CLEARING ROADBLOCKS FOR ZERO-EMISSION MEDIUM- AND HEAVY-DUTY TRANSPORTATION

C2ES CLIMATE INNOVATION 2050

by

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Achieving net-zero emissions will require large-scale change across all sectors of the economy, and efforts to drive this transition are intensifying. Over the past several years, through the Climate Innovation 2050 initiative, the Center for Climate and Energy Solutions (C2ES) has engaged closely with leading companies across diverse sectors to examine challenges and solutions to decarbonizing the U.S. economy by 2050. As we laid out in *Getting to Zero: A U.S. Climate Agenda*, reaching net-zero will require this large-scale change, but it will also require us to address a number of discrete and urgent challenges. To inform policymakers considering these near- and long-term questions, C2ES launched a series of *"Closer Look"* briefs to investigate important facets of the decarbonization challenge, focusing on key technologies, critical policy instruments, and cross-sectoral challenges. These briefs explore policy implications and outline key steps needed to reach net-zero by mid-century.

EXECUTIVE SUMMARY

Medium- and heavy-duty (MHD) vehicles are outsized contributors to the transportation sector's emissions of carbon dioxide and other air pollutants. While most MHD vehicles currently run on diesel, zero-emission battery and hydrogen fuel cell options are becoming more available. Although adoption of these alternatives is not yet nearly as robust as it is in the light-duty passenger vehicle sector, a growing number of MHD use cases are conducive to electrification, including delivery vehicles, school and transit buses, regional freight trucks, drayage vehicles, and other work vehicles.

Electrifying the medium- and heavy-duty portion of the transportation sector, however, faces some unique challenges. These include higher up-front costs for vehicles and associated charging/refueling infrastructure, a lack of widespread access to charging and refueling infrastructure, strain on local electric grids, reduced cargo capacity due to the size and weight of batteries, conflicts between recharging/refueling needs and regulations on drivers' hours of service, and the upstream emissions associated with hydrogen fuel production. At the same time, MHD vehicle electrification also presents significant opportunities.

In addition to the environmental and public health benefits, MHD vehicle electrification could offer greater long-term fuel cost savings and enhanced community resilience.

Numerous federal and state regulations, incentives, and programs are already in place to support the electrification of the MHD vehicle fleet. These include federal emissions standards, state clean truck regulations, federal funding programs for innovation and deployment, and state rebate programs. Still, additional policy measures are necessary to overcome the range of challenges facing MHD vehicle electrification, including:

- *Supporting technology development and innovation:* Congress should provide additional funding to support innovations in battery efficiency and to improve green hydrogen production efficiency and costs. The Department of Energy (DOE) should also conduct battery-swapping pilots for federal and commercial MHD fleets to explore cost and performance feasibility.
- *Expanding accessible MHD charging and refueling infrastructure:* Congress and state legislatures should increase the amount of, and expand eligibility for, commercial charging/refueling infrastructure tax credits. Congress should also fund grants to enable utilities to make grid upgrades to support charging infrastructure, and the DOE should prioritize clean hydrogen development along freight corridors. In addition, federal regulators should update regulations, including on drivers' hours of service, to accommodate charging times and other technology-specific constraints.
- *Accelerating vehicle deployment:* The Environmental Protection Agency (EPA) and National Highway Traffic Safety Administration (NHTSA) should strengthen federal emissions standards to reach 100 percent zero-emissions MHD vehicle sales no later than 2040, and earlier where possible. Congress should also provide block grants for states and municipalities to replace government MHD vehicles with zero-emission vehicles, prioritizing high-pollution areas. To overcome potential wariness about newer technologies, the Departments of Transportation, Labor, and Education should fund and provide education, outreach, and workforce training initiatives to fleet owners, operators, drivers, and service technicians on zero-emission vehicle operation, charging management, and cost-benefit analysis.

Proactive policy at all levels is needed to accelerate the decarbonization of the medium- and heavy-duty vehicle fleet and the transition to a zero-emission transportation future.

INTRODUCTION

Transportation is the highest-emitting sector of the U.S. economy, responsible for more than 27 percent of total U.S. greenhouse gas emissions in 2020.[1] Within the transportation sector, medium- and heavy-duty vehicles have an outsized impact; they make up less than 5 percent of all vehicles on the road but are responsible for almost 30 percent of the sector's on-road carbon dioxide emissions.[2] Without active efforts to decarbonize medium- and heavy-duty vehicles, this sub-sector is expected to make up an even larger share of transportation emissions going forward. This is due both to increasing shipping volumes—the shipment of U.S. goods is forecast to increase 23.5 percent by 2025 and 45 percent by 2040—and parallel reductions in emissions from the passenger fleet due to the increasing uptake of electric vehicles.[3] These market realities make reducing emissions from MHD vehicles indispensable to a holistic, economy-wide net-zero strategy.

In addition to emitting climate pollutants, medium- and heavy-duty vehicles are also responsible for a disproportionate share of air pollutants and noise pollution, which are often most concentrated in lower- and middle-income communities, as well as Black, indigenous, or people of color (BIPOC) communities.[4] MHD vehicles are responsible for 60 percent of all nitrogen oxide (NOx) tailpipe pollution,[5] and the noise pollution they generate harms communities and ecosystems. (For humans, chronic exposure to traffic noise pollution is linked to increased risk of cardiovascular disease and stroke, obesity, and diabetes, while species from birds to mammals experience impacts to their ability to find food and mates.[6]) Drivers of medium- and heavy-duty vehicles, too, are exposed to air pollutants, noise levels, and vibrations that can produce physical harms.[7] Addressing the range of impacts from MHD vehicles is both an environmental and a public health imperative.

In considering how to address these harms from MHD vehicles, it is important to understand the range of vehicle types and uses (See Table 1). Medium- and heavy-duty vehicles are divided into eight classes, based on gross vehicle weight rating (See Figure 1).

Most medium- and heavy-duty vehicles on the road—around 77 percent of the national fleet in 2021—are powered by diesel.[8] Gasoline-powered vehicles made up a further 20 percent, with alternative fuel vehicles covering the remaining 3 percent. Most of the alternative fuel vehicles on the road are E85 (high-level ethanol-gasoline blend) vehicles, while others use fuels such as compressed natural gas or propane. Only a very small number are electric vehicles relying on batteries or hydrogen fuel cells, which are the only alternative fuel models that produce no harmful tailpipe emissions.[9]

The number of zero-emission vehicle (ZEV) options for fleet operators to choose from, however, is rapidly expanding. In 2021, more than 110 battery electric medium- and heavy-duty models were available from more than 45 manufacturers.[10] Across all ZEV technologies, there were more than 150 medium- and heavy-duty models available in the United States and Canada in 2021, and more than 200 in 2022 (See Figure 2).[11]

