Electrifying Trucks: From Delivery Vans to Buses to 18-Wheelers

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Abstract

Electrification of trucks and buses can bring many benefits, including lower energy use, emissions, and operating costs. Currently, however, these vehicles cost more up front, often have reduced range compared to conventional trucks, and must depend on limited charging infrastructure. To gain the full benefit of vehicle electrification, we will need continuous 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 vehicles are the most varied of the segments and will soon reach net cost parity (considering operating, finance, and other costs) with diesel trucks for a number of market segments. They thus could serve as a bridge to electric truck use in an array of applications. Heavy pickup trucks are also an important segment; electric light-duty pickups are on the way, and the technology will eventually 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 their range and 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 2020 and 2021. The majority of truck routes are less 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 cost 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 is now developing, 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.

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

Introduction

To address climate challenges, many actions will be needed to reduce emissions of greenhouse gases (GHGs). A recent ACEEE report finds that energy efficiency can be used to cut US GHG emissions in half by 2050. Of these emissions reductions, nearly 9% are from electrifying trucks (Nadel and Ungar 2019), which is thus the focus of this paper.

Electric vehicles are generating considerable excitement these days, in no small part due to their potential to help address climate change. Transportation now accounts for more US GHG emissions than any other sector; in 2017, transportation was 37% of US carbon dioxide emissions, and 79% of those emissions were from on-road vehicles (EIA 2019a).

Though purchase prices are still high, electric vehicles (EVs) are generally much more energy efficient than internal combustion engine vehicles and thus are cheaper to run. And, while most 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 the technology, as commercial vehicle owners are very sensitive to fuel costs and EVs help reduce them.

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, 27% of vehicle fuel use, and 27% of vehicle-emitted carbon dioxide (see figure 1) (FHA 2019; EIA 2019a).

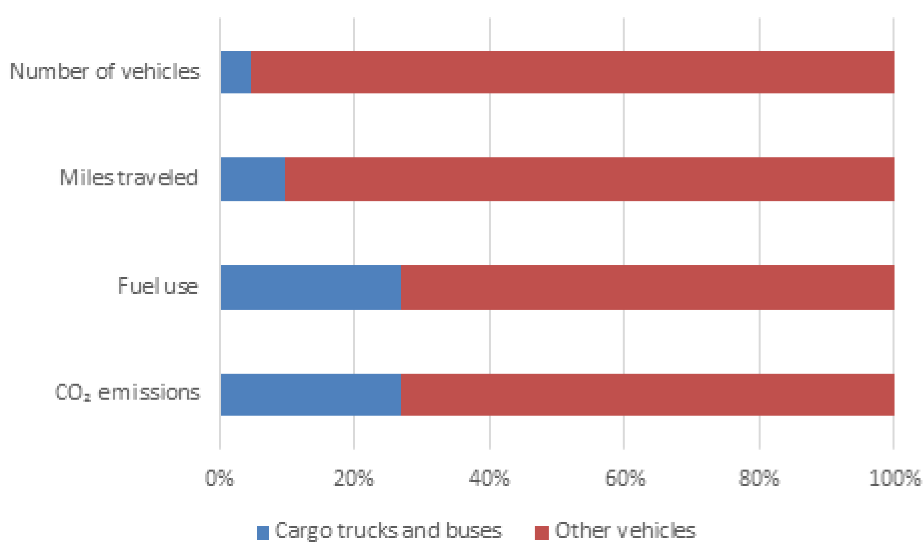

Figure 1. Freight trucks and buses (vehicle Classes 3–8) as a proportion of all vehicles. ***Source:*** **Data from FHA 2019 and EIA 2019a.**

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 its payload capacity. Figure 2 illustrates common vehicles by class.

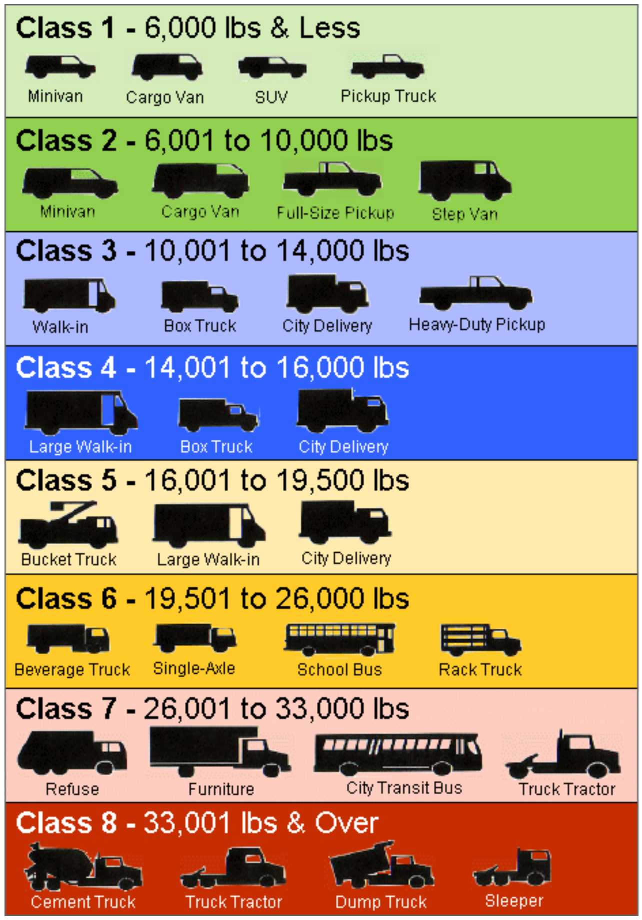

Figure 2. Truck classes. *Source:* DOE 2011.

This report addresses Classes 2b–8, which range from large pickup trucks (over 8,500 pounds) to 18-wheel tractor-trailers. Trucks 8,500 pounds and below are largely personal vehicles and are not considered here. Further, the term *electric vehicle* is sometimes used to refer to battery-only EVs or to both hybrid-EVs (in which an on-board engine charges the batteries) and fuel-cell vehicles. Here, we discuss only battery-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 paper 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 in order 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 the benefits electrification can bring to these vehicles, if effectively deployed.

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] 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 (see table 1). 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 the upfront and operating costs of equivalent electric and diesel vehicles by vehicle class using data from the California Air Resources Board (CARB 2019). For the average application, the simple payback for an electric truck is three to seven years. As noted later,

[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."

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 2019b.

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. However full fuel-cycle emissions associated with EVs are generally lower than emissions of conventional vehicles.[2] Figure 3 illustrates this for California, which has a cleaner generation mix than the national average.

[2] 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 this paper.

