



TRANSITIONING TO ZERO-EMISSION HEAVY-DUTY FREIGHT VEHICLES

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EXECUTIVE SUMMARY

A clear path toward decarbonization of the heavy-duty freight sector has been elusive. Barriers to the growth of electric and hydrogen fuel cell heavy-duty commercial freight trucks include limited technology availability, limited economies of scale, long-distance travel requirements, payload mass and volume constraints, and a lack of refueling and recharging infrastructure. Many governments and companies are seeking to break down such barriers to help decarbonize heavy-duty freight trucks.

In this report, we assess zero-emission heavy-duty vehicle technology to support decarbonization of the freight sector. We compare the evolution of heavy-duty diesel, diesel hybrid, natural gas, fuel cell, and battery electric technologies in the 2025–2030 timeframe. We synthesize data from the research literature, demonstrations, and low-volume commercial trucks regarding their potential to deliver freight with zero tailpipe emissions. We analyze the emerging technologies by their cost of ownership and life-cycle greenhouse gas emissions for the three vehicle markets of China, Europe, and the United States.

Based on this work, we assess the relative advantages and disadvantages among the various emerging electric-drive technologies. Table ES-1 summarizes our findings regarding the zero-emission heavy-duty vehicle technology benefits and barriers to widespread adoption. The table shows results for the three main zero-emission technology areas: plug-in electric, catenary or in-road charging electric, and hydrogen fuel cell vehicles. Each technology offers the prospect of lower carbon emissions, no tailpipe emissions, and greater renewable energy use. Matching specific electric and hydrogen technologies to particular truck segments can help overcome barriers such as traveling range, infrastructure, and recharging time.

Table ES-1. Summary of promising segments, benefits, and barriers for zero-emission heavy-duty freight vehicle technologies.

Technology	Benefits	Prevailing barriers to widespread viability	Promising segments for widespread commercialization
Electric (plug-in)	<ul style="list-style-type: none"> • Reduce greenhouse gas emissions • Eliminate local air pollution • Reduce fueling costs • Reduce maintenance costs • Increase energy efficiency • Increase renewable energy use 	<ul style="list-style-type: none"> • Limited electric range • Vehicle cost (battery) • Charging time (unless battery swapping is utilized) • Cargo weight and size 	<ul style="list-style-type: none"> • Light commercial urban delivery vans • Medium-duty regional delivery trucks • Refuse trucks
Electric (catenary or in-road charging)	<ul style="list-style-type: none"> • Reduce greenhouse gas emissions • Eliminate local air pollution • Reduce fueling costs • Reduce maintenance costs • Increase energy efficiency • Increase renewable energy use • Enable regional travel 	<ul style="list-style-type: none"> • Infrastructure cost • Standardization across regions • Complete infrastructure network before vehicle deployment • Visual obstruction (catenary) 	<ul style="list-style-type: none"> • Medium-duty trucks and heavy-duty tractor-trailers on medium-distance routes with high freight use • Drayage trucks around ports
Hydrogen fuel cell	<ul style="list-style-type: none"> • Reduce greenhouse gas emissions • Eliminate local air pollution • Increase energy efficiency • Enable quick refueling time • Increase renewable energy use 	<ul style="list-style-type: none"> • Refueling infrastructure cost • Renewable hydrogen cost • Vehicle costs (fuel cell) 	<ul style="list-style-type: none"> • Heavy-duty tractor-trailers in long-haul operation • Drayage trucks around ports

We also assess and discuss these factors to better understand the prospects for widespread commercialization over the 2025 and beyond timeframe. Based on the research findings, we draw the following three conclusions regarding emerging vehicle zero-emission technologies for heavy-duty vehicles.

Electric-drive heavy-duty vehicle technologies are essential to fully decarbonize the transport sector. Heavy-duty freight trucks are disproportionate contributors to pollution, representing less than one tenth of all vehicles but roughly 40% of their carbon emissions, and their activity keeps growing. Electric-drive technologies, similar to those being commercialized in cars, will be essential to decarbonize the heavy-duty sector and help meet climate stabilization goals. Whereas the more efficient potential diesel technologies can reduce carbon emissions by about 40%, electric-drive technologies powered by renewable sources can achieve over an 80% reduction in fuel life-cycle emissions.

By 2030, electric-drive heavy-duty vehicle technologies could offer cost-effective opportunities for deep emission reductions. Major projects involving heavy-duty electric and hydrogen fuel cell vehicle technologies show great potential due to their much greater efficiency and use of available low-carbon fuel sources. We find that overhead catenary electric heavy-duty vehicles would cost approximately 25%–30% less, and hydrogen fuel cells at least 5%–30% less, than diesel vehicles to own, operate, and fuel in the 2030 timeframe. Key drivers for cost-effectiveness are battery pack costs dropping to below \$150 per kilowatt-hour, hydrogen fuel costs dropping to below the per-energy-unit cost of diesel, and the cost of the associated infrastructure decreasing over time.

Different electric-drive technologies are suitable for different heavy-duty vehicle segments, but massive infrastructure investments would be needed. Advances in battery packs and other electrical components will enable shorter distance urban commercial vans to become plug-in electric, similar to cars. Battery electric vehicles with overhead catenary or in-road charging can enable electric zero-emission goods transport on and around heavily traveled freight corridors. Hydrogen fuel cell technology might be especially key for longer-distance duty cycles. These technologies each have formidable barriers and will require sustained and extensive infrastructure investments by government and industry (e.g., overhead transmission, in-road charging, hydrogen refueling stations).

I. INTRODUCTION

The transition to electric-drive vehicles is widely regarded as critical for the transportation sector. Electric-drive vehicles, including battery electric, plug-in hybrid, and hydrogen fuel cell vehicles, offer the potential for a vehicle fleet to shift away from petroleum fuels and bring dramatic emission reductions that are needed to achieve long-term air quality and climate change goals. The transition to electric drive is already beginning for passenger automobiles, with millions of electric cars on roads around the world as of early 2017, and the same technology is now available for light commercial vans. In addition, hundreds of thousands of electric buses have been put into local service. Progress with heavy-duty commercial freight vehicles has been more limited, with dozens of demonstrations and prototypes, but few commercial offerings around the world.

There is growing interest in deploying advanced technologies in heavy-duty freight vehicles for a number of reasons, including climate change, energy diversification, and local air quality. The challenge of climate change provides a major overarching motivation for most major national and local governments, and the breakdown of truck activity helps underscore the imperative to focus not just on cars, but on heavy-duty freight vehicles as well.

Figure 1 summarizes the breakdown of the world vehicle population, travel activity, and greenhouse gas emissions. Freight trucks, which primarily operate on diesel (and sometimes gasoline or natural gas), account for a large and growing share of local pollutant and greenhouse gas emissions. Despite representing merely 9% of the global vehicle stock and 17% of the total vehicle miles driven, freight trucks accounted for approximately 39% of the life-cycle road vehicle greenhouse gas emissions, with the share being even higher for other pollutants (ICCT, 2017; Miller and Façanha, 2014).

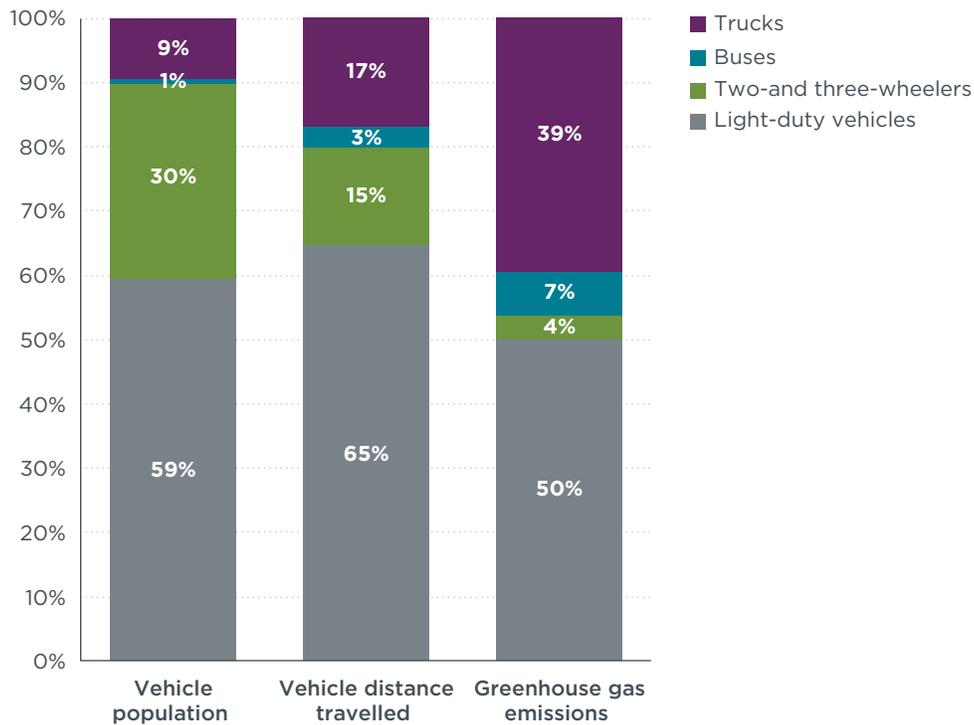


Figure 1. Global vehicle stock, distance traveled, and life-cycle road transport greenhouse gas emissions by vehicle type in 2015.

Heavy-duty vehicles' disproportionate contribution to global greenhouse gas emissions is expected to increase for decades to come due to a substantial increase in road freight activity. Figure 2 illustrates the global freight activity and the life-cycle greenhouse gas emissions in carbon dioxide equivalent (CO₂e) from 2015 projected through 2050 (ICCT, 2017; Miller and Façanha, 2014). The figure shows freight activity for light, medium, and heavy trucks in trillions of freight payload multiplied by distance traveled (corresponding to the left axis). The figure also, with the grey line, illustrates the associated life-cycle greenhouse gas emissions, including vehicle exhaust and upstream emissions to produce the trucks' fuels, based on business-as-usual vehicle efficiency trends (right axis). As shown, from 2015 to 2050, global truck freight activity and truck life-cycle greenhouse gas emissions are estimated to at least double under the business-as-usual scenario. The figure also illustrates how much of the heavy-duty freight activity is from the heaviest trucks—typically these are combination tractor-trailers with the tractors classified as Class 8 in the North America, or trucks with greater than 15-ton weight capacity in Europe. These heaviest vehicles represent over 60% of the freight truck metric ton-kilometer activity and over 75% of the freight truck carbon dioxide (CO₂) emissions and are the primary focus of this report.