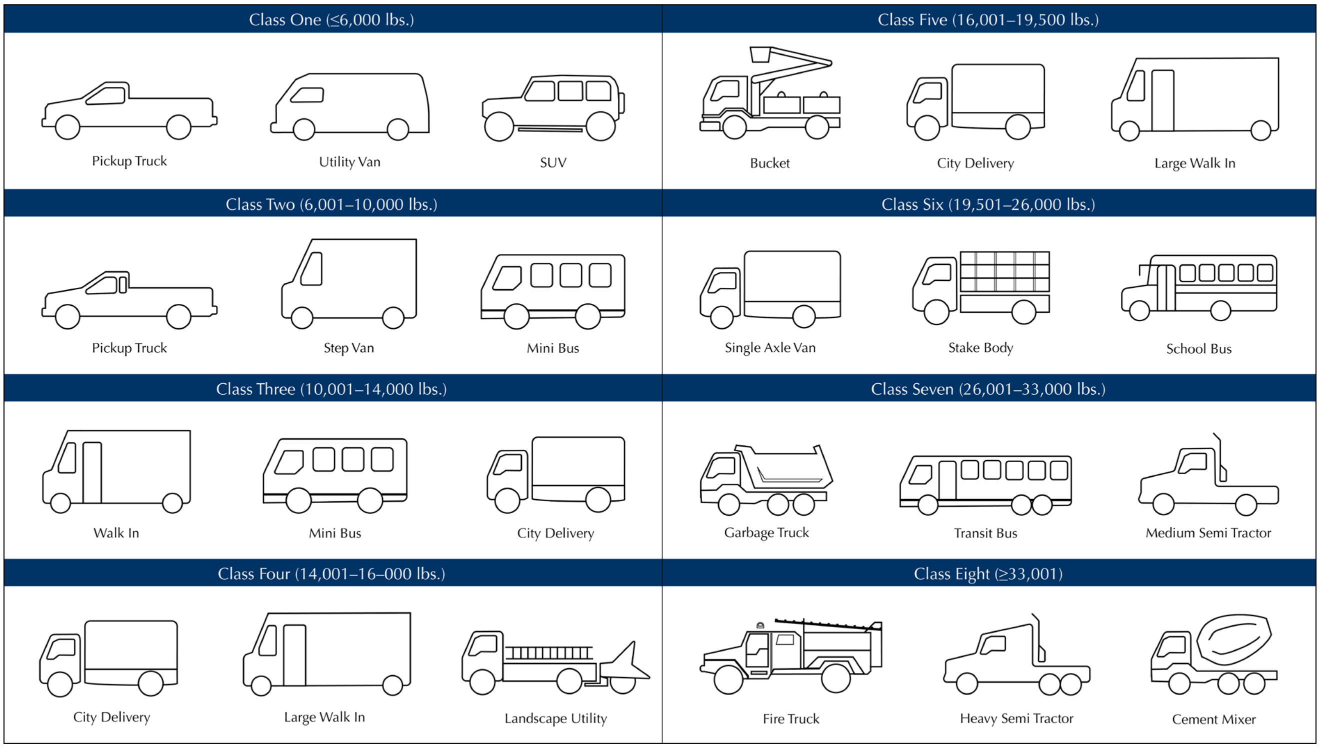
Still, while the light-duty passenger vehicle market has started to pass a critical threshold for electric vehicle adoption, the medium- and heavy-duty market faces additional barriers to decarbonization. This paper reviews the near- and long-term outlook for ZEV technologies in this sub-sector and discusses some of the challenges and opportunities these technologies face. The paper then reviews the range of policy levers that support the electrification of the MHD vehicle fleet and offers policy recommendations for accelerating MHD vehicle decarbonization.

TABLE 1: Applications and Use Cases of Medium- and Heavy-Duty Vehicles

USE CASE	VEHICLE EXAMPLES	CLASS(ES)	AVERAGE DAILY MILES TRAVELED	APPLICATION
Long-Haul Freight Trucking	semi tractor; semi sleeper	Class 8	≥500	Moves large quantities of goods over long distances, such as from ports to distribution centers or from distribution centers to large retailers.
Short-Haul Freight Delivery	semi tractor; high profile semi	Class 7–8	≤300	Moves large quantities of goods over shorter distances, such as from warehouses or distribution centers to retailers.
Local/ Last-Mile Delivery	city delivery, conventional van, walk-in, step van, rack	Class 2–6	100–150	Moves smaller quantities of goods, such as from distribution centers or warehouses to end users (e.g., package delivery).
Drayage	semi tractor, flatbed	Class 6–8	100–150	Moves goods and equipment between ports and urban centers, or locally around industrial facilities, ports, work sites, and other facilities with a large footprint.
Long-Haul Buses	tour bus	Class 7–8	≥300	Moves large numbers of passengers over long distances, often between urban centers.
Transit Buses	transit bus	Class 6–7	100–150	Moves large numbers of passengers over short distances, with routes traveled frequently on a regular transit schedule, often in urban areas.
Municipal And Other Work Vehicles	bucket truck, fire engine, refuse, fuel	Class 5–8	25–150	Emergency vehicles such as fire trucks or utility repair vehicles.

Source: Center for Climate and Energy Solutions

FIGURE 1: Vehicle Weight Class Examples



MHD vehicles are often used for commercial purposes, generally moving either goods (e.g., freight and delivery) or passengers (e.g., transit and buses). Table 1 describes the most common applications and use cases for medium- and heavy-duty vehicles.

Source: U.S. Department of Energy, Alternative Fuels Data Center (2012).[1]

MEDIUM- AND HEAVY-DUTY ZEV TECHNOLOGIES AND APPLICATIONS

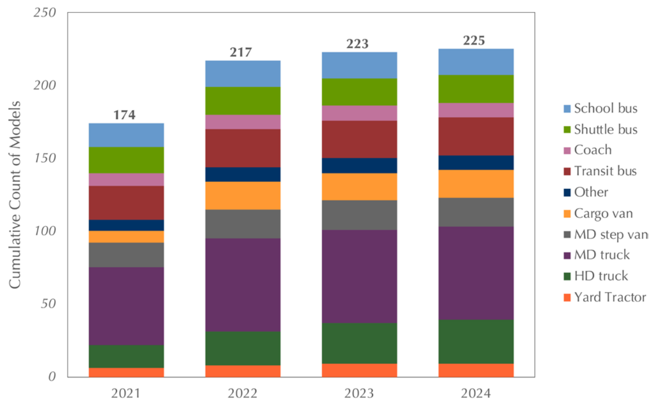
OVERVIEW: BATTERY ELECTRIC VEHICLES AND HYDROGEN FUEL CELL ELECTRIC VEHICLES

The main ZEV options for medium- and heavy-duty vehicles are battery electric vehicles (BEVs) and hydrogen fuel cell electric vehicles (FCEVs). BEVs run on batteries that have stored power from the electricity grid, whereas FCEVs generate their own electricity from hydrogen gas stored in a tank onboard the vehicle.

Current market trends predict a forthcoming shift in the rate of adoption for BEVs in the United States. In the light-duty passenger vehicle space, battery electric vehicles made up more than 5 percent of the sector's total new U.S. vehicle sales in the first half of 2022.[12] Data from other countries suggests that this may be a key threshold, after which societal technological preferences begin to shift and adoption rates begin to rise rapidly; if the United States follows the trend seen in other countries, the percentage of sales could grow from 5 percent to as much as 25 percent in just three years.[13] While up-front costs remain relatively high, total costs of ownership (including maintenance and fuel for the lifetime of the BEVs) are equivalent to or lower than their internal combustion engine (ICE) counterparts for many models, especially taking into account state and federal incentives for ZEVs.[14] Light-duty BEVs are also capable of providing similar range per charging cycle to ICE vehicles' ranges per fueling cycle.

BEV adoption in the medium- and heavy-duty sector is not nearly as robust, due in part to challenges described more fully later in this paper. For example, expensive battery inputs and technological limitations can lead to higher up-front costs and lower ranges for BEV models compared to their ICE counterparts. Even so, benefits like reduced emissions and noise pollution, better performance, more comfortable driving experiences,

FIGURE 2: Zero-Emission Medium- and Heavy-Duty Vehicle Model Availability in the United States and Canada



Source: Global Commercial Vehicle Drive to Zero, "ZETI Data Explorer," CALSTART (2022).[2]

and cheaper fueling and maintenance costs are encouraging BEV adoption among fleet operators.[15]

Hydrogen fuel cell electric vehicles offer similar performance and tailpipe emissions benefits as battery electric vehicles, but FCEVs have fueling times similar to diesel vehicles, allowing them to more easily fit into the fuel time and fueling infrastructure expectations of the current transportation industry. However, they face similar challenges as BEVs, as described later in this paper. For example, hydrogen fuel cell vehicles tend to have even higher up-front costs than their battery electric counterparts, with reduced savings on total cost of ownership relative to diesel due to the cost of hydrogen fuel. There is also a lack of public hydrogen refueling infrastructure outside of the state of California.[16] Additionally, the climate benefits of hydrogen depend heavily on the method of hydrogen production, and most current hydrogen production is very emissions-intensive.

Across the use cases, some MHD vehicles are more conducive for electrification with current technologies than others. The rest of this section explores the different electrification options for various use cases of medium- and heavy-duty vehicles.

DELIVERY VEHICLES

Class 4 delivery vehicles and box trucks represent an almost ideal use case for current MHD BEVs. Their low average speeds and frequent stops allow them to maximize efficiency gains from the electric motor and regenerative braking. Their predictable, scheduled routes allow them to be deployed strategically to maximize range while allowing for downtime to charge, including overnight, when electricity rates are low. Delivery vehicles often operate in suburban neighborhoods or densely populated urban areas, so replacing diesel delivery vehicles with BEVs provides air quality and noise pollution benefits for vulnerable populations such as children and people with asthma.

