Quick Insights

Charging Loads and Infrastructure Requirements for Electrification of Long-Haul Heavy-Duty Trucking

RESEARCH QUESTIONS

What are anticipated real-world loads and charging infrastructure needs for combination long-haul heavy-duty electric trucks, and how might electrification of these vehicles impact air quality, infrastructure planning, and transport decarbonization?

KEY POINTS

- Combination long-haul heavy-duty trucks account for about 15% of total energy consumption and 20% of total NOx emissions by on-road internal combustion engine vehicles in the United States.
- Assuming market acceptance, electrification of long-haul heavy-duty trucking has near-term potential for improving air quality and can support deep decarbonization.
- A battery size of about 1 MWh appears adequate for meeting the expectations of long-haul truck drivers—in terms of daily driving distance and downtime—assuming sufficient charging infrastructure.
- Depending on highway speed, heavy-duty trucks starting the workday with a fully charged battery will require at least one 30-minute fast charging session at average and peak rates of 1500 kW and 3000 kW, respectively.
- U.S. regulations requiring individual drivers to rest for 10 hours before starting a new workday will allow for slow charging, with an average session rate of 100 kW, to restore 100% state of charge (SOC).
- Charging stations sized in the range of 11 to 12 MW can simultaneously provide fast charging to about 7 en-route electric trucks while bringing about 100 trucks to 100% SOC over a 10-hour period.
- Larger stations will be required to support broad electrification—on the order of 45 to 50 MW to provide fast charging to about 30 en-route trucks and post-workday charging to about 400 trucks.

INTRODUCTION

Transport electrification is a critical deep decarbonization pathway and delivers the immediate benefit of reducing pollutant emissions. Passenger cars, trucks, and other light-duty (LD) vehicles have earned the most attention from electric vehicle (EV) developers and charging providers. Electric medium-duty (MD) and heavy-duty (HD) vehicles are attracting growing interest across diverse applications. Incumbent manufacturers and EV startups offer commercial HD trucks, and the first customer delivery of Tesla's Semi occurred in late 2022.[1] This *Quick Insights* explores the implications of electrifying the largest and most-energy-intensive over-the-road vehicles—combination long-haul HD trucks, commonly referred to as big rigs, semis, or tractor trailers. The focus is on characterizing charging loads and infrastructure requirements based on the real-world driving patterns of long-haul truckers, complementing a previous *Quick Insights* that examines possible impacts of widespread adoption of autonomous EVs on charging needs.[2] Specifically, charging infrastructure is considered for Class 8 combination HD trucks traveling on highway routes with minimal traffic congestion where the business priority is to cover as many miles per day as possible.

IMPORTANCE OF LONG-HAUL TRUCKING

Combination long-haul trucks underpin the U.S. economy, transporting shipping containers and perishable and nonperishable goods across international borders and state lines and to and from ports, manufacturers, warehouses, and distribution centers. The average daily driving distance of these vehicles is 675 miles (1080 km),[3] helping ensure that California strawberries and the like are available across the nation. Total annual distance driven for individual long-haul HD trucks often exceeds 100,000 miles (160,000 km) but varies across a broad distribution.[4]

The U.S. Environmental Protection Agency (EPA) Motor Vehicle Emission Simulator (MOVES) is based on about 1.8 million operational combination long-haul trucks for 2022, compared to the LD passenger car and truck categories totaling about 116 million and 128 million, respectively, with sport utility vehicles (SUV) falling into the latter group.[4] The Sankey diagram based on MOVES projections that is shown in Figure 1 illustrates the significant energy consumption attributable to long-haul HD trucking, relative to other types and classes of on-road vehicles powered by internal combustion engine (ICE) technologies. The MOVES model classifies any single day trip of more than 200 miles (320 km) as "long haul."[4]

