ELECTRIFYING TRUCKS: FROM DELIVERY VANS TO BUSES TO 18-WHEELERS

By Steven Nadel and Peter Huether

RESEARCH REPORT
JUNE 2021

ACEEE
American Council for an Energy-Efficient Economy

Contents

About ACEEE

The American Council for an Energy-Efficient Economy (ACEEE), a nonprofit research organization, develops policies to reduce energy waste and combat climate change. Its independent analysis advances investments, programs, and behaviors that use energy more effectively and help build an equitable clean energy future.

About the Authors

Steven Nadel has been ACEEE's executive director since 2001. He has worked in the energy efficiency field for more than 30 years and has over 200 publications. His current research interests include energy and climate change policy; strategies to decarbonize the buildings, transportation, and industrial sectors; utility sector energy efficiency programs and policies; and appliance and equipment efficiency standards. Steve earned a master of science in energy management from the New York Institute of Technology and a master of arts in environmental studies and a bachelor of arts in government from Wesleyan University.

Peter Huether is a senior research analyst with the transportation program at ACEEE. He conducts research and analysis with a focus on light-duty fuel efficiency and electric vehicles. Peter works on promoting equitable access to electric vehicles and leads the annual life-cycle emissions analysis of light-duty vehicles for ACEEE's Greenercars.org. Peter holds a master of science in public policy and management from the Heinz College at Carnegie Mellon University and a bachelor of arts in economics and global environmental change and sustainability from Johns Hopkins University.

Acknowledgments

This paper was made possible through internal ACEEE funds and support from an anonymous foundation. The authors gratefully acknowledge external reviewers and internal reviewers, colleagues, and sponsors who supported this study. In particular, we thank Shruti Vaidyanathan, director of the ACEEE transportation program, and Therese Langer, the former program director, who both provided guidance, materials, and review. This report updates a prior ACEEE white paper co-authored with Eric Junga. The earlier paper had extensive external expert review including Mike Roeth from the North American Council for Freight Efficiency (NACFE); Ben Sharpe from the International Council on Clean Transportation (ICCT); Patricio Portillo from the Natural Resources Defense Council (NRDC); Michael Laughlin, Madhur Boloor, and Rachel Nealer from the U.S. Department of Energy; and a representative of a major truck manufacturer who wishes to remain anonymous. External review and support do not imply affiliation or endorsement. Last, we would like to thank Mary Robert Carter and Mariel Wolfson for managing the editorial process; Keri Schreiner, Phoebe Spanier, and Sean O'Brien for copyediting, proofreading, and assistance with references; Kate Doughty for assistance with the graphics; and Wendy Koch and Ben Somberg for their help in launching this paper into the world.

Suggested Citation

Nadel, S., and P. Huether. 2021. *Electrifying Trucks: From Delivery Vans to Buses to 18-Wheelers*. Washington, DC: American Council for an Energy-Efficient Economy. www.aceee.org/research-report/t2102.

Executive Summary

KEY TAKEAWAYS

- Trucks, ranging from heavy-duty pickup trucks to 18-wheelers, account for 22% of vehicle carbon dioxide emissions. They also emit substantial amounts of other pollutants, contributing to climate change and health problems.
- Growing numbers of electric truck and bus models are reaching the market or are scheduled to be on the market soon, with models ranging from heavy-duty pickup trucks to 18-wheel tractor-trailers.
- Multiple cities have committed to fully electrifying their transit bus fleets over about the next decade. Other growing markets are delivery vans and school buses.
- For transit buses and many vocational vehicles, electric vehicles are often near cost parity with conventional vehicles on a life-cycle cost basis.
- For large tractor-trailers, shorter regional-haul routes will be the best initial opportunity for electrification; long-haul routes will take longer to develop and will require widespread deployment of high-power recharging infrastructure.
- A variety of policies are encouraging the use of electric trucks, including utility and state incentives and zero-emission vehicle sales targets recently adopted in California.
- For electric trucks to thrive, a variety of steps will need to be taken, particularly to reduce purchase costs and expand charging infrastructure. Governments, utilities, truck manufacturers, and truck purchasers/users all have important steps they can take.

Electrification of trucks and buses can bring many benefits, including lower energy use, emissions, and operating costs. Compared to conventional trucks, however, these vehicles currently cost more up front, often have reduced range, and must depend on limited charging infrastructure. To gain the full benefit of vehicle electrification, we will need continual progress on battery weight and cost, vehicle efficiency, charging infrastructure, and cleanup of the electric grid used for charging.

Dozens of electric trucks and buses are now on the market, and many more models are expected to enter it in the next few years. Leading states and cities have begun to transition their bus fleets to electricity, putting buses at the forefront of heavy-duty electrification. Vocational trucks (e.g., delivery vans and trucks) are the most varied of the market segments and will soon reach net cost parity (considering operating, financing, and other costs) with diesel trucks for a number of market segments. They could therefore serve as a bridge to electric truck use in an array of applications. Heavy pickup trucks are also an important segment; although options in this category are not yet being delivered to consumers, electric light-duty pickups are imminent, and electric-vehicle technology will soon reach the market's heavier segment.

Tractor-trailers are by far the largest energy user in the truck sector, and they present an important but challenging target for electrification due to the long range they often require and their charging requirements. Electric models currently on the market have a short range, but models with longer ranges (one manufacturer is claiming up to 500 miles) are scheduled to enter the market in 2021 and 2022. The majority of truck routes are shorter than 500 miles; for longer hauls, fuel-cell tractors will be an alternative to battery-electrics and are scheduled to enter the market in late 2022.

In all of these market segments, electric vehicles (EVs) have substantially higher upfront costs than conventional vehicles, due primarily to the cost of batteries. To help bridge this gap, financial incentives and financing will be useful, if not essential. Zero-emission truck mandates, as California has recently finalized, are likely to play a pivotal role in increasing electric truck adoption.

Another critical issue will be electric charging infrastructure for fleets and truck stops. The fact that charging stations suitable for heavy-duty vehicles are virtually nonexistent today is one of the largest obstacles to heavy-duty EV adoption. We must prioritize utility rate design and promotion of managed charging if we want to make EV operating costs attractive while being fair to all ratepayers.

The current status of different truck markets and suggested next steps are summarized in figure ES-1.

Electric trucks have a promising future, but much near-term work remains to overcome present challenges. Priority should be given to overcoming initial cost barriers, including through financial and other incentives, and to building out charging infrastructure.

	Current status	Next steps
Electric trucks and buses overall	Approximately 2000 electric trucks were on U.S. roads at the end of 2019.	Continue RD&D support; establish federal incentives for vehicle purchases and installation of EV charging infrastructure; expand utility planning and assistance for fleet electrification. States set ZEV requirements for clean vehicle market share, based on the California model.
Heavy-duty pickups	Initial units will soon reach market.	Manufacturers bring electric models to market that will appeal to consumers, aided by items above.
Vocational trucks	Units are available; delivery vans in particular are growing in popularity.	Manufacturers expand model availability and sales aided by items above; local governments give preferential access to delivery zones for
Buses	Hundreds of electric transit and school buses currently in use; some jurisdictions have committed to transitioning entire fleets over a decade.	Set deployment targets for school bus and transit bus fleet turnover and establish schedules to fully electrify.
Tractor-trailers	A few short-range units available, mid-ranges will be available soon.	Truck owners should employ electric trucks on popular regional routes.

Figure ES-1. Summary of electric truck current status and suggested next steps for different truck types

Introduction

To mitigate the most serious impacts of climate change, many actions will be needed to reduce greenhouse gas (GHG) emissions. A recent ACEEE report finds that energy efficiency can be used to cut U.S. GHG emissions in half by 2050. Of these emission reductions, nearly 9% are from electrifying trucks (Nadel and Ungar 2019), which is the focus of this report.

Electric vehicles (EVs) are generating considerable excitement these days, not least because of their potential to help address climate change. Transportation now accounts for more U.S. GHG emissions than any other sector; in 2020, transportation was 35% of U.S. carbon dioxide emissions, and 83% of those emissions were from on-road vehicles (EIA 2021). Though purchase prices are still high, EVs are generally much more energy efficient than internal combustion engine (ICE) vehicles and thus are cheaper to run. And, while much of the current buzz is about electric cars, heavy-duty vehicles—that is, commercial trucks and buses—are attracting a great deal of interest. Indeed, they can be a key application of EV technology, as commercial vehicle owners are very sensitive to fuel costs and EVs help reduce them. Research firm Wood Mackenzie estimates that there were 2,000 electric trucks on U.S. roads at the end of 2019, but predicts that this number will grow to 54,000 by the end of 2025 (Stinson 2021).

Freight trucks and buses are responsible for a substantial part of the carbon dioxide emissions and fuel consumption of all vehicles on the road. While they account for less than 5% of US vehicles in operation, they are driven more miles on average and consume far more fuel per mile than passenger vehicles. As a result, in the United States, freight trucks and buses account for 10% of vehicle miles traveled, 22% of vehicle fuel use, and 28% of vehicle-emitted carbon dioxide (see figure 1) (FHA 2021; EIA 2021).

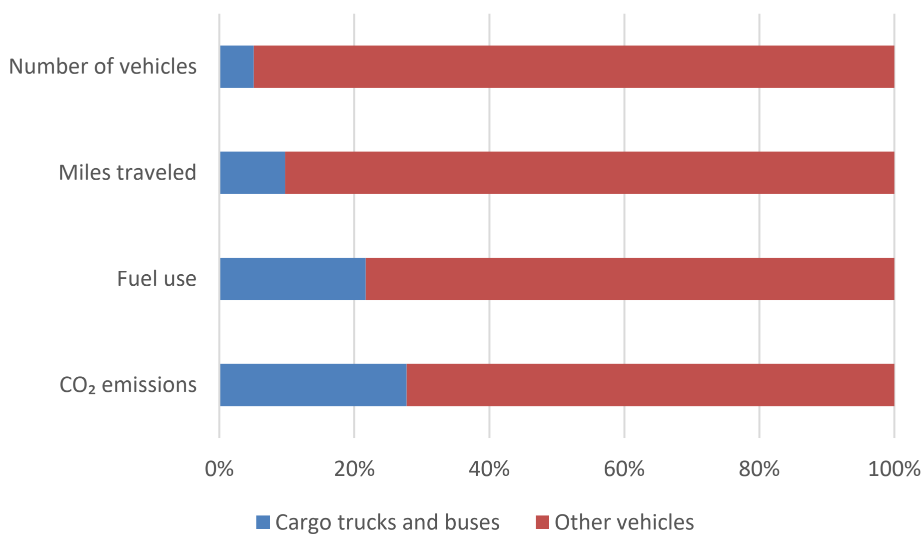


Figure 1. Freight trucks and buses (vehicle Classes 3–8) as a proportion of all vehicles. *Sources:* FHA 2021 and EIA 2021.

Trucks are commonly divided into eight classes based on their gross vehicle weight rating (GVWR), which is the sum of the vehicle's curb weight and payload capacity. Figure 2 illustrates common vehicles by class.

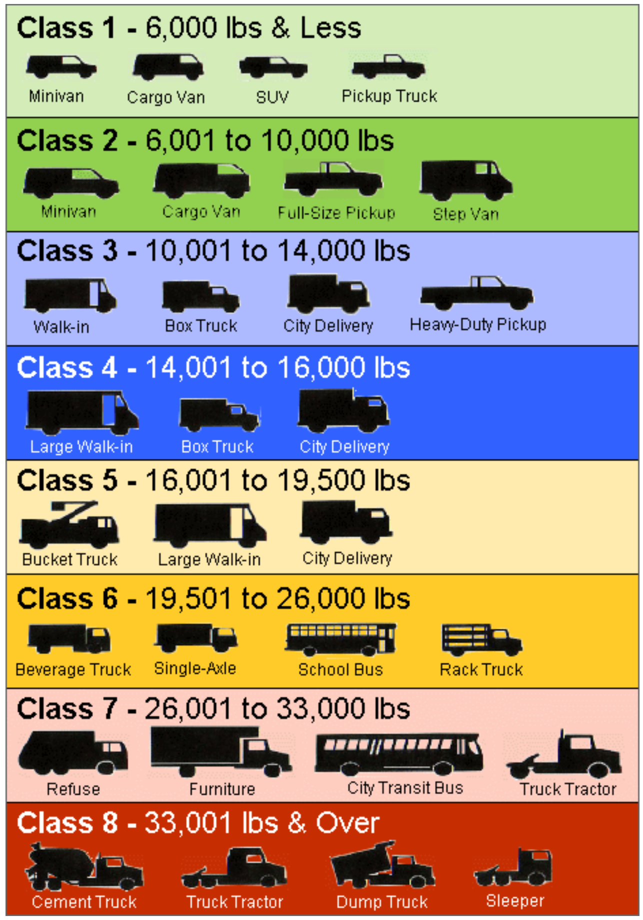


Figure 2. Truck classes. *Source:* DOE 2011.

This report addresses Classes 2b–8, which range from large pickup trucks (over 8,500 pounds) to 18-wheel tractor-trailers. Trucks that are 8,500 pounds or less are largely personal vehicles and are not considered here. Further, the term *electric vehicle* is sometimes used to refer to battery-only EVs but may also include both hybrid-EVs (in which an on-board engine charges the batteries) and fuel-cell vehicles. Here, we discuss only battery-only EVs, except for a text box on fuel-cell tractor-trailers.

Along with its very large potential benefits, electrification presents special challenges for heavy-duty vehicles. Indeed, in some cases, EVs may not be the solution. This report surveys the opportunities and barriers for electrification of trucks and buses, the state of the market, and the policy landscape. We summarize available information on battery-electric heavy-duty vehicles from many disparate sources to provide a foundation for efforts by ACEEE and others to encourage rapid growth in electric trucks where such a transition makes sense. We conclude with a recommended path forward to capture electrification's benefits for these vehicles, assuming they are effectively deployed.

Our report updates a prior ACEEE paper with the same title published in January 2020. Since this time, there have been substantial developments in truck and bus markets and policies, which this report aims to capture.

Why Electrify Trucks?

The benefits of electric trucks include lower energy use and operating costs, lower emissions, higher torque, lower maintenance costs, and quieter operation.

Energy Use and Operating Costs

Gao et al. (2018) examined the energy use of electric and petroleum-fueled vehicles in a variety of heavy-duty applications. In making this comparison, the authors accounted for the energy required to generate and distribute the electricity to charge the EVs (i.e., they included upstream energy use).[1] As table 1 shows, the EV saves energy in all of the applications examined, ranging from a 24% reduction for tractors used to move cargo in ports to a 44% reduction for school buses. The simple average improvement for the applications they examined was a 37% energy use reduction.

Table 1. Comparison of truck fuel economy in several applications

Vehicle	Conventional vehicle fuel economy (mpg)	Battery-electric vehicle		Energy use reduction (%)
		Battery energy (kWh/mile)	Equivalent fuel economy (mpg)	
Class 8: Port drayage	4.4	2.7	5.8	24%
Class 8: Refuse truck	3.2	3.2	4.9	35%
Class 7: Food delivery truck	5.7	1.6	9.5	40%
Class 7: City bus	4.9	2	7.7	36%
Class 6: School bus	7.8	1.1	13.9	44%
Class 5: Linen delivery van	8.9	1	13.4	34%
Class 5: Food delivery truck	7.8	1.1	12.8	39%
Class 4: Parcel delivery van	9.5	0.9	14.3	34%
Class 3: Food delivery truck	11.1	0.8	16.4	40%
Class 3: Bucket truck	9.8	0.8	16.4	40%

Fuel economy figures are from 2018 and do not reflect recent improvements; we provide this information to illustrate the magnitude of the potential savings. We have added percentage reduction to the original. *Source:* Gao et al. 2018.

For vehicles driven tens of thousands of miles per year, the reduction in operating costs can pay off an electric truck's higher initial purchase cost in just a few years. Table 2 compares

[1] Gao et al. state: "The BEV diesel-equivalent fuel economy is calculated based on the assumption that diesel is used as fuel in a power plant with 45% efficiency, and the produced electricity is delivered to a charging station with 95% distribution efficiency."

the upfront and operating costs of equivalent electric and diesel vehicles by vehicle class using data from the California Air Resources Board (CARB 2019). This table uses projections of vehicle costs for 2024; as of 2021, EV cost increments are generally greater than shown here, and thus table 2 shows where the market is expected to be in a few years and not where it is today.[2] For the average application shown in table 2, the simple payback for an electric truck is three to seven years. This can be compared to the typical truck life of 10–15 years (Clasp Auto 2021). As noted later, other issues such as availability of charging points and resale price will factor into the market demand for electric trucks, but payback is a useful indicator.

Table 2. Comparison of annual energy costs for diesel and electric trucks

	Approx. upfront cost (US$)	Annual miles	Fuel economy (mpg or mi/kWh)	Total fuel or electricity consumption (gal or kWh)	Annual energy costs (US$)	Payback (years)
Class 2b–3 diesel	50,000	23,725	12.5	1,898	5,755	3.7
Class 2b–3 electric	67,000		2.0	11,863	1,151	
Class 4–5 diesel	55,000	36,500	9.3	3,946	11,964	3.3
Class 4–5 electric	85,500		1.3	28,077	2,723	
Class 6–7 diesel	85,000		7.0	5,214	15,810	3.5
Class 6–7 electric	125,000		0.8	45,625	4,426	
Class 7–8 tractor diesel	130,000	51,100	8.8	5,807	17,606	7.5
Class 7–8 tractor electric	200,000		0.6	85,167	8,261	
Class 8 tractor (long-haul) diesel	130,000	110,000	8.8	12,500	37,900	5.5
Class 8 tractor (long-haul) electric	240,000		0.6	183,333	17,783	

Electric vehicle efficiency, vehicle prices, and annual miles from CARB 2019 unless otherwise noted; these figures are for model year 2024. For long haul, we use 110,000 miles (suggested by NACFE) and increase the vehicle price by $40,000 to account for the larger battery size. Energy prices are from EIA 2021.

The table above indicates where the economics of electric trucks are heading, but the cost differential between diesel and electric vehicles is higher today on average. The Hewlett Foundation summarized a variety of studies on how the economics of electric trucks are changing over time. Their analysis, which figure 3 summarizes, shows that electric step-vans and delivery vehicles often have a lower cost of ownership than their ICE counterparts today, while estimates for when tractor-trailers will have a breakeven total cost of ownership range from 2023 to 2039, depending on the study and application (Hewlett Foundation 2020).

[2] For further information on this issue, see O'Dea (2019), which includes a summary of electric truck economics for 2018–2020 and for 2030.

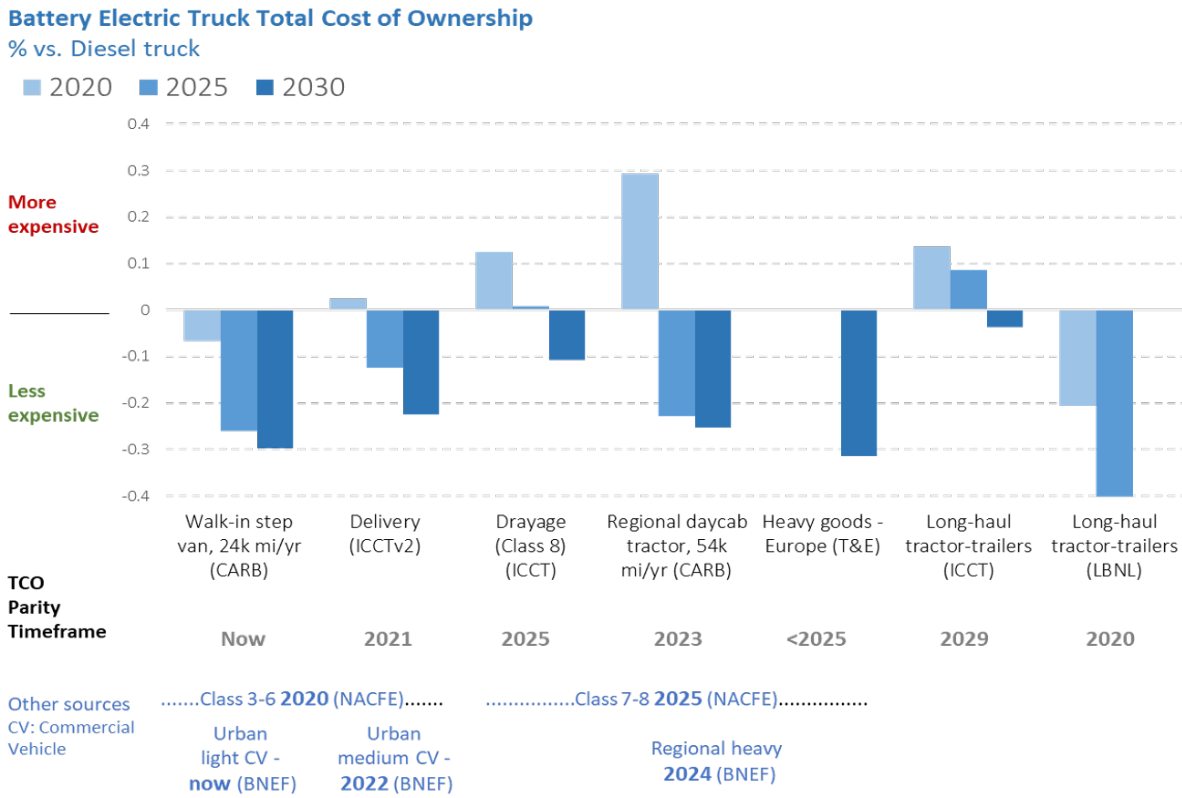


Figure 3. Comparison of diesel and battery-electric trucks on total cost of ownership (TCO). CARB = California Air Resources Board. ICCT = International Council on Clean Transportation. T&E = Transport and Environment. LBNL = Lawrence Berkeley National Laboratory. BNEF = Bloomberg New Energy Finance. NACFE = North American Council for Freight Efficiency. *Source:* Hewlett Foundation 2020.

EMISSIONS

While EVs have no tailpipe emissions, the generation of electricity used to charge them produces both GHGs and criteria pollutants, such as nitrogen oxides (NOx) and fine particulates. For example, figure 4 shows U.S. emissions of NOx by source. More than half of emissions come from the transportation sector, with heavy-duty vehicles the second biggest share (narrowly behind light-duty vehicles, despite the fact that light-duty vehicles outnumber heavy-duty vehicles by about 20 times).

