Ready for Work 2.0

On the Road to Clean Trucks

HIGHLIGHTS

Medium- and heavy-duty vehicles are an essential part of our economy, moving billions of tons of cargo each year. But they are also responsible for a massively disproportionate amount of pollution from on-road vehicles. Although medium- and heavy-duty vehicles make up just over 1 in 10 of the vehicles on our roads, they are responsible for over half of the fine particulate matter and nitrogen oxides emitted from on-road vehicles and as well as a disproportionate and increasing amount of climate-warming pollution. This pollution contributes to significant health issues including premature deaths and respiratory illnesses—particularly among populations close to ports, railyards, warehouses, and freight corridors.

Electrifying our on-road freight system is the surest way to reduce truck pollution and improve air quality. The number of zero-emission trucks on the road has grown significantly recently, and key policies are accelerating their adoption. These policies not only reduce pollution but can also lower up-front costs directly and indirectly, enabling fleets to benefit from the operational savings of electric trucks sooner.

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Union of Concerned Scientists

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Introduction

Transportation electrification in the United States has grown significantly over the past decade. In 2023, over 1 million new electric light-duty passenger vehicles hit the road, representing over 7 percent of all new vehicles registered nationwide (Manzi 2023). Electric vehicle infrastructure has also grown at a rapid pace, with over 65,000 publicly available charging stations in operation across the country—a sixfold increase between 2014 and 2023 (DOE n.d.). The growth in electric light-duty vehicles (LDVs) is both impressive and a vital step toward reducing pollution from the transportation sector. Still, electrifying MHDVs, like the trucks that move our goods and the buses that move us around town, is particularly critical to reducing transportation-related air pollution and climate warming emissions. Trucks and buses make up a relatively small share of the vehicles on our roads and highways, but they contribute an outsize proportion of pollution.

Battery-electric trucks and buses are starting to gain traction in the market but at a pace unmatched to the urgency needed to reduce exposure to harmful diesel pollution, improve access to clean air in communities historically overburdened by freight pollution, and address the existential threat of climate change. In these early stages of truck and bus electrification, opportunities and barriers have arisen regarding technology, market, and policy related to reducing the pollution from our nation's fleet of MHDVs, shedding light on a road map for policymakers, communities, industry, and advocates to affect a feasible, effective, and lasting accelerated shift to a sustainable freight system.

In this paper, we highlight and explore some of these opportunities and barriers, with a particular focus on accelerating MHDV electrification in the near term. As such, we focus primarily on battery-electric MHDVs given that battery-electric vehicles are the predominant technology driving MHDV electrification today. This is due primarily to the growing technical capabilities and economic upsides of battery-electric trucks and buses over hydrogen fuel-cell electric vehicles (Wilson 2023c).

Why Electrify?

Our Transportation System Is a Major Source of Air Pollution

Pollution from on-road vehicles in the United States has serious consequences for both people and the planet. Each year in this country, transportation pollution is estimated to result in over 10,000 premature deaths as well as tens of thousands of cases of respiratory illnesses and over 5 million lost days of school and work (Davidson et al. 2020). Diesel-powered heavy-duty vehicles, such as trucks and buses, are responsible for the largest share of premature deaths associated with exposure to fine particulate matter and ground-level ozone pollution from among different types of vehicles (Davidson et al. 2020).

Nationwide, the transportation sector is the largest source of climate-warming emissions and a significant source of toxic air pollution (See Figure 1). The cars, trucks, and buses operating on our roads and highways emit over one-quarter of all human-caused climate-warming emissions and for some time have consistently been the largest source of nitrogen oxides (NO_x)—a precursor pollutant to smog-forming ground-level ozone—and lung-damaging fine particulate matter, or $PM_{2.5}$ (EPA 2024g; EPA 2024h). Although on-road vehicles tend to account for a relatively small percentage of primary $PM_{2.5}$ pollution nationwide, concentrations of vehicle-sourced $PM_{2.5}$ pollution are shown to be significantly elevated near busy roadways and within cities, leading to greater exposure for the 45 million US residents living near roads and highways (EPA 2014; EPA 2024h; Yanosky et al. 2018).

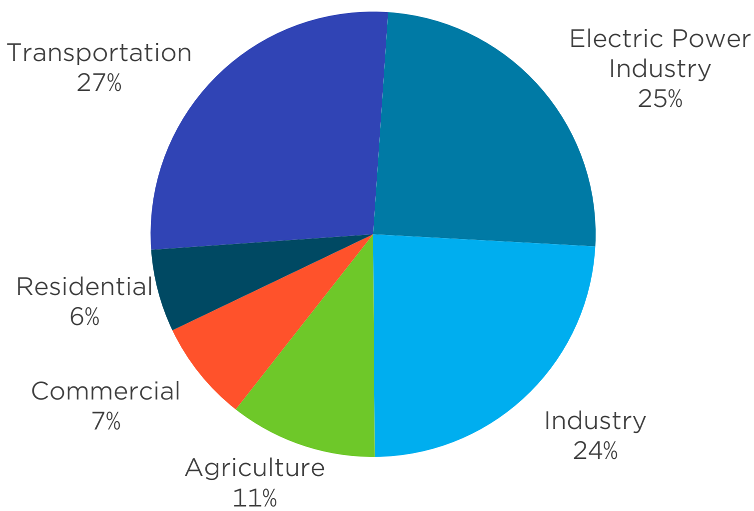
Both short- and long-term exposure to $PM_{2.5}$ pollution can lead to serious health consequences, including respiratory and cardiovascular illnesses and premature mortality, while long-term $PM_{2.5}$ exposure has been linked to increased rates of cancer (EPA 2022b). Nitrogen oxides are both primary and secondary pollutants; they have direct health impacts but also react in the atmosphere to create other pollutants, like particulate matter and ground-level ozone. Both short- and long-term exposure to nitrogen dioxide (NO_2), a primary NO_x pollutant, can worsen respiratory conditions, whereas long-term exposure can lead to the development of asthma and respiratory infections (EPA 2024a). Exposure to elevated levels of ground-level ozone can aggravate respiratory conditions as well, particularly for children, older adults, and people with asthma (EPA 2020; EPA 2024f; Friedman et al. 2024). Additionally, elevated ground-level ozone is harmful to plants and responsible for billions of dollars in lost yields of staple crops, such as wheat (Emberson 2020).

Medium- and Heavy-Duty Vehicles Are Major Polluters

Trucks are the workhorse of our economy, transporting the products and enabling the services that make society function. However, trucks are also a major source of air pollution and climate-warming pollution.

Each year, trucks move approximately two-thirds of the total freight tonnage shipped within the United States (around 13 billion tons in 2023)—more than all other transportation modes combined (BTS n.d.-c). By 2050, the national tonnage shipped by trucks is expected to increase by around 50 percent (BTS n.d.-c). Trucking's contribution to the national gross domestic product (GDP) is unrivaled among transportation modes in the freight sector and tripled between 2012 and 2021—from around $124 billion annually to nearly $390 billion annually (BTS n.d.-b).

Figure 1. National Climate-Warming Emissions by Economic Sector, 2020



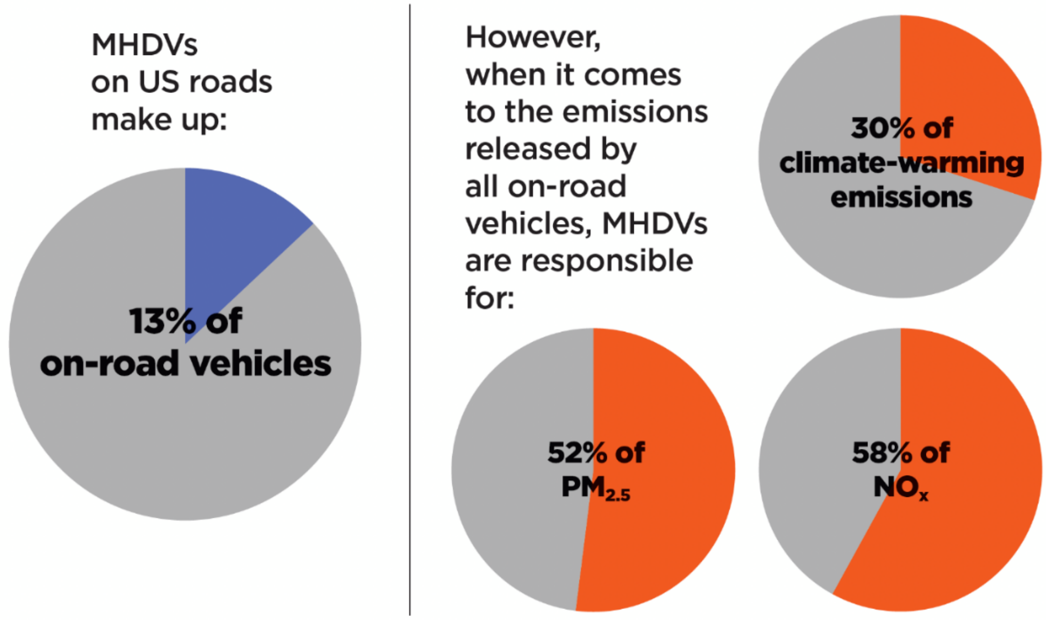
The transportation sector represents the largest source of climate-warming emissions in the United States. Reducing these emissions from vehicles is a vital step toward addressing climate change.

Source: EPA 2024g.

While trucks are a vital part of our economy, they are also responsible for the largest share of $PM_{2.5}$, NO_x, and climate warming pollution among the freight sector, which includes trains, ships, and some aircraft (EPA 2024h; EPA 2024g). Exposure to pollution from MHDVs is estimated to result in between 4,400 and 6,200 premature deaths each year as well as 8,900 emergency room visits and nearly 2 million lost days of school, totaling nearly $100 billion in monetized negative health impacts (Cooke 2024a). The communities historically and disproportionally affected by truck pollution are left to deal with the consequences, paying with their health and lives. Electrifying MHDVs is a key part of reducing the harmful impacts our freight and transportation systems have on people and the planet.

Historically, trucks and buses have produced a disproportionate amount of pollution compared to other vehicle types. **Despite making up just 13 percent of vehicles on the road, MHDVs are responsible for 58 percent of smog-forming NO_x emissions, 52 percent of lung-damaging $PM_{2.5}$ emissions, and 30 percent of climate-warming emissions from vehicles nationwide** (BTS 2023; EPA 2024g; EPA 2024h). Pollution from on-road vehicles powered by diesel fuel, most of which are heavy-duty trucks and buses, is responsible for an estimated 43 percent of transportation-attributable mortalities in the United States (Anenberg et al. 2019).[1]

Figure 2. Pollution Contributions of Medium- and Heavy-Duty Vehicles



MHDVs are responsible for a significant and disproportionate amount of pollution from on-road vehicles. The share of pollution from MHDVs among on-road vehicles has increased in recent years due to growing VMT and slower fuel efficiency improvements compared to other vehicle types.

Sources: BTS 2023; EPA 2024g; EPA 2024h.

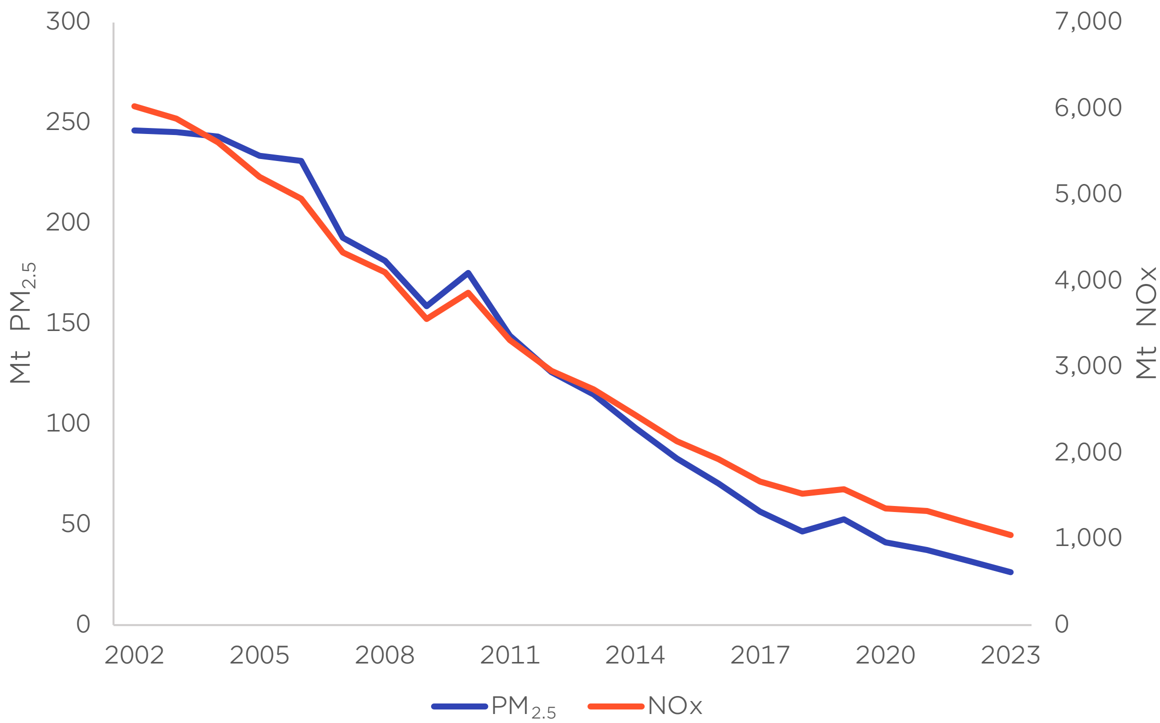
Truck Pollution Remains Harmful, Despite Some Progress

Between 2010 and 2020, emissions of both NO_x and $PM_{2.5}$ from MHDVs declined by over half despite a 4 percent increase in vehicle miles traveled (VMT) (See Figure 3) (BTS 2023; EPA 2024h). This decline was due in large part to state and federal truck and bus emission standards as well as the retirement of older, dirtier vehicles. Given that freight movement by trucks is estimated to increase by nearly 70 percent between 2020 and 2050, regulations and

[1] As of the date of this publication, the 2020 National Emissions Inventory data are the most current. The COVID-19 pandemic caused significant changes in both passenger travel and freight patterns, with reductions in passenger vehicle miles traveled (VMT) and increases in MHDVs' VMT influencing corresponding changes in patterns of pollution. Although some disruptions in travel patterns were temporary, particularly for light-duty passenger vehicles, other changes brought on by COVID-19 have remained, such as increased online shopping and home deliveries. These changes influence on-road freight VMT and corresponding pollution. Additionally, given the continued retirement of older LDVs and greater gains in efficiency and reductions in pollution among LDVs relative to MHDVs, it is likely that trends in the share of pollution among on-road vehicle types seen in 2020 may remain.

standards that both reduce their tailpipe and life-cycle pollution and improve their energy efficiency are necessary to ensure that progress is maintained in the future (FHA 2024a).