U.S. ENERGY USE BY ON-ROAD VEHICLES

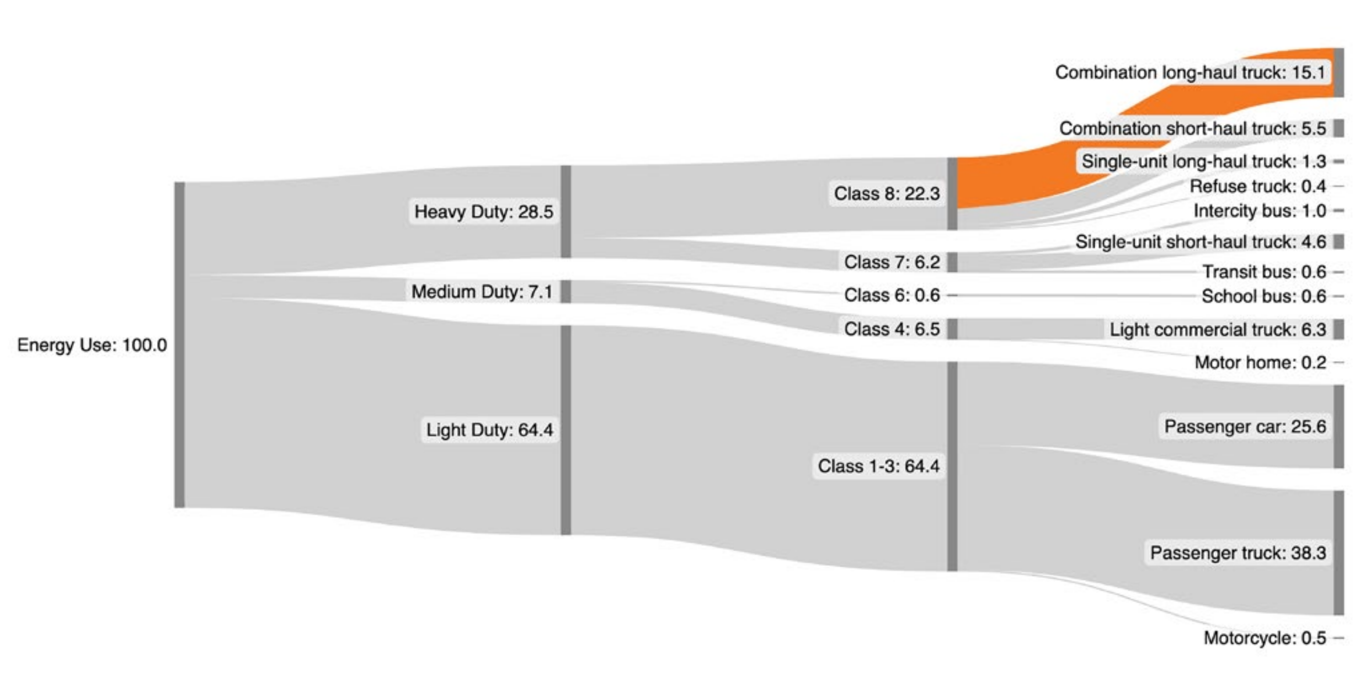

Figure 1: Sankey Diagram: Share of U.S. Energy Use by On-Road Vehicle Class and Category (Data Source: U.S. EPA, 2021[4]; diagram created using SankeyMATIC, https://sankeymatic.com)

Figure 1 also quantifies the approximate amount of new load that would be required annually to electrify 100% of U.S. on-road transport services currently provided by ICE vehicles.[4] Long-haul tractor trailers account for 15.1% of the additional 1880 TWh/yr, third highest among all vehicle types and more than all other HD vehicle types combined. Similarly, these HD trucks account for 20% of total annual U.S. NOx emissions from on-road ICE vehicles, second only to SUVs and other LD passenger trucks.[4] Both additional load and NOx emission reduction represent reasonable proxies for the decarbonization benefits associated with switching long-haul HD trucking from diesel fuel to electric energy.