The United States Postal Service (USPS) has made a commitment to purchase at least 33,800 new battery electric delivery vehicles over ten years, with the first vehicles going into service in 2023.[17] With the addition of $3 billion appropriated by the Inflation Reduction Act of 2022 (IRA) for the agency to purchase ZEVs and associated service equipment, the USPS may further accelerate its fleet electrification plans.[18] Electrifying the USPS fleet is key to demonstrating the performance and tailpipe emissions advantages of BEVs both to drivers and the communities that will see the vehicles every day.

The USPS is not alone in pursuing electrification of delivery fleets. In the private sector, Amazon has partnered with Rivian to purchase 100,000 custom battery electric delivery vans by 2030 for use in communities across the country.[19] Similarly, FedEx, which has more than 200,000 vehicles in its fleet, has contracted with BrightDrop to make BEVs 50 percent of its pickup and delivery vehicle fleet purchases by 2025 and 100 percent by 2030.[20] At a smaller scale, UPS has committed to purchasing up to 10,000 custom battery electric delivery vehicles from Arrival, and Walmart will purchase at least 4,500 battery electric delivery vehicles from Canoo.[21] Other examples across the private sector delivery market abound.

While very few delivery trucks on the road today are electric, the commitments of the USPS alongside private companies with large fleets will increase the number of BEVs exponentially in the coming years. The magnitude of commitments and orders, with further electrification on the horizon, creates more certainty in the market and will encourage private investment in BEV production and technology development. Delivering on the ambitious near-term targets from USPS and major companies will make it possible to reach close to 100 percent delivery vehicle electrification by 2050.

SCHOOL AND TRANSIT BUSES

School and transit buses are strong candidates for electrification with current technologies, as they too have predictable routes, slow speeds, and frequent stops. School buses in particular often sit idle in the middle of the day as well as at night, making them uniquely suited to take advantage of charging when renewable generation is at its peak (solar mid-day, wind at night). As many families are served by school and/or transit buses, the air quality benefits for children are outsized and significant. Diesel pollution from school buses raises the risk to children of developing asthma and cancer, which could be reduced considerably by electrifying these buses.[22] Furthermore, people of color and people with lower incomes in cities face concentrations of pollutants from diesel exhaust, such as NO2, at rates of around 28 percent higher than the national average (with significantly higher disparities in areas with the greatest pollution), meaning replacing diesel buses with electric ones would have a heightened benefit to disproportionately impacted communities.[23]

As of September 2021, more than 3,500 electric transit buses—about 95% percent BEV and 5 percent FCEV—have been adopted in the United States, demonstrating their utility and feasibility across the country in real-world conditions; there have also been more than 1,700 battery electric school buses funded, ordered, delivered, or deployed.[24] Many of the electric buses on the road today are funded through utility, state, or federal grant programs, and funding in the bipartisan Infrastructure Investment and Jobs Act of 2021 (IIJA) will further accelerate the electrification of the nation's bus fleet.[25]

FREIGHT TRUCKING

Currently, the best applications for battery electric freight trucking are for local/regional trips of up to 250–300 total miles, given the average range of most battery electric Class 8 tractor models available today. The feasibility of long-haul battery electric freight trucking will hinge upon the ultimate availability and accessibility of charging infrastructure (particularly along highways rather than in depots), including whether charging speed and battery range align with the optimal timing of drivers' stops. Proliferation of electric short-haul freight trips could support the build-out of this infrastructure and ultimately enable long-haul applications.

For long-haul freight trucking, hydrogen fuel cell vehicles offer a driving and fueling experience that is more similar to conventional diesel-powered vehicles, giving them an advantage over BEVs. For example, Nikola's forthcoming Class 8 FCEV will have up to 500 miles of range, in comparison to the 350 miles of range for its equivalent battery electric model, and the company soon hopes to offer a hydrogen fuel cell model with up to 900 miles of range.[26] Hydrogen refueling stops would also be comparable to diesel fueling stops, only requiring 15–20 minutes, rather than 2- to 18-hour battery recharging cycles, which could make it easier for drivers to comply with federal regulations on hours of service.[27] In addition, the reduced weight of hydrogen fuel compared to battery cells could provide advantages in complying with gross vehicle weight restrictions.[28]

DRAYAGE

Drayage vehicles are used to transport goods over short distances, often between ports and railroad terminals, and sometimes to transport equipment and goods around facilities with large footprints, such as airports, industrial facilities, or warehouses.[29] These vehicles often have predictable idle times and locations, making them logistically easier to electrify than other use cases that rely on public or on-route charging. While electric drayage vehicles are often built by the same manufacturers as diesel drayage vehicles, BEV up-front costs remain higher than diesel. However, the difference may be comparatively lower than the costs of some other MHD classes.[30] Hydrogen fuel cell drayage vehicles could be useful in facilities that produce hydrogen on-site and may be preferred by operators for their short refueling times.

As with delivery vehicles and buses, electrifying drayage vehicles offers significant, concentrated air pollution benefits to communities and workers, particularly disadvantaged communities around ports and industrial facilities. The IIJA and the IRA offer significant funding for reducing emissions at ports, including funding for electric vehicles and other zero-emissions equipment.[31]

OTHER WORK VEHICLES

Municipalities and utilities around the country are beginning electrification of Class 5 and above vehicles, including emergency vehicles (e.g., fire trucks), service vehicles (e.g., refuse trucks), and utility maintenance vehicles (e.g., bucket trucks). For example, in May 2022, the Los Angeles Fire Department deployed the first electric fire truck in North America, which it celebrated for not only reducing carbon emissions from the vehicle, but also reducing diesel fumes inhaled by firefighters and lowering noise pollution.[32] Similarly, utilities including Xcel Energy in Colorado, ConEdison in New York, San Diego Gas & Electric, and the Los Angeles Department of Water and Power are beginning to deploy all-electric bucket trucks.[33]

CHALLENGES AND OPPORTUNITIES IN ELECTRIFYING MEDIUM- AND HEAVY-DUTY VEHICLES

Electrifying the medium- and heavy-duty portion of the transportation sector faces some unique challenges, but it also presents unique opportunities.

CHALLENGE: COST

As referenced earlier, a key barrier to adoption is the up-front cost of battery or fuel cell electric MHD vehicles, which is currently significantly higher than the up-front cost of an equivalent internal combustion engine vehicle. For example, a battery electric Class 8 tractor can have a manufacturer's suggested retail price (MSRP) of up to triple the MSRP of a comparable diesel model (before incentives), while the purchase price of a hydrogen fuel cell MHD vehicle can be four to five times as much as a comparable diesel vehicle.[34] The National Renewable Energy Laboratory (NREL) projects longer-range ZEV trucks will not reach cost parity with ICE vehicles until 2035, though shorter-range applications may reach cost parity as early as 2026.[35] Due to the smaller size of the medium- and heavy-duty market relative to the light-duty market, manufacturers have been less able to take advantage of economies of scale that can put significant downward pressure on cost and price.

Given the up-front cost differential, incentives are a necessity. In the public transit space, which has been the most proportionally electrified transportation sub-sector, grants to defray up-front costs have been available since the 2009 American Recovery and Reinvestment Act (ARRA). ARRA appropriated $100 million for a discretionary grant program for transit capital projects that reduced greenhouse gas emissions—the Transit Investments in Greenhouse Gas and Energy Reduction (TIGGER) program—including funding for projects to purchase zero-emission transit buses.[36] While each applicant only purchased a small number of buses, the program supported the nascent market and helped the ZEV transit bus industry to grow the scale of its production and delivery. The Federal Transit Administration's Low or No Emission Vehicle program likewise has provided funding for years to support deployment of low- and no-emission transit buses.[37] In the commercial space, however, until the recent passage of the Inflation Reduction Act of 2022, no major tax credits or rebates were available at the federal level for commercial purchasers of zero-emission MHD vehicles, and only a limited set of state-level incentives were available.