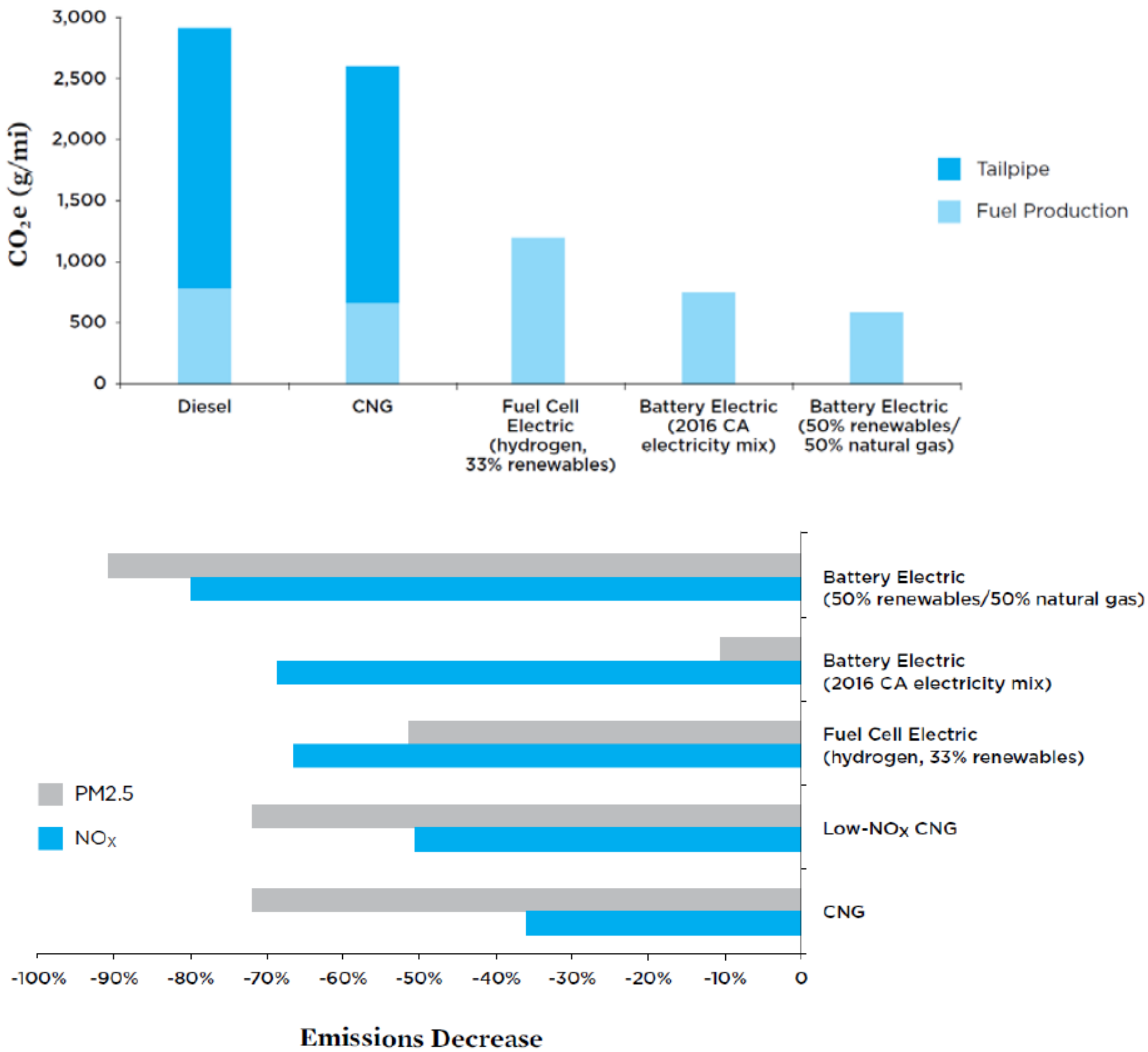

Figure 3. Tailpipe and fuel production emissions of GHG (top) and PM 2.5 and NOx (bottom) from various vehicle and fuel pathways for buses considering the California 2016 electricity generation mix and a cleaner generation mix. *Source:* Chandler, Espino, and O'Dea 2017.

Figure 3 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.[3] 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

[3] 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 2019a).

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, 16% of total US NOx emissions and 15% of US black carbon emissions are from heavy-duty on-road vehicles. Of NOx emissions from vehicles, 47% are from heavy vehicles. Heavy-duty trucks are also a significant source of emissions of fine particles—about 9% of US PM 10 emissions (EPA 2018).[4]

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).

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, experience here is limited but shows that, after separating out some early failures that are common with new technologies, these vehicles have lower maintenance costs than diesel vehicles over the long run (NACFE 2018).

NOISE

Electric vehicles 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

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

some cities, due to noise, there are 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 4 summarizes the results. For the fleet managers, the largest motivators are helping to meet sustainability and environmental goals and lowering the cost of ownership. This implies that both ensuring that EVs help meet environmental goals and improving EV economics will be particularly important.

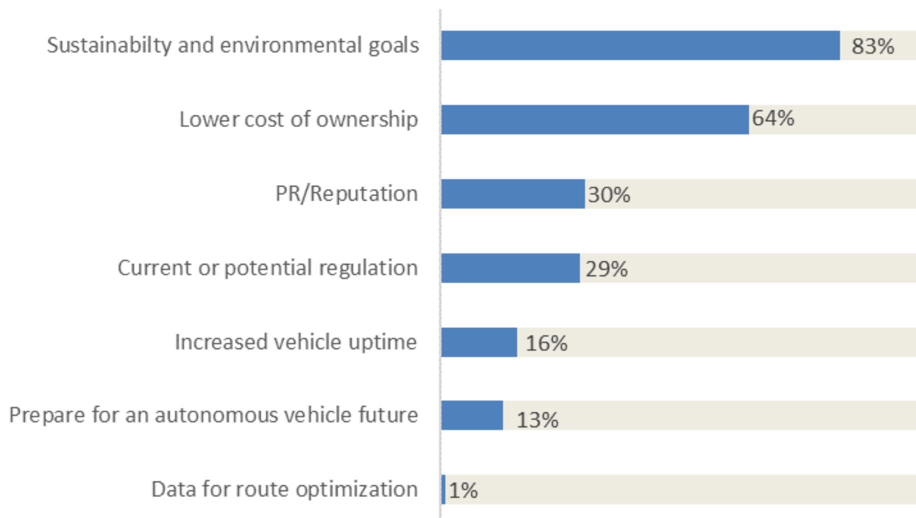

Figure 4. Motivators for fleet electrification. *Source:* UPS and GreenBiz 2018.

Challenges for Electric Trucks

While electric trucks offer substantial benefits, their deployment involves many challenges. These issues include the limited number of electric trucks now 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 US market. The US Department of Energy (DOE) maintains a list of alternative fuel vehicles, including EVs. In December 2019, it listed 61 all-electric truck models[5]: 36 buses, 10 vocational trucks, 9 vans and step vans, 3 tractors, 2 street sweepers, and 1 refuse truck (AFDC 2019). The tractors are for drayage applications, typically with a range of 80 miles.[6] As we discuss later, more electric truck models are scheduled to be introduced in the market soon. By comparison, there are typically a dozen

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

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

or more manufacturers for each of the major conventional truck types, with each manufacturer offering 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%.[7] Likewise, an electric transit bus costs about $750,000, which is about $315,000 (73%) more than a diesel bus (Blanco 2018). As table 2 shows, the extra cost might pay back over three to seven years (table 2), 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 need to be replaced after about 10 years,[8] 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.[9] 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 period of time is commonly on the order of five years, but it varies widely (Worktruck 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).

RANGE

Driving range is usually 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 70 to 135 miles. Such ranges will be adequate for some applications, such as local deliveries and drayage, but they are too short for intercity travel. 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 ranges this long 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). When a driver needs to stop, eight hours of rest is required, which generally provides time to charge batteries. A speed of 60–65 mph means a range on the order of 600–650 miles for solo drivers.

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

[8] There is limited experience with electric trucks, but 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.

[9] 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.

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 just 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 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-use 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. 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.

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. Fleets will want to have 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 they manage load weight and temperature impacts to assure acceptable battery performance. As one reviewer noted, even low-cost, low-tech technologies such as side skirts and low-rolling-resistance tires do not have 100% adoption after more than a decade in the market.

RANKING THE BARRIERS TO FLEET ELECTRIFICATION

UPS and GreenBiz (2017) also surveyed truck fleet managers about the barriers to fleet electrification; figure 5 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 to promote electric trucks.