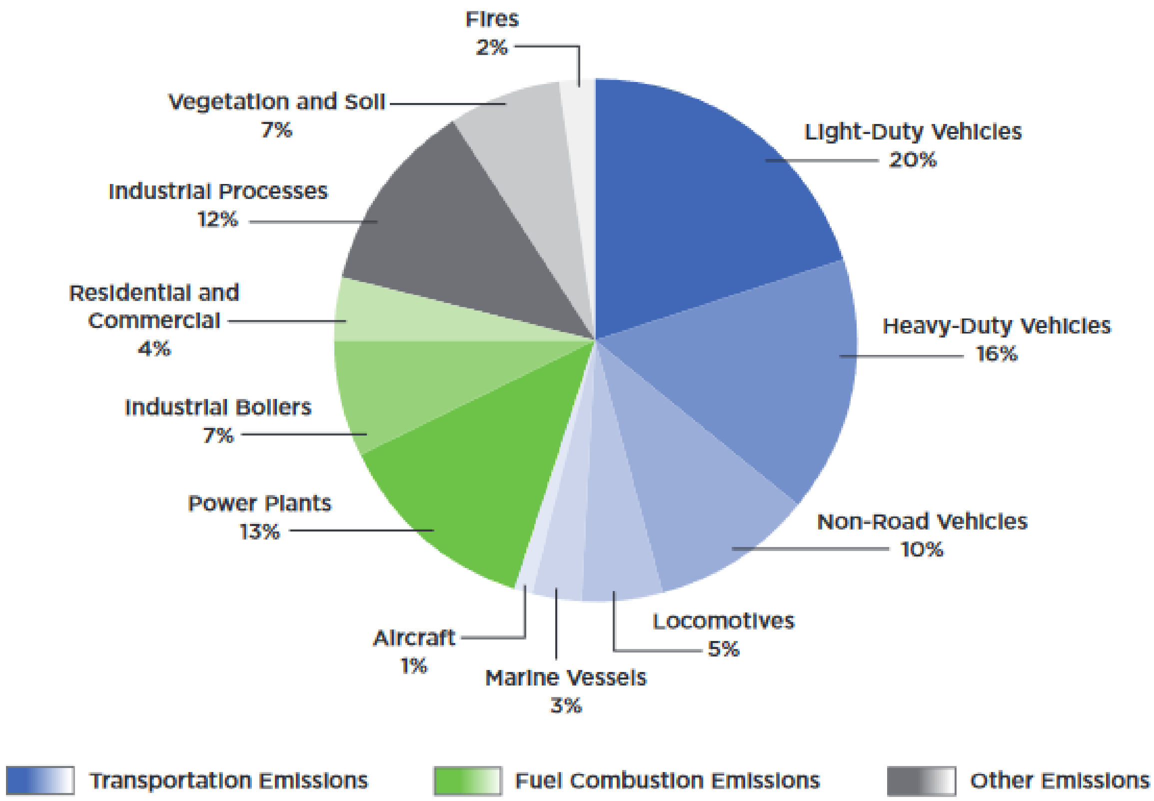


Figure 4. National emissions of nitrogen oxides by source of emissions. *Source:* O'Dea 2019 based on EPA data for 2014. The latest EPA data that became available after this graphic was developed show slightly reduced emissions, as discussed below.

However, as figures 5–7 show, full fuel-cycle emissions associated with EVs are generally lower than emissions of conventional vehicles.[3] Figure 5 illustrates this for California, which has a cleaner generation mix than the national average.

[3] A life-cycle analysis of electric vs. petroleum-fueled vehicle emissions would also include emissions associated with the production and disposal of the vehicle, including batteries. This complex topic is beyond the scope of our paper.

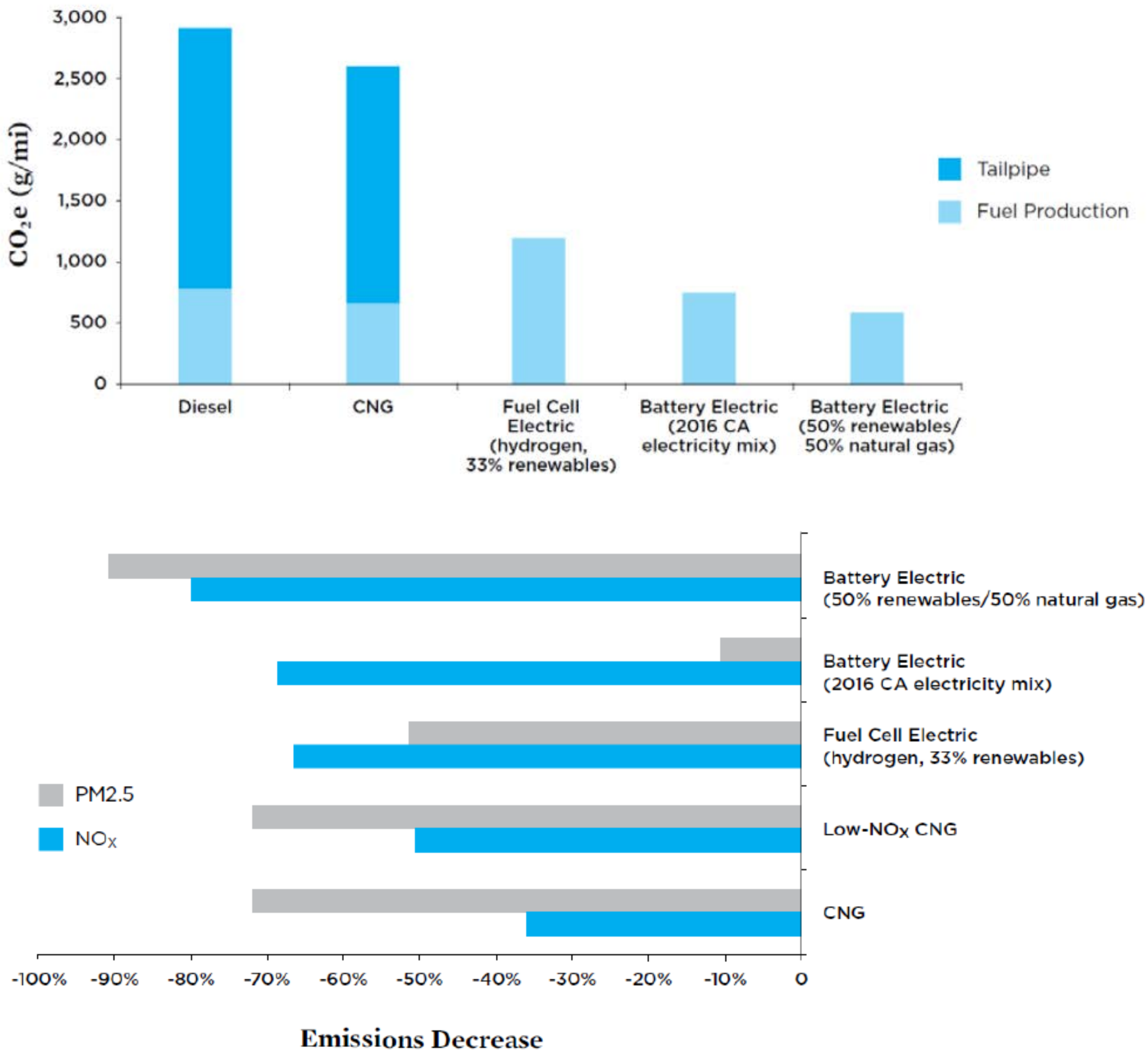


Figure 5. Tailpipe and fuel production emissions of GHG (top) and PM 2.5 and NOx (bottom) from various vehicle and fuel pathways for buses considering the California 2016 electricity generation mix and a cleaner generation mix. *Source:* Chandler, Espino, and O'Dea 2017.

Figure 6 shows per-mile emissions for the 2016 California grid. While today's national average emission rate is higher, the battery-electric bus would still have much lower emissions than the diesel or compressed natural gas (CNG) buses on the national average grid, and slightly lower emissions in even the region with the highest grid emissions.[4] Other regions' grid emissions will move closer to those of the 2016 California generation mix as they clean up their electric grids, driven by Clean Air Act requirements and declining renewable energy prices, as well as by higher renewable energy requirements in many states and challenging economics for many coal-fired power plants (Ramseur 2019). For

[4] These findings are based on national and regional grid mixes from the *Annual Energy Outlook* (EIA 2019) and generation carbon emission rates from Argonne National Laboratory's Greet1_2018 model.

example, under the "renewable" scenario in the 2019 *Annual Energy Outlook*, the national average would match the 2016 California level by 2042 (EIA 2019).

The potential impacts on air quality are illustrated in a recent analysis of the Houston area, which found that electrifying 40% of the medium and heavy trucks used in the region would reduce NOx emissions from mobile sources (including trucks and cars) by 25% and also substantially reduce emissions of fine particles (Meitiv and Xu 2021).

Based on a national average grid mix, figure 5 illustrates how diesel and electric trucks and buses compare on GHG emissions, with EVs typically having less than half the emissions of diesel vehicles. The main bars for EVs are at national average electric emissions rates, but whiskers on the green bars show how emissions vary across regions. Even in the regions with the highest electricity emissions, however, electric trucks and buses still have lower GHG emissions than diesel trucks and buses.

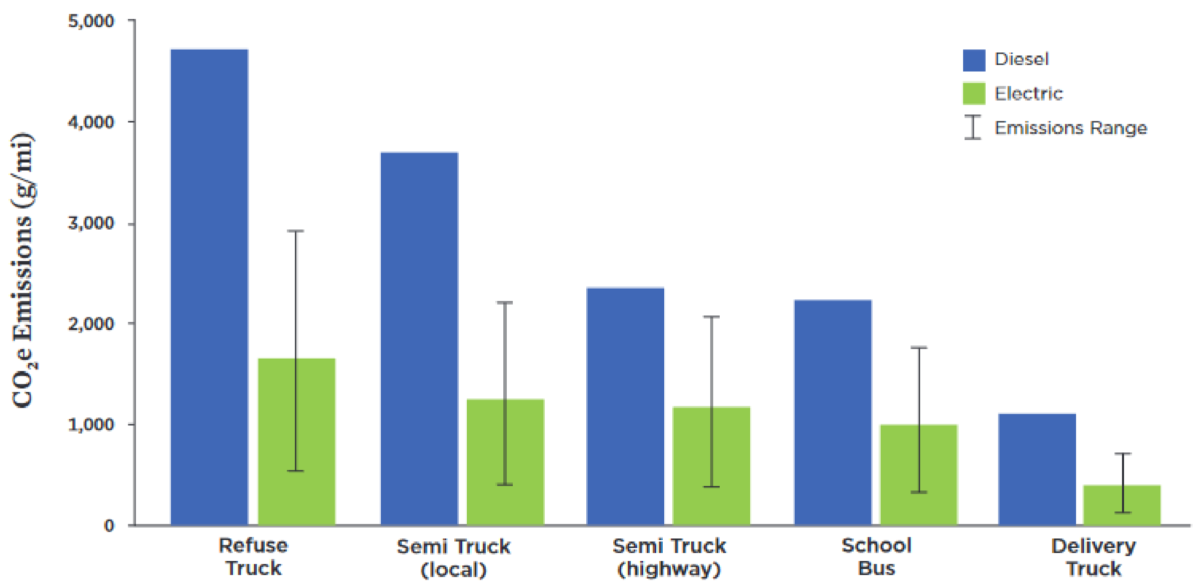


Figure 6. Life-cycle greenhouse gas emissions from different types of vehicles. For electric emissions, the green bar is for average 2016 emissions per kWh; the whisker is based on the range of emissions per kWh across regions. *Source:* O'Dea 2019.

Figure 7 provides information on relative GHG emissions another way: by comparing diesel and electric Class 5 truck emissions based on the power generation mix in each regional power pool. In all regions, the electric truck has lower emissions, ranging from 88% lower in New York State to 36% lower in Oahu, Hawaii (where much of the power comes from burning oil).

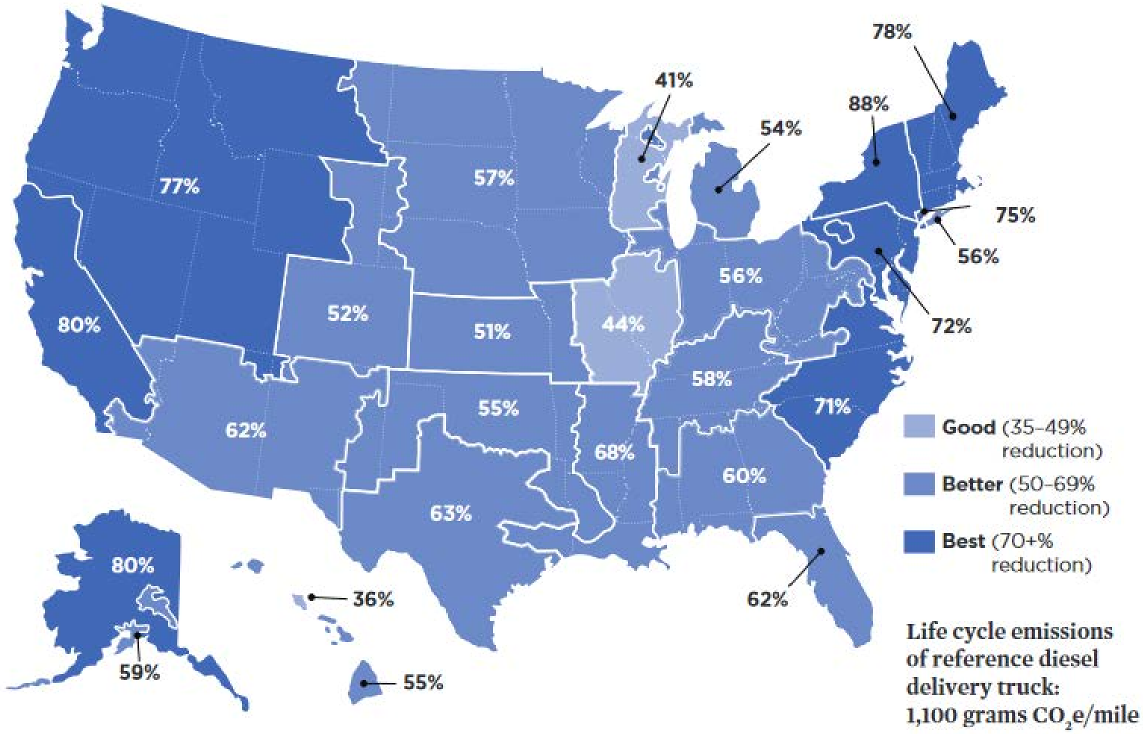


Figure 7. Reduction in lifecycle greenhouse gas emissions by region from an electric Class 5 vehicle relative to a diesel Class 5 vehicle. *Source:* O'Dea 2019.

HEALTH

Trucks emit black carbon, a potent contributor to global warming that also has adverse health impacts. Trucks contribute disproportionately to emissions of NOx as well. According to the latest EPA National Emissions Inventory (with data from 2017), 12% of total U.S. NOx emissions and 10% of U.S. black carbon emissions are from heavy-duty on-road vehicles. Of those NOx emissions from vehicles, 42% are from heavy vehicles (EPA 2021).[5]

Health impacts of criteria pollutant emissions depend strongly on exposure levels, which are determined by the location of power plants, roadways, and other emission sources relative to population centers. For example, diesel tractors and trucks often have concentrated emissions around ports. The EPA has documented the problem and encouraged efforts to reduce emissions and pollutant levels at ports (EPA 2016). The ports of Los Angeles and Long Beach are now implementing a plan to use only zero-emissions equipment, including trucks, by 2035. Health issues are one of the main drivers for these plans (Barboza 2017). Likewise, pollutant levels are often higher along major roadways, which can contribute to health problems for nearby residents (EPA 2014). It is common for low-income communities to be near these high-pollution sources (e.g., Smith 2019).

[5] *PM 10* means particulate matter with a diameter of 10 microns or less.

TORQUE

Electric motors can deliver peak torque almost instantly, allowing them to do very well in towing large loads from a dead start or up a gradient. On a practical level, for a truck, this means quicker speeds going up a grade and quicker acceleration from rest, both attributes that truck fleets favor. For example, Tesla claims that its forthcoming Semi tractor can accelerate from 0 to 60 mph in 20 seconds with an 80,000 lb. load (Tesla 2019). Also, quicker acceleration can sometimes shave time off a route for delivery trucks (Bouton et al. 2017).

MAINTENANCE AND REPAIRS

Electric trucks have a much simpler overall design, which should reduce maintenance costs and potentially reduce time in the shop and other downtime. However, the electric truck industry is early in its development and does not yet have substantial field experience. To date, this limited experience shows that, after separating out early failures that are common with new technologies, these vehicles have lower maintenance costs than diesel vehicles over the long run (NACFE 2018).

NOISE

EVs are generally quieter than diesel and gasoline vehicles. While we are not aware of any formal noise studies on electric trucks, lower noise from electric trucks has been reported in several news stories (MacDonald and Palmer 2018; Cunningham 2017). In some cities, noise pollution from trucks has led to restrictions on delivery times. Manufacturers hope these restrictions might be lifted for quieter EVs (Hirsch 2018b). Reduced noise will also be attractive to truck fleets such as utilities that frequently operate in residential districts and other noise-sensitive areas.

RANKING THE MOTIVATORS FOR FLEET ELECTRIFICATION

United Parcel Service (UPS) and GreenBiz (2018) surveyed truck fleet managers about the motivations for fleet electrification; figure 8 summarizes the results. For the fleet managers, the largest motivators are helping to meet sustainability and environmental goals and lower the cost of ownership. This implies that both ensuring that EVs help meet environmental goals and improving EV economics will be particularly important.

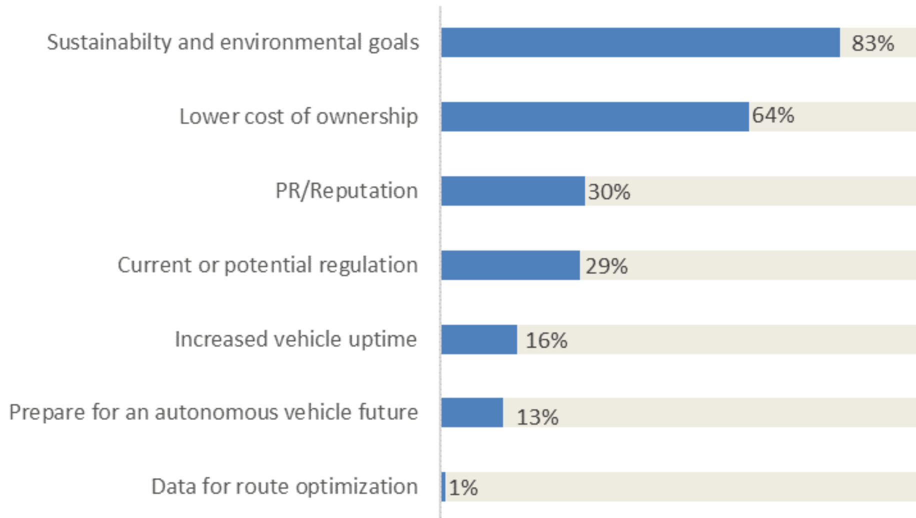


Figure 8. Motivators for fleet electrification. *Source:* UPS and GreenBiz 2018.

Challenges for Electric Trucks

While electric trucks offer substantial benefits, their deployment involves many challenges. These issues include the limited number of electric trucks available on the market, the high upfront cost and limited range of these vehicles, and charging challenges.

MODEL AVAILABILITY

Few electric trucks are presently sold on the U.S. market. The U.S. Department of Energy (DOE) maintains a list of alternative fuel vehicles, including EVs. In April 2021, it listed 89 all-electric truck models:[6] 54 buses, 13 vocational trucks, 8 vans and step vans, 7 tractors, 2 street sweepers, and 5 refuse trucks (AFDC 2021). The tractors are for drayage applications, typically with a range of 80 miles.[7] As we discuss later, additional electric truck models are scheduled to be introduced in the market soon. By comparison, each of the major conventional truck types typically has multiple manufacturers, each of which offers multiple configurations of its basic model.

UPFRONT COST

Electric trucks typically cost more than comparable diesel and gasoline trucks, due primarily to the cost of batteries. For example, as table 2 shows, an electric tractor might cost about $75,000 more than a diesel tractor—an increase of 60%.[8] Likewise, an electric transit bus costs about $750,000, which is about $315,000 (73%) more than a diesel bus (Blanco

[6] In addition to battery-EVs, the full DOE list includes hybrid and alternative fuel vehicles.

[7] *Drayage* is the transport of goods over a short distance as part of a longer trip in the shipping and logistics industries.

[8] The figures in table 2 are from CARB 2019. As we discuss later in this paper, Tesla is claiming a lower price for its new electric tractor. On the other hand, a major manufacturer (who wished to remain anonymous) told us that it thought an electric tractor will cost more than twice the price of a diesel tractor.

2018). As the table also shows, the extra cost might pay back over three to seven years, but financing the additional upfront cost can be a barrier.

There are also concerns about battery life and resale value. Typical estimates show that batteries for passenger vehicles must be replaced after about 10 years,[9] but since trucks are generally driven more miles per year than cars, truck batteries are likely to have shorter lives. Replacing batteries is a major expense.[10] These concerns in turn influence the resale value; many fleet owners use their trucks for a defined period of time and then sell them. This time period is typically around five years for trucks, but it varies widely (Work Truck 2014). However, some fleets, such as regional-haul fleets, may keep vehicles for much longer, and these fleets may be good initial uses for electric trucks (M. Roeth, executive director, North American Council on Freight Efficiency, pers. comm., November 14, 2019). Likewise, transit bus operators often plan on keeping vehicles for 12 years (MacKechnie 2019).

RANGE

Driving range is often limited for many EVs. For example, among those EVs with a listed range in the DOE database of alternative fuel vehicles, the ranges vary from 75 to 240 miles. Such ranges will be adequate for some applications, such as local deliveries and drayage, but they are often too short for intercity travel except to nearby cities. However, ranges are rapidly increasing; in the January 2020 version of this paper, the high-end of the range was only 135 miles. As we discuss later, vehicles scheduled to enter the market have claimed ranges of up to 500 miles, although some observers think that near-term claims of such ranges are unrealistic. Diesel tractor-trailers can often go 1,000 miles or more between fill-ups, but the key statistic is generally how far a driver can travel under hours-of-service regulations, which limit drivers to 10.5 hours of driving per day (Schubert 2019). So, for solo drivers, a speed of 60–65 mph means a range of approximately 600–650 miles. When a driver needs to stop, eight hours of rest is required, which generally provides time to charge batteries.

CHARGING

Electric trucks generally have larger batteries than electric passenger vehicles, which means that they either need more time to charge or they need higher-power chargers. For companies that operate only a few medium trucks that can charge overnight, charging may not be a big issue. DC fast chargers for passenger vehicles will work for many medium trucks (although the cost of these fast chargers is substantial). However, for heavy vehicles such as transit buses and tractors, the high-voltage chargers needed are currently in short

---

[9] Although experience with electric trucks is limited, batteries for electric cars are commonly warranted for eight years (EVANEX 2019) and, on average, the life of a part is longer than its warranty period. The life of batteries for electric trucks will depend on many factors, particularly the distance traveled and the number and type of recharge cycles. Since trucks are often driven more than cars, truck batteries are likely to have shorter lives.

[10] For example, the list price of a replacement battery for a Chevrolet Bolt passenger car is just over $15,000 (www.greencarreports.com/news/1110881_how-much-is-a-replacement-chevy-bolt-ev-electric-car-battery). Truck batteries will cost more—generally a lot more. On the other hand, battery replacement costs can be reduced by reselling the batteries either for use in second-life applications that do not have the same power demands as vehicles (e.g., stationary power storage) or for reclaiming valuable materials in the battery.

supply and installing them may require upgrades to local power distribution systems (Deb et al. 2018). Furthermore, many trucks are operated by fleets, which will require multiple chargers at their depots and the power to supply these multiple chargers. Likewise, truck stops will need to install multiple high-power chargers, often requiring increased power service to these facilities to meet the needs of long-haul trucks. While electric distribution systems can be designed to serve these loads, substantial reinforcement to existing networks may be needed, which requires both time and expense. Additionally, working with local utilities to make these upgrades can be a complex process, and truck owners who lease their facilities will need to work with owners to work out arrangements on allocating costs of electric upgrades. At a recent Commercial ZEV Summit, lack of resilient charging infrastructure was rated as the commercial EV industry's biggest bottleneck (Fehrenbacher 2019). We discuss these charging issues more extensively later in this paper.