For every operational long-haul tractor trailer, 64 passenger cars and 70 passenger trucks are on the road. Figure 2 displays relative energy and environmental impacts: Annually, each long-haul HD truck consumes the same amount of energy as 38 passenger cars or 28 passenger trucks and emits as much NOx as 85 passenger cars or 38 passenger trucks.[4]

Under the MOVES projection shown in Figure 1, full electrification of combination long-haul HD trucking would involve new load of more than 280 TWh annually, along with a nationwide reduction in annual on-road vehicle NOx emissions of more than 700,000 tons.[4] Serving this load would result in additional power plant emissions, but previous analysis has shown that such increases would be relatively small and would decrease over time as grid transformation continues.[5]

Public health benefits attributable to any level of electrification will depend on local conditions, including proximity to long-haul trucking routes or large service stations. According to recent EPRI research, high EV penetration has potential to mitigate the historical inequalities in environmental exposure to NO_2 and PM2.5 that face communities with more people of color and less educational attainment living along a busy California highway serving one of the nation's largest port areas.[6]

While EPRI does not project 100% electrification, diverse energy-economy modeling studies—including the "Net-Zero 2050" analysis completed under the Low Carbon Resources Initiative (LCRI)[7]—anticipate substantial EV penetration for long-haul HD trucking. The charging infrastructure required to support broad deployment is not well characterized, motivating the following analysis.

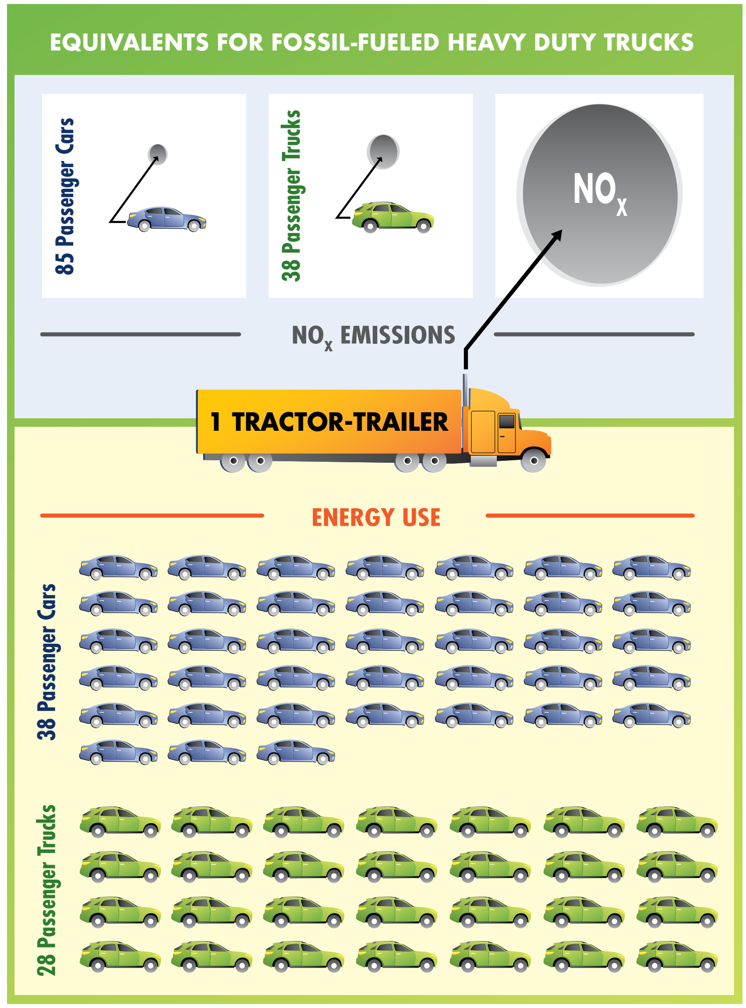

Figure 2: Energy Use and NOx Emissions by Combination Long-Haul Heavy-Duty Trucks and Light-Duty Passenger Vehicles (Data Source: U.S. EPA, 2021[4])

ENERGY PROFILE & DAILY DUTY CYCLE

Combination long-haul HD trucks generally travel along major highways, often traversing parts of the country with minimal traffic congestion. Their operation is governed largely by safety requirements, contract agreements and pay structures, parking and fuel availability, and the attendant preferences of drivers.[8]

Under U.S. federal "hours of service" (HOS) regulations, individual drivers travelling across state lines generally are limited to a maximum of 11 hours of driving time within a 14-hour workday. They also are required to stop for 30 minutes within the first 8 hours and must take a 10-hour rest period before a new workday can begin.[9] Because earnings are often determined by miles driven, a common motivation is to maximize daily travel distance within the allotted period.

