Ready for Work

Now Is the Time for Heavy-Duty Electric Vehicles

HIGHLIGHTS

Electric trucks and buses represent the next frontier for electric vehicles. Increasingly available, they have zero tailpipe emissions and lower life cycle global warming emissions compared with other types of trucks or buses. Widespread electrification already makes sense for several classes of heavy-duty vehicles based on their operating characteristics, the range of today's battery technologies, and similar if not cheaper ownership costs. While internal combustion engines have been in use for more than a century, three types of policies can accelerate the electrification of trucks and buses: financial incentives, investments in charging infrastructure, and standards that increase the manufacture and purchase of heavy-duty electric vehicles. All of these policies should center on improving air quality in communities most burdened by vehicle pollution.

Light-duty electric vehicles in the United States hit a major milestone at the end of 2018: total sales-to-date passed the 1 million mark (Auto Alliance n.d.). While significant uptake of electric passenger vehicles is still needed to reduce the climate and air quality impacts of the light-duty vehicle sector, signals in policy, technology, and the market suggest that widespread electrification of cars, SUVs, and light pickup trucks is possible.

What about electrifying the other vehicles on the road, heavy-duty vehicles? While further from reaching 1 million sales, trucks and buses are undoubtedly the next frontier for widespread electrification of vehicles.

Today's heavy-duty vehicles, fueled predominately with diesel, have a big impact on air quality, public health, and the climate. But electric trucks and buses have zero tailpipe emissions, and, powered by today's electricity grid, produce fewer global warming emissions than their combustion counterparts. Increasing availability and decreasing costs point to a bright future for heavy-duty electric vehicles. Policy support will be critical, however, to transition from the ubiquity of internal combustion engines.

Jimmy O'Dea/UCS

Semi trucks that transport cargo containers to and from ports and railyards ("drayage trucks") often travel short distances per trip and are well-suited for electrification. Several electric models, with ranges up to 300 miles, are already in demonstration today.

Union of Concerned Scientists

Why Trucks and Buses?

Nationally, the transportation sector represents the largest source of global warming emissions—29 percent of all emissions (EPA 2019).[1] It is also a major source of air pollution in the United States. Within the transportation sector, heavy-duty vehicles disproportionately contribute to emissions.

Despite comprising just 10 percent of vehicles on US roads, heavy-duty vehicles contribute 28 percent of global warming emissions from the nation's on-road transportation sector (EIA 2016; FHWA 2016; EPA 2019) (see Box 1).[2] They are also responsible for 45 percent of on-road NO_x emissions (oxides of nitrogen) (see Figure 1) and 57 percent of on-road, direct $PM_{2.5}$ emissions (particulate matter less than 2.5 micrometers in diameter) (EPA 2018a).[3] NO_x—a precursor to smog and $PM_{2.5}$—and particulate matter are major sources of air pollution, and they pose significant health risks at all stages of life, from premature births to premature deaths (Caiazzo et al. 2013; Darrow et al. 2009). Heart attacks, cancer, reduced lung function, and exacerbation of asthma are the health effects most frequently associated with air pollution from vehicles, but researchers have reported negative health outcomes for many other parts of the body as well (ALA 2019).

On-road sources of air pollution disproportionately burden communities of color and low-income communities due to their proximity to roads and vehicular traffic. Asian Americans, African Americans, and Latinos are exposed to 34 percent, 24 percent, and 23 percent more $PM_{2.5}$ pollution (respectively) from cars, trucks, and buses than the national average (Reichmuth 2019a; Reichmuth 2019b).

The disproportionate contribution of heavy-duty vehicles to global warming emissions results from both the large amount of fuel consumed per mile and the high mileage they travel compared with light-duty vehicles. In 2017, diesel transit buses averaged 4.0 miles per gallon (mpg); tractor (semi) trucks, 6.0 mpg; and single-unit trucks (i.e., non-semi trucks), 7.4 mpg; while cars averaged 24.2 mpg (FHWA 2019; FTA 2018). Additionally, the average semi truck travels more than 60,000 miles per year (with newer trucks traveling close to 90,000 miles per year), compared with less than 12,000 miles for the average passenger car (FHWA 2019; Komanduri 2019).

The prevalence of diesel engines in heavy-duty vehicles also contributes to their large share of NO_x and $PM_{2.5}$ emissions compared with light-duty vehicles, which predominantly use gasoline engines (see Box 2, p. 4). More than 50 percent of

> [***Despite comprising just 10 percent of vehicles on US roads, heavy-duty vehicles contribute 45 percent of NO_x emissions from the nation's on-road transportation sector.***]

BOX 1.

What Is a Heavy-Duty Vehicle? 2b or Not 2b?

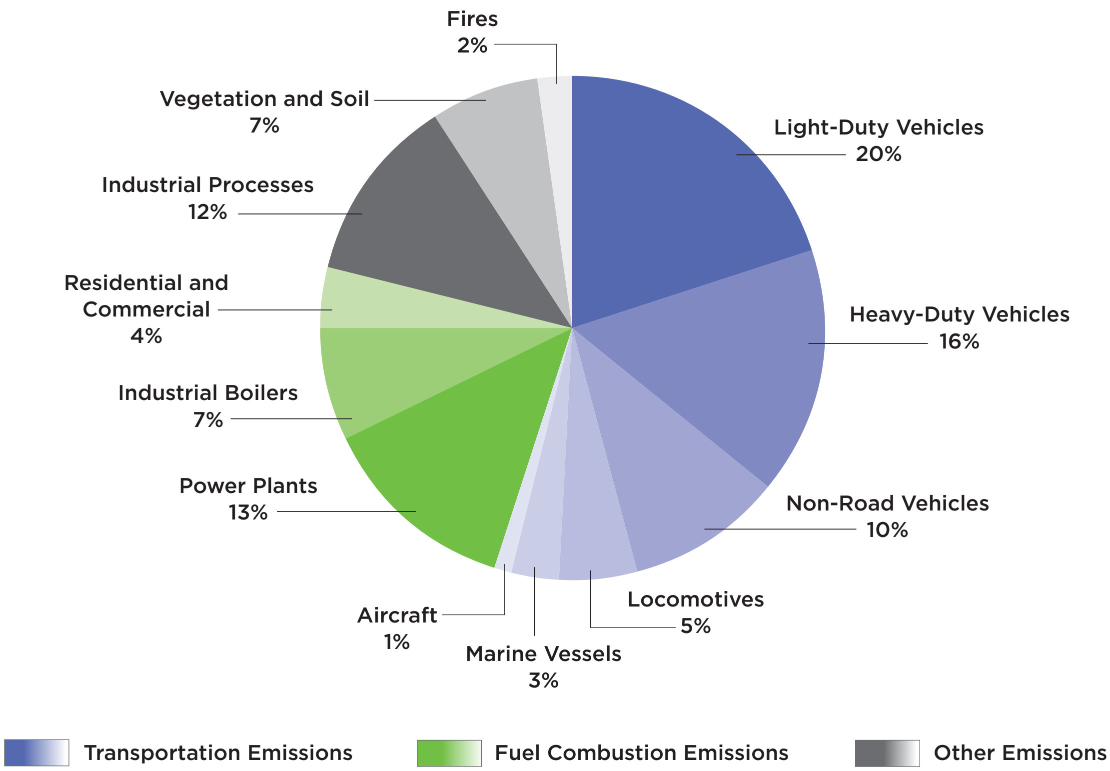
Ask three people, three databases, or three government agencies to define a heavy-duty vehicle and you will get three different answers (AFDC n.d.). Vehicles are categorized into "classes" based on their gross vehicle weight rating (GVWR), ranging from Class 1 (cars and most SUVs) to Class 8 (semi trucks and transit buses). GVWR is the maximum weight at which a fully loaded vehicle is rated to operate, including cargo, passengers, etc.

Definitions of heavy-duty vehicles vary on which classes they include, especially whether or not they include Class 2b vehicles (GWVR of 8,501 to 10,000 pounds). Given the large number of Class 2b vehicles compared with other heavy-duty vehicles (roughly 50 percent or more of all Class 2b–8 vehicles), it is important to recognize whether data include this class or not (Birky et al. 2017). Heavy-duty vehicle statistics cited in this report include Class 2b vehicles.

Vehicles in the Class 2b category cover a range of commercial and personal applications, including cargo vans (e.g., Mercedes-Benz Sprinter) and pickup trucks (e.g., Ford F-250). Unlike Class 3–8 vehicles, roughly three-quarters of which use diesel, Class 2b vehicles more commonly have gasoline engines than diesel (roughly two-thirds are gasoline) (CARB 2018a; Davis et al. 2017; Birky et al. 2017). In light-duty vehicles, diesel comprises less than 1 percent of the population (EIA 2019b).

Note, GVWR is different than a vehicle's "curb weight"—the weight of the vehicle without a load—and "gross vehicle weight"—the actual weight of the vehicle and load during operation (40 US Code). In general, a person must have a commercial driver's license to operate a vehicle with GVWR over 26,000 pounds or for transporting hazardous materials or 15 or more passengers (FMCSA 2017). GVWR also does not include the weight of a trailer. For that, there is "gross vehicle *combined* rating."

FIGURE 1. National Emissions of Nitrogen Oxides, by Sector



In the United States, heavy-duty vehicles are the second largest source of nitrogen oxides, a major air pollutant.

SOURCE: EPA 2018A.

Jimmy O'Dea/UCS

Delivery trucks are ideal candidates for electrification, given their local routes and operating ranges. Most delivery trucks travel less than 100 miles per day, well within the range of electric models on the market today.

BOX 2.

Why Diesel Engines Emit More Pollutants

A gasoline engine compresses a mixture of fuel and air and ignites it with the help of a spark. A diesel engine compresses air to higher pressures, increasing its temperature enough to ignite the diesel when it subsequently enters the engine's cylinder. The long crankshaft used to compress air in a diesel engine produces a higher torque than gasoline engines, which makes diesel the preferred fuel over gasoline for vehicles carrying heavy loads. However, the higher operating temperature of diesel engines favors the formation of NO_x compared with gasoline engines. Higher emissions of particulate matter from diesel engines result from higher levels of incomplete fuel combustion. The same advantages that diesel offers over gasoline—higher torque and better efficiency—are features that electric motors offer over diesel (Chandler, Espino, and O'Dea 2016).