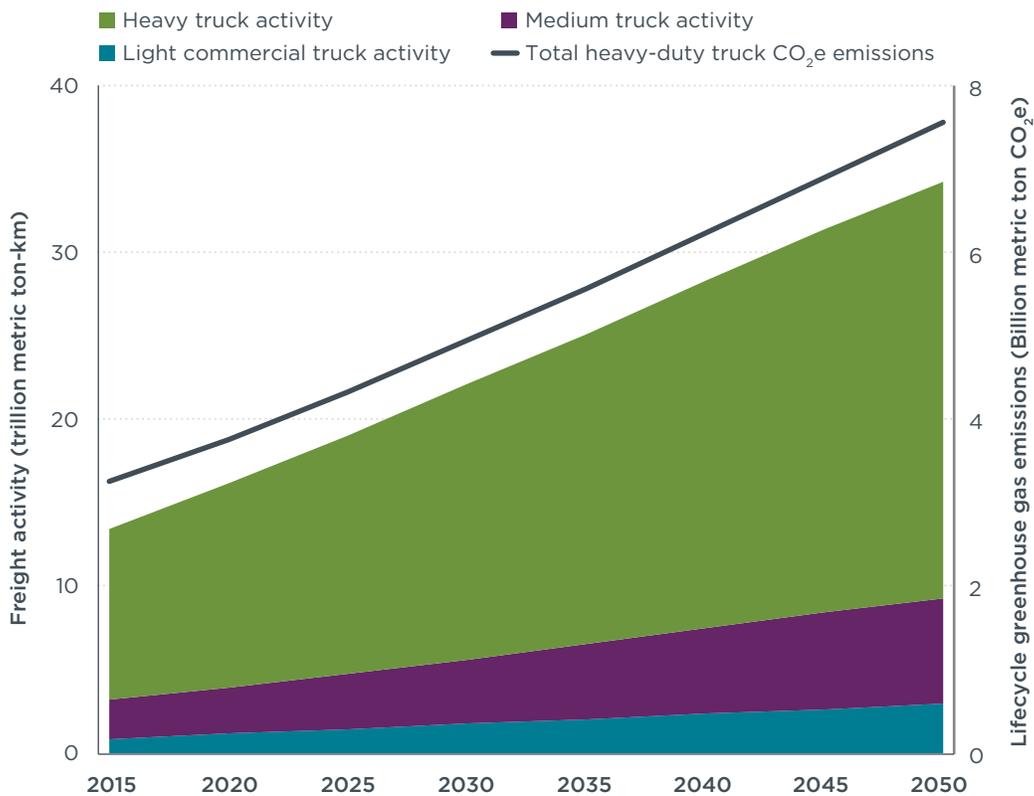


Figure 2. Projected global freight activity and life-cycle greenhouse gas emissions from 2015 to 2050.

In addition to the climate issues associated with the greenhouse gas emissions from freight transport, the associated local air pollution, particularly of oxides of nitrogen and particulate matter emissions, negatively impacts health and quality of life, particularly in areas near concentrated freight activity. These burdens are disproportionately experienced by the communities that live closest to freight hubs and corridors, most typically populated by low-income residents.

Although increased vehicle efficiency and modern aftertreatment technology to reduce tailpipe emissions offer the lowest-cost emissions reductions, there are a number of more advanced emerging zero-emission vehicle technologies that could bring much deeper reductions. The increasing scale of electric car production, with cumulative global electric cars sales surpassing 2 million in the beginning of 2017, brings forth major cost reductions in batteries. New longer range models are paving the way for mainstream adoption. Furthermore, charging infrastructure to support such vehicles continues to grow (Hall & Lutsey, 2017). Feeding the progress, governments around the world are setting ever-ambitious targets to phase out combustion in favor of electric cars and reinforcing efforts with supporting policy, incentives, and infrastructure (e.g., see Lutsey, 2015; Lutsey, 2017; Slowik & Lutsey, 2016).

Many governments seek to break down barriers to help decarbonize heavy-duty freight trucks by leveraging their ongoing progress on electric cars. The activity and emissions trends introduced above increasingly indicate that long-term climate and air quality goals require that all major transport modes, including those for commercial freight, move toward much lower emissions, including with the broad application of plug-in electric and hydrogen fuel cell technology. Many of these technologies, in greater use in light-duty vehicles, are also being explored for deployment in heavy-duty freight vehicles.

Zero-emission buses are being deployed in growing numbers, and this could also help pave the way for zero-emission freight. Through 2016, this market development has been dominated by China; the country had over 280,000 electric buses, or over 95% of the world electric bus market (EV sales, 2017a, 2017b). Deployments of all-electric, plug-in hybrid, and fuel cell buses in Europe and the U.S. are increasing (e.g., Eudy, Post, & Jeffers, 2016; European Alternative Fuels Observatory, 2017). These bus deployments increase the production volume of batteries, fuel cell stacks, on-vehicle power electronics, electric motors, and charging and refueling equipment. This increasing component volume helps the development of a supplier base that is also likely to support heavy-duty freight technology. Likewise, the growing experience of charging and refueling providers on these bus deployments puts them in stronger position for installations for similar zero-emission freight applications in the future.

To inform such government activities on zero-emission heavy-duty vehicles, it is important to gain a clearer understanding of the potential viability for the various zero-emission heavy-duty vehicle technologies. Especially for the heaviest long-haul tractor-trailers, the activity and emissions appear to be the most problematic, and there appears to be a number of potential technology paths. Which technologies are most appropriate for which applications? What are the potential climate benefits of these vehicles considering their various fuel sources? What are the associated vehicle technology costs? This paper seeks to address these questions and discuss the potential for an electric drive heavy-duty fleet.

To help address these questions about the potential for deep emission cuts for heavy-duty vehicles, we focus on electric and hydrogen fuel cell vehicle technologies. Various forms of these technologies would leverage electric and fuel cell developments in cars, light-commercial vans, and buses. Beyond simply plugging in to the electric grid, electric heavy-duty vehicles could use battery swapping stations or “e-roads” with inductive dynamic charging embedded in roadways or via overhead catenary electricity transmission. E-roads provide a continuous source of power to vehicles, directly transmitting electricity to the electric motor and charging an on-board battery.

When these catenary systems are deployed on various highway segments, they allow for greater range and significantly smaller batteries. The vehicles used on e-roads are equipped with either full electric drivetrains, where the pantograph or inductive coils and power electronics are combined with a battery pack, or a hybrid drivetrain, with a combustion engine. The hybrid drivetrain or additional battery capacity allow the vehicle to travel greater range from the e-roads. Fuel cells use on-board hydrogen storage and electrochemically convert hydrogen to electricity to power the vehicle to enable long-range and quick fuel times. Each of these options provides the potential for much greater on-vehicle efficiency and renewable energy sources.

In Section II, we review heavy-duty vehicle technology developments to compile data from the research literature, demonstration fleets, and low-volume commercial truck models and provide context for analysis of zero-emission technologies that follows. Then, in Section III, we assess the major vehicle technologies, comparing the evolution of diesel, diesel hybrid, natural gas, fuel cell, battery electric, dynamic induction grid, and overhead catenary in the 2025–2030 timeframe in a vehicle-related cost-of-ownership framework. In Section IV, we analyze these technologies by their life-cycle greenhouse gas emissions, including upstream fuel cycle emissions, based on the three vehicle markets of China, Europe, and the U.S. Finally, in Section V, we summarize and discuss the results.

II. REVIEW OF HEAVY-DUTY VEHICLE TECHNOLOGY DEVELOPMENTS

To provide context and additional background for the analysis below, this section first introduces existing heavy-duty vehicle policy. In the subsequent subsections, we summarize the associated research literature, physical truck demonstrations, and announced commercial truck offerings regarding zero-emission heavy-duty vehicle technologies.

HEAVY-DUTY VEHICLE POLICY BACKGROUND

Because of the projected increase in heavy-duty activity, and with more stringent efficiency standards implemented for light-duty vehicles compared to heavy-duty-vehicles, the portion of greenhouse gas emissions from heavy-duty vehicles is expected to continue to increase under business-as-usual conditions. A primary driver for this trend is that freight vehicle efficiency will tend to remain relatively constant without regulations that require available efficiency technologies be deployed (Davis, Williams, & Boundy, 2016; Muncrief & Sharpe, 2015). To date, only a handful of countries—Canada, China, Japan, and the U.S.—have implemented efficiency and greenhouse gas emissions standards. The European Union is widely expected to propose heavy-duty CO₂ regulations in the near future. Standards in the EU will likely open the doors for other countries in Asia and Latin America that pattern their standards on the European Commission's vehicle regulations. Less than half of heavy-duty new vehicle sales globally are regulated for efficiency or CO₂, compared to over 80% of the world's passenger vehicles (Miller and Façanha, 2014).

By improving engine efficiency, aerodynamics, and aftertreatment technology, there is the potential for substantial, highly cost-effective improvements in heavy-duty vehicle efficiency and emissions. In the U.S., the efficiency and CO₂ regulations will cut business-as-usual heavy-duty vehicle fuel use by over one third by 2050 (Sharpe et al., 2016). Although the necessary technology improvements to meet those standards have an associated increase in technology costs, the fuel efficiency improvements lead to expected payback periods ranging from 2 to 4 years for the various vehicle types. The efficiency regulations include special provisions for electric trucks (e.g., disregarding upstream emissions and providing multipliers to count them multiple times), but they are not expected to play significantly in regulatory compliance (Lutsey, 2017; U.S. EPA and U.S. DOT, 2016). Electric-drive truck technology is similarly not needed to comply with near-term conventional pollutant emission regulations, where technologies such as exhaust gas recirculation systems and diesel particulate filters can greatly reduce negative health impacts associated with heavy-duty diesel engines. For manageable costs of approximately \$7,000 per vehicle, nitrogen oxide (NO_x) and particulate matter (PM) emissions could be reduced by over 95% (Posada, Chambliss, & Blumberg, 2016) for vehicles that can typically cost well over \$100,000.

These technologies are attractive for near-term progress, but this incremental approach is more limited in the long-term, when much deeper emission cuts are necessary to meet government environmental goals and global climate protection commitments. In the 2030–2045 timeframe, advanced efficiency technologies are expected to offer a potential fuel consumption reduction of 40%–52% in combination tractor-trailers, and up to 30%–36% for rigid delivery trucks (Delgado, Miller, Sharpe, & Muncrief, 2016). Looking beyond truck efficiency improvements, freight transport efficiency gains through further optimization of routes and sharing trucks and warehouses between companies

could reduce CO₂ emissions by one third (OECD/ITF, 2017). In addition, biofuels can be a partial solution, if and when broader sustainability and indirect land use change impacts are more fully addressed. However, with the anticipated increase in heavy-duty vehicle freight shipping and with their slow fleet turnover, even widespread adoption of these approaches would still not result in a net improvement in CO₂ emissions and fuel consumption in 2050 compared to 2015. To meet international climate stabilization goals, more ambitious emissions-reduction approaches, including zero-emission heavy-duty vehicles using low-carbon upstream energy sources, will be necessary.

REVIEW OF RESEARCH LITERATURE

Although few zero-emission heavy-duty commercial freight vehicles are on the road today, a variety of studies over the past 5 years have considered the feasibility of a number of technologies and their potential to reduce emissions. Table 1 lists the associated technical research studies and identifies the vehicle types, technologies, and analytical estimates in each report. Because of the uncertain and quickly changing technologies involved, cost estimates and conclusions vary greatly between the reports. In addition, the scope of each report varies greatly, including which region, truck types, duty cycles, and fuel cost assumptions were considered.

Table 1. Quantitative studies of medium- and heavy-duty electric-drive vehicles.

Study	Region	Timeframe	Vehicle Types			Technology			Analysis		
			LCV	MDV	HDV	Battery electric	Fuel Cell	Catenary	Cost	CO ₂	Fleet
den Boer, Aarnink, Kleiner, & Pagenkopf, 2013	Europe	2030		X	X	X	X	X	X	X	
Fulton & Miller, 2015	California	2050			X	X	X		X	X	X
Gladstein, Neandross & Associates, 2012	California	2020			X	X	X	X	X		X
Wood, Wang, Gonder, & Ulsh, 2013	United States	Present	X	X		X	X		X		
Silver & Brotherton, 2013	California	2050		X	X	X				X	X
Kleiner et al, 2015	Europe, South Korea, Turkey	Present	X			X	X		X		X
CARB, 2015a	California	2030		X	X	X			X		X
CARB, 2015b	California	2025		X	X		X		X		X
Zhao, Burke, & Zhu, 2013	United States	Present			X	X	X		X	X	
Connolly, 2016	Denmark	2050			X	X		X	X	X	
Löfstrand et al., 2013	Sweden	2025		X	X	X			X		
Sen, Ercan, & Tatari, 2016	United States	2040			X	X			X	X	
Lee & Thomas, 2016	United States	Present		X		X			X	X	

LCV = light commercial vehicle; MDV = medium-duty vehicle; HDV = heavy-duty vehicle

Based on the research literature, plug-in electric vehicles are being considered for a number of applications in the medium- and heavy-duty sectors. Electric vehicles' high efficiency, generally 3 to 4 times more efficient than diesel and natural gas engines, results in a reduction in primary energy use and greenhouse gas emissions (e.g., Chandler, Espino, & O'Dea, 2016). These vehicles are most suited for applications with short ranges and duty cycles that can take advantage of regenerative braking and where required electric battery packs sizes are lower (CARB, 2015b). An analysis of duty cycles suggests urban delivery vans and delivery trucks, refuse trucks, and drayage trucks as targets for electrification (Kelly, 2016).