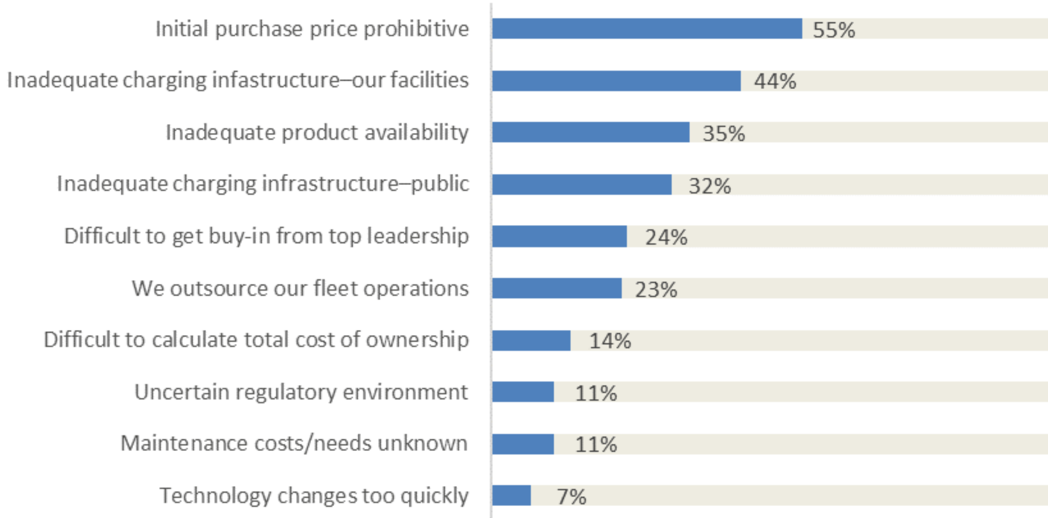

Figure 5. Barriers to fleet electrification. *Source:* UPS and GreenBiz 2018.

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 dominates truck sales volume, followed by Classes 3 and 8. In 2018, Class 2b accounted for approximately 50% of retail truck sales, while Class 3 accounted for 19% and Class 8 for 16% (figure 6).
- Class 8 dominates energy consumption, accounting for 63% of fuel use by Classes 3–8 (figure 7). Buses account for only 4% of energy consumption (figure 8).
- Vehicles in Classes 3–6 are used primarily for short trips; as figure 9 shows, about 95% of those trips are 100 miles or less.
- Use of Class 7 and 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 (figure 9).
- Major truck uses include for-hire operations, construction, agriculture, retail, wholesale, and waste management (figure 10).

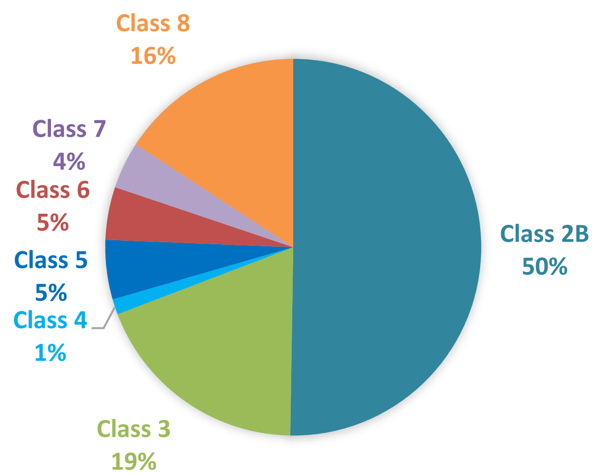

Figure 6. New retail truck sales in 2018 by vehicle class. *Source:* Davis and Boundy 2019. Class 2b sales extrapolated from Davis and Boundy based on data in EIA 2019a.

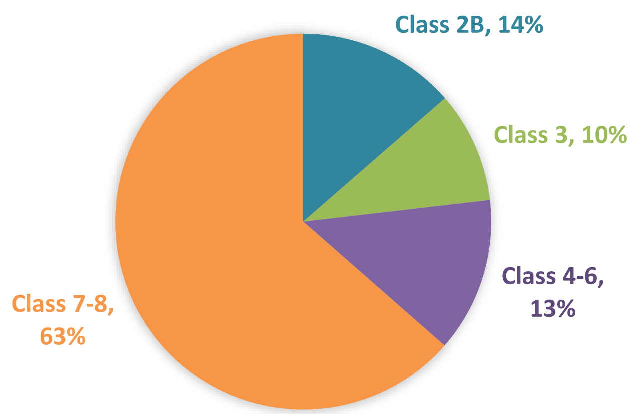

Figure 7. Energy consumption of Classes 2b–8 vehicles, 2018. *Source:* EIA 2019a.

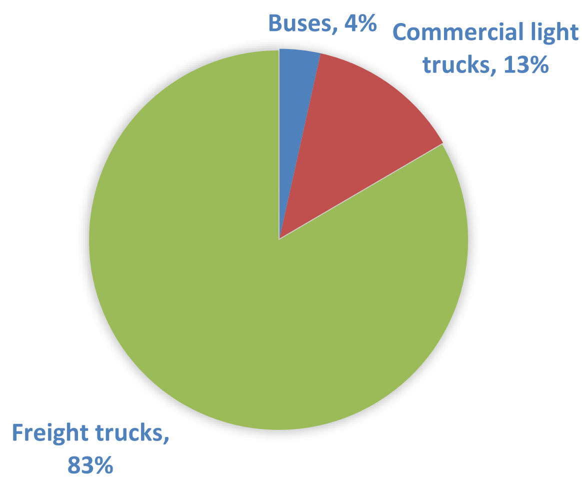

Figure 8. Energy consumption of commercial light trucks (Class 2b), freight trucks (Classes 3–8, not including buses), and buses. CO_2 emissions have a very similar distribution. *Source:* EIA 2019a

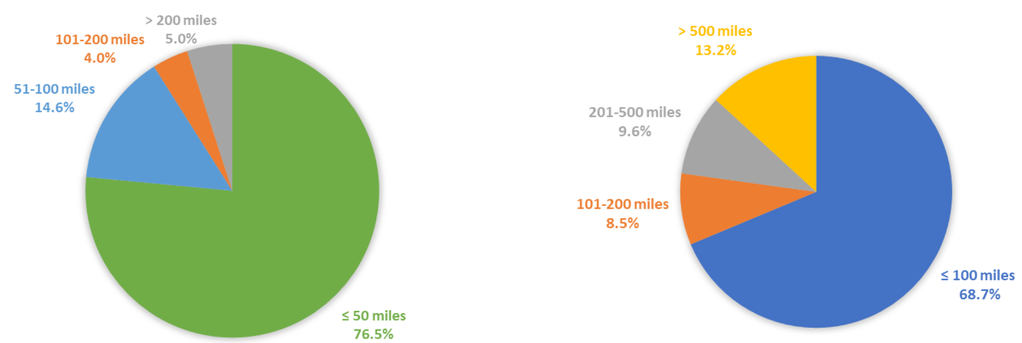

Figure 9. Typical trip miles or range of operation for 2002 (Classes 3–6 on the left, Classes 7 and 8 on the right). More recent comprehensive data are not available. *Source:* Davis and Boundy 2019.

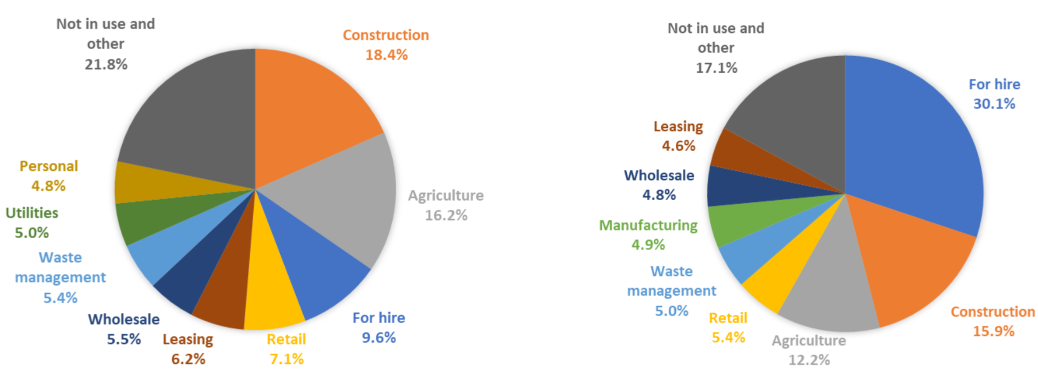

Figure 10. Percentage of trucks by major use, 2002 (Classes 3–6 on the left, Classes 7 and 8 on the right). More recent data are not available. *Source:* Davis and Boundy 2019.