Even with incentives, the up-front costs of zero-emission MHD vehicles can still be a challenge for those with tight budgets. For example, for municipalities purchasing fleet vehicles, budgetary guidelines and restrictions often focus on up-front cost rather than total cost of ownership; in other words, since budgets are balanced year-to-year, they cannot take into account the payback period from reduced fuel and maintenance costs. Municipal budgets may also fail to provide enough resources to cover both the cost of the vehicle(s) and the installation cost of associated charging/refueling infrastructure, either of which may be a prohibitive barrier to access. School districts with small budgets may similarly find the high up-front costs of both electric school buses and the associated charging infrastructure to be prohibitive. Likewise, smaller businesses can have limited up-front purchasing power—an obstacle compounded by the fact that it may not make economic sense for each operator of a small fleet to install its own charging/refueling infrastructure. In such cases, access to public or shared charging can be a prerequisite for adoption.

CHALLENGE: ACCESS TO CHARGING AND REFUELING INFRASTRUCTURE

Purchasing zero-emission medium- and heavy-duty vehicles is essential to decarbonizing the sector, but deployment can only be successful with widespread access to charging and refueling infrastructure. The current fuel distribution system is built to cater to the needs of diesel-powered vehicles.

Most recent efforts to incentivize installation of charging infrastructure have focused on meeting the needs of light-duty vehicles, meaning most public charging infrastructure does not provide sufficient charging capacity to serve battery electric MHD vehicles. For example, most public direct current fast charging (DCFC) equipment provides power capacity of up to 150 kilowatts (kW). This may be sufficient to charge a Tesla Model 3 up to 80 percent in 30 minutes, but it would take almost 3 hours to fully charge a Class 4 delivery vehicle with a battery capacity of 600 kilowatt-hours (kWh).

For hydrogen fuel cell vehicles, access to refueling infrastructure is very limited. Almost all U.S. hydrogen fueling stations are currently located in California, mostly around Los Angeles and the Bay Area, but efforts are ongoing to build out hydrogen refueling corridors elsewhere.[38] Recent federal funding and incentives for hydrogen production and fueling stations make it likely that additional hydrogen refueling infrastructure will be built out across the country in the coming years, although both the up-front cost of installation and the cost of hydrogen as a fuel remain significantly higher than electric charging stations.

In addition to the lack of hydrogen fueling stations, existing infrastructure must be expanded and appropriately sited to supply refueling stations with hydrogen. For example, pressurized gas or liquid hydrogen must be transported from the site of production to fueling stations, either via pipeline or tankers and trucks, depending on distance and the amount of hydrogen demand.[39] Locating hydrogen production facilities near fueling corridors can minimize delivery costs, as well as hydrogen leakage (which is a risk given hydrogen's small molecular size).[40] It may also be possible to leverage the existing natural gas network and produce hydrogen at the point of consumption using methane pyrolysis, a clean technique using natural gas and electricity that produces no carbon dioxide.

CHALLENGE: GRID IMPACT

As battery electric MHD vehicles and their associated charging infrastructure proliferate, the demands on the electricity grid will be significant, ultimately creating demand for new power generation and expanded infrastructure.

For example, battery electric Class 8 tractors currently have batteries with 450 kWh or more in capacity that provide 250+ miles when fully charged; for fast charging to provide 80–100 percent of its full range in 60–90 minutes of charging time, it would have to operate at a load of 350kW or greater.[41] A bank of four medium- and heavy-duty-grade fast chargers at this capacity would draw more than 1 megawatt (MW) of power simultaneously. For comparison, an outdoor sports stadium draws around 5MW, according to National Grid.[42] As technology evolves, heavy-duty ZEV developers are targeting chargers with 1MW capacity that could fully charge a 450kWh battery in half an hour; however, a bank of 20+ of these chargers used simultaneously would draw the power loads of a small town.[43]

Charging multiple high-capacity EVs will therefore draw significant electric loads—much greater than for light-duty vehicles—which could put considerable strain on existing local electric grids, especially if the infrastructure is sited in less developed areas along freight corridors that may not have sufficient power capacity to bring on major new loads. At the local level, many areas are already at the limits of their current grid capacity and will be challenged by rapid expansion of MHD vehicle charging infrastructure, particularly when large fleets plug in many vehicles at once and rapidly raise the instantaneous demand for power.[44] On an individual facility level, charging a fleet of 50 light-duty vehicles would require only around 360kW of instantaneous power, whereas 50 medium-duty trucks (e.g., box trucks, delivery vehicles) would draw around 750kW and a similarly sized fleet of Class 8 trucks would draw up to 9 MW—equivalent to the demand of the Empire State Building (See Figure 3).[45] Initially, the existing grid might be able to accommodate the extra loads with the addition of on-site energy storage, local transmission upgrades, and/or the construction of additional substations, but as demand from all types of vehicles increases over time, significant additional capacity (i.e., new sources of power generation) will also be needed.

To prevent straining local grid infrastructure beyond its capacity, considerations around siting charging infrastructure for MHD vehicles must include not only where it will be most conducive to commercial operations, but also the condition and capacity of local electric grids. By proactively engaging with local utilities, companies can help optimize siting decisions. However, as most fleets are currently powered by diesel fuel, commercial relationships with utilities in the vehicle procurement process are lacking. Many companies are likely unprepared to engage the utility early enough in the charger siting process to provide sufficient lead time for grid upgrades ahead of the planned charging infrastructure installation.[46] While utilities are accustomed to working with developers to assess the grid's capacity to support new electric loads, such as when new manufacturing facilities or other large buildings come online, those kinds of facilities often are required to provide significantly longer lead times between proposal and construction than charging infrastructure—even charging infrastructure with a similar electricity demand footprint. Fleet owners, charging infrastructure installers, and utilities must coordinate to ensure charging infrastructure build-out can proceed at the pace necessary to keep up with fleet electrification while preserving reliability in local grid integration. Since grid infrastructure upgrades can be prohibitively expensive for a single project but can benefit communities and facilitate subsequent projects, funding for major grid infrastructure upgrades should come not only from project developers and local utilities, but also from federal and state sources.

In addition to siting decisions, fleet operators can support reliable grid integration by taking steps to manage the amount of power they draw from the grid at once. In the light-duty sector, incentives such as time-of-use rates and systems utilizing bidirectional charging can help shave demand peaks, minimizing strain on the grid. Similarly, operators of battery electric MHD fleets should consider their vehicles' impacts on the local grid when scheduling charging times. In the near term, scheduling charging for overnight, when power demand is low, could be the most productive way to do this. As smart metering technologies get more sophisticated in the coming years, fleet charging behaviors could be managed on a large scale to maximize charging time when zero-carbon energy generation exceeds power demand, ensuring better utilization of clean electricity.