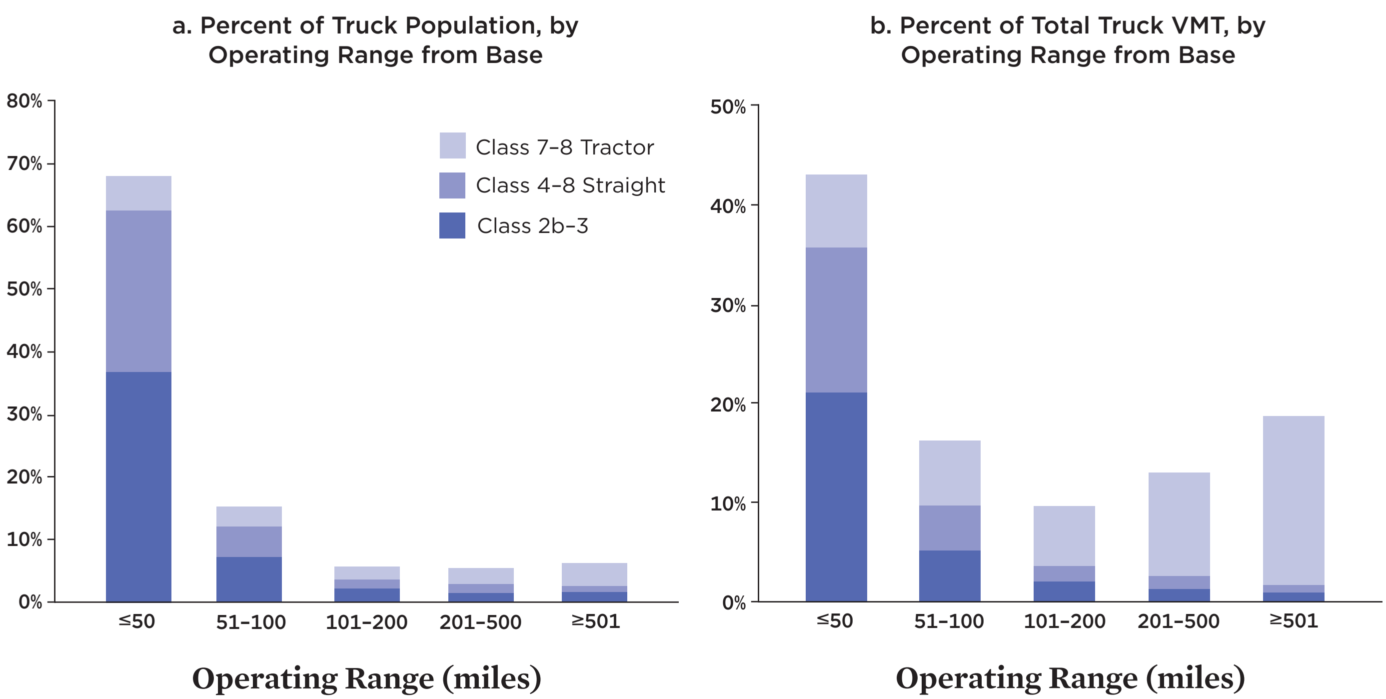
heavy-duty vehicles (Classes 2b–8) have diesel engines, compared with less than 1 percent of light-duty vehicles. In the heaviest of vehicle classes (e.g., semi trucks), nearly every vehicle is diesel-powered (Komanduri 2019).

ELECTRIFICATION CAN MEET MOST VEHICLES' NEEDS

A common question about electric vehicles is whether their range can meet the needs of a given application. The answer is yes; today's battery technology is suitable for many uses of trucks and buses.

Heavy-duty vehicles often travel to predictable destinations with consistent mileage, making them good candidates for electrification. Many trucks and buses operate over short urban routes and stop frequently (USCB 2004). Nationally, more than 80 percent of all heavy-duty trucks (Class 2b and above) have a primary operating range (the farthest distance from the vehicle's home base) of less than 100 miles; nearly 70 percent have an operating range of less than 50 miles (Figure 2).[4]

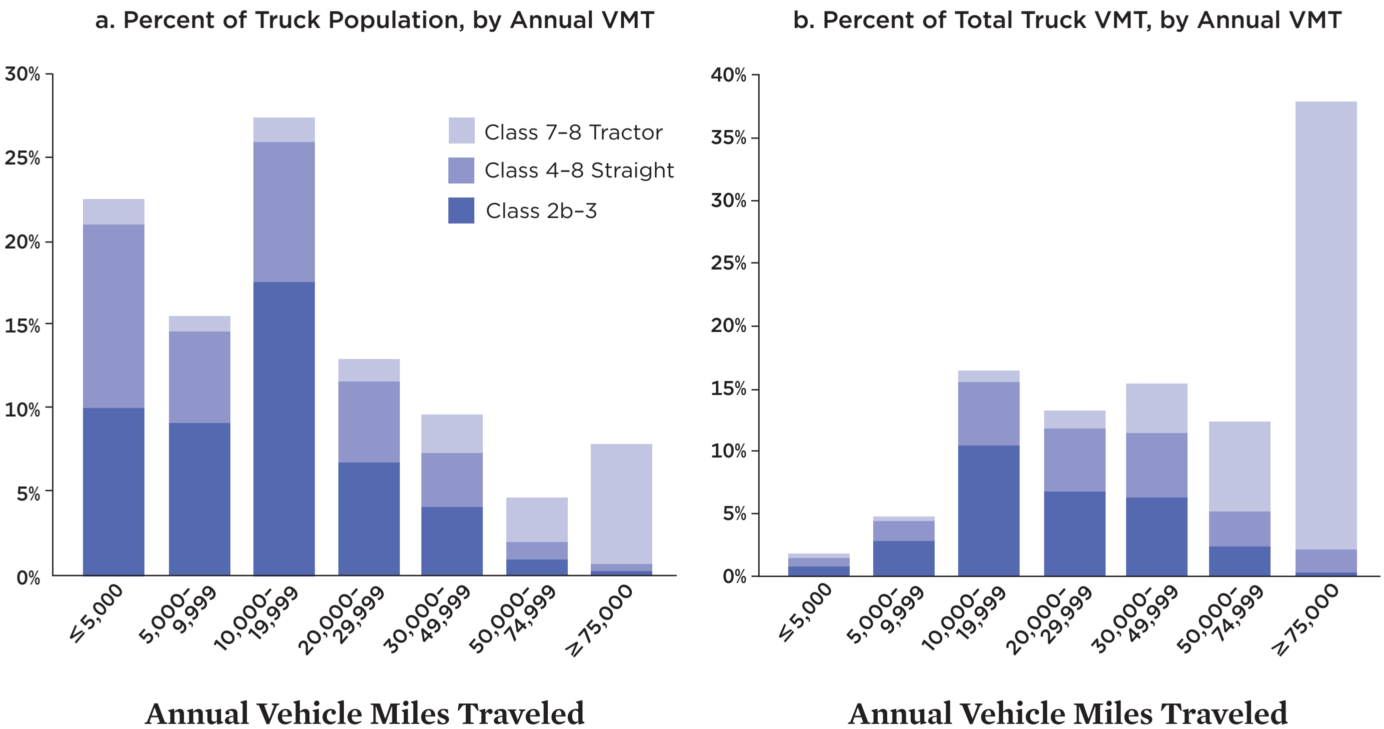
FIGURE 2. Operating Range of Heavy-Duty Trucks



Many heavy-duty trucks operate within 100-mile ranges (left), and many vehicle miles traveled (VMT) are attributable to trucks with operating ranges less than 100 miles (right). These trucks are particularly well-suited to early electrification efforts.

SOURCE: USCB 2004.

FIGURE 3. Annual Mileage of Heavy-Duty Trucks



Many trucks have annual mileages that suggest compatibility with today's battery and fuel cell technologies (left), although a small fraction of vehicles account for the bulk of the total miles traveled by trucks (right).

SOURCE: USCB 2004.

Data on annual mileage further illustrate the nature of trucks' daily operation. More than 75 percent of heavy-duty vehicles travel 30,000 miles or less each year (120 miles per day, assuming they operate five days per week and 50 weeks per year); 65 percent travel less than 20,000 miles each year (80 miles per day, assuming they operate five days per week and 50 weeks per year) (Figure 3). These daily distances are well within the range of existing heavy-duty electric vehicles on a single charge or tank of hydrogen—from roughly 90 miles to 500 miles or more, depending on the vehicle's make and model. Especially well-suited for electrification are fleet vehicles operating in defined areas and parked at central depots where they can recharge.

Conversely, a small percentage of vehicles, consisting almost exclusively of Class 7 and 8 semi, or tractor, trucks, travel many miles each year and account for a large fraction of the total miles traveled by heavy-duty vehicles. Vehicles with annual mileages greater than 50,000 miles (200 miles per day, assuming they operate five days per week and 50 weeks per year) make up about 10 percent of heavy-duty vehicles yet account for about 50 percent of the total miles traveled within this sector. However, many Class 7 and 8 tractors have lower annual mileages. A similar number of trucks in these categories travel less than 50,000 annual miles (45 percent) as trucks traveling more than 50,000 annual miles (55 percent).

> ***Heavy-duty vehicles often travel to predictable destinations with consistent mileage, making them good candidates for electrification.***

While semi trucks are often considered more challenging to electrify, several manufacturers (e.g., BYD, Daimler, Tesla, Volvo, Xos) have developed and are testing such vehicles in real-world operations. These demonstrations are proving it is entirely possible to electrify a vehicle segment once thought a moonshot. And recent analyses indicate similar if not lower total costs of ownership for vehicles purchased within the next 5 to 10 years, if not earlier, for electric semi trucks compared with diesel, whether operating in long haul or regional contexts (CARB 2019a; Di Filippo, Callahan, and Golestani 2019; Hall and Lutsey 2019; ICF n.d.a.; Phadke et al. 2019).

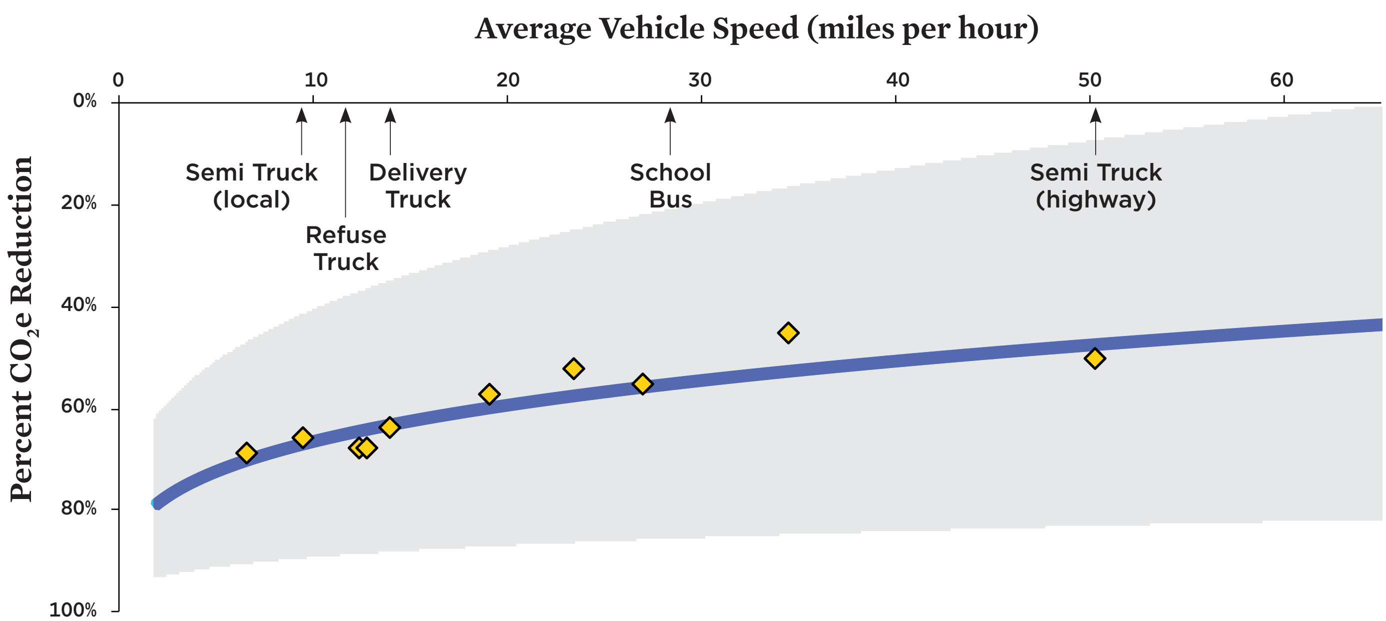
Figures 2 and 3 present average values. Some types of vehicles will operate above and others below those averages. For example, drayage trucks, which carry cargo to and from ports, railyards, and distribution centers, travel a wide range of distances depending on whether they operate near the port or travel to warehouses on the far side of the region they serve. But even considering the varied nature of truck and bus operations, the data indicate that today's technology offers opportunities for electrifying every type of heavy-duty vehicle.

ELECTRIC TRUCKS AND BUSES OFFER SIGNIFICANT CLIMATE AND AIR QUALITY BENEFITS

No matter the operating characteristics of the vehicle or electricity grid, battery-electric heavy-duty vehicles have lower global warming emissions than diesel vehicles (Figure 4). This advantage comes in addition to the public health benefits resulting from zero tailpipe emissions of harmful air pollutants such as particulate matter and nitrogen oxides.