The potential for electric-drive medium-duty delivery trucks was analyzed in several different studies. Löfstrand et al. (2013) estimate that battery electric trucks will have the lowest total cost of ownership of any powertrain option by 2025 for scenarios with short routes and high utilization. Similarly, the California Hybrid, Efficient and Advanced Truck Research Center expects electrified delivery trucks to be ready for widespread commercial implementation, with a 3- to 5-year return-on-investment, around 2020 (Silver & Brotherton, 2013). Other assessments are even more optimistic, with one showing that battery electric delivery vehicles are already cheaper in total cost of ownership than diesel vehicles in several countries when considering tax policies (Kleiner et al., 2015).

Battery-powered drivetrains could also be used in other types of heavy-duty vehicles, including various types of vocational vehicles. Drayage trucks, which operate over shorter distances (less than 60 miles) around ports, could be an early market for heavy-duty truck electrification (Chandler et al., 2016). Refuse trucks, which have similar duty cycles to urban buses and are based out of a central location each day, are potentially well suited to be powered by batteries, reducing noise and pollution in urban environments (CARB, 2015a).

To overcome the charging time barrier of plug-in battery electric medium- and heavy-duty vehicles, battery-swapping technology could be used. Such an approach would require that truck or tractor designs accommodate multiple daily battery pack swaps, battery-swapping stations are deployed on key routes, and a larger stock of battery packs is managed as a system. The time to replace the battery would then become competitive with refueling time, but they would still require more stops daily than conventional diesel if used on long-haul operation (see den Boer et al., 2013). Because of the infrastructure and system level complexities, only a few projects have become operational. Since 2013, a fleet of electric buses in Qingdao, China, have extensively utilized battery swapping, and testing is expected on electric trucks in Québec starting in 2018 (La Presse, 2016; Phoenix Contact, 2013). The India-based partnership between Ashok Leyland and Sun Mobility also began investigating options in 2017 for a battery-swapping system, starting with bus and delivery van applications (Mohile, 2017).

Fuel cells are also receiving significant attention as an option for medium- and heavy-duty applications. Using hydrogen as their fuel source, fuel cell electric vehicles offer longer ranges with shorter refuel times, compared to battery-electric vehicle recharging. Fuel cell stacks, capable of greater than 50% efficiency, are much more efficient than diesel systems, which typically have maximum engine efficiencies of 37%–39% (Chandler et al., 2016; Thiruvengadam et al., 2014). Several studies have identified fuel cells as a potential solution to applications like suburban delivery trucks, drayage trucks, and shuttle buses where flexibility and long range is needed. One estimate suggests that hydrogen fuel-cell range-extending motors become competitive with plug-in electric vehicles at ranges over

60 miles, although falling battery prices may affect this trade-off (Wood et al., 2013). Nonetheless, hydrogen-powered vehicles face challenges, including high hydrogen costs and a lack of refueling infrastructure, which government interventions are seeking to overcome (CARB, 2015b). Because of the high costs of fuel cells and hydrogen, Kleiner et al. (2015) calculate that fuel cell delivery vehicles have higher total cost of ownership compared to conventional, hybrid, or battery electric vehicles.

E-roads and catenary electric-drive technologies have also been proposed as a long-term solution for the heavy-duty sector. Such projects have higher infrastructure costs and are therefore primarily considered for heavily used freight corridors (e.g., near ports or highways between major cities). Despite these high up-front investments, catenary-hybrid trucks offer low fuel and maintenance costs, and one study found them to be competitive with conventional heavy-duty Class 8 vehicles (i.e., those over 15-ton weight capacity) for near-dock drayage applications (Gladstein, Neandross & Associates, 2012). This technology, whether combined with an internal combustion engine or a limited battery system, results in lower vehicle prices compared to full electric or fuel cell heavy-duty trucks, but the primary obstacle is the construction of a catenary system (den Boer et al., 2013). Other types of “e-roads” are also under consideration, including inductive charging and conductive on-road strips. These systems could potentially lower infrastructure costs and enable use by a wider variety of vehicles and be relatively cost-effective in the future, although these technologies are generally less mature than overhead catenary systems (Connolly, 2016).

DEMONSTRATIONS AND EXAMPLES

Electric vehicles are starting to enter the medium- and heavy-duty vehicle markets through fleets and demonstration projects. Electric transit buses, school buses, shuttle buses, and medium-duty vehicles (primarily for delivery purposes) are becoming increasingly commercially available, but the transition to zero-emission heavy-duty long-haul tractor-trailers is particularly challenging and is currently only in the prototype phase. The various zero-emission vehicle technologies face cost barriers, and in some cases real-world performance barriers as well, but the demonstration projects help resolve such issues while costs are decreasing.

Tables 2 through 5 summarize available information on such zero-emission truck projects across vehicle technology types and vehicle classes. The demonstration projects are categorized according to medium-duty electric (Table 2), heavy-duty electric (Table 3), in-road and catenary electric charging (Table 4), and hydrogen fuel cell trucks (Table 5). We apply the approximate designation of “medium-duty” as U.S. weight Classes 3 through 6 (below 12-metric ton gross curb weight in Europe) and typically straight trucks, and “heavy-duty” as U.S. weight Classes 7 and 8 (above 12 metric tons in Europe) that are normally combination tractor-trailers. However, there is some ambiguity in that the demonstration truck projects do not all have clear weight specifications, and some of the projects span vehicle types. As shown, the wide-ranging zero-emission truck initiatives cover a spectrum of technologies, locations, fleet applications, manufacturer and other stakeholders, and truck fleet sizes.

Table 2. Medium-duty electric vehicle demonstration projects.

Technology	Organization	Location	Time frame	Description	Source
Class 6 electric delivery trucks	Frito Lay	United States	2013	More than 250 Smith Newton electric delivery trucks. Project evaluates 10 of these delivery trucks to better understand the effectiveness of electric trucks in real-world applications.	Frito Lay, (2016); Prohaska, Ragatz, Simpson, & Kelly (2016)
Fuso Canter E-Cell/ Fuso eCanter	Daimler Trucks	Portugal	2014-2015	Eight vehicles used in trials for short-range delivery and inner-city transport.	FUSO (2015)
		Stuttgart, Germany	2016	Testing of five Fuso Carter E-Cell trucks by the parcel service provider Hermes.	Daimler (2016a,b)
Electric delivery vehicles for urban distribution	CWS, Boco, UPS, Smith Electric Vehicles, EFA-S, TCDi, Busch-Jaegen	North Rhine-Westphalia, Germany	2011-2015	A 2-year demonstration project that took data of 107,402 km driven by battery-powered electric trucks for urban distribution.	Stütz (2015)
Electric delivery trucks	Renault Trucks	Paris, France	2015	Testing of the all-electric D-range on delivery rounds of over 200 km with multiple battery recharge times during a 24-hour operating cycle.	Volvo Group (2015)
E-trucks—all electric trucks with refrigerated body	Renault Trucks	Switzerland	2016	Renault Trucks is testing two concept trucks that combined Renault's all-electric Midlum with an electric powered refrigerated body capable of carrying 3 metric tons of refrigerated products.	Volvo Group (2015)
Electric parcel and letter delivery trucks	German Post AG, StreetScooter GmbH, Langmatz GmbH, RWTH Aachen University, BMUB	Bonn, Germany	2012-2016	CO ₂ GoGreen aimed to improve the vehicle technology, infrastructure technology, energy supply, and process design for using electric vehicles in parcel and letter delivery.	Appel (2013); BMUB (2016c)
Maxity electric delivery truck	Renault Trucks	France	2010	Pilot customers operated between 10 and 30 pre-production all electric trucks for deliveries.	Renault Trucks (2010)
Electric parcel delivery trucks	CalHEAT, California Energy Commission, Navistar, FCCC, Smith	Southern California	2012	Comprehensive performance evaluation of 3 E-Truck models using in-use data collection, on-road-testing, and chassis dynamometer testing.	Gallo & Tomić (2013)
Electric delivery truck	UPS, EVI	California	2013	UPS deployed 100 electric medium-duty delivery trucks to their California fleet, offsetting 126,000 gallons of conventional motor fuel per year.	EVI (2011); UPS (2017)
Electric delivery trucks	BAAQMD, CARB, San Francisco Goodwill, the Center for Transp. and Environment, BYD Corp.	Bay Area, California	2017	Goodwill is introducing 11 all-electric trucks to its truck fleet in 3 Californian counties, a \$4.4 million project funded through California's cap-and-trade program, BAAQMD, and Goodwill.	CARB (2016a, 2016b)
Electric delivery trucks	SJVUAPCD, Motiv Power Systems, AmeriPride Services, CALSTART, First Priority Bus Sales	Central Valley, California	2016	Deployment of 20 zero-emission electric walk-in-vans and the necessary charging infrastructure for deliveries in the Central Valley, focused on disadvantaged communities. Funded through \$7.1M grant from CARB, \$5.8M from partners.	CARB (2016a, 2016b); SJVUAPCD (2016)
Electric parcel delivery truck	SJVAPCD, USPS, EDI, Motiv Power Systems, Morgan Olson, CALSTART, SunEdison	Stockton & Fresno, California	2016	Deployment of 15 all electric USPS "step vans" and the necessary charging infrastructure to form the basis of a USPS Advanced Vehicle Cluster. The project received \$4.5M in California funds.	CARB (2016a, 2016b)
Electric delivery truck	UPS, H-GAC, CTE, US DOE, Workhorse Group	Houston-Galveston area, Texas	2015	Deployment of 18 all electric delivery trucks, estimated to avoid the consumption of 1.1 million gallons of diesel fuel over 20 years.	UPS (2015)
Electric delivery truck	UPS Limited	Feltham, UK	2017	Implementation of a smart charging system with energy storage to increase the number of vehicles that can be charged at a depot.	UK (2017)
Electric delivery vehicles	Gnewt Cargo	Southwark, UK	2017	Lease of 33 electric vehicles for last-mile logistics.	UK (2017)
Electric delivery truck	Nordresa, Purolator	Québec, Canada	2017	Purolator is testing of an all-electric delivery truck developed by Nordresa. The trials show electric trucks saving an average of 0.60 \$CAN per kilometer resulting in profitable operation within 2 years.	AVEQ (2017)
Electric delivery truck	UPS, FREVUE	Rotterdam, Netherlands; London, UK	2014-2015	Deployed and tested 16 7.5-ton electrically retrofitted P80E Mercedes T2 in London and 4 in Rotterdam with charging infrastructure.	FREVUE (2017b, 2017c)
Electric logistics truck	FREVUE, Arup, Smith Newton, The Crown Estate, Clipper Logistics	London, UK	2014	Deployment of a 10-ton and 12-ton all electric Smith Newton to accommodate increased delivery volume from a depot to a consolidation center.	FREVUE (2017e)
Electric delivery trucks	UPS	Amsterdam, Netherlands	2013	UPS deployed 6 electric parcel delivery trucks in Amsterdam.	Netherlands Enterprise Agency (2016)

Table 3. Heavy-duty electric vehicle demonstration projects.