The primary data source for attributes and usage of trucks in the United States has been the Department of Commerce's *Vehicle Inventory and Use Survey*, which was discontinued after the 2002 survey. This is why figures 9 and 10 use 2002 data. Restoration of 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 (LoadDelivered 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 a number of 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 late 2020 or early 2021. Specifically, Tesla, Daimler, and Volvo seem to be farthest 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 late 2020. The truck has been in field trials including towing full loads (figure 11). 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). Recently, the company claimed that it has 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 that Tesla can deliver on these promises.

Daimler North America's Freightliner division is planning an electric version of its Cascadia truck. It is planning a full line of electric trucks and buses and plans to ramp up to full-scale production of initial models by 2021. 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).

Figure 11. 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 recently announced the sale of 21 units to Budweiser that will be built and used in California (Szymkowski 2019). Volvo recently unveiled its electric VNR truck. It plans to produce the truck in Virginia, with road tests scheduled to start in late 2019 and limited commercial sales beginning in late 2020 (it will lease the trucks, with the lease including maintenance and insurance). Volvo is targeting regional routes of about 200 miles or less (Hirsch 2019b; Fisher 2019). Peterbilt is now building 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). Also, Xos, a Los Angeles start-up, is planning an electric tractor called the ET-One (Xos Trucks 2019).

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 a variety of attributes. As figure 12 summarizes, NACFE's results indicate that electric trucks will 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, finding that operating cost parity will not be achieved until about 2025.

NACFE published an updated assessment on just Class 7 and 8 vehicles in late 2019. It notes expected product introductions in the early 2020s but sees this production as being 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 predicts a future zero-emission freight world (e.g., by 2040) with only electric-based vehicles (battery electric, fuel-cell, and catenary electric), but with a "messy middle" between now and then as things shake out (NACFE 2019c).

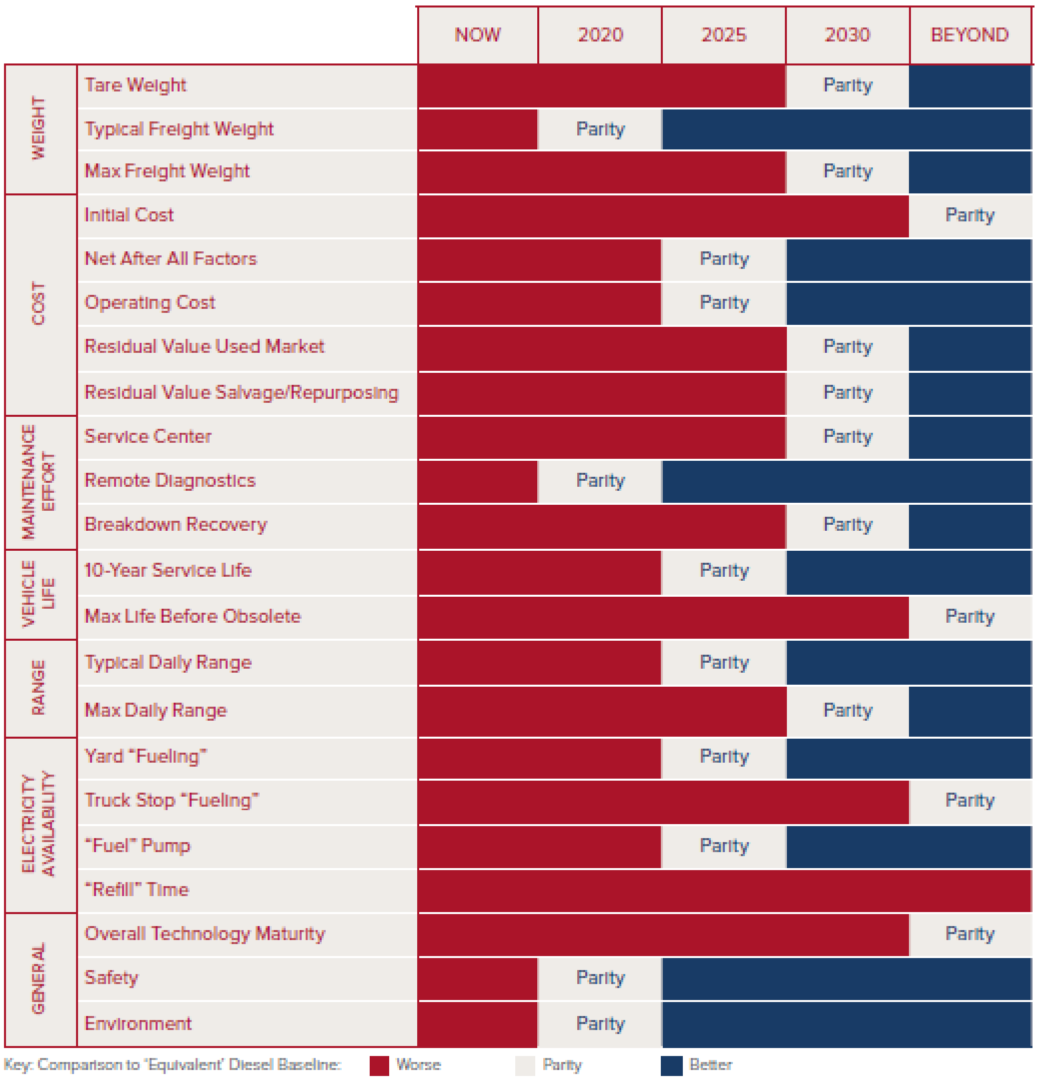

Figure 12. Comparison of electric and diesel Class 7 and Class 8 trucks on a variety of attributes. *Source:* NACFE 2018.

Fuel-Cell Tractor-Trailers

For long-haul routes, tractors powered by fuel cells may be preferable to battery-electric trucks because they 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. Nikola is now raising capital to build its production facilities as well as a nationwide network of hydrogen refueling stations. Production is scheduled to start in late 2022. The refueling stations will be powered with renewable energy and will extract hydrogen from water (Ohnsman 2019). The trucks themselves (figure 13) 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) and tons less than a comparable electric truck (Ohnsman 2019). They plan to lease the trucks for $5,000–7,000 per month, including fuel and insurance (Gnaticov 2018).

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. As of October 2019, the Kenworth assembly plant in Renton, Washington, has produced four hydrogen fuel-cell EVs. The program's first vehicle to enter service will go to Toyota Logistics Services by the end of 2019 for operation at Los Angeles ports. The full contingent of 10 fuel-cell vehicles is expected to enter operation in the Los Angeles basin in 2020, and will be placed into service by UPS, Toyota Logistics, TTSI, and Southern Counties Express (Gilroy 2019).

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 power 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.

Figure 13. 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 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 breaking extends the EV range for a given battery size.

As of December 2019, the DOE Alternative Fuels Data Center lists 19 electric vocational vehicles on the market; we extract its basic information in table 3.

Table 3. Electric vocational trucks on the US market

Manufacturer	Type	Model
BYD	Step van	Step Van
	Vocational/cab chassis	T5
		T7
Chanje	Van	V8100 Panel Van
First Priority GreenFleet	Vocational/cab chassis	Medium Duty Truck
		Walk-In Van
Ford	Van	Transit Van/Wagon Transit 350 Van/Wagon
	Vocational/cab chassis	E450 Cutaway E450 Stripped Chassis
		F-59 Stripped Chassis
		Transit CC-CA 250, 350
US Hybrid	Step van	eCargo
Zenith Motors	Van	Cargo Van
	Step van	Step Van
	Vocational/cab chassis	Chassis Cab
		Cutaway Cab
ZeroTruck	Vocational/cab chassis	ZeroTruck

Source: **AFDC 2019.**

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. A picture of the new van has been released (figure 14), but technical details are not yet available.

Figure 14. Rivian electric van. *Source:* Lambert 2019a.

Other manufacturers are also planning medium-duty electric trucks. For example, Freightliner is now field testing its eM2 truck (figure 15, 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 15, right) (Volvo Trucks 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. Ford, Mercedes-Benz, and Navistar are also developing van and medium-duty truck products (O'Dell 2018).