The life cycle emissions of operating an electric vehicle compared with an internal combustion vehicle depend primarily on two factors: the vehicle's energy efficiency and the sources of electricity used to charge the vehicle. Battery-electric vehicles are considerably more energy efficient than diesel, natural gas, or gasoline vehicles, which is a major reason that electric vehicles have lower life cycle emissions than combustion vehicles, even though fossil fuels are the largest (yet declining) source of electricity in the United

FIGURE 4. Better for the Climate at Any Speed



No matter the electricity grid in the United States or the average vehicle speed, electric heavy-duty vehicles offer significant benefits toward minimizing global warming emissions compared with diesel heavy-duty vehicles. The efficiency benefits of electric heavy-duty vehicles are greatest at low average speeds, characterized by frequent acceleration and deceleration.

Notes: The gray band represents emissions reductions from the US electricity grid as a whole, from the most carbon-intensive (top edge) to the least carbon-intensive (bottom edge). The blue line shows emissions reductions of an electric vehicle on the average grid in the United States. Diamonds represent findings from studies of the energy efficiency improvements of battery-electric heavy-duty vehicles compared with diesel vehicles for a range of average speeds. Arrows show representative average speeds for different types of heavy-duty vehicles. The average speeds for the trucks listed above were determined as follows: refuse truck corresponds to real-world data collected from the operation of six front-loader trucks; delivery truck corresponds to a Class 5 stepvan tested on the Hybrid Truck Users Forum Parcel Delivery Class 4 (HTUF4) drive cycle; school bus corresponds to a 72-passenger bus tested on the Urban Driving Dynamometer Schedule for Heavy Duty Vehicles (UDDSHDV) drive cycle; local and highway semi trucks correspond to drive cycles designed to simulate drayage truck operations.

SOURCES: CARB 2018B; EPA 2018B; SANDHU ET AL. 2014; BARNITT AND GONDER 2011.

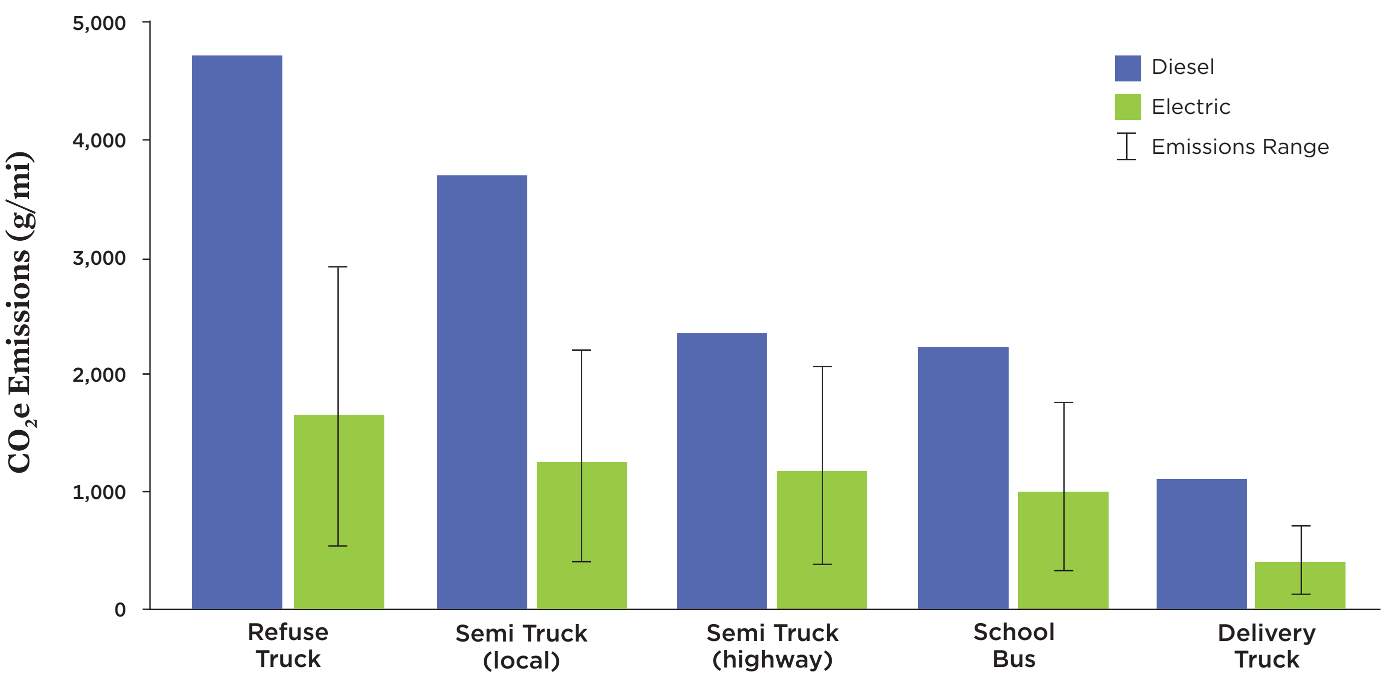
States (EIA 2019c). For trips involving frequent stopping, accelerating, or idling (average speeds of about 10 miles per hour or less), heavy-duty battery-electric vehicles are five to seven times more efficient than diesel vehicles. Even at highway speeds, heavy-duty battery-electric vehicles are 3.5 times more efficient (CARB 2018b).

The poor efficiency of combustion engines is recognizable in the heat emanating from their engines and exhausts. The heat represents chemical energy in the fuel (gasoline, diesel, or natural gas) that was not converted into mechanical energy to propel the vehicle. Energy losses are much smaller with battery-electric vehicles.

The Union of Concerned Scientists has documented the climate benefits that electric cars and transit buses offer over their combustion counterparts on all electricity grid regions in the United States (Nealer, Reichmuth, and Anair 2015; O'Dea 2018a; Reichmuth 2018). The same benefits arise for other types of heavy-duty vehicles, including delivery trucks, refuse trucks, school buses, and drayage trucks. Combining energy efficiencies for a range of vehicle types and operating characteristics with the global warming emissions associated with electricity production in every US grid region, Figure 4 shows the emissions reductions of electric vehicles traveling at average speeds ranging from 2 to 65 miles per hour (CARB 2018b).[5]

With the average sources of electricity in the United States, a heavy-duty electric vehicle reduces global warming emissions by 44 to 79 percent depending on a vehicle's average speed over the course of its trip (see the blue line in Figure 4). Using estimates of average speeds for different types of vehicles, Figure 5 shows that electric delivery trucks, refuse trucks, and locally operating semi trucks offer 65 percent reductions compared with equivalent diesel vehicles; electric semi trucks with highway-based operations and school buses offer 50 percent reductions in global warming emissions. Figure 6 (p. 8) shows the emissions reductions for a delivery truck operating in all grid regions across the

FIGURE 5. Life Cycle Global Warming Emissions for Different Heavy-Duty Electric Vehicles on the Average US Grid (generation-weighted) in 2016

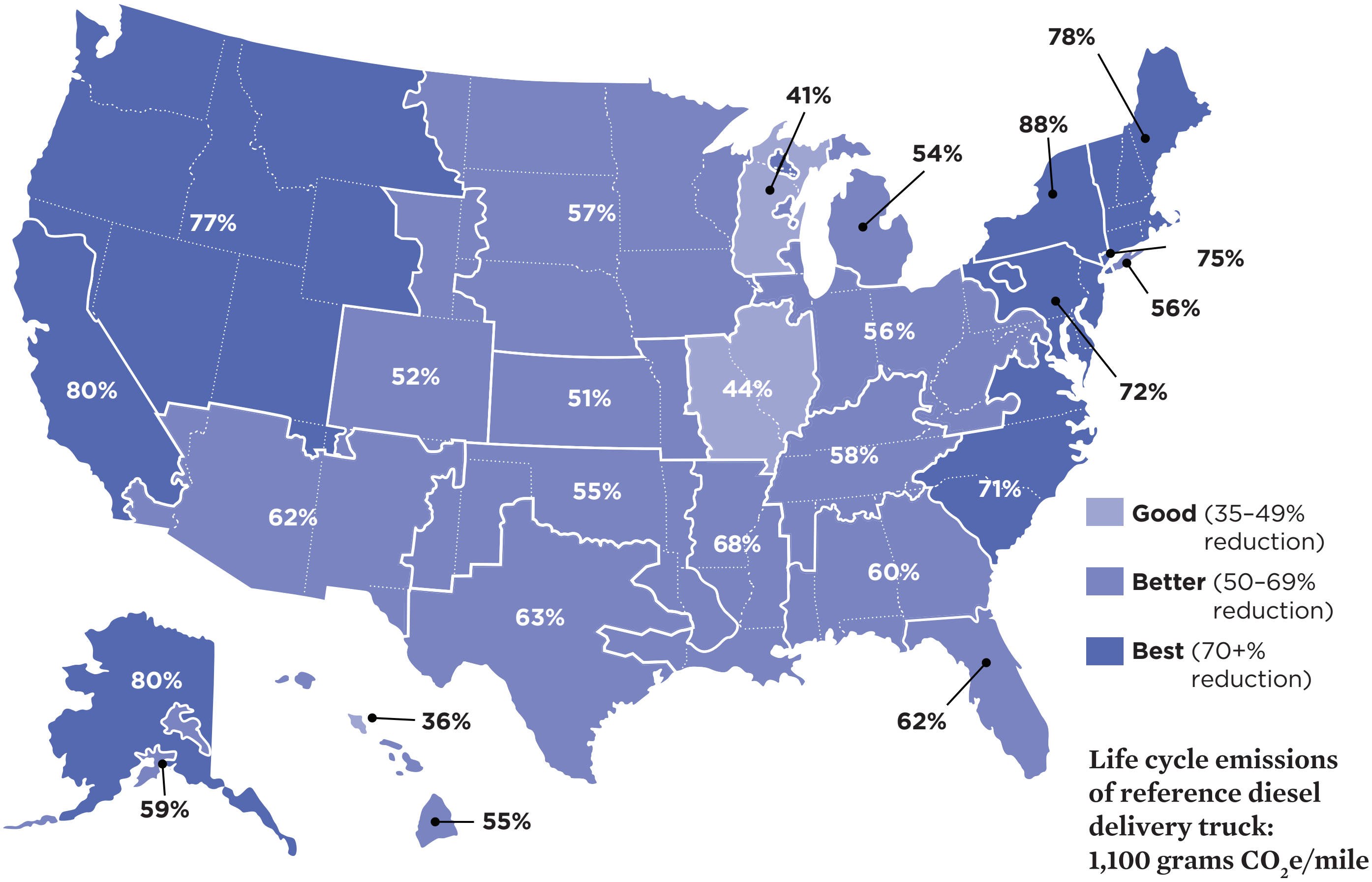


Per-mile life cycle global warming emissions vary for different types of heavy-duty vehicles depending on a vehicle's fuel efficiency. Shown are life cycle emissions from diesel and electric versions of five common heavy-duty vehicles. Bars for electric vehicles represent life cycle global warming emissions for vehicles charged on the average grid in the United States. Range bars represent emissions from the most and least carbon-intensive electricity grids in the United States.

Note: Fuel economies for the electric refuse truck and school bus were estimated based on the fuel economy of the corresponding diesel vehicle and its average speed. Fuel economies for the electric delivery truck and semi trucks were measured directly.

SOURCES: CARB 2018B; EPA 2018B; SANDHU ET AL. 2014; BARNITT AND GONDER 2011.