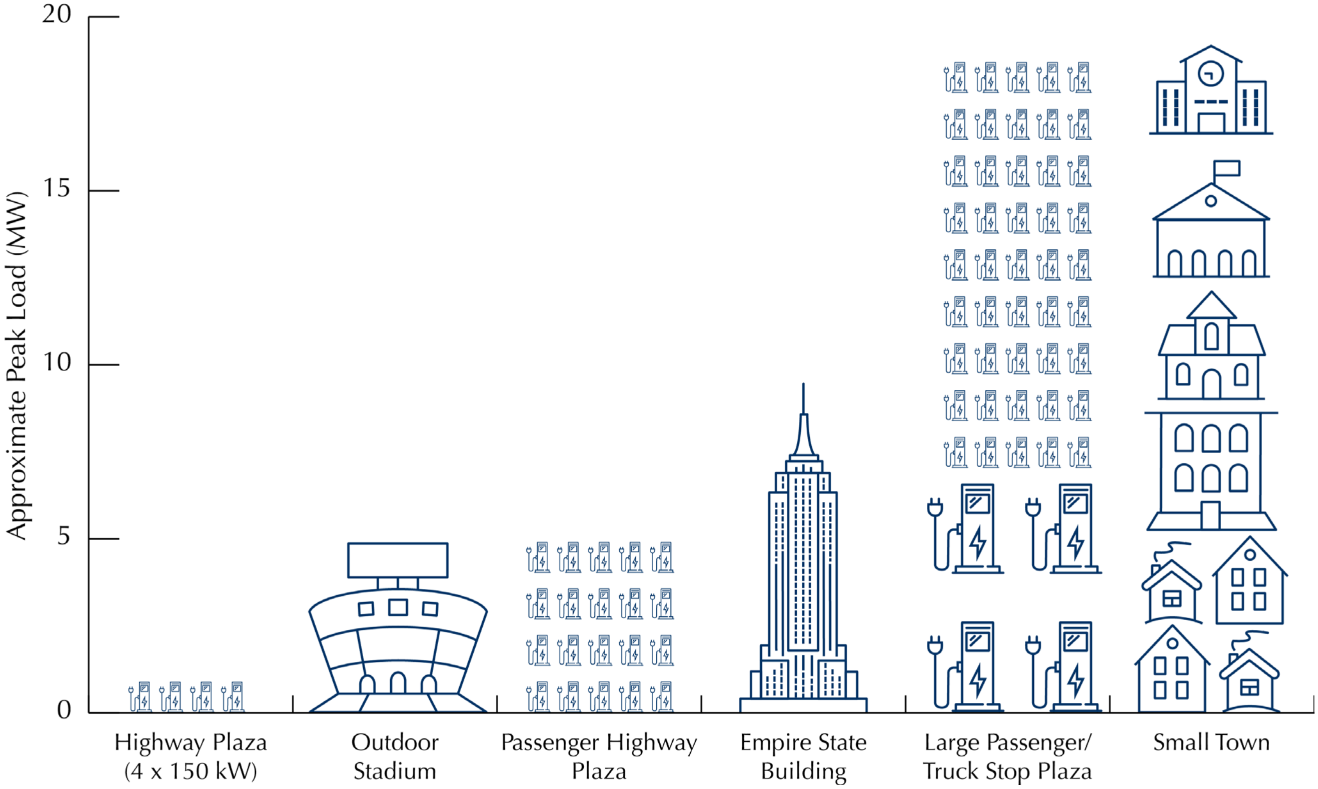
A potential alternative to a massive buildout of grid infrastructure to support MHD vehicle charging could involve battery swapping. A battery swapping station hosts a central bank of batteries that are charging at a low, constant speed throughout the day (or when electricity rates are lowest); when a vehicle's battery is depleted, its battery is removed and replaced with a fully charged one. The swapping process can be performed in a matter of minutes, rather than hours, and the size of the new charged battery can be tailored to the vehicle's use. For example, a delivery vehicle that only travels 120 miles in a day could use a smaller battery with 150 miles of range that is swapped every day, rather than a larger battery, thereby reducing weight and improving performance efficiency. Battery swapping for light-duty cars and two- and three-wheeled vehicles is relatively common in some Asian markets, but it has not taken off in the United States due to its current relatively high costs per mile, the lack of battery standardization among automakers, and consumer skepticism.[47] Battery swapping also has not been proven feasible in the United States for commercial and fleet purposes, and the federal push to develop faster and more efficient fast charging technology has largely eclipsed the opportunity to scale battery swapping in the U.S. market. That said, battery swapping could, in the long term, offer an alternative to fast charging that could avoid adding to demand peaks and might even help reduce them (since a bank of charged batteries could serve as a stationary backup power source).

CHALLENGE: BATTERY SIZE AND WEIGHT

Battery electric MHD vehicles require large, heavy batteries. The additional weight and volume occupied by the batteries may reduce the total cargo capacity of the vehicles—not only because the batteries take up space that could otherwise be used for cargo, but also because gross vehicle weight is strictly limited by federal regulation to 80,000 pounds.[48] Some states offer 2,000-pound allowances for low- or zero-emission freight vehicles on state roads, which can help reduce the weight advantage of diesel vehicles, but as deployment scales up, significant usage by overweight vehicles could have long-term infrastructure impacts.[49]

The significant size and weight of MHD vehicles and their cargo also create technological challenges for manufacturers in terms of producing battery electric vehicles with equivalent range and energy efficiency by weight as diesel models. Class 8 long-haul freight vehicles, for instance, often travel more than 500 miles per day on a single tank of fuel, while electric models so far have only been able to provide around 250–300 miles in range before requiring a time-intensive stop for charging.

FIGURE 3: Comparison of Electric Loads for EV Charging & Analogous Facilities



Source: National Grid, Electric Highways: Accelerating and Optimizing Fast-Charging Deployment for Carbon-Free Transportation (2021).[3]

CHALLENGE: HOURS OF SERVICE

The time spent charging is itself a barrier to adoption, as current regulations on drivers' hours are designed to accommodate short fuel stops rather than hours-long charging stops. Federal regulations on drivers' hours of service are stringent and reflect a national freight transportation system powered by diesel fuel. The Federal Motor Carrier Safety Administration, a division of the Department of Transportation, specifies the maximum amount of time drivers are permitted to be on duty, which includes both driving time and rest periods. Drivers carrying cargo, for instance, are limited to a maximum of 11 hours of driving after 10 consecutive hours off duty, and even with breaks in between driving hours, they may not drive beyond the 14th consecutive hour after coming on duty.[50] Even assuming a range of 500 miles and access to today's fastest charging technology, drivers of battery-electric trucks would need to stop to charge at least once within that time period for at least an hour, thus cutting into the number of consecutive hours they are legally allowed to be on duty. The regulation creates a significant disadvantage for drivers of BEV trucks in comparison to their competitors driving ICE trucks, at least in long-haul freight or passenger applications where vehicles cannot return to a depot overnight to charge.

CHALLENGE: UPSTREAM EMISSIONS

While zero-emission MHD vehicles produce no harmful tailpipe emissions, upstream emissions must also be considered. Battery-electric MHD vehicles, for example, will most advance decarbonization when the grid that is charging the batteries provides zero-emission power; continued decarbonization of the electricity grid will further improve the climate benefits of MHD BEVs over time. FCEVs, likewise, will provide the most benefit when the emissions associated with the production of their hydrogen fuel are lowest. Currently, global hydrogen production is almost entirely "gray hydrogen"—or hydrogen produced from fossil fuels through steam methane reforming or gasification. This production technique, which accounts for 99 percent of hydrogen currently produced in the United States, generates significant carbon dioxide emissions (See Figure 4).[51] Hydrogen produced from fossil fuels can lower emissions when paired with carbon capture and storage, which is known as "blue hydrogen," and methane pyrolysis (mentioned earlier) is another promising clean production pathway. "Green hydrogen"—produced via electrolysis of water, powered by renewable energy—generates no emissions in its production. Production of green hydrogen globally and in the United States, however, is more expensive than other forms of hydrogen due to the large amount of electricity required. Green hydrogen is rare in the current production mix, but it is expected to grow significantly in the coming years. There are many other colors in the hydrogen rainbow as well, including "pink hydrogen," which, like green, is produced via electrolysis from zero-emission electricity, but its source is nuclear. As hydrogen FCEV models become more available, accessible, and common in the fleet, decarbonization of hydrogen fuel must be prioritized and accelerated.

OPPORTUNITY: ELECTRICITY PRICE STABILITY

While electrification of medium- and heavy-duty vehicles has a range of obstacles to overcome, it also presents some important opportunities. In addition to the more readily apparent opportunities, such as the environmental and public health benefits discussed earlier, electrifying MHDV vehicles could produce cost savings and enhance price certainty for fleet operators.

The reduced cost of electricity in comparison to diesel fuel could produce significant cost savings for vehicle operators that switch to electric models, and the relative stability of electricity prices compared to diesel prices could allow fleet managers to predict future costs with more certainty (See Figure 5). For fleets charging at a depot, especially those that can do most of their charging overnight, operators can install onsite charging infrastructure that can charge vehicles at comparatively low off-peak electricity prices. That said, for early adopters, these dividends will be realized only over relatively long timescales, given the up-front costs of vehicles and charging infrastructure.