Figure 15. 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 2020, 2025, and 2030 (figure 16). In particular, it expects electric trucks on average to be competitive on net costs (purchase and operating) by about 2020, 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 heavy-duty electric trucks.

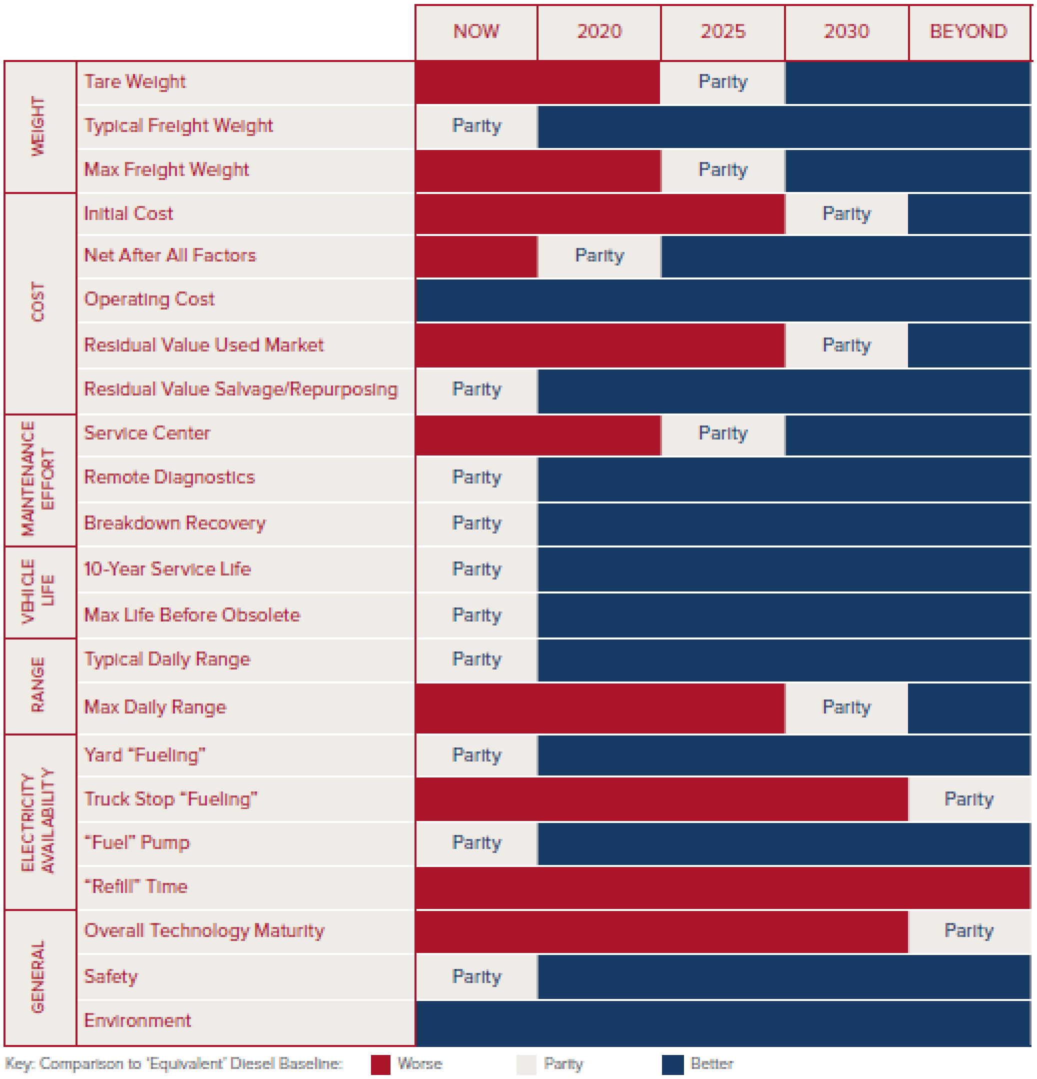

Figure 16. Comparison of electric and diesel Classe 3–6 trucks on a variety of attributes. *Source:* NACFE 2018.

BUSES

As the headline of a recent article 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 US roads, and in 2018, the federal government awarded funding for 52 projects in 41 states including several major cities through the US Department of Transportation (DOT) Low- or No-Emission Grant Program. DOT made awards under this program for another 38 projects in 38 states in 2019 (DOT 2019). Buses are another application with frequent braking, providing an opportunity for energy savings with regenerative braking. Most of the US activity has been in public transit buses, but interest in electric school buses has recently increased (see figure 17). There are also smaller electric shuttle buses. In this paper, we concentrate on electric transit buses, as they are higher energy users that typically run throughout the day. We also briefly discuss electric school buses.

Figure 17. Electric transit bus (left) and 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 2019). 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 a variety of factors) (Blanco 2018). On a total (life-cycle) cost of ownership basis, e-buses can be up to 25% less expensive, particularly as the daily miles traveled increases (figure 18).

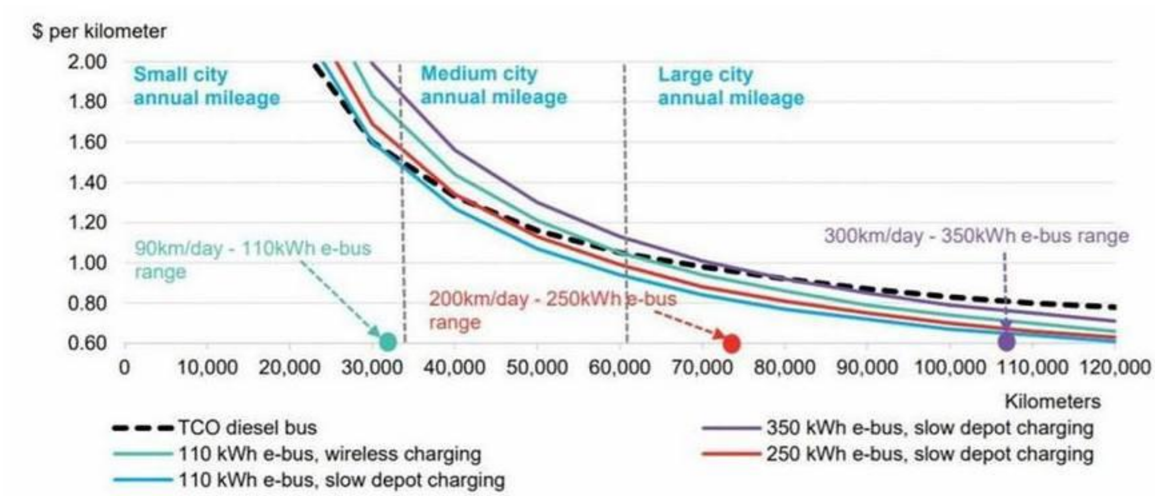

Figure 18. Total cost of bus ownership by bus type as a function of annual miles traveled. *Source:* Marcacci 2018.

Creative financing options such as leasing are often needed to address the high initial costs of electric buses. These can include several federal grant programs for which transit agencies are eligible, use of Volkswagen diesel emissions settlement funds (discussed further in the policy section of this paper), some 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 now offered by one manufacturer—Proterra—since batteries are the largest component of electric bus costs (Roman 2019).[10]

New York, Los Angeles, and San Francisco have made commitments to switch all municipal buses from diesel to e-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 US market development and have faced some problems. For example, electric bus performance degrades at low temperatures, and this factor must be managed. The increased resistance at low temperatures can reduce battery ranges and charging speeds. The use of electric heaters to keep the bus and components warm further reduces range.[11] 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 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 need to be planned carefully, and the bus matched to the route (Haggiag 2019). For example, Foothills Transit (serving the east side of Los Angeles County) operates 33 electric buses, 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 uses fast-charge buses (40 mile range) that charge in less than 10 minutes on routes with fast chargers (Margolis 2019).

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

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

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 due to the fact that 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, 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 (UCS 2019). Electric vehicles can reduce on-road emissions that contribute to these differences.