FIGURE 6. Electric Delivery Trucks Offer Significant Reductions in Life Cycle Global Warming Emissions in All Grid Regions of the United States



This map shows life cycle global warming emissions as a function of different sources of electricity for a common type of delivery truck (Class 5 stepvan). Percentages represent emissions reductions for the electric delivery truck compared with a similar diesel delivery truck.

SOURCES: CARB 2018B; EPA 2018B; SANDHU ET AL. 2014; BARNITT AND GONDER 2011.

United States, ranging from 36 percent to 88 percent lower life cycle global warming emissions than a diesel delivery truck.

> ***No matter the operating characteristics of the vehicle or electricity grid, battery-electric heavy-duty vehicles have lower global warming emissions than diesel vehicles.***

As the grid continues to become cleaner through commitments by states such as Hawaii, California, Nevada, New Mexico, Washington, and New York, emissions from electric vehicles will continue to decline (DSIRE 2019; Reichmuth 2018). From 2009 to 2016, global warming emissions from the production of electricity decreased by 18 percent, from 1,222 pounds CO_2e per megawatt-hour (lb/MWh) to 1,004 lb/MWh (EPA 2018b).

A Growing Market for Heavy-Duty Electric Vehicles

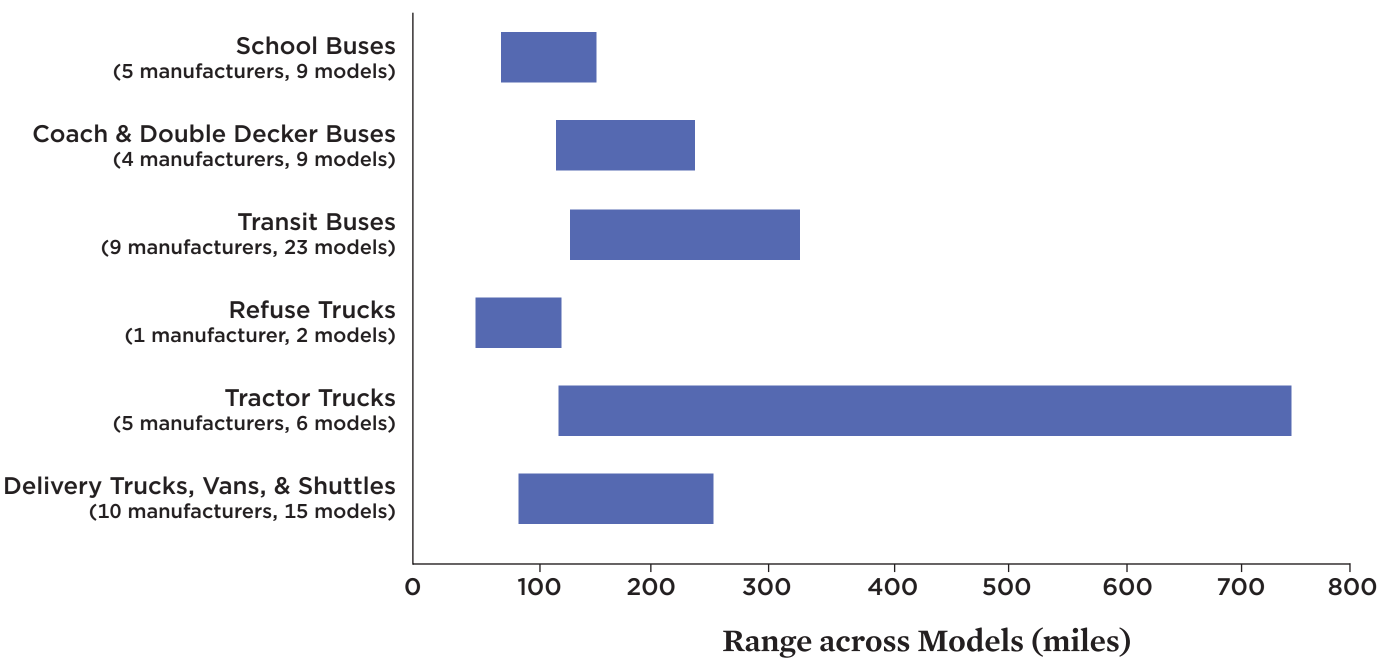
The availability of heavy-duty electric vehicles has grown rapidly in recent years (Figure 7; also see the Appendix at *www.ucsusa.org/resources/ready-work*). In the United States, there are 70 models and counting—from 27 manufacturers—of electric trucks and buses that are available today or with production announced for the next two years (see Appendix). In 2014, eight manufacturers offered 25 models of electric trucks and buses that were eligible for purchase incentives in California (HVIP 2015).

As an indicator of rapid progress in the transit bus industry, three manufacturers (BYD, New Flyer, and Proterra) offer vehicles with ranges up to, if not beyond, 200 miles, depending on the operating conditions. Five manufacturers of school buses offer electric versions, including established manufacturers and new entrants. Ten different manufacturers offer electric trucks in the delivery truck and straight truck categories. Product choices are limited for Class 7 and Class 8 trucks, yet eight manufacturers are beginning to deploy and test vehicles in these large truck categories.

New entrants dominate the heavy-duty electric vehicle market, but traditional truck manufacturers appear to be ramping up efforts on electric vehicles as well. Some of the new entrants are large companies, such as BYD and Tesla, that also produce light-duty electric vehicles. Other companies are less well-known but quickly establishing themselves. Still others are "upfitters," smaller companies filling a critical void left by original equipment manufacturers that do not offer electric versions of their vehicles. Upfitters take vehicles made by companies like Ford or GM and replace the engine with an electric drivetrain.[6] With this business model,

[In the United States, there are 70 models of electric trucks and buses, from 27 manufacturers, that are available today or with production announced for the next two years.]

FIGURE 7. Electric Trucks and Buses Fit Many Needs



Multiple manufacturers have electric heavy-duty trucks and buses on the road today or targeted for production within the next one to two years. The battery ranges offered by these vehicles provide numerous options for companies and municipalities interested in switching from diesel to electric models.

Notes: Mileage ranges represent the maximum value provided by manufacturers. The number of models includes those currently available for purchase and those announced for production by 2021. Excluded from the figure are yard trucks (four models available from four manufacturers) and street sweepers (two models available from one manufacturer), for which battery range is measured in hours of operation instead of miles, as well as models for which future availability is unknown. See the Appendix for detailed information on individual model ranges, battery capacity, and production status.

Jimmy O'Dea/UCS

Four manufacturers already offer electric versions of yard trucks, which move cargo containers within port, railyard, and warehouse complexes.

customers that want a Ford or Chevy truck can get it in an electric version. The disadvantage is scale, but as upfitters have established their expertise on electric drivetrains and electronics, they are beginning to partner with large vehicle manufacturers to build electric vehicles on assembly lines; this will greatly increase production rates.

ADOPTION COULD COME FAST

While deployment of heavy-duty electric vehicles on US roads lags that of electric passenger vehicles, progress in the transit bus industry is one indicator of the rate at which other heavy-duty electric vehicles could also be adopted. In the United States, electric transit buses already account for 10 percent of annual sales.[7] In contrast, passenger electric vehicles represented less than 2 percent of national automobile sales in 2018 (Auto Alliance n.d.). The rapid early adoption of electric buses stems largely from the significant investments and financial incentives provided by state and federal policies.

While electric trucks have yet to account for a significant fraction of sales in the United States, China's adoption of heavy-duty electric vehicles also indicates how quickly a transition can be made. More than 400,000 electric transit buses have been sold in China since 2012 (Albanese 2019; Eckhouse 2019). The city of Shenzhen alone has 16,000 electric transit buses (Keegan 2018). Even larger has been that city's deployment of electric vans and delivery trucks. From 2015 through 2018, Shenzhen's fleet of these vehicles expanded from nearly zero to more than 60,000. Electric models now represent about 35 percent of the city's urban delivery vehicles (McLane and Mullaney 2019).

ENERGY USE WILL SIGNIFICANTLY DECREASE, WHILE ELECTRICITY NEEDS WILL MODERATELY INCREASE

Transitioning from diesel and gasoline to electricity as the fuel for trucks and buses will decrease demand for the former fuels, and it will increase demand for electricity and hydrogen. If all trucks in the United States were suddenly battery-electric, the energy needed to power them would decline significantly. This is because electric vehicles are much more efficient than diesel, natural gas, and gasoline vehicles.

To power all these vehicles would increase overall electricity consumption. In 2017, heavy-duty vehicles on US roads consumed roughly 41 billion gallons of diesel and 10 billion gallons of gasoline (EIA 2019d). From these values, it is possible to estimate the amount of energy required to power these vehicles if they were electric. Using a vehicle efficiency improvement of four times for electric compared with diesel and accounting for efficiency losses in the transmission of electricity (6 percent) and efficiency losses associated with charging a vehicle (10 percent), it would take 560 terawatt-hours (TWh) of electricity to power all heavy-duty trucks in the United States with electricity.[8] This would represent a 13 percent increase in electricity generation compared with the 4,200 TWh used in the United States in 2017, but a 71 percent decrease in energy compared to the consumption of diesel and gasoline by heavy-duty vehicles (1,900 TWh) (EIA n.d.a; EIA n.d.b). For a sense of scale, the residential sector consumed nearly 1,400 TWh of electricity in 2017; air conditioning alone consumed more than 200 TWh (EIA n.d.c; EIA n.d.d).

Of course, electrification of trucks and buses will not occur all at once. Electrifying 10 percent of the diesel fleet over a decade would increase electricity demand similarly to the rise in demand from data servers, which increased from 35 TWh in 2000 to 70 TWh in 2008 (and then leveled off as the energy efficiency of data servers improved) (Azevedo et al. 2016). Consider, too, the speed at which the United States has added clean sources of electricity: annual generation from wind and solar increased more than 300 TWh from 2008 to 2018 (EIA 2019e).

Improving the utilization of existing sources of electricity can minimize the need for new power plants to meet increased demand from electric vehicles. Because the electricity grid is designed to accommodate the highest demand experienced on it, much of its generation capacity sits idle during periods of non-peak demand. Electric vehicles can use the idle capacity if they charge at off-peak times such as when solar or wind generate excess electricity. Better utilization of grid capacity spreads fixed costs (for example, transmission lines) over increased electricity sales, which lowers electricity rates for all customers (CUB n.d.).

Electric vehicles can provide grid services in addition to utilizing idle or curtailed generation resources. Charging at off-peak times or times of high renewable electricity generation can level out daily energy demands and reduce the need for ramping electricity generation up or down, periods that generate significant emissions (Wisland 2018). The need to reduce extreme power ramping is particularly acute in places such as California, with significant deployment of solar energy and large peaks and valleys in the daily electricity demand. Electricity rates that are lower during off-peak periods can encourage owners of electric trucks and buses to charge at times that are beneficial to the grid.

A unique aspect of electric trucks and buses compared with cars is the larger amount of instantaneous energy (power) required for charging their larger batteries. Cars currently charge at rates from 5 kW to 250 kW, with home and workplace charging falling on the slow end and "DC fast chargers," typically located at travel stops or public charging stations, representing the fast end. For trucks and buses, whose batteries can store anywhere from 2 to 10 times the amount of energy simply by having more battery cells, rates of 20 kW to 200 kW are used for overnight charging depending on the size of the vehicle's battery. Even faster on-route chargers used by some transit buses charge at 150 kW to 400 kW (Proterra 2019). Charging at lower power rates and at times with lower demand from other sources is optimal for the grid. One strategy that can lessen impacts on the grid is to charge a vehicle's battery from stationary batteries built into charging stations.

The Economic Case for Heavy-Duty Electric Vehicles

Fuel and maintenance savings can offset the higher upfront costs of heavy-duty electric vehicles, making them cheaper than a diesel or natural gas vehicle over the life of a vehicle. This is especially the case for higher mileage truck and bus applications: for these, fuel costs can greatly exceed vehicle costs—more than twice as much depending on the application. The economics shift even further in favor of electric vehicles as the prices of batteries and fuel cells decrease and the prices of diesel and natural gas engines increase to meet clean air standards.