Figure 3. National Emissions of $PM_{2.5}$ and NO_x from On-Road MHDVs

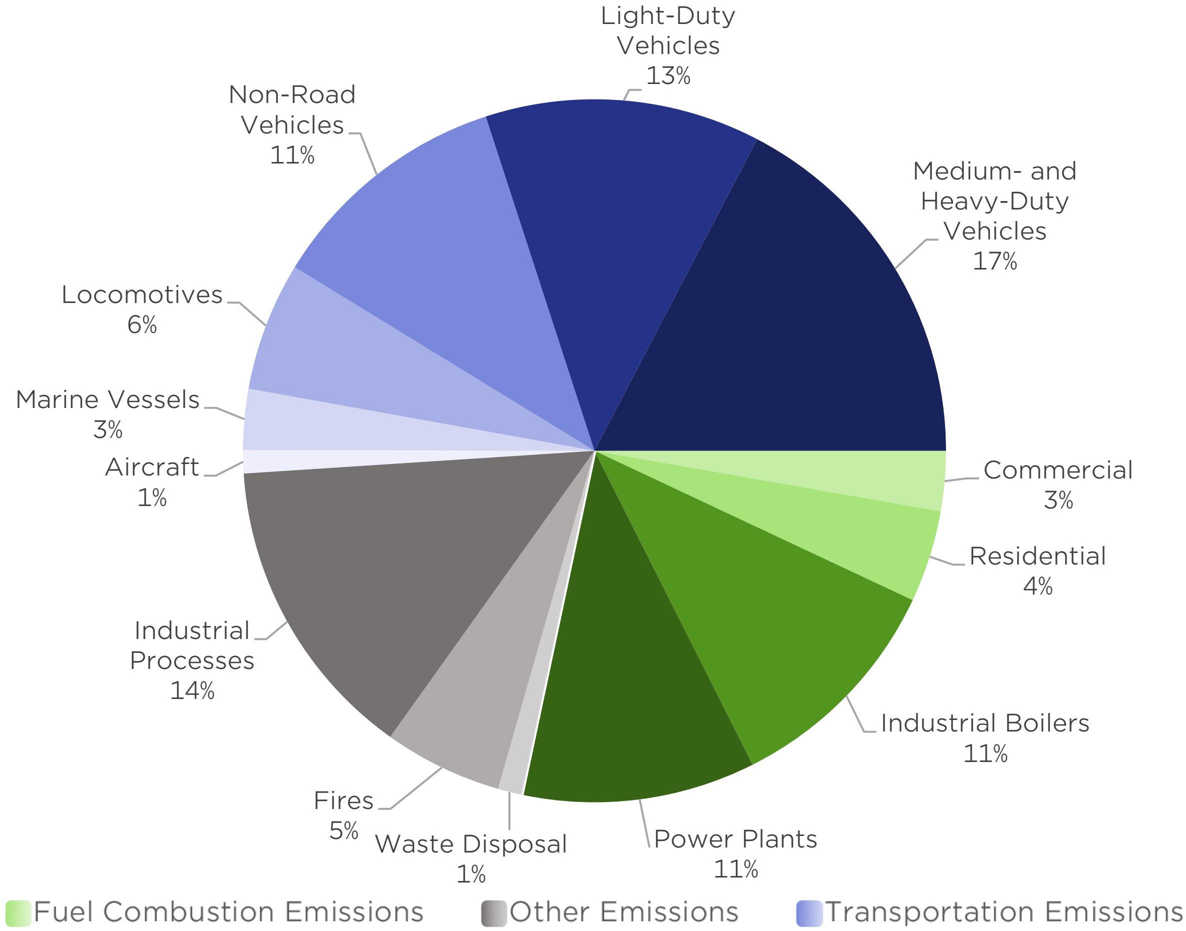


Meaningful reductions in truck pollution have occurred in recent years, but exposure to pollution and the resulting negative health impacts remain high, particularly in communities adjacent to freight corridors. Given that truck VMT is estimated to increase by around 70 percent through 2050, continued reductions in tailpipe pollution are necessary.

Sources: EPA 2024h.

Despite meaningful progress, MHDVs remain the largest source of NO_x emissions in the United States and exposure to their pollution continues to be a significant driver of sickness and premature mortality across the country (See Figure 4) (EPA 2024h ; Davidson et al. 2020). Negative health impacts from truck pollution are particularly notable in urban areas as well as neighborhoods and communities close to ports, railyards, warehouses, and freight corridors, where concentrations of pollution from transportation sources are disproportionately high (Shen and Reichmuth 2022). Research has shown that, while vehicle pollution has decreased nationwide, areas with the highest historical rates of pollution continue to struggle with disproportionately high rates and the resulting negative health outcomes (Colmer et al. 2020). These communities tend to be composed of higher concentrations of low-income households and people of color than areas with healthier air quality (Rowangould 2013; Pinto de Moura and Reichmuth 2019).

Figure 4. National Emissions of Nitrogen Oxides (NOx) by Economic Sector, 2020



Medium- and heavy-duty vehicles are the largest source of NOx pollution in the United States. These vehicles continue to be significant drivers of sickness from exposure to transportation pollution, particularly in areas adjacent to ports, warehouses, and freight corridors. Electric vehicles eliminate tailpipe pollution as well as significantly reduce life-cycle pollution.

Source: EPA 2024h.

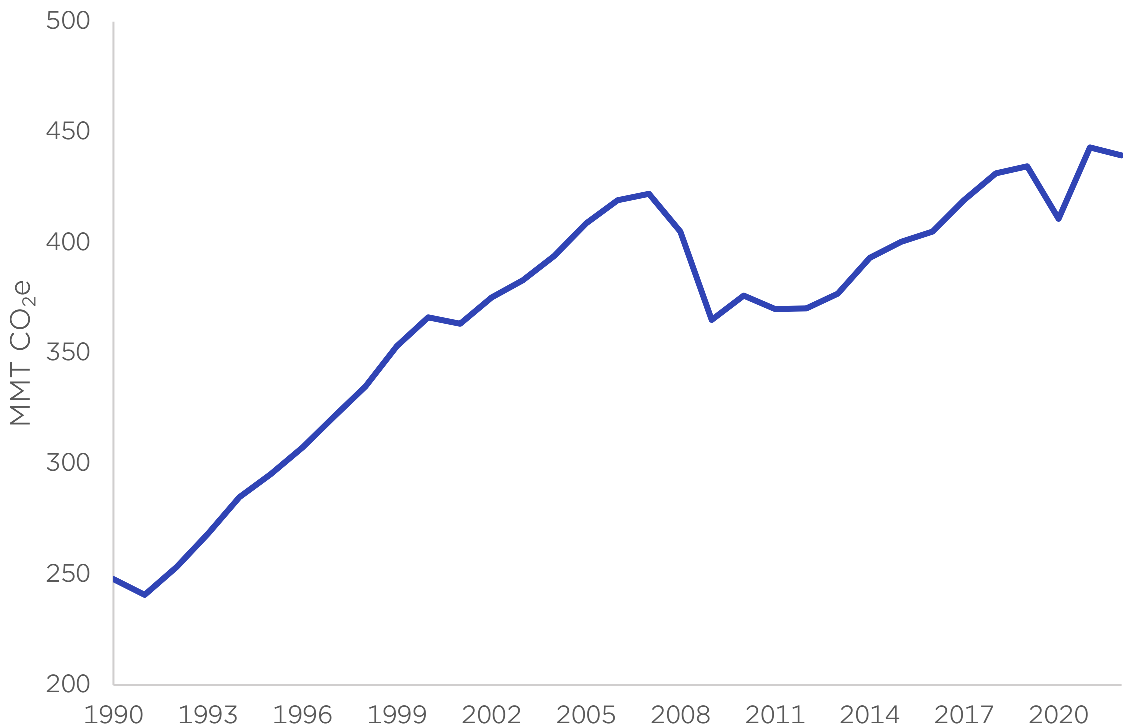
Climate-Warming Pollution from Trucks Is on the Rise

Trucks and buses produce significant amounts of climate-warming emissions. Nationwide, MHDVs emit nearly 440 million metric tons (MMT) of CO_2e each year (See Figure 5), which is roughly equivalent to the climate-warming emissions of 113 coal-fired power plants or *around half* of all energy use from US homes (EPA 2024g; EPA 2024e; EIA n.d.).[2] Despite emitting less climate pollution than LDVs overall, MHDVs far outpaced light-duty cars and trucks in growth

[2] CO_2e stands for *carbon dioxide equivalent* and is a standard unit that equates the varying global warming potential of different heat-trapping gases, such as methane and nitrous oxide, to that of CO_2.

in climate-warming emissions over the past several decades. **While 2022 climate-warming emissions from US LDVs were approximately 9 percent higher than 1990 levels, these emissions from MHDVs increased by over 77 percent during this time** due to increased truck VMT and smaller increases in MHDV fuel efficiency relative to that of LDVs (BTS 2023; BTS 2024; Davis and Boundy 2022; EPA 2024g).

Figure 5. Annual On-Road Emissions of Climate-Warming Greenhouse Gases from US Heavy-Duty Trucks and Buses, 1990–2020



Annual emissions of climate-warming emissions from MHDVs have increased significantly over the past several decades and at a rate much higher than other groups of vehicles. This is because of relatively small gains in vehicle efficiency in MHDVs and increases in VMT. As VMT among MHDVs is expected to grow in the future, electrifying trucks and buses can deliver meaningful reductions in the impact our transportation system has on climate change.

Source: EPA 2024g.

Truck VMT is influenced by a number of factors, including national GDP, consumption of goods, disposable income per capita, and growth in population and employment (FHA 2024b). Between 2011 and 2021, tractor truck and straight truck VMT grew around 1.6 percent and 2.2 percent each year, respectively, several times the annual growth rate of 0.5 percent among all on-road vehicles (BTS 2023). This growth in truck VMT is projected to continue, with tractor-trailer truck and single-unit/straight truck VMT growing at 39 percent and 66 percent, respectively, from 2020 to 2040 under business-as-usual scenarios (BTS 2023).

Electric Trucks Deliver Both Tailpipe and Life-Cycle Pollution Reductions

Electrifying MHDVs can help to reduce both air pollution and climate-warming emissions, even as VMT is projected to increase. Moreover, electric trucks and buses have significantly lower life-cycle emissions, which include emissions from manufacturing, vehicle use, and end-of-life recycling and disposal (O'Connell et al. 2023). Even when considering increased pollution from power plants, electrifying MHDVs results in meaningful net reductions in air pollution (Cooke 2024a; Camilleri et al. 2023).

Studies have shown that BETs powered by renewable energy produce the lowest life-cycle climate-warming impacts per mile among all fuel types, and BETs operating on today's electricity grid are far cleaner than combustion models (Iyer, Kelly, and Elgowainy 2023; O'Connell et al. 2023). Life-cycle pollution created by vehicles is influenced by two factors: vehicle cycle (i.e., material and vehicle production and end-of-life disposal and recycling) and vehicle use (i.e., fuel production and tailpipe emissions). Over the lifetime of a truck, vehicle use is responsible for the overwhelming majority of pollution impacts—well over 80 percent in some cases (Iyer, Kelly, and Elgowainy 2023; O'Connell et al. 2023). In part because battery-electric drivetrains are by far the most energy efficient drivetrain technology available, BETs operating on today's grid show far fewer life-cycle climate impacts compared to other fuel types. A study of European battery-electric delivery and tractor-trailer trucks charging on today's grid found these trucks to have less than around half of the life-cycle climate impacts of comparable diesel trucks, and preliminary results from a study on US trucks also suggest deep reductions of climate-warming emissions (O'Connell et al. 2023; O'Connell et al. n.d.). Additionally, as the share of renewable energy on the electricity grid grows, the climate impacts of BETs will become even less.

Compared to vehicle use of diesel trucks, that of BETs leads to a significantly lesser degree of negative health impacts that result from exposure to emissions of NO_x, $PM_{2.5}$, and other toxic air pollutants. UCS analysis found that a model year 2023 battery-electric tractor truck operating a drayage duty cycle reduced negative health impacts between 86 percent and 89 percent over an average diesel drayage truck (Cooke 2024a).[3] In fact, BETs of all types are able to reduce negative health impacts compared to analogous diesel-powered truck types on the road today (See Table 1). These reductions in health impacts occur even when considering the pollution associated with today's electricity grid (averaged nationally). And, as with climate impacts, the public health impacts associated with BETs will continue to decline as the electricity grid becomes cleaner.

[3] Drayage trucks are short- and regional-haul commercial vehicles that transport cargo containers and goods from ports, railyards, and intermodal facilities to warehouses and other distribution centers. These vehicles, typically Class 7 and 8 tractor trucks, play a critical role in our freight system; however, they are also responsible for a significant amount of truck pollution, particularly in areas adjacent to freight and distribution centers.

Table 1. Well-to-Wheel Lifetime Health Impact and Climate-Warming Emissions Reduction Potential Among MY23 MHDVs

Vehicle Type	Health Impact Reduction	Climate-Warming Emissions Reduction
Delivery truck	73%–78%	77%
Delivery van	74%–79%	77%
Refuse truck	89%–91%	85%
School bus	92%–93%	86%
Tractor (Drayage)	86%–89%	82%
Tractor (Line-haul)	64%–71%	64%
Tractor (Regional)	70%–76%	69%
Transit bus	89%–91%	81%

Even when operating on today's electricity grid, electric trucks and buses can significantly reduce both climate-warming emissions and health-impacting air pollution compared to combustion models. This highlights both the public health and climate benefits of electrifying MHDVs and that increasing the share of renewable energy on our electricity grid will further these benefits.

Source: Cooke 2024a.