OPPORTUNITY: RESILIENCE

Zero-emission MHD vehicles could also enhance community climate resilience. Battery-powered MHD vehicles with bidirectional charging capabilities could serve as mobile backup power sources in the event of a power outage or other disruption. In areas that experience hurricanes, for instance, fleets could be charged in advance of a storm's arrival and then used to power hurricane shelters. Some school districts piloting electric school buses are already exploring their potential to provide backup battery power when schools serve as storm or heat shelters in extreme weather scenarios.[52] Similarly, electric vehicles could serve as low- or emissions-free generators (depending on the carbon intensity of the electricity used for vehicle charging) on job sites cleaning up from natural disasters while the grid is being restored. This potential was illustrated recently in Kentucky, where Ford F-150 Lightning pickups were used by crews to power necessary equipment at cleanup sites after a catastrophic flooding event.[53]

As with hours of service and other aspects affected by the unique characteristics of electrified MHD vehicles, the broader administrative and regulatory system in which the vehicles operate has not yet been adjusted to take advantage of and encourage such resilience opportunities. For example, electric trucks' battery warranties are based on the number of charge cycles, while warranties for diesel trucks are based on mileage. For electric vehicles that feed backup power to the grid or provide power following disasters, mileage may remain low even as charge cycles increase.[54]

EXISTING POLICY LEVERS FOR DECARBONIZING MEDIUM- AND HEAVY-DUTY TRANSPORTATION

Numerous federal and state regulations, incentives, and programs support the electrification of the MHD vehicle fleet, including transformative levels of financial support in recent federal legislation. These represent vital levers to accelerate MHD vehicle decarbonization, but even more policy action will be needed to support innovation and deployment of infrastructure and ZEVs.

FEDERAL AND STATE REGULATIONS

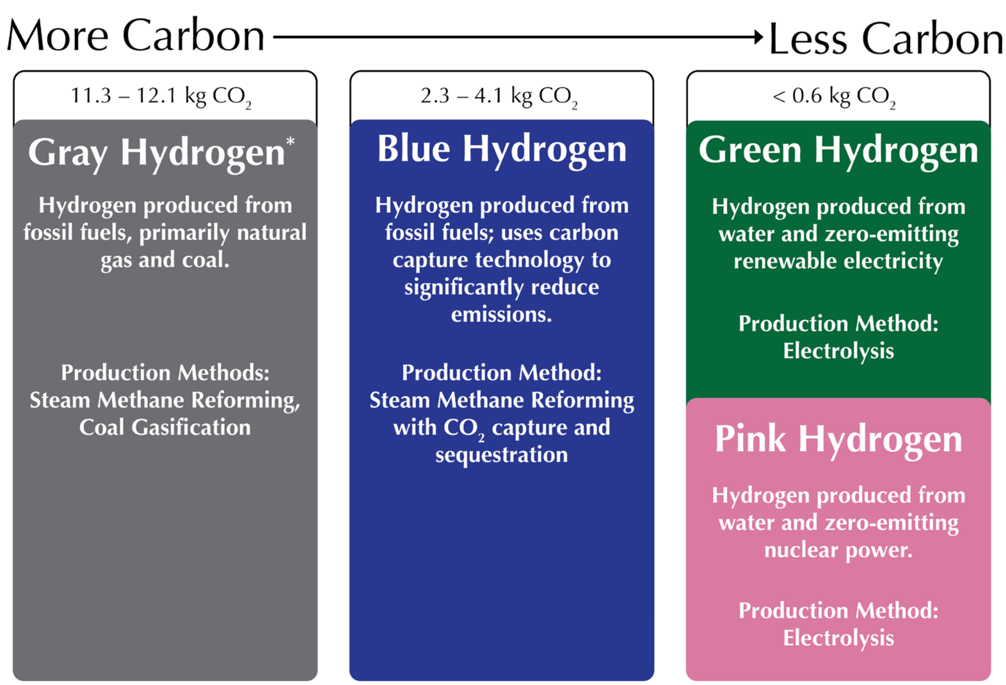
EPA emissions standards

The U.S. Environmental Protection Agency and the National Highway Traffic Safety Administration set greenhouse gas emission and fuel economy standards for medium- and heavy-duty vehicles (as they do for light-duty vehicles). In early 2022, the EPA proposed a new rule that would set significantly more stringent NOx and greenhouse gas emissions standards on MHD vehicles beginning in model year 2027.[55] In light of the IRA's transformative funding opportunities for decarbonizing MHD vehicles, the EPA announced in September 2022 that it would consider adopting even more stringent greenhouse gas emissions standards than proposed to reflect the significant impact IRA funding will have on accelerating medium- and heavy-duty ZEV adoption. These standards were ultimately released on December 20, 2022.[56] The EPA has also stated that it plans, in separate regulatory actions, to set stronger emissions standards for medium-duty commercial vehicles for model year 2027 and later. They also plan to set greenhouse gas emissions standards for MHD vehicles beginning in model year 2030 that are "significantly stronger" than the model year 2027 standards.[57]

Advanced Clean Trucks and Fleets regulations

In California and the states following its standards (under Section 177 of the Clean Air Act), MHD vehicles are held to more stringent emissions standards than at the federal level. California's Advanced Clean Trucks regulation includes two components: a manufacturer

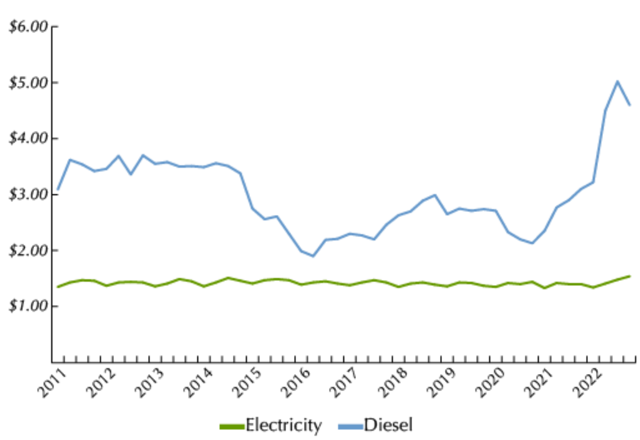
FIGURE 4: Common forms of hydrogen production in the United States by carbon intensity



Source: Center for Climate and Energy Solutions (drawing on data from Ewing et al. (2020) and Elgowainy (2021)) sales ZEV mandate and a reporting requirement. The ZEV mandate requires manufacturers who certify Class 2b to Class 8 medium- and heavy-duty chassis or vehicles to sell ZEV models as an increasing percentage of their annual California sales from 2024 to 2035, reaching 55 percent of Class 2b-3 truck sales, 75 percent of Class 4-8 straight truck sales, and 40 percent of truck tractor sales by 2035.[58] Several states have followed California in adopting the Advanced Clean Trucks rule, including Connecticut, Massachusetts, New Jersey, New York, Oregon, Vermont, and Washington—with several more states considering adopting the regulations as well.[59] Together, the states that have adopted the rule cover more than 20 percent of the nation's MHD fleet.[60]

In addition, the California Air Resources Board (CARB) is developing an Advanced Clean Fleets regulation with the goal of achieving a zero-emission truck and bus fleet in California no later than 2045 where feasible—and earlier for some market segments. The proposed regulation would apply to state and local agencies, federal government agencies, fleets performing drayage operations, and high-priority fleets (i.e., at least 50 vehicles or at least $50 million or more in gross annual revenue).[61] As proposed, the rule would require manufacturers to sell only zero-emission MHD vehicles beginning in 2040, require state and local government fleets to ensure 50 percent of vehicle purchase are ZEVs beginning in 2024 and 100 percent in 2027, and require all drayage vehicles in the state to be zero-emission by 2035.[62] If enacted, the regulation could accelerate fleet decarbonization in California and in states that choose to adopt its standards under Section 177 of the Clean Air Act.

