Electric Medium- and Heavy-Duty Vehicle Charging Infrastructure Attributes and Development

Bonnie Powell, Caley Johnson, Arthur Yip, and Amy Snelling

National Renewable Energy Laboratory

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Cover Photo by NACFE's Run on Less – Electric DEPOT: NREL 92880.

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List of Acronyms

AC	alternating current
AFDC	Alternative Fuels Data Center
CCS	Combined Charging System
DCFC	direct-current fast charger
EV	electric vehicle
EVSE	electric vehicle supply equipment
FHWA	Federal Highway Administration
HD	heavy duty
HDV	heavy-duty vehicle
LDV	light-duty vehicle
MCS	Megawatt Charging System
MD	medium duty
MDV	medium-duty vehicle
NEVI	National Electric Vehicle Infrastructure
NREL	National Renewable Energy Laboratory
VIUS	Vehicle Inventory and Use Survey
VMT	vehicle miles traveled

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1 Introduction

Although more established for light-duty vehicles, advancements in EV charging technology are being made in the medium- and heavy-duty (MD/HD) sector. Progress is also being made with the electrification of MD/HD vehicles, including transit buses, school buses, MD trucks, and HD trucks. The diverse set of operational requirements and duty cycles for each vocation as well as the range in the size of fleets present unique charging and infrastructure requirements (Muratori et al. 2021).

This report focuses on charging requirements for MD/HD vehicles and synergies with light-duty vehicle (LDV) infrastructure. This analysis leans towards the qualitative rather than quantitative because relevant model inputs are in development and will not be established for few years, as EV deployments are more mature in the LDV sectors than MD/HD. The report begins with an overview of MD/HD vehicle classes and types of charging, including depot and residential charging, among others (Section 2). Section 3 analyzes the home bases (overnight dwell location) of existing MD/HD vehicles, with an emphasis on depot and residential home bases, and discusses implications for charging infrastructure. Section 4 discusses the key characteristics for determining if, when, and where MD/HD vehicles can leverage LDV charging infrastructure rather than requiring dedicated chargers. These considerations include electricity demand, connectors, physical space requirements, payment considerations, and impacts on the grid. Section 5 summarizes shared characteristics for MD/HD vehicles that are appropriate for near-term electrification and includes a summary of the outlook of the electric MD/HD vehicle market. The conclusion (Section 6) summarizes the report's findings and outlines areas for future research.

2 Vehicle Classes, Populations, and Types of Charging

Examples of MD and HD vehicles are shown in Figure 1, classified into light, medium, and heavy duty. Definitions of these sectors differ between the U.S. Department of Transportation, Environmental Protection Agency, and U.S. Census Bureau. All agencies classify vehicle class based on gross vehicle weight rating, but the numbers differ (Alternative Fuels Data Center 2024b; National Highway Traffic Safety Administration 2024). The Environmental Protection Agency defines vehicle classes for fuel economy and emissions regulation purposes. This report classifies MD/HD vehicles according to definitions from the Federal Highway Administration (FHWA), which falls under the U.S. Department of Transportation.

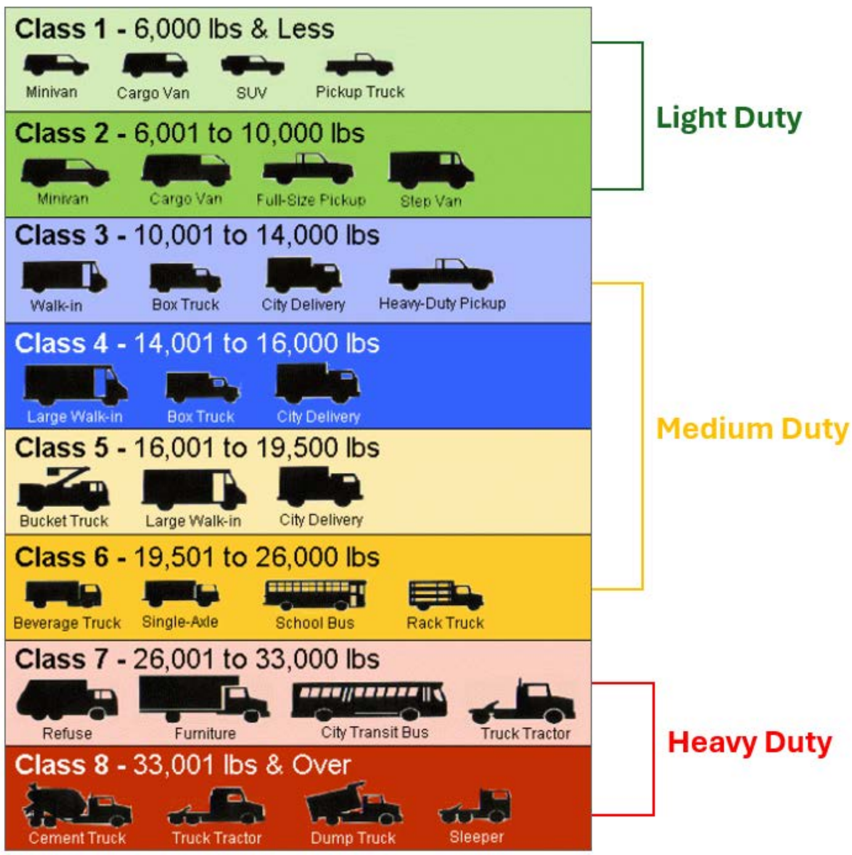


Figure 1. FHWA class definitions and examples of vehicles in different classes.

Source: Modified from Vehicle Technologies Office (2011); Alternative Fuels Data Center (2024b)

Although there are more medium-duty vehicles (MDVs) by stock, heavy-duty vehicles (HDVs) consume more energy and emit more carbon dioxide due to higher annual vehicle miles traveled (VMT) and lower vehicle fuel economies, as shown in Figure 2.

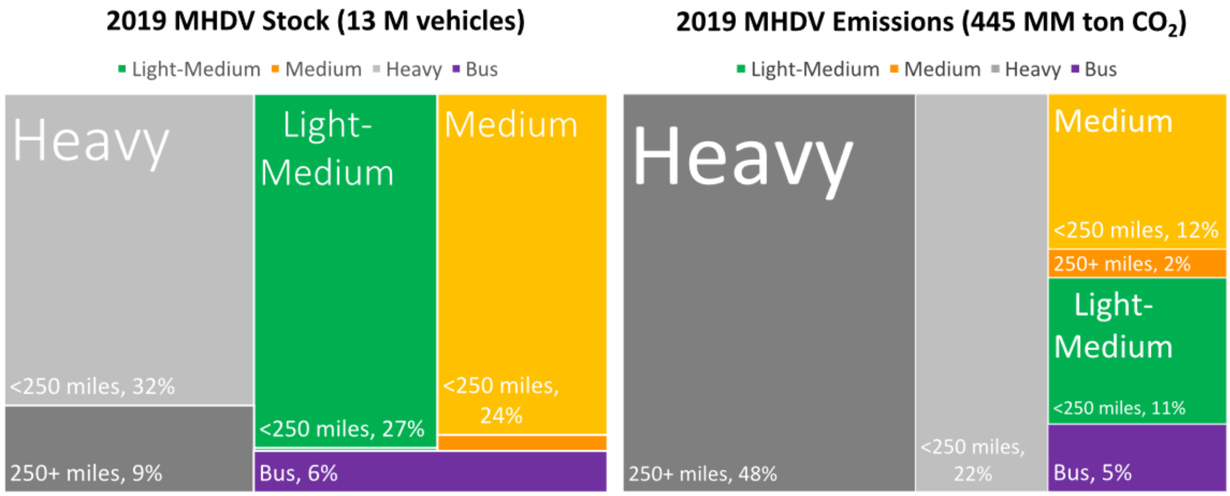


Figure 2. U.S. light-medium duty (Class 3), medium-duty (Class 4–6), and heavy-duty (Class 7–8) vehicle stock (millions of vehicles) and carbon dioxide emissions (millions of metric tons) by vehicle sector.