> ***Depending on the application, battery-electric trucks can be cost-competitive today.***

Depending on the application, battery-electric trucks can be cost competitive with diesel today on a total-cost-of-ownership basis. In nearly every vehicle case examined, including long-haul semi trucks, battery-electric trucks and buses are cheaper than diesel vehicles on a total-cost-of-ownership basis for vehicles purchased within the next 10 years (CARB 2019a; Hall and Lutsey 2019; ICF n.d.a.; Phadke et al. 2019). Those are the conclusions of recent analyses conducted by the California Air Resources Board, the International Council on Clean Transportation, and ICF. The studies, summarized in Figures 8 and 9, analyzed the total cost of ownership for vehicles purchased today and in 2030 for Class 6 delivery trucks and Class 8 short-haul semi trucks. All three studies reached similar conclusions despite different assumptions for many parameters including vehicle purchase prices, annual mileage, years of vehicle ownership, maintenance costs, electricity rates, and vehicle fuel efficiencies.

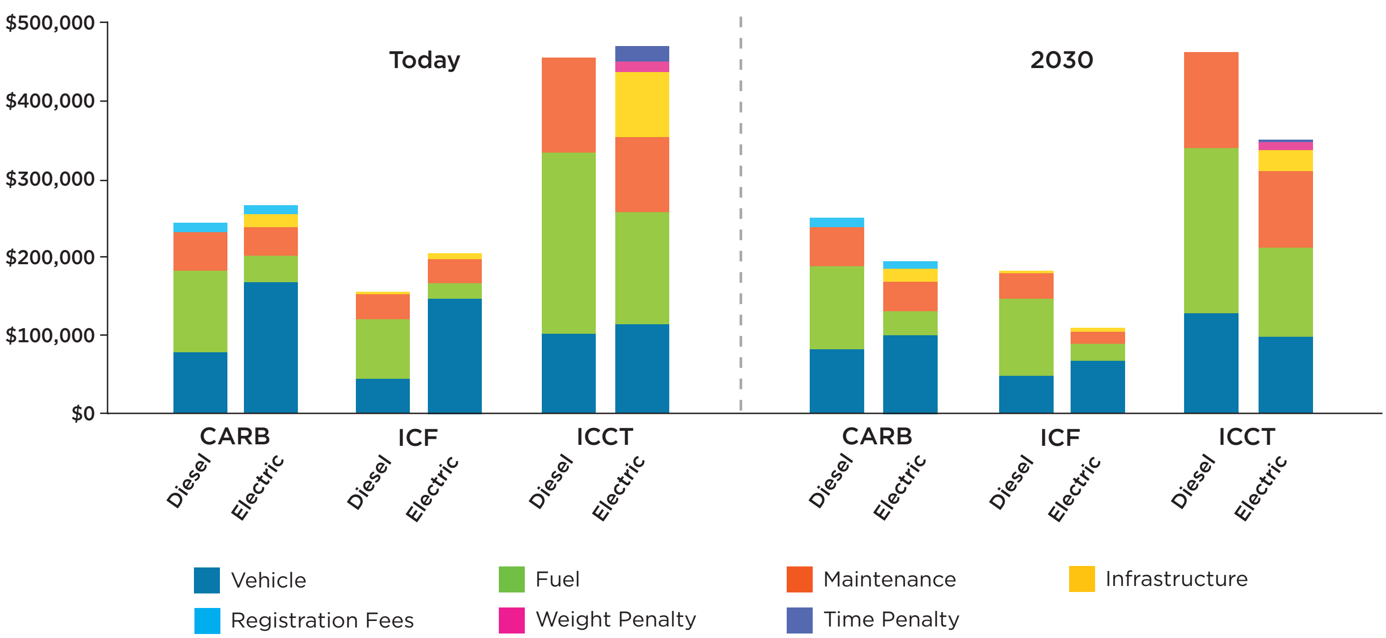
The largest impact comes from savings on fuel costs: compared with diesel, electricity reduces fuel costs an estimated 30 to 75 percent, depending on assumptions for vehicle efficiency and fuel prices. In most scenarios examined, the vehicle purchase price remains higher than that of its diesel counterpart through 2030, yet total ownership costs are significantly lower.

All three analyses focus on California, which allows for comparable assumptions for electricity rates and diesel costs. Otherwise, the cost assumptions apply to all markets in the United States.[9] Given that California's electricity rates are among the nation's highest, electric vehicles would offer even greater fuel savings elsewhere.[10]

While California's policies and incentives significantly offset the costs of vehicle purchases, fuel, and charging infrastructure, Figures 8 and 9 exclude these financial benefits as they are not currently available in other states (HVIP 2019; O'Dea 2019a; Barbose and Martin 2018). With California's policies and incentives, however, the total cost of ownership is lower than diesel today for 19 of 20 vehicle scenarios examined in the three studies. The scenarios include several types of delivery trucks, semi trucks, transit buses, and school buses. Vehicle applications with the least savings are those with lower annual mileages and higher operating speeds, which offer less improvement in fuel efficiency compared with diesel vehicles. California's Low Carbon Fuel Standard, which financially penalizes fuels with carbon intensities above a set standard and rewards fuels below it, can lower the electricity rates for heavy-duty vehicles approximately \$0.09 to \$0.14 per kWh today and \$0.07 to \$0.12 per kWh in 2030, depending on the fuel efficiency improvements of an electric vehicle compared with a diesel vehicle.[11]

The three studies also examined the total cost of ownership for hydrogen fuel cell vehicles (not shown in Figures 8 and 9). Fuel cell vehicles have higher total costs of ownership compared with battery-electric vehicles across all vehicle types today. Significant reductions in the costs of fuel cells

FIGURE 8. Total Cost Comparisons, Class 6 Delivery Trucks

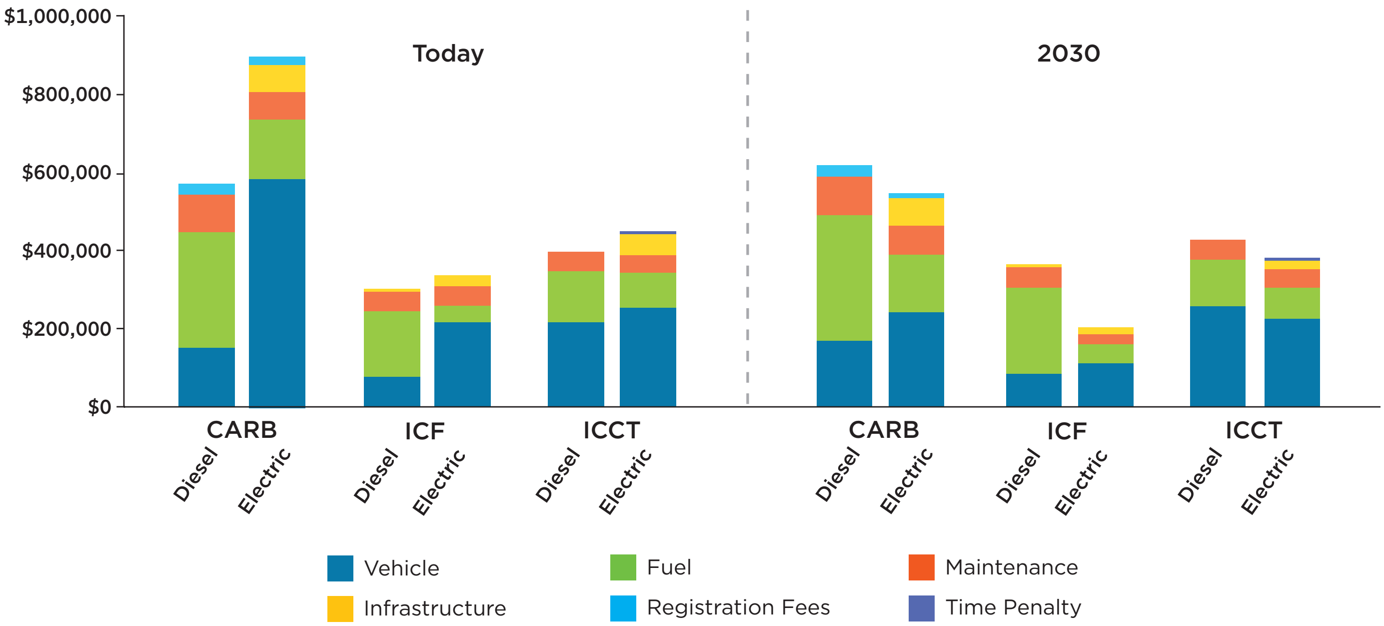


The total cost of ownership for Class 6 electric delivery trucks is competitive with diesel vehicles today and estimated to be significantly lower within the next decade.

Notes: In the ICCT study, "today" corresponds to 2020; in the CARB and ICF studies, 2018. Vehicle costs in the ICF and CARB analyses account for the residual value of the vehicle at the end of its assumed period of ownership.

SOURCES: HALL AND LUTSEY 2019; ICF N.D.A, CARB 2019A.

FIGURE 9. Total Cost Comparisons, Class 8 Short-Haul/Drayage Trucks



The total cost of ownership for Class 8 electric short-haul/drayage trucks can be lower than diesel today with financial incentives, and is estimated to be lower for diesel trucks within the next decade without such incentives.

Notes: In the ICCT study, "today" corresponds to 2020; in the CARB and ICF studies, 2018. Vehicle costs in the ICF and CARB analyses account for the residual value of the vehicle at the end of its assumed period of ownership.

SOURCES: HALL AND LUTSEY 2019: ICF N.D.A, CARB 2019A.

and hydrogen are needed for these vehicles to compete with diesel vehicles (see Box 3).

How to Get More Electric Trucks and Buses on the Road

Considering their local operating characteristics, the range of today's battery technologies, and similar if not reduced ownership costs, widespread electrification makes immediate sense in several classes of heavy-duty vehicles. However, internal combustion engines have dominated the truck and bus marketplace for more than a century, presenting significant barriers to transforming these markets. Policies are needed to shift from an industry dominated by diesel to one powered by electricity or hydrogen.

Three types of policy are important to deploying heavy-duty electric vehicles: financial incentives, infrastructure investments, and manufacturing and purchasing standards. All of these policies must center on improving air quality in communities most burdened by pollution from vehicles.

FINANCIAL INCENTIVES

Overcoming the higher upfront cost of electric trucks is an important strategy for increasing their adoption. For example, a federal tax credit that provides up to $7,500 has been key

BOX 3.

What About Fuel Cells?

Batteries and fuel cells both generate electricity that an electric motor converts to mechanical energy to move a vehicle. Batteries use compounds of lithium and graphite to produce electricity, while fuel cells produce electricity from hydrogen and oxygen gases. Both types of electric vehicles have zero tailpipe emissions and are significantly more energy efficient than heavy-duty vehicles powered by diesel or natural gas. The main advantage of fuel cells over batteries are shorter fueling times, but higher vehicle and fuel prices have slowed their commercialization compared with battery electric vehicles.

Jimmy O'Dea/UCS

Electric school buses can reduce global warming emissions by about 50 percent compared with diesel buses, based on the US average grid mix. Five manufacturers offer electric school buses today.

> ***Electric utilities and utility regulators should ensure that heavy-duty vehicle operators have access to fair rates that account for these vehicles' demands and benefits to the grid.***

in reducing the upfront cost of passenger electric vehicles. No similar federal policy exists for electric trucks and buses, but California's Hybrid and Zero-Emission Truck and Bus Voucher Incentive Project (HVIP) has demonstrated that incentives to lower the upfront cost of electric vehicles can accelerate adoption. This program has funded more than 2,400 electric vehicles over the past nine years and vehicle demand annually exceeds the allocated state funding (CARB 2019b).