Technology	Organization	Location	Time frame	Description	Source
Zero-emission drayage trucks	SCAQMD, the State of California, BYD, Kenworth, Peterbilt, and Volvo	California	2016	Statewide demonstration project of 43 zero-emission battery electric and plug-in hybrid drayage trucks used to transport goods over short distances from ports to distribution centers and rail yards.	SCAQMD (2016a)
Electric Class 8 truck	TransPower	California	2015	Demonstration of 4 Class 8 fully battery electric trucks from San Diego County 110 miles to the Los Angeles-Long Beach port region.	TransPower (2015)
Electric Class 8 yard trucks & Class 5 medium-duty service trucks	BYD, San Bernardino Associated Governments (SANBAG), & BNSF Railway	San Bernardino, Commerce, & Fontana, California	2016–2018	Two-year demonstration project of 23 battery-electric Class 8 yard trucks and 4 Class 5 medium-duty service trucks for use in rail yards and large-scale freight distribution centers, replacing diesel-powered heavy-duty tractors. The State of California awarded \$9 million, through the California Climate Investments (CCI) program.	BYD (2016); CARB (2017)
Electric heavy-duty refuse truck	Motiv Power Systems & the City of Chicago	Chicago, Illinois	2014	The City of Chicago uses an all-electric refuse truck in different refuse and recycling routes up to 60 miles long.	Motiv (2014)
Zero-emission distribution trucks	EMOSS B.V., Hytruck	Netherlands	2013–2014	Zero-emission city distribution project- 8 hybrid and electric trucks with 2 fully electric 19-ton trucks (largest electric trucks of their kind in Europe)	EMOSS (2016)
Battery electric waste disposal	FAUN Umwelttechnik GmbH & Co. KG, DFKI, BEG, BMUB	Germany	2017–2019	Battery electric waste disposal with robot support (BEAR) is a project that develops and implements a fully electric refuse pilot truck to be tested by the Bremerhaven waste disposal company for 12 months.	BMUB (2016a)
Electric heavy-duty refuse truck	Waste Management NZ & EMOSS	Auckland & Christchurch, New Zealand	2016–2017	One electric body waste collection truck and two side-loader waste collection trucks for late 2016/ early 2017. Electricity will come from the gas emissions for a local landfill. First step in Waste Management transition to all electric.	Bradley (2016); Waste Management NZ (2016)
Electric heavy-duty logistic trucks	INTERREG, EU, LIOF, FIER Automotive, Köppen, Samskip, CTV, KLG Europe, Meulenbergh Transport, Limburg	North Limburg, Netherlands & Duisburg, Germany	2017	Green Electric Last Mile (eGLM)—A project implementing 9 40- to 50-ton electric heavy-duty trucks in the cross-border logistics region of North Limburg-Duisburg	eGLM (2017); Weken & Kroon (2017)
Electric heavy-duty trucks for beverage distribution	FREVUE, Heineken, Simon Loos,	Amsterdam & Rotterdam, Netherlands	2017	Testing of 6 12-ton and 1 19-ton electric freight trucks in Heineken's delivery truck fleet.	FREVUE (2017a)
Electric freight trucks	Autobus Lion, TM4, AddÉnergie Technologies, Solution Adetel, Alcoa Canada	Québec, Canada	2017	Designing and manufacturing four prototypes (two freight trucks and two passenger buses). The project is valued at 17.2 million CAN with 8.6 million \$CAN funding from the government.	Government of Québec (2016)
Electric refuse truck	Phoenix Danmark, Norsk Gjenvinning	Sparsborg, Norway	2017	Two refurbished electric refuse trucks, each truck is expected to save 60 metric tons of CO ₂ per year	Norsk elbilforening (2017)
Electric delivery truck	ASKO	Oslo, Norway	2016	Norway's first electric distribution truck in operation, used to deliver food to city-center shops. 18-ton refrigeration truck with 240-kWh battery capacity, 200 km range, and cost ~\$4 million NOK (~\$470,000), twice that of diesel truck.	Dalløkken (2016)
Electric refuse truck	Motiv Power Systems, Crane Carrier, Loadmaster, and the City of Sacramento	Sacramento, California	2017	State's first all-electric garbage truck deployed in the city of Sacramento. It is expected to save 6,000 gallons of fuel per year.	PR Newswire (2017)
Electric delivery truck	EMOSS, FREVUE, BREYTNER	Rotterdam, Netherlands		Testing of one 19-ton EMOSS truck in Rotterdam by BREYTNER Transportation.	FREVUE (2017d)
Electric truck	BMW Group, SCHERM Group, Terberg	Munich, Germany	2015	40-ton electric truck for material transport from a logistic center, charged with renewable electricity	BMW Group (2015)
Electric commercial vehicles	Fraunhofer IML, TU Berlin, Hochschule Fulda, Florida Eis, Meyer Logistik, Meyer&Meyer, BMUB	Germany	2017–2019	"EN-WIN" is 18-month field trial of electric vehicles in the food, textile, and distribution logistics. Data to develop forecasting tool on e-commercial vehicles. Part two of project is to construct a 26 t electric vehicle for urban traffic use.	BMUB (2017a)
Freight electric vehicles	Emons Spedition, BMUB	Dresden, Germany	2016–2018	CiE-Truck project: Emons to deploy three electric heavy-duty vehicles (12t and 18t)	BMUB (2016b)
Electric terminal truck	Terex MHPS, Hamburger Hafen und Logistik, Hermann Paus, Neuss Trimodal, Maschinenfabrik	Neuss & Hamburg, Germany	2012–2017	Terminal truck project to develop and test battery-powered terminal trucks for container handling.	BMUB (2016g)

Table 4. In-road and catenary charging heavy-duty electric vehicle demonstration projects.

Technology	Organization	Location	Time frame	Description	Source
Conductive rail to charge all vehicles	Elonroad and Lund University	Outside Lund, Sweden	2017	Developing a 200-meter test tract to demonstrate “Elonraod” (a conductive rail that is laid on top of the road to charge all vehicle types).	Elonroad (2016)
Wireless power road	INTIS	Lathen, Germany		Currently testing a 25-meter track with contactless inductive charging of all vehicles.	INTIS, 2016
Conductive rail to charge all vehicles	Elvåg AB, NCC, KTH University, Swedish Energy Agency, & Arlandastad Holding AB	Sweden		Demonstrated conductive underneath charging for all vehicles on a test track and currently a 2 km pilot is under construction.	Connolly, D. (2016)
Conductive in-road charging for heavy-duty vehicles	Volvo and Alstom	Hällered, Sweden	2012	400-meter test track with two power lines built into the surface of the road and a current collector on the truck that connects to the road.	Volvo Trucks (2013)
Catenary electric trucks	Siemens, Volvo, SCAQMD	Los Angeles & Long Beach, California	2017	One-mile of highway equipped with a catenary system in both direction for freight transport near ports.	Siemens (2014, 2016b)
Catenary electric system—heavy commercial	Siemens, BAST, TU Dresden, EDAG, DLR, LBST, NOW, IFEU	Germany	2016–2019	ELANO project is a research and development project for catenary electric system powered by renewable energy for heavy-duty commercial vehicles.	BMUB (2016d)
Catenary heavy commercial vehicles	Siemens	Outside of Berlin, Germany	2010–2011	ENUBA - a study and demonstration on a private road that examined the electrification of heavy-duty commercial vehicles in conurbations with a catenary system.	BMUB (2016e)
Catenary electric trucks, eHighway	DLR, Siemens, TU Dresden, BMUB, Scania	Gross Dölln, Germany	4/2012–12/2015	ENUBA 2 - a 2km overhead catenary system for heavy-duty vehicles and an extension for bus applications. The project researched vehicle technology, the relevant traffic, energy, ecological, economic, and legal aspects and tested the functionality and reliability of such vehicles.	BMUB (2016f), Scania (2014)
eHighway field trial—overhead catenary electric trucks	LBV-SH, Forschungs-und Entwicklungszentrum Fachhochschule Kiel GmbH	Hamburg - Lübeck, Schleswig Holstein, Germany	1/1/2017–12/31/2018	FESH I - Planning and construction phase of 6 km of overhead catenary infrastructure in both directions, supported by a €14 million subsidy from BMUB.	BMUB (2017b)
	LBV-SH, TU Dresden, FH Keil, Spedition Bode, Stadtwerke Lübeck, Lübecker Hafengesellschaft, Scania, Siemens		mid 2018–2021	FESH II - Field testing of the system supported by a €3-4 million subsidy from BMUB. The goal of the system is to have trucks powered purely electrically the 25 km from the Lübeck harbor to the logistics center - 12 km (6 km each direction) through a catenary system and the remaining 38 km through an onboard battery pack. Initially diesel hybrid trucks will be included in the study to ensure reliability.	BMUB (2017b)
eHighway field trial—overhead catenary electric trucks	Hessen Mobil Strassen - und Verkehrsmanagement, TU Darmstadt	Frankfurt - Darmstadt, Hesse, Germany	1/1/2017–12/31/2018	ELISA I - Planning and construction of about 6 km of overhead catenary lines in both directions to allow for trucks to travel over 15 km electrically powered. The project is funded by a €14.6 million subsidy from BMUB.	BMUB (2017b)
	Power Supplier, Vehicle Manufacture (possibly Scania), Siemens		mid 2018–2021	ELISA II - Field testing of the system supported by a €3-4 million subsidy from BMUB. The goal is to allow for emission-free delivery of goods in the Frankfurt urban area and to provide a guide and basis for future system expansion.	BMUB (2017b)
eHighway	Siemens and Scania	Sweden	June 2016–2018	World's first eHighway system on public roads. Operating two adapted diesel hybrid vehicles under a catenary system spanning two kilometers on the highway.	Siemens (2016a)

Table 5. Medium- and heavy-duty hydrogen fuel cell vehicle demonstration projects.

Technology	Organization	Location	Time frame	Description	Source
Hydrogen fuel cell medium-duty parcel delivery truck	FedEx, US Department of Energy, Plug Power, Workhorse Group	Memphis, Tennessee & California	May 2016–October 2019	Demonstration of 20 hydrogen fuel cell extended-range battery electric parcel delivery trucks operating one 10-hour shift for 260 days annually for approximately 1.92 years (~5,000 hours per truck). Project received \$3.0 million in funding from the DOE and \$3.367 million from partners.	Griffin (2016)
Maxity Electric Truck with fuel cell range extender	Renault Trucks and French Post Office	France	2015	A year field test by the French Post Office of Renault's Maxity Electric Truck equipped with a hydrogen-powered fuel cell.	Renault Trucks (2015)
Hydrogen fuel cell hybrid electric parcel delivery truck	CTE, UPS, University of Texas, EVI, Hydrogenics USA, Valance Technology	California	2014–	The project will retrofit 17 delivery vans with fuel cell hybrid technology and test them at distribution facilities in California.	CTE (2016); Satyapal (2014)
Hydrogen fuel cell drayage truck	Environmental Defense Fund, US DOE, (H-GAC), Gas Technology Institute, US Hybrid, Richardson Trucking, University of Texas	Port of Houston, Texas	2015–	Three-year demonstration project of three zero-emission heavy-duty Class 8 drayage trucks powered by a hydrogen fuel cell – electric hybrid power system at the Port of Houston. The project received \$3.4 M in federal funding and the project partners committed to funding \$3.0 M.	Wolfe (2015)
Fuel cell drayage truck	Hydrogenics, Siemens, Total Transportation Services (TTSI)	Alameda Corridor, Port of Los Angeles & Long Beach, California	2015–	The "Advanced Fuel Cell Vehicle Technology Demonstration for Drayage Truck" is a project demonstrating a hydrogen fuel cell powered Class 8 drayage truck.	Hydrogenics (2015)
Hydrogen fuel cell hybrid battery electric drayage trucks	SCAQMD, CTE, TransPower, U.S. Hybrid, Hydrogenics USA	Port of Los Angeles & Long Beach, California	June 2015–September 2018	Development and demonstration of 6 battery electric trucks with hydrogen fuel cell range extenders for drayage applications.	SCAQMD (2014, 2016b)
Hydrogen fuel cell distribution trucks	Scania and Asko	Norway	2016	3 three-axle electric distribution trucks powered by hydrogen fuel cells used for distribution services of almost 500 km. The hydrogen gas will be locally produced from solar cells.	Scania (2016)
Fuel cell drayage truck	Toyota	Ports of LA & Long Beach, California	Summer 2017	Toyota will test fuel cell trucks system, Project Portal, to determine the feasibility of using fuel cell trucks for port drayage applications.	Toyota (2017)