Source: Ledna et al. (2022)

MD/HD battery-electric vehicles can be charged via public or private alternating-current (AC) Level 2 chargers or direct-current fast chargers (DCFCs). Unlike LDVs, it is not practical to charge MD/HD vehicles using AC Level 1 charging. For example, an electric delivery van with a 100-kWh battery would take 100 hours to charge from fully depleted to 100% charged using AC Level 1 charging (1-kW power output).[1]

Charging types for MD/HD vehicles include:

- **Depot:** Also known as "return-to-base" charging; charging occurs where the vehicle is stored, typically overnight. Depots are typically private industrial or commercial locations.
- **Driver residence:** Some MD/HD vehicles are parked at the driver's home overnight, rather than returning to a depot. In these cases, charging would occur at or near the driver's residence, utilizing home AC Level 2 chargers. This type of charging is further discussed in Section 3.
- **En route:** Charging occurs while the vehicle is en route to its destination, at either a public or private charging station. This could be a dedicated charging station for the MD or HD vehicle or an existing charging station intended primarily for LDV usage. En route charging typically requires "fast" charging (MW+) to remain on schedule (Muratori and Borlaug 2021).
- **Opportunity:** Charging occurs while the vehicle is parked for another purpose, such as during loading/unloading, or while at a truck rest stop. Muratori et al. (2023) describe opportunity charging as "public or semipublic locations where vehicles routinely dwell."
- **Destination:** Charging occurs at the vehicle's destination, such as a store where it is delivering goods. The destination may or may not be owned by the company owning the

[1] Assuming the specifications are similar to the Rivian Delivery 700 van: rivian.com/fleet.

vehicle. This is different from a depot, which is a dedicated area where vehicles are intended to be stored.

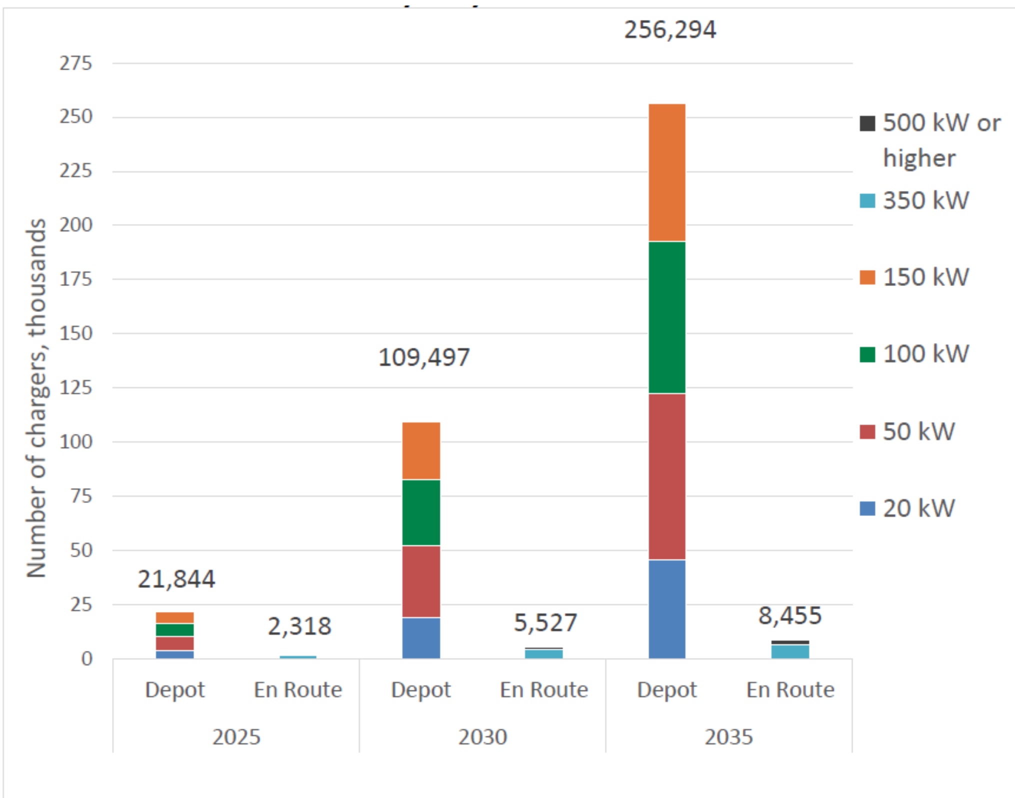
The electric MD/HD vehicle market is most mature for transit and school buses (Alternative Fuels Data Center 2024a; Lowell and Culkin 2021). Electric buses—along with electric delivery trucks, which have more recently penetrated the MD/HD vehicles market—have predictable, low-mile routes that end in the same place they begin. These circular routes enable high specificity in EV battery sizing, which can make vehicles that operate on these established routes more cost competitive with conventional models than vehicles subject to a highly variable drive cycle. Despite this, the upfront costs of electric transit and school buses in-particular are still high; however, grants such as those for electric school buses can offset the high upfront costs, enabling a higher adoption rate(U.S. Environmental Protection Agency 2021). Electric delivery vehicles are typically depot charged at warehouses where the vehicles pick up goods and/or are parked overnight. For example, as of April 2024, Amazon has 17,000 chargers located at 120 warehouses across the United States(Day 2024). Nearly all of these are AC Level 2 chargers. UPS and FedEx have also purchased electric delivery vans (Baertlein et al. 2024).

Initial electric MD/HD applications will require a lower daily VMT, with operating ranges less than 200 miles in return-to-base operations to allow vehicles to charge at a central location. Furthermore, these early fleets will have off-shift dwell periods that provide ample opportunity for charging. Early electric MD/HD vehicle deployments—including transit buses, school buses, and delivery vans, as mentioned above—meet these criteria (pictured in Figure 3). For example, school buses in the United States drive around 50 miles per day on average; transit buses average around 140 miles per day (Bruchon et al. 2024a). Rated ranges for electric school and transit buses are around 150–250 miles, meeting or exceeding these mileage requirements (Environmental Defense Fund, n.d.). Fleet managers may be more comfortable with shorter ranges for fleet vehicles than individual drivers of LDVs due to the predictability and consistency of daily mileage for certain MD/HD fleet vehicles.

Figure 3. Electric school buses (left) and delivery trucks (right) have penetrated the MDV market.

Photos by John Gonzales, NREL 74748 (left) and Trish Cozart, NREL 19543 (right)

In addition, around 87% of U.S. MD/HD vehicles have operating ranges less than 200 miles, and the development of depot charging for these vehicles will be essential to enable electrification (Muratori and Borlaug 2021). Due to the convenience and cost-effectiveness of depot charging compared to en route charging, it is estimated that 75%–90% of chargers for MD/HD vehicles will be at depots by 2030 (McKenzie et al. 2021). In addition, in 2024, the California Energy Commission Assembly Bill 2127 projected approximately 95% of MD/HD vehicle chargers as depot chargers in 2030 and roughly 97% in 2035, as shown in Figure 4 (California Energy Commission 2024). However, there are other charging options that may see increased deployments over time.