At U.S. highway speeds, 11 hours of allowable driving time at an average of 60, 70, or 80 mph (96, 112, or 128 km/hr) translate to a maximum range of 660, 770, or 880 miles (1056, 1232, or 1408 km) per regular workday, respectively. Conventional ICE trucks have large fuel tanks allowing for multiple days of operation, drivers can take advantage of the existing network of filling stations and truck stops, and refueling takes 5 to 15 minutes depending on dispenser speed.[8] Battery capacity, vehicle efficiency, and the availability of high-power fast charging infrastructure are major factors influencing whether EV trucks deliver comparable convenience and performance.

Tesla's Semi is purported to consume less than 2 kWh/mile (3.2 kWh/km) at highway speeds when fully loaded and to have a driving range of more than 500 miles (800 km) when fully charged.[10] These claims have attracted scrutiny, especially because Tesla has not disclosed the energy storage capacity and weight of the vehicle's battery system.

An analysis based on fundamental physics and engineering principles presented in a YouTube video[11] recommended by an EV truck industry leader[12] highlights the plausibility of Tesla's claims. Key determinants of energy consumption per distance driven at a given speed are conversion efficiency; rolling resistance, which depends primarily on vehicle weight and tire friction; and aerodynamic drag, influenced by vehicle profile (drag coefficient) and frontal area. Aerodynamic forces become increasingly important at higher speeds.

Based on publicly available data, basic principles, and several key assumptions, Table 1 indicates that a Tesla Semi operating with a full load at U.S. highway speeds will consume in the range of 1.99 to 2.58 kWh/mile (1.24 to 1.61 kWh/km) and 1314 to 2270 kWh per workday.[11] For comparison, passenger vehicles require about 0.3 kWh/mile (0.19 kWh/km), passenger trucks need 0.5 kWh/mile (0.31 kWh/km) and 1.0 kWh/mile (0.62 kWh/km) or more when towing, and the estimated daily use of a single long-haul HD truck at constant speed of 70 mph (112 km) is more than double the monthly use of the average U.S. residential utility customer, which totaled 886 kWh in 2021.[13]

Table 1: Power Requirement and Energy Use by Tesla Semi at Different Speeds[11]

Highway Speed	Maximum Driving Distance Per Workday	Power Requirement	Energy Use per Unit Distance at 90% Drivetrain Efficiency	Maximum Energy Use per Workday
60 mph (96 km/h)	660 miles (1056 km)	107.49 kW	1.99 kWh/mile (1.24 kWh/km)	1314 kWh
70 mph (112 km/h)	770 miles (1232 km)	142.55 kW	2.26 kWh/mile (1.41 kWh/km)	1740 kWh
80 mph (128 km/h)	880 miles (1408 km)	185.51 kW	2.58 kWh/mile (1.61 kWh/km)	2270 kWh

Table 1 provides idealized estimates for a tractor trailer based on Tesla-released specifications and traveling over flat terrain, without consideration of variable traffic, weather, and other conditions. Of particular note is the claimed drag coefficient of 0.36, a little over half that of a conventional HD diesel truck and below the independently validated aerodynamic performance of Tesla's Cybertruck LD pickup.[14] Aerodynamic drag does not exceed rolling resistance until the Semi's speed surpasses about 75 mph (120 km/h); this switch occurs in the range of 60 to 65 mph (96 to 104 km/h) for conventional trucks and 30 to 40 mph (48 to 64 km/h) for passenger vehicles.[11]

On the other hand, Table 1 is based on a Semi weighing 80,000 lbs (36,363 kg)—the maximum allowable for ICE vehicles on U.S. interstate highways; the limit for EV trucks is slightly higher at 82,000 lb (37,273 kg).[15] Long-haul HD trucks commonly transport lightweight materials or travel with partial loads. This reduces resistance attributable to inertia and friction—the primary determinant of the Semi's energy consumption below about 75 mph (120 km/h) and a significant contributor at higher speeds.

DAILY DUTY CYCLE & CHARGING PROFILE

The U.S. charging profile of combination long-haul EVs will be contingent on the attributes of on-board batteries and the expectations of human drivers as governed by HOS regulations. Starting from 100% SOC and delivering 11 hours of operation, though physically possible, poses tradeoffs: EV batteries are not only costly but heavy, meaning that higher-capacity systems reduce the allowance for transportable goods under the U.S. loading limit. And in any case, U.S. regulations require drivers to take a 30-minute work break.