Second, for a substantial number of 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.

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 go into business serving transportation needs identified by the local community (Espino and Truong 2015).

School Buses

Annual US school bus sales average approximately 34,000 vehicles, 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. In the United States, electric school buses are currently sold by Blue Bird, Lion, and Thomas (AFDC 2019), which are based in Georgia, Quebec, and North Carolina, respectively. Blue Bird and Thomas are two of the three major school bus manufacturers who dominate the North American school bus market; IC Bus is the third major manufacturer; it has shown an electric school bus concept with an expected start of deliveries in 2020 (IC Bus 2019). Thomas is a subsidiary of Daimler.

According to one large school district (Montgomery County, Maryland), an electric school bus costs roughly $185,000—about $65,000 more than a conventional school bus (Peetz 2019). The challenge for electric school buses is that they typically do not travel very far in a day; they are used in mornings and afternoons for short runs, but typically sit unused for most of the day and in the summer. One estimate is that 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 2018). This reduces the operating cost savings needed to repay the higher cost of an electric bus.

Thus, until bus prices come down 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). The California Energy Commission is funding a broadly similar program (Carpenter 2019). Further, Delmarva Power & Light in Delaware, Public Service Electric and Gas in 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 on line by 2025, starting with 50 in 2020 (Dominion Energy 2019). 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 includes 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 both buses and chargers (Maryland Dept. of Environment 2019).

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. 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.

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, even varying 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 today, no automaker has announced plans to develop battery-electric heavy-duty pickups. Small and emerging automakers such as Atlis Motor Vehicles, Rivian, Bollinger, Fisker, and Tesla are developing battery-electric light-duty pickup trucks, and large automakers such as Ford and General Motors are developing battery-electric versions of the F-150 and the Silverado/Sierra, respectively (Loveday 2019).

Light- and heavy-duty pickups often share a variety of components, which reduces cost by increasing production volumes (Birky et al. 2017). The Atlis XT pickup truck, currently in development, is claimed to offer payload capacities as high as 5,000 pounds, which would likely push its GVW into a heavy-duty classification (see figure 19). And the Tesla Cybertruck may be medium duty (Lambert 2019b). Ultimately, EV production in the higher-volume light-duty sector, combined with the electrification activity for Classes 3 and up, could make electrification of heavy-duty pickups more viable (Birky et al. 2017).

Figure 19. 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.

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 20 summarizes battery cost trends and projections. In 2018, according to Bloomberg New Energy Finance, the volume-weighted average battery back price was $176 per kilowatt-hour (kWh), and this is projected to decline by two-thirds by 2030 (Goldie-Scot 2019). However, as noted by CARB (2019) and Moultak, Lutsey, and Hall (2017), the prices below are for batteries for light-duty vehicles; batteries for heavy-duty vehicles are somewhat different and are likely to take about five additional years to reach the price points shown in figure 20.

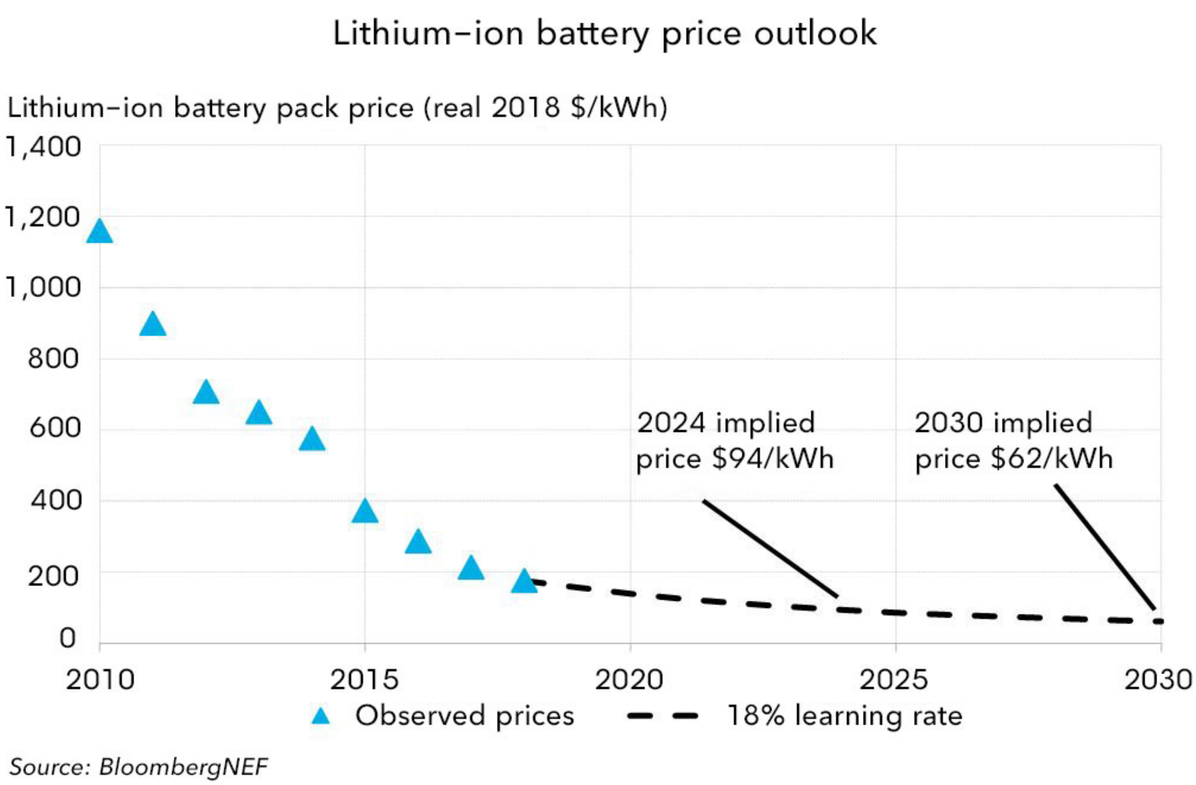

Figure 20. Past and projected price of lithium-ion batteries. *Source:* Goldie-Scot 2019.

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—typically starting around 6 kW for a level 2 charger (240 volts) that might be used for pickup or smaller delivery trucks, 15–70 kW for larger mid-range trucks, 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

Potential applications are ACEEE assessments. *Sources:* Charging levels and peak demand: SAE 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, 100 medium-duty electric box trucks charging simultaneously with level two 15 kW chargers would place 1.5 MW of load on the grid. For 50 transit busses charging at 60 kW, the demand could reach 3.0 MW, and increase dramatically if faster charging is required (Gallo 2015). This is illustrated in figure 21.

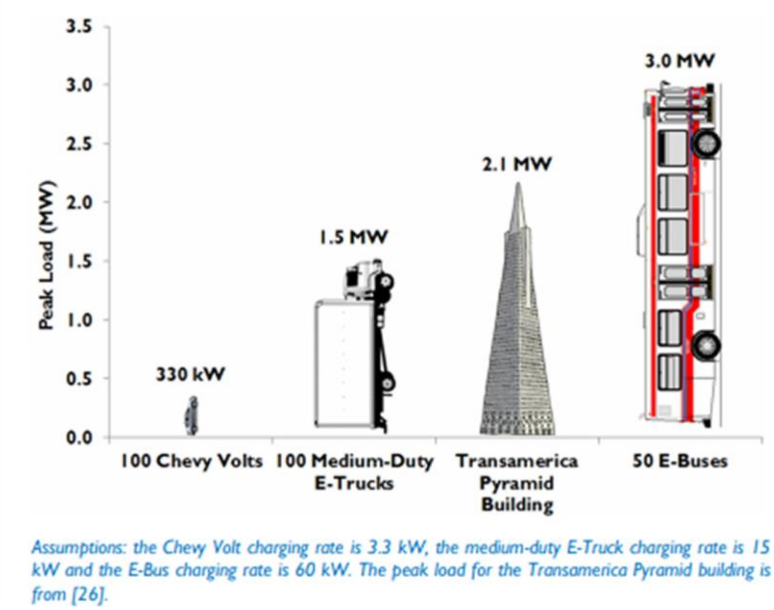

Figure 21. Peak loads for various EV fleets without mitigating grid impacts.
Source: Gallo 2015.