Policy strategies to reduce the upfront costs of electric trucks and buses include establishing federal and state tax credits or rebates, or waiving federal, state, and local sales taxes for the purchase of these vehicles. While 11 states and Washington, DC, have incentives for buying electric passenger vehicles, only California, Colorado, New York, Texas, and Utah offer incentives for buying heavy-duty electric vehicles (Colorado Department of Revenue 2019; HVIP 2019; NYTVIP n.d.; Tesla n.d.; TCEQ n.d.; 59 Utah Code).[12] Other states could do this also, and design programs to ensure deployment of electric trucks and buses occurs in communities most affected by air pollution. Requirements for the amount of funding that benefits these communities and higher incentives for electric trucks and buses deployed there, as set forth in California's HVIP program, can ensure that air quality benefits occur where they are needed most.

In addition to reducing upfront costs, incentives to lower the operating expenses of electric vehicles compared with diesel can also help make a more compelling business case to go electric. Several policy strategies exist in this regard.

Ensure fair and reasonable electric utility rates for truck and bus charging: Most commercial electricity rates were designed without electric trucks and buses in mind. However, these vehicles place different demands on, and offer different services to, the electricity grid compared with buildings and equipment traditionally associated with commercial electricity use (Houston 2019). Electric utilities and utility regulators should ensure that heavy-duty vehicle operators have access to fair rates that account for these vehicles' demands and benefits to the electric grid. Such rates would provide the opportunity for vehicle operators to save on fuel costs, especially operators that charge trucks or buses at off-peak times and during periods when renewable electricity generation is high.

Establish state-level clean fuels standards: In state programs like California's Low Carbon Fuel Standard and Oregon's Clean Fuel Program, fleets can earn clean-fuel credits for electric operation and sell those into a credit market (Barbose and Martin 2018). The credits can add up. For example, an electric transit bus in California can generate

Dennis Schroeder/NREL

Powering trucks and buses with electricity is not only better for the climate than diesel—even in the most carbon-intensive electricity grid regions of the United States—but also offers significant savings in fuel costs.

more than $10,000 of credits annually, lowering its electricity rate by $0.14 per kWh.

Include electricity in federal fuels policy: Current federal policy supports increased use of biodiesel and biomethane, but it does not provide equivalent support for the use of electricity, even if that electricity is produced from biomethane. Creating pathways for electricity under existing or future fuels policy would provide incentives for electrification commensurate with those available to biodiesel and biomethane.

Create low- or zero-emissions zones: Cities seeking to accelerate the adoption of electric trucks could implement fees on higher-emitting trucks or provide preferred access to electric trucks. The Port of Los Angeles and the Port of Long Beach have committed to plans that will charge diesel and natural gas trucks to access the ports, while exempting electric trucks. While the strategy is not prevalent in the United States, low-emissions zones, where fees or exclusions apply to higher polluting commercial vehicles, are prominent in European cities (European Union n.d.). Similarly, states can incentivize electric truck adoption by reducing or waiving annual registration fees.

INVESTMENTS IN CHARGING INFRASTRUCTURE

Successfully deploying electric trucks will require investments in charging infrastructure. In the near term, financial support for installing charging infrastructure can encourage fleets to adopt electric trucks and reduce the upfront costs of transitioning to electric vehicles. Utilities' and utility regulators' support for investments in charging infrastructure can catalyze truck electrification as can federal policy.

Utility investments: In addition to offering fair and affordable electricity rates, utilities have a significant role to play in the widespread electrification of heavy-duty vehicles by investing in charging infrastructure (Houston 2019). Many utilities have begun implementing programs to facilitate the adoption of electric trucks and buses. These include installing and upgrading infrastructure on customers' sites (upgrading electric panels, trenching, installing wiring) or offering rebates for infrastructure improvements. Utilities could also consider financing options that allow their customers to pay back the cost of infrastructure installations on future utility bills. Such programs should provide greater support for charging facilities in communities affected by pollution to ensure that clean air benefits come where they are most needed.

State and federal support for truck charging infrastructure: For electric trucks to reach their potential, publicly accessible charging/fueling sites on major travel corridors will need to complement depot-based charging and

> ***Utilities have a significant role to play in the widespread electrification of heavy-duty vehicles.***

hydrogen fueling infrastructure. For example, the West Coast Clean Transit Corridor is a regional effort by several utilities and agencies across state lines to determine the infrastructure needs for long-haul electric trucking on the Interstate 5 corridor (SMUD 2019). State and federal policymakers can support such efforts by providing grants or other financial incentives to promote coordination and spur the installation of robust charging networks.

GOALS AND STANDARDS

While financial incentives can encourage the early adoption of technologies, it also will take standards, laws, and regulatory measures to accelerate the adoption of electric trucks and buses. This "carrot and stick" strategy has succeeded in the market for passenger electric vehicles. California's disproportionate share of electric cars in the United States illustrates the impact of these strategies. Despite having 11 percent of US vehicles and 12 percent of the nation's population, California has roughly 50 percent of the million-plus electric cars sold in the country (including plug-in hybrids) (FHWA 2019; Auto Alliance n.d.; USCB n.d.).

The main reason California is a leader in electric cars is state policy (UCS 2019). In addition to incentive and infrastructure policies, California requires car manufacturers to sell electric vehicles in the state, and it is considering a similar requirement for truck manufacturers.

Beyond such a requirement, policymakers can consider ways to compel fleets—whether public or private—to transition to electric. California recently adopted measures to require transit agencies and companies operating airport shuttle buses to move toward electrifying their fleets over the next decade (O'Dea 2019b; O'Dea 2018b). Similar measures targeting port drayage trucks and delivery vehicles are expected.

Local governments can also adopt policies for electrifying municipal trucks and buses. Contracts for refuse services or school bus services could include targets for deploying electric vehicles. Several transit agencies' boards have approved plans to transition their entire fleets to electric. Such fleet requirements can increase sales volumes, and thereby lower costs, and drive investments in charging infrastructure. In all, no one policy will lead to the widespread electrification of trucks and buses. Instead it will take key policies that lower costs, support charging infrastructure, and set standards for the availability and adoption of electric trucks and buses.

Jimmy O'Dea *is a senior vehicles analyst in the UCS Clean Transportation Program.*

ACKNOWLEDGMENTS

This report was made possible by the generous support of the Common Sense Fund, the 11th Hour Project of the Schmidt Family Foundation, the Farvue Foundation, the William and Flora Hewlett Foundation, the John D. and Catherine T. MacArthur Foundation, the John Merck Fund, and UCS members.

The author thanks Gideon Weissman at Frontier Group; and Don Anair, Dave Cooke, and Samantha Houston at UCS for helpful feedback and discussions.

Organizational affiliations are listed for identification purposes only. The opinions expressed herein do not necessary reflect those of the organizations that funded the work or the individuals who reviewed it. The Union of Concerned Scientists bears sole responsibility for the report's contents.

ENDNOTES

1 *Transportation emissions exclude those related to the production of fuels (e.g., diesel and gasoline). On-road sources of emissions represent 24 percent of total US global warming emissions; aircraft, ships, boats, rail, pipelines, and lubricants comprise 5 percent. Heavy-duty vehicles defined in the EPA's emissions inventory include vehicles with gross vehicle ratings of 8,501 pounds (Class 2b) and above. For consistency with vehicle population and NO_x and $PM_{2.5}$ emissions, global warming emissions represent data from 2014. For the latest data available (2017), the fraction of global warming emissions from heavy-duty vehicles relative to all on-road vehicles (30 percent) remains similar to the 2014 values cited in the text. Overall emissions from both heavy- and light-duty vehicles increased from 2014 to 2017, from 421 to 451 million metric tons of CO_2e (EPA 2019).*

2 *The population of Class 2b–8 heavy-duty vehicles was determined by combining an estimate of the Class 2b population (13.1 million vehicles) from the US Department of Energy and the Class 3–8 population (12.9 million vehicles) from the Federal Highway Administration, including buses (EIA 2016; FHWA 2016). Vehicle population represents that in 2014 to match the latest NO_x and $PM_{2.5}$ emissions data. Using data from the EIA's 2019 Annual Energy Outlook and the FHWA's Highway Statistics 2017, the population of Class 2b and Class 3–8 vehicles in 2017, the latest data available, is 13.8 million vehicles for each category, or 10 percent of total vehicles as in 2014 (EIA 2019a; FHWA 2019). Previous UCS analyses found Class 2b–8 vehicles comprise 7 percent of total vehicles (Chandler, Espino, and O'Dea 2016; Cooke 2015). Data in the EIA's 2016 Annual Energy Outlook and later show significantly more Class 2b vehicles than previously estimated, explaining the increase.*

3 *Transportation, including off-road modes, is the largest source of NO_x emissions in the United States. Heavy-duty vehicles account for 30 percent of the transportation sector's NO_x emissions and 16 percent of all NO_x emissions. For $PM_{2.5}$, heavy-duty vehicles account for 28 percent of transportation's emissions, but less than 2 percent of all $PM_{2.5}$ emissions including dust and fire sources (EPA 2018a). Diesel particulate matter, however, remains a critical pollutant to minimize as it has been classified as a carcinogen by the World Health Organization (CARB n.d.).*

4 *Excluding Class 2b vehicles does not significantly affect the fraction of vehicles with operating ranges less than 50 or 100 miles. Eighty percent of Class 3–8 trucks have a primary operating range of less than 100 miles; 63 percent have an operating range of less than 50 miles. An updated survey of heavy-duty vehicles in California found similar weighted-distributions of vehicle population (by truck class and vehicle age) and vehicle miles traveled (by truck class, but not commodity) from 2002 and 2017, suggesting results from the 2002 vehicle inventory and use survey (VIUS) still roughly reflect present-day trends in the truck industry in the absence of a newer national VIUS and despite a small sample size for pickup trucks in the 2002 survey (Komanduri 2019; Birky et al. 2017).*

5 *The average truck speed on interstate highways is 50 to 60 miles per hour (DOT n.d.; EERE n.d.).*

6 *Sometimes the company arranges to procure vehicles without the engine, which is preferable.*

7 *Annual sales of standard and articulated transit buses averaged 4,400 per year over the last five years (2012–2016) (FTA 2018). This number of sales reflects a 14-year lifespan, or a 7 percent annual turnover compared with the 63,300 total buses. The number of electric buses awarded, as tracked by the Center for Transportation and the Environment, increased from roughly 400 in 2015 to 800 in 2016, 1,200 in 2017, and 1,600 in 2018 (Raudebaugh 2018). The number of electric buses deployed, awarded, or on order as tracked by CALSTART increased from 1,650 in 2018 to 2,255 in 2019 (Silver, Jackson, and Lee 2019; Popel 2018). Whether considering just new awards or a combination of new awards, orders, and deployed buses, sales of electric buses already exceed 10 percent of annual sales.*

8 *Electric heavy-duty vehicles are three to eight times more energy efficient than comparable diesel vehicles, depending on the nature of the vehicle's operation, namely its average speed (CARB 2018b).*

9 *The CARB and ICF analyses used statewide averages for electricity rates; the ICCT study used rates specific to Southern California Edison.*

10 *Only Alaska and Hawaii have higher electricity rates than California. Connecticut has similar if not slightly lower electricity rates than California. Electricity is roughly 50 percent cheaper in most other states compared with California (EIA n.d.e). While diesel is also more expensive in California than other states, the price differential is less than electricity, roughly 15 percent (EIA n.d.f).*

11 *Estimates of Low Carbon Fuel Standard revenues use credit values of \$100 per metric ton of CO_2e and a carbon intensity of electricity in California of 93.11 grams CO_2e per megajoule (MJ) in 2019 (based on the California Energy Commission's grid mix for 2019), and 54.43 grams CO_2e per MJ in 2030 (based on the California Public Utilities Commission's Integrated Resource Plan) (ICF n.d.b.).*

12 *State incentives for the purchase of electric vehicles listed in the text exclude programs funded through the Volkswagen Environmental Mitigation Trust. Maine offers incentives for the purchase of electric passenger vehicles with this funding and several states offer incentives for the purchase of electric trucks and buses with this funding (Efficiency Maine n.d.).*

REFERENCES

40 US Code CFR § 86.082-2. Electronic code of federal regulations (e-CFR), Title 40. Protection of environment, Chapter I. Environmental Protection Agency, Subchapter C. Air programs, Part 86. Control of emissions from new and in-use highway vehicles and engines, Subpart A. General provisions for heavy-duty engines and heavy-duty vehicles, Section 86.082-2. Definitions. Online at *www.law.cornell.edu/cfr/text/40/86.082-2*, accessed November 15, 2019.