ELECTRIC RATES

Most commercial facilities are charged for their maximum electric demand. For EV charging, these charges can be substantial, even if the maximum use is in the middle of the night when power demand is low. To address this challenge, utilities will need to consider rate reforms, and fleet owners will need to manage their charging in a variety of ways. We elaborate on these issues later in the paper.

POWER OUTAGES

Electric power periodically goes out, which will affect electric charging. Short outages can be managed, but long outages may mean that trucks will sit idle. Although battery storage will help, large amounts of storage are expensive. Many fleets can deal with infrequent outages, just as they might deal with snowstorms. But for some critical services, such as buses and trash pickup, attention to outages will be needed.

OTHER CHALLENGES

In addition to the above major challenges, trucking is a conservative business and fleets will be reluctant to shift to electric trucks until they are confident that they will equal or exceed diesel in terms of cost of ownership, reliability, and durability. Diesel is entrenched within fleets, and owners will need confidence that there are sufficient supply chains and service networks in place to serve electric trucks. They will also have to retrain service technicians and drivers, as well as consider how to manage load weight and temperature impacts to assure acceptable battery performance. As one reviewer of this paper noted, even low-cost, low-tech technologies such as side skirts and low-rolling-resistance tires still do not have 100% adoption after more than a decade in the market.

RANKING THE BARRIERS TO FLEET ELECTRIFICATION

UPS and GreenBiz (2018) also surveyed truck fleet managers about the barriers to fleet electrification; figure 9 summarizes the results. For the fleet managers, the largest barriers are high initial purchase price, inadequate charging infrastructure, and inadequate product availability. These results suggest that overcoming these three particular challenges should be a priority if we want to successfully promote electric trucks.

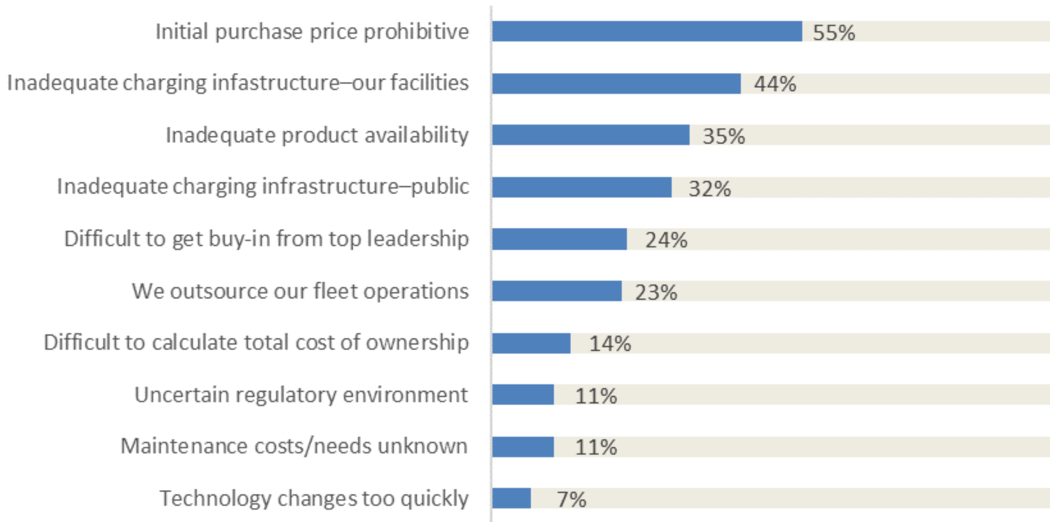


Figure 9. Barriers to fleet electrification. *Source:* UPS and GreenBiz 2018.

Truck Sales, Energy Consumption, and Use by Class

Before we proceed to a discussion of plans for new electric trucks, it is useful to review data on truck sales and use. From these data, a few key points emerge:

- Class 2b (e.g., heavy pickup trucks) dominates truck sales volume, followed by Class 3 (e.g., small delivery trucks) and Class 8 (e.g., 18-wheelers). In 2019, Class 2b accounted for approximately 58% of retail truck sales, while Class 3 accounted for 16% and Class 8 for 14% (see figure 10).
- The number of major manufacturers in each vehicle class varies considerably, ranging from three to eight (see figure 11).
- Class 8 dominates energy consumption, accounting for 62% of the fuel use by Classes 3–8 (figure 12), while buses account for only 2% of energy consumption (figure 13).
- Vehicles in Classes 3–6 (e.g., delivery trucks of various sizes) are used primarily for short trips; as figure 14 shows, about 91% of those trips are 100 miles or less.
- Use of Class 7 (e.g., transit buses) and Class 8 vehicles is more varied, with about 69% of trips at 100 miles or less, 18% at 100–500 miles, and 13% at more than 500 miles (see figure 14).
- Across the truck classes, trucks are typically driven 10,000–19,999 miles per year and travel less than 50 miles per trip (figure 15), although simple averages mask the large variation in uses.
- Major truck uses include for-hire operations, construction, agriculture, retail, wholesale, and waste management (see figure 16).

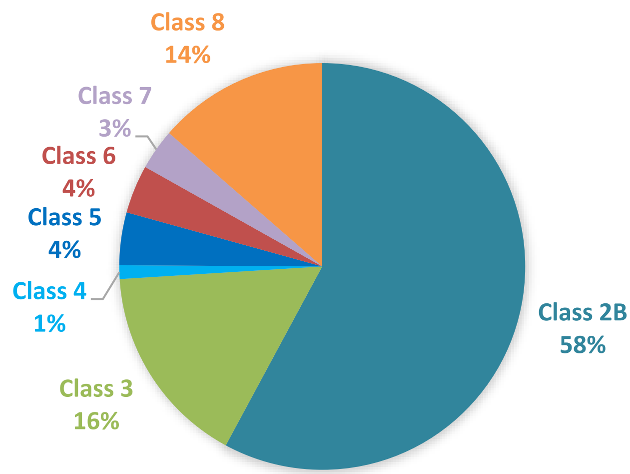


Figure 10. New retail truck sales in 2019 by vehicle class. *Source:* Davis and Boundy 2021. Class 2b sales extrapolated from Davis and Boundy based on data in EIA 2021.

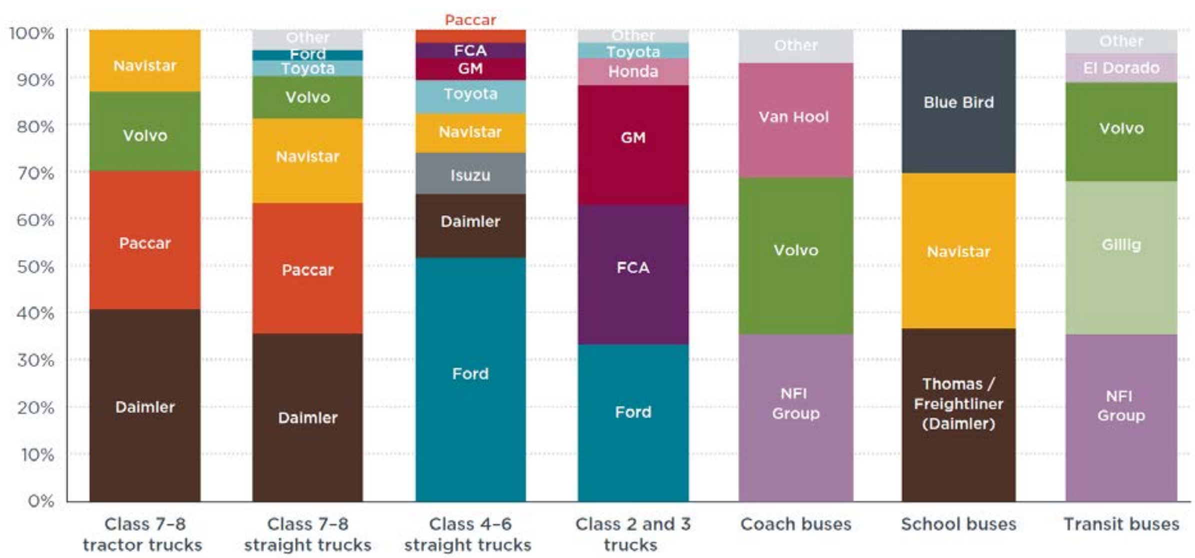


Figure 11. Heavy-duty vehicle market share (model year 2019) by corporate parent. *Source:* Sharpe et al. 2020.

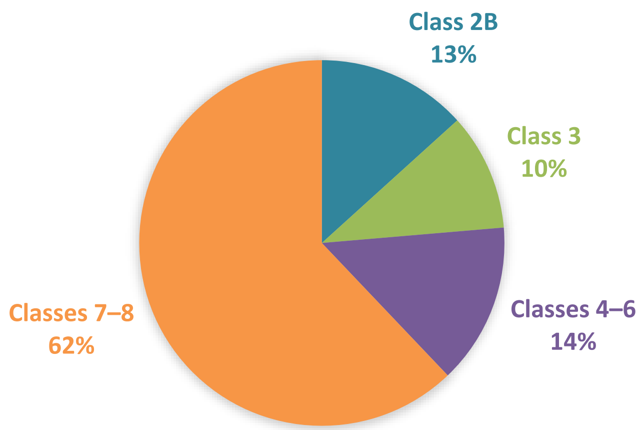


Figure 12. Energy consumption of Classes 2b–8 vehicles, 2020. *Source:* EIA 2021.

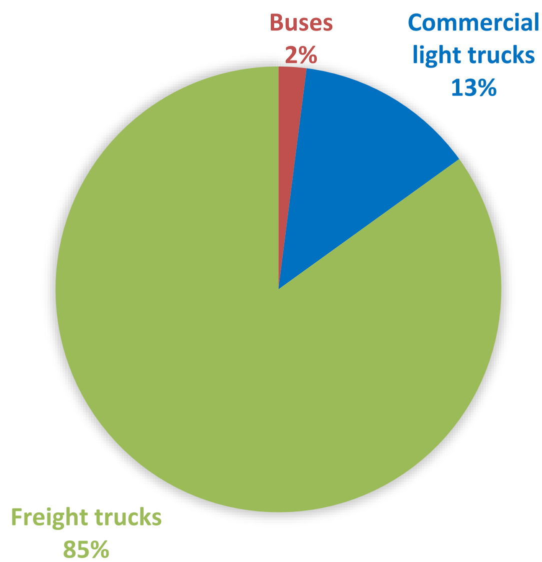


Figure 13. Energy consumption of commercial light trucks (Class 2b), freight trucks (Classes 3–8, not including buses), and buses. CO_2 emissions have a similar distribution. *Source:* EIA 2021.

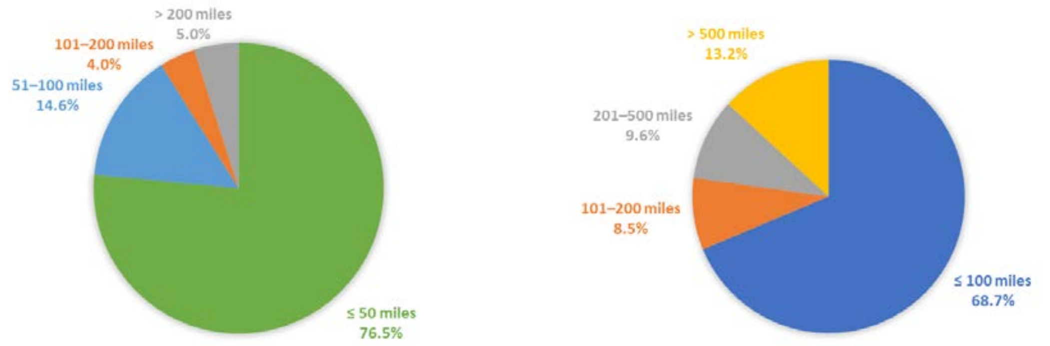


Figure 14. Typical trip miles or range of operation for 2002 (Classes 3–6 on the left, and Classes 7 and 8 on the right). More recent comprehensive data are not available. *Source:* Davis and Boundy 2021.

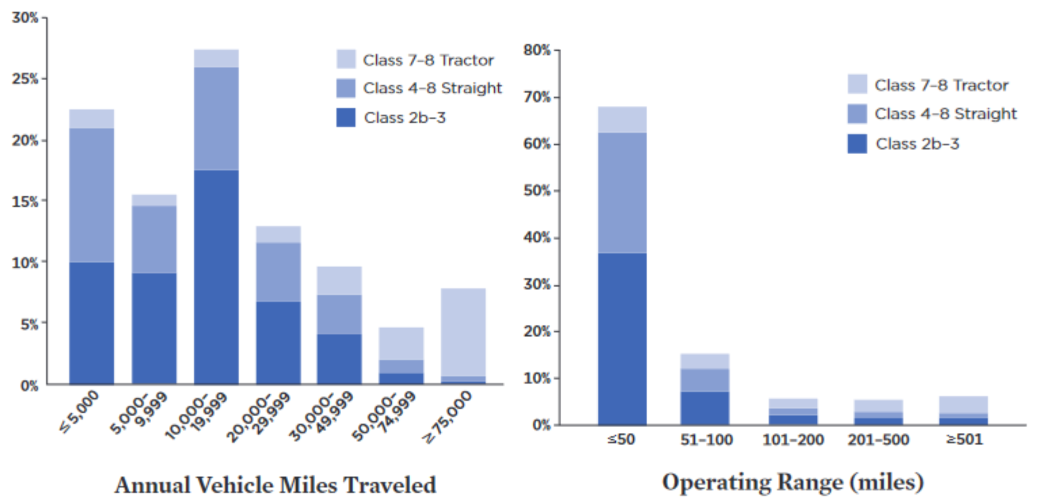


Figure 15. Percent of truck population by annual vehicle miles traveled (VMT) on the left and by vehicle operating range on the right. *Source:* O'Dea 2019.

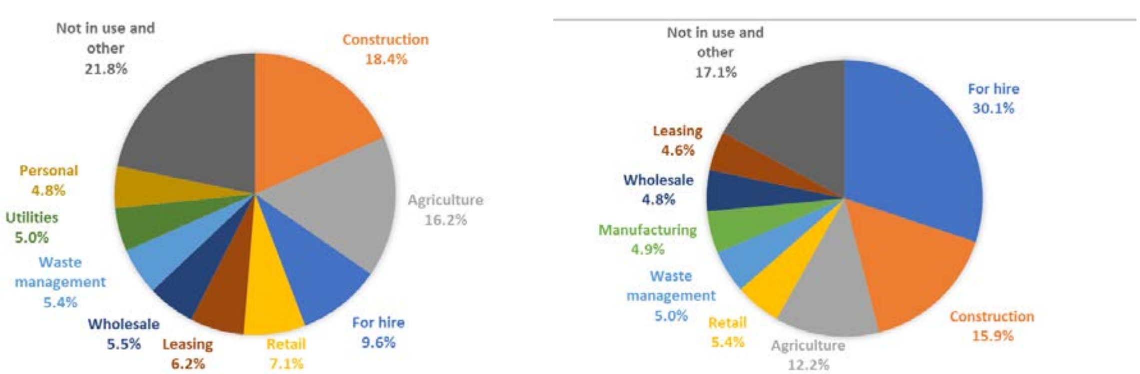


Figure 16. Percentage of trucks by major use, 2002 (Classes 3–6 on the left, and Classes 7 and 8 on the right). More recent data are not available. *Source:* Davis and Boundy 2021.

The primary data source for attributes and usage of U.S. trucks has been the Department of Commerce's *Vehicle Inventory and Use Survey*, which was discontinued after the 2002 survey (but is fortunately coming back with a new survey planned for 2022; see BTS 2021). This is why figures 14 and 16 use 2002 data. Restoring a robust data collection effort is necessary for sound commercial transportation planning; infrastructure requirements for heavy-duty electrification are a case in point.

Finally, while the comprehensive survey data are old, a variety of recent articles have noted that, in recent years, the average haul length has shortened due to factors such as increased Internet commerce, increasingly decentralized and regional distribution networks that locate inventory near customers, and increased regional and last-mile truck shipping to accommodate consumer expectations for faster, more frequent deliveries (Capstone Logistics 2019).

Current Status of Electric Trucks

In this section, we review recent and expected developments in the market for electric trucks, discussing tractor-trailers, vocational vehicles, buses, and heavy pickups.

TRACTOR TRUCKS

As noted earlier, a few electric tractors are currently on the market, but these are short range and sold for drayage applications. However, many major manufacturers are now road-testing electric tractor prototypes for hauls significantly longer than 100 miles, with plans to introduce them to the market in low volumes in 2021. Daimler, Peterbilt, Tesla, and Volvo seem to be furthest along, but several other companies are also developing products.

Tesla announced its Semi truck in November 2017; after some delays, it is now scheduled for limited production and initial deliveries in the second half of 2021. The truck has been in field trials, including towing full loads (see figure 17). It features four independent motors on the tractor tandem axles, yielding a claimed 0 to 60 mph acceleration with a full load in 20 seconds and the purported ability to sustain 60–65 mph up a 5% grade, which is about 50% faster than the average truck. Tesla plans to sell Semi versions with 300- and 500-mile ranges at an estimated base price of $150,000 and $180,000, respectively (Tesla 2019; Lambert 2017). Subsequent to these announcements, the company claimed to have found ways to extend the range, and it might be closer to 600 miles (Lambert 2019d). Tesla has been taking advanced orders for the Semi, including from Pepsi, FedEx, Walmart, UPS, and Sysco (Garber 2019). About 2,000 trucks were on order as of mid-2018 (Halvorson 2018). The company also plans a network of "megachargers" that would add about 400 miles of range in 30 minutes. This means that the chargers will use up to 1.6 megawatts (MW) of power (Lambert 2019c). Some observers are skeptical, however, that Tesla can deliver on these promises.

Volvo unveiled its electric VNR in 2019, started road tests in 2020, and is now taking orders. It plans to produce the truck in Virginia, beginning in early 2021 (Jensen 2020). It will lease the VNRs, with the lease including maintenance and insurance. Volvo is targeting regional routes of about 200 miles or less (Hirsch 2019b; Fisher 2019).

Peterbilt has built 12 electric tractors and three electric refuse trucks for testing, with a range of 150–250 miles depending on the application (Lambert 2018a; Menzies 2018). They are now taking pre-orders for the Model 579EV, which has a range of up to 150 miles and is designed for regional-haul, drayage, pickup and delivery, and last-mile operations. Production is scheduled to begin in 2021 (Peterbilt 2020). Kenworth has also announced a 150 mile-range electric tractor, with production also scheduled to begin in 2021 (Kenworth 2020). Peterbilt and Kenworth are both owned by Paccar.

Daimler North America's Freightliner division has developed an electric version of its Cascadia truck. It is planning a full line of electric trucks and buses. The company's initial e-Cascadia will have a range of up to 250 miles and can be charged to add 200 miles in 90 minutes. It is targeting local and regional distribution, as well as drayage (Hirsch 2018a), and has provided prototypes to several trucking companies to test in real-world applications (Daimler Trucks 2019; Halvorson 2018). Commercial production is scheduled to begin in mid-2022 (Freightliner 2020).

Figure 17. Tesla Semi (left) and Daimler e-Cascadia (right). *Sources:* Lambert 2018b; Hirsch 2018a.

Other companies are also working on electric tractors. Chinese manufacturer BYD is already selling short-range tractors, and it announced the sale of 21 units to Budweiser that will be built and used in California (Szymkowski 2019). Lion Electric, a Canadian manufacturer, is also developing electric Class 5 and Class 8 trucks. Lion delivered the first two Class 8 trucks to Amazon for use on middle-haul operations between warehouses, and eight more trucks are on order (Lion Electric Co. 2020).

For electric tractor-trailers to become common, they will need to compete with diesel trucks across a range of attributes. In 2018, the North American Council for Freight Efficiency (NACFE) published a detailed assessment, including its estimate of when electric heavy-duty trucks (Classes 7 and 8) would be competitive with diesel trucks on various attributes. As figure 18 summarizes, NACFE's results indicate that electric trucks were expected to reach parity on some attributes by 2020 and many more attributes by 2025 and 2030. As the figure shows, on operating costs, NACFE results are more conservative than the data in table 2; it finds that operating cost parity will not be achieved until about 2025.

NACFE published an updated assessment on Class 7 and 8 vehicles in late 2019. At that time, it noted expected product introductions in the early 2020s, but viewed that production as limited, with "significant production volumes . . . likely not feasible until the latter half of the decade." This could cause "traditionally risk-averse fleets to delay investment in or gain experience with new technologies." NACFE predicted a future zero-emission freight world (e.g., by 2040) with only electric-based vehicles (battery electric, fuel-cell, and catenary electric[11]), but with a "messy middle" between now and then as things shake out (NACFE 2019c).

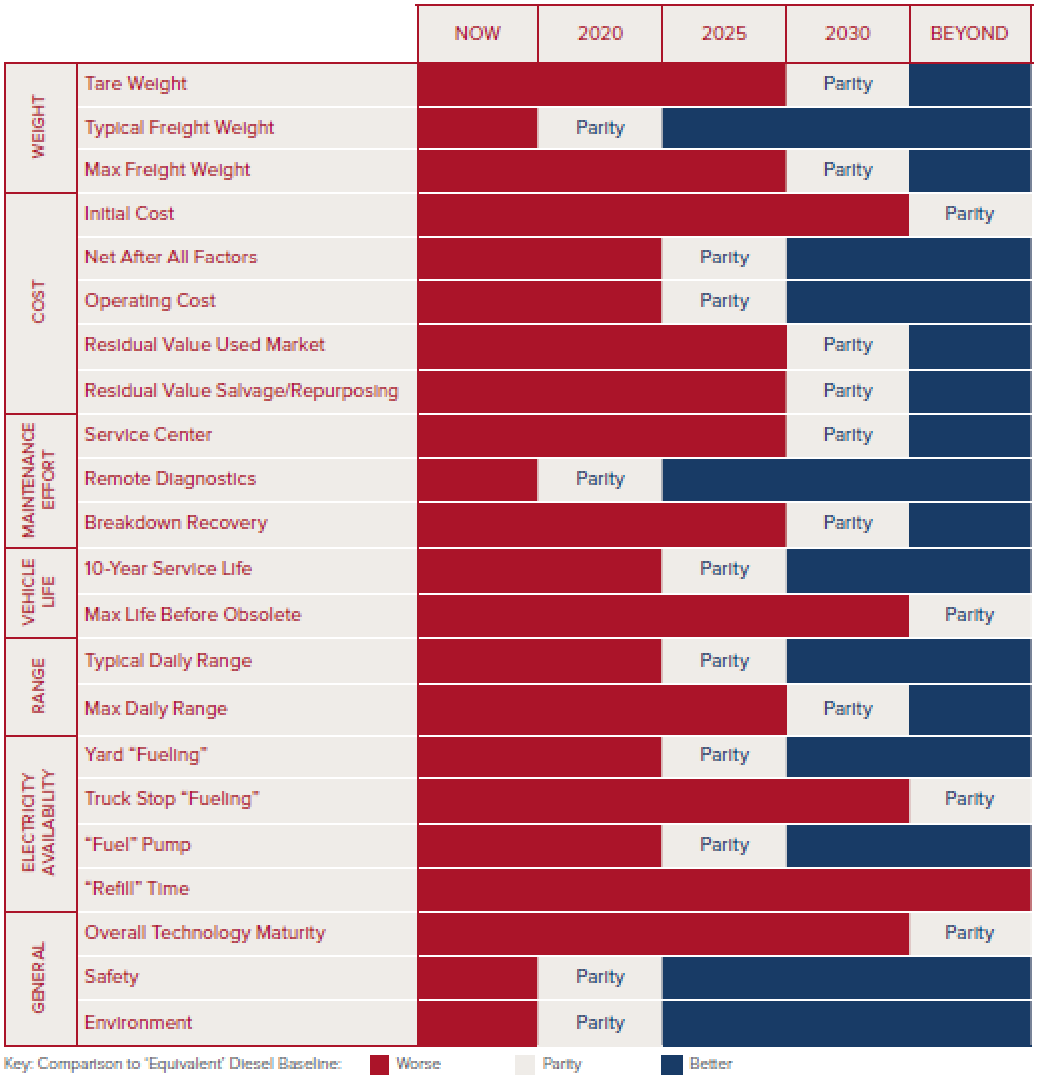


Figure 18. Comparison of electric and diesel Class 7 and Class 8 trucks on a variety of attributes. ***Source:*** **NACFE 2018.**

More recently, NACFE published a report on electric truck use for regional routes. The report identifies eight regions in which having electric regional-haul trucks operating for about 230 miles or less per shift or per day makes particular sense. The regions selected are based on freight demand, air quality concerns, adequate infrastructure and incentive support, and electricity prices. The regions are Southern California, Northern California, Cascadia (the Northwest U.S. plus greater Vancouver), the Northeast U.S., the Texas Triangle (Dallas, Houston, and San Antonio), and the Denver, Montreal, and Toronto

[11] Catenary vehicles use overhead wires connected to the vehicle with a spring-loaded device on the top of the vehicle. For example, a number of U.S. cities have catenary transit bus networks.

regions. NACFE finds that regional haulers in these regions have the potential to begin shifting to electric trucks now (NACFE 2020a).