Box 1. Hydrogen-Powered Trucks

Hydrogen-powered fuel-cell electric trucks are often discussed as a solution to on-road freight pollution. Indeed, both public and private sectors have invested billions of dollars to promote fuel-cell electric trucks and fueling infrastructure. However, today's hydrogen fuel comes with significant public health, climate, energy efficiency, and economic concerns (Wilson 2023c). Though the share of fuel-cell electric truck deployments to date among US zero-emission MHDVs has been miniscule (approximately 0.3% through 2023), the technology must be developed in such a way that avoids potentially negative consequences of wider-scale adoption (S&P Global Mobility 2024).

Today, over 95 percent of hydrogen fuel is produced from fossil fuels (i.e., natural gas and coal) in a process called steam methane reformation (SMR), negating the many climate and air quality benefits of producing hydrogen from renewable fuels (DOE 2023a). While areas with high amounts of air pollution from trucks could benefit from this zero-tailpipe emissions technology, more research is needed to better understand the net pollution impacts in areas adjacent to hydrogen fuel production facilities (i.e., supplanting diesel fuel production with hydrogen fuel production), given today's prominent hydrogen production methods. A truly equitable transition to a clean freight system must mitigate situations where pollution is simply pushed from one community to another.

Hydrogen produced through electrolysis (a process that creates hydrogen from water using electricity) avoids the pollution associated with production through SMR, but consumes around three times more energy, mile for mile, than battery-electric vehicle technologies. Furthermore, hydrogen is by far the most expensive transportation fuel on the market today (Wilson 2023c). These economic and energy efficiency issues are compelling hindrances to the adoption of hydrogen as a sustainable transportation fuel.

For hydrogen to realize its potential as a clean fuel, the deployment of fuel-cell trucks must be strategic, where the fuel is the best-use scenario and is from renewable sources. For more on the issue, see our 2023 report *Hydrogen-Powered Heavy-Duty Trucks: A Review of the Environmental and Economic Implications of Hydrogen Fuel for On-Road Freight*.

Electric Trucks Deliver Growing Economic Benefits to Fleets

As with many emerging technologies, zero-emission trucks and buses often have higher up-front costs than more conventional and established technologies. However, BETs offer significant fuel and maintenance savings over conventional trucks—an important factor in the total-cost of ownership (TCO) over a vehicle's lifetime (Burnham et al. 2021). Both purchase price and TCO between battery-electric MHDVs and those powered by combustion engines are approaching parity, if not already realized, among certain smaller truck types (Mulholland 2022). Even for larger tractor trucks, TCO parity between battery-electric and diesel trucks could be reached by the end of the decade (Basma et al. 2023; NREL 2024).

Despite the higher up-front costs incurred by early adopters of electric trucks, fleet operators may already be saving on operational and maintenance costs by switching to battery-electric models. As up-front prices decline, these savings will be realized even sooner. Market forces such as economies of scale, developing technologies and manufacturing capacities, and incentives for purchasing zero-emission trucks and buses will influence downward pressure on the up-front purchase price of zero-emission MHDVs, which will then accelerate the adoption of clean trucks and buses.

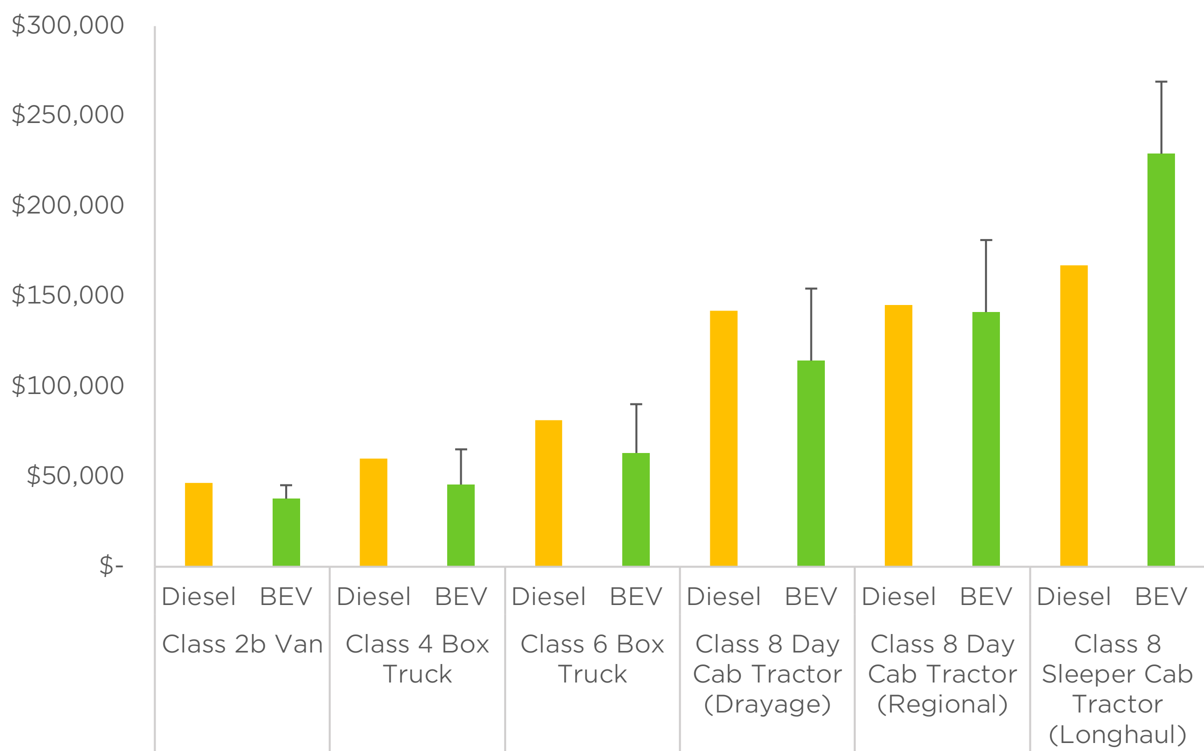
What Drives the Cost of Trucks?

The two largest cost components over the lifetime of an MHDV are its up-front purchase price and its operational costs. The share of these costs over the lifetime of the vehicle depends significantly on its use case. Depending on the vehicle type, especially for high-mileage use cases, lifetime operational costs (e.g., fuel, maintenance, etc.) can be greater than initial capital costs (e.g., MSRP, taxes, etc.). Because they tend to travel short distances, smaller vehicle types like cargo vans and last-mile delivery vehicles can have lower lifetime operational costs than capital costs, whereas the lifetime operational costs of regional- and long-haul tractor trucks may be greater than their up-front purchase prices because of high annual VMT, despite the high capital costs of these vehicle types (Ledna et al. 2024; Mulholland 2022). Fleet owners will take these cost factors into account when operational and capital planning. For instance, larger fleets with greater access to capital and low-cost financing may be more likely to focus on lifetime costs over purchase price, while smaller fleets may be more likely to focus on up-front costs.

Up-front prices for electric trucks and buses are expected to continue to decline, but concerns have been raised regarding stagnant prices for the largest electric trucks on the US market, especially as MSRPs continue to decline in other international markets (CARB 2024; Ortiz 2024). Still, all types of BETs are projected to reach price parity with comparable combustion models as the market matures and technology costs lessen. Federal purchase incentives (See Figure 6) are accelerating this timeline, with most truck types estimated to reach purchase price parity by the end of the decade (NREL 2024; Slowik et al. 2023).

Some smaller types of electric MHDVs are nearing price parity with combustion models and in some cases have already achieved an up-front price preference, thanks to clean vehicle incentives. For example, the MSRPs of the battery-electric and combustion-powered models of Ford's popular Transit cargo van are $51,095 and $47,165, respectively, a difference of approximately $4,000 (Ford Motor Company n.d.). However, because the electric model is eligible for a $7,500 tax credit, the off-the-lot cost of the base electric model is less than that of the base combustion model. In California, certain fleets are eligible for an additional $7,500 rebate for small electric trucks and vans, further reducing up-front costs. This up-front price parity is in part the reason for the meteoric rise in electric cargo van adoption in the early years of freight electrification (Wilson 2023a).

Figure 6. Model Year 2030 Truck Prices among Fuel Types with Federal Incentives (2022$)



By 2030, most BET types are estimated to have similar or lower purchase prices than equivalent combustion models due in part to federal tax incentives. Some states offer incentives in addition to those provided by the federal government. California's HVIP provides up to $120,000 for battery-electric tractor trucks. Error bars indicate up-front prices without federal incentives.

Source: NREL 2024.[4]

[4] Cost projections from the National Renewable Energy Laboratory's Annual Technology Baseline referenced in this report utilize their Advanced Scenario estimates. We find this scenario to be most consistent with several other analyses projecting battery-electric truck costs.

Electric Trucks Can Deliver Savings to Fleets

Fuel and maintenance costs for battery-electric trucks and buses are far lower than for any other fuel type (Hunter et al. 2021). BETs are estimated to cost over one-third less per mile for operation and maintenance than trucks powered by diesel or natural gas, although savings vary based on local fuel costs (Hunter et al. 2021). These savings are largely due to the higher energy efficiencies and reduced regular maintenance of battery-electric drivetrains compared to those of combustion drivetrains. Indeed, battery-electric trucks and buses exhibit the highest energy efficiency among all drivetrain technologies today—a trend estimated to continue even as efficiencies of internal combustion engines increase (Islam et al. 2021).

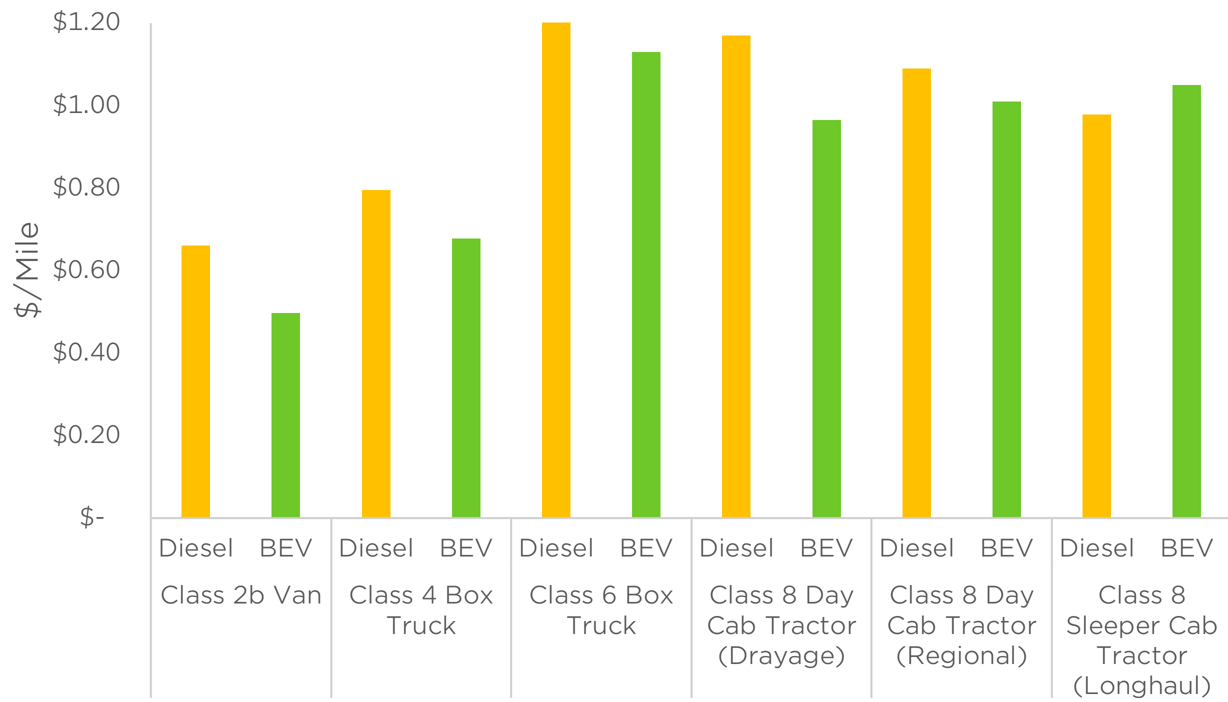
Operational and maintenance savings can offset the higher up-front costs of battery-electric trucks and buses in some cases, leading to a preferable TCO. For example, while a model year 2025 battery-electric regional-haul tractor truck is anticipated to have around a $50,000 price premium after incentives over a comparable diesel model, an electric model operating in California is estimated to have a TCO over $100,000 less than the diesel model (Slowik et al. 2023; CARB 2021). Still, it is important to recall the apparent price disparity between analogous US and European battery-electric tractor truck models, an issue that is delaying TCO preference among larger zero-emission trucks. The divergence between the two regions does not seem to be founded on economics or inherent differences in manufacturing costs, a fact that highlights the important role that regulations play in ensuring and promoting a fair and competitive market with transparent pricing (Ortiz 2024).

Early adopters of BETs are beginning to realize the economic benefits they deliver. PepsiCo, for instance, deployed a fleet of battery-electric Class 8 tractor trucks in 2022 for regional-haul duty cycles in Northern California. In speaking to the economics of operating BETs, Adam Buttgenbach, PepsiCo's director of Fleet Engineering and Sustainability, recently remarked,

We've seen in certain duty cycles and in certain asset classes that the economics already make sense from the fuel savings, from the maintenance savings, from the driver turnover and positive impact on our employees operating the vehicles. We see electric vehicles in certain asset classes making sense today without grants and initiatives. (NACFE n.d.-d)

By the end of the decade, battery-electric trucks are expected to have the lowest TCO among all fuel types for most major MHDV types, even without purchase incentives or accounting for revenue generated from low-carbon fuel programs in many cases (See Figure 7) (Basma et al. 2023; Ledna et al. 2024; NREL 2024). Even so, federal and state purchase incentives are important for reducing up-front costs and lowering TCO today, helping to accelerate the market for clean trucks (Linn and Look 2022). When considering these incentives, many zero-emission vehicle types show a total-cost preference today, with most all vehicle types achieving up-front cost parity before the end of the decade (See Figure 6). California fleets, for example, benefit from both federal Commercial Clean Vehicle incentives and a state program that helps with up-front cost differences between zero-emission and combustion models, covering upward of $200,000 for certain larger battery-electric and fuel-cell electric trucks (California HVIP n.d.). Other states, including Washington and New York, already have or will soon implement similar programs.