As seen in Tables 2 through 5, many of the truck demonstration projects to date have been concentrated in California, Germany, and the Netherlands, with several of the electric road charging projects being carried out in Sweden. The Californian, German, and Swedish governments have spurred demonstration projects in their respective regions with government support, both financially and through direct government involvement. For the 2014–2015 and 2015–2016 fiscal years alone, the California Air Resources Board allocated \$84 million in grants for zero-emission truck and bus pilot commercial deployment projects (CARB, 2015c, 2015d). Governments have also shown support through direct involvement in carrying out research and development projects. For example, in 2016, the government of Québec supported a project for all-electric heavy-duty vehicles that included the manufacturing of four prototypes, including two passenger buses and two freight trucks. In 2017, as part of their partnership for innovation, the German and Swedish governments have been conducting a joint study on the electrification of roads to explore the various technical options and business models, as well as how to overcome cross-border interoperability questions and gain European level support (Die Bundesregierung & Government of Sweden, 2017).

Drayage applications around ports in the United States, particularly the ports of Los Angeles and Long Beach, have become a focal point for innovative heavy-duty fuel cell and catenary truck zero-emission demonstration projects. This is driven in large part by the area being a hot spot for increased pollution and public health impacts, resulting in heightened demand for greater emission reductions there. The duty cycle, short distance traveled, and heavily traveled routes of drayage trucks around ports makes them particularly suited for zero-emission technologies, as limited infrastructure (either catenary wires or hydrogen fueling stations) is required to supply a large number of trucks. In addition, plug-in battery electric trucks have made great strides in the medium-duty delivery sector, with companies—especially those located across the United States and Europe—incorporating thousands of delivery trucks into their fleets. In terms of companies, Siemens has been at the forefront of heavy-duty catenary demonstration projects, partnering with various companies, universities, and government agencies to carry out three projects in California, Germany, and Sweden. Data collection and results from demonstration projects are crucial in leading the way to commercialization of zero-emission vehicles by helping to improve technology, drive down costs, familiarize truck owners and operators with the new technology, and determine and demonstrate best suited applications for the various technologies.

COMMERCIAL ZERO-EMISSION TRUCKS

Many vehicle manufacturers, both those long established in the industry and new start-up companies, are developing zero emission medium- and heavy-duty vehicles, and some are already producing vehicles at low volume. Among the larger automotive companies, Daimler has announced that it expects to begin production on a fully electric heavy-duty truck in 2020 (Daimler, 2016a). Tesla has revealed that heavy-duty trucks are in the early development phase with a reveal of a prototype electric semi-tractor slated to occur in September 2017 (Musk, 2016). Toyota announced that it is exploring hydrogen fuel cells for heavy-duty drayage truck applications through a California-based feasibility study beginning in summer 2017 (Toyota, 2017). BYD is currently producing Class 5, 6, and 8 electric trucks (BYD, 2016). Renault has also released electric and fuel cell trucks (Renault Trucks, 2015). Among the start-ups that have entered the zero-emission truck market are Nikola Motor Company (a U.S.-based company developing a hydrogen fuel cell powered semi-truck), Charge (a U.K.-based company developing electric trucks), and E-Force (a Switzerland-based company producing fully electric Class 8 trucks). See the Annex for details on the various commercial zero-emission commercial vehicles in development or production.

Among the key specifications for these companies is the available range of vehicle and what vehicle segment the companies envision for these electric and fuel cell vehicles. Figure 3 shows the range of commercial electric and hydrogen fuel cell trucks that are under development, have been announced, or are being produced, according to their respective truck classes. As shown in the figure, plug-in battery electric vehicles encompass the majority of the commercial medium- and heavy-duty trucks with ranges that are generally between 100 to 200 km. Fuel cell electric vehicles allow for significantly higher range across all truck classes. The Nikola One fuel cell announcement indicated a range of over 1,200 km for a Class 8 tractor-trailer application (Nikola, 2016). Further details, including the manufacturer, technology, range, current status, and detailed technology specifications, on these medium- and heavy-duty zero-emission commercial vehicles can be found in the Annex.

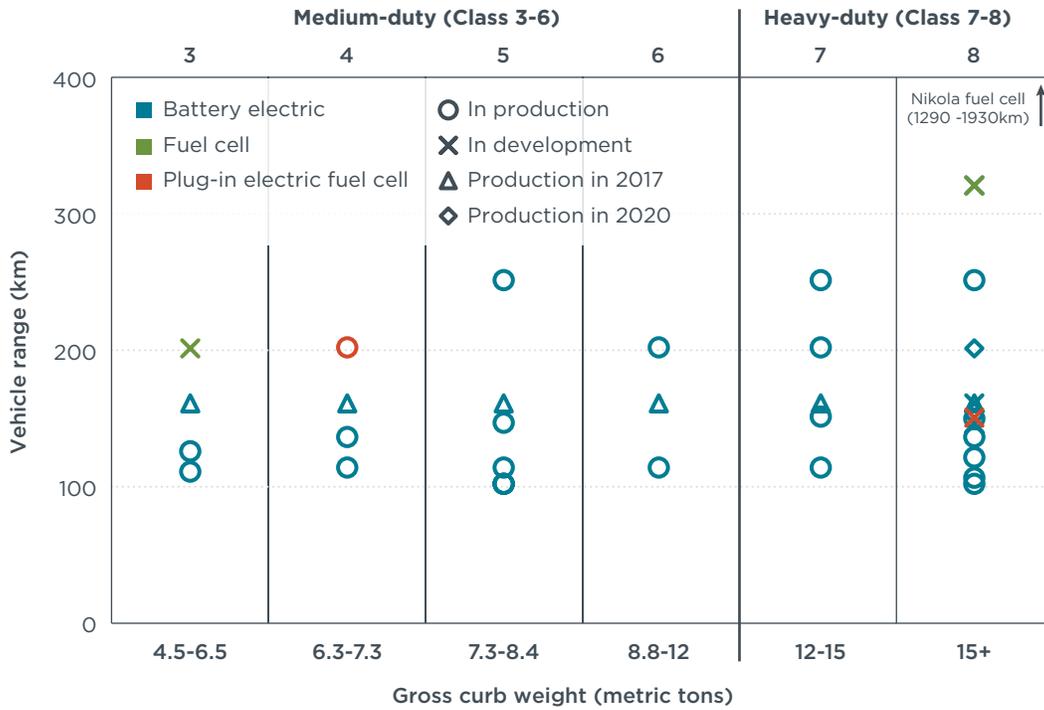


Figure 3. Ranges of zero-emission medium- and heavy-duty trucks currently in development or production broken down by truck class.

III. TECHNOLOGY COST ANALYSIS

To assess zero-emission vehicle technology costs, in this section we develop a cost-of-ownership evaluation of the various vehicle technology alternatives and discuss broader infrastructure costs.

VEHICLE COST OF OWNERSHIP

To gain an understanding of the viability of various zero-emission heavy-duty technologies for long-haul heavy-duty tractor-trailer applications, we analyzed the technologies under a vehicle-related cost of ownership framework. We base the analysis on the research and available data on vehicle technology costs, efficiency, and emissions from the projects outlined above. We report on results for 2015 through 2030 to show our best estimates of the progression of the costs over time.

The objective of the cost analysis is to illustrate the cost differences of various tractor-trailer technologies over different periods of time. The cost of ownership analysis includes capital costs (tractor-trailer purchase price), maintenance costs, and fuel costs experienced by the owner over the vehicle lifetime. The fuels and technologies considered in the analysis are diesel, diesel hybrid, compressed natural gas, liquefied natural gas, overhead catenary electric, dynamic induction electric, and hydrogen fuel cell. Due to uncertainties related to potential battery-swapping systems, including how many extra battery packs would be needed, we do not include an electric battery-swapping scenario in the analysis. All costs in the analysis are in 2015 U.S. dollars. The analysis is constrained to vehicle and fuel costs. Motor vehicle taxes, insurance costs, driver wages, tolls, and road fees are excluded. The analysis is for vehicle costs; infrastructure costs are discussed further below. We make a series of assumptions on average annual vehicle use, efficiency technology, cost, and fuel cost to develop bottom-up cost models for the various tractor-trailer technologies.

Vehicle use. We analyze the costs for tractor-trailers over 10 years of long-haul freight activity. The more uncertain and varied use of the vehicle after its more intensive long-haul use (perhaps repurposed for less-mileage-intensive applications) in regional or drayage operation is excluded from the analysis, although of course there would still be fuel-saving benefits in that later stage. The vehicle miles traveled with vehicle age over the 10-year period are based on the U.S. EPA's regulatory analysis (U.S. EPA and DOT, 2011), with China and Europe adjusted downward to account for 27% and 40% lower average annual driving distances, respectively. For consistency, the alternative vehicle technologies are assumed to have comparable functionality and reliability as diesel powertrains. The catenary and dynamic inductive grid-operated trucks are assumed to run on 100% electricity and are capable of traveling approximately 80 km powered by the onboard battery pack, assuming an 80% depth of discharge (den Boer et al., 2013). The baseline tractor-trailer is assumed to have three trailers per common industry practice to account for there being three long-haul trailers, on average, in operation for every tractor (Meszler, Lutsey, & Delgado, 2015). The average annual distance traveled for each region over the lifetime of the vehicle along with additional data sources and assumptions are provided in the Annex.

Efficiency. The average tractor-trailer fuel consumption for China, Europe, and U.S. diesel tractor-trailers are taken from various regulatory and research studies. The 2015 fuel economy is assumed to be 5.4 mpg (44 L/100km) in China, 6.9 mpg (34 L/100km)

in Europe, and 5.9 mpg (40 L/100km) in the U.S. (based on Delgado, 2016; Muncrief & Sharpe, 2015). The fuel efficiency for the new U.S. tractor-trailers is assumed to improve, following the Phase 2 U.S. greenhouse gas emissions and fuel efficiency standards, which result in a 2027 fuel economy of 9.1 mpg (26 L/100km) (Sharpe et al., 2016). Europe tractor-trailer fuel efficiency is based on the 2015 real-world testing of tractor-trailers of 6.9 mpg (34 L/100km) (Muncrief & Sharpe, 2015). When considering improved technology in Europe from 2021 on, we assume a 2.5% per year annual fuel consumption reduction. This is based on the average between incremental and moderate improvements analyzed in Delgado et al. (2016) and assumes that CO₂-reduction standards will be implemented in Europe. For China, the fuel efficiency is assumed to follow the Stage 3 China fuel consumption standards, achieving 6.3 mpg (37 L/100km) in 2020 (Delgado, 2016). After 2020, the China tractor-trailer fuel consumption is assumed to improve by 2.5% annually, similar to Europe, assuming new standards will be implemented there.