Finally, in March 2021, the Environmental Defense Fund (EDF), working with an environmental consulting firm, published a detailed analysis on the actual patterns of two freight fleets, and how electrification might work for those fleets. It found that 71–93% of trips over the analysis period could be handled by electric tractor-trailers, with the low end for trucks that can go about 250 miles on a charge and the high end for trucks that can go about 500 miles on a charge (GNA 2021). EDF also examined the economics of electric trucks for these firms, including installing chargers and paying for electricity; it found that charging infrastructure investments are significant and vary dramatically from site to site. It also found that managed charging and installing batteries and solar (to help reduce and manage peak demand) will be critical to making electric trucks affordable (MacDougall and O'Connor 2021).

Fuel-Cell Tractor-Trailers

For long-haul routes, tractors powered by fuel cells may be preferable to battery-electric trucks because the fuel-cell models have a longer range, are lighter, and are quicker to refuel. Nikola, an Arizona-based start-up, has developed several models of fuel-cell tractor-trailers and claims to have orders for 14,000 trucks (Fialka 2019). The company is targeting routes of 500 miles or more, and is planning production facilities in Arizona as well as a nationwide network of hydrogen refueling stations. The refueling stations will be powered with renewable energy and will extract hydrogen from water (Ohnsman 2019). The trucks themselves (figure 19) will have a range of 500–750 miles, will take 10–15 minutes to refuel, and will weigh about the same amount as a diesel truck (Nikola 2019), which is tons less than a comparable electric truck (Ohnsman 2019). Nikola plans to lease the trucks for $5,000–7,000 per month, including fuel and insurance (Gnaticov 2018). It plans to both complete construction of phase one of its factory and begin testing prototypes by the end of 2021. The company is also developing a battery-electric tractor (the Tre) and hopes to have prototypes available to customers by the end of 2021. Construction of the factory is scheduled for completion in 2023 (Stinson 2020b).

In addition to Nikola, several other companies are also developing fuel-cell tractors. Hyundai recently unveiled a concept fuel-cell truck, and Kenworth and Toyota have partnered to build 10 trucks for use in Southern California (Hirsch 2019a). Under this partnership, Kenworth builds the trucks and Toyota provides the fuel-cell stacks. The program's first vehicle to enter service went to Toyota Logistics Services for operation at Los Angeles ports. The first two vehicles entered service in December 2020 with remaining vehicles scheduled for delivery in 2021. These vehicles will be placed into service by UPS, Toyota Logistics, TTSI, and Southern Counties Express (Gilroy 2019; HDT 2020). Navistar is also developing fuel-cell Class 8 trucks in partnerships with Cummins and General Motors (Stinson 2020a, Ferris 2021a).

A few fuel-cell passenger vehicles are currently on the market, and they have a higher initial cost than most battery-electric cars. The Nikola lease price implies the same will hold true for trucks, and hence the focus on long-haul applications, where using battery-electric trucks will be challenging. It should be noted that there are energy losses in the process to produce hydrogen from water and, as with battery-EVs, if the hydrogen fuel is produced with fossil fuels, then the vehicles are not truly zero-emission. Furthermore, hydrogen fueling infrastructure is extremely limited in the United States, making widespread usage of fuel-cell trucks of any type a longer-term proposition.

NACFE (2020b) has published a detailed report on fuel-cell trucks, finding that such trucks are still early in development and that production in any quantities is unlikely until the 2023–2025 timeframe. It also finds that hydrogen-fueled trucks will depend on the emergence of a broader hydrogen market for industrial and other applications; these larger scales will be needed to drive hydrogen production and economies of scale. NACFE suggests that fuel-cell and battery-electric trucks will ultimately compete and that fuel-cell trucks may have advantages for long-distance routes over 500 miles, where winter conditions are significant to operations (as batteries do not function as well in the cold), where tractor weight is critical to maximizing payload, where 24-hour a day operation is desired, and where regions are incentivizing hydrogen use.

Figure 19. Nikola One fuel-cell powered sleeper cab. *Source:* Gnaticov 2018.

VOCATIONAL VEHICLES

Vocational vehicles range from fairly small delivery vans to large single-unit trucks. With the growth in e-commerce, use of these vehicles is growing, increasing emissions and noise pollution in residential areas (Haag and Hu 2019). Many of these applications have drive cycles with frequent stops, providing an opportunity to use regenerative braking in an all-electric or hybrid-EV that recaptures energy otherwise lost in braking. Regenerative braking extends the EV range for a given battery size.

As of April 2020, the DOE Alternative Fuels Data Center lists 21 electric vocational vehicles on the market; we extract its basic information in table 3.

Table 3. Electric vocational trucks on the U.S. market

Manufacturer	Type	Model
BYD	Vocational/Cab Chassis	6F
Chanje	Van	V8100 Panel Van
Ford	Van	Transit 250/350 Cargo Van
	Step Van	E-450 Step Van
		F-59 Step Van
	Vocational/Cab Chassis	E-450 Box Truck
		E450 Cutaway
		E450 Stripped Chassis
		E-450 Work Truck
		F-59 Stripped Chassis
		F-650 Box Truck
		Transit CC-CA 250, 350
GreenPower Motor Company	Van	EV Star Cargo
	Vocational/Cab Chassis	EV Star Cargo+
		EV Star CC
Lion Electric	Vocational/Cab Chassis	LION6
		LION8
Mercedes-Benz	Van	eSprinter
PeterBilt	Vocational/Cab Chassis	220EV
US Hybrid	Step Van	eCargo
Workhorse	Step Van	C-Series

Source: AFDC 2021

In addition to these models, a number of other models are scheduled to enter the market soon. Perhaps the most widely publicized is Rivian, a start-up company that recently landed an order from Amazon for 100,000 electric delivery vans. The vans will be built on the same chassis as a pickup truck that Rivian is developing. Initial prototypes are being used by Amazon for deliveries (see figure 20). Plans are to introduce the electric vans into 15 major U.S. markets in 2021, and to have 10,000 vehicles on the road by the end of 2022 (Ferris 2021b)

Figure 20. Rivian electric van. *Source:* Priddle 2021.

Other manufacturers are also planning delivery trucks and vans. For example, UK-based Arrival is teaming with UPS in an arrangement that includes a UPS equity-stake in Arrival, an order for 10,000 vehicles, and priority access to purchase additional vehicles (Fretty 2020). Road trials started in the UK in the summer of 2020, with planned U.S. trials following shortly. Plans are to start production in the second half of 2022 (Fretty 2021). GM is also planning a delivery van (Ferris 2021c), and Ford is planning an electric version of its popular Transit van. Ford's strategy includes not only selling the vans but also offering value-added services such as driver and fleet-manager notifications regarding driver behavior and maintenance needs (Ferris 2020).

Larger medium-duty electric trucks are also being planned. For example, Freightliner is now field testing its eM2 truck (figure 21, left), which is designed for local distribution, pickup, and delivery and has a range of up to 230 miles (Hirsch 2018a; Gilboy 2018). Volvo is selling its FL truck in Europe (figure 21, right) (AB Volvo 2019). It is designed for local deliveries, with a range of up to 186 miles. The FL operates at about 69 decibels compared to 79 for a diesel; people will perceive this decrease as being about half of the diesel's noise level. Volvo hopes this factor will pave the way for distribution trucks to operate during night and early morning hours, a practice now banned by some cities (Hirsch 2018b). Off-hour deliveries can reduce congestion and can often reduce delivery costs as a result. In addition, Peterbilt has announced its 220EV trucks, including Class 6 and 7 models available with 100- or 200-mile ranges (Peterbilt 2021).

Figure 21. Freightliner eM2 (left) and Volvo FL electric (right). *Sources:* Gilboy 2018; Hirsch 2018b.

As with tractor trucks, for electric vocational trucks to become common, they will need to compete with diesel trucks across a range of attributes. The 2018 NACFE report also includes a detailed estimate of when electric medium-duty trucks (Classes 3–6) will be competitive with diesel trucks. The report finds that electric trucks have already reached parity on many attributes and will reach parity on more by 2025 and 2030 (see figure 22). In particular, it expects electric trucks to now on average be competitive on net costs (purchase and operating), although this will vary widely from application to application. In other words, the report found that parity will be reached sooner for medium-duty than for heavy-duty electric trucks.

Figure 22. Comparison of electric and diesel Classes 3–6 trucks on a variety of attributes. *Source:* NACFE 2018.

BUSES

As a recent article's headline declared, "China dominates the electric bus market, but the US is getting on board." Electric buses are widely used in China, with more than 400,000 currently operating on Chinese roads (Margolis 2019). Electric buses have recently gained significant momentum in the United States. At the end of 2017, about 300 "e-buses" were running on U.S. roads, and in 2018, the federal government awarded funding for 52 projects in 41 states, including several major cities, through the U.S. Department of Transportation (DOT) Low- or No-Emission Grant Program. In 2019, DOT made additional awards under this program for 38 projects in 38 states (DOT 2019). Buses are another application with frequent braking, providing an opportunity for energy savings with regenerative braking. Much of the U.S. activity has been in public transit buses because they typically run throughout the day and hence often have a positive total cost of ownership (discussed below). But interest in electric school buses has been growing, driven in part by health concerns. Figure 23 shows pictures of electric transit and school buses; although not shown or covered here, smaller electric shuttle buses also exist. Here, we first discuss the current market status of electric transit buses, followed by that of electric school buses.

Figure 23. Electric transit buses (left) and an electric school bus (right). *Sources:* Williams 2017; School Bus Fleet 2019.

Transit Buses

In the United States, electric transit buses are now sold by Proterra, BYD, New Flyer, Nova Bus (owned by Volvo), and Green Power Bus (AFDC 2021). Proterra is based in California, BYD is a Chinese company with a factory in California, and the other three are all Canadian companies. Electric transit buses cost more than standard diesel buses (e.g., about $750,000 versus $435,000, respectively), but operating costs are substantially lower (e.g., $25,000–50,000 lower per bus annually, depending on various factors) (Blanco 2018). On a total (life-cycle) cost of ownership basis, electric buses can be up to 25% less expensive, particularly as the daily miles traveled increases (figure 24).

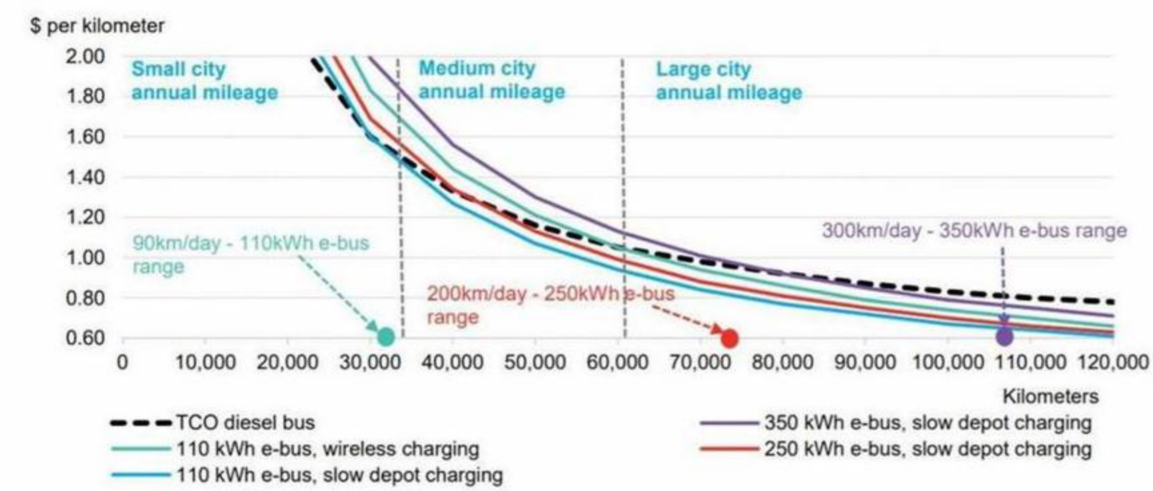


Figure 24. Total cost of bus ownership by bus type as a function of annual miles traveled. *Source:* Marcacci 2018.

Creative financing options such as leasing are often needed to address the high initial costs of electric buses. Other financing options include federal grant programs for which transit agencies are eligible, use of Volkswagen diesel emissions settlement funds (discussed later in the policy section), state programs (also discussed below), and financing offered by some electric bus manufacturers, which includes capital and operating leases, as well as a battery leasing program that Proterra now offers (since batteries are the largest component of electric bus costs) (Roman 2019).[12] Utility-provided financing has also been proposed, as utilities can readily raise capital and stand to gain from increased electric sales (Clean Energy Works 2021).

New York City, Los Angeles, and San Francisco have made commitments to switch all municipal buses from diesel to electric buses by 2030–2040 (varying by city) (Marcacci 2018). CARB has also established a regulation to transition public transit agencies to zero-emissions technologies (electric or fuel-cell). The regulation specifies the percentage of purchases that must be zero-emission over the 2023–2029 period, ramping up to 100% in 2029. All fossil fuel buses must be phased out by 2040; only zero-emission buses will be permitted thereafter (Kane 2018).

While electric buses have a number of advantages, such as zero tailpipe emissions, quieter operation, and lower operating costs, they are still early in their U.S. market development and have faced some problems that must be managed. For example, electric bus performance degrades at low temperatures, where increased resistance can reduce battery ranges and charging speeds. The use of electric heaters to keep the bus and components warm further reduces range.[13] In Minneapolis, the range of electric buses on cold days declined enough that buses could not always complete their normal routes. Very high temperatures can also degrade performance due to the energy needed for air-conditioning (Levy 2019). Solutions to these problems are being developed; they include the use of heat

[12] Also, with leasing, battery-life risk is assumed by the lessor.

[13] This is generally not an issue with diesel buses, as they use heat from the engine to heat the interior of the bus.

pumps instead of electric resistance heat to reduce heating energy use and quick-charging to top-up batteries at various points along the route.

Also, electric bus fleets usually require dedicated charging infrastructure. Electric buses typically must be charged at main depots (on the order of a $50,000 cost per charger) and potentially also at quick chargers at the end of long routes (Marshall 2019). Electric buses do not go as far on a charge as diesel buses go on a tank of fuel. As a result, routes must be planned carefully, with the bus matched to the route (Haggiag 2019). For example, Foothill Transit (serving the east side of Los Angeles County) operates 33 electric buses, or about 10% of its fleet. It has extended-range buses (approximately 190 miles on a charge) that operate throughout the day and are charged at night, and it uses fast-charge buses (40 mile range) that charge in less than 10 minutes on routes with fast chargers (Margolis 2019).

Equity and Electric Buses and Vans

Skeptics of policies to promote EVs often claim that they primarily benefit the rich. In part this is due to EV penetration in the luxury car market and also because new vehicle purchases tend to be made by households with above-average income; households with more modest incomes tend to purchase used vehicles. As more used EVs enter the market, however, the income distribution of EV owners will gradually change.

Electric trucks and buses can help to address equity issues in several ways. First, low-income households are more likely to live near ports and major roads, and therefore are more likely to face pollution from diesel vehicles. For example, a study in the Los Angeles basin of vehicle-related emissions of fine particles (PM 2.5) found that low-income households on average live in areas with 10% higher pollutant levels than the state average while high-income households on average live in areas 13% below the state average (Reichmuth 2019). EVs can reduce on-road emissions that contribute to these differences.

Second, for many low- and moderate-income households, buses are an important transportation mode, and thus electrifying buses is one way to bring EVs to this segment of the population, reducing diesel emissions along transportation routes and providing quieter rides. Buses are also disproportionately used by African Americans, as compared to rail transit (which is generally electrified already) and riding the bus instead of driving can save households thousands in transportation costs annually (Huether 2021).

Third, while buses may be a good place to start, more is needed to address the transportation needs of low- and moderate-income communities while bringing EV benefits. In California, significant EV funding is also going to fund various other services such as offering electric van services to bring workers to jobs and addressing other transportation needs for communities not adequately served by public transit. To start such services, grants and loans may be given to local entrepreneurs to purchase vans and start businesses that serve transportation needs identified by the local community (Espino and Truong 2015).

School Buses

U.S. school bus sales average approximately 34,000 vehicles annually, which is about six times more than average transit bus sales (Carpenter 2019). Electric school buses are in their infancy, with a number of school districts testing a few buses, often with encouragement and incentives from their state government or electric utility. Blue Bird, Lion, and Thomas, which are based in Georgia, Quebec, and North Carolina, respectively, have sold electric school buses in the United States for several years; Blue Bird and Thomas, a Daimler subsidiary, dominate the North American school bus market, along with IC Bus, which is a subsidiary of Navistar and received its first electric school bus order in September 2020 (AFDC 2021, IC Bus 2020). Lion announced in May 2021 that it will build a factory in Illinois, with production scheduled to begin in late 2022 (Iaconangelo 2021).

One of the major drivers for electric school buses is concern about the impacts of diesel emissions on school children. For example, a major campaign is underway in New York State and New York City to enact policies to transition school buses to electricity (NYLCVEF 2020). The group known as Mothers Out Front (2021) aids other local campaigns, such as in Virginia, in similar efforts. Multiple public health studies have documented significant pollution levels inside buses, such as from elevated levels of diesel exhaust, including black carbon and ultrafine particles (e.g., PM 2.5[14]). Many of these pollutants have been linked to elevated cancer levels and other health effects (EDF undated). These impacts often fall disproportionately on disadvantaged communities and communities of color, and hence some activists consider electric school buses an equity imperative.[15]

According to one large school district in Montgomery County, Maryland, an electric school bus costs roughly $185,000—about $65,000 more than a conventional school bus (Peetz 2019). The economic challenge for electric school buses is that they typically do not travel very far in a day; most are used in mornings and afternoons for short runs but sit unused for most of the day and in the summer. According to one estimate, a school bus travels an average of 66 miles per day (roughly 12,000 miles per year), which is about one-third as much as a transit bus (AFDC 2020a). This reduces the operating cost savings, which are necessary to repay the higher cost of an electric bus (low operating miles mean the payback period is longer).

Thus, until bus prices decrease further, creative solutions are needed. CARB has provided grants to 15 school districts to purchase two electric buses each and install charging infrastructure (Carpenter 2019). In a pilot program, New York utility Consolidated Edison paid a school district $100,000 per bus in return for the rights to use the buses in the summer as energy storage (De La Rosa 2019). Five buses are now providing about 10 kW of power each (Con Edison 2020). The California Energy Commission is funding a similar program (Carpenter 2019). Earlier work in California found that each electric school bus could generate more than $6,000 annually by sending power back to the grid (Evans and Folger 2021). Further, Delmarva Power & Light in Delaware, Public Service Electric and Gas in

---

[14] Particulates with a diameter of 2.5 microns or less.

[15] For example, efforts to electrify school buses in Maryland have been led by Chispa, a Latino-based organization (Chispa means *spark* in Spanish) (Chispa Maryland 2021).

New Jersey, San Diego Gas & Electric, and Arizona Public Service are all proposing incentives for school buses, often including a vehicle-to-grid-ready component (Brutz et al. 2018). Dominion Energy, Virginia's largest utility, is proposing what it claims is the largest such program: one that will bring 1,000 electric school buses online by 2025, starting with 50 in a first phase that began in fall 2020 (Dominion Energy 2019, Lake 2020). Given all of these examples, it is clear that school buses are likely to be an early application of vehicle-to-grid (V2G) technologies.

As one observer noted, "school buses are following the same trends as transit buses, but they're delayed four to five years" (Carpenter 2019). The Maryland legislature nonetheless adopted a law in 2019 requiring all new school buses purchased in the state after October 2019 to be zero-emission vehicles (ZEVs). To help make passage possible, the bill included a zero-emission school bus transition fund to provide school districts money for new buses (Peetz 2019). Initial grants use funds from the Volkswagen settlement fund and include funds to cover the costs of buses and chargers (Maryland Dept. of Environment 2019). Creative financing is also being used. Maryland's largest school district, Montgomery County Public Schools, recently contracted to pay $1.3 million per year for 12 years to Highland Electric Transportation, a firm that will own and maintain 300 electric school buses and install charging equipment. This amount of money is about the same as the school district pays to own and operate 300 diesel buses. Highland Electric is counting on lower maintenance costs and selling summer peak power to the local utility (Mufson and Caplan 2021).

Finally, the federal government has also begun to play what looks to be an expanding role. In April 2021, EPA announced awards for electric school buses to 137 school bus fleets in 40 states under the Diesel Emissions Reduction Act (DERA) program. Further, the Biden administration has proposed major federal investments in electric school buses, as have several senators in the recently introduced "Clean Commute for Kids Act" (Skibell 2021).

Heavy Pickup Trucks

Pickup trucks with a GVWR below 8,500 pounds are considered light-duty vehicles and are commonly used as personal vehicles. Pickups with a GVWR of 8,501 pounds or more are considered heavy-duty vehicles. These pickups have a longer life expectancy than light-duty pickups, along with greater payload and towing capacities (NRC 2012). Heavy-duty pickups are often used as trade and commercial vehicles, and commonly share a platform with heavy-duty vans, delivery trucks, box trucks, walk-in style vans, and other commercial trucks.

In commercial applications, these vehicles are usually driven for a limited number of miles each day, parked at a central location, and carry both crews and equipment to job sites (Birky et al. 2017). Applications for heavy-duty pickups are diverse, and even vary day to day for a particular company or owner. Some vehicles are sold as bare chassis and outfitted by a third party to serve as utility vehicles, tow trucks, and more. The potential for electrification depends in significant part on the specific use case.