The HEVI-LOAD model for medium- and heavy-duty vehicle charging infrastructure projects that about 109,000 depot chargers, ranging from 20 kW through 150 kW, and 5,500 en route chargers, ranging from 350 kW through 1.5 megawatts (MW), are needed to support about 155,000 medium- and heavy-duty plug-in electric vehicles in 2030. In 2035, the charging need grows to about 256,000 depot chargers and 8,500 en route chargers.

Source: CEC and LBNL

Figure 4. Projected MD/HD vehicle charging needs in 2025, 2030, and 2035 by type (depot or en route) and power level for the state of California.

Source: California Energy Commission (2024)

As of 2024, approximately 577,000 unique businesses registered with the Federal Motor Carrier Safety Administration owned or leased at least one truck, with 95.5% of fleets containing 10 vehicles or fewer (American Trucking Associations 2024). Companies owning small fleets are less likely to have the resources to invest in EV infrastructure for depot charging. However, although small fleets dominate, they account for less than half of total MD/HD vehicles (Smart et al. 2020). Therefore, investments made by larger companies (with bigger fleets) would impact a high percentage of trucks on the road.

Although much of the MD/HD vehicle charging is anticipated to occur at depot locations, such as the one pictured in Figure 5, during a typical overnight dwell (McKenzie et al. 2021), larger operating ranges will likely have to rely on some en route or destination charging to satisfy longer trips. Vehicles parking at driver residences will require disparate charging infrastructure. In order to better understand the potential prevalence of depot vs. driver residence charging, the primary overnight dwell location of current MD/HD vehicles was analyzed.

Figure 5. A truck fleet depot with electric trucks.

Photo by Mike Simpson, NREL 28804

3 MD/HD Vehicle "Home Base" Analysis: Depot vs. Residence

The type of charging solution required for electric MD/HD vehicles will vary based on where the vehicle is parked while off-duty.

An analysis of the 2021 Vehicle Inventory and Use Survey (VIUS) data (Bureau of Transportation Statistics 2021) was performed to estimate the "home base" (defined as "the location where the vehicle was usually parked when it was not on the road," which we interpret as the primary off-duty dwell location) of different classes of existing trucks. Although these vehicles are overwhelmingly conventional internal combustion engine vehicles, their current home base could indicate where charging would need to occur if the vehicles were electrified to minimize a disruption to current operations. The estimated proportion of MD/HD trucks that are parked at a commercial/industrial location,[2] private residence, or a mix of the two are shown sequentially in Figure 6.

[2] VIUS respondents selected one of the following: corporate office/headquarters, terminal or motor pool, distribution center, manufacturing plant, farm/agricultural production, mining or other energy production site, truck leasing company, or port.

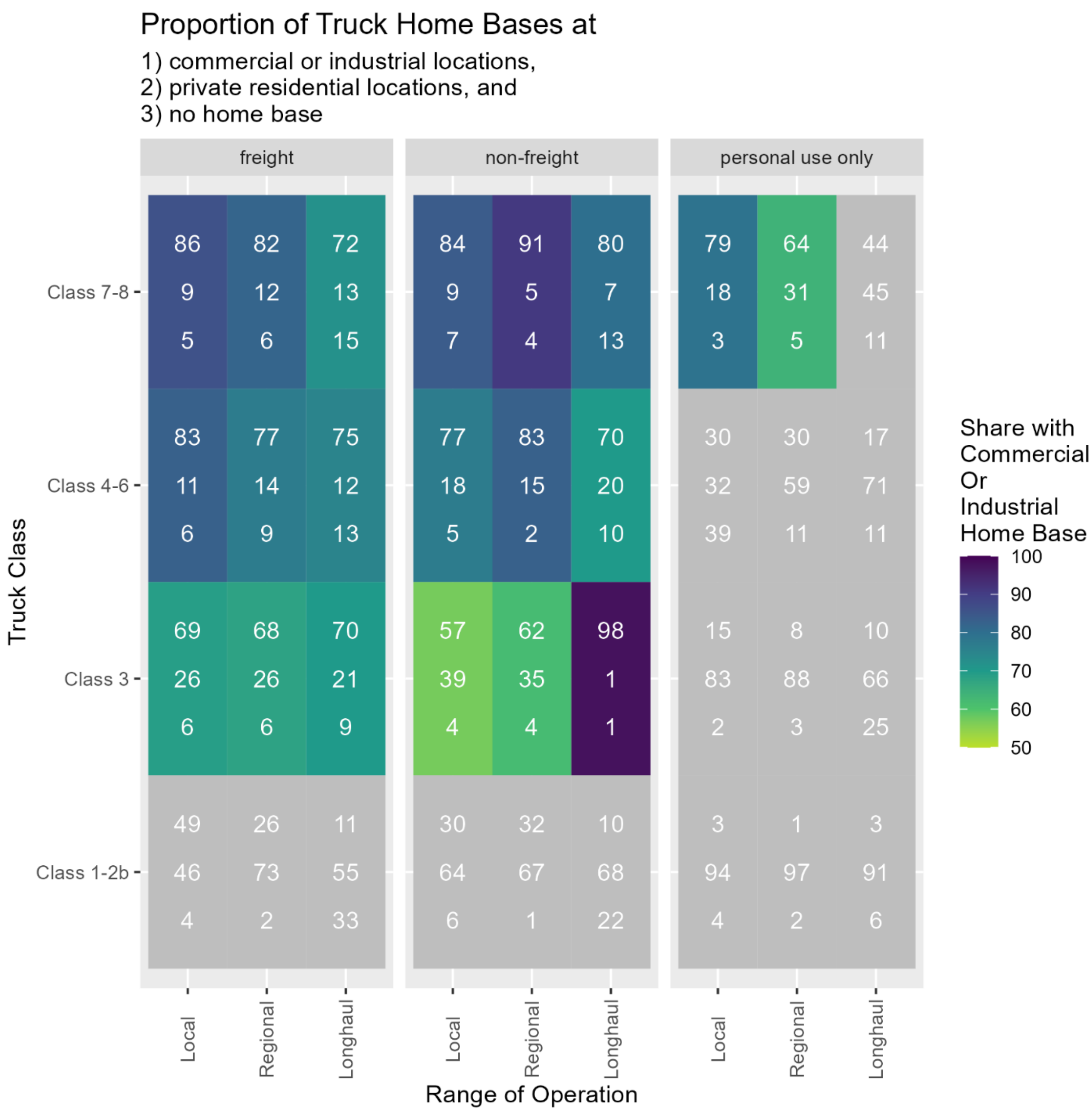


Figure 6. Estimated truck primary overnight dwell locations (home bases) in the United States based on vehicle class, range, and primary use, according to a statistical analysis performed on 2021 VIUS survey data.

Local ranges: 0–99 miles; regional ranges: 100–249 miles; long-haul ranges: 250 miles or greater

The majority of MD/HD vehicles—both freight and non-freight and across all ranges of operation—are parked at commercial or industrial locations (likely a depot) while off-duty. The percentage of non-personal vehicles with a commercial/industrial home base varies between 70% and 83% for Class 4–6 MDVs and 72% and 91% for HDVs. In contrast, between 11% and 20% of MDVs and 5% and 13% of HDVs are regularly parked at residential locations, depending on range and use case.

Figure 6 separates each truck class first by freight and non-freight use cases,[3] and then by local, regional, and long-haul (defined by range of operations less than 100 miles, between 100 and 250 miles, and above 250 miles, respectively) applications. Non-freight MDVs are at the upper end of the residential parking range, with long-haul-range vehicles parking at residences most often (20%), followed by local ranges (18%) and regional ranges (15%). In comparison, between 11% and 14% of freight MDVs regularly park at residences. Fewer HDVs park at residences compared to MDVs, but freight HDVs are more likely (9%–13%) to than non-freight HDVs (5%–9%). Surprisingly, within the HDV class it is the long-haul freight vehicles that park at residences most often (13%), excluding HDVs used for personal use.