For diesel hybrid tractor-trailers, we assume a reduction in fuel consumption of 5% in the U.S. and China and 7% in Europe relative to the conventional diesel average (Rodriguez, Muncrief, Delgado, & Baldino, 2017). Natural gas engines are assumed to follow the same fuel efficiency improvements as diesel engines at a 10% and 15% efficiency loss for compression ignition (CI) and spark ignition (SI) engines, respectively (Delgado & Muncrief, 2015; Kasten et al., 2016). The energy consumption for fuel cell, catenary electric, and dynamic induction electric tractor-trailers are taken to be 9.5 megajoule per kilometer (MJ/km), 5.7 MJ/km, and 9.0 MJ/km, based on a variety of sources, and are assumed improve by 1% annually for catenary electric and 2% for fuel cell and dynamic induction electric (based on Akerman, 2016; den Boer, 2013; Kasten et al., 2016; Schmied, Wüthrich, Zah, Althaus, & Friedl, 2015). The energy consumption assumptions for these vehicle technologies are provided in the Annex.

Technology cost. The base diesel tractor-trailer in the U.S. is assumed to cost \$210,000, including a tractor at \$135,000 with three trailers at \$25,000 each (Meszler et al., 2015). The comparable base tractor-trailer cost for Europe is estimated to be approximately the same, before future efficiency technology is considered. Based on data on comparable tractor and trailer costs, the heavy-duty tractor-trailer is approximated at \$90,000 for China. Battery and fuel cell system costs vary widely in the literature, depending on innovation, supplier competition, and economies of scale that are underway largely as a result of light-duty vehicle developments. We base our electric-drive vehicle costs on Slowik et al. (2016) and Wolfram & Lutsey (2016). Slowik et al. (2016) summarized a range of lithium ion battery pack costs from 2015 to 2023 for medium- and high-volume scenarios, and found costs ranging from approximately \$230/kWh to \$420/kWh in 2015 and \$150/kWh to \$225/kWh in 2023. The battery costs applied here are within that study's medium- and high-volume projections. The expected reduction in lithium-ion battery costs is attributed to the replacement of high-cost materials, economies of scale, improvements to battery design and production methods, manufacturing improvements, and competition among suppliers.

Table 6 shows our key component cost assumptions for 2015–2030. We apply estimates from Wolfram & Lutsey (2016) to estimate fuel cell system costs. Based on annual production of 1,000, fuel cell system costs are estimated at \$240 per kilowatt (kW) in 2015; with increasing production to 10,000 in 2025, the cost drops to \$89/kW, then to production of 50,000 in 2030 to \$59/kW. Both battery pack and fuel cell systems are assumed to use similar technology in heavy-duty applications as in light-duty, and

therefore these component prices are assumed to follow price projections for light-duty vehicles. This allows greater economies of scale in heavy-duty applications. The assumption is in line with Tesla's statement that the upcoming Tesla Semi will share parts with its electric car production and Toyota's announcement that its Class 8 fuel cell tractor will use its Mirai passenger car fuel cell stacks (Lambert, 2017; Toyota, 2017). Cost of the additional required fuel cell and battery electric systems are the electric systems (power electronics, battery management systems, etc.) necessary to control the power transfer. These additional costs are anticipated to decrease over time as the technology increases in volume and continues to improve.

Table 6. Estimated vehicle component costs for vehicles purchased in 2015–2030.

Component Costs	2015	2020	2025	2030
Battery (\$/kWh)	326	228	168	120
Electric motor fixed cost (\$)	120	94	85	75
Electric motor (\$/kW)	22	18	16	14
Fuel cell system (\$/kW)	240	166	89	59
Additional fuel cell systems (\$/kW)	38	34	31	28
Overhead catenary vehicle grid connection (\$)	71,700	49,600	21,200	21,200
Dynamic induction vehicle grid connection (\$)	16,700	11,800	11,500	10,800
Additional electric vehicle systems (\$/kW)	55	52	46	41

Based on den Boer et al., 2013; Slowik et al., 2016; Wolfram & Lutsey, 2016

Internal combustion engine costs are forecasted to increase over time as additional improvements and new technologies will be required to meet tightening efficiency and exhaust after-treatment regulations (den Boer et al., 2013). The baseline cost for internal combustion engines is assumed, based a study done by CE Delft (2013), to be \$118/kW. The forecasted costs associated with engine improvements and vehicle efficiencies are based on a study conducted by Meszler et al. (2015). That study estimated a wide range of technology packages that are applicable for meeting global heavy-duty vehicle efficiency standards; therefore, we apply technology costs from that study for the projected costs of advanced efficiency technologies for heavy-duty vehicles to meet the expected incremental efficiency improvements (as mentioned above) in the 2020–2030 timeframe.

Based on the above assumptions, Table 7 summarizes the tractor-trailer capital costs for 2015–2030. The total tractor-trailer capital cost is amortized over 10 years at a 10% interest rate. The analysis excludes analysis of the residual value of the tractor-trailer because previous studies have found that the residual value is insignificant to the overall outcome of the cost analysis (see Lee & Thomas, 2016). As shown, the total vehicle costs for all alternative vehicles are more expensive than diesel vehicles initially. Over time, the total costs for alternative vehicle types are forecasted to be less than diesel as the costs of new technologies decrease greatly as a result of anticipated increases in production. The alternative vehicles and their components benefit from economies of scale, technology improvements, and production optimizations, greatly reducing their overall costs. The total initial vehicle purchase cost, rounded to the nearest thousand, is shown in Table 7, and the total breakdown of costs for the components of each vehicle is shown in the Annex.

Table 7. Total estimated tractor-trailer capital costs (in thousands of 2015 U.S. dollars).

		2015	2020	2025	2030
China	Diesel	90	91	95	100
	Hybrid electric	101	101	103	108
	Liquefied natural gas (compression ignition)	118	116	115	116
	Liquefied natural gas (spark ignition)	153	147	143	141
	Compressed natural gas (spark ignition)	113	110	108	109
	Hydrogen fuel cell	256	196	164	150
	Electric overhead catenary	220	178	138	131
	Electric dynamic induction	251	140	128	121
	Diesel	204	204	208	218
Europe	Hybrid electric	229	226	227	236
	Liquefied natural gas (compression ignition)	267	260	255	255
	Liquefied natural gas (spark ignition)	239	232	228	228
	Compressed natural gas (spark ignition)	256	246	239	237
	Hydrogen fuel cell	342	281	249	236
	Electric overhead catenary	306	262	222	218
	Electric dynamic induction	251	225	213	208
	Diesel	210	220	223	250
United States	Hybrid electric	234	242	242	268
	Liquefied natural gas (compression ignition)	270	270	260	273
	Liquefied natural gas (spark ignition)	242	242	233	246
	Compressed natural gas (spark ignition)	259	256	255	255
	Hydrogen fuel cell	345	281	253	255
	Electric overhead catenary	309	272	227	236
	Electric dynamic induction	254	234	218	226

Values rounded to nearest 1,000

Maintenance costs. Baseline maintenance and repair costs are based on those from Argonne National Laboratory's GREET model. The model assumes similar incremental maintenance and repair costs across various vehicle types but considers the reduced costs for hybrid and electric drive heavy-duty vehicles (Burnham, 2016). The costs are provided on a per-kilometer basis and are assumed to remain constant for vehicles produced in 2015 through 2030. The maintenance and repair costs are assumed to be \$0.12 per kilometer for diesel and natural gas tractor-trailers and \$0.11 per kilometer for diesel hybrid, electric powered, and fuel cell tractor-trailers. As tractor-trailers become more efficient over time in the analysis, the maintenance costs become a higher percentage of the total vehicle operating costs.

Fuel cost. We base our forecasted diesel fuel price on the International Energy Agency (IEA) World Energy Outlook (WEO) 2015 and the natural gas prices from U.S. EIA (IEA, 2015; U.S. EIA, 2017a). The differences between fuel prices in China, Europe, and the U.S. are assumed to be the same as their historical differences. The historical natural gas prices are from the Eurostat database for Europe and from a study done by the Oxford Institute for Energy Studies for China (Eurostat, 2017a; Li, 2015). Historical

diesel fuel prices are based on World Bank data (World Bank, 2017). The IEA WEO projects crude oil prices from \$50 per barrel in 2015, increasing to \$128 per barrel through 2040. Electricity price projections for the U.S. follow the U.S. EIA's Annual Energy Outlook 2017 transportation electricity price projections (U.S. EIA, 2017b), and prices in China and Europe are based on Eurostat and Lawrence Berkeley National Laboratory data (Eurostat, 2017b; LBNL, 2014). Our estimated hydrogen fuel price decreases from \$12 per kilogram in 2017 to \$4 in 2030 for natural gas-based hydrogen (based on Fulton & Miller, 2015). In addition, we assume that the cost of hydrogen drops to \$5 per kilogram for hydrogen produced from renewable energy electrolysis (Fulton & Miller, 2015). The future fuel costs are discounted using a 4% discount rate to determine the net present value for each vehicle purchase.

Vehicle-related cost of ownership. Figure 4 shows the vehicle-related cost of ownership for trucks in China, Europe, and the U.S. for long-haul heavy-duty tractor-trailers for 2015 through 2030. The graphs show the breakdown of the tractor-trailer capital cost, maintenance cost, and fuel cost over 10 years of operation. The cost analysis excludes infrastructure cost for the dynamic inductive grid and overhead catenary technologies, which are discussed further below. By analyzing the 10-year operating cycle, we intend to cover at least the first phase of the tractor life while it is in long-haul operation. With uncertainties about total electricity throughput, charging-discharging cycles, and any degradation over time for catenary and in-road charging electric tractors, we do not include battery replacements. The results are summarized for the various vehicle technologies as compared to conventional diesel (which increases in efficiency over time), diesel hybrid (which retains an efficiency advantage over conventional diesel), and three natural gas technologies (liquefied compression ignition, liquefied spark ignition, and compressed spark ignition). Two fuel cell technology pathways are shown, first for natural gas-derived hydrogen and second for renewable source-derived hydrogen.



Figure 4. Cost of ownership in China, Europe, and the United States for each long-haul heavy-duty truck technology for a vehicle purchased in 2015–2030 broken down by capital cost, maintenance cost, and fuel cost.

Figure 4 illustrates the results on the various technologies' associated costs. The figure shows how conventional diesel vehicle costs increase incrementally, but are relatively consistent in future years, as compared to the alternative fuel technologies. Essentially all the other technologies see reduced cost of ownership over time, primarily because their capital technology costs decrease from 2015 through 2030. Natural gas, especially the liquefied natural gas with compression ignition, consistently offers among the lowest cost of ownership.

The zero-emission vehicle technologies show the greatest cost reductions from 2015 to 2030. Fuel cell technology shows the largest reduction in cost over time, due to both the expected drops in fuel cell costs and hydrogen costs. Excluding infrastructure costs, the two electric vehicle scenarios, induction and overhead catenary, ultimately arrive at among the lowest total vehicle cost in the 2025–2030 timeframe, similar to natural gas. Compared with diesel vehicles in 2030, overhead catenary results in 25%–30% lower costs, in-road induction results in 15%–25% lower costs, and hydrogen fuel cells result in 5%–30% lower costs to own, operate, and fuel. The reduced vehicle costs for electric tractor-trailers result in upfront costs that are similar to conventional diesel trailers in the 2025–2030 timeframe—aided, of course, by the distributed electric power, which allows smaller battery packs than would otherwise be needed. The gap in costs between conventional diesel and electric technology further widens across regions, as diesel tractor-trailers become incrementally more advanced and as compliance with future efficiency regulations becomes more expensive. Overall, when comparing the costs across the three major regions, the technologies show similar relative technology comparisons, although in absolute terms the costs are higher in the U.S., as a result of the U.S. having the largest annual distance traveled per truck.

