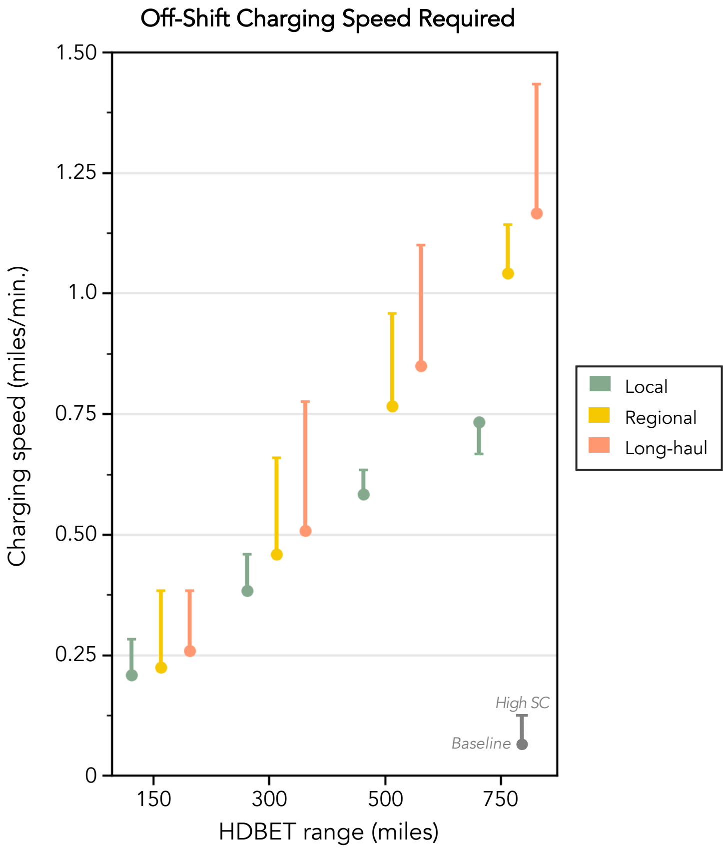

Fig. 8. Off-shift slow charging speeds (in miles of range added per minute) required to fully recharge electric semi-trailer trucks (HDBETs) during off-shift dwell periods, by HDBET range and operating segment. Reprinted from [1] with permission.

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).

3.3 Geographic Charging Demands

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.

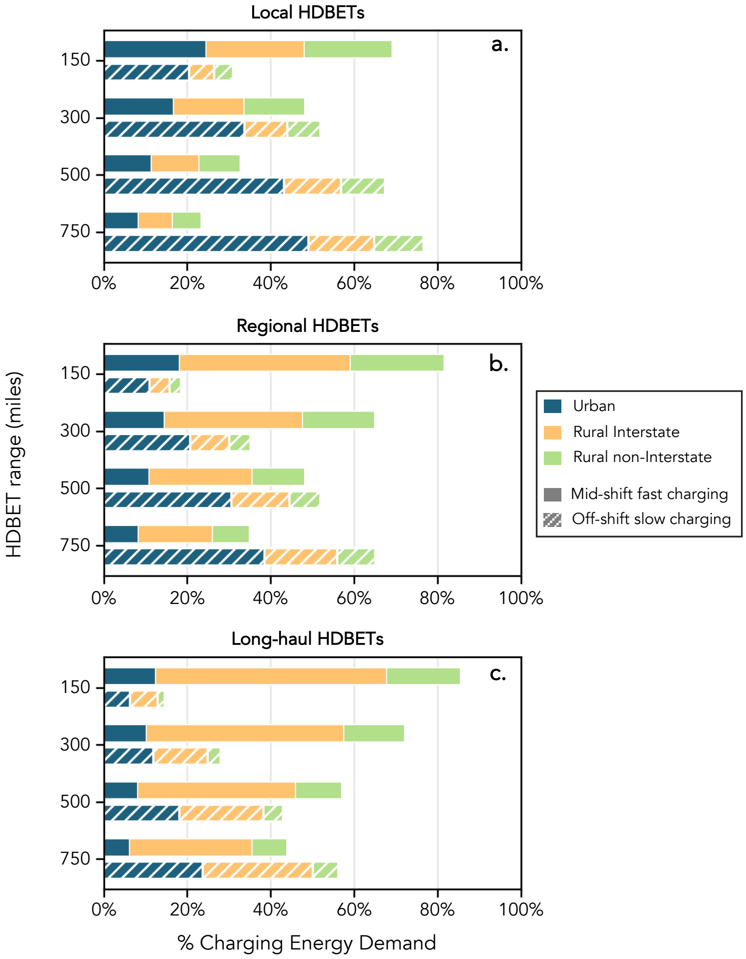

Fig. 9. Share of electric semi-trailer truck (HDBET) energy demand by HDBET range and operating segment within different location types – urban, rural interstate, rural non-interstate. Reprinted from [1] with permission.

In all truck operating segments, when HDBET range increases, 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. 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.

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Presenter Biography

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