This demonstrates that although most off-duty commercial MD/HD vehicles park at a private depot, a substantial proportion of both medium- and heavy-duty commercial vehicles park at residential locations. In particular, non-freight MDVs with regional and local ranges have the highest incidence of a residential home base—between 15% and 20%. These vehicles will require targeted charging solutions if electrified. Vehicles utilizing street parking will face a particular challenge, as a power source is typically not nearby.

[3] Non-freight MD and HD vehicles refer to VIUS respondents that did not select "transporting goods/products" as the vehicle's commercial activity.

4 En Route MD/HD Vehicle Charging: Dedicated MD/HD Vehicle Chargers vs. Leveraging LDV Infrastructure

Although most MD/HD vehicle charging is expected to occur at a home base or depot (McKenzie et al. 2021; Lowell and Culkin 2021), some MD/HD vehicles—mostly HD—will need en route charging to enable longer-distance trips. One study predicted that long-haul tractors are the only MD/HD vehicle market segment for which almost all vehicles will require en route chargers, along with some regional-haul tractors and some Class 6–8 box trucks (Lowell and Culkin 2021). The analysis estimated that all other MD/HD vehicle categories will nearly exclusively utilize home base charging. However, these vehicles may still need access to public chargers in extenuating circumstances (such as a failed overnight charge). Table 1 shows the estimated charging types by MD/HD vehicle category from Lowell and Culkin (2021). Note that categories may appear in more than one charging bin (indicating that the charging needs for those categories will differ based on the vehicle/application).

Table 1. Estimated Charging Requirements by MD/HD Vehicle Market Segment (Lowell and Culkin 2021)

Market Segment	% MD/HD Truck Greenhouse Gas Emissions	Home Base (AC Level 2)	Home Base (DCFC)	Public
Long-haul tractor	47.8%			✓
Heavy-duty pickup and van	15.7%	✓	✓	
Regional-haul tractor	11.9%		✓	✓
Delivery truck	2.7%		✓	
Dump truck	2.6%		✓	
Box truck (Class 8)	1.9%			✓
Service van	1.7%	✓		
Shuttle bus	1.3%		✓	
School bus	1.1%	✓		
Delivery van	1.0%	✓		
Service truck	0.8%	✓		
Stake truck (Class 3–5) [a]	0.7%	✓		
Transit bus	0.7%		✓	
Refuse hauler	0.6%		✓	
Stake truck (Class 6–7)	0.5%	✓		
Box truck (Class 6–7)	0.5%		✓	✓
Box truck (Class 3–5)	0.3%	✓		

[a] Stake trucks are trucks with a flat bed and removable gates; these gates allow oversized cargo to be carried.

For the MD/HD vehicles requiring public chargers, the question remains whether these vehicles will utilize existing LDV public charging infrastructure (including DCFCs) or require dedicated electric vehicle supply equipment (EVSE). This requires consideration of electricity demand, physical space requirements, connector availability, pricing and costs, and impacts on the electricity grid. These considerations are discussed in the following subsections.

4.1 Electricity Needs

Due to their size, MD/HD vehicles require a significant amount of energy, with operational efficiency estimated around 2.4 kWh/mile (Gladstein, Neandross & Associates 2021; Uddin 2021), although this efficiency varies based on the type of vehicle. Comparing this to the light-duty average (sales-weighted) operational efficiency of 0.29 kWh/mile (Gohlke and Zhou 2021) means MD/HD vehicles will consume roughly 8 times more energy per mile than LDVs, suggesting an even greater need for higher power to support charging (U.S. Department of Energy and U.S. Environmental Protection Agency 2023).

Fleets of multiple trucks or buses charging in one location, such as a depot or travel center, may require several megawatts of power in total. This requires expensive charging infrastructure, potentially including costly and time-consuming grid upgrades, to provide the higher voltage and current levels that fleet vehicles may need (Muratori et al. 2021).

Conversely, some fleet operations can be supported by depot charging at power levels in line with light-duty charging equipment. For example, electric Amazon delivery vans primarily use AC Level 2 chargers during overnight dwell times. These electric delivery vans have a 100-kWh battery and a rated range of 153 miles (Neil 2024).[4] Using a standard AC Level 2 charger rated at 6.6 kW, the van takes approximately 15 hours to fully charge once fully depleted. With only 1 hour of charging, the delivery van could travel roughly 10 miles. This example illustrates that AC Level 2 charging is sufficient for charging during longer (typically overnight) dwell periods at depots but is not suited for midday or en route charging. In other words, much of the depot charging during longer dwell periods could be satisfied through 6.6-kW EVSE, but the quick charge times required for midday or en route charging would require EVSE with power ratings exceeding 1 MW (Borlaug et al. 2021).

The Charging Interface Initiative (CharIN) is currently developing a Megawatt Charging System (MCS) standard to support MD/HD vehicle charging. Also known as the SAE J3271 charging standard, MCS will be capable of supplying up to 3.75 MW of power, which is 7 times higher than the current light-duty fast charging technology, which peaks at 500 kW (Bohn 2023; Meintz 2023). MCS charging stations and trucks are being built and tested in pilot deployments, with fleet-level deployments expected in 2024 (Bohn 2023). However, locations that plan to install these chargers will likely require significant infrastructure upgrades to facilitate the grid interconnection. The SAE J3068 connector is also mentioned as a connector "appropriate for MD/HD charging" and proposed in the National Electric Vehicle Infrastructure (NEVI) program funding requirements as allowable but not required (Federal Highway Administration 2023).

One way to estimate the need for public (or en route) chargers is by comparing the typical daily VMT of vehicles to the estimated range of current electric versions of those vehicles. Lowell and

[4] Assuming the specifications are similar to the Rivian Delivery 700 van: rivian.com/fleet.

Culkin (2021) performed this analysis in 2021 and found that vehicle range exceeded daily VMT for 11 vehicle types (63% of the fleet), indicating these vehicles could have been electrified in 2021 and not required a charge until an overnight dwell period. In other words, the batteries for these vehicles have large enough capacities to handle daily mileage, and en route charging would not be required. Table 2 shows the vehicle types with ranges exceeding, between 60% and 100%, and less than 60% of average daily mileage. It may take longer for EVs to enter the marketplace for vehicle types with ranges less than average daily mileage due to the EVs requiring more expensive (i.e., larger) batteries or additional en route EV charging stations. It is important to note there have been advancements in EVs, battery technology, and charging infrastructure since this study was published in 2021.

Table 2. Estimated EV Range and Average Daily Mileage by Vehicle Type (Lowell and Culkin 2021)

Range > Average Daily Mileage	60% < Range < 100% of Average Daily Mileage	Range < 60% of Average Daily Mileage
• Heavy-duty pickup and van • Transit bus • School bus • Delivery van • Service van • Service truck • Refuse hauler • Box truck (Class 3–5) • Box truck (Class 6–7) • Stake truck (Class 3–5) • Stake truck (Class 6–7)	• Regional-haul tractor • Delivery truck (Class 6–7) • Dump truck	• Long-haul tractor • Shuttle bus • Box truck (Class 8)

In addition to daily mileage, dwell time data for different MD/HD vehicle types can be used to evaluate their patterns and determine which are the best candidates for electrification. Daily mileage and dwell time can be used to determine the required range and charging speed for electric MD/HD vehicles. Dwell time is the time potentially available for charging, and daily miles traveled must be less than the vehicle range, unless dwell time occurs throughout the day rather than overnight. The variability of these data (for a particular fleet) is also an important consideration. As an example, Figure 7 shows the dwell time (as well as daily mileage) for transit buses in the United States. The median daily mileage for transit buses is roughly 140 miles, and the dwell time is approximately 11 hours. These data are from a national dataset developed by the National Renewable Energy Laboratory (NREL) for MD/HD vehicles (Bruchon et al. 2024b).