Figure 7. Levelized Cost of Driving for Model Year 2030 Truck Types without Federal Incentives (2022$)

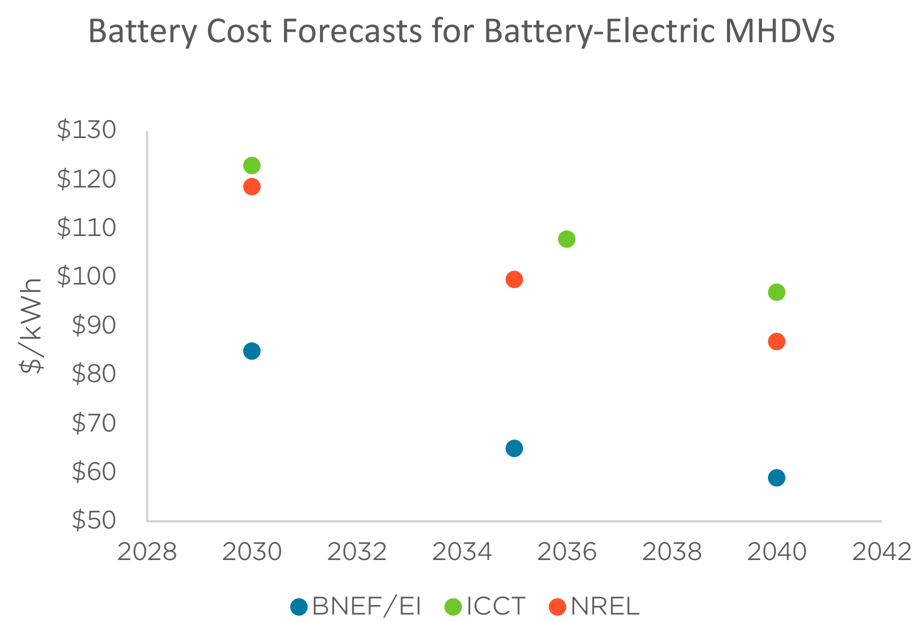


By 2030, most battery-electric truck types are estimated to have lower driving expenditures compared to analogous diesel trucks when accounting for costs including vehicle purchase, fuel, maintenance, repair, and charging equipment. Federal and state incentives for clean vehicles purchases and charging equipment and potential revenue from low-carbon fuel programs are not included in these estimates but can significantly lower lifetime ownership costs. Such incentives are important for accelerating the market for and uptake of zero-emission MHDVs in the near term.

Source: NREL 2024.

Box 2. Battery Costs Are Anticipated to Decrease

Just as for light-duty passenger electric vehicles, battery costs are a primary driver of the up-front price premium for battery-electric trucks and buses. However, heavy-duty battery packs tend to be more expensive because of the increased needs related to energy density, durability, and thermal management (Busch 2024). Despite their high cost today, batteries are predicted to decrease significantly over the next several years (Phadke et al. 2021; NREL 2024). Where many studies estimated HDV battery pack prices to be well over $250 per kilowatt-hour (kWh) in 2020, prices have been estimated to decline to as low as $85 per kWh in 2030 and $59 per kWh in 2040 (Islam et al. 2021; Xie, Basma, and Rodriguez 2023; Busch 2024; NREL 2024).



Batteries are a primary cost driver for BETs but have declined significantly over the past several years. These costs are forecasted to continue declining in the future. Declining battery costs will have a significant impact on up-front vehicle costs, leading to lower lifetime ownership costs for BETs.

Source: Xie, Basma, and Rodriguez 2023; Busch 2024; NREL 2024.

Technological Rationale for Electrification

On-Road Freight in the Age of E-Commerce

Over the past several decades, our freight system has evolved with the rise of e-commerce, with trucks remaining the dominant workhorse. The hub-and-spoke distribution system that has become characteristic of on-road freight has increased systemic efficiencies and allowed consumers to receive deliveries in a matter of hours or days, but it has also influenced an increase in the size of warehouses and the related truck traffic in neighborhoods and on highways. Both warehouse construction and the size of these facilities have more than doubled since 2010, with the number of loading docks at new warehouses up around 400 percent in this time (Kerr et al. 2024).

This growth, along with an increase in the clustering of warehouses, has been shown to increase the amount of associated air pollution both nationally and in areas close to warehouse districts (Kerr et al. 2024). These emissions often go unregulated, as warehouses themselves are not considered to be a “point source,” or a direct pollution source (such as a power plant, smelter, or other facility with smokestacks). Even so, they are responsible for influencing truck traffic, which greatly affects emissions of air pollution and climate-warming emissions. As such, warehouses and other facilities that significantly affect truck traffic and pollution are increasingly referred to as “indirect sources” of pollution.

Regulations and programs that attempt to address these indirect sources of pollution are beginning to be implemented, but they are scarce. In 2021, the South Coast Air Quality Management District, the agency tasked with regulating air quality in much of Southern California, adopted the Warehouse Actions and Investments to Reduce Emissions Program, which requires certain large warehouses to reduce the pollution associated with their operations (SCAQMD 2021b). This program functions as a flexible point-based system and allows flexibilities for warehouses subject to the rule to create their own plans for pollution reductions. In 2024, California passed AB 98, which begins to address warehouse pollution statewide through a number of requirements for certain new facilities, including measures to reduce idling and encourage planning for zero-emission truck charging.

Box 3. Electrifying the USPS

The United States Postal Service committed to transitioning the vast majority of its last-mile delivery fleet to battery-electric vehicles over the coming years, helping to both reduce pollution from one of the world's largest vehicle fleets and usher in significant operational and maintenance savings. Battery-electric vehicles are particularly well suited for USPS deliveries, given that the average US postal route is 21 miles. This means that shorter-range vehicles may not need to charge daily, allowing additional savings with vehicles sharing chargers (Wilson 2022b).

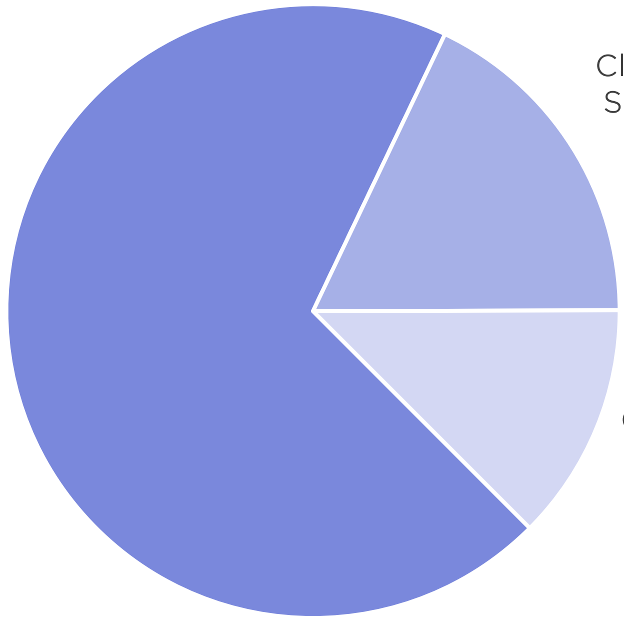
The Postal Service originally committed to replacing its aging fleet of highly inefficient and maintenance-intensive delivery vehicles with a new fleet that includes around 10 percent zero-emission vehicles; however, UCS and our partners successfully advocated for the USPS to increase this commitment to around two-thirds zero-emission vehicles for the first phase of fleet replacement and 100 percent beginning in 2027 (Wilson 2023b).

In 2024, the USPS began installing charging equipment at their sorting and delivery centers and took in around 6,000 electric delivery vehicles over the course of the year (Postal Service Oversight 2024). The significantly cleaner and more efficient vehicles began operating in several cities in 2024; more are expected to be deployed across the nation in the coming years. If the incoming Trump administration cancels the existing contracts for battery-electric delivery trucks, however, as was suggested by reports in late 2024, these benefits for the USPS, taxpayers, and the climate could be lost (Renshaw and Ulmer 2024).

Today's Battery-Electric Trucks Can Meet Most Duty Cycle Demands

Range is often perceived as a limiting factor for vehicle electrification. But commercial vehicles often operate on predictable routes over short distances, meaning that currently available battery-electric models are a viable option for many, if not most, commercial vehicle uses today. While a long-haul tractor truck may come to mind for many when invoking an example of a commercial truck, the largest group of commercial vehicles is Class 2b and 3 (See Figure 8), which make up around 70 percent of MHDVs on the road today (BTS n.d.-d).

Figure 8. In-Use MHDV Population



Most MHDVs on the road today are smaller vehicles, such as cargo vans, vocational trucks, and the like. These vehicles are well suited for early electrification given their lower up-front costs, short range duty cycles, and tendency to return to their home bases for extended periods of time. The potential to electrify larger MHDV models is expanding significantly given declining costs, growing model availability, and technological advancements. Electrifying larger trucks and buses is key to reducing pollution from the MHDV sector.

Source: US Census Bureau et al. 2023.

In fact, as shown in Figure 9, over 90 percent of MHDVs travel fewer than 200 miles per day, and around 70 percent travel fewer than 50 miles per day (US Census Bureau et al. 2023). Thus, the vast majority of MHDVs function well within the range capability of the available zero-emission MHDV models without the need to refuel during their daily routes.

Many commercial fleet vehicles return to a central depot after their routes or are parked for several hours daily, providing ample time to charge at varying speeds and be ready for their next shift. A survey of trucks that operate on shift schedules found that over 75 percent of MHDVs are parked for over 6 hours per day (See Table 2) (NACFE 2018).

Table 2: Percent of MHDV Trucks by Time Parked in 24-Hour Period

Time Parked Daily	Class 3 Delivery	Class 4-6 Box Truck	Class 7-8 Tractor (City)	Class 7-8 Tractor (Regional)	Class 7-8 (Long Haul)
<1 Hour	0%	0%	0%	1%	0%
1-2 Hours	0%	0%	2%	4%	13%
3-4 Hours	0%	0%	18%	15%	9%
5-6 Hours	8%	0%	12%	10%	10%
7-8 Hours	25%	50%	3%	14%	15%
>9 Hours	67%	50%	65%	56%	54%

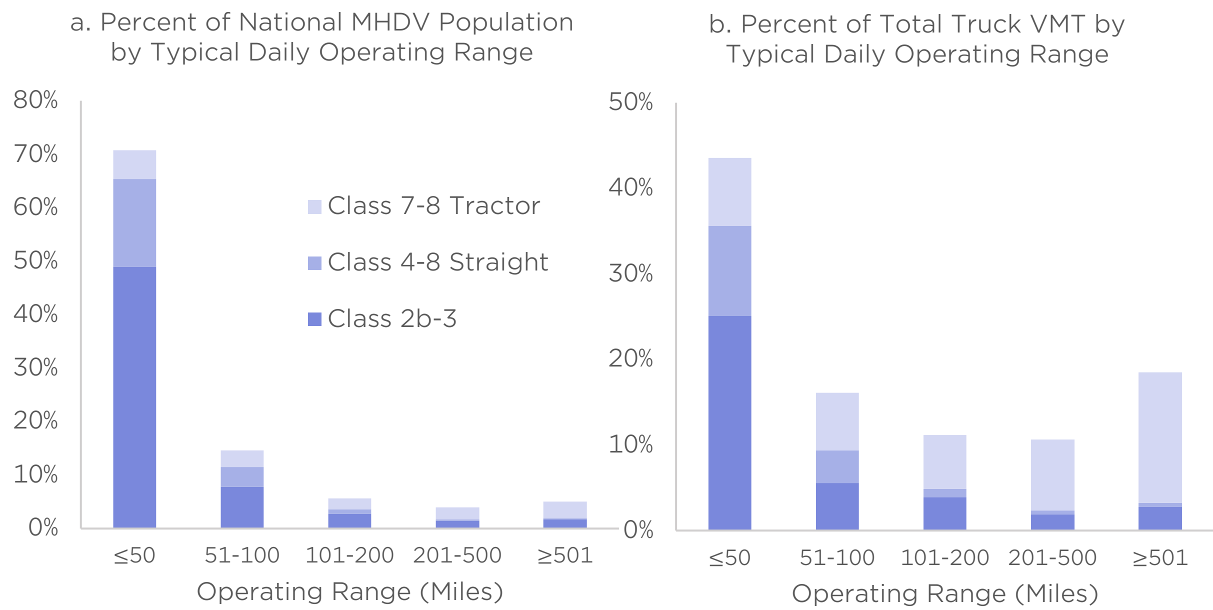
Across many vehicle segments and duty cycles, most MHDVs are parked for over 6 hours each day. The time these vehicles are parked represents charging opportunities, whether they are loading or unloading goods or off-duty. Fleet owners may choose to install less expensive, lower-level charging equipment to support vehicles parked for extended periods of time.

Source: NACFE 2018.

Daily operating range varies among different classes and types of vehicles (See Figure 9). For example, over 90 percent of Class 2b and 3 trucks, which tend to be vocational trucks and delivery vans, travel fewer than 100 miles per day. Similarly, just under 90 percent of Class 4–8 straight-body trucks, like box trucks, dump trucks, and buses, travel fewer than 100 miles per day. Understandably, Class 7 and 8 tractor trucks tend to travel greater distances each day, although over half of these vehicles travel fewer than 100 miles daily (Census 2023).

While an overwhelming percentage of the population of commercial vehicles can make it through a workday on a single charge and then refuel overnight at the depot, a small but quite consequential group of trucks may need to refuel during the day, often relying on public-facing and shared charging sites. Although only around 20 percent of tractor trucks travel greater than 500 miles each day, this group travels considerable distances each year. Tractor trucks account for the most VMT annually among the national population of commercial MHDVs, and tractor trucks that travel greater than 500 miles daily account for just over one-third of the total annual VMT by MHDVs nationwide (US Census Bureau et al. 2023). That is, a small portion of the trucks on our roads and highways account for an outsized portion of national VMT each year.

Figure 9. Operating Range of Medium- and Heavy-Duty Trucks



Over 90 percent of MHDVs operate within 200-mile ranges on a daily basis (left), and over 70 percent of MHDV vehicle miles traveled (VMT) are attributable to trucks with operating ranges less than 200 miles (right). These trucks are particularly well-suited for near-term electrification given both zero-emission MHDV model availability and the ability to charge at their home base during off-duty hours.

Source: US Census 2023.