FIGURE 5: Average Retail Fuel Prices in the United States for Diesel and Electricity



Source: U.S. Department of Energy, "Average Retail Fuel Prices in the United States" (2022).[4]

FEDERAL PROGRAMS, FUNDING, AND INCENTIVES

Technology development and innovation

Several programs exist at the federal level through the Department of Energy to accelerate the development of low- and zero-emissions MHD vehicle technology. For example, DOE's Office of Energy Efficiency and Renewable Energy (EERE) hosts the SuperTruck program, a research and development (R&D) funding project focused on making significant efficiency improvements through technology development. SuperTruck 1 (launched in 2009) and SuperTruck 2 (launched in 2016) focused on improving fuel economy. SuperTruck 3, the third round of funding that launched in 2021, provides up to $100 million over four years to pioneer technologies and concepts focused on electrification, including battery electric, plug-in hybrid, and hydrogen fuel cell technologies.[63]

Alongside the SuperTruck funding, in 2021 DOE announced its Low Greenhouse Gas Vehicle Technologies Research, Development, Demonstration, and Deployment program, which will offer more than $62 million over four years to fund expanded EV infrastructure and charging, as well as the development of advanced engines and fuels that operate with lower emissions.[64] While this funding opportunity includes light-duty vehicles and infrastructure, as well as non-electric fuels, it also supports work on electrified construction vehicles.[65]

To support cost reductions for clean hydrogen fuel, DOE launched a Hydrogen Shot initiative in June 2021, seeking to reduce the cost of zero-emissions hydrogen 80 percent, to $1 per kilogram, by 2031. The initiative establishes a framework and foundation for clean hydrogen deployment, including support for demonstration projects.[66] DOE estimates achieving the cost reduction goal could produce at least a fivefold increase in clean hydrogen use in the United States. Reducing the cost of hydrogen fuel is essential to making hydrogen FCEVs feasible for fleet operators across the country.

Charging and refueling infrastructure

Together, the IIJA and the IRA provide unprecedented levels of funding to support charging infrastructure for electric vehicles in ways that will be beneficial to MHD vehicle electrification. For example, the IIJA provides $7.5 billion in funding over five years to build a "seamless network" of public EV chargers along designated alternative fuel corridors across the United States. While the intent of the funding programs is to provide access to fast charging for light-duty vehicles, the build-out of this national network will support the build-out of grid infrastructure that will be needed for electrification of commercial vehicles as well.

The IRA provides more direct incentives for the installation and maintenance of EV chargers for commercial vehicles. The IRA includes a tax credit of up to $100,000 per charger, usable by businesses with operations in non-urban census tracts where at least 80 percent of the population falls below the national median income.[67] Previously, this credit was capped at $30,000, so the updated credit could provide significantly greater support and further reduce up-front cost barriers.

Vehicle deployment

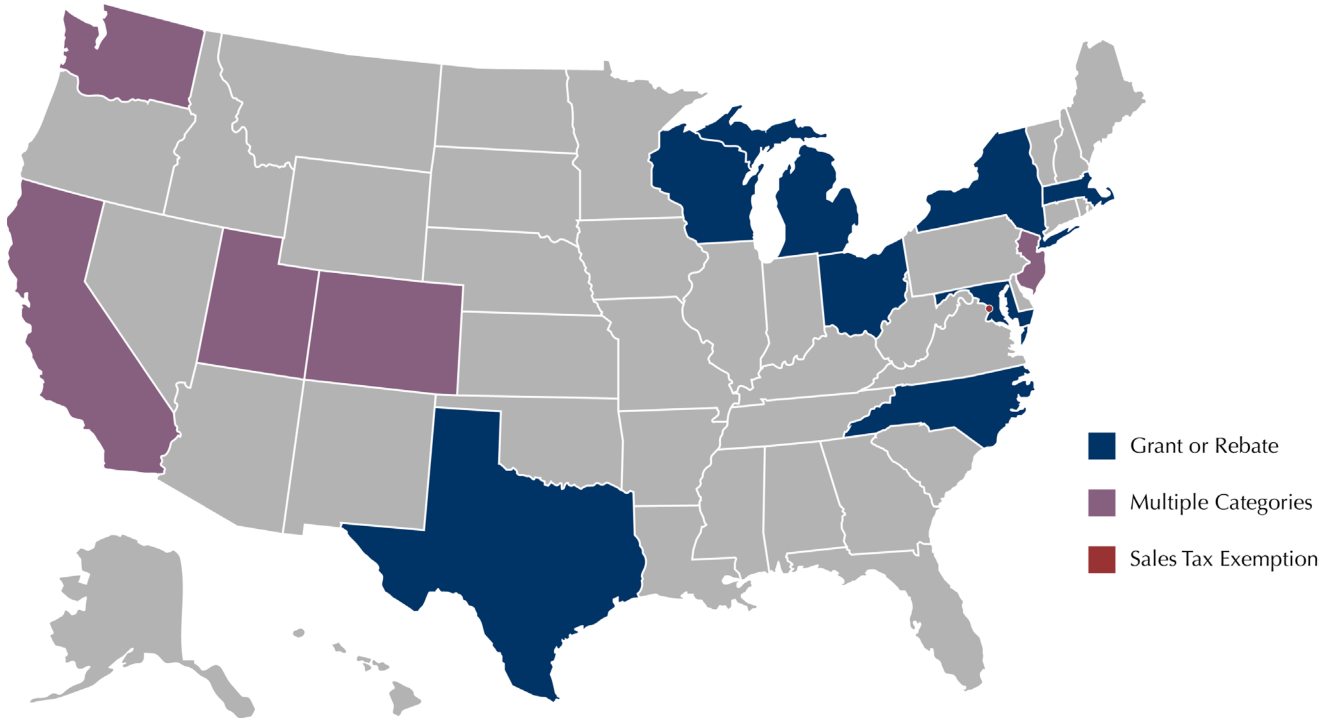
New funding from the IIJA and the IRA, as well as continuing programs through federal agencies, will support the deployment of medium- and heavy-duty ZEVs by helping operators—particularly those operating in areas where neighborhoods are most at risk of health harms from diesel tailpipe pollution—overcome up-front cost barriers. For example, for state and local governments, funding has long been available through the Congestion Mitigation and Air Quality (CMAQ) program (administered by the Federal Highway Administration) for projects to reduce congestion and improve air quality in areas that do not meet the National Ambient Air Quality Standards for ozone, carbon monoxide, and particulate matter.[68] The IIJA updates the CMAQ program to provide funding eligibility for the purchase of medium- and heavy-duty ZEVs—and provides more than $13 billion over five years to fully fund the program.[69] This funding will support communities' access to zero-emission buses, which could have an outsized impact on air quality in lower-income communities, where air quality non-attainment areas tend to be concentrated. As noted earlier, the Federal Transit Administration's Low or No Emission Vehicle program has also provided funding for years to support deployment of low- and no-emission transit buses.[70]

In addition to funding for municipal buses, the IIJA creates a new Clean School Bus program at the EPA, which will distribute $5 billion over five years for school districts to replace their existing school buses with low- and zero-emission school buses (with funding divided evenly between the two categories of vehicle).[71] With almost 500,000 school buses in operation across the country, the funding will not be sufficient to replace all buses, but if deployed as the EPA intends—targeting the oldest, highest-emitting buses in districts with the fewest resources to purchase new and higher-priced ZEV buses—the funding could jumpstart the conversion of the nation's school bus fleet and have a significant impact on the amount of diesel tailpipe pollution the nation's most vulnerable students are exposed to.[72] The Clean School Bus program builds upon an existing school bus program under the Diesel Emissions Reduction Act (DERA), which first funded EPA's School Bus Rebate program beginning with $7 million in 2008.[73] DERA funds a diverse suite of low- and zero-emissions technologies to reduce diesel tailpipe emissions, including through national, state, and tribal and insular area grants covering equipment and engine replacements, retrofits, and upgrades.[74]

The IIJA also creates a new $250 million program to reduce emissions from trucks at port facilities, including funding to test and deploy port electrification technology with a focus on heavy-duty commercial vehicles and other port-related operations.[75] This funding could jumpstart the electrification of equipment like Class 8 tractors and other drayage vehicles, and the fact that commercial entities are eligible means it can cover most operations at ports rather than only publicly-owned equipment. Like the CMAQ program, this funding will have an outsized impact in improving air quality in lower-income communities, which tend to be the ones located around ports.

In addition to these IIJA provisions, the IRA creates a new tax credit for qualified commercial clean vehicles, set at the lesser of 15 percent of the vehicle's base price or the additional cost of the ZEV over the cost of a comparable internal combustion engine vehicle, up to $40,000.[76] With this new tax credit, available through December 31, 2032, commercial fleet operators will be able to better access the higher-priced ZEV models while still realizing long-term savings on fuel and maintenance.

FIGURE 6: MHD ZEV Purchase Incentives by State



A total of thirteen states offer at least one kind of financial incentive for adoption of electric MHD vehicles, including grants or rebates, loan programs, sales tax exemptions, and tax credits. Of these, a grant or rebate is the most common financial incentive offered.