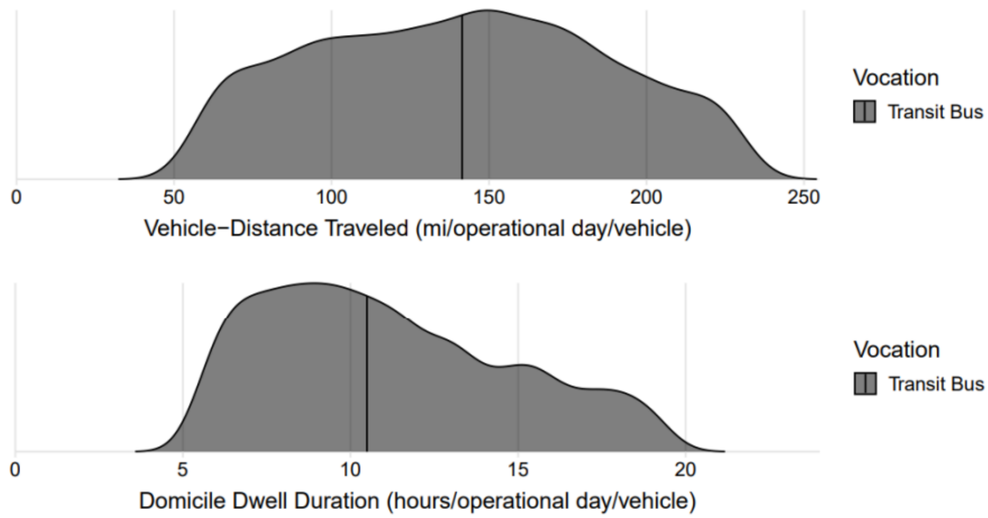


Figure 7. Distribution of daily VMT (top) and domicile dwell duration (bottom) for U.S. transit bus data. Vertical lines mark the median (weekdays, 10th–90th percentile range).

Source: Bruchon et al. (2024a)

4.2 Physical Space Needs

In addition to higher-power charging stations, existing EVSE intended primarily for LDV use could also be utilized by MDVs or possibly HDVs. However, the station must be physically accessible by the larger vehicle.

In order to estimate how many light-duty EVSE could physically fit medium- and/or heavy-duty vehicles, the Alternative Fuels Data Center (AFDC) Station Locator was used. The AFDC Station Locator tracks public and private EV charging stations, both installed and planned. An example station is shown in Figure 8. Planned stations were included in this figure as an indicator of the direction that future charging infrastructure is going.

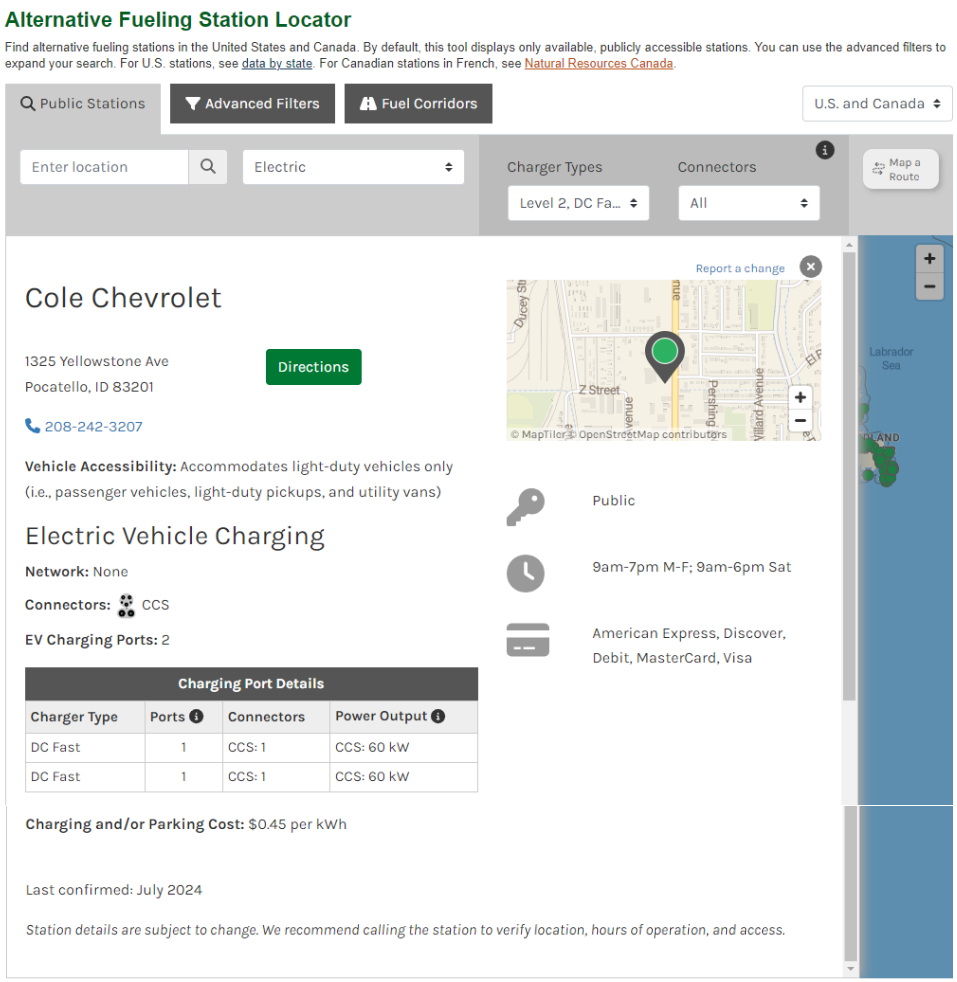


Figure 8. Example DCFC station details for a charging station in Idaho from the AFDC Alterative Fueling Station Locator. Vehicle accessibility (light-, medium-, and/or heavy-duty vehicles) is shown in addition to connector type, charging costs, hours of operation, and accepted payment methods.

Source: AFDC

The maximum (largest) vehicle class that can access the charging station is included for 16% of open stations tracked, as shown in Table 3 (and just over 8% of planned stations tracked). These are the stations for which the station point of contact responded to the AFDC's question about vehicle class accessibility. Of this 16%, 0.6% are accessible by MDVs and 0.2% by HDVs. AFDC determines the maximum class by asking station points of contact to estimate if certain types of vehicles could fit, considering station canopy height (if applicable) and vehicle turning radius.

Table 3. Charging Station Locations Classified by Vehicle Accessibility.

Includes both public and private station locations; data from the AFDC Station Locator for Oct. 2, 2024.

Maximum Vehicle Class	Open Stations		Planned Stations	
	Number	Percentage	Number	Percentage
Light duty (Class 1–2)	13,275	15.9%	156	8.6%
MD (Class 3–5)	526	0.6%	15	0.8%
HD (Class 6–8)	162	0.2%	30	1.6%
Not reported	69,451	83.3%	1,622	89.0%
Total charging stations	**83,414**	**100.0%**	**1,823**	**100.0%**

FHWA's NEVI Formula Program provides funding to states for EVSE installation (Alternative Fuels Data Center, n.d.). The NEVI minimum requirements do not address specific site designs to accommodate MD/HD vehicles; however, FHWA received feedback requesting such requirements and responded to these comments in the final ruling. In their response, FHWA stated:

> "FHWA strongly encourages States and other designated recipients to consider recommendations in addition to and beyond those provided for through the "Design Recommendations for Accessible Electric Vehicle Charging Stations" guidance published by the U.S. Access Board in 2022. Some considerations could include allowing for **one or more pull-through charging stations** and **on-site circulation** and **ingress/egress design** that **accommodates medium- and heavy-duty vehicles** that may access the site for charging" (emphasis added).