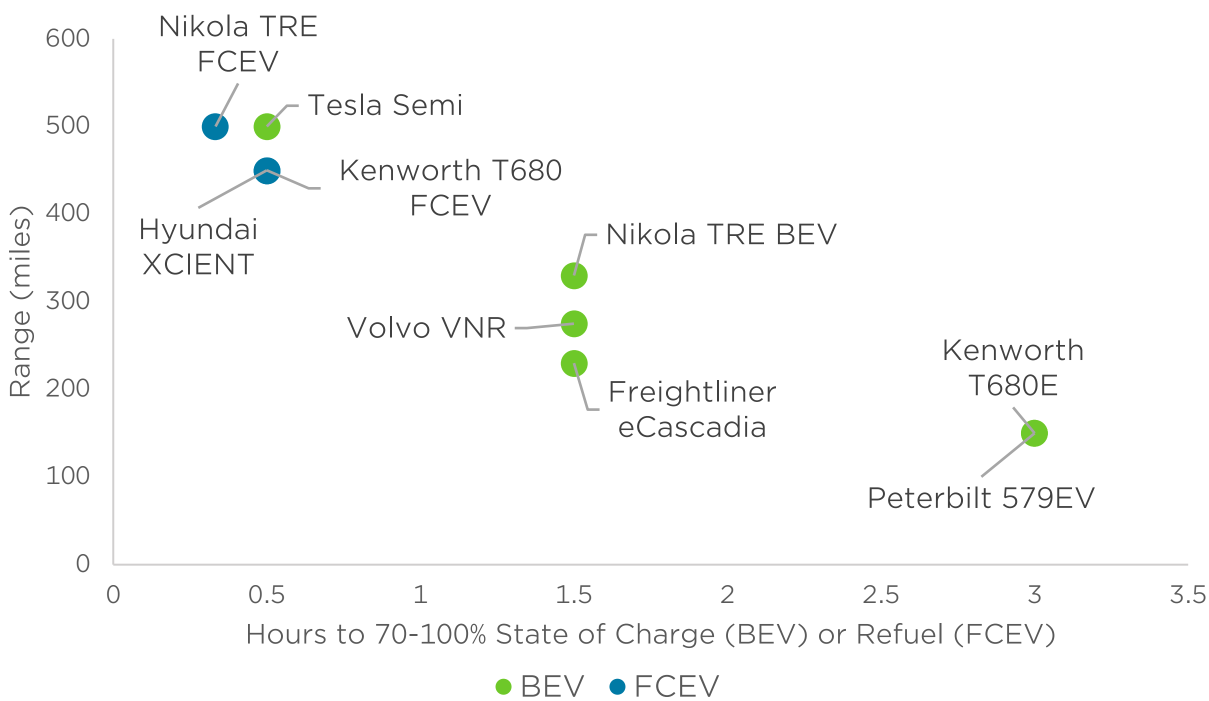
Despite the absence of zero-emission sleeper cab tractor models on the market, the technology to electrify this critical sector is heading in the right direction. In 2022, PepsiCo received the first round of Tesla's 500-mile-range battery-electric Class 8 tractor trucks and began using them to make long-haul deliveries in California and Nevada. Their routes included loads up to the federal weight limit of 82,000 pounds and distances of over 850 miles in a single day (NACFE n.d.-a). This example shows that today's emerging technology is suitable for certain long-haul duty cycles, but wide-scale deployment of fast-charging stations for large BETs and increased availability of long-range, fast-charging battery-electric tractor trucks is necessary for expanding the viability of zero-emission long-haul freight nationwide.

Zero-Emission Trucks Are in It for the Long Haul

Range capabilities among today's zero-emission tractor trucks have grown over the past several years. In fact, the three most widely-deployed battery-electric tractor models in the United States—Nikola TRE BEV, Freightliner eCascadia, and Volvo VNR—can exceed the typical daily range requirements of around two-thirds of tractor trucks on the road today (See Figure 10) (S&P Global Mobility 2024; US Census Bureau et al. 2023).

Though today's available battery-electric tractor truck models are often well suited for regional-haul duty cycles, longer range, faster-fueling models will be necessary to electrify long-haul routes. Long-range battery-electric and hydrogen fuel-cell tractor truck models are currently being deployed for limited beta testing across the country. Tesla's (n.d.) upcoming Class 8 Semi model, for example, can travel up to 500 miles on a single charge and recharge to 70 percent in roughly 30 minutes. Fleets testing Tesla's Semi have reported daily mileage of around 800 miles (charging once during the day) at a maximum weight capacity of 82,000 pounds (NACFE n.d.-a). As Figure 10 illustrates, hydrogen fuel-cell models from Nikola, Hyundai, and Kenworth show similar range and charging capabilities.

Figure 10. Range and Fueling Time of Available Zero-Emission Class 7 and Class 8 Tractor Trucks



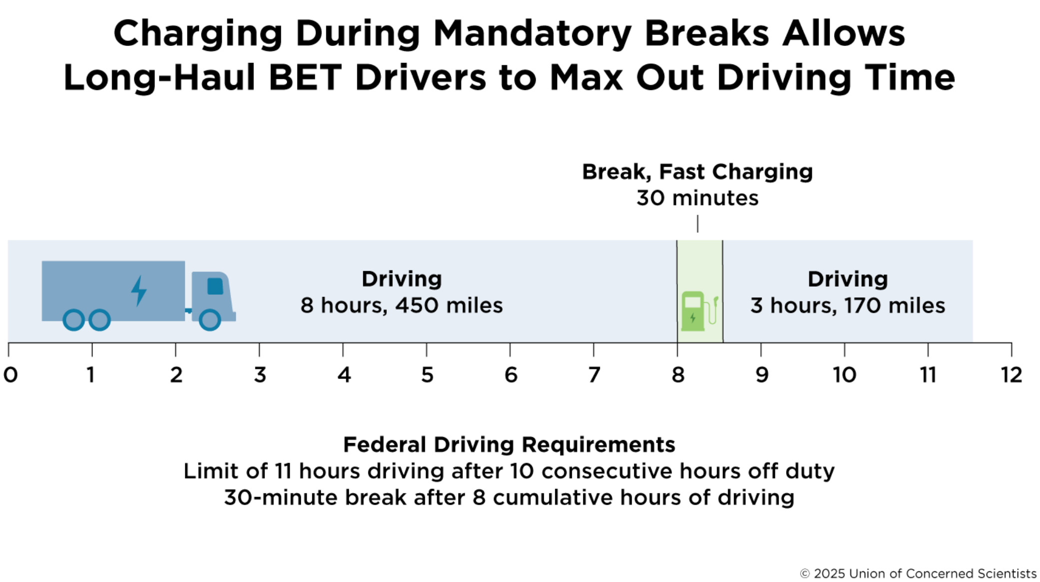
Zero-emission tractor truck models vary in maximum ranges and charging speeds. Currently available battery-electric models can fuel to a 70% to 100% state of charge in 30 minutes to three hours, depending on the maximum charging rates of the truck and charging equipment. Fuel-cell electric models tend to have longer ranges and shorter fueling times than battery-electric models; however, forthcoming battery-electric models are approaching range and fuel time parity.

Sources: Freightliner n.d.; Hyundai n.d.; Kenworth n.d.-a; Kenworth n.d.-b; Nikola Motor n.d.-a; Nikola Motor n.d.-b; Peterbilt n.d.; Volvo Trucks n.d.

Longer-range capabilities will certainly help to stoke the market for zero-emission tractor trucks and there appears to be an optimal vehicle range of around 500 miles for long-haul duty cycles. This creates a strong case for the further development of 500-mile-range battery-electric tractor trucks with fast-charging capabilities.

Considering average highway speeds (around 55 mph nationally) and federal driver safety regulations, the longest distance a long-haul truck driver can typically travel before a mandatory rest break is approximately 450 miles (FMCSA 2020; FHA 2010). Under most circumstances, truck operators are required under federal rules to take a 30-minute break after driving for eight hours. Today, coming online are fast-charging technologies for large trucks, such as the Megawatt Charging System and Tesla's Megacharger, that can provide an electric tractor truck with several hundred miles of range during this short break. Given that truck drivers are limited to driving 11 hours during a workday, the range provided to the vehicle during the rest period can be sufficient for a driver to complete their maximum allowable time on the road.

Figure 11. Emerging Battery-Electric Truck Range and Charging Speeds Align with Federal Driving Requirements



Federal requirements limit the amount of time truck drivers can operate vehicles before a 30-minute mandatory rest break (8 hours) as well as total time driving during a shift (11 hours). When considering US average highway speeds (55 mph), this means that long-haul truck drivers could drive a maximum of around 450 miles before needing to break for 30 minutes. Newly deployed fast-charging technologies can provide a BET with several hundred miles of range during this break period.

Sources: FMCSA 2020; FHA 2010

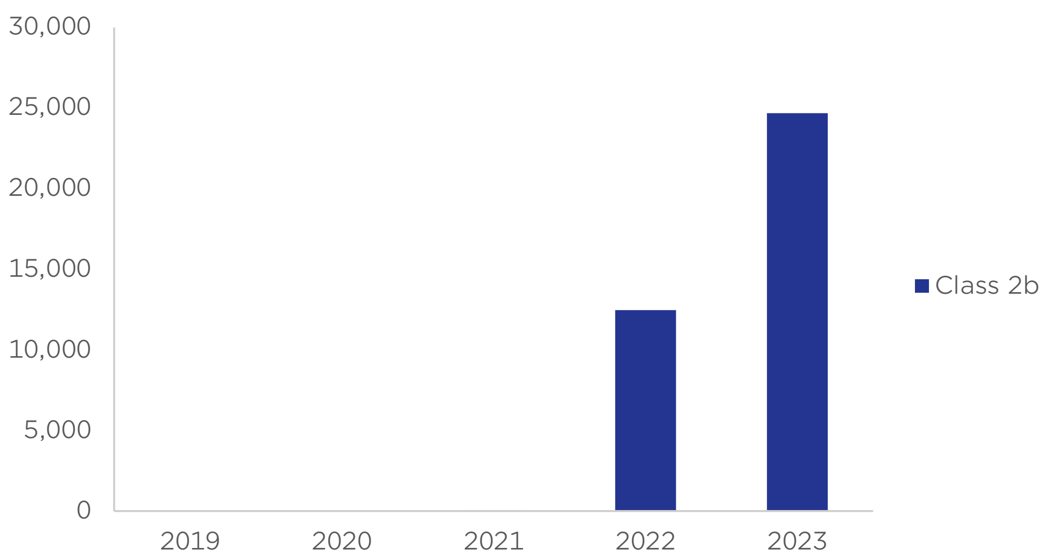
This creates a clear sweet spot for manufacturers to target in developing fast-charging, zero-emission tractor models with range capabilities based on the distance a truck driver can travel before a mandatory rest break and the ability to recharge the vehicle during the break. Models currently being piloted, such as Tesla's Semi, already possess the technical capabilities to create this optimal situation. As new battery-electric tractor models and fast-charging technologies become available and the distribution of charging sites expands, the perceived range issues will apply to fewer and fewer fleets.

Zero-Emission Truck and Bus Deployments Are Growing

Electric trucks and buses are beginning to hit the roads across the nation. From small businesses to large corporations and government agencies, fleets are deploying zero-emission trucks and buses at increasing rates each year. Just a few years ago, zero-emission MHDVs were largely concept models deployed in niche demonstration situations, but today their scope has meaningfully expanded. From regional-haul tractor trucks to delivery vans, over 70 models of zero-emission trucks and buses are in current operation across the United States. The number of available zero-emission MHDV models has grown meaningfully in recent years and this trend is anticipated to continue.

Zero-emission trucks and buses are now in use in every state across the nation. Fewer than 1,000 MHDVs were registered in 2019 compared to over 27,500 registered in 2023, representing around 2.5 percent of truck and bus registrations nationwide (S&P Global Mobility 2024). Of the deployments thus far, over 99 percent are of battery-electric models. The growth in zero-emission MHDV deployments was led in large part by smaller vehicles like delivery vans (See Figure 12), but larger vehicles like tractor trucks, transit and charter buses, and school buses have been consistently and significantly growing over the past several years (See Figure 13). For instance, deployments of zero-emission tractor trucks more than doubled each year between 2021 and 2023.

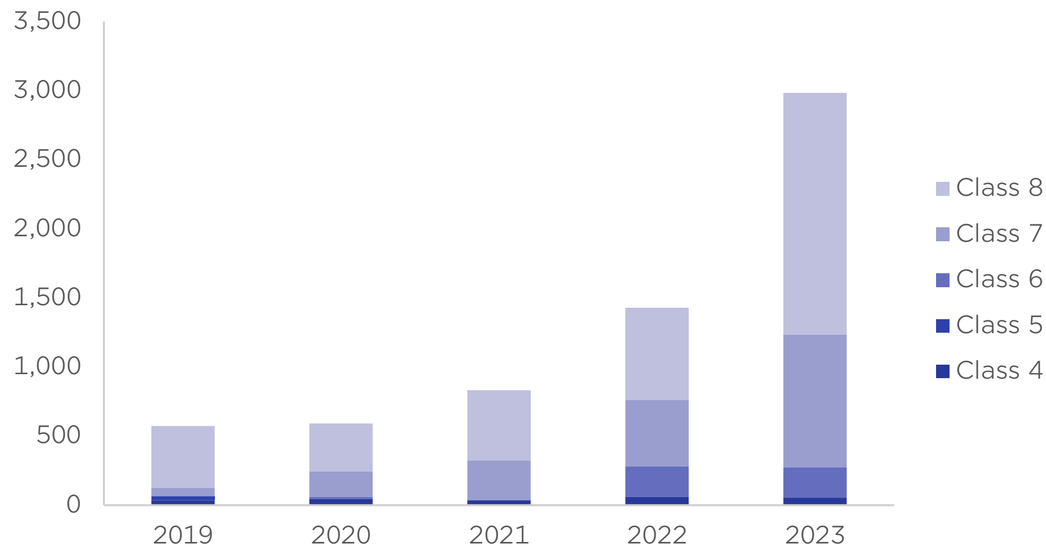
Figure 12. US Registrations of New Zero-Emission Medium-Duty Vehicles



Registrations of Class 2b medium-duty zero-emission vehicles have grown significantly in recent years. In 2023, battery-electric models made up over seven percent of new registrations among all Class 2b cargo and delivery vans. This early growth has bene mostly driven by large fleets (>500 vehicles), however many small businesses have also deployed electric vans.