Two charging modes are anticipated: en-route charging to maximize daily driving distance, and post-workday charging—often overnight—to achieve 100% SOC prior to the next driving assignment. As general rules, EV batteries charge fastest when between 5% and 80% SOC, and achieving 100% SOC can require extended periods due to reduced charge rates at high SOC. Charging speed can be limited by many other factors, including available charging power, conductor sizing within the vehicle, ambient temperature, and battery pack temperature. In practice, the maximum charge rate of the fastest-charging commercial EV batteries is around three times their capacity—for example, a 100 kWh battery can charge at 300 kW.

Detailed consideration of the charging characteristics of EV truck batteries is outside the scope of this *Quick Insights*, but the Semi's available capacity is assumed to be about 1 MWh. This battery size is consistent with the pronounced range of 500 miles (800 km) at an energy consumption under 2 kWh/mile (1.25 kWh/km).[10] It implies that the battery pack will be able to accommodate a peak charge rate around 3000 kW.

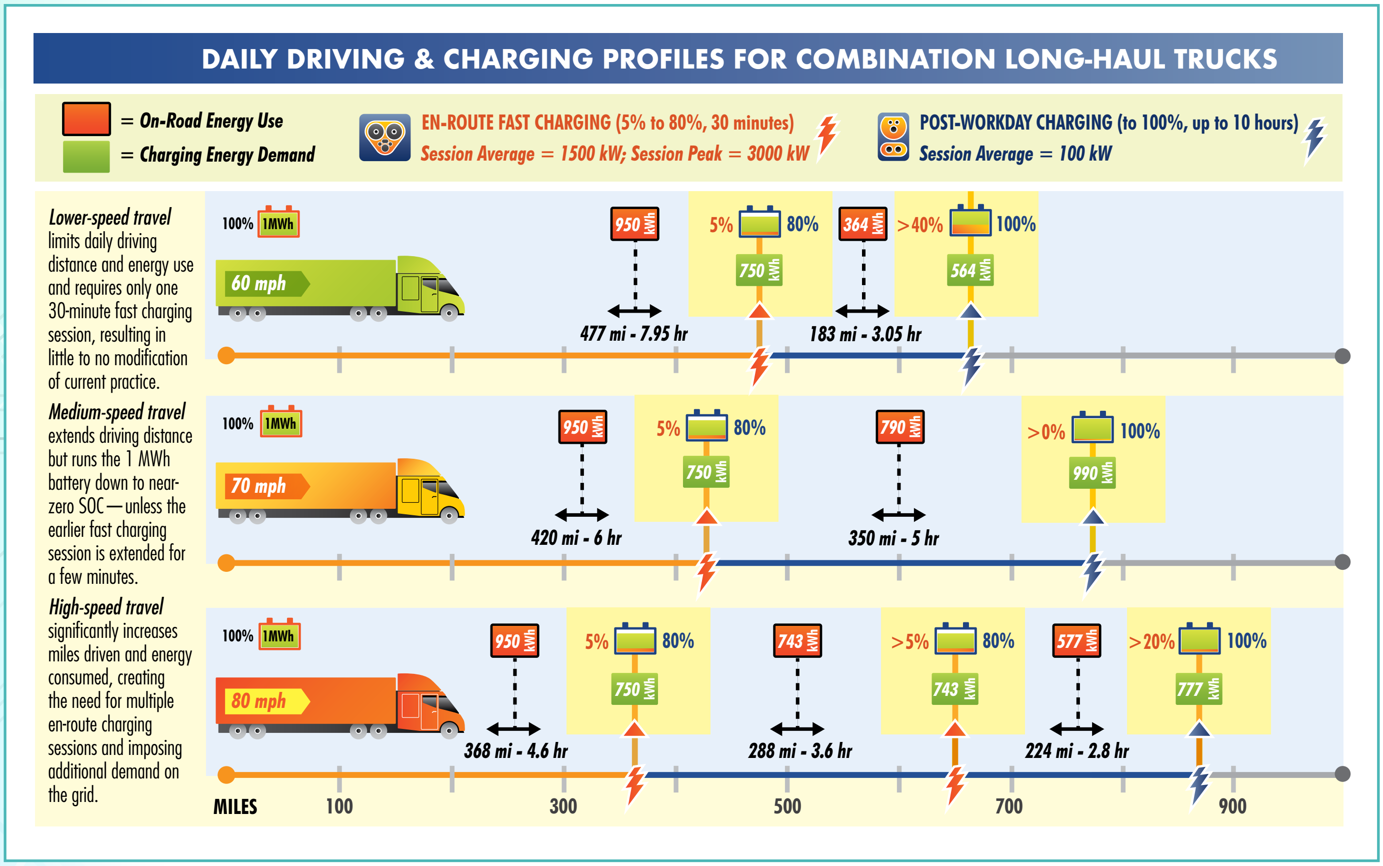

Figure 3: Sample Daily Driving and Charging Profiles for Tractor Trailers at Different Speeds

Developed based on data presented in Table 1, Figure 3 illustrates daily travel and charging profiles for a fully loaded Semi driven by a single individual at highway speeds ranging from 60 to 80 mph (96 to 128 km/hr). In all cases, the assumed battery size is adequate for maximizing daily driving distance with minimal to modest disruption of present practice.

For example, the Semi can pull a full load at 70 mph (112 km/hr) for 6 hours, using 950 kWh and reducing SOC to 5% before stopping for en-route fast charging in combination with the mandatory break. A 30-minute session can restore the battery pack to 80% SOC, drawing a total of 750 kWh at an average power level of 1500 kW and peak around 3000 kW. Traveling 70 mph (112 km/hr) across the remaining 5 hours of drive time brings total workday mileage to 770 miles (1232 km) and can be accomplished by running the battery down to almost 0% SOC, then parking at a charging location suitable for achieving 100% SOC within the mandatory 10-hour rest period. Alternatively, the driver can extend the earlier fast charging session to achieve more than 80% SOC—or stop for a second session—and still reach their daily mileage target plus perform additional tasks during the 14-hour workday.