States can specify additional requirements beyond the NEVI minimum requirements in their EV infrastructure deployment plans. For example, Louisiana's plan includes draft scoring criteria that the Louisiana Department of Transportation and Development will use to score funding applications (in addition to meeting the federal requirements). One of these criteria is "ability to accommodate oversized vehicles and commercial trucks" (Louisiana Department of Transportation & Development 2023). Illinois' plan mentions requests for MD/HD vehicle requirements ("higher power levels and pull-through designs"); however, MD/HD vehicle requirements were not adopted in the 2023 plan update. Specifically, the Illinois plan states: "Based on concerns expressed by stakeholders that these requirements could significantly limit the number of viable sites for public charging and/or increase costs to an extent that would make charging installation infeasible in some areas of the state, [the Illinois Department of Transportation] revised its approach to take a more site/corridor specific approach to these issues" (Motsinger 2023).

4.3 Connectors

Most of the 526 open MD/HD vehicle charging stations tracked by the AFDC have J1772 connectors. As of Oct. 4, 2024, nearly 80% of EV charging stations accessible to HD or smaller classes of vehicles have J1772 connectors as the only connector option, and 99% are J1772 compatible (either J1772 or J1772 combination plug). Figure 9 shows a Nissan LEAF plugged in at a charging station, and Figure 10 shows two connectors under the plug cover of a Nissan LEAF.

Figure 9. A Nissan LEAF plugged in at a charging station.

Photo from Erik Nelsen, ICF, NREL 65889

Figure 10. Under the plug cover of a Nissan LEAF, showing a J1772 charging plug for AC Level 1 and Level 2 charging (right) and a CHAdeMO charging plug for DCFC (left).

Photo from Erik Nelsen, ICF, NREL 41589

The number of electricity charging station locations classified by vehicle accessibility is included in Table 4. Note that some charging stations reported more than one connector type; those with at least one of the connector types are included in the table. Overall, many light-duty EVSE plugs are compatible with MD/HD vehicles (prior to the adoption of the Combined Charging System [CCS] standard), and MD/HD vehicles can find adequate charging stations (that are powerful enough and have enough physical space for the vehicle to fit) by searching on the AFDC Station Locator (Alternative Fuels Data Center 2023).

Table 4. EV Connector Type at the 526 Open MD/HD Charging Stations Tracked by the AFDC.

Some stations reported more than one connector type; data from the AFDC Station Locator for Oct. 2, 2024.

	Number of Stations [a]		Percentage of Stations	
EV Connector Type	**MD (Class 3–5)**	**HD (Class 6–8)**	**MD (Class 3–5)**	**HD (Class 6–8)**
J1772	434	128	82.5%	79.0%
CCS Type 1 (J1772 + CCS)	93	32	17.7%	19.8%
NEMA	5	0	1.0%	0.0%
CHAdeMO	44	20	8.4%	12.3%
NACS (Tesla)	5	1	1.0%	0.6%
Not reported	4	3	0.8%	1.9%
Total number of stations	**526**	**162**	**100.0%**	**100.0%**

[a] Some stations contained more than one kind of connector; therefore, the sum of all rows is greater than the total number of stations.

NEVI Formula Program funding requirements published in 2023, established to create EV corridors, specify that DCFC ports must have a CCS Type 1 connector (Federal Highway Administration 2023). Note that the CCS Type 1 connector is used in North America—there is also a CCS Type 2 connector that is commonly used in Europe (Rachid et al. 2023).

4.4 Payment and Pricing Considerations

In addition to electricity needs, connectors, and physical space requirements, charging pricing and payment methods are key considerations for MD/HD vehicles. A logistical simplification from the depot charging model is using private chargers that are owned by the same company as the fleet, eliminating the need for payments. In addition, the longer dwell times at depot chargers typically allow for AC Level 2 chargers rather than DCFCs. Public DCFCs are more expensive than AC Level 2 chargers. Cost models for public DCFCs vary—costs can be per kilowatt-hour, per minute of charging, a set fee per month (subscription model), and/or can consider peak power (kW). Larger vehicles require larger-capacity batteries (i.e., more kilowatt-hours) and therefore typically have higher associated charging costs.

Electricity costs vary substantially by state as well. As of April 2024, the cost of electricity for residential customers varied between $0.11/kWh (Utah) and $0.45/kWh (Hawaii), with an average around $0.17/kWh. This represents the cost for home AC Level 2 charging. The state-level costs for commercial customers is slightly less, with a minimum of $0.07/kWh (North Dakota), a maximum of $0.41/kWh (Hawaii), and an average of $0.13/kWh (U.S. Energy Information Administration 2024). Industrial electricity was even less expensive—$0.10/kWh on average. The commercial and industrial electricity rates could represent the cost for AC Level 2 charging at a depot location. Costs for the public charging stations tracked by the AFDC include various models, including free, per minute, per hour, per kilowatt-hour, variable by time of use, with and without service fees, with and without parking fees, and combinations of the above (Alternative Fuels Data Center 2023). Table 5 summarizes the average charging costs in the United States for home AC Level 2, public AC Level 2, and DCFCs. Public AC Level 2 charging is more expensive than home AC Level 2 charging due to a profit margin included for the public charging station owner.

Table 5. Approximate Average Charging Costs in the United States for Different Charging Levels (U.S. Energy Information Administration 2024; Clarke 2024)

AC Level 2 (Home/Private)	AC Level 2 (Public)	DCFC (Public)
~$0.17/kWh (residential) ~$0.13/kWh (commercial) ~$0.10/kWh (industrial)	~$0.20–$0.25/kWh	~$0.40–$0.60/kWh

Some of the same reliability issues facing LDV charging today in regard to payment at public charging stations also apply to MD/HD vehicles. These include the network connectivity problems facing payment systems, among other issues, outlined in multiple reports from the National Charging Experience (ChargeX) Consortium (Joint Office of Energy and Transportation 2023). In these reports, ChargeX recommends solutions including minimum required error codes for debugging EVSE, the use of certain credit card readers that have a payment card industry certification, and network best practices to strengthen connectivity.

4.5 Grid Considerations

Owners of MD/HD vehicles must consider the impacts that charging their vehicles will have on the electricity grid. Depot charging systems may strain existing facility electrical systems by adding a significant load that was not planned previously at the facility, impacting the feasibility and economics of electrification (Borlaug et al. 2021). This could also be an issue for other types of charging (beyond depot charging) as well.

Smart charge management strategies are a fundamental component of planning for MD/HD fleet charging that can address this strain. In recent years, as EV adoption and the prevalence of connected devices have increased, managed charging programs are moving from time-of-use rates and behavioral or passive managed charging to active managed charging through direct load control (Blair, Fitzgerald, and Dougherty 2021). Active managed charging through direct load control can reduce expensive and timely grid upgrade costs associated with EV charging for fleets, as well as operational costs. MD/HD fleets are an attractive use case to orchestrate depot EV charging to reduce the magnitude and timing of peak loads, as their operations are highly sensitive to operating costs and are often coordinated by a professional fleet manager (Borlaug et al. 2021). Because MD/HD vehicles have high power demands, mitigating power spikes can not only help the electricity grid, but also reduce costs (U.S. Department of Energy 2023). Additionally, initial MD/HD electric fleet applications will typically have predictable duty cycles and potentially long dwell times, presenting an opportunity to optimize charging without any disruption to meeting a fleet's operational needs (Blair, Fitzgerald, and Dougherty 2021).