Sources: Atlas EV Hub (2022) and U.S. Department of Energy, Alternative Fuels Data Center (2022).[5]

STATE ACTIONS AND INCENTIVES

Complementing the suite of federal programs and incentives is an array of initiatives and incentives at the state level. For instance, 17 states, Washington, D.C., and Quebec committed through the Multi-State Medium- and Heavy-Duty Zero Emission Vehicle Memorandum of Understanding (MOU) to working together to foster the zero-emission MHD vehicle market, including striving to make at least 30 percent of new MHD vehicle sales ZEVs by 2030 and 100 percent by 2050.[77] In July 2022, this group released an action plan, containing a policy framework and near-term strategy recommendations for state policymakers to support widespread MHD vehicle electrification.[78]

Many states are already taking action. Several states, for instance, offer rebate programs for electric buses and trucks (see Figure 6), including California's Hybrid and Zero-Emission Truck and Bus Voucher Incentive Project (HVIP), New York's Truck Voucher Incentive Program (NYTVIP), and New Jersey's Zero-Emission Incentive Program (ZIP).[79] Other states offer sales tax exemptions or other financial incentives to support the ownership of MHD ZEVs.[80]

BOX 1: Priorities for medium- and heavy-duty transportation to 2030

Accelerated decarbonization of the medium- and heavy-duty transportation sector is a necessary component of meeting the United States' 2030 climate target of reducing emissions 50–52 percent from a 2005 baseline. In the medium-duty sector—particularly among delivery vehicles and other use cases where electrification is already approaching cost-competitiveness—additional financial incentives, stricter emissions standards, and investment in charging infrastructure will be needed to ensure the transition happens on pace. Education and outreach to drivers and fleet operators will also be crucial to reducing barriers to access. In the heavy-duty sector, where less progress has been made, the focus in the near term should be on developing and demonstrating the technology through pilot programs and targeted deployment.

The next decade is critical to laying the foundations for the rapid uptake of ZEVs in the decades thereafter. By 2030, access to charging and refueling infrastructure must be widespread and fleet owners must have the tools and resources they need to shift their fleets. Anticipating the significant increase in electricity demand as the fleet shifts mostly electric, grid modernization and resilience measures must be undertaken now to integrate these vehicles into the existing transportation system. Finally, policy now and in the future must center justice, recognizing that the heaviest burden of pollution from these vehicles has often fallen disproportionately on marginalized communities. Policy and investment must prioritize these communities for access to and deployment of ZEVs.

POLICY RECOMMENDATIONS

Even with the recent flurry of funding and activity supplementing the efforts of various long-standing initiatives, additional policy measures are necessary to overcome the range of challenges facing MHD vehicle electrification.

SUPPORTING TECHNOLOGY DEVELOPMENT AND INNOVATION

While ZEV technology has been developing at a rapid pace in recent years, further innovation is necessary to meet the needs of the current transportation system while accelerating decarbonization. Recent legislation has injected billions of dollars into DOE's research, development, and demonstration (RD&D) programs, but more targeted investment is needed, particularly in the development of more efficient, smaller batteries for MHD vehicles that can provide longer ranges with charging times more comparable to conventional fueling. Additional RD&D is also needed to support cost reductions in emissions-free hydrogen fuel production and delivery, as well as hydrogen fuel cell vehicle technology.

Recommendations:

- Congress should provide additional RD&D funding to support technological innovation that can improve battery efficiency, including increasing funding for applied battery research through DOE's Vehicle Technologies Office.
- Congress should provide RD&D funding to improve green hydrogen production efficiency and reduce costs, including increasing funding to DOE's Hydrogen Shot, with an explicit focus on increasing the feasibility of hydrogen fuel cell MHD vehicles.
- The Department of Energy should pilot MHD fleet battery swapping to explore cost and performance feasibility, as well as grid demand response opportunities, among federal fleets and by funding limited commercial pilots through the Vehicle Technologies Office.

EXPANDING ACCESSIBLE MEDIUM- AND HEAVY-DUTY CHARGING AND REFUELING INFRASTRUCTURE

Access to public charging and refueling infrastructure along freight corridors that can meet the needs of medium- and heavy-duty vehicles is paramount to integrating ZEV technology into the existing freight trucking industry, and interstate cooperation will be essential to ensuring that accessibility. For commercial fleets building private depot charging, financial incentives to bring down installation costs, as well as support for proactive grid planning and upgrades, are essential to ensuring the necessary integration of large-scale fleet charging into the existing power system. For fleets deploying hydrogen fuel cell vehicles, expanded production and distribution of emissions-free hydrogen will be essential to reaching decarbonization goals.

Recommendations:

- Congress and state legislatures should increase the amount of, and expand eligibility for, commercial charging/refueling infrastructure tax credits, to cover installation costs including indirect costs such as local grid upgrades and interconnection costs, with additional incentives to prioritize fleets operated by small businesses or in areas where infrastructure has yet to be deployed (charging deserts).
- Congress should fund and require the U.S. Department of Transportation to provide grants to state departments of transportation for the purpose of enabling utilities to make grid upgrades to support charging infrastructure where the existing grid infrastructure is or is projected to become strained.
- In deploying any Hydrogen Hubs whose end-use focus is on the use of clean hydrogen in the transportation sector, the Department of Energy should prioritize geographic selection along freight corridors, in areas where electrification will not be sufficient.

Relatedly, as more ZEV options enter the nation's fleets, federal regulators should update regulations, including on drivers' hours of service to accommodate charging times and other technology-specific constraints.

ACCELERATING VEHICLE DEPLOYMENT

Without a regulatory environment putting pressure on the transportation system to decarbonize, the deployment of ZEVs will not take place at a pace sufficient to meet necessary mid-century decarbonization goals. Federal and state standards and targets must be set at levels ambitious enough to put the full medium- and heavy-duty fleet on a path to zero emissions by 2050 at the latest, taking into account stock turnover. There must also be continued, enhanced efforts to overcome up-front cost hurdles. Additionally, even when switching to ZEVs makes economic sense, fleet operators and purchasers may be wary of the new technology or believe it is not able to perform sufficiently to meet their needs. Overcoming this wariness means outreach, education, and workforce training are essential to spurring early adoption (and to maximizing the vehicles' performance).[81]

Recommendations:

- The Environmental Protection Agency and National Highway Traffic Safety Administration should strengthen federal greenhouse gas and tailpipe emissions standards to reach 100 percent zero-emissions MHD vehicle sales no later than 2040, and set an earlier timeframe for decarbonizing vehicles in sectors where the technology and business case already exist (e.g., delivery vans, box trucks).
- Congress should provide block grants for states and municipalities to replace internal combustion engine government-owned MHD vehicles with zero-emission vehicles, with priority for areas with the highest air pollution from on-road MHD vehicles.
- The Departments of Transportation, Labor, and Education should fund and provide education, outreach, and workforce training initiatives to fleet owners, operators, drivers, and service technicians, particularly education and training in ZEV operation, charging management, and long-term cost-benefit analysis.

CONCLUSION

The United States is on the cusp of a transition to a decarbonized medium- and heavy-duty vehicle fleet. Technologically, both BEV and FCEV models will soon become available to fill virtually every need currently met by ICE vehicles, and the infrastructure needed to support ZEVs is on the horizon. That said, there remain significant challenges to integrating ZEVs into the current transportation system. Overcoming these challenges is key to accelerating the development of ZEV technology and deploying the charging/refueling infrastructure at the pace and scale necessary to meet midcentury decarbonization goals. Proactive policy at both the state and federal levels is needed to pave the way for the zero-emission transportation future.

Related C2ES Publications:

Getting to Zero: A U.S. Climate Agenda
https://www.c2es.org/document/getting-to-zero-a-u-s-climate-agenda/

Reaching for 2030: Climate and Energy Policy Priorities
https://www.c2es.org/document/reaching-for-2030-climate-and-energy-policy-priorities/

Power Infrastructure Needs for Economywide Decarbonization
https://www.c2es.org/document/power-infrastructure-needs-for-economywide-decarbonization/

Insights on Electric Trucks for Retailers and Trucking Companies
https://www.c2es.org/document/insights-on-electric-trucks-for-retailers-and-trucking-companies/

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