Figure 3 also indicates that individual drivers traveling 60 mph (96 km/hr) can conclude their 11 hours of daily driving time with substantial remaining SOC despite making only a single charging stop, whereas a second 30-minute fast charging session is required to achieve the daily distance target at 80 mph (128 km/hr). Using multiple drivers for individual trucks creates opportunities to increase daily mileage but poses tradeoffs in managing SOC to both minimize downtime and maximize battery pack lifetime.

The profiles shown in Figure 3 are specific to an EV truck with a 1 MWh battery pack and are intended to be illustrative. Real-world factors—such as elevation change, wind direction, precipitation, and traffic congestion—can substantially influence energy consumption per unit distance and thus day-to-day charging needs. In addition, these profiles are contingent on a critical assumption: broad availability of suitable charging infrastructure.

CHARGING INFRASTRUCTURE REQUIREMENTS

To facilitate electrification of long-haul HD trucking, charging infrastructure likely will need to function like current truck stops and rest areas—convenient to highways, serving en-route vehicles, and accommodating drivers during rest periods and at the end of their workday. Existing facilities, which vary widely in the number of fuel pumps and/or long-duration parking spaces, will require electrical service upgrades to accommodate new demand. Purpose-built charging stations also will need grid service. Peak loads will depend on drivers' work schedules and mileage objectives, as well as their choices on when and where to stop.

Fast charging at an average session power of 1500 kW is essential to minimize downtime for en-route trucks, whereas the mandatory 10-hour rest period will allow 1 MWh batteries at 0% SOC to be fully recharged with an average charge rate of 100 kW. Assuming variability in the beginning and end of fast charging sessions, peak rates of 3000 kW per vehicle can be balanced by lower demand across the connected population.

As shown in Figure 4, a charging station with capacity in the range of 11 to 12 MW can bring about 100 electric trucks to 100% SOC over a 10-hour period, accounting for losses in the process. Because en-route charging needs will be greater during hours of the day when more trucks are driving and post-workday charging will be more prevalent during periods when fewer trucks are driving, the same delivery point can take advantage of this natural load diversity to provide fast charging service to about 7 trucks.