As of April 2021, several battery-electric heavy-duty pickup trucks have been announced. These models are often variations on existing light-duty pickups and vary by payload capacity (gross vehicle weight, or GVW, combines the weight of the truck plus its payload capacity and the weight of fuel and the driver). For example, the Tesla Cybertruck is likely to be classified as a Class 2B vehicle (Lambert 2019b). The Atlis XT pickup truck, currently in development, claims to offer payload capacities as high as 5,000 pounds, which would likely push its GVW into a heavy-duty classification (see figure 25). The same applies to the Bollinger pickup truck, with a payload capacity over 5,000 pounds (Payne 2021). The Rivian delivery van for Amazon is also Class 2B (Payne 2021), implying perhaps that at least some of its pickup trucks (which are built on the same platform as the delivery van) will also be Class 2B. The GM Hummer will also come in several weights, potentially even including Class 3 (Allen 2020). Light- and heavy-duty pickups often share a variety of components, which reduces cost by increasing production volumes (Birky et al. 2017).

Figure 25. Artist's rendering of Atlis XT pickup truck. *Source:* Williams 2018.

Electrification of heavy pickups could provide additional benefits that may boost demand. With on-board energy storage, a battery-electric pickup could provide a source of auxiliary electric power, which "can be valuable to [medium- and heavy-duty vehicle] operators for a variety of purposes that include the powering of tools and lifts" (NASEM 2015). This could include powering tools at a job site or replacing generators or engine-driven accessories such as air compressors and hydraulic pumps.

Refuse Trucks

Roughly estimated, the United States has approximately 50,000 refuse trucks.[16] Garbage trucks can be a good early application of electric heavy-duty vehicles because EVs are better suited than diesel or gasoline vehicles to stop-and-go driving at low speeds over short distances. Stop-and-go driving increases diesel maintenance expenses, whereas electric trucks can use regenerative braking, which reduces the need for brake pad replacements (Daniels and Nelder 2021).

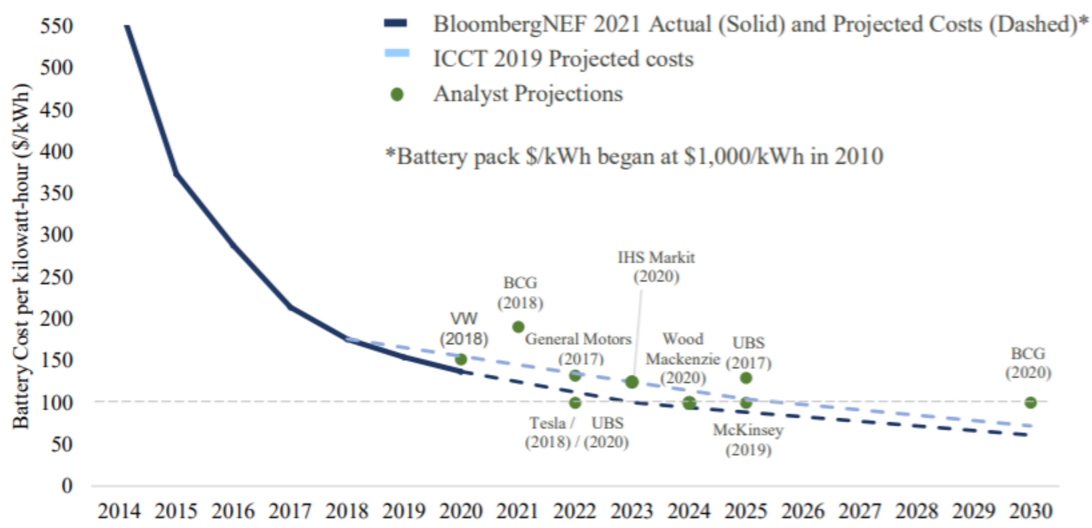
[16] Loki (2016) finds there is enough trash generated each day to require 60,000 trucks, but we round down because not all trash is hauled away in garbage trucks.

In recent years, natural gas refuse trucks have begun to replace diesel trucks; as of 2020, more than 17,000 U.S. refuse trucks were fueled with natural gas and about 60% of new refuse truck sales were natural gas vehicles (Lovely 2020). In the past year, however, electric trucks have gained ground, with trucks now available from Lion, Peterbilt, and BYD (see figure 26). One estimate (from an electric truck vendor) is that a diesel truck costs $5,000 per month for fuel and maintenance, and that electric trucks can reduce this by 80% (Lovely 2020). The purchase price of electric trucks is much higher, however. California is leading the way with incentives available for $120,000 per refuse truck from their HVIP program and a requirement that 75% of truck sales be zero-emission by 2035 (these policies are discussed in more detail in the policy section of this report).

Figure 26. Electric side-load and rear-loading refuse trucks. *Source:* California HVIP 2021.

Battery Price Trends

For all electric trucks, batteries are a major component of vehicle cost. These trucks are now competitive in some applications because battery costs have come down dramatically in recent years. Just as important, cost declines are expected to continue, which will improve the competitiveness of electric trucks going forward. Figure 27 summarizes battery cost trends and projections. In 2020, according to Bloomberg New Energy Finance, the volume-weighted average battery pack price was $137 per kilowatt-hour (kWh), and this is projected to decline to $58 per kWh by 2030 (BNEF 2020). However, as CARB (2019) and Moultak, Lutsey, and Hall (2017) have noted, these prices are for light-duty vehicle batteries; batteries for heavy-duty vehicles are somewhat different and will take additional time to reach the price points that figure 27 shows.



Cost projection shown are for battery packs. Several of the listed sources estimated battery cell costs; for these estimates the value shown includes a 25 percent mark-up to estimate pack costs.

Figure 27. Past and current price of lithium-ion batteries. *Source:* Lowell and Huntington 2021.

Key Issues: Charging and Charging Infrastructure

Charging heavy-duty vehicles presents not only a technological challenge, but also a temporal and spatial challenge for both fleet owners and utilities. Heavy-duty vehicles are diverse in their characteristics and use patterns, ranging from pickups that are used daily to carry crews and tools to nearby job sites, to busses and delivery vehicles making frequent stops, to Class 8 long-haul trucks driving hundreds of highway miles every day. The deployment and availability of charging infrastructure relies on case-by-case solutions with respect to vehicle operational requirements, power demand, and potential operational savings (Gallo 2015).

Charging equipment for these vehicles is similarly diverse. Chargers for trucks can use a lot of power—from 6 kW for a level 2 charger (240 volts) that might be used for pickup or smaller delivery trucks to 15–70 kW for larger midrange trucks to 60–200 kW for transit busses, and even as high as 1,600 kW (as with Tesla's planned megachargers) for Class 8 trucks. Table 4 lists charging levels and peak demand.

Table 4. EV charging levels and peak demand

Charging level	Peak demand (kW)	Potential applications
Level 1	1.4–1.9	Smaller vehicles, lightly used
Level 2	Up to 19.2	Overnight charging of small/medium vehicles
DC fast charging (sometimes called Level 3)	36–240	Fast charging of small/medium vehicles, overnight charging of larger vehicles
Tesla megacharger	1,000–1,600	Class 8 long-haul tractors

The potential applications are ACEEE assessments. *Sources:* Charging levels and peak demand: SAE International 2017; Tesla megacharger peak demand: Liu 2017.

Choosing the correct type of charger, and where to install it, will require several major considerations. First, the type of vehicle and how it is used will determine the battery's size and capacity. Next, characteristics of the business or fleet and how quickly a vehicle must return to the road will determine the charging level. Finally, and perhaps most importantly, selecting a site for chargers will require consideration both of where the vehicles will be used and stored, and of the availability of sufficient grid infrastructure to meet the expected electrical demand.

For delivery vehicles and transit busses, business owners and fleet operators generally prefer that charging take place where the vehicles are typically parked when not in service, such as in a warehouse parking lot or at a bus depot. Long-haul trucks could also charge at a warehouse, but for longer routes, such as those made by sleeper cabs, the trucks will ideally use chargers en route at rest stops or other locations. This presents multiple challenges for the grid infrastructure, especially given the likelihood of multiple chargers operating simultaneously.

For a fleet of vehicles parked together, power demand can be very high. For example, as figure 28 shows, 100 medium-duty electric box trucks charging simultaneously with level two 15 kW chargers would place 1.5 MW of load on the grid, while the demand of 50 transit busses charging at 60 kW could reach 3.0 MW, and increase dramatically if faster charging is required (Gallo 2015).

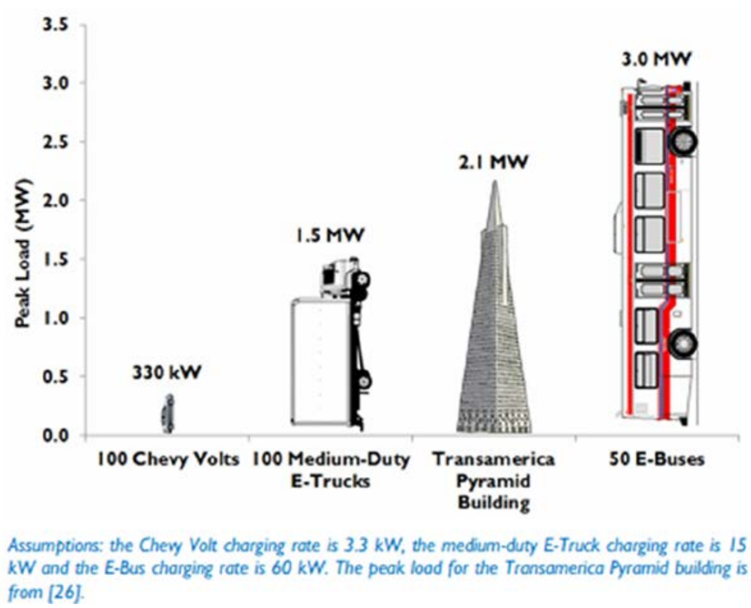


Figure 28. Peak loads for various EV fleets without mitigating grid impacts.
Source: Gallo 2015.

In Amsterdam, a 100-bus transit fleet serving Amsterdam's Schiphol airport and nearby areas is powered by a set of slow and fast chargers that together have a peak load of 13 MW (Manthey 2018). The existing load is equivalent to the power used by a typical large factory, and the airport and its bus-system contractor are thinking of expanding the fleet to 250 buses. A rough estimate of the power needed to serve a fleet of 200 delivery vans at an

Amazon fulfillment center is about 4 MW (Kellison 2019). For electric 18-wheelers, a recent proposal calls for charging stations located every 100 miles along the U.S. West Coast's I-5 corridor, each with a peak load of 23.5 MW (HDR et al. 2020).

These examples show the need for more power at a given site than most utilities can provide without substantial planning and investment. Meeting these needs will often require changes to primary and secondary power distribution systems (feeders that deliver power to distribution transformers and to end customers) and substation upgrades. For large loads, a new substation may be needed. A paper recently released by the California Electric Transportation Coalition (2020) estimates that for loads over 5 MW, distribution system and substation upgrades will be needed most of the time. According to the paper, typical utility costs are $1,000,000–9,000,000 for substation upgrades, $150,000-6,000,000 for primary distribution upgrades, and $5,000-100,000 for secondary distribution upgrades. Black & Veatch, in their paper on electric fleets, also provide general guidance (see table 5), while recognizing that each site is unique.

Table 5. Distribution upgrades typically needed as a function of new load

Amount of new load (MW)	Upgrade typically needed
20	New substation
10	New transformer bank
5	New circuit
2	Customer needs to take higher voltage service
1	Upsizing wire or cable to the site or reconductoring

Source: Black & Veatch 2019

Installing several chargers at a depot, truck stop, or filling station involves many players to obtain permits, undertake construction, and work with the utility to ensure that adequate power is available when and where needed. NACFE (2019a) has laid out a recommended process, shown in figure 29. Although some large companies may undertake the process themselves, most will need guidance from a firm specializing in this process. To provide just one example, Siemens has a growing business building truck chargers and managing their installation (Fehrenbacher 2019).

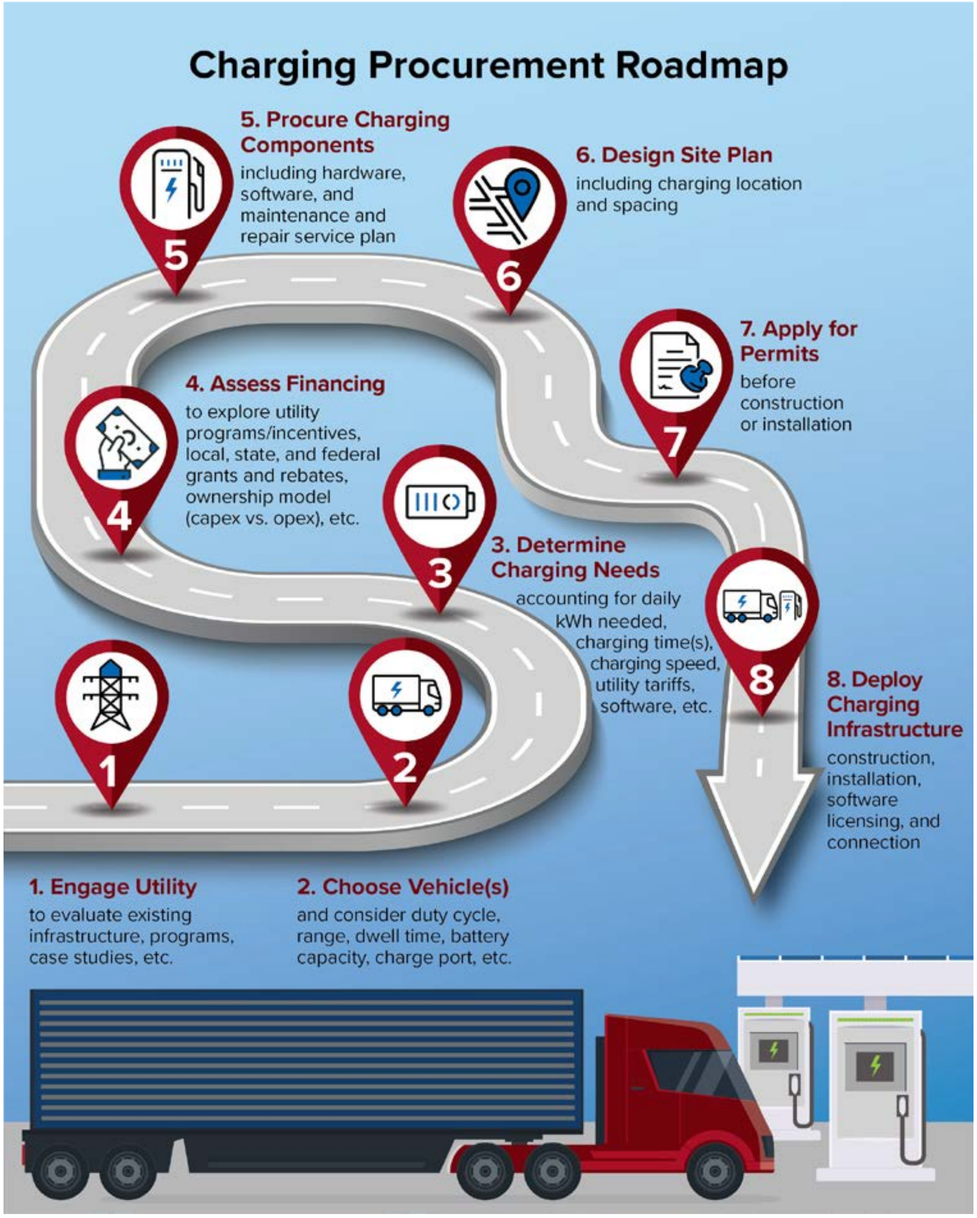


Figure 29. The process to install electric chargers for trucks. *Source:* NACFE 2019a.

The utility itself must evaluate whether existing infrastructure is sufficient to meet charging demand. A fleet could be limited in the number or power throughput of chargers by the infrastructure's ability to safely meet its demand. Utilities will play an important role in planning EV charger siting, collaborating with fleet owners on each unique charging site to determine viability and any necessary investments. Distribution upgrades can take many months to execute. Although additional power can be brought to existing fleet facilities in some cases, utilities may also suggest new locations to which it will be easier to bring power.

In some cases, fleet owners will be required to pay for any necessary utility investments. Many utilities, however, have programs to help pay for the make-ready of infrastructure needed before chargers can be installed. These programs are typically funded by all ratepayers since everyone can benefit from the better grid utilization and optimization enabled by EVs.

In the United States, California utilities are leading the way on this issue. These utilities operate programs that work with fleet owners to install the necessary infrastructure for EV fleets. For example, Southern California Edison operates the Charge Ready Transport program for medium- and heavy-duty fleets. Normally, when customers request new or upgraded service from the utility, there are fees associated with the new upgrade. With Charge Ready, the utility generally pays these costs, and it will sometimes pay half the cost of chargers; the fleet operator is responsible for the other half and for charger installation costs. Sites with at least two EVs are eligible, but program managers report that at least five vehicles are often needed for the economics to make sense for the utility (SCE 2021).

One way to plan for fleet charging needs is to develop and implement a phased plan, with some components sized for future planned growth and other components added as needed. Southern California Edison, for example, has 24 commitments so far, and has a five-year goal of 870 sites, with an average of 10 chargers per site. The utility notes that one charger can usually serve several vehicles and that cycling of charging, some storage, and other load management techniques can reduce capacity needs (e.g., a nominal 10 MW load can often be reduced below 5 MW) (J. Bardin, Sr. Project Manager, Operations, SCE, pers. comm., May 27, 2020).

Through programs like Charge Ready, utility representatives are regularly talking with fleet operators, and they can use these discussions to help identify needed upgrades to the utility grid. For example, California transit agencies are now doing the planning to meet a CARB mandate for 100% electric or fuel-cell buses by 2040; utilities are talking with the agencies and their consultants as part of this process. California utilities are finding that grid capacity is often adequate in the short term, but that upgrade needs will likely grow in the medium term (e.g., 7–10 years out). They can manage grid needs with good planning (e.g., school buses can generally be charged overnight and don't need fast chargers), load management techniques, and some battery storage to address peak needs.

As part of charging system optimization, fleet owners may consider on-site generation (e.g., solar arrays) and battery storage to help reduce electric demand. Fleets also should determine if their utility offers special rates for EVs, such as off-peak rates and load management programs that offer discounts if the utility has some control over when the charging occurs (typically with an option for customer override). Some of these options might reduce the amount of power needed, potentially avoiding or reducing build-out costs.

Electric Rates and Demand Charges

Electric rate design can have a substantial impact on the economics of EVs. Many utilities impose demand charges based on a customer's peak power demand in a month, measured in kilowatts. Demand charges are a tool for utilities to encourage customers to spread their electricity use over time, as utilities need to maintain system capacity to meet customer needs during times of maximum grid energy use. Chargers for trucks can use a lot of power; as we noted in the charging section, power draws can range from 6 kW to as much as 1,600 kW for Tesla's planned megachargers. Demand charges vary from utility to utility, and can even vary between the rate schedules an individual utility offers. In the United States, $15/kW is a typical demand charge (McLaren 2017). Thus, for the four examples in figure 26, the monthly demand charge would be $4,950, $22,500, $31,500, and $45,000, respectively.

If a charger is used many times a day, the demand charge can be spread over many charging episodes and is not a big part of the total bill. But if a charger is used only a few times a day, the demand charges can dwarf the energy charges (cost per kWh of electricity used). Figure 30, excerpted from a fast charging study in the Midwest, illustrates this. Depending on how much power a charger uses and the number of uses per day, the demand charge can be the majority of the electric bill.[17] As a result, the study's authors estimate that it will take five uses per day to break even on a 50 kW charger (based on average rates in the study region); 18 uses per day to break even on a 150 kW charger (a typical new, fast charger); and 51 uses per day to break even on a 450 kW charger (McFarlane et al. 2019). These specific results are for light-duty vehicles; heavy-duty vehicles will use far more energy per charge. So, for a given charging station power rate, fewer charges per day are required to keep demand charges at a manageable share of charging cost.

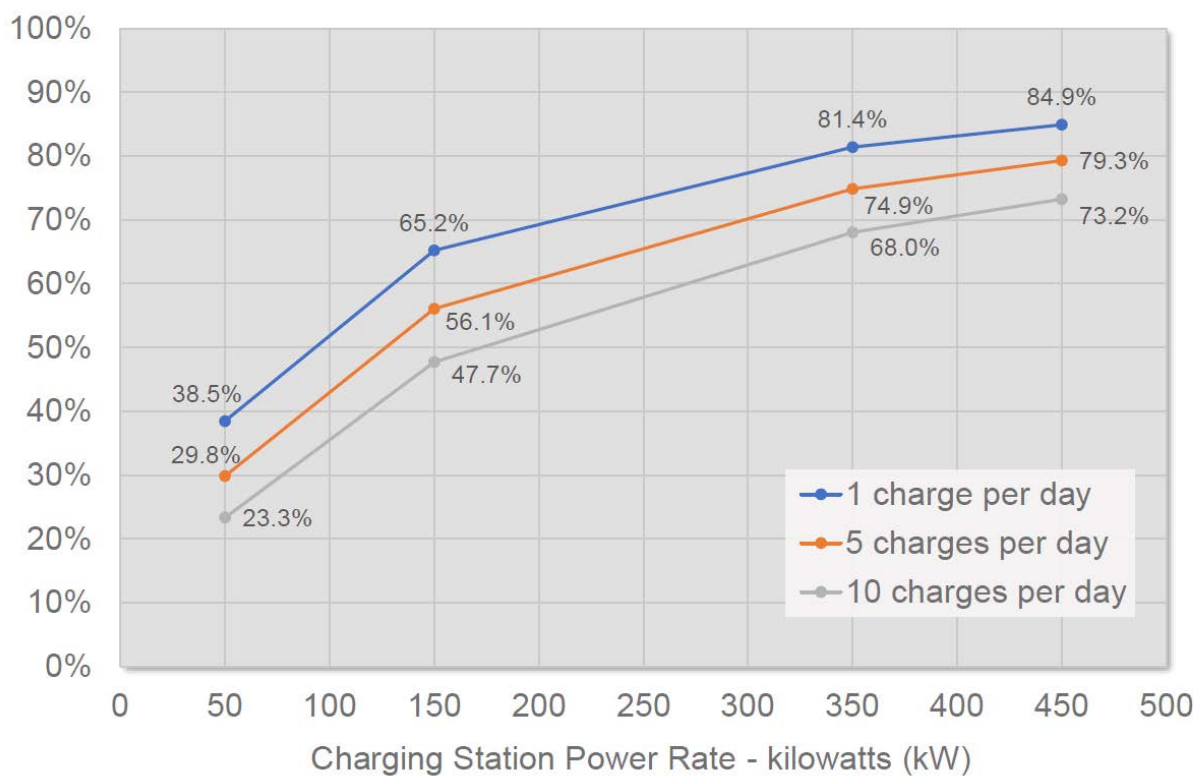


Figure 30. Demand charge share of a direct-current fast charger station cost as a function of charger power draw and the number of charges per day. *Source:* McFarlane et al. 2019.

[17] This study covered charger types that passenger vehicles and small/medium trucks might use.

Some states and utilities are seeking to mitigate this EV adoption obstacle at the early stages. For example,

- Southern California Edison now has optional commercial tariffs for EV charging that do not have demand charges, but instead use time-of-use rates to recover costs. The intent is that as EV, charger use, and kWh bills increase, demand charges will represent a decreasing portion of the total energy bill and can be restored.
- Pacific Gas & Electric (PG&E) was recently approved to offer an optional EV charging rate that replaces the demand charge with a small monthly subscription fee based on the total charging capacity selected by the customer (essentially, this is a cap on power draw) (Muller 2020).