59 Utah Code §7.618. Title 59. Revenue and Taxation, Chapter 7. *Corporate Franchise and Income Taxes, Part 6. Credits, Section 618. Tax credit related to alternative fuel heavy duty vehicles.* Online at *https://le.utah.gov/xcode/Title59/Chapter7/59-7-S618.html?v=C59-7-S618_2017050920170509*, accessed November 20, 2019.

Albanese, N. 2019. Oral presentation, Zero-Emission Bus Conference, San Francisco, CA. September 26.

Alternative Fuels Data Center (AFDC). No date. Vehicle weight classes & categories. Washington, DC: US Department of Energy. Online at *https://afdc.energy.gov/data/10380,* accessed September 23, 2019.

American Lung Association (ALA). 2019. State of the air. Online at *www.lung.org/assets/documents/healthy-air/state-of-the-air/sota-2019-full.pdf*, accessed October 1, 2019.

Atlas Public Policy. No date. National EV market. Online at *www.atlasevhub.com/materials/national-ev-sales* (subscription required), accessed October 1, 2019.

Auto Alliance. No date. Advanced technology vehicle sales dashboard. Online at *https://autoalliance.org/energy-environment/advanced-technology-vehicle-sales-dashboard,* accessed September 23, 2019.

Azevedo, I., R. Brown, M. Herrlin, N. Horner, J. Koomey, W. Lintner, E. Masanet, S. Shehabi, S. Smith, and D. Sartor. 2016. *United States Data Center energy usage report*. Berkeley, CA: Lawrence Berkeley National Laboratory.

Barbose, J., and J. Martin. 2018. California's clean fuel standard boosts the electric vehicle market. Cambridge, MA: Union of Concerned Scientists. Online at *www.ucsusa.org/resources/californias-clean-fuel-standard-boosts-electric-vehicle-market,* accessed October 8, 2019.

Barnitt, R., and J. Gonder. 2011. Drive cycle analysis, measurement of emissions and fuel consumption of a PHEV school bus. NREL/CP-5400-50251. Golden, CO: National Renewable Energy Laboratory. Online at *www.nrel.gov/docs/fy11osti/50251.pdf*, accessed November 21, 2019.

Birky, A., M. Laughlin, K. Tartaglia, R. Price, B. Lim, and Z. Lin. 2017. Electrification beyond light duty: Class 2b-3 commercial vehicles. Oak Ridge, TN: Oak Ridge National Laboratory. Online at *https://info.ornl.gov/sites/publications/Files/Pub72938.pdf,* accessed September 23, 2019.

Caiazzo, F., A. Ashok, I.A. Waitz, S.H.L. Yim, and S.R.H. Barrett. 2013. Air pollution and early deaths in the United States. Part I: Quantifying the impact of major sectors in 2005. *Atmospheric Environment* 79:198–208. doi:10.1016/j.atmosenv.2013.05.081.

California Air Resources Board (CARB). 2019a. Advanced Clean Trucks: Total cost of ownership discussion document. Sacramento, CA. Online at *http://ww2.arb.ca.gov/sites/default/files/2019-02/190225tco_0.pdf,* accessed October 8, 2019.

California Air Resources Board (CARB). 2019b. Public workshop on the fiscal year 2019–20 funding plan for clean transportation incentives for low carbon transportation investments and air quality improvement program: Discussion document. Sacramento, CA. Online at http:*//ww2.arb.ca.gov/sites/default/files/2019-06/fy1920lct-discussiondoc.pdf,* accessed September 23, 2019.

California Air Resources Board (CARB). 2018a. Emission Factors (EMFAC) model v1.0.2. Accessed May 20, 2019. Online at *www.arb.ca.gov/emfac/2017.*

California Air Resources Board (CARB). 2018b. Battery electric truck and bus energy efficiency compared to conventional diesel vehicles. Sacramento, CA. Online at *http://ww2.arb.ca.gov/resources/documents/advanced-clean-trucks-battery-electric-truck-and-bus-energy-efficiency-paper.*

California Air Resources Board (CARB). No date. Summary: Diesel particulate matter health impacts. Online at *http://ww2.arb.ca.gov/resources/summary-diesel-particulate-matter-health-impacts*, accessed November 16, 2019.

Citizens Utility Board (CUB). No date. The ABCs of EVs: A guide for policy makers and consumer advocates. Chicago, IL. Online at *https://citizensutilityboard.org/wp-content/uploads/2017/04/2017_The-ABCs-of-EVs-Report.pdf,* accessed October 8, 2019.

Colorado Department of Revenue. 2019. Income 69: Innovative motor vehicle and innovative truck credits. Online at *www.colorado.gov/pacific/sites/default/files/Income69.pdf*, accessed November 20, 2019.

Cooke, D. 2015. *Engines for change: From cell phones to sodas, how new truck standards can improve the way America ships goods.* Cambridge, MA: Union of Concerned Scientists. Online at *www.ucsusa.org/resources/engines-change,* accessed September 23, 2019.

Darrow, L.A., M. Klein, W.D. Flanders, L.A. Waller, A. Correa, M. Marcus, J.A. Mulholland, A.G. Russell, and P.E. Tolbert. 2009. Ambient air pollution and preterm birth: A time-series analysis. *Epidemiology* 20(5):689–698. doi:10.1097/EDE.0b013e3181a7128f.

Database of State Incentives for Renewables and Efficiency (DSIRE). 2019. Renewable and clean energy standards. Raleigh, NC: North Carolina Clean Energy Technology Center. Online at *https://s3.amazonaws.com/ncsolarcen-prod/wp-content/uploads/2019/07/RPS-CES-June2019.pdf,* accessed September 23, 2019.

Davis, S.C., S.E. Williams, R.G. Boundy, and S. Moore. 2017. 2016 vehicle technologies market report. Oak Ridge, TN: Oak Ridge National Laboratory. Online at *https://tedb.ornl.gov/wp-content/uploads/2019/04/2016_Vehicle_Technologies_Market_Report.pdf, accessed November 15, 2019*.

Di Filippo, J., C. Callahan, and N. Golestani. 2019. Zero-emission drayage trucks: Challenges and opportunities for the San Pedro Bay ports. Los Angeles, CA: University of California–Los Angeles. Online at *https://innovation.luskin.ucla.edu/wp-content/uploads/2019/10/Zero_Emission_Drayage_Trucks.pdf,* accessed October 31, 2019.

Eckhouse, B. 2019. The U.S. has a fleet of 300 electric buses. China has 421,000. Bloomberg, May 15. Online at *www.bloomberg.com/news/articles/2019-05-15/in-shift-to-electric-bus-it-s-china-ahead-of-u-s-421-000-to-300*, accessed October 8, 2019.

Efficiency Maine. No date. EV Accelerator. Online at *www.efficiencymaine.com/ev/drive-electric*, accessed November 20, 2019.

Energy Information Administration (EIA). 2019a. Annual Energy Outlook 2019: Table: Transportation fleet car and truck stock by type and technology. Washington, DC: US Department of Energy. Online at *www.eia.gov/outlooks/aeo/data/browser/#/?id=55-AEO2019&sourcekey=0,* accessed November 16, 2019.

Energy Information Administration (EIA). 2019b. Annual Energy Outlook 2019: Table: Light-duty vehicle stock by technology type. Washington, DC: US Department of Energy. Online at *https://www.eia.gov/outlooks/aeo/data/browser/#/?id=49-AEO2019&cases=ref2019&sourcekey=0,* accessed November 15, 2019.

Energy Information Administration (EIA). 2019c. What is US electricity generation by energy source? Washington, DC: US Department of Energy. Online at *www.eia.gov/tools/faqs/faq.php?id=427&t=3*, accessed October 25, 2019.

Energy Information Administration (EIA). 2019d. Annual Energy Outlook 2019: Table: Transportation sector energy use by fuel type within a mode. Washington, DC: US Department of Energy. Online at *www.eia.gov/outlooks/aeo/data/browser/#/?id=46-AEO2019&region=0-0&cases=ref2019&start=2017&end=2019&f=A&linechart=ref2019-d111618a.2-46-AEO2019&sourcekey=0*, accessed September 23, 2019.

Energy Information Administration (EIA). 2019e. U.S. renewable electricity generation has doubled since 2008. Today in Energy, March 19. Washington, DC: US Department of Energy. Online at *www.eia.gov/todayinenergy/detail.php?id=38752,* accessed September 23, 2019.

Energy Information Administration (EIA). 2016. Annual Energy Outlook 2016: Transportation fleet car and truck stock by type and technology. Washington, DC: US Department of Energy. Online at *www.eia.gov/outlooks/aeo/data/browser/#/?id=55-AEO2016&sourcekey=0,* accessed November 16, 2019.

Energy Information Administration (EIA). No date a. Table 1.1. Total electric power industry summary statistics, 2017 and 2016. Washington, DC: US Department of Energy. Online at *www.eia.gov/electricity/annual/html/epa_01_01.html,* accessed September 23, 2019.

Energy Information Administration (EIA). No date b. Frequently asked questions: What is U.S. electricity generation by energy source? Washington, DC: US Department of Energy. Online at *www.eia.gov/tools/faqs/faq.php?id=427&t=3,* accessed September 23, 2019.

Energy Information Administration (EIA). No date c. Electricity data browser: Retail sales of electricity. Washington, DC: US Department of Energy. Online at *www.eia.gov/electricity/data/browser/#/topic/5?agg=0,1&geo=g&endsec=vg&linechart=ELEC.SALES.US-ALL.A~ELEC.SALES.US-RES.A~ELEC.SALES.US-COM.A~ELEC.SALES.US-IND.A&columnchart=ELEC.SALES.US-ALL.A~ELEC.SALES.US-RES.A~ELEC.SALES.US-COM.A~ELEC.SALES.US-IND.A&map=ELEC.SALES.US-ALL.A&freq=A&ctype=linechart&ltype=pin&rtype=s&maptype=0&rse=0&pin=,* accessed September 23, 2019.

Energy Information Administration (EIA). No date d. Frequently asked questions: How is electricity used in U.S. homes? Washington, DC: US Department of Energy. Online at *www.eia.gov/tools/faqs/faq.php?id=96&t=3*, accessed September 23, 2019.

Energy Information Administration (EIA). No date e. Average retail price of electricity, monthly. Washington, DC: US Department of Energy. Online at *www.eia.gov/electricity/data/browser/#/topic/7?agg=1,0&geo=00fvvvvvvvvvo&endsec=fg&freq=M&start=200101&end=201908&ctype=linechart&ltype=pin&rtype=s&maptype=0&rse=0&pin=*, accessed November 20, 2019.

Energy Information Administration (EIA). No date f. Petroleum: Data—Weekly retail gasoline and diesel prices. Online at *www.eia.gov/dnav/pet/pet_pri_gnd_a_epd2d_pte_dpgal_a.htm,* accessed September 23, 2019.