Source: S&P Global Mobility 2024.

Figure 13. US Registrations of New Zero-Emission Heavy-Duty Vehicles



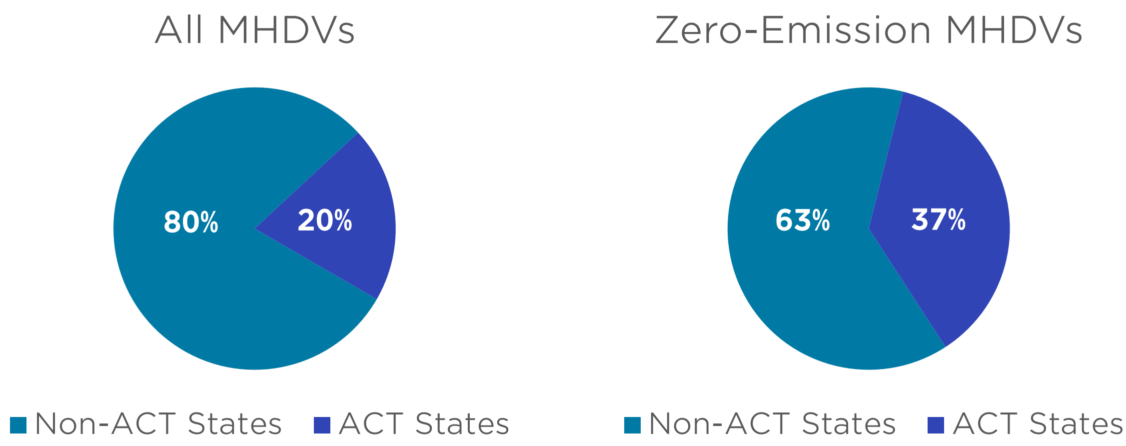
New registrations of zero-emission heavy-duty vehicles (Class 4 and above) have grown consistently and significantly over the past several years. This growth was led by deployments of Class 7 and 8 tractor trucks, school buses, and transit and charter buses. Electrifying this sector is key to reducing pollution from MHDVs, given that larger trucks are responsible for the greatest share of pollution from MHDVs.

Source: S&P Global Mobility 2024.

Nationwide, the increase in zero-emission truck and bus adoption has been substantial, but states are adopting these zero-emission vehicles at different rates. In four states—Washington, Florida, Georgia, and California—zero-emission vehicles composed over 5 percent of all truck and bus registrations in 2023, with Washington reaching nearly 10 percent. And in Washington, Georgia, and Florida, battery-electric models made up over 20 percent of cargo van deployments in 2023 (S&P Global Mobility 2024).

As of 2024, 11 states have adopted California's Advanced Clean Trucks regulation (ACT), which requires manufacturers to sell an increasing share of zero-emission truck and bus models. Although several of the states currently leading the nation in zero-emission MHDV registrations have not adopted this rule, ACT states have tended to register these vehicles at higher rates. According to S&P Global Mobility (2024), ACT states accounted for around 20 percent of total MHDVs registered between 2019 and 2023 but nearly 37 percent of zero-emission MHDVs registered during this time (See Figure 14). Notably, compliance had not yet begun in 2023, the regulation coming into effect in various states between 2024 and 2027. It is likely that proactive state policies are driving the deployment of zero-emission trucks and buses, even before the start of compliance under ACT.

Figure 14. Registrations of New Zero-Emission Trucks and Buses in ACT and Non-ACT States, 2019–2023



States that have adopted California's Advanced Clean Trucks regulation, which requires manufacturers to offer and sell increasing numbers of zero-emission MHDV models, are deploying electric trucks and buses at greater rates than other states even before compliance under the regulation has begun. Although states that have adopted ACT represent only 20 percent of the national MHDV market, nearly 40 percent of zero-emission MHDV were registered in these states.

Source: S&P Global Mobility 2024.

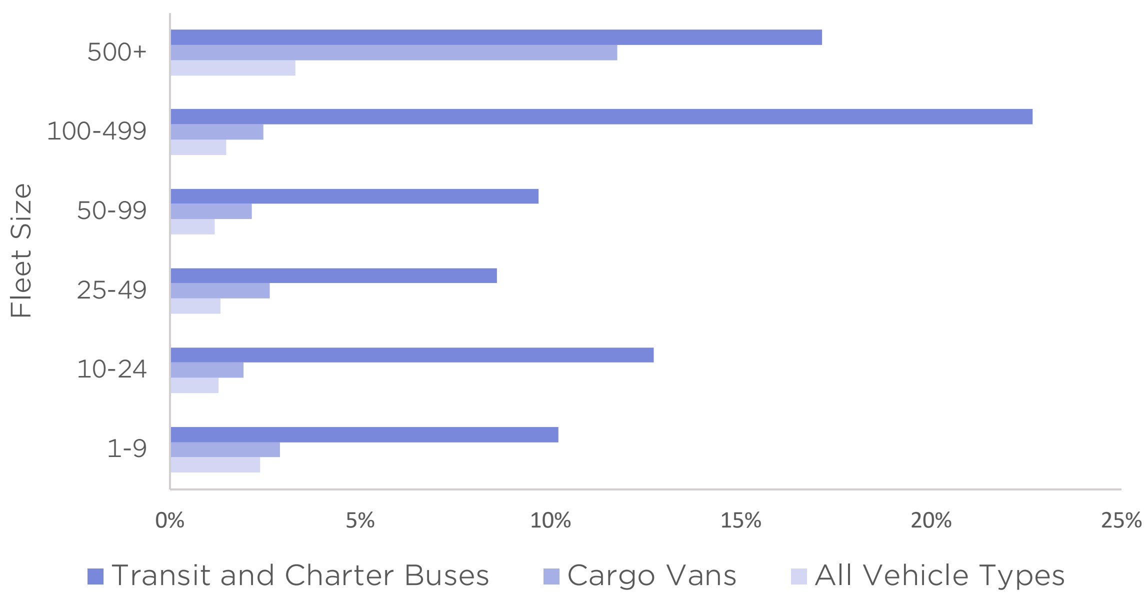
Smaller Vehicles and Buses Are Driving Initial Zero-Emission Truck Deployments

As mentioned previously, cargo vans and buses are driving much of this early growth. These vehicle types have proven to be ripe for early electrification given their predictable duty cycles and the opportunity for operational cost savings (Wilson 2024). Additionally, the recently increased availability and near up-front price parity among some models of cargo vans are likely to have influenced the fast uptick in zero-emission registrations.

In 2023, zero-emission transit and charter buses accounted for over 15 percent of registrations among all fuel types—up from just under 5 percent in 2019 (S&P Global Mobility 2024). Today, zero-emission buses are on the road in nearly every state. Between 2019 and 2023, five states showed zero-emission buses at or greater than 20 percent market penetration. In California, which has the largest transit and charter bus market in the country, nearly one in four buses deployed during this timeframe were zero-emission vehicles. This growth has been primarily driven by transit agencies, although large companies that operate or contract employee commuter bus programs have also begun to deploy zero-emission buses. Despite the attention on fuel-cell tractor trucks, buses represent the largest deployment of fuel-cell electric vehicle technology among all vehicle types to date, with hydrogen powering 5 percent of the zero-emission buses registered between 2019 and 2023 (S&P Global Mobility 2024).

Electric cargo van models grew from a meager share of new registrations in 2019 to over 7 percent of registrations for this vehicle type nationwide in 2023. This growth is being propelled by large businesses; however, businesses of all sizes have adopted these models. While the largest fleets, those with over 500 vehicles, showed the highest rate of adoption of battery-electric cargo vans at around 12 percent, fleets with fewer than 10 vehicles showed the second-highest rate of adoption at around 3 percent (Figure 15). The situation was similar among all vehicle types and classes, with the largest fleets leading zero-emission vehicle adoption at 3.3 percent in 2023, followed by the smallest fleets at 2.4 percent (S&P Global Mobility 2024).

Figure 15. Share of Zero-Emission MHDVs among 2023 New Vehicle Registrations by Fleet Size



Larger companies and transit fleets are leading the adoption of zero-emission trucks and buses during the early years of electrification. This trend is expected, given that many zero-emission models have higher up-front costs today and larger businesses tend to have more access to capital. Although some smaller businesses are deploying zero-emission models, policies that accelerate the market for zero-emission MHDVs, programs that expand access to capital for small businesses, and incentives that lower up-front purchase barriers will help to accelerate the transition to clean transportation.

Source: S&P Global Mobility 2024.

Electrifying Tractor Trucks Is Critical to Reducing Pollution

Electrification of tractor trucks is vital for reducing pollution from the on-road freight sector. Although these vehicles are a small percentage of MHDVs and an even smaller percentage of the vehicles on the road, they are responsible for a massive amount of pollution. For example, **tractor trucks are just 1 percent of vehicles on the road in California, but they are responsible for around one-third NO_x emissions, one-quarter of $PM_{2.5}$ emissions, and just**

under 15 percent of climate-warming emissions from the state's on-road vehicles (Wilson 2022a). These figures highlight the importance of proactive public policy to help drive the availability and adoption of zero-emission tractor trucks.

Nationally, around 0.5 percent of tractor trucks registered in 2023 were zero-emission vehicles. In California, however, the state with the second highest on-road freight movement measured by ton-miles, over 3 percent of tractor trucks registered were zero-emission vehicles, up nearly sixfold from 2021 (BTS n.d.-a; S&P Global Mobility 2024). Certain industrial sectors, too, are deploying zero-emission tractor trucks more quickly than others. Finished-product manufacturers, which include companies that make retail products, deployed zero-emission Class 8 tractor trucks at the highest rate—5.6 percent of all Class 8 tractor truck registrations for this industry type (S&P Global Mobility 2024).

Weighs and Cubes: Battery-Electric Truck Capacity in Reality

Despite the increases in vehicle weight associated with today's electric trucks, reduced payload is not a significant barrier to wide-scale zero-emission tractor truck adoption. Some fleet owners have raised concerns about reduced payload capabilities because electric trucks tend to weigh more than analogous combustion models, consuming a larger share of the available payload weight allowed under federal vehicle weight limitations (80,000 pounds, or 82,000 for certain alternative fuel modes). However, research and data suggest that current potential payload losses are small and will likely decline in the future for two reasons: the common loads transported by tractor trucks and the anticipated advancements in battery and vehicle designs leading to reduced weight. Given this, the potential economic impacts of lost payload may be negligible in the near future (Hunter et al. 2021).

The battery-electric tractor truck models available today are capable of handling many of the payloads typically carried by these trucks, even with the estimated payload capacity losses of between 5 percent and 20 percent (Phadke et al. 2021; Basma et al. 2023). Studies of local-, regional-, and long-haul tractor truck transits show that payloads are typically space limited rather than weight limited (FHA 2015; Transportation Research Board and National Research Council 2010). This issue is commonly referred to as "cube-out" versus "weigh-out." A 2018 survey of Class 7 and Class 8 tractor truck operators found that over 50 percent of the loads carried were less than 39,500 pounds, and 2015 Department of Transportation data suggest that nearly 70 percent of loaded five-axle tractor truck miles occur at 10,000 pounds or more below the federal weight limit (NACFE 2018; FHA 2015).

More recent data from US Census Bureau et al. (2023) suggest that a small percentage of annual tractor truck VMT occurs near the federal weight limit. For nearly three-quarters of the national fleet of all Class 7 and 8 tractor types, only 3 percent of tractors were operated at the federal weight limit for over 90 percent of their annual mileage.

Advancements in battery technologies and vehicle designs are anticipated to increase the payload capacity of BETs, further increasing the share of electrifiable tractor trips and VMT. By 2035, these improvements are expected to narrow the payload capacity gap between diesel and electric tractor models to around 2 percent (Basma et al. 2023). The market is likely to push battery weight reductions through design and efficiency improvements, but regulations, programs, and incentives could also help to accelerate this development by promoting technologies or rewarding manufacturers leading in battery energy density and efficiencies.

Infrastructure to Support Clean Trucks

As the market for and deployment of zero-emission trucks continues to grow, expanded access to fueling and charging infrastructure must grow proportionately. Here, we discuss the varying fueling needs of different types of zero-emission MHDVs and fleets, the energy demand needed to support this electrification, the growth of public and private investments in infrastructure, and the continued planning necessary to make clean freight a reality.

Access to Zero-Emission Fueling for Trucks Is Expanding Nationwide

The number of zero-emission truck and bus fueling and charging stations has grown at a rapid pace over the past few years, with many depot and public fast-charging stations now in operation and under construction. In the last two years, public agencies, utilities, and businesses have invested over $25 billion in developing direct current (DC) fast-charging stations specifically for MHDVs. According to research by Atlas Public Policy (n.d.), over 1,600 DC fast-charging charging positions at over 50 sites across the country are operational, under construction, or planned. The recent influx of federal investments is poised to supercharge this development, with the Inflation Reduction Act (IRA) providing an incentive of up to $100,000 for each commercial charging port (IRS 2024).

California fleets and charging service providers have taken significant early steps in developing both public and depot charging sites, with nearly 11,000 MHDV chargers of various speeds in operation or under development (CEC n.d.). California agencies such as the California Energy Commission (CEC) have invested millions of dollars in accelerating the development of MHDV charging locations using both state and federal funds. In early 2025, the CEC was awarded an additional $56 million through the federal Charging and Fueling Infrastructure Discretionary Grant Program (CFI Program) to deploy over 130 high-power charging ports along the state's most trafficked drayage corridors.

Where Will MHDVs Charge?

Fleets will choose charging speeds, locations, and schedules based on duty cycles, dwell times, and vehicle types. Both today and in the future, most electric MHDVs are likely to charge at their depot. Given that over 90 percent of MHDVs travel fewer than 200 miles daily, over 75 percent of trucks are parked for more than 6 hours each day, and that the majority of both straight and tractor trucks return to their home base at the end of the day, overnight and off-duty charging at depots is likely to be commonplace (See Table 2) (Houston 2023a; US Census Bureau et al. 2023; Lund, Mihelic, and Roeth 2019; NACFE 2018).