Although the peak demand of charging sites could be mitigated through smart charge control strategies, sometimes the only reasonable alternative to expensive grid upgrades is the installation of local distributed energy resources. These local resources, such as solar photovoltaics or energy storage, could supply some of the power needed during high coincidence peaks of multiple chargers, thereby reducing the peak demand from the grid. Distributed energy resources could also be used to power the charger entirely in an off-grid scenario (Figure 11). Furthermore, utilizing distributed energy resources aligns with federal transportation decarbonization goals to consider the electricity generation source used to fuel EVs and maximize the amount of renewable energy used for each fueling session (U.S. Department of Energy et al. 2023).

Figure 11. Solar EV charger on the NREL campus.

Photo by Dennis Schroeder, NREL 62517

5 Targeting Appropriate Fleets

The primary considerations when evaluating which vehicles are best candidates for electrification include route length, route predictability, home base location, typical dwell times, and kinetic intensity of the vehicle. Kinetic intensity is a vehicle's acceleration divided by its speed, and a higher value indicates greater stop-and-go driving. The vehicle characteristics that are generally easier for fleet electrification are shown in Table 6, although there are exceptions.

Table 6. Key Characteristics When Considering MD/HD Vehicle Electrification

Category	Characteristic That Is Generally Preferable for Electrification	Reason
Route length	Shorter	Allows for smaller/less expensive battery pack
Route predictability	More predictable	Reduces the required number of charging stations
Home base location	Depot	Allows for less expensive installation of charging stations
Typical dwell times	Longer (~12+ hours per day)	Enables lower-power/less expensive equipment; additional flexibility for load management
Kinetic intensity of the vehicle	Higher kinetic intensity takes better advantage of EV attributes, resulting in increased performance and lower greenhouse gas emissions.	EVs outperform internal combustion engine vehicles during stop-and-go drive cycles because they accelerate more efficiently and have regenerative braking.

This framework shows school/transit buses and delivery vans are excellent candidates for electrification due to their short and predictable routes with long dwell times at depots. However, they do not make up a substantial portion of MD/HD truck greenhouse gas emissions (see Table 1). Long-haul tractors constitute nearly half of all MD/HD truck greenhouse gas emissions in the United States. Routes are long, and the trucks typically do not return to depots on a daily basis, requiring en route public (or private) charging stations. This presents a greater challenge for fleet electrification. However, there is a trend toward "hub-and-spoke" routes (see Figure 12) that are more predictable and better aligned for charging at a central hub. The hub-and-spoke model involves a central distribution center (the "hub") and delivery points radiating outward. The direct bidirectional routes that trucks follow to these delivery points are the "spokes." This model is more logistically simple than the point-to-point model, as inventory is kept at the central hub rather than scattered locations, and some truck drivers prefer the hub-and-spoke model as it allows them to be back home at night more often (Hirsch 2020). Charging infrastructure could be built out at the central hub for depot charging, or along certain spokes, for fleets that follow the hub-and-spoke model.

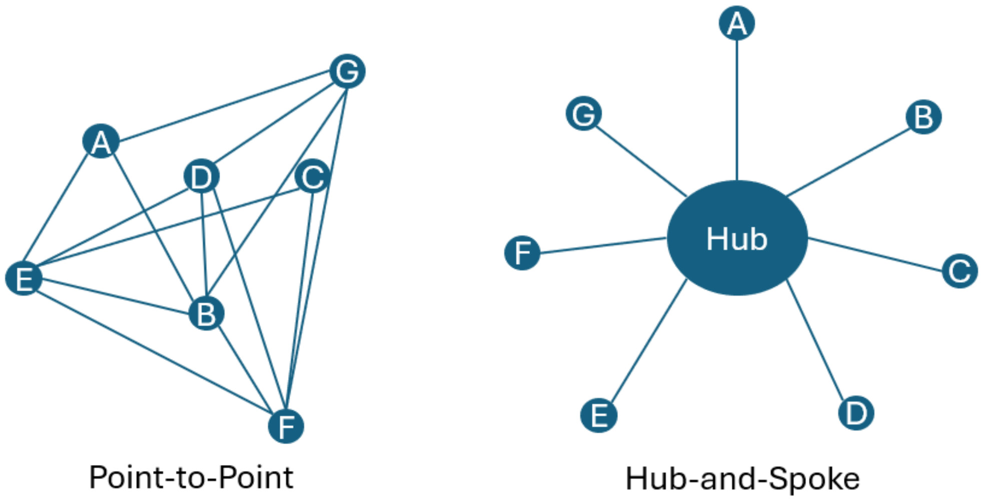


Figure 12. Point-to-point vs. hub-and-spoke distribution models.

Analyzing the current penetration of electric MD/HD vehicles, as well as model offerings, can help us better understand the current state of the MD/HD vehicle market and where it may be heading.

VIUS is conducted by the U.S. Census Bureau in order to understand the quantity and characteristics of private and commercial trucks on a national and state level. Sponsored by the Bureau of Transportation Statistics, FHWA, and the U.S. Department of Energy, VIUS was conducted every 5 years between 1963 and 2002 and resumed in 2021 (U.S. Census Bureau, n.d.). The survey is a unique insight into a market that is difficult to track due to its decentralized manufacturing process, where vehicle components are sourced from and assembled by many different specialty companies. It is the authoritative survey in the U.S. MD/HD vehicle field, and the survey data are used for freight movement analysis, highway cost allocation, commercial motor vehicle safety analysis, and more.

According to the VIUS 2021 survey results—using the provided tabulation weighting factors as outlined in the public use file user guide (U.S. Census Bureau 2023)—only 0.3% of national trucks (light, medium, and heavy duty) in the United States use electricity as the "type of fuel most often used." Note that plug-in hybrid trucks that are not regularly charged (i.e., liquid fuel is most often used) and traditional hybrid trucks are not accounted for in this total. Excluding light-duty trucks (minivans and SUVs) brings the percentage of MD/HD trucks that are fully electric down to 0.1%. Table 7 lists the estimated percentage of electric trucks in the United States by vehicle class and type.

Table 7. Estimated Percentage of Electric Light-, Medium-, and Heavy-Duty Trucks Nationally in the United States by Vehicle Type.

Data from the VIUS 2021 public use survey results and extrapolated to the national level using the provided tabulation weighting factors. Any body types not shown had zero electric trucks.

Light, Medium, or Heavy Duty	Body Type [a] Description	Number of Electric Trucks	Total Number of Trucks	Percent Electric
Light duty	Minivan	1,335	11,274,064	0.01%
Light duty	SUV	528,737	95,617,656	0.55%
MD/HD	Tank, liquid, or gases	128	192,404	0.07%
MD	Van, walk-in	185	274,558	0.07%
Unknown	Other	146	223,522	0.07%
Total		**530,530**	**179,817,852** [b]	**0.30%**

[a] Body type refers to the “type of body that is permanently attached to the power unit” (U.S. Census Bureau 2024).

[b] Categories do not add to the total number of trucks because categories without EVs were omitted.