Other utilities are also proposing to either waive or reduce demand charges for EV charging for a limited period, including the following:

- NV Energy (a demand charge discount that gradually declines)
- Philadelphia Electric (a five-year demand credit)
- Public Service Electric and Gas (monthly rebates over a five-year period)
- Orange and Rockland Utilities (a 20% discount)
- Pacific Power (no demand charges at first, with charges gradually instituted over years 3–12 that the rate is offered)
- National Grid Rhode Island (a credit to offset the demand charge for three years) (Brutz et al. 2018)

In contrast, some utility requests to reduce demand charges for EV charging have not been approved. For example, the Massachusetts Department of Public Utilities (2019) denied National Grid Massachusetts' request to provide such a discount until an evaluation of an earlier pilot program could be completed.

Policy Efforts

Policies to promote electric trucks are being pursued in multiple jurisdictions. Perhaps the most extensive efforts are in California and China. In the following sections, we first discuss efforts in California and China, then proceed to efforts elsewhere in the United States and briefly touch on efforts in Europe.

CALIFORNIA

California has adopted numerous programs to accelerate commercial vehicle electrification, driven partly by Senate Bill 350, which established the goal of reducing GHG emissions by 40% in 2030 and 80% in 2050 from their 1990 levels (California Energy Commission 2021). The state has adopted a ZEV program for trucks requiring sales percentages from 5–9% in 2024 (varying with vehicle class) and 40–75% in 2035. Figure 31 summarizes the targets by year. CARB has also voted to adopt the heavy-duty omnibus rule, which will slash pollution 90% from new trucks by 2027, especially targeting NOx and particulate matter emissions (Portillo 2020).

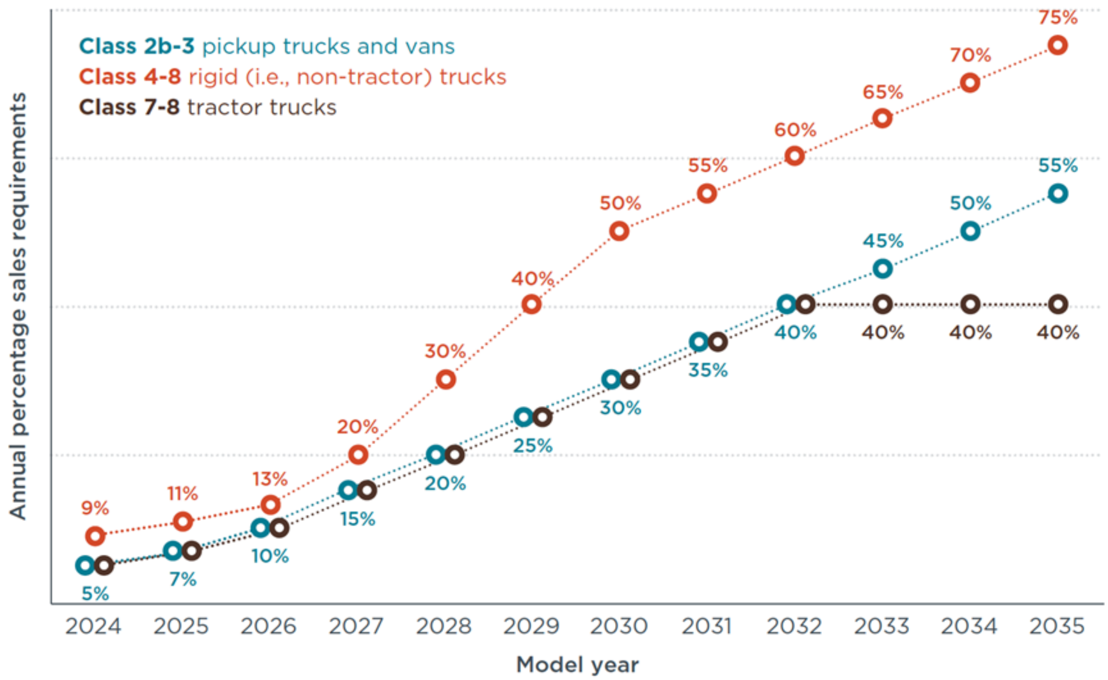


Figure 31. Zero-emissions sales percentage schedule by vehicle group and model year. *Source:* Buysse and Sharpe 2020.

In addition to the manufacturing requirement, CARB is "developing a medium and heavy-duty zero-emission fleet regulation with the goal of achieving a zero-emission truck and bus California fleet by 2045 everywhere feasible and significantly earlier for certain market segments such as last mile delivery and drayage applications. The initial focus would be on high-priority fleets with vehicles that are suitable for early electrification" (CARB 2021). These programs support CARB's stated target of achieving 100% zero-emission pickup-and-delivery in local applications by 2040 (CARB 2019). Both the electric truck manufacturing and fleet purchasing programs are being developed under California's authority from the Clean Air Act to develop its own standards for mobile source emissions. Other states can then elect to follow California's truck emission standards, similar to what 13 states did with its light-duty vehicle standards. The CARB program to require public transit agency buses to be zero-emission by 2029 was discussed above (Kane 2018).

California also has purchase vouchers and demonstration and pilot projects for zero-emission heavy-duty vehicles, several of which are in partnership with CALSTART. The voucher program provided up to $198,000 for an electric school bus ($240,000 for a fuel-cell transit bus) in 2021, including a bonus for deployment in a disadvantaged community (California HVIP 2021). However, in recent years, a substantial wait list for funds has developed (Abt 2019).

Broader policies such as the Low Carbon Fuel Standard (LCFS), the Sustainable Freight Action Plan, and the Ports' Clean Air Action Plan also support heavy-duty vehicle electrification (CARB 2018). Truck and bus fleets can earn incentives through the LCFS. For example, transit agencies in California can earn up to $9,000 per year for each electric bus in their fleet (Barbose and Martin 2018). The California Department of Transportation, through the Transit and Intercity Rail Capital Program (TIRCP), also supports the adoption of zero-emission buses (ZEBs) by buying ZEBs for its fleet, building EV charging stations, and providing grants to modernize California's intercity bus, urban rail, and bus and ferry transit systems (California DOT 2021). These broader policies contributed to California being ranked first overall on ACEEE's *State Electrification Scorecard* as well as earning top scores for multiple categories, including planning and goals and incentives for EV deployment (Howard et al. 2021).

California also has taken steps toward electrification of its marine port and airport ground vehicles. All major ports including Los Angeles, San Diego, Oakland, and Long Beach have identified paths toward ZEVs. The ports of Los Angeles and Long Beach have committed to move completely away from ICE trucks by 2035 (Vock 2019). California Energy Commission grants of $80 million and $5.9 million for Long Beach and San Diego, respectively, will allow these ports to invest in charging infrastructure for electric trucks and forklifts (SDG&E 2018).

In May 2021, the South Coast Air Quality Management District adopted a rule requiring approximately 3,000 large warehouses (those with more than 100,000 square feet in floor area) to reduce emissions of trucks serving their sites (e.g., by using zero-emission trucks) or to take other actions to reduce air pollution and its impacts (e.g., install solar panels or have air filters installed in local homes, schools, and hospitals). The new rule establishes a point system, with specific actions earning points toward the total number of points a warehouse must earn (Tabuchi 2021).

In addition, as discussed above in the rates section, California utilities often provide special rates for EV charging, including reduced demand charges.

CHINA

China is well ahead of the United States in advancing EVs, particularly electric cars and buses. As of early 2019, China had 421,000 electric buses compared to 300 in the United States. China began its "new vehicle" efforts in 2009 as a strategy to reduce pollution and become a leader in an emerging global industry. The central government developed a comprehensive set of policies, regulations, and subsidies to help create a new industry (Eckhouse 2019). In 2009, the central government identified 13 Chinese cities to pilot electric public transport; it then provided subsidies, with each city developing its own implementation plans. For example, the city of Shenzhen (bordering Hong Kong) used electric buses to help with transportation for a 2011 sporting event it hosted for university athletes. The program steadily grew from pilots to large-scale implementation; as a result, Shenzhen has converted virtually its entire fleet to electric buses. Shanghai hopes to do the same in the next few years (Aldama 2019). The program now includes many more cities, with each city taking its own approach regarding which vehicle types to emphasize, how to handle charging, and so on. He et al. (2018) list 22 cities and the commitments they have made to EVs including cars, taxis, buses, sanitation trucks, delivery vehicles, and trucks, as well as charging stations. The central government provides some funding for these efforts, but local funding is also involved, sometimes matching the central government funding. In addition to direct purchase subsidies, incentives sometimes include reduced vehicle licensing fees, reduced tolls on roads, and bulk purchase incentives (He et al. 2018). The government has also directed state-owned enterprises to purchase EVs and install charging stations, even if it is not economical for them to do so (Aldama 2019).

A Rocky Mountain Institute study examined Shenzhen's efforts to promote electric logistics vehicles in more detail. Over the 2015–2018 period, Shenzhen's fleet of electric logistics vans and trucks expanded from 300 to more than 60,000. This was aided by strong model availability (more than 45 brands) and the emergence of leasing companies that bundle vehicles, charging infrastructure, and maintenance for a flat monthly or annual fee. Policies also played a strong role, including vehicle purchase and operational subsidies, exemptions from urban access restrictions, strict emissions requirements for conventional vehicles, charging infrastructure subsidies and mandates, low electricity prices for charging stations, and regulated charging service fees that provide predictable revenue. Shenzhen also learned some important lessons, including lessons related to user preferences for fast charging and daytime charging, a shortage of chargers in central areas of the city, conventional vehicles parking at chargers and thereby blocking access to them, and problems with nonfunctioning chargers and charging payment systems (Crow et al. 2019).

China takes a top-down approach from its central government that would be difficult to apply in the United States and many other countries. However, the Chinese example in general and the Shenzhen example in particular are useful in showing what is possible when local governments are motivated to expand EV use substantially and rapidly.

MULTI-STATE MEDIUM- AND HEAVY-DUTY ZERO-EMISSION VEHICLE INITIATIVE

In December 2019, in an effort coordinated by Northeast States for Coordinated Air Use Management (NESCAUM), a group of states signed a statement of intent to work together to develop a "multi-state memorandum of understanding to support and accelerate the deployment of medium- and heavy-duty ZEVs through a collaborative process." Other states have joined since; presently 15 states and the District of Columbia are signatories, with several other states likely to join soon.[18] NESCAUM and the signatory states have convened a task force to develop a multi-state action plan to support electrification of medium- and heavy-duty vehicles. They will consider actions to accomplish the MOU's goals, including limiting all new medium- and heavy-duty vehicle sales in the signatory states to ZEVs by 2050. The signatory states will also seek to accelerate the deployment of medium- and heavy-duty ZEVs to benefit disadvantaged communities and explore opportunities to coordinate and partner with key stakeholders (AFDC 2020b). The states are also considering adopting California's heavy-duty omnibus rule, discussed above, with New Jersey being the first state to formally adopt the California rules (Baker 2021).

TRANSPORTATION CLIMATE INITIATIVE

The Transportation Climate Initiative (TCI) is a regional collaboration of Northeast and mid-Atlantic states and the District of Columbia that seeks to reduce carbon emissions from the transportation sector, improve sustainable transportation access, and develop the clean

[18] The states are California, Colorado, Connecticut, Delaware, Maine, Maryland, Massachusetts, New Jersey, New York, North Carolina, Oregon, Pennsylvania, Rhode Island, Vermont, and Washington, as well as the District of Columbia. Several other states are considering joining.

energy economy. In December 2020, three states (Connecticut, Massachusetts, and Rhode Island) and the District of Columbia signed an MOU outlining the details of the Transportation & Climate Initiative Program (TCI-P). At the same time, eight other states (Delaware, Maryland, New Jersey, New York, North Carolina, Pennsylvania, Vermont, and Virginia) joined the four MOU signatories in issuing a statement saying that they would continue to work together to develop the regional program's details while also pursuing state-specific initiatives to reduce emissions and provide clean transportation solutions (TCI 2020a).

Under the TCI-P MOU (TCI 2020b), emissions from finished gasoline and on-road diesel would be capped in the participating states. Wholesale fuel suppliers would be the regulated entity and would need to obtain allowances at auction for the emissions associated with the fuels they distribute for sale in signatory jurisdictions. Each TCI-P jurisdiction will decide how to invest allowance proceeds in projects that would reduce transportation emissions and the health effects of these emissions. The program will run from 2022 through 2032.

As part of the policy development process, the states worked with consultants and research partners to conduct economic and health modeling. Preliminary modeling results indicate that the initiative will modestly increase GDP, income, and jobs, and that health benefits will total hundreds of millions of dollars (TCI 2021). The hope is that the model rule will be developed in 2021, and states will then formally adopt the policy so that emissions reporting can begin in 2022 and the first TCI-P compliance period will begin in 2023. As revenues begin to accrue, spending on truck electrification programs should play a significant role, as should policy activity.

OTHER U.S. ACTIVITIES

Policies to promote truck electrification are also advancing in other parts of the United States. For example, incentive programs to promote electric truck purchases are operating in Chicago (Drive Clean Chicago, funded by a federal grant [Drive Clean Chicago 2017]) and in New York State (the NY Truck Voucher Incentive Program, funded by the New York State Energy Research and Development Administration [NYSERDA 2020]). Also, Colorado and Utah provide tax credits for the purchase of heavy-duty EVs (ACEEE 2020).

In April 2021, the New York legislature passed a bill requiring that all new light-duty vehicle sales in the state be zero-emission as of 2035, and that all new medium- and heavy-duty vehicle sales be zero-emission by 2045. As of late May 2021, the governor has not decided whether to sign or veto this legislation.

All U.S. states received substantial funds from the settlement of Volkswagen's diesel emissions fine. Under that settlement, states can use funds to repower or replace vehicles, develop shore power for ports, build-out EV charging station infrastructure, and expand other emissions-reducing programs (NASEO and NACAA 2021). A review of state spending plans for Volkswagen settlement funds found that 30 states are prioritizing electric bus purchases over diesel bus purchases in their plans (Casale and Mahoney 2019). ACEEE also found that states are using their Volkswagen funds to support transportation electrification, with only 6 of 31 states assessed allocating no funds toward electrification (Howard et al. 2021).

In addition to state-led efforts, many U.S. cities are taking steps to encourage and use electric trucks and buses. For example, as noted above in the bus section, New York City, Los Angeles, and San Francisco have made commitments to switch their public buses to electric buses, as has Minneapolis. Quite a few other cities are starting to use some electric buses, while a few cities—nationally and internationally—are testing electric garbage trucks, including Los Angeles (Taub 2018), Seattle (Gitlin 2019), and Sacramento; Hamburg, Germany; and Shenzhen, China (Shrubb 2019).

Cities can also encourage electric delivery vehicles by providing preferred access. Santa Monica, California, working with the Los Angeles Cleantech Incubator, has begun a pilot program to provide preferred access to loading zones in the heart of downtown for zero-emissions delivery vehicles, including electric vans, e-cargo scooters, and small delivery bots. The collaborators received a grant from the Governor's Office of Business and Economic Development to fund the pilot, which includes hiring a curb management company, Automotus, to analyze and monitor vehicle activity within the zone, collecting anonymized data to evaluate the effect on congestion, emissions, deliveries, and safety (Crowe 2021).

EUROPE

Europe has many programs and policies to encourage electric passenger vehicles. It also launched a European Clean Bus Deployment Initiative under which cities, regions, manufacturers, and transport organizations declare their intent to promote large-scale deployment of clean, alternatively fueled buses (European Commission 2019). The Netherlands has mandated that public transit purchase only zero-emissions buses by 2025 and convert their entire fleets by 2030 (dePee et al. 2018).

But, overall, Europe appears to be doing much less for trucks. For example, a recent European Parliament briefing document, *Electric Road Vehicles in the European Union*, includes only a single paragraph on trucks and buses, noting that about 2,500 electric buses are in use in Europe (Niestadt and Bjornavold 2019). Another report on EVs in Europe mentions trucks only twice—first to note that trucks are also eligible for EV incentives in Amsterdam, and second to briefly note differences between car and truck batteries (Amsterdam Roundtable Foundation and McKinsey & Company 2014).

Private-Sector Commitments to Electric Trucks

Private company commitments to purchase electric trucks can help provide an early market for these vehicles and help assure investors that the market is ready. As discussed above, many leading companies have made commitments to purchase electric trucks. Amazon has committed to purchase 100,000 delivery vans from Rivian, while Pepsi, FedEx, Walmart, UPS, and Sysco have been among those placing early orders for the Tesla Semi. FedEx plans on electrifying all of its delivery vehicles, currently totaling 180,000, by 2040, and plans to have half of its new vehicle purchases be electric by 2025 (Butler and Mufson 2021). Other significant commitments include orders by Anheuser-Busch for 800 Nikola fuel-cell trucks (Fialka 2019), by UPS for 950 electric delivery vans, and by Duke Energy for 500 electric pickup trucks (Taub 2018). More broadly, the Climate Group is undertaking a program under which companies make commitments to purchase EVs and related equipment including electric cars and trucks; 103 companies have signed on to date, including IKEA, which plans to electrify all of its home delivery vehicles by 2025, and Unilever (Climate Group 2021; Buholtz et al. 2021).

Recommended Path Forward

This paper addresses the current status of electric tractor-trailers, vocational trucks, buses, and heavy-duty pickups. As figures 12 and 13 show, of these four segments, by far the largest energy use (and hence the largest opportunities for reductions in GHG emissions) is in tractor-trailers, yet these high-consuming long-haul tractors also present the greatest challenges in terms of range and charging infrastructure. Electric buses are a smaller opportunity in terms of total energy use, but they are the furthest advanced of the four segments. Electric buses are in widespread use in China, and several U.S. states are starting to require their purchase for public transit fleets (California) and school buses (Maryland). Vocational trucks are the most varied of the segments, but as figure 22 shows, they are reaching parity with diesel trucks sooner than is true for heavier trucks. They could therefore be a possible bridge to more widespread use of electric trucks in broader applications. Heavy pickup trucks are also a significant segment, with multiple products soon to enter the market. In the following, we elaborate on critical steps forward for electric trucks overall and for each of these four segments. We conclude this section with a table summarizing recommended actions by market actor.

OVERALL

Across all of the truck categories, there is a critical need for charging infrastructure. Trucks need more juice than passenger vehicles and will often need to be charged quickly, which requires high-capacity chargers. Much of this infrastructure will be centralized at charging stations dedicated to specific fleets. But public charging will also be needed for long routes, such as at truck stops. These chargers will often require high power draws, so electric utilities will need to work with fleet owners and truck stops to figure out the best locations for this charging infrastructure. Further, in many locations, reinforcements to local power distribution networks will be needed. Electric utilities need to start planning these efforts now. They also need to design outreach efforts and rate structures (e.g., demand charges) to encourage use of managed charging strategies in order to minimize electric contributions to peak utility loads. Development of markets for electric trucks can be spurred by initial purchases by market leaders, such as government agencies and forward-looking private firms. These efforts should be expanded. Government at all levels should also expand funding for key transition investments, with the efforts of CARB illustrating how a comprehensive effort can work. However, even in California, demand for funds is exceeding supply, and additional resources would be useful. California's light-duty ZEV program has been an important driver of U.S. electric car sales to date; the recently finalized heavy-duty vehicle program is likely to do the same for trucks.

Critical to a successful effort is continued progress on heavy-duty fuel efficiency and GHG standards. Despite recent progress, a full transition to electric trucks is more than a decade away, and incremental advances on conventional and hybrid trucks are required to cut emissions in the meantime and help drive the technologies—including batteries and motors, advanced materials, and improved aerodynamics—needed for a successful transition to zero-emissions trucks. Additionally, fuel-cell vehicles may be the best solution for certain heavy-duty applications (e.g., for tractors needing to drive more than 500 miles), and research and testing must continue in that area as well.

In 2006–2009, federal tax incentives for advanced trucks were available, promoting hybrid, fuel-cell, and other advanced vehicles. Congress should consider updating and restarting this program. The current federal tax credit of up to $7,500 for EV purchase applies to vehicles up to 14,000 lbs. GVW, which includes heavy-duty pickups and Class 3 vocational vehicles; a federal credit for heavier EVs would be very useful to launch these crucial segments. In May 2021, the Senate Finance Committee reported out the Clean Energy for America Act, which includes federal tax incentives for 30% of the cost of commercial EVs, capped at the incremental cost of an EV compared to a similar ICE vehicle. The bill includes a provision that, for tax-exempt entities, the vehicle seller may take the tax credit (Senate Finance Committee 2021). While tax incentives are useful, not all purchasers pay taxes and there may be cashflow issues before the tax credit can be booked. Rebates that can be subtracted from the purchase price would be even better, such as those offered in California and New York State.

Finally, manufacturers need to continue ongoing efforts to improve their products, increasing range and addressing such issues as cold and hot weather performance.

BUSES

Multiple states, cities, transit agencies, and school systems are making commitments to electric buses. Financing will be important, as the upfront cost of electric buses is substantial for both the buses and the charging infrastructure. To some extent, private companies can offer financing, but given tight municipal and school district budgets, additional assistance will be needed from federal and state governments, and perhaps from electric utilities.

For buses in particular, cold and hot weather performance has been an issue that manufacturers must continue to address.

State and local policymakers should consider establishing specific transition schedules like California and the Netherlands have done for transit buses and Maryland has done for school buses. Priority for transit and school bus electrification should be given to low- and moderate-income communities and other communities with historically higher exposure to air pollution, and especially diesel exhaust.

VOCATIONAL TRUCKS

Vocational trucks are diverse and come in many shapes and sizes. Many more models are needed to serve vocational needs in order to complement the 21 models listed in table 3; fortunately, manufacturers are now developing many new models. Incentives such as those that California, Colorado, New York, Utah, and Chicago are implementing are useful (ACEEE 2020), and additional states and cities should follow their example.

Local governments have a role to play in advancing electric trucks in order to limit exposure to diesel emissions in densely populated areas. Several cities globally have set dates beyond which no diesel or ICE vehicle will be permitted to enter. As noted previously, the ports of Los Angeles and Long Beach will transition entirely to ZEVs and equipment by 2035. In the meantime, cities can take steps such as considering pilot programs to relax nighttime delivery restrictions on electric delivery vehicles (due to their quieter operation). Offering preferred access to core delivery zones (as Santa Monica is doing) should also be considered for electric trucks to reduce noise and pollution while giving clean, quiet vehicles an opportunity to provide additional value to customers.

TRACTOR-TRAILERS

Electric tractors that can travel medium distances (approximately 250 miles) or long distances (approximately 500 miles) on a single charge under load are not presently available, but such vehicles are now in road testing and scheduled to enter the market in the coming year. Hopefully, these vehicles will have good performance and manufacturers will meet their price targets. Electric tractors will have a large price premium, but the premium will decline as the cost of batteries and other components continue to fall. Lead-off purchasers will be important, including many of the private companies discussed above in the "Private-Sector Commitments" box, as will government purchases, such as by the U.S. Army or Postal Service.

NACFE has identified regional haul as a particularly promising market segment for electrification due to its growth, the distances involved (typically under 300 miles per haul), the increasing use of systems to collect and analyze data and optimize use, and the types of companies serving these markets (NACFE 2019b).

Another major priority will be high-power chargers along major trucking routes. Tesla's megacharger will need about 1.6 MW. A coalition (CharIN) has formed to develop a common charger specification (Lambert 2019c), which should aid deployment. Utilities and truck stops will need to work together on charging networks; having government financial assistance for initial charger deployments would be useful. Given the high power draw of electric tractors, charging infrastructure is perhaps more challenging for them than for other truck segments.