Off-duty depot charging will likely be carried out for vehicles with duty cycles that allow it, given the fuel cost and flexibility advantages over public charging. Last-mile delivery fleets, such as the vans and box trucks that deliver packages to their final destinations, and vocational vehicles, such as those operated by service and utility providers, are prime examples. These low-daily-mileage vehicles can reasonably and reliably be supported by lower-level charging technologies like the 240-volt Level 2 chargers commonly found today in garages and depots. Fleets charging at depots off duty may choose this option over faster-charging options, as Level 2 chargers are sufficient to support their needs and avoid the more significant costs of fast-charging technology.

More, many early adopters of electric trucks are finding that every vehicle does not need its own dedicated charger; rather, vehicles can reliably share chargers, further lowering the infrastructure cost of electrification. In some cases, the ratio of vehicle to charger has been as high as five to one (Mihelic and Roeth 2024). Particularly for delivery vehicles that operate shorter daily routes, charging may be required only every several days. The US Postal Service, for example, reported that some of their fleet's new electric delivery vehicles are recharging every three days (*Postal Service Oversight* 2024).

Many regional-haul and drayage tractor trucks may also rely mostly on depot charging, given that around two-thirds of all tractor trucks on the road today travel fewer than 200 miles and are parked for over seven hours daily (US Census Bureau et al. 2023; NACFE 2018). These depots could require significantly higher power levels for charging than those supporting smaller vehicles because of the larger battery sizes and higher daily energy consumption of tractor trucks.

On-route charging options will be necessary to support certain truck types with high daily mileage. These sites may more closely resemble today's truck stops and will most likely employ fast-charging technologies. On-route charging will probably come in two varieties—publicly available "gas station models" and reserved "charging-as-a-service" stations (Barendregt 2024). Much of the private investments in MHDV infrastructure development are going toward the latter model, whereas the public investments have seemed to support the former. Because fleets tend to operate on fixed, planned routes, it is probable that some fleets will choose charging-as-a-service in the early years rather than rely on the gas station model, where space may not be available when needed.

What about Long-Haul Trucks?

Although most tractor trucks return to their home base each night, many of those with a higher daily mileage will require a combination of charging options, including depot, on-route, and destination charging. Particularly for on-route and destination charging, high-powered fast chargers will often be required to support electric trucks with large-capacity batteries. Today, two fast-charging standards for large electric vehicles are beginning to be deployed: Tesla's proprietary Megacharger and the Megawatt Charging System created by CharIn, a nonprofit association of relevant manufacturers and stakeholders. Both systems aim to accelerate the adoption of electric trucks and buses by charging at rates on the order of one megawatt, significantly reducing charging time (CharIN n.d.).

Promising results have been reported from fleets piloting fast-charging technologies for trucks. PepsiCo, for example, has been operating on daily routes exceeding 800 miles using Tesla's Class 8 Semi loaded to the legal weight capacity (NACFE n.d.-b). In these trials, the electric trucks were supported by 750 kW chargers able to provide a 70 percent state of charge in around 45 minutes (NACFE n.d.-c).

While these pilots show tremendous potential for fast-charging technologies to catalyze battery-electric tractor truck deployments, several hurdles must be cleared before achieving large-scale adoption of these high-mileage trucks. Perhaps the most prominent challenge is the lack of a widespread network of high-power fast-charging stations and the grid upgrades necessary to support it. Today, just a handful of on-route truck charging stations are in operation, with most located around ports in California. The number of these stations is expected to grow significantly over the near term mostly because of the public and private investments mentioned previously. Further, the trucks' predictable routes and geographic patterns allow for a concerted effort in planning the prioritized and phased-in charging locations and tools currently being developed to assist fleets, utilities, and regulators in accelerating deployment of charging infrastructure (Xie and Minjares 2023).

From Pipelines to Power Lines: Powering MHDV Electrification

Transitioning our on-road freight system from one powered by liquid combustible fuels to one powered by electricity will affect significant reductions in harmful air pollution and net energy consumption (Clemmer et al. 2023). It will also affect an increased demand on the electricity grid. This in turn will require grid upgrades and additional electricity production. But this transition is not like flipping a switch—demand will increase gradually over decades, allowing regulators, grid operators, and utilities to plan well in advance for upgrades and increased electricity production. These planning activities have already begun in earnest across the country, and in 2024, the Biden administration released a national comprehensive road map for freight electrification.

By 2030, over 1 million zero-emission MHDVs are expected to be in operation nationally. These vehicles are anticipated to increase national electricity consumption by around 140,000 MWh daily, which equates to approximately 1 percent of the national energy demand in 2021 (Ragon et al. 2023). Increases in energy demand from MHDV charging are anticipated to be concentrated in and around freight hubs and along corridors. In these areas, increased demand is likely to be significantly higher than 1 percent, which suggests that regulators, grid operators, and utilities should focus their planning efforts on developing these early hubs. Additionally, this boost in electricity consumption further highlights the need for onboarding additional renewable energy generation to support the transition toward clean on-road freight.

Building Out a Nationwide Truck-Charging Network

Over the past several years, planning efforts for building out the national fueling network for battery-electric and hydrogen fuel-cell trucks have amplified. In March 2024, the White House released its National Zero-Emission Freight Corridor Strategy (National Strategy), a multiagency effort working to map out the national electric truck charging system to support an accelerated transition to zero-emission freight (Houston 2023b). This plan suggests a long-term, phased approach through 2040 to develop the nationwide and public clean freight charging and fueling network arising concurrently with the uptake of clean trucks. In addition to public agency planning, several strategic agreements have been announced from groups of vehicle manufacturers, utilities, and investors devising the development of clean freight corridors and readying the grid to support this development (Edison Electric Institute 2024; Daimler Truck 2022).

The first phase of building the national network, happening now, is focused on areas with the highest density of freight operations, such as principal seaports and intermodal port facilities. These initial efforts will largely support local and regional zero-emission trucks conducting out-and-back daily runs and returning to their home bases each night. California is leading these earlier efforts, with nearly 2,000 publicly accessible MHDV charging and hydrogen fueling positions currently in development or operation (CEC n.d.). These stations are largely clustered around the state's freight hubs of Los Angeles, Long Beach, and Oakland; however, stations that provide on-route fast charging are also under development.

These efforts have been spurred by significant state and federal investments that align well with the National Strategy. Two examples of these targeted grant programs are the Clean Ports Program (CPP) and the CFI Program, funded by the IRA and the Bipartisan Infrastructure Law (BIL). The CFI Program provides $2.5 billion to support the development of publicly accessible charging and alternative fueling sites for both LDVs and MHDVs in a wide range of locations. The CPP grants, which amount to $3 billion, will fund projects that support the electrification of port operations, including building out charging and fueling infrastructure for zero-emission drayage trucks and renewable energy generation to support these stations. Targeted public funding is critical for accelerating the establishment of these initial clean freight hubs across the country. Some states, like California, have also made substantial investments in deploying charging infrastructure for electric trucks (CEC 2024).

After the initial clean freight hubs are established, the National Strategy calls for the implementation of future phases. Occurring between 2027 and 2040, these phases will electrify corridors that provide interstate connections among the primary hubs, allowing long-haul zero-emission trucks to operate cross-country.

Recent Policy Progress Poised to Accelerate Clean On-Road Freight

In recent years, state policies and programs have led the push toward zero-emission trucks and buses, whereas federal regulations have provided some progress in reducing pollution from combustion MHDVs. In addition, federal laws such as the IRA and BIL have provided record investments to deploy zero-emission trucks and related charging and fueling infrastructure.

Both state and federal actions have helped to accelerate vehicle markets and technologies, increasing both the supply of and demand for zero-emission MHDVs as well as furthering the development of fueling infrastructure. During this initial phase of the transition to zero-emission freight, the continuation and expansion of these regulations and programs is paramount to a successful accelerated shift away from harmful truck pollution as private investments in zero-emission MHDV manufacturing and infrastructure grow.

State Truck Rules Push Supply and Demand for Cleaner and Zero-Emission Trucks

California standards have proven to be the most consequential state actions to on-road freight electrification. ACT, adopted in 2020, requires manufacturers to sell a gradually increasing percentage of electric MHDVs over the next decade. To date, 11 states (including California) have adopted ACT, representing over 20 percent of the national market for MHDVs. Although manufacturers currently offer zero-emission MHDVs for most vehicle types, ACT will help to accelerate the availability of clean trucks in new states that adopt the regulation, leading to increased uptake and environmental benefits. For example, 2022 research contracted by UCS and the Natural Resources Defense Council found that ACT adoption in Illinois would result in nearly 30,000 additional zero-emission MHDVs on the road by the end of the decade (Robo et al. 2022).

California adopted the Advanced Clean Fleets regulation (ACF) in 2023 to serve as the demand-side counterpart to ACT by requiring large businesses, public agencies, and drayage fleets to electrify their fleets over the next two decades. The rule also required all new MHDVs sold in the state to be zero-emission vehicles after 2036. Because portions of the rule may have required approval from EPA, California requested a waiver of preemption under the federal Clean Air Act. However, California chose to withdraw their waiver request ahead of President Trump's 2025 inauguration due to his administration's previous actions on California waivers.

As originally adopted, ACF would have accelerated the adoption of zero-emission trucks and buses by around 80 percent though 2050 in the state, delivering massive reductions in tailpipe pollution and leading to reductions in statewide truck emissions of NO_x and climate-warming emissions by around two-thirds and $PM_{2.5}$ by around one-third (Wilson 2023d). The rule was anticipated to result in immense savings to fleets—estimated at $48 billion through 2050, even when considering costs related to higher up-front vehicle purchase prices, installation of charging infrastructure, and retraining of drivers and mechanics (CARB 2023).

While the fate of ACF remains uncertain, California has many options to accelerate the adoption of zero-emission MHDVs that do not require federal approval. Such options could include policies and programs that bolster charging infrastructure planning, investments, and deployment, develop programs to assist small businesses with clean vehicle financing, strengthen existing zero-emission truck purchase incentives, create low- and zero-emission zones around freight pollution hotspots, and require preferable queuing for zero-emission drayage trucks at ports. We discuss several of these options in the following chapter.

Around the time of ACF's adoption in 2023, California and nearly all major MHDV manufacturers entered into an agreement known as the Clean Trucks Partnership, in which, among other things, manufacturers committed to selling only zero-emission models after 2036 regardless of waivers or the state's authority to implement certain regulations (CARB and EMA 2023). This agreement will help preserve some of the market signals ACF set for the clean truck market and deliver meaningful air quality benefits while helping to drive down up-front costs for zero-emission truck models.

California has also adopted regulations to reduce emissions from new combustion-powered trucks. First adopted by the state in 2020, the Heavy-Duty Omnibus (HDO) rule requires truck manufacturers to reduce emissions of both NO_x and $PM_{2.5}$ from certain trucks of model years 2024 and beyond. To date, nine other states have adopted the HDO rule. This regulation, like many others, is based on a crediting system, providing manufacturers with flexible compliance options while still reducing emissions overall from new trucks. In 2023, California altered the rule, mostly aligning it with the recently passed federal standards for NO_x and $PM_{2.5}$ for manufacturers to comply after model year 2027.

Federal Truck Emissions Regulations Make Modest Gains

Over the past several years, EPA updated two key truck tailpipe pollution regulations—one aimed at reducing NO_x and $PM_{2.5}$ from trucks, colloquially called the "2027 Rule," and the Phase 3 standards, which focuses on reducing climate-warming emissions from trucks. While both rules will create meaningful reductions in pollution from trucks, they fell far short of what was technologically possible through electrification and are significantly less stringent than existing state rules (Cooke 2022).

The 2027 Rule was EPA's first update to the smog- and soot-forming truck pollution standards in two decades. Beginning in model year 2027, this rule creates a standard around 80 percent stronger than its predecessor and is estimated to result in thousands of fewer premature deaths, sicknesses, and lost workdays as well as millions of lost school days for children through 2045 (EPA 2022a).

In 2023, EPA adopted the Phase 3 Greenhouse Gas standards, which aims to reduce climate-warming emissions from trucks. Compared to the previous standards, the regulation will reduce climate pollution by up to 62 percent for vocational trucks and up to 40 percent for tractor-trailer trucks in 2032, resulting in $13 billion in annualized net benefits through 2055 (EPA 2024c). While Phase 3 was not predicated on the deployment of zero-emission vehicles, EPA did acknowledge that the market for zero-emission truck technology has become available more quickly than the agency previously projected, supporting the feasibility of accelerated and more cost-competitive on-road freight electrification (EPA 2024d).

Vehicle Incentives and Rebates Continue to Play an Important Role

Today, both state and federal purchase incentives and rebates are available for zero-emission trucks and buses. Studies have shown that these programs can help to kickstart the adoption of clean MHDVs and reduce emissions on a meaningful scale (Linn and Look 2022).

An increasing number of states offer purchase incentives for clean trucks and buses that help bridge up-front costs between zero-emission and combustion models. The Clean Truck and Bus Voucher Incentive Project (HVIP), a California program, is designed to cover the incremental purchase price difference between the vehicle models. To date, HVIP has assisted in the purchase of thousands of zero-emission trucks, with most located in marginalized communities (California HVIP n.d.). Other states, including New York and Washington, currently or will soon offer similar incentives and rebates.

Federal incentives for electric LDV purchases have existed for well over a decade, but the IRA extended these purchase incentives to electric trucks and buses for the first time. Truck and bus fleets operated by businesses, governments, and nonprofit organizations are eligible for purchase incentives of up to $40,000, depending on vehicle size, as well as up to $100,000 per vehicle charger, depending on location (Inflation Reduction Act of 2022). Though the impact of these incentives on electric MHDV adoption may take several years to realize, investments in electric vehicle manufacturing have accelerated significantly since the IRA's passage.

Record Federal Investments in MHDV Electrification

In addition to the consumer incentives for vehicle and infrastructure purchases, the IRA and BIL allocated billions of dollars in direct investments for MHDV electrification in the form of grants and loans to US manufacturers, ports, and other entities facilitating and supporting freight movement.

One of the IRA's most consequential programs for freight electrifications is the CPP, which provides around $3 billion for the electrification of port operations (including trucks, trains, vessels, and cargo equipment), air quality monitoring and planning, and engagement with port-adjacent communities. In October 2024, EPA selected 55 applications from 27 states and territories to be awarded under the program. The Port of Oakland, one of the nation's largest seaports, received over $350 million and is an exemplar of the diverse projects the program funds. In partnership with community organizations and businesses, the Port of Oakland plans to deploy 475 zero-emission drayage trucks, electrify nearly 200 pieces of cargo-handling equipment, build out solar-powered charging facilities on-site, accelerate construction of off-site drayage truck charging, and develop a new local air quality monitoring system to assess the effectiveness of the program. The air quality monitoring system will also provide regulators and communities with crucial data for better addressing the impacts and burdens of port-related pollution.