Existing infrastructure at these sites may not be capable of serving such loads. Meeting this demand could require upgrades to or the build-out of new infrastructure, often at considerable cost. For example, a Southern California facility had to install a $470,000 transformer after the meter to meet the demand of deploying 20 electric trucks (Gallo 2015).

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, as figure 22 illustrates. Although some large companies may undertake the process themselves, often a firm specializing in this process will be needed. To provide just one example, Siemens has a growing business building truck chargers and managing their installation (Fehrenbacher 2019).

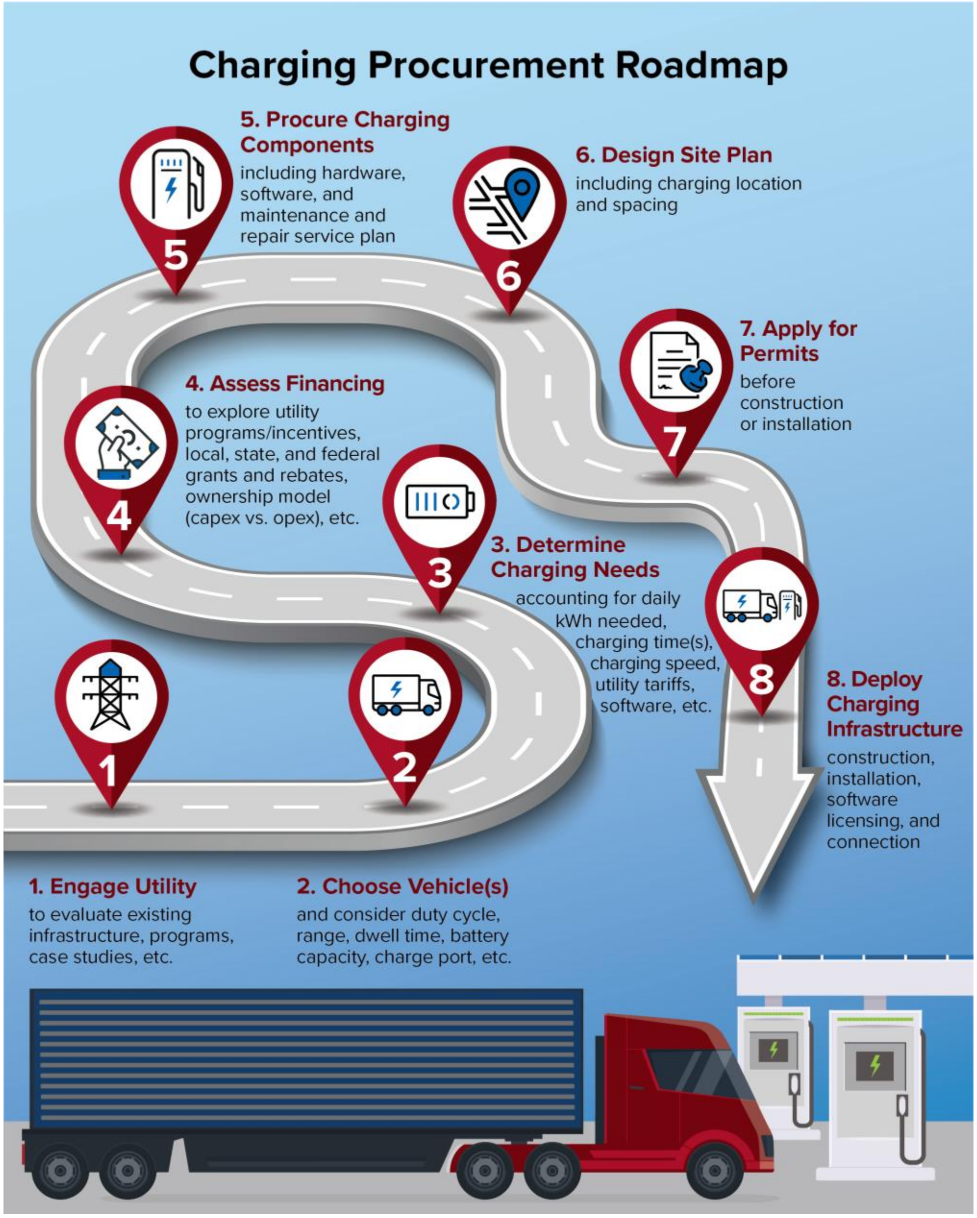

Figure 22. The process to install electric chargers for trucks. *Source:* NACFE 2019a.

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 the demand. Utilities will play an important role in planning EV charger siting. Utilities and fleet owners will have to collaborate on each unique charging site to determine viability and any necessary investments. The higher a given facility's power draw, the less likely that the existing infrastructure will be adequate and the more likely that upgrades will be required. Such upgrades can take many months to execute. Sometimes additional power can be brought to existing fleet facilities, but some utilities may suggest new locations to which it will be easier to bring power. Fleet owners will sometimes 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 (Tonachel 2017).

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 might provide discounts if the utility can have some control over when 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 about 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 20, 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). This is illustrated in figure 23, which is excerpted from a study on fast charging in the Midwest. 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.[12] As a result, the 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 breakeven on a 150 kW charger (a typical new, fast charger); and 51 uses per day to breakeven 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.

[12] This study covered chargers of the type that might be used by passenger vehicles and small/medium trucks.

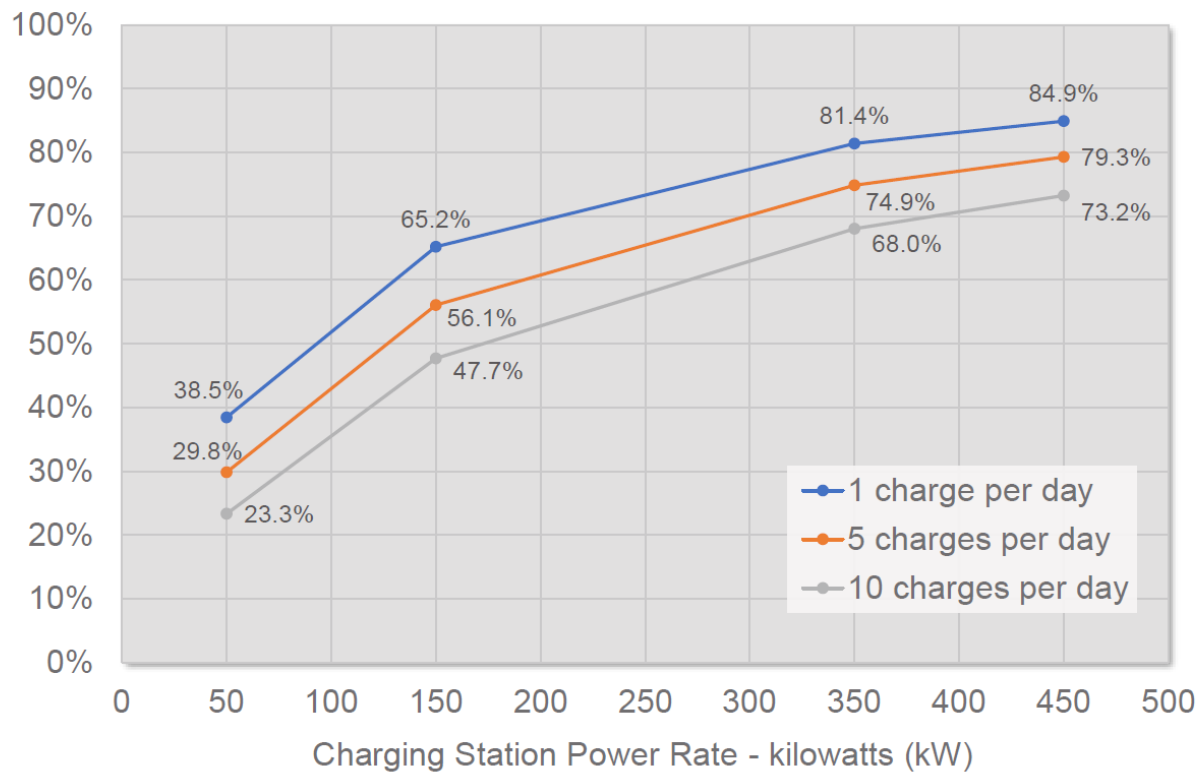

Figure 23. Demand charge share of a direct-current fast charger station cost as a function of charger power draw and the number of charges per day. *Source:* McFarlane et al. 2019.