Environmental Protection Agency (EPA). 2019. Inventory of US greenhouse gas emissions and sinks. Washington, DC. Online at *www.epa.gov/sites/production/files/2019-04/documents/us-ghg-inventory-2019-main-text.pdf*, accessed October 8, 2019.

Environmental Protection Agency (EPA). 2018a. National Emissions Inventory, 2014 Version 2. Washington, DC. Online at *www.epa.gov/air-emissions-inventories/2014-national-emissions-inventory-nei-data*, accessed October 8, 2019.

Environmental Protection Agency (EPA). 2018b. Emissions and generation resource integrated database (eGRID). Washington, DC. Online at *www.epa.gov/energy/emissions-generation-resource-integrated-database-egrid,* accessed October 8, 2019.

European Union. No date. Urban access regulations in Europe. Online at *https://urbanaccessregulations.eu*, accessed November 16, 2019.

Federal Highway Administration (FHWA). 2019. Highway statistics 2017. Washington, DC: US Department of Transportation. Online at *www.fhwa.dot.gov/policyinformation/statistics/2017/vm1.cfm,* accessed October 8, 2019.

Federal Highway Administration (FHWA). 2016. Highway Statistics 2014. Washington, DC: US Department of Transportation. Online at *www.fhwa.dot.gov/policyinformation/statistics/2014,* accessed October 8, 2019.

Federal Motor Carrier Safety Administration (FMCSA). 2017. Drivers: Overview. Washington, DC: Federal Highway Administration, US Department of Transportation. Online at *www.fmcsa.dot.gov/registration/commercial-drivers-license/drivers*, accessed September 23, 2019.

Federal Transit Administration (FTA). 2018. National Transit Database: 2017 Fuel and Energy. Washington, DC: US Department of Transportation. Online at *www.transit.dot.gov/ntd/data-product/2017-fuel-and-energy,* accessed October 8, 2019.

Hall, D., and N. Lutsey. 2019. Estimating the infrastructure needs and costs for the launch of zero-emission trucks. Washington, DC: The International Council on Clean Transportation. Online at *https://theicct.org/sites/default/files/publications/ICCT_EV_HDVs_Infrastructure_20190809.pdf,* accessed October 8, 2019.

Houston, S. 2019. Electric utility investment in truck and bus charging: A guide for programs to accelerate electrification. Cambridge, MA: Union of Concerned Scientists. Online at *www.ucsusa.org/resources/electric-utility-investment-truck-and-bus-charging,* accessed September 23, 2019.

Hybrid and Zero-Emission Truck and Bus Voucher Incentive Project (HVIP). 2019. HVIP eligible vehicle catalog. Online at *www.californiahvip.org/how-to-participate/#Eligible-Vehicle-Catalog*, accessed September 23, 2019.

Hybrid and Zero-Emission Truck and Bus Voucher Incentive Project (HVIP). 2015. HVIP eligible vehicle catalog. Online at *https://web.archive.org/web/20150321055754/http://californiahvip.org/docs/HVIP_Year4_EligibleVehicles.pdf*, accessed September 23, 2019.

ICF. No date a. Comparison of medium- and heavy-duty technologies in California: Technology assessment. San Jose, CA. In press.

ICF. No date b. Comparison of medium- and heavy-duty technologies in California: Scenario analysis. San Jose, CA. In press.

Keegan, M. 2018. Shenzhen's silent revolution: World's first fully electric bus fleet quietens Chinese megacity. *The Guardian,* December 12. Online at *www.theguardian.com/cities/2018/dec/12/silence-shenzhen-world-first-electric-bus-fleet*, accessed October 8, 2019.

Komanduri, A. 2019. Oral presentation, Southern California Association of Governments (SCAG) Modeling Task Force, Los Angeles, CA. January 23. Online at *www.scag.ca.gov/committees/CommitteeDocLibrary/mtf012319_CAVIUS.pdf,* accessed October 8, 2019.

McLane, R., and D. Mullaney. 2019. Shenzen: A city miles ahead. Rocky Mountain Institute, June 30. Online at *https://rmi.org/shenzhen-a-city-miles-ahead*, accessed October 8, 2019.

Nealer, R., D. Reichmuth, and D. Anair. 2015. *Cleaner cars from cradle to grave: How electric cars beat gasoline cars on lifetime global warming emissions.* Cambridge, MA: Union of Concerned Scientists. Online at *www.ucsusa.org/resources/cleaner-cars-cradle-grave,* accessed October 8, 2019.

New York Truck Voucher Incentive Program (NYTVIP). No date. Online at *www.nyserda.ny.gov/All-Programs/Programs/Truck-Voucher-Program*, accessed November 20, 2019.

O'Dea, J. 2019a. More charging infrastructure coming for electric trucks and buses in California. *The Equation*. Cambridge, MA: Union of Concerned Scientists. Blog, August 15. Online at *https://blog.ucsusa.org/jimmy-odea/more-charging-infrastructure-coming-for-electric-trucks-and-buses-in-california*, accessed October 17, 2019.

O'Dea, J. 2019b. Electric airport shuttle buses are taking off. *The Equation*. Cambridge, MA: Union of Concerned Scientists. Blog, June 27. Online at *https://blog.ucsusa.org/jimmy-odea/electric-airport-shuttle-buses*, accessed November 22, 2019.

O'Dea. J. 2018a. Electric vs. diesel vs. natural gas: Which bus is best for the climate? *The Equation*. Cambridge, MA: Union of Concerned Scientists. Blog, July 19. Online at *https://blog.ucsusa.org/jimmy-odea/electric-vs-diesel-vs-natural-gas-which-bus-is-best-for-the-climate*, accessed November 22, 2019.

O'Dea, J. 2018b. California gets one step closer to zero-emission transit buses. *The Equation*. Cambridge, MA: Union of Concerned Scientists. Blog, September 6. Online at *https://blog.ucsusa.org/jimmy-odea/california-gets-one-step-closer-to-zero-emission-transit-buses,* accessed November 22, 2019.

Office of Energy Efficiency & Renewable Energy (EERE). No date. Fact #671: April 18, 2011 average truck speeds. Washington, DC: US Department of Energy. Online at *www.energy.gov/eere/vehicles/fact-671-april-18-2011-average-truck-speeds,* accessed September 23, 2019.

Phadke, A., A. Khandekar, M. McCall, N. Karali, and D. Rajagopal. 2019. Long-haul battery electric trucks are technically feasible and economically compelling. Berkeley, CA: Lawrence Berkeley National Laboratory. Online at *http://eta-publications.lbl.gov/sites/default/files/working_paper_005_battery_electric_trucks_906_0.pdf,* accessed October 8, 2019.

Popel, E.J. 2018. *Breathing easy: A survey of zero emission buses across America*. Pasadena, CA: CALSTART. Online at *https://calstart.org/wp-content/uploads/2018/11/Breathing-Easy-August-2018.pdf,* accessed November 16, 2019.

Proterra. 2019. Catalyst: 40 foot bus performance specifications. Online at *www.proterra.com/wp-content/uploads/2019/06/Proterra-Catalyst-40-ft-Spec-Sheet.pdf,* accessed September 23, 2019.

Raudebaugh, D. 2018. Oral presentation, Zero-Emission Bus Conference, Los Angeles, CA. September 10. Online at *http://zebconference.com/wp-content/uploads/2018/04/Dan_Final.pdf.zip*, accessed October 8, 2019.

Reichmuth, D. 2019a. Air pollution from cars, trucks, and buses in the US: Everyone is exposed, but the burdens are not equally shared. *The Equation*. Cambridge, MA: Union of Concerned Scientists. Blog, October 16. Online at *https://blog.ucsusa.org/dave-reichmuth/air-pollution-from-cars-trucks-and-buses-in-the-u-s-everyone-is-exposed-but-the-burdens-are-not-equally-shared,* accessed October 17, 2019.

Reichmuth, D. 2019b. Inequitable exposure to air pollution from vehicles in California: Who bears the burden? Cambridge, MA: Union of Concerned Scientists. Online at *https://www.ucsusa.org/resources/inequitable-exposure-air-pollution-vehicles-california-2019*, accessed September 23, 2019.

Reichmuth, D. 2018. New data show electric vehicles continue to get cleaner. *The Equation*. Cambridge, MA: Union of Concerned Scientists. Blog, March 8. Online at *https://blog.ucsusa.org/dave-reichmuth/new-data-show-electric-vehicles-continue-to-get-cleaner,* accessed September 23, 2019.

Sacramento Municipal Utility District (SMUD). 2019. West Coast power providers explore EV charging for zero-emission shipping along I-5, connecting routes. Press release. Online at *www.smud.org/en/Corporate/About-us/News-and-Media/2019/2019/West-Coast-Clean-Transit-Corridor-Initiative,* accessed September 23, 2019.

Sandhu, G., H. Frey, S. Bartelt-Hunt, and E. Jones. 2014. In-use measurement of the activity, fuel use, and emissions of front-loader refuse trucks. *Atmospheric Environment* 92:557–565. doi:10.1016/j.atmosenv.2014.04.036.

Silver, F., J. Jackson, and B. Lee. 2019. *Zeroing in on ZEBS*. Sacramento, CA: CALSTART. Online at *https://calstart.org/wp-content/uploads/2019/10/Zeroing_In_on_ZEBs_Final_10182018-10.21.19.pdf,* accessed November 16, 2019.

Tesla. No date. Electric vehicle and solar incentives. Online at *www.tesla.com/support/incentives,* accessed November 20, 2019.

Texas Commission on Environmental Quality (TCEQ). No date. Texas Clean Fleet Program. Online at *www.tceq.texas.gov/airquality/terp/tcf.html,* accessed November 20, 2019.

Union of Concerned Scientists (UCS). 2019. What is ZEV? Online at *www.ucsusa.org/resources/what-zev,* accessed September 23, 2019.

US Census Bureau (USCB). 2004. Vehicle Inventory and Use Survey. Washington, DC. Online at *http://web.archive.org/web/20150405052852/http://www.census.gov/svsd/www/vius/Revised2002MDF.zip,* accessed September 23, 2019.

US Census Bureau (USCB). No date. Community faces: Census 2010 population. Washington, DC. Online at *https://factfinder.census.gov/faces/nav/jsf/pages/community_facts.xhtml,* accessed September 23, 2019.

US Department of Transportation (DOT). No date. Freight facts and figures 2017. Washington, DC. Online at *www.bts.dot.gov/sites/bts.dot.gov/files/docs/FFF_2017.pdf,* accessed September 23, 2019.

Wisland, L. 2018. Turning down the gas in California: The role of natural gas in the state's clean electricity future. Cambridge, MA: Union of Concerned Scientists. Online at *www.ucsusa.org/resources/turning-down-gas-california*, accessed October 8, 2019.

Union of Concerned Scientists

FIND THIS DOCUMENT AND TECHNICAL APPENDIX ONLINE:
www.ucsusa.org/resources/ready-work

The Union of Concerned Scientists puts rigorous, independent science to work to solve our planet's most pressing problems. Joining with people across the country, we combine technical analysis and effective advocacy to create innovative, practical solutions for a healthy, safe, and sustainable future.

NATIONAL HEADQUARTERS
Two Brattle Square
Cambridge, MA 02138-3780
Phone: (617) 547-5552
Fax: (617) 864-9405

WASHINGTON, DC, OFFICE
1825 K St. NW, Suite 800
Washington, DC 20006-1232
Phone: (202) 223-6133
Fax: (202) 223-6162

WEST COAST OFFICE
500 12th St., Suite 340
Oakland, CA 94607-4087
Phone: (510) 843-1872
Fax: (510) 843-3785

MIDWEST OFFICE
One N. LaSalle St., Suite 1904
Chicago, IL 60602-4064
Phone: (312) 578-1750
Fax: (312) 578-1751

PRINTED ON RECYCLED PAPER USING VEGETABLE-BASED INKS