A well-planned network of charging stations at this scale could suffice at low levels of market penetration. Larger stations will be required to support broad electrification. For example, stations on the order of 45 to 50 MW—providing fast charging to about 30 combination long-haul trucks and post-workday charging to about 400—may become common. Currently, the largest U.S. service center, Iowa 80, accommodates 900 trucks.[16]

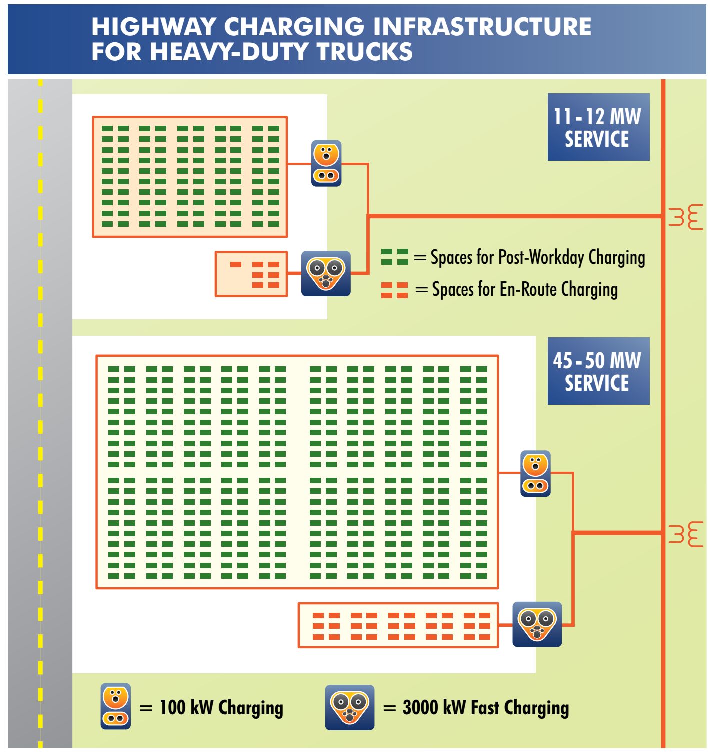

Figure 4: Representative Sizes of Electric Truck Charging Stations

The current shortage of long-duration truck parking along highways presents a challenge to electrification, both independently and in combination with regulations under the Federal Aid Highway Act of 1956, which created the interstate system. Most types of commercial activity, including service stations and, in turn, charging stations, are forbidden at the public rest stops commonly used by off-duty long-haul truck drivers.[8]

IMPLICATIONS AND NEXT STEPS

Electrification of combination long-haul HD trucking has significant potential to reduce on-road emissions of NOx and CO_2 while creating new load centers along highways.

Upgrading electrical service at existing truck stops and bringing adequate service to additional charging locations can largely take advantage of existing supply chains and engineering knowledge from a hardware perspective—similar to interconnecting a solar power plant but running in the opposite direction. EPRI's Electric Transportation Program is conducting a detailed technology gap analysis, to be published in 2023.

Research questions revolve around technology deployment, network planning, funding, and the development of individual delivery points, which at the scale indicated could require from a few years to a decade depending on charging station location. Example questions include the following:

- What are capital and operating costs and environmental attributes of commercial electric HD truck platforms, relative to incumbent ICE technology, novel fuels, and fuel cells?
- What are the options for serving new HD trucking loads—including in less developed areas and remote regions—at varying levels of penetration, and what are the costs of providing charging service?
- What are anticipated public health benefits for various deployment scenarios and electrification levels, and where can disadvantaged communities realize early benefits from EV truck charging infrastructure?
- What are private, public, and utility business models for developing infrastructure and providing charging services, and what are the potential roles of regulators, ratepayers, and taxpayers?
- What changes in policy and regulation are recommended to distinguish recharging from refueling and to ensure efficient utilization of charging infrastructure and long-duration parking spaces, including at public rest stops?
- What policies, incentives, and other government support mechanisms can be used to motivate EV truck purchases, fleet conversions, and the development of charging infrastructure?

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