Some states and utilities are seeking to mitigate this obstacle to EV adoption 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 and charger use increases 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 total charging capacity as selected by the customer (essentially this is a cap on power draw) (Muller 2019).

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

- 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)

On the other hand, 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 discuss efforts in California and elsewhere in the United States, as well as efforts in China and Europe for the lessons they teach.

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 2019). The state has proposed a zero-emissions vehicle (ZEV) program for trucks requiring sales percentages from 3–7% in 2024 (varying with vehicle class) and 15–50% in 2030 (CARB 2019). In-state advocates are suggesting that the proposed targets be increased substantially so that 15% of trucks on the road in 2030 are covered, up from about a 4% penetration under the CARB proposal (O'Dey 2019). CARB plans to finalize this regulation in 2020.

In addition to the manufacturing requirement, CARB is considering a complementary fleet program to encourage fleets with 100 or more vehicles to purchase and use zero-emission trucks (Portillo 2019). 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 how 13 states have chosen to do so for light-duty vehicles. The CARB program to require public transit agency buses by 2029 was discussed above (Kane 2018).

California also has purchase vouchers and demonstration and pilot projects for zero-emissions heavy-duty vehicles, several of these in partnership with CALSTART. The voucher program provided up to $165,000 for an EV ($315,000 for a fuel-cell truck) in 2019, including a bonus for deployment in a disadvantaged community (California HVIP 2019). 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 (Union of Concerned Scientists 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 2019).

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 internal combustion engine 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 addition, as discussed above in the rates section, California utilities are often providing 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, while the United States had only 300. 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. The central government provided subsidies, and each city developed 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, with the result that 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, and 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 recent 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.

Other Parts of the United States

Policies to advance truck electrification are also advancing in other parts of the United States. For example, incentive programs to promote electric truck purchases are operating in both Chicago—Drive Clean Chicago funded by a federal grant (Drive Clean Chicago 2017)—and New York State—the N.Y. Truck Voucher Incentive Program, funded by the New York State Energy Research and Development Administration2019 (NYSERDA 2019). Colorado and Utah provide tax credits for the purchase of heavy-duty EVs (ACEEE 2019).

All US 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 2019). 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).

In December 2019, a group of eight states plus the District of Columbia 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."[13] They plan to present a proposed memorandum of understanding to the governors of the eight states and the mayor of the District of Columbia for consideration in the summer of 2020 (California et al. 2019). No further details are available.

Another major initiative is the Transportation Climate Initiative (TCI), which is being developed by 12 Northeastern and Mid-Atlantic states and the District of Columbia. TCI "seeks to improve transportation, develop the clean energy economy and reduce carbon emissions from the transportation sector including both light and heavy vehicles" (TCI 2019c). TCI has developed a proposal for a regional "cap and invest program" that would cap transportation-related GHG emissions in the region, auction off emissions allowances to stay within the cap, and then distribute the funds collected to the participating states "for them to invest to achieve carbon emission reductions and other policy goals—like improved air quality and more affordable access to transportation. Additionally, jurisdictions may identify shared priorities for investment of proceeds including to maximize the efficiency of the regional program and to ensure greater benefits." A draft framework was issued in October 2019 (TCI 2019a) and plans are to refine it and also to develop a model state rule to

[13] The states are California, Connecticut, Maine, Massachusetts, New Jersey, Oregon, Rhode Island, and Vermont.

implement the program in 2020. States would then take 2021 to develop regulations and legislation to implement the rule. The program could begin as early as 2022 (TCI 2019b). TCI is of relevance to electric trucks as the cost of emissions allowances would improve the economics of ZEVs as well as create a funding stream for states to use for clean transportation initiatives.

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

EUROPE

Europe has many programs and policies to encourage electric passenger vehicles. It also has 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 ensure investors that there is a ready market for electric trucks. 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. Other significant commitments include orders by Anheuser-Busch for 800 Nikola fuel-cell trucks (Fialka 2019), UPS for 950 electric delivery vans, and 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; 31 companies have signed on to date, including IKEA and Unilever (Holder 2019).

Recommended Path Forward

This paper addresses the current status of electric tractor-trailers, vocational trucks, buses, and heavy-duty pickups. As figure 8 shows, of these four segments, by far the largest energy use (and hence 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 farthest-advanced of the four segments. Electric buses are in widespread use in China, and several US 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 17 shows, they are reaching parity with diesel trucks sooner than for heavier trucks. They could therefore be a possible bridge toward more widespread use of electric trucks in broader applications. Heavy pickup trucks are also a significant segment and, while there are not yet any all-electric vehicles on the market, technology for battery-electric light-duty pickups entering the market in the next few years should carry over to the heavier segment of the pickup market. In the paragraphs below, we elaborate on critical steps forward for electric trucks overall and for each of these four segments. At the end of this section, we include 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 and satellite charging stations dedicated to specific fleets. But for long routes, public charging will also be needed, 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. In many locations, reinforcements to local power distribution networks will be needed. Electric utilities need to start planning these efforts now. 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 a primary driver of electric car sales in the United States to date; the recently proposed 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 technologies (batteries and motors, advanced materials, 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. gross vehicle weight, 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 November 2019, the House Ways and Means Committee released a discussion draft of a tax incentive bill that includes a 10% federal tax credit for battery-electric and fuel-cell vehicles over 14,000 lbs., with a maximum incentive of $100,000 per vehicle (GREEN Act 2019). In our view, given the high initial costs of these vehicles, the incentive should be raised to 20% until specified sales targets are reached (e.g., 3% of annual vehicle sales within a class), but the maximum incentive per vehicle can be reduced.

In addition, government should improve data collection efforts on truck characteristics and use. The last *Vehicle Inventory and Use Survey* gathered data in 2002; more recent data, regularly collected and published, will help aid efforts to improve truck transport, including EVs, conventional trucks, and transportation system issues.

Finally, manufacturers need to continue on-going 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 up-front 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 need to 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. The economics for transit buses appear to be much better than for school buses, so efforts should start there. Priority for transit and school bus electrification should be given to low- and moderate-income communities and other communities that have historically had higher exposure to air pollution, and especially diesel exhaust.

VOCATIONAL TRUCKS

Vocational trucks are diverse and come in many shapes and sizes. Many more products are needed to serve vocational needs in order to complement the 19 products listed in table 3. Incentives such as those that California, Colorado, New York, Utah, and Chicago are implementing are useful (ACEEE 2019), 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 internal combustion engine 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). Preferred access to core delivery zones 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 next few years. 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 US 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), 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, and 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 five 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 such an important role in the US 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 5 summarizes our recommendations.

Table 5. 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</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 such as lower energy use and emissions (assuming a moderately clean electric grid), higher torque, and less maintenance requirements. However they cost more up front, present 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 2020 and 2021. 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 late 2022. 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 toward 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, developments in lighter pickups will eventually reach the heavier segment of this market.

For all of these markets, compared to conventional vehicles, EVs have substantially higher upfront cost driven primarily by the cost of batteries. To help bridge this gap, financial incentives and financing will often be useful. Zero-emission truck mandates (such as those California is now developing) can also be helpful. 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 out 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. Where 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 these leaders.

Electric trucks have a promising future, but much work needs to be done in the near term 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 US electric car sales to date, with more than 10 other states adopting its program. The recently proposed California heavy-duty vehicle program and a potential expansion to other leading states could well do the same for trucks.

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