SUPPORTING INFRASTRUCTURE COSTS, VIABILITY, AND IMPLEMENTATION

Beyond the cost of ownership, the cost, availability, and implementation of the required infrastructure is also of great importance in determining the viability of zero-emission technologies in the heavy-duty sector. The required infrastructure is particularly important for the long-haul heavy-duty applications analyzed above, as these trucks cover large distances and would need extensive charging (overhead catenary wires, or in-road inductive or conductive charging) or natural gas or hydrogen refueling infrastructure. On the other hand, the required infrastructure to support regional heavy-duty, waste, and drayage trucks tends to be easier to implement and less costly as these trucks tend to follow set routes, have greater downtime, and cover much shorter distances. Required infrastructure for regional heavy-duty vehicles could be quite similar to the charging and hydrogen infrastructure for battery electric and hydrogen fuel cell buses, which have been implemented in some regions, especially in China (and also increasingly in some cities in Europe and the U.S.).

Although there is considerable uncertainty, approximate first estimates are available for the applicable charging infrastructure costs. Overhead catenary wires provide a continuous supply of power to trucks, requiring an extensive and continuous network of energy infrastructure along roadways. In addition to the catenary wires, infrastructure to support the necessary supply of electricity (substations, connection to the grid, transformer, and rectifiers) need to be added to motorways (den Boer et al., 2013). Catenary wires are estimated to cost between \$0.8 million and \$3.8 million per kilometer, with annual operation and maintenance costs of 1%–2.5% of the initial capital

cost of the catenary and energy infrastructure (based on den Boer et al., 2013; Gladstein, Neandross & Associates, 2012; Siemens, 2016b). Once completed in various regions, these electric charging systems would enable high utilization, which would allow for the overall system costs to be spread over many heavy-duty vehicles over time.

Similar to catenary wires, dynamic grid inductive or conductive charging requires expensive energy support infrastructure in addition to the necessary charging on top of, or under, the roadway. The installation of underground infrastructure could be more costly and invasive than overhead catenary wires, but it could have lower maintenance requirements, because there is no wear and tear on the components. Dynamic grid in-road infrastructure is estimated to cost between \$2.5 million and \$4 million per kilometer, with annual operation and maintenance costs of 1% of the initial installation cost of the charging infrastructure (Connolly, 2016; den Boer et al., 2013). These road charging systems would enable high utilization.

Hydrogen fueling station cost estimates have ranged from \$350,000 to \$5.3 million (Wolfram & Lutsey, 2016). Hydrogen refueling times are comparable to conventional diesel and gasoline vehicles. Quick refueling times allow for the possibility of high utilization of fueling stations and therefore distributes the investment costs over the use of many vehicles. Estimating the cost of hydrogen fueling stations on a per-vehicle basis is difficult because it is dependent upon the station's utilization and hydrogen throughput, which are uncertain. In the hydrogen case, how quickly the shift toward high station utilization happens could be partially dependent upon whether both passenger and heavy-duty freight vehicle approaches grow and co-evolve. Other key considerations with hydrogen cost implications are the exact production, transport, and distribution system (e.g., compressed or liquefied hydrogen, pipeline or truck distribution) involved with supplying the fuel to stations.

To help inform on infrastructure and system-level costs, we summarize results from a directly applicable study by the Öko Institut. Kasten et al. (2016) conducted a comprehensive study comparing the cost of energy supply, energy supply infrastructure (investment, maintenance and operation, and connection costs for gas stations or charging infrastructure), and vehicle purchase cost for alternative vehicle technologies to conventional fossil fuel-powered vehicles. The study compared four alternative scenarios to decarbonize and reduce air pollution from the German fleet of trucks in the long-haul freight sector. These scenarios were (a) internal combustion, with power-to-liquid fuels with very low lifecycle carbon emissions; (b) overhead catenary line electricity for hybrid diesel-electric powertrain; (c) liquefied natural gas from low-carbon power-to-gas methane; and (d) fuel cell with liquefied power-to-gas hydrogen. The study estimated the additional cost for each of the scenarios from 2010 to 2050 compared to the reference case, where the whole long-haul heavy-duty fleet would otherwise be powered by conventional diesel fuel.

The results from Kasten et al. (2016) on the energy supply, infrastructure, and vehicle costs for long-haul freight road transport are shown in Figure 5. As shown, the costs range from \$100 billion to \$400 billion dollars from 2010 to 2050, so any of these approaches would amount to a major transportation overhaul to help decarbonize the freight sector. Because the scenarios were set to have comparable emission-reduction benefits, the scenario with the lowest total cost (i.e., overhead catenary electric system) provides the most cost-effective long-term greenhouse gas reduction. The analysis does not consider the relative practical feasibility of implementing the different alternative

technologies. The figure shows that even though the overhead electric option is infrastructure intensive, it compares very favorably against the options to use renewable power to develop liquid combustion diesel replacements, natural gas, and hydrogen—each of which has significant energy supply, infrastructure, and vehicle costs.

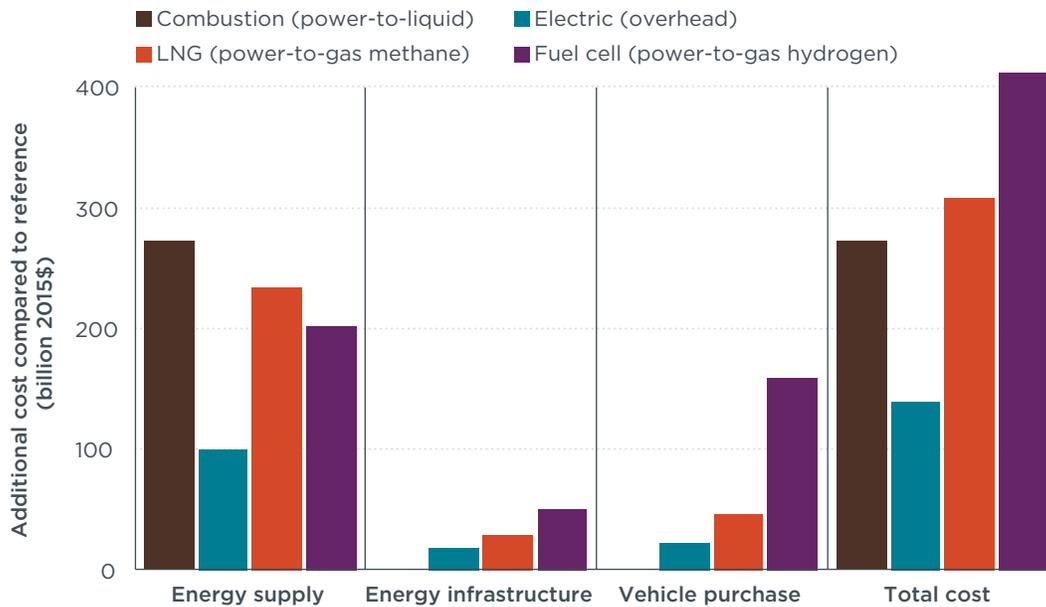


Figure 5. Additional cost for four different greenhouse gas reduction scenarios compared to the reference case (all fossil fuel use) for the long-haul heavy-duty freight transport sector in Germany (based on Kasten et al., 2016).

For further information on the Kasten et al. (2016) study summarized in the figure, the trucks powered by the overhead catenary system are assumed to be hybrids, powered by electric energy 75% of the time through the catenary wires or the small on-board battery and the remaining 25% of the time by an internal combustion engine powered by power-to-liquid fuel. For this case, it is assumed that 4,000 km (approximately 30%) of the German federal motorways are electrified. The market introduction of the overhead catenary trucks is assumed to begin in 2025 and ramp up to 90% of new registrations by 2050. For the power-to-gas natural gas scenario, trucks will enter the market in 2015 and reach full penetration by 2035. In the power-to-gas hydrogen case, fuel cell trucks would be introduced to the market in 2020 and reach full penetration by 2035. In the combustion scenario, the trucks would be fully powered by low-carbon power-to-liquid fuels by 2050.

Although road electrification has high upfront costs from the required energy infrastructure, these costs are dwarfed in the long term by cheaper energy supply costs compared to alternative liquid fuels. The study indicates that the cost of energy infrastructure is relatively small compared to the high cost of energy supply and vehicle costs over the long-term, leading to the result that electrification is the most cost-effective technology for freight transport in the long-term. A similar effect can be seen for the power-to-gas hydrogen case, for which the costs of the market introduction of fuel cell heavy-duty trucks drives the high costs of vehicle purchase. In this case, the cheap energy supply costs and the low system costs (both compared to the

power-to-liquid and the power-to-methane option) would become effective after the transformation process and in a longer timeframe than 2050.

Although it is the most cost-effective option, road electrification would require sustained political support to offset the upfront cost and the initially unprofitable operation of charging infrastructure. It would also need public support, high fleet participation and utilization, and international coordination. All scenarios require broad support but could be implemented, to some degree, in a modular and incremental way, focusing on one region, with one or several fuel production facilities and refueling stations and several nearby routes at a time.

IV. ANALYSIS OF EMISSIONS IMPACTS

VEHICLE TECHNOLOGY GREENHOUSE GAS EMISSIONS

To gain an understanding of the emissions impacts of the various tractor-trailer technologies, we analyze the lifecycle greenhouse gas emissions for each technology for a truck purchased in 2015 through 2030. In addition to the assumptions used above in the cost ownership analysis, we include the upstream fuel cycle emission impacts associated with the production of the various fuel. We apply the carbon intensities of diesel, natural gas, and hydrogen for 2015 from California's Low Carbon Fuel Standard (LCFS) across all regions.

Table 8 shows the assumed fuel carbon intensities that we apply to our lifecycle analysis. Carbon intensities for diesel and natural gas are assumed to remain constant from 2015 through 2030, whereas the carbon intensity of hydrogen is expected to decrease significantly as hydrogen transitions from being produced mainly from fossil fuels through steam-methane reformation to being produced from renewable energy sources. For hydrogen's carbon intensity, we assume a 5% annual reduction based on continued policy to ensure that fuel supply was low carbon. The carbon intensity of electricity is based on the IEA WEO 2015 electricity assumptions for each of the respective regions and similarly assumes sustained efforts to decarbonize (i.e., their 2°C climate stabilization scenario). We note that there are many regions (e.g., Norway and Québec) where the electricity carbon intensity is already near zero, as a result of electricity generation predominantly coming from renewable energy sources. In such cases, electric vehicle applications offer over a 95% reduction in carbon emissions.

Table 8. Fuel carbon intensities (gCO₂e/MJ) for 2015 and 2030 and the percent reduction in emissions from 2015 to 2030.

Fuel	Region	Fuel carbon intensity (gCO ₂ e/MJ)		Greenhouse gas emission reduction in 2030*
		2015	2030	
Diesel	All	102	102	-
Compressed natural gas	All	81	81	-
Liquefied natural gas	All	86	86	-
Hydrogen	All	151	70	54%
Electricity	United States	144	49	66%
	Europe	101	44	57%
	China	202	82	60%

*Greenhouse gas emission reduction includes on-vehicle efficiency improvement (i.e., relative MJ per kilometer)

The total lifecycle wheel-to-well greenhouse gas emissions in carbon dioxide equivalents (CO₂e) for each long-haul heavy-duty freight truck technology for tractor-trailers purchased in 2015 through 2030 are shown in Figure 6. The three panes represent the unique assumptions and characteristics (e.g., vehicle efficiency, annual vehicle travel activity over vehicle life) for the trucks purchased and operated in China, Europe, and the U.S.