HEAVY PICKUP TRUCKS

Heavy-duty pickups, to a far greater degree than the other truck types discussed here, can piggyback on the burgeoning investment in light-duty batteries, motors, and charging infrastructure to establish a presence in the EV market. As manufacturers roll out battery-electric versions of their high-volume, light-duty pickups over the next few years, it will be important to watch and build on their ability to promote EVs as a capable substitute for—and improvement upon—the high-powered, high-performing vehicles that play an important role in the U.S. market. Given the substantially higher percentage of trucks used as work vehicles in Class 2b than among their light-duty counterparts, capabilities such as worksite power provision should be a greater selling point for the heavy-duty versions.

Availability of the $7,500 federal tax credit for EVs up to 14,000 lbs. could support this market in the early years, so it is important that the program be extended in ways that allow these vehicles to emerge.

SUMMARY

Table 6 summarizes our recommendations.

Table 6. Summary of recommended actions by market actor

<table>
<tr><th>Action</th><th>Federal policy</th><th>State policy</th><th>Local policy</th><th>Utilities</th><th>Vehicle manufacturers</th><th>Vehicle users</th></tr>
<tr><td rowspan="2">Charging</td><td colspan="6">Help fund build-out of charging</td></tr>
<tr><td></td><td></td><td>Address charger siting issues</td><td>Plan for new large loads at fleet lots and truck stops; encourage managed charging</td><td></td><td></td></tr>
<tr><td>Incentives/tax credits for vehicle purchases</td><td colspan="4">Provide/fund</td><td></td><td></td></tr>
<tr><td>Purchases</td><td colspan="4">Make early purchases</td><td></td><td>Make early purchases</td></tr>
<tr><td>Zero-emission sales share requirements</td><td>Consider</td><td>Enact, as California is doing for many trucks and Maryland is doing for school buses</td><td>Enact for buses (as in multiple cities)</td><td></td><td></td><td></td></tr>
<tr><td>Other</td><td>Improve data collection</td><td></td><td>Relax delivery restrictions for quiet vehicles; provide preferred access for EVs in core zones; restrict diesel vehicles in residential neighborhoods</td><td></td><td>Develop more products and improve existing products (e.g., range and hot and cold weather performance)</td><td></td></tr>
</table>

Conclusion

A growing number of electric trucks are now on the market, and many more models are expected to enter the market in the next few years. Electric trucks often have a number of advantages over conventional trucks, including lower energy use and emissions (assuming a moderately clean electric grid), higher torque, and lower maintenance requirements. However, they cost more up front, current models often have limited range, and charging infrastructure is limited.

Leading states and cities have begun to transition their entire bus fleets to electricity. Buses are thus leading the way on heavy-duty electrification, although issues of performance in very hot and cold weather still need to be addressed. Tractor-trailers are the biggest opportunity for reducing truck energy use and emissions, though they pose the greatest challenges with regard to batteries and charging infrastructure. Models currently on the market have a short range, but models with longer ranges (up to 500 miles) are scheduled to enter the market in 2021 and 2022. With ranges this long, the majority of truck routes can be served. For hauls of more than 500 miles, fuel-cell tractor-trailers are scheduled to enter the market in approximately 2023. Vocational vehicles are the most varied of the segments and will soon reach parity with diesel trucks for a number of market segments. They could therefore be a potential bridge to more widespread use of electric trucks in broader applications. Heavy pickup trucks are also a significant segment and, while there are not yet any electric products, multiple products are scheduled to enter the market in the next few years.

For all of these markets, compared to conventional vehicles, EVs have substantially higher upfront costs, driven primarily by the cost of batteries. To help bridge this gap, financial incentives and financing are often useful. Zero-emission truck mandates (such as those California has developed) also help. In addition, for electric trucks to advance, we will need progress on electric charging infrastructure as well as on electric rates. Charging infrastructure now being built for passenger vehicles can often be used for lighter trucks, but to serve all truck markets, substantial additional charging infrastructure will be needed at bus depots, truck stops, and fleet home bases. When a substantial number of chargers are needed at a particular location, reinforcement of the electric grid may be needed. And, until chargers are used frequently, electric demand charges can be a substantial cost. To address this problem, some utilities are implementing alternatives to demand charges, and other utilities should follow their lead.

Electric trucks have a promising future, but much near-term work must be done to help realize their many benefits and overcome present challenges. Particular priorities are to encourage initial purchases (including through financial and other incentives) and build out charging infrastructure. Also, California's light-duty ZEV program has been a primary driver of U.S. electric car sales to date, with 13 other states adopting its program to date. The recently enacted California heavy-duty vehicle program and a potential expansion to other leading states could well do the same for trucks.

References

Abt, N. 2019. "OEMs Closely Monitoring California's Proposal on Electric Truck Sales." *Fleet Owner*, November 21. www.fleetowner.com/resource-center/regulations/article/21704505/oems-closely-monitoring-californias-proposal-on-electric-truck-sales?fbclid=IwAR0Q7Lc2yLD_90JBDj3kHvFDMHIMHo0KzwJePDWjRZKRhtrEZRcJomQIpLg.

AB Volvo. 2019. "Volvo Trucks Launches Sales of Electric Trucks for Urban Transport." *Cision PR Newswire*, November 6. www.volvotrucks.com/en-en/news/press-releases/2019/nov/pressrelease-191106.html.

ACEEE. 2020. "Incentives for High-Efficiency Vehicles." www.database.aceee.org/state/incentives-high-efficiency-vehicles.

AFDC (Alternative Fuels Data Center). 2020a. "Average Annual Vehicle Miles Traveled by Major Vehicle Categories." www.afdc.energy.gov/data/widgets/10309.

——. 2020b. "Medium- and Heavy-Duty Zero Emission Vehicle (ZEV) Deployment Support." www.afdc.energy.gov/laws/12459.

——. 2021. "Alternative Fuel and Advanced Vehicle Search." www.afdc.energy.gov/vehicles/search/.

Aldama, Z. 2019. "Powered by the State, China Takes Charge of Electric Buses, with Shenzhen Taking the Lead." *South China Morning Post Magazine,* January 17. www.scmp.com/magazines/post-magazine/long-reads/article/2182466/powered-state-china-takes-charge-electric-buses.

Allen, L. 2020. "GMC Hummer EV Expected to Span Multiple GVWR Classes." *Muscle Cars & Trucks*, November 9. www.musclecarsandtrucks.com/gmc-hummer-ev-to-span-multiple-classes/.

Amsterdam Roundtable Foundation and McKinsey & Company. 2014. *Evolution – Electric Vehicles in Europe: Gearing Up for a New Phase?* Amsterdam: Amsterdam Roundtable Foundation and McKinsey & Company. www.mckinsey.com/featured-insights/europe/electric-vehicles-in-europe-gearing-up-for-a-new-phase.

Baker, L. 2021. "New Jersey First State to Adopt California Electric Truck Sales Mandate." *FreightWaves,* January 1. www.freightwaves.com/news/new-jersey-first-state-in-nation-to-adopt-california-electric-truck-sales-mandate.

Barbose, J., and J. Martin. 2018. *California's Clean Fuel Standard Boosts the Electric Vehicle Market*. Cambridge, MA: UCS (Union of Concerned Scientists). www.ucsusa.org/sites/default/files/attach/2018/01/cv-fact-sheet-lcfs.pdf.

Barboza, T. 2017. "Plan Calls for L.A., Long Beach Ports to Go to Zero-Emissions Technology; Cost Could Hit $14 Billion." *Los Angeles Times*, July 19. www.latimes.com/local/lanow/la-me-ports-clean-air-20170719-story.html.

Birky, A., M. Laughlin, K. Tartaglia, R. Price, B. Lim, and Z. Lin. 2017. *Electrification beyond Light Duty: Class 2b-3 Commercial Vehicles*. Prepared by Oak Ridge National Laboratory. Washington, DC: DOE (Department of Energy). www.osti.gov/servlets/purl/1427632.

Black & Veatch. 2019. *Electric Fleets: 8 Step to Medium and Heavy-Duty Fleet Electrification*. Overland Park, KS: Black & Veatch. www.bv.com/sites/default/files/2019-11/Electric_Fleets_Ebook_2019.pdf .

Blanco, S. 2018. "The U.S. Just Spent $84M on Electric Buses." *Forbes*, August 31. www.forbes.com/sites/sebastianblanco/2018/08/31/84-million-electric-buses/#268fe5bd5e40.

BNEF (Bloomberg New Energy Finance). 2020. "Battery Pack Prices Cited Below $100/kWh for the First Time in 2020, While Market Average Sits at $137/kWh." *BNEF Blog*, December 16. about.bnef.com/blog/battery-pack-prices-cited-below-100-kwh-for-the-first-time-in-2020-while-market-average-sits-at-137-kwh/.

Bouton, S., E. Hannon, L. Haydamous, B. Heid, Stefan Knupfer, T. Naucler, F. Neuhaus, J. Nijssen, and S. Ramanathan. 2017. *An Integrated Perspective on the Future of Mobility, Part 2: Transforming Urban Delivery*. New York: McKinsey Center for Business and Environment. www.mckinsey.com/~/media/mckinsey/business%20functions/sustainability/our%20insights/urban%20commercial%20transport%20and%20the%20future%20of%20mobility/an-integrated-perspective-on-the-future-of-mobility.ashx.

Brutz, H., A. Carr, B. Lips, A. Proudlove, and D. Sarkisian. 2018. *50 States of Electric Vehicles: Q3 2018 Quarterly Report – Executive Summary*. Raleigh: North Carolina Clean Energy Technology Center. www.nccleantech.ncsu.edu/wp-content/uploads/2018/11/Q3-18_EV_execsummary_Final_2.pdf.

BTS (Bureau of Transportation Statistics). 2021. "Vehicle Inventory and Use Survey." www.bts.gov/vius.

Buholtz, T., A. Burger, S. Gander, B. Nelson, B. Prochazka and N. Swalnick. 2020. *Electrifying Freight: Pathways to Accelerating the Transition*. Washington, DC: Electrification Coalition. www.electrificationcoalition.org/electrifying-freight-pathways-to-accelerating-the-transition/.

Butler, D., and S. Mufson. 2021. "Can the Market Save the Planet? FedEx is the Latest Brand-Name Firm to Say It's Trying." *Washington Post*, March 5. www.washingtonpost.com/climate-environment/2021/03/05/more-than-50-companies-have-vowed-be-carbon-neutral-by-2040/.

Buysse, C., and B. Sharpe. 2020. *California's Advanced Clean Trucks Regulation: Sales Requirements for Zero-Emission Heavy-Duty Trucks*. Washington, DC: ICCT (International Council on Clean Transportation). www.theicct.org/sites/default/files/publications/CA-HDV-EV-policy-update-jul212020.pdf.

California DOT (Department of Transportation). 2021. "Transit and Intercity Rail Capital Program (TIRCP)." www.dot.ca.gov/programs/rail-and-mass-transportation/transit-and-intercity-rail-capital-program.

California Energy Commission. 2021. "Clean Energy and Pollution Reduction Act—SB 350." www.energy.ca.gov/rules-and-regulations/energy-suppliers-reporting/clean-energy-and-pollution-reduction-act-sb-350.

California HVIP (Hybrid and Zero-Emission Truck and Bus Voucher Incentive Project). 2021. "Clean-Air Vehicles at a Fraction of the Price." californiahvip.org/purchasers/.

Capstone Logistics. 2019. "Trend Watch 2019: Length-of-Haul Shift Reshapes Trucking." *Capstone Logistics Blog*, March 29. www.loaddelivered.com/blog/trend-watch-2019-length-of-haul-shift-reshapes-trucking/.

CARB (California Air Resources Board). 2018. *Assessment of a Zero Emissions Vehicle Requirement for Light and Heavy-Duty Vehicle Fleets*. Sacramento: CARB. ww3.arb.ca.gov/msprog/zev_fleet_workshop_presentation_083018.pdf.

———. 2019. *Public Hearing to Consider the Proposed Advanced Clean Trucks Regulation – Staff Report: Initial Statement of Reasons*. Sacramento: CARB. ww3.arb.ca.gov/regact/2019/act2019/isor.pdf.

———. 2021. "Advanced Clean Fleets." ww2.arb.ca.gov/our-work/programs/advanced-clean-fleets/about.

Carpenter, S. 2019. "Can Electric School Buses Make the Grade?" *Trucks.com*, March 22. www.trucks.com/2019/03/22/can-electric-school-buses-make-the-grade/.

Casale, M., and B. Mahoney. 2019. *Volkswagen Settlement State Scorecard*. Washington, DC: U.S. PIRG Education Fund. www.uspirg.org/reports/usp/volkswagen-settlement-state-scorecard.

Chandler, S., J. Espino, and J. O'Dea. 2017. *Delivering Opportunity: How Electric Buses and Trucks Can Create Jobs and Improve Public Health in California*. Cambridge, MA: UCS (Union of Concerned Scientists). Oakland: Greenlining Institute. www.ucsusa.org/clean-vehicles/electric-vehicles/freight-electrification.

Chispa Maryland. 2021. "Clean Buses Healthy Niños." www.marylandconservation.org/cbhk.

Clasp Auto. 2021. "Average Lifespan of a Truck—Here's What You Need to Know." www.claspauto.com/average-lifespan-of-a-truck/.

Clean Energy Works. 2021. "PAYS for Clean Transport—FAQ." www.cleanenergyworks.org/pays-for-clean-transport-faq/.

Climate Group. 2021. "EV100 Members." www.theclimategroup.org/ev100-members.

Con Edison (Consolidated Edison). 2020. "Con Edison Test Driving E-School Buses Toward Improved Reliability and Cleaner Air." www.prnewswire.com/news-releases/con-edison-test-driving-e-school-buses-toward-improved-reliability-and-cleaner-air-301190805.html.

Crow, A., D. Mullaney, Y. Liu, and Z. Wang. 2019. *A New EV Horizon: Insights from Shenzhen's Path to Global Leadership in Electric Logistics Vehicles*. Basalt, CO: RMI (Rocky Mountain Institute). www.rmi.org/insight/a-new-ev-horizon/.

Crowe, C. 2021. "Santa Monica, California, Aims to Create Zero-Emissions Delivery Zone Playbook." *Smart Cities Dive*, March 3. www.smartcitiesdive.com/news/santa-monica-LACI-zero-emission-delivery-zone-cities/595919/.

Cunningham, W. 2017. "Chanje's Electric Delivery Truck Flattens Noise and Pollution." *Road Show by CNET*, August 10. www.cnet.com/roadshow/news/chanje-reduce-city-noise-pollution-electric-trucks-fossil-fuel/.

Daimler Trucks. 2019. "Daimler Trucks North America Recognized with Clean Air Technology Award." www.daimler-trucksnorthamerica.com/company/newsroom/press-releases/PressDetail/daimler-trucks-north-america-recognized-with-2019-10-04.

Daniels, L., and C. Nelder. 2021. *Steep Climb Ahead: How Fleet Managers Can Prepare for the Coming Wave of Electrified Vehicles*. Basalt, CO: RMI. www.rmi.org/wp-content/uploads/dlm_uploads/2021/01/steep_climb_ahead_fleets_survey_2021.pdf.

Davis, S., and R. Boundy. 2021. *Transportation Energy Data Book, Edition 39*. Prepared by ORNL (Oak Ridge National Laboratory). Washington, DC: DOE (Department of Energy). tedb.ornl.gov/wp-content/uploads/2021/02/TEDB_Ed_39.pdf.

Deb. S., K. Tammi, K. Kalita, and P. Mahanta. 2018. "Impact of Electric Vehicle Charging Station Load on Distribution Network." *Energies* 11 (1): 178. www.mdpi.com/1996-1073/11/1/178/pdf.

De La Rosa, S. 2019. "Are Zero-Emission School Buses Efficient Enough to Merit the Cost?" *Education Dive*, April 16. www.educationdive.com/news/are-zero-emission-school-buses-efficient-enough-yet-to-merit-the-cost/552606/.

de Pee, A., H. Engel, M. Guldemond, A. Keizer, and J. van de Staaij. 2018. "The European Electric Bus Market Is Charging Ahead, but How Will It Develop?" *McKinsey Insights*, July 2. www.mckinsey.com/industries/oil-and-gas/our-insights/the-european-electric-bus-market-is-charging-ahead-but-how-will-it-develop.

DOE (Department of Energy). 2011. "Fact #707: December 26, 2011 Illustration of Truck Classes." www.energy.gov/eere/vehicles/fact-707-december-26-2011-illustration-truck-classes.

Dominion Energy. 2019. "Dominion Energy Proposes Largest Electric School Bus Initiative in the Country." news.dominionenergy.com/2019-08-29-Dominion-Energy-Proposes-Largest-Electric-School-Bus-Initiative-in-the-Country.

DOT (Department of Transportation). 2019. "U.S. Department of Transportation Announces $85 Million in Grants for Projects Nationwide to Expand Advanced Bus Technologies." www.transit.dot.gov/about/news/us-department-transportation-announces-85-million-grants-projects-nationwide-expand.

Drive Clean Chicago. 2017. "Funding Announcement." www.drivecleanchicago.com.

Eckhouse, B. 2019. "The U.S. Has a Fleet of 300 Electric Buses. China Has 421,000." *Bloomberg*, May 15. www.bloomberg.com/news/articles/2019-05-15/in-shift-to-electric-bus-it-s-china-ahead-of-u-s-421-000-to-300.

EDF (Environmental Defense Fund). Undated. *Emissions from School Buses Increase Pollution Levels Inside the Bus*. New York: EDF. www.edf.org/sites/default/files/5342_School_bus_pollution_studies.pdf.

EIA (Energy Information Administration). 2019. *Annual Energy Outlook 2019*. Washington, DC: EIA. www.eia.gov/outlooks/archive/ieo19/.

———. 2021. "Electric Power Monthly." www.eia.gov/electricity/monthly/.

EPA (Environmental Protection Agency). 2014. *Near Roadway Air Pollution and Health: Frequently Asked Questions*. Washington, DC: EPA. www.epa.gov/sites/production/files/2015-11/documents/420f14044_0.pdf.

———. 2016. *National Port Strategy Assessment: Reducing Air Pollution and Greenhouse Gases at U.S. Ports*. Washington, DC: EPA. www.epa.gov/ports-initiative/national-port-strategy-assessment-reducing-air-pollution-and-greenhouse-gases-us.

———. 2021. *2017 National Emissions Inventory Report*. Washington, DC: EPA. gispub.epa.gov/neireport/2017/.

Espino, J., and V. Truong. 2015. *Electric Carsharing in Underserved Communities: Considerations for Program Success*. Oakland: Greenlining Institute. www.greenlining.org/wp-content/uploads/2015/01/Electric-Carsharing-in-Underserved-Communities-print-friendly.pdf.

European Commission. 2019. "European Clean Bus Deployment Initiative." www.ec.europa.eu/transport/themes/urban/cleanbus_en.

EVANNEX. 2019. "Just How Long Will an EV Battery Last?" *Inside EVs*, September 3. www.insideevs.com/news/368591/electric-car-battery-lifespan/.

Evans, E., and M. Folger. 2021. *Accelerating the Transition to Electric School Buses.* Washington, DC: U.S. PIRG Education Fund. www.uspirg.org/sites/pirg/files/reports/US_EL%20buses%202021%20scrn.pdf.

Fehrenbacher, K. 2019. "The Great EV Infrastructure Challenge." *GreenBiz*, November 13. www.greenbiz.com/article/great-ev-infrastructure-challenge.

Ferris, D. 2021a. "Navistar, GM Partner to Build Hydrogen Trucks by 2024." *Energywire*, January 28. www.eenews.net/stories/1063723727.

——. 2021b. "'Accelerated': How Amazon Plans to Deploy Electric Vans." *Energywire*, February 4. www.eenews.net/stories/1063724359/print.

——. 2021c. "GM Venture Takes Aim at EV Frontier: Delivery Vans." *Energywire*, January 13. www.eenews.net/stories/1063722429.

——. 2020. "Ford's EV Plan: It's the Service, Not the Van." *Energywire*, November 13. www.eenews.net/stories/1063718399/.

FHA (Federal Highway Administration). 2021. "Highway Statistics 2019." www.fhwa.dot.gov/policyinformation/statistics/2019/.

Fialka, J. 2019. "Meet the CEO Who's Building 14K Hydrogen Semitrucks." *Climatewire*, September 12. www.eenews.net/stories/1061113811.

Fisher, J. 2019. "Volvo's First Electric VNR Ready for the Road." *FleetOwner*, September 17. www.fleetowner.com/blue-fleets/volvo-s-first-electric-vnr-ready-road.

Freightliner. 2020. *eCascadia: Leading the Charge in eMobility*. Portland, OR: Freightliner. www.act-news.com/wp-content/uploads/2020/10/DDCTEC-14842-eCascadia-Sell-Sheet_1.1.pdf.

Fretty, P. 2020. "Why Is UPS Betting on the Arrival of a New EV?" *IndustryWeek*, September 16. www.industryweek.com/technology-and-iiot/article/21141940/why-is-ups-betting-on-the-arrival-of-a-new-ev.

——. 2021. "Arrival's EV Van Hits the Road." *IndustryWeek*, March 4. www.industryweek.com/technology-and-iiot/article/21156906/arrivals-ev-van-hits-the-road.

Gallo, J. 2015. *Electric Truck & Bus Grid Integration: Opportunities, Challenges & Recommendations*. Pasadena: CALSTART, Inc. www.calstart.org/wp-content/uploads/2018/10/Electric-Truck-and-Bus-Grid-Integration_-Opportunities-Challenges-and-Recommendations.pdf.

Gao, Z., Z. Lin, S. Davis, and A. Birky. 2018. "Quantitative Evaluation of MD/HD Vehicle Electrification Using Statistical Data." *Transportation Research Record* 2672 (24): 109–21. journals.sagepub.com/doi/abs/10.1177/0361198118792329.

Garber, J. 2019. "Tesla Semi Gets 'Real World Validation.'" *Fox Business*, October 7. www.foxbusiness.com/lifestyle/tesla-semi-gets-real-world-validation.

Gilboy, J. 2018. "Daimler Delivers First Freightliner eM2 Commercial Electric Truck to Penske." *The Drive*, December 25. www.thedrive.com/news/25626/daimler-delivers-first-freightliner-em2-commercial-electric-truck-to-penske.

Gilroy, R. 2019. "Kenworth, Toyota Partner on Hydrogen Fuel Cell Class 8 Trucks." *Transport Topics*, October 27. www.ttnews.com/articles/kenworth-toyota-partner-hydrogen-fuel-cell-class-8-trucks.

Gitlin, J. 2019. "Seattle Makes History with Electric Garbage Truck." *Ars Technica*, May 22. www.arstechnica.com/cars/2019/05/seattle-makes-history-with-electric-garbage-truck/.

GNA (Gladstein, Neandross & Associates). 2021. *California Heavy-Duty Fleet Electrification Summary Report*. New York: EDF. blogs.edf.org/energyexchange/files/2021/03/EDF-GNA-Final-March-2021.pdf.

Gnaticov, C. 2018. "Nikola One Hydrogen Electric Semi Hits the Road in Official Film." *Carscoops*, January 26. www.carscoops.com/2018/01/nikola-one-hydrogen-electric-semi-hits-road-official-film/.

Haag, M., and W. Hu. 2019. "1.5 Million Packages a Day: The Internet Brings Chaos to N.Y. Streets." *New York Times*, October 27. www.nytimes.com/2019/10/27/nyregion/nyc-amazon-delivery.html.