However, there have been developments in the MD/HD electric vehicle space since 2021, and the number of in-use electric MD/HD vehicles has likely increased since VIUS 2021 was administered. According to the International Energy Agency, 3.1% of truck sales and 2% of bus sales in the United States in 2022 were EVs (International Energy Agency 2023). There are 121 unique models of fully electric MD/HD vehicles that are commercially available in 2024, according to the AFDC, up from 99 in 2021. The number of commercial MD/HD all-electric and plug-in hybrid electric vehicle models available in 2024 by vehicle type are listed in Table 8 for 2024 and 2021 (Alternative Fuels Data Center 2024a). The number of all-electric models offered has increased or stayed the same in these 3 years in every vehicle type category except for passenger van/shuttle bus. In 2024, transit and school buses have the most electric models available, followed by vocational/cab chassis, passenger van/shuttle bus, and tractors. This may be due to transit and school buses having predictable, short routes, making them more suitable for electrification. Vehicle types with unpredictable and/or longer routes will take longer to electrify. All-electric vehicles are more common than plug-in hybrid electric vehicles for the MD/HD vehicle market.

Table 8. Number of Electric MD/HD Vehicle Models by Category in 2024 (and 2021) (Alternative Fuels Data Center 2024a; Davis and Boundy 2022)

Vehicle Type	Electric Vehicle	Plug-In Hybrid Electric Vehicle	Total [a]
Van	5 (4)	0 (0)	5 (4)
Passenger van/shuttle bus	15 (19)	0 (2)	15 (21)
Step van	4 (4)	0 (1)	4 (5)
Vocational/cab chassis van	1 (1)	0 (0)	1 (1)
Vocational/cab chassis	22 (12)	0 (0)	22 (12)
School bus	16 (14)	0 (0)	16 (14)
Transit bus	32 (30)	0 (0)	32 (30)
Street sweeper	3 (2)	2 (0)	5 (2)
Refuse	8 (5)	0 (0)	8 (5)
Tractor	15 (8)	0 (1)	15 (9)
Total	**121 (99)**	**2 (4)**	**123 (103)**

[a] Hybrid vehicle models are not included in these counts.

When assessing patterns and trends for nascent markets such as electric MD/HD vehicles, it is worth looking internationally for larger sample sizes and to include more developed markets. Figure 13 shows that not only have countries beyond the United States increased electric MD/HD vehicle model offerings over time, but overall, there is a trend toward EVs with higher ranges.

Notes: Although the inventory is continuously updated, this snapshot may not be fully comprehensive due to new model announcements and small manufacturers not yet captured in the inventory. Zero-emission vehicles (ZEVs) include battery electric vehicles (BEVs), plug-in hybrid electric vehicles (PHEVs) and fuel cell electric vehicles (FCEVs). "Other" includes garbage, bucket, concrete mixer, mobile commercial and street sweeper trucks. The heavy-duty truck and transit bus figures include announced models for 2023-2024.

Source: IEA analysis based on the Global Drive to Zero ZETI tool database.

Figure 13. Number of commercial electric and fuel cell MD/HD vehicle models by release date, range, and country.

Source: International Energy Agency (2023)

In addition to the number of electric MD/HD vehicle model offerings, there are multiple other factors that may impact electric MD/HD vehicle adoption and the maturity of the electric MD/HD vehicle and charging market. Hoehne et al. (2023) used the Transportation Energy & Mobility Pathway Options (TEMPO™) model to project that policy mandates for zero-emission MD/HD vehicles would have the largest impact on electric MD/HD vehicle stock shares, followed by reduced EV costs, as shown in Figure 14. Electricity prices were projected to have the lowest impact of the evaluated considerations.

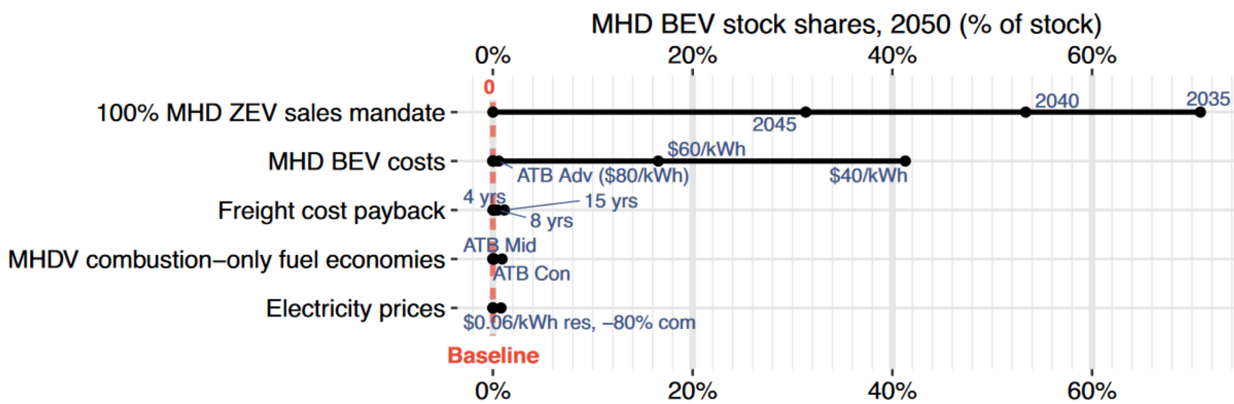


Figure 14. Isolated impacts on MD/HD battery-electric vehicle (BEV) stock shares in 2050.

Source: Hoehne et al. (2023)

6 Conclusion

Vehicle class/type, vehicle use, vehicle range, and home base are key characteristics that inform the potential for fleet electrification. MD/HD vehicle electrification has already begun with vehicles that have short (low daily range), predictable routes and a depot home base, such as delivery vans and school/transit buses. Most MD/HD fleet charging can be satisfied with AC Level 2 and DCFC depot charging, but certain circumstances and vehicle types will require public or private en route charging infrastructure. There are also other situations including residential home bases that will require unique charging models. This report outlines the key considerations for MD/HD vehicle electrification and associated charging infrastructure, including addressing the question of whether and when MD/HD vehicles can utilize existing LDV charging infrastructure rather than dedicated MD/HD vehicle charging infrastructure. Overall, MD/HD vehicles—particularly HDVs—will typically require dedicated infrastructure due to higher electricity needs, different connectors, larger physical space requirements, different payment structures, and higher potential for electricity grid impacts. However, LDV charging station plugs are currently typically compatible, and MD/HD vehicles can find appropriate charging stations that are powerful enough and have enough physical space for an MD/HD vehicle to fit by searching on the AFDC Station Locator. MD/HD vehicles vary drastically by class and use, and each fleet must be uniquely analyzed.

There are multiple areas in need of future work. First, the residential home base analysis could be disaggregated to the state level (rather than national). Determining whether and how MD/HD vehicles parked at private residential locations overnight vary based on state, as well as potential implications for electrification, could be discussed. Second, a more detailed route analysis of MD/HD vehicle required battery sizes could be performed to determine which MD/HD vehicles have the greatest potential for rapid electrification, building upon Section 4.1. This could be done by calculating the size of EV batteries required for different types of MD/HD vehicles based on typical daily ranges and EV efficiency. The number of public charging stations required for these vehicles—and accompanying required power levels—could also be estimated based on home base location, typical daily trip distances, trip dwell times, and the ranges of current MD/HD vehicles on the market. With the recent publication of the VIUS 2021 survey data (Bureau of Transportation Statistics 2021), NREL's dataset of nationally representative MD/HD vehicle typical travel patterns (Bruchon et al. 2024b), and NREL's Heavy-Duty Electric Vehicle Integration and Implementation (HEVII) tool (National Renewable Energy Laboratory, n.d.), there is opportunity for greater analysis and discussion related to MD/HD vehicle electrification and charging.

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