Another IRA program anticipated to accelerate MHDV electrification is the Domestic Manufacturing Conversion Grant Program. This program offered over $1.5 billion in federal funding and over $50 million in matching state funding to help manufacturers convert 10 at-risk or shuttered vehicle and component manufacturing and assembly lines from producing fossil-fueled vehicles to zero-emission vehicles. The program will support the construction of both cars and trucks, but notable MHDV projects selected include nearly $80 million to Blue

Bird Corporation for electric school bus construction in Georgia, around $210 million to Volvo North America to produce zero-emission heavy-duty trucks in Pennsylvania, Maryland, and Virginia, and $75 million to Cummins to support zero-emission powertrain production in Indiana (DOE 2023b).

The BIL also provided billions in funding for both new and existing programs geared toward cleaning the freight sector. One notable program funded is the Port Infrastructure Development Program, which provided nearly $580 million for projects that reduce emissions, improve efficiency, and enhance resiliency to climate change, among other things (DOT 2024). The BIL also provided $5 billion to help reduce pollution from school buses across the country, accelerating the deployment of cleaner and quieter battery-electric school buses (EPA 2024b).

Private Sector Investments in MHDV Electrification Are Accelerating

The recent direct investments in transportation electrification from federal policies could be game-changing for accelerating clean freight; better, they have also spurred significant actions from the private sector. Investments in electric vehicle manufacturing have grown in the wake of the passage of the IRA and BIL. Research by the Environmental Defense Fund shows that over 60 percent of electric vehicle manufacturing investments among the private sector occurred since the passage of these influential laws (EDF 2025). To date, the private sector has invested $6.5 billion specifically for zero-emission MHDV manufacturing in the United States and many billions more in related supply chain, battery, and infrastructure manufacturing projects to support light-, medium-, and heavy-duty zero-emission vehicles (EDF 2025).

Recommended Policies and Programs to Accelerate the Switch to Clean Trucks

Electric trucks and buses are a key part of transitioning our economy into one that is cleaner, more equitable, and more climate friendly. Battery-electric trucks and buses are beginning to hit the market, with early-adopting fleets enjoying the benefits of lower fuel and maintenance costs and drivers enjoying cleaner and quieter operations.

While the recent growth in battery-electric trucks and buses has been impressive, strategic public policy is needed to ensure that the transition accelerates, endures, and avoids unintended negative outcomes for communities and the environment. Additionally, policies that drive innovation and efficiency can help drive down costs for fleets. Both state and federal policies and programs have helped to drive early electrification, and both near- and long-term policies will ensure the success of this transition.

Continued Adoption of Existing State Sales, Fleet, and Fuel Standards

In these early stages of freight electrification, policies that set clear market expectations are necessary to safeguard the successful deployment of infrastructure, influence manufacturers to offer increasing numbers of zero-emission models at a growing scale, and help fleets plan for switching away from fossil-fueled trucks and buses. Regulations like California's ACT are primary examples of such policies in the United States.

As mentioned previously, states representing over 20 percent of the national MHDV market have adopted ACT, and although it is just now coming into effect, early data show that zero-emission trucks and buses are being adopted at higher rates than in non-ACT states (S&P Global Mobility 2024). In the absence of analogous federal regulations, it is important for other states to adopt ACT to strengthen market signals nationally and ensure that clean trucks and buses are readily available in more states. Additionally, regulations like ACT will help to drive down the up-front cost of electric trucks and buses through economies of scale and continued manufacturer investments in clean technologies.

Where ACT provides certainty of supply to fleet owners, fleet electrification policies like ACF would provide certainty of demand to manufacturers by requiring the largest and highest-revenue fleets to gradually transition to zero-emission vehicles. While ACF in its originally adopted form may not be fully implemented, similar policies and programs would help to drive the zero-emission truck and bus market while significantly reducing air and climate pollution. Such policies should focus on reducing pollution from drayage trucks given their contribution to health impacts in communities adjacent to port and freight hubs. States with ongoing air quality issues may see fleet electrification policies and programs as a win-win solution in achieving National Ambient Air Quality Standards while accelerating economic benefits to commercial and public fleets.

Clean fuel standards can also provide significant financial support for the electrification of trucks and buses. The standards allow fleets to generate revenue by earning credits when fueling their zero-emission vehicles and then selling these credits to oil companies (Martin 2020). To date, California, Oregon, Washington, and New Mexico have adopted clean fuel standards, along with British Columbia and the European Union.

Such standards have the potential to generate significant revenue for fleets operating clean trucks and buses, but their technology-neutral design means they also provide substantial support for alternative combustion fuels, including bio-based diesel and renewable natural gas. Clean fuel standards go beyond existing biofuel policies like the federal Renewable Fuel Standard program in recognizing the central role of electric vehicles and renewable electricity in decarbonizing transportation; compliance with these standards is measured by reduced emissions rather than increased biofuel production. Thoughtful policy design of standards regarding biofuel expansion is warranted, including putting protections in place to ensure that benefits and burdens are equitably shared and to avoid harmful "food-versus-fuel" conflicts and land use changes.

Continued Investments, Purchase Incentives, and Innovative Financing

During the early stages of on-road freight electrification, continued public and private investments in manufacturing as well as vehicle incentives will be critical to expand the accelerated adoption of electric trucks and buses. Purchase incentives for zero-emission trucks and buses will spur cost parity in the near term as manufacturers ramp production, which will in turn drive adoption (Linn and Look 2022). For instance, the Commercial Clean Vehicle Credit provided under the IRA may help contribute to the proliferation of electric trucks and buses on our roads and highways in the near future; the continuation of these incentives throughout the early- and mid-stages of truck and bus electrification will help maintain this momentum.

Targeted federal investments, such as those provided by EPA's CPP, will also help drive electrification among the freight sector. Where the CPP's investments were largely targeted toward water ports, additional funding focused on inland or "dry" ports and warehouses could advance regional- and long-haul truck electrification and reduce emissions in these key freight areas. Continued growth in warehouse loading docks and parking spaces provides additional opportunities for truck charging while containers are loaded and unloaded. Furthermore, although the rise in warehouse clustering presents an environmental challenge, it is also an opportunity work toward grid readiness as fleets transition to zero-emission trucks (Kerr et al. 2024).

State and local programs providing low- or no-interest financing to small, independent, or self-employed business owners could help those without access to the massive capital assets that large businesses may have. Given that independent truck owners and operators tend to drive older and higher-polluting trucks, low- and no-interest clean truck financing programs could get the dirtiest trucks off the road and make BETs and the operational savings they deliver more accessible.

For the transition to electric trucks to be successful, measures are needed to create and maintain high-quality jobs for workers building the batteries, components, vehicles, and infrastructure that will power our future. For example, federal investments should prioritize loan and grant applicants that follow high-road labor and community engagement standards. The right to unionize and bargain needs also to be protected, and employers who interfere with unionization efforts or violate labor laws must be held accountable.

Focus on Increasing Equitable Access to Healthy Air

Although incentives and investments targeting warehouses will help to push electrification in these pollution hot spots, policies that require the electrification of warehouse, railyard, and port operations will provide greater certainty of pollution reductions and allow for strategic planning on a wider scale. Policies like these, referred to as indirect source rules, require facility operators to flexibly and gradually reduce emissions based on a point or credit system. Such regulations are beginning to arise, with Southern California leading in the adoption of the nation's first indirect source rule in 2021. This regulation, Rule 2305, is expected to result in up to $2.7 billion in health benefits from reduced pollution exposure throughout its first decade (SCAQMD 2021a). The adoption of similar policies in other freight hubs, both inland and coastal, would expand these significant benefits to more communities.

While pollution mitigation is perhaps the most obvious critical step in creating more equitable access to clean air, these efforts could be strengthened through expanded and enhanced local air quality monitoring. Today, air quality standard attainment is determined through ambient air quality monitoring; however, some critical data are missed in this approach. For instance, communities located adjacent to a port, highway, or other freight operations can and often experience unhealthy levels of air pollution despite being located within a larger area achieving the National Ambient Air Quality Standards.

Localized air quality monitoring in these areas can help decisionmakers, researchers, and community members better understand how to create strategies that improve equitable access to clean air. While such programs are rare today, localized monitoring programs are beginning to be implemented, such as that by the West Oakland Environmental Indicators Project with the support of the Bay Area Air Quality Management District. This project, called the West Oakland Air Quality Monitoring Network, deployed over 20 black carbon and $PM_{2.5}$ sensors around the neighborhood of West Oakland, an area historically and disproportionately affected by freight pollution (WOEIP n.d.). Projects like this identify specific pollution sources on a hyperlocal scale instead of the regional monitoring system used today that may obscure block-by-block pollution exposure.

While data from localized air quality monitors are not appropriate for determining attainment of the National Ambient Air Quality Standards, state and local air quality agencies can use this information to inform policies, programs, and projects to reduce pollution. Although not based on hyperlocal data, a statewide policy in Washington requires officials to identify areas disproportionately harmed by pollution. The policy was adopted in the state's 2021 Climate Commitment Act to reduce the effects of pollution on overburdened communities. The Washington State Department of Ecology (2023) is now working to make access to clean air more equitable in the communities most affected.

Accelerating Infrastructure Development

Comprehensive deployment of charging infrastructure is a lynchpin in the transition to clean trucks and buses. Policies and programs that enable strategic infrastructure deployment through enhanced grid planning, charging standardization, community collaboration, and continued investment in the development of stations will accelerate the adoption of zero-emission trucks and buses.

Given that one of the greatest challenges to infrastructure deployment lies in local grid capacity, the coordination of electric utilities, utility regulators, and vehicle fleets is of utmost importance. Researchers are developing data-driven tools to help regulators and utilities better anticipate where and when electric truck charging will be needed. Using geographic data and load profile projections, utilities will identify the substation and other grid upgrades necessary to support fleet charging. In some states, legislation may be needed to shift the state's utilities from making "just-in-time" grid upgrades—which result in larger charging projects being completed too late relative to vehicle delivery—to a process much more proactive and practical.

Other software tools are being developed to help fleet owners plan routes based on load and duty cycle characteristics, charging availability, electricity prices, and other relevant factors. Fleet-side tools like this can also help distribute grid load from charging trucks, concentrating charging in areas where electricity is readily available (Yu and Ye 2024). Today, some ports offer digital queuing and routing platforms to truck drivers and fleet operators for reducing truck traffic and improving turnaround times (Port of Oakland n.d.). Ports should consider incorporating truck charging into these applications, allowing early adopters of electric trucks to plan for appropriate refueling and routing.

Right-Sizing Investments in Hydrogen Transportation Fuel

Considering the availability of cleaner and more cost-effective battery-electric technologies in the on-road transportation sector, hydrogen fuel is likely to play a role in niche heavy-duty applications, such as energy-intensive specialty vehicles and certain long-haul duty cycles, but is optimally reserved for decarbonizing sectors such as transoceanic shipping and aviation. Because over 95 percent of the hydrogen powering fuel-cell electric vehicles is produced from natural gas and coal gasification, policies that transition hydrogen fuel production toward renewable feedstocks is vital for hydrogen to realize its potential as a zero-emission fuel (Wilson 2023c). It is also important for such policies to ensure reduced impacts to communities adjacent to developing hydrogen production facilities.

Moreover, right-sizing the deployment of hydrogen fuel-cell trucks and buses will help to drive demand in the most relevant sectors. As mentioned, BETs are anticipated to be the most technically and economically viable option for fleets as well as the option with the highest energy efficiency and lowest life-cycle air pollution and climate impacts (Islam et al. 2021; Cooke 2024a). As such, policies and programs should prioritize battery-electric vehicles where possible and conduct thorough and well-informed engagement processes with relevant parties, particularly disproportionately affected communities, to right-size fuel-cell electric vehicle deployments when battery-electric vehicles are not feasible. In the short term, such deployments may include cross-country, long-haul transits in areas without developed battery-electric charging infrastructure. Longer term, hydrogen fuel-cell technology may be best suited for vehicles with energy-intensive duty cycles. These may include vehicles like vacuum trucks, on-road construction equipment, and other specialty vehicles.

Increasing Efficiency and Reducing Environmental Impact from Trucks

As the market for and technologies supporting electric trucks and buses mature, policies, incentives, and programs that work to reduce environmental impacts from vehicle production and energy consumption during operation will further the sustainability of our freight and transportation systems. Additionally, continuing to push for increased efficiencies and for reductions in criteria pollutant emissions from new combustion truck models will help to reduce pollution as these vehicles sunset over the next few decades (Cooke 2024b).

Standards for electric LDV battery recycling that could drastically lower the embodied environmental impacts of producing electric vehicles and reduce the demand for critical minerals are currently being considered in various US states (Dunn et al. 2024). In 2022, the European Union passed regulations requiring the recycling of traction batteries (those that power an electric vehicle's drivetrain), providing a road map for the United States and other countries. Because the traction batteries in battery-electric trucks and buses can be several times larger than those in electric LDVs, the potential for recycling to reduce impact is even greater.

Battery-electric vehicle technology is the most energy-efficient vehicle propulsion technology available on the market today in terms of both vehicle cycle and vehicle operation (Wilson 2023c). Still, federal standards could optimize these advantages by requiring increased energy efficiency among zero-emission truck and bus models, which could significantly lower vehicle life-cycle impacts, reduce electricity consumption from the grid, and accelerate operational savings for fleets (Dunn et al. 2024). Federal standards have historically driven efficiency gains for combustion models in the light- and heavy-duty vehicle sectors, but no such standards exist for zero-emission vehicles. Decisionmakers should begin to work with researchers and manufacturers to plan for regulations that promote innovative improvements in the fuel efficiency of zero-emission trucks and buses over time as the deployment of these vehicles accelerates and the market strengthens.

Similarly, federal standards that continue to decrease health-harming and global warming pollution from new combustion truck models should be considered. These models will continue to hit the road over the next decade, and the vehicles deployed in the mid-2030s may be in operation into the 2050s. And although recent federal truck pollution standards help to reduce harmful emissions, the disproportionate pollution impacts from MHDVs warrant stronger federal standards that push truck manufacturers in innovative ways to reduce harmful emissions from their products.

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