Haggiag, A. 2019. "3 Things You Need to Know about Electric Buses." *Metro*, September 30. www.metro-magazine.com/zero-emissions/article/735729/3-things-you-need-to-know-about-electric-buses.

Halvorson, B. 2018. "Is Tesla's Semi on the Back Burner?" *Car and Driver*, May 4. www.caranddriver.com/news/a20165777/is-teslas-semi-on-the-back-burner/.

HDR, CALSTART, S-Curve Strategies, and Ross Strategic. 2020. *West Coast Clean Transit Corridor Initiative: Interstate 5 Corridor – California, Oregon, Washington, Final Report.* Omaha, NE: HDR. www.hdrinc.com/portfolio/west-coast-clean-transit-corridor-initiative.

HDT (Heavy-Duty Trucking). 2020. "Hydrogen-Fuel-Cell Trucks Going to Work at SoCal Ports." *Heavy-Duty Trucking, Trucking Info*. Dec. 10.

www.truckinginfo.com/10132268/kenworth-t680s-with-toyota-hydrogen-fuel-cell-powertrains-go-to-work-at-the-port.

He, H., L. Jin, H. Cui, and H. Zhou. 2018. *Assessment of Electric Car Promotion Policies in Chinese Cities*. Washington, DC: ICCT. www.theicct.org/publications/assessment-electric-car-promotion-policies-chinese-cities.

Hewlett Foundation. 2020. *Zero Emission Road Freight Strategy, 2020-2025*. Menlo Park, CA: Hewlett Foundation. www.hewlett.org/library/zero-emissions-road-freight-strategy/.

Hirsch, J. 2018a. "Daimler Unveils Electric Freightliner Cascadia." *Trucks.com*, June 6. www.trucks.com/2018/06/06/daimler-unveils-electric-freightliner-cascadia/.

——. 2018b. "First Drive: Volvo FL Electric Trucks Show the Technology Is Ready." *Trucks.com*, June 21. www.trucks.com/2018/06/21/first-drive-volvo-fl-electric-trucks/.

——. 2019a. "Hyundai Unveils Fuel Cell Truck, Explores U.S. Commercial Vehicle Market." *Trucks.com,* October 28. www.trucks.com/2019/10/28/hyundai-plans-fuel-cell-truck-explores-commercial-vehicle-market/.

——. 2019b. "Volvo Trucks Unveils Electric Truck, Readies Commercialization." *Trucks.com*, September 13. www.trucks.com/2019/09/13/volvo-unveils-vnr-electric-truck/.

Howard, B., S. Vaidyanathan, C. Cohn, N. Henner, and B. Jennings. 2021. *The State Transportation Electrification Scorecard*. Washington, DC: ACEEE. www.aceee.org/research-report/t2101.

Huether, P. 2021. *Siting Electric Vehicle Supply Equipment (EVSE) with Equity in Mind.* Washington, DC: ACEEE. www.aceee.org/white-paper/2021/03/siting-electric-vehicle-supply-equipment-evse-equity-mind.

Iaconangelo, D. 2021. "Electric Bus Maker Rolls Out Plan for U.S. Factory." *Energy Wire*, May 10. www.eenews.net/energywire/2021/05/10/stories/1063732081.

IC Bus. 2020. "IC Bus Announces First Electric CE School Bus Order." *School Transportation News*, September 8. www.stnonline.com/industry-releases/ic-bus-announces-first-electric-ce-school-bus-order/.

Jensen, S. 2020. "Commercial Availability of Electric Vehicles and Equipment Increases." *OEM Off-Highway*, December 17. www.oemoffhighway.com/trends/electrification/article/21207226/commercial-availability-of-electric-vehicles-and-equipment-increases.

Kane, M. 2018. "California Mandates Electric Buses Only by 2040." *Inside EVs*, December 17. www.insideevs.com/news/341620/california-mandates-electric-buses-only-by-2040/.

Kellison, B. 2019. "4 Takeaways from Amazon's Huge Electric Delivery Van Order." *Greentech Media*, September 26. www.greentechmedia.com/articles/read/4-takeaways-from-amazons-huge-electric-delivery-van-order-with-rivian.

Kenworth. 2020. "Kenworth Launches its First-Ever Class 8 Battery-Electric Model – Kenworth T680E." *Kenworth News*, October 14. www.kenworth.com/about-us/news/t680e/.

Lake, S. 2020. "Dominion Launches Electric School Bus Program." *Virginia Business*. Oct. 28. www.virginiabusiness.com/article/dominion-launches-electric-school-bus-program/.

Lambert, F. 2017. "Tesla Semi Met and Then Crushed Almost All of Our Expectations." *Electrek*, November 17. www.electrek.co/2017/11/17/tesla-semi-electric-truck-specs-cost/.

——. 2018a. "Peterbilt Becomes Latest Truck Maker to Work on All-Electric Class 8 Truck to Compete with Tesla Semi." *Electrek*, May 2. www.electrek.co/2018/05/02/peterbilt-truck-maker-all-electric-class-8-tesla-semi/.

——. 2018b. "Watch Tesla Semi Prototypes Drive with Cargo for the First Time." *Electrek*, March 9. www.electrek.co/2018/03/09/watch-tesla-semi-prototypes-driving-cargo-trailer/.

——. 2019a. "Rivian Unveils First Picture of New Electric Van." *Electrek*, September 19. www.electrek.co/2019/09/19/rivian-electric-van-picture/.

——. 2019b. "Tesla Cybertruck Is a 'Medium-Duty Truck' Due to Payload Capacity, Says Tesla in CARB Filing." *Electrek*, October 13. www.electrek.co/2019/12/13/tesla-cybertruck-medium-duty-vehicle-carb/.

——. 2019c. "Tesla Is Pushing for Its Own >1 MW High-Power Charging Standard for Electric Trucks." *Electrek*, July 10. www.electrek.co/2019/07/10/tesla-high-power-charging-standard-electric-trucks/.

——. 2019d. "Tesla Semi Electric Truck Exceeds Range Expectation Almost Fully Loaded, Says Test Driver." *Electrek*, August 15. www.electrek.co/2019/08/15/tesla-semi-electric-truck-exceeds-range-expectation-test-driver/.

——. 2019e. "Tesla Semi Electric Truck Production to Start 'with Limited Volumes' in 2020." *Electrek*, October 23. www.electrek.co/2019/10/23/tesla-semi-electric-truck-production-limited-volume-2020/.

Levy, A. 2019. "The Verdict's Still Out on Battery-Electric Buses." *CityLab*, January 17. www.citylab.com/transportation/2019/01/electric-bus-battery-recharge-new-flyer-byd-proterra-beb/577954/.

Lion Electric Co. 2020. "Lion Electric to Deliver 10 All-Electric Trucks to Amazon." *Cision PR Newswire*, September 23. www.prnewswire.com/news-releases/lion-electric-to-deliver-10-all-electric-trucks-to-amazon-301136284.html.

Liu, G. 2017. "Close-Up Look at the Tesla Semi 'Megacharger' Charging Port." *Teslarati,* November 17. www.teslarati.com/tesla-semi-megacharger-charging-port-close-up-look/.

Loki, R. 2016. "America Is a Wasteland: The U.S. Produces a Shocking Amount of Garbage." *Salon*, July 15. www.salon.com/2016/07/15/america_is_a_wasteland_the_u_s_produces_a_shocking_amount_of_garbage_partner/.

Lovely, L. 2020. "CNG Trucks Still Used by Many in the Industry, but Electric Vehicles Gaining Ground." *Waste Dive*, September 2. www.wastedive.com/news/cng-rng-waste-trucks-electric-fleet/584374/.

Lowell, D., and A. Huntington. 2021. *Electric Vehicle Market Status – Update.* Concord, MA: M.J. Bradley & Associates. www.mjbradley.com/sites/default/files/EDF_EV_Market_Report_January_2021_Update_0.pdf.

MacDonald, C., and A. Palmer. 2018. "'Sounds Like Some Kind of Spacecraft': Listen to the Unusual Noise of a Tesla Semi Electric Truck Accelerating with a Trailer." *Daily Mail*, September 27. www.dailymail.co.uk/sciencetech/article-6203343/Listen-unusual-noise-Tesla-Semi-electric-truck-accelerating-trailer.html.

MacDougall, P., and T. O'Connor. 2021. *Charging Forward: Recommendations for Reducing Charging Infrastructure Costs for Heavy-Duty Trucks*. New York: EDF. blogs.edf.org/energyexchange/files/2021/03/EDF-ChargingForward-FINAL.pdf.

MacKechnie, C. 2019. "How Long Do Buses and Other Transit Vehicles Last?" *liveaboutdotcom*, January 16. www.liveabout.com/buses-and-other-transit-lifetime-2798844.

Manthey, N. 2018. "Extra Large 13 MW Charge Depot for 100 e-buses Live in Amsterdam." *Electrive*, March 28. www.electrive.com/2018/03/28/extra-large-13-mw-charge-depot-for-100-e-buses-live-in-amsterdam/.

Marcacci, S. 2018. "Electric Buses Can Save Local U.S. Governments Billions. China's Showing Us How It's Done." *Forbes*, May 21. www.forbes.com/sites/energyinnovation/2018/05/21/electric-buses-can-save-americas-local-governments-billions-chinas-showing-us-how-its-done/?sh=6001bf9a5f78.

Margolis, J. 2019. "China Dominates the Electric Bus Market, but the US Is Getting on Board." *The World*, October 8. www.pri.org/stories/2019-10-08/china-dominates-electric-bus-market-us-getting-board.

Marshall, A. 2019. "Why Electric Buses Haven't Taken Over the World—Yet." *Wired*, June 7. www.wired.com/story/electric-buses-havent-taken-over-world/.

Maryland Department of the Environment. 2019. "Department of the Environment Funds Electric and Alternative Fuel School Buses under Volkswagen Settlement." www.news.maryland.gov/mde/2019/09/26/department-of-the-environment-funds-electric-and-alternative-fuel-school-buses-under-volkswagen-settlement/.

Massachusetts DPU (Department of Public Utilities). 2019. *Petition of Massachusetts Electric Company and Nantucket Electric Company, Each Doing Business as National Grid, Pursuant to G.L. c. 164, § 94 and 220 CMR 5.00, for Approval of General Increases in Base Distribution Rates for Electric Service*. D.P.U. 18-150, September 30. Boston: Massachusetts DPU. fileservice.eea.comacloud.net/FileService.Api/file/FileRoom/11262053.

McFarlane, D., M. Prorok, B. Jordan, and T. Kemabonta. 2019. *Analytical White Paper: Overcoming Barriers to Expanding Fast Charging Infrastructure in the Midcontinent Region*. Minneapolis: Great Plains Institute. www.betterenergy.org/wp-content/uploads/2019/08/GPI_DCFC-Analysis.pdf.

McLaren, J. 2017. *A Survey of U.S. Demand Charges*. Prepared by NREL (National Renewable Energy Laboratory). Washington, DC: DOE. www.nrel.gov/solar/assets/pdfs/2017-us-demand-charges-webinar.pdf.

Meitiv, A., and Y. Xu. 2021. *Tailpipe Emission Benefits of Medium- and Heavy-Duty Truck Electrification in Houston*. College Station: Texas A&M Transportation Institute. carteehdata.org/library/document/tailpipe-emission-benefit-7ea6.

Menzies, J. 2018. "Driving an Electric Peterbilt 579." *Truck News*, June 27. www.trucknews.com/test-drive/driving-an-electric-peterbilt-579/.

Mothers Out Front. 2021. "Electric School Bus." Accessed April. www.mothersoutfront.org/campaigns/electric-school-bus-2/.

Moultak, M., N. Lutsey, and D. Hall. 2017. *Transitioning to Zero-Emission Heavy-Duty Freight Vehicles*. Washington, DC: ICCT. www.theicct.org/sites/default/files/publications/Zero-emission-freight-trucks_ICCT-white-paper_26092017_vF.pdf.

Mufson, S., and S. Kaplan. 2021. "A Lesson in Electric School Buses." *Washington Post*, February 24. www.washingtonpost.com/climate-solutions/2021/02/24/climate-solutions-electric-schoolbuses/.

Muller, M. 2020. "Reforming Rates for Electric Trucks, Buses and Fast Chargers." *National Resources Defense Council Expert Blog*, May 4. www.nrdc.org/experts/miles-muller/reforming-rates-electric-trucks-buses-fast-chargers-0.

NACFE (North American Council for Freight Efficiency). 2018. *Electric Trucks: Where They Make Sense*. Fort Wayne, IN: NACFE. www.nacfe.org/future-technology/electric-trucks/.

——. 2019a. *Amping Up: Charging Infrastructure for Electric Trucks*. Fort Wayne, IN: NACFE. www.nacfe.org/future-technology/amping-up-charging-infrastructure-for-electric-trucks/.

——. 2019b. *More Regional Haul: An Opportunity for Trucking?* Fort Wayne, IN: NACFE. www.nacfe.org/regional-haul/.

——. 2019c. *Viable Class 7/8 Electric, Hybrid, and Alternative Fuel Tractors*. Fort Wayne, IN: NACFE. www.nacfe.org/future-technology/viable-class-7-8/.

——. 2020a. *High-Potential Regions for Electric Truck Deployments*. Fort Wayne, IN: NACFE. www.nacfe.org/emerging-technology/electric-trucks/high-potential-regions-for-electric-truck-deployments/.

——. 2020b. *Making Sense of Heavy-Duty Hydrogen Fuel Cell Tractors*. Fort Wayne, IN: NACFE. www.nacfe.org/emerging-technology/electric-trucks-2/making-sense-of-heavy-duty-hydrogen-fuel-cell-tractors/.

Nadel, S., and L. Ungar 2019. *Halfway There: Energy Efficiency Can Cut Energy Use and Greenhouse Gas Emissions in Half by 2050*. Washington, DC: ACEEE. www.aceee.org/research-report/u1907.

NASEM (National Academies of Sciences, Engineering, and Medicine). 2015. *Review of the 21st Century Truck Partnership: Third Report*. Washington, DC: National Academies Press. www.nap.edu/catalog/21784/review-of-the-21st-century-truck-partnership-third-report.

NASEO and NACAA (National Association of State Energy Officials and National Association of Clean Air Agencies). 2021. "VW Settlement Clearinghouse: About the Settlement." Accessed April. www.vwclearinghouse.org/about-the-settlement/.

NRC (National Research Council). 2012. *Review of the 21st Century Truck Partnership, Second Report*. Washington, DC: National Academies Press. www.nap.edu/catalog/13288/review-of-the-21st-century-truck-partnership-second-report.

Niestadt, M., and A. Bjørnåvold. 2019. *Electric Road Vehicles in the European Union: Trends, Impacts and Policies*. Brussels: European Parliamentary Research Service. www.europarl.europa.eu/thinktank/en/document.html?reference=EPRS_BRI(2019)637895.

Nikola Motor Company. 2019. "Nikola One." nikolamotor.com/one.

NYLCVEF (New York League of Conservation Voters Education Fund). 2020. *Clean Bus Guide*. New York: NYLCVEF. www.nylcvef.org/back-to-school-time-to-get-on-the-clean-bus/.

NYSERDA (New York State Energy Research and Development Authority). 2020. "Truck Voucher Incentive Program." www.nyserda.ny.gov/All-Programs/Programs/Truck-Voucher-Program.

O'Dea, J. 2019. *Ready for Work: Now Is the Time for Heavy-Duty Electric Vehicles*. Cambridge, MA: Union of Concerned Scientists. www.ucsusa.org/sites/default/files/2019-12/ReadyforWorkFullReport.pdf.

Ohnsman, A. 2019. "Startup Nikola Bets Hydrogen Will Finally Break Through with Big Rigs." *Forbes*, April 14. www.forbes.com/sites/alanohnsman/2019/04/14/can-a-15-billion-bet-on-fuel-cell-big-rigs-be-a-game-changer-for-hydrogen/#4be3d81dfe4c.

Payne, H. 2021. "Bollinger Motors Debuts 2022 Electric Work Trucks." *Detroit News*, March 12. www.detroitnews.com/story/business/autos/2021/03/12/bollinger-motors-debuts-2022-electric-work-trucks/4662325001/.

Peetz, C. 2019. "Legislature Passes Electric School Bus Mandate; Montgomery Looks into Testing." *Bethesda Magazine*, April 10. www.bethesdamagazine.com/bethesda-beat/schools/legislature-passes-electric-school-bus-mandate-montgomery-looks-into-testing/.

Peterbilt. 2020. "Peterbilt Model 579EV Available for Customer Orders." www.peterbilt.com/about/news-events/news-releases/peterbilt-model-579EV-now-available-for-customer-orders.

———. 2021. *Peterbilt 220 EV: Zero Emissions Vehicle*. Brochure. Denton, TX: Peterbilt. www.peterbilt.com/resources-support/manuals-brochures.

Portillo, P. 2020. "California Omnibus Rule Adds Momentum to Cut Truck Pollution." *Natural Resources Defense Council Expert Blog*, August 27. www.nrdc.org/experts/patricio-portillo/california-omnibus-rule-adds-momentum-cut-truck-pollution.

Priddle, A. 2021. "Rivian Busy with Three Electric Vehicle Launches, Big Future Plans." *MotorTrend*, February 26. www.motortrend.com/news/rivian-electric-suv-truck-van-on-sale-future-vehicles/.

Ramseur, J. 2019. *U.S. Carbon Dioxide Emissions in the Electricity Sector: Factors, Trends, and Projections.* Washington, DC: CRS (Congressional Research Service). www.fas.org/sgp/crs/misc/R45453.pdf.

Reichmuth, D. 2019. *Inequitable Exposure to Air Pollution from Vehicles in California*. Cambridge, MA: UCS. www.ucsusa.org/sites/default/files/attach/2019/02/cv-air-pollution-CA-web.pdf.

Roman, A. 2019. "New Financing Tools Make Electric Bus Buying Easier." *Metro*, March 25. www.metro-magazine.com/technology/article/733398/new-financing-tolls-make-electric-bus-buying-easier.

SAE (Society of Automotive Engineers) International. 2017. "SAE Electric Vehicle and Plug in Hybrid Electric Vehicle Conductive Charge Coupler J1772_201710." www.sae.org/standards/content/j1772_201710/.

SCE (Southern California Edison). 2021. "Charge Ready Transport Program." crt.sce.com/overview.

School Bus Fleet. 2019. "Blue Bird, Cummins Partner on Electric School Bus Support in California." *School Bus Fleet*, September 3. www.schoolbusfleet.com/news/735456/blue-bird-cummins-partner-on-electric-school-bus-support-in-california.

Schubert, H. 2019. "DOT Freight and Trucking Hours of Service Limit Regulations." *The Balance Small Business*, November 20. www.thebalancesmb.com/freight-trucking-dot-hours-1361484.

SDG&E (San Diego Gas & Electric Company). 2018. "Greening the Port with Zero-Emission Vehicles and Equipment." *SDG&E News*, July 26. www.sdgenews.com/article/greening-port-zero-emission-vehicles-and-equipment.

Senate Finance Committee. 2021. *Clean Energy for America Act*. Washington, DC: Senate Finance Committee. www.finance.senate.gov/imo/media/doc/Clean%20Energy%20for%20America%20Act.pdf.

Sharpe, B., C. Buysse, J. Mathers, and V. Poudelet. 2020. *Race to Zero; How Manufacturers are Positioned for Zero Emission Commercial Trucks and Buses in North America.* Washington, DC: ICCT. www.theicct.org/sites/default/files/publications/Canada-race-to-zero-EN-oct2020.pdf.

Shrubb, R. 2019. "Electric Garbage Trucks: Another Way for Cities to Tackle Emissions." *B2BEV*, January 13. www.b2bev.com/electric-garbage-trucks/.

Skibell, A. 2021. "Democrats Push Bill to Electrify School Buses." *E&E News PM*, April 21. www.eenews.net/eenewspm/stories/1063730575/print.

Smith, J. 2019. "State Money Is Funding Anti-Pollution Efforts in San Diego." *Los Angeles Times*, January 27. www.latimes.com/local/lanow/la-me-ln-san-diego-portside-communities-20190127-story.html.

Stinson, J. 2020a. "Cummins and Navistar Prototype Hydrogen Truck with 300-Mile Range." *Utility Dive*, November 13. www.utilitydive.com/news/Navistar-Cummins-Werner-Class-8-hydrogen-truck/588980/.

——. 2020b. "Nikola Manufacturing Plans on Track Despite Milton Departure." *Transport Dive*, October 2. www.transportdive.com/news/Nikola-strategic-plan-manufacturing-electric-hydrogen-Milton/586268/.

——. 2021. "2021: When Electric Trucks Trickle In." *Transport Dive*, February 8. www.transportdive.com/news/electric-class-8-trucks-battery-hydrogen/593512/.

Szymkowski, S. 2019. "First Nikola, Now BYD: Budweiser Brewer to Deploy Fleet of Electric Semi Trucks." *Road Show by CNET*, October 8. www.cnet.com/roadshow/news/byd-electric-semi-budweiser-anheuser-busch/.

Tabuchi, H. 2021. "E-Commerce Mega-Warehouses, a Smog Source, Face New Pollution Rule." *New York Times*, May 8. www.nytimes.com/2021/05/08/climate/e-commerce-warehouse-smog-regulation.html.

Taub, E. 2018. "Buses, Delivery Vans and Garbage Trucks Are the Electric Vehicles Next Door." *New York Times*, June 21. www.nytimes.com/2018/06/21/business/electric-buses-garbage-trucks.html.

TCI (Transportation and Climate Initiative). 2020a. "Massachusetts, Connecticut, Rhode Island, D.C. Are First to Launch Groundbreaking Program to Cut Transportation Pollution, Invest in Communities." www.transportationandclimate.org/final-mou-122020.

——. 2020b. *Transportation and Climate Initiative Program: Memorandum of Understanding*. Washington, DC: Georgetown Climate Center. www.transportationandclimate.org/sites/default/files/TCI%20MOU%2012.2020.pdf.

——. 2021. *Estimating the Regional Environmental, Health, and Economic Benefits and Costs of the Transportation and Climate Initiative Program*. Washington, DC: Georgetown Climate Center. www.transportationandclimate.org/sites/default/files/TCI-P_modeling-summary_12-21-2020.pdf.

Tesla. 2019. "Semi."www.tesla.com/semi.

UPS (United Parcel Service) and GreenBiz. 2018. *Curve Ahead: The Future of Commercial Fleet Electrification*. Atlanta: UPS. Oakland: GreenBiz. sustainability.ups.com/media/UPS_GreenBiz_Whitepaper_v2.pdf.

Vock, D. 2019. "Can America's Biggest Ports Go Green?" *Governing*, May 20. www.governing.com/topics/transportation-infrastructure/gov-california-ports-emissions-air-pollution.html.

Williams, E. 2017. "City of Montreal Adds Three All-Electric Transit Buses." *HybridCars*, May 31. www.hybridcars.com/city-of-montreal-adds-three-all-electric-transit-buses/.

Williams, M. 2018. "Are Capable Electric Pickup Trucks on the Horizon?" *PickupTrucks.com*, September 7. news.pickuptrucks.com/2018/09/are-capable-electric-pickup-trucks-on-the-horizon.html.

Work Truck. 2014. "Determining the Optimal Lifecycle for Truck Fleets." *Work Truck*, November 14. www.worktruckonline.com/155754/determining-the-optimal-lifecycle-for-truck-fleets.