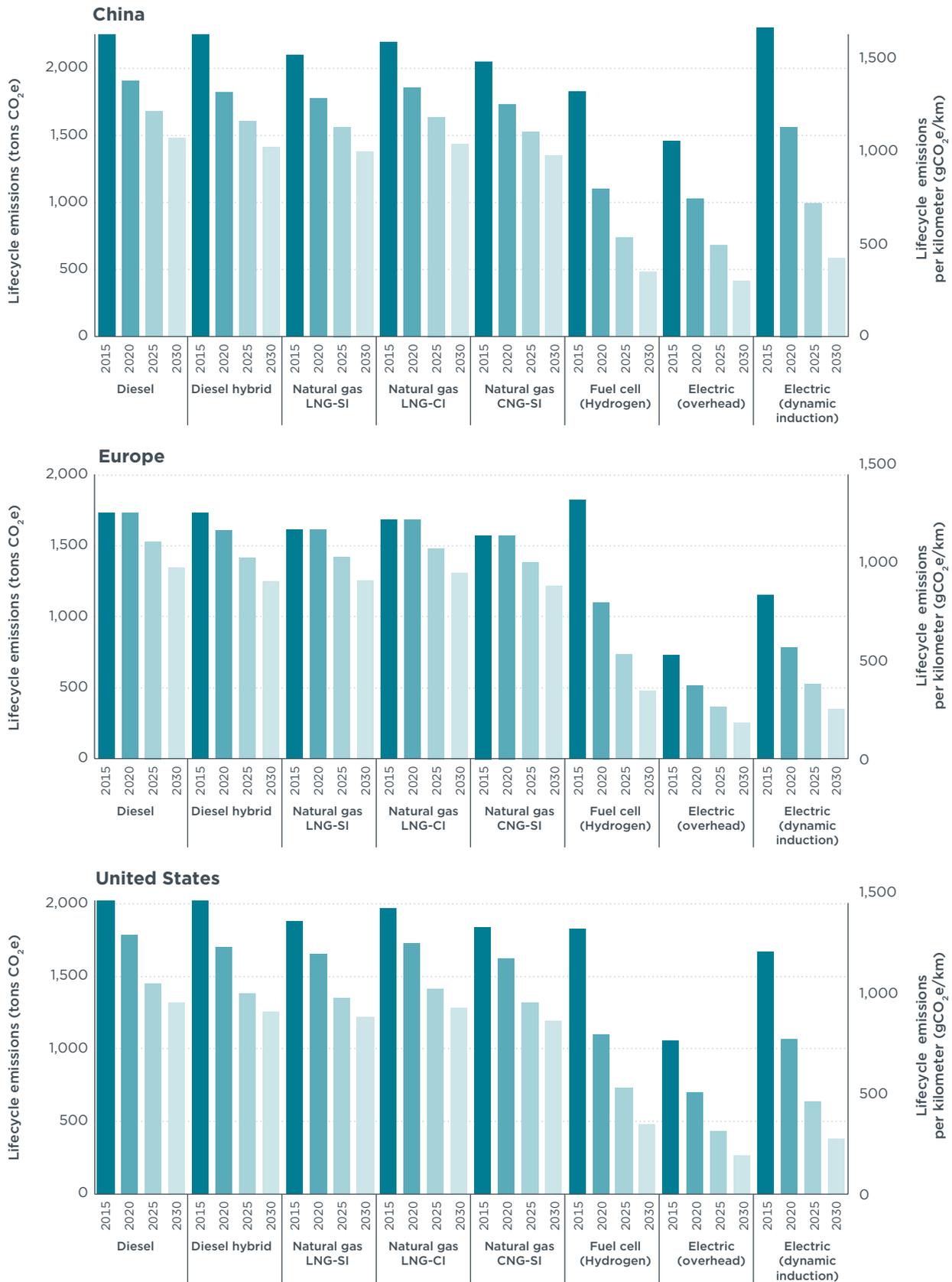


Figure 6. China, Europe, and U.S. lifecycle CO₂ emissions over vehicle lifetime (left axis) and per kilometer (right axis) by vehicle technology type.

Major emission differences across the technologies and over time are apparent from the figure. For 2015, catenary electric vehicles have 35%, 58%, and 48% lower lifetime CO₂e emissions than conventional diesel vehicles in China, Europe, and the U.S., respectively, while fuel cell vehicles have 19%, 5%, and 10% lower emissions. We note that in the case of China, dynamic induction electric vehicles have comparable CO₂e emissions to diesel in 2015 as a result of high grid emissions and reduced efficiency of dynamic grid electric vehicle in comparison to catenary electric, but the emissions significantly decrease over time as the grid decarbonizes. The diesel and natural gas technologies are relatively similar in their CO₂ emission levels. As shown in Figure 6, there is the potential for major reductions in all the vehicle technology types in the 2025–2030 timeframe. In the case of the diesel and natural gas technologies, the emission reductions are driven by efficiency technology on the vehicle. On the electric and fuel cell technologies, the emission reductions are driven primarily by the reduced fuel carbon intensity. The diesel tractor-trailer is shown with greatly reduced carbon intensity, with a 22%–35% reduction from 2015 to 2030. The fuel cell technology results in a 73% reduction in carbon emissions from 2015 to 2030. The catenary and dynamic induction electric vehicle technology show a reduction of 66%–76% and 61%–77%, respectively, by 2030 across the three regions.

Overhead catenary electric heavy-duty trucks have the lowest lifetime emissions in each region. In China, catenary electric trucks deliver a 72% reduction from the 2030 high-efficiency diesel emission level (an 82% reduction from the 2015 diesel baseline). In Europe, the catenary electric truck provides an 81% reduction in emissions as compared with the high-efficiency 2030 diesel truck (an 87% reduction from the 2015 baseline). In the U.S., catenary electric trucks deliver an 80% reduction over the high-efficiency 2030 diesel (an 88% reduction from the 2015 baseline). The emission benefits from the hydrogen fuel cell technology cases were also very substantial: The CO₂ reductions were 62%–67% as compared with the 2030 high-efficiency diesel (73%–78% reduction from the 2015 baseline diesel).

FLEET LEVEL IMPACTS OF ZERO-EMISSION TRUCK PENETRATION

To further inform the question about how zero-emission trucks could contribute toward climate change goals, we conducted a narrower analysis of the penetration of zero-emission trucks in one particular market—Europe. As indicated earlier, many of the details of the above vehicle cost analysis are uncertain, and the analysis is driven by a series of assumptions without firm real-world data. Beyond questions about the cost and necessary infrastructure and energy supply deployment, the future penetration of the technologies is even more uncertain because it is dependent on many industry, government, and market factors. Yet, we provide an illustrative, first-order analysis of fleet emissions to assess the potential impact of greater deployment electric-drive heavy-duty vehicle technologies if the prevailing technology and institutional barriers are overcome.

The broader context for long-term climate scenarios is the Paris climate agreement, signed by nearly every nation, which establishes the goal of limiting the increase in global average temperatures to below 2°C above the pre-industrial temperature. The leaders of the European Union adopted the 2030 climate and energy framework in 2014. The framework sets a binding target for the EU to reduce total greenhouse gas emissions by at least 40% below 1990 levels in 2030 and reduce emissions from transportation by 30% relative to 2005 levels by 2030 (European Commission, 2017a). The European Commission created the Energy Roadmap 2050 to explore the options of transitioning the energy system to meet the long-term goals of cutting emissions 80%–95% from 1990 levels by 2050 in the most

competitive manner while achieving maximum energy security (European Commission, 2017a, 2017b). The transport sector is required to reduce emissions at least 60% below 1990 levels by 2050 while allowing for increased mobility and a competitive transport sector (European Commission, 2011a, 2011b).

We analyze the impact of the penetration of zero-emission heavy-duty vehicle technologies in the European fleet from 2015 to 2050 to estimate the CO₂ emission impact. Our analysis is focused on the tractor-trailer portion of the heavy-duty fleet. The analysis applies the International Council on Clean Transportation (ICCT) Roadmap vehicle stock-turnover model (see ICCT, 2017). This model simulates advanced technologies being phased into the fleet beginning in 2020 as new vehicles increasingly take over larger fractions of freight activity through 2050, whereas older vehicles' activity decreases over time until they are eventually retired from the fleet. The vehicle stock-turnover model provides greater perspective on how quickly the climate benefits accrue from transitioning to zero-emission technologies over time.

Figure 7 shows four scenarios for lifecycle CO₂ emissions of tractor-trailers in Europe, reflecting varying technology penetrating the new vehicle fleet from 2020 through 2050. The first scenario is the base case, which assumes the entire European tractor-trailer fleet remains completely composed of internal combustion engine vehicles powered by diesel fuel without adopting additional efficiency standards that promote greater efficiency. The second scenario assumes that efficiency standards are implemented, leading to advanced diesel efficiency improvements based on the best available technology. We include two zero-emission vehicle scenarios, with each reflecting the possibility that one technology becomes the leading technology over time, while the other remains in more niche applications in the fleet. The two zero-emission vehicle scenarios build upon the diesel efficiency improvements (i.e., all the scenarios other than the base case include the diesel improvements). The fuel cell-intensive scenario has initial fuel cell tractor-trailer sales starting in 2020 and ramping up to reach 50% of the sales share in 2050, and overhead catenary electric tractor-trailer sales starting in 2020 and reaching 15% of the sales share in 2050. The final electric-intensive scenario has electric sales starting in 2020 and ramping up to 50% of the sales share in 2050, and fuel cells starting in 2020 and reaching 15% in 2050.

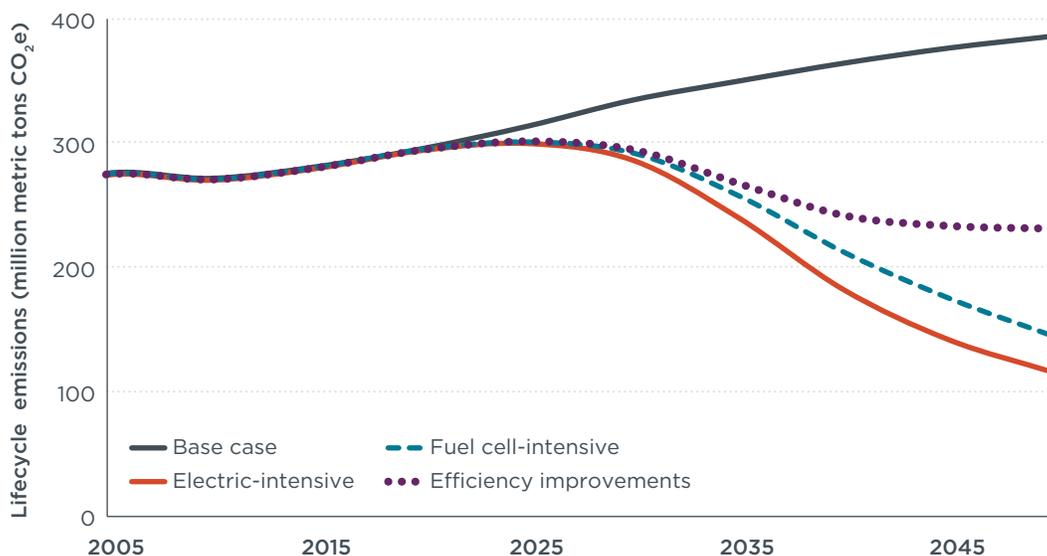


Figure 7. Lifecycle CO₂e emissions from Europe heavy-duty tractor-trailer fleet from 2015–2050, with base case, efficiency improvements, fuel cell-intensive, and electric-intensive scenarios.

Table 9 summarizes several key greenhouse gas emission results from the vehicle deployment scenarios shown in Figure 7. Under the base case, the lifecycle emissions are estimated to increase approximately 38% from 2015 to 2050, from 281 to 386 million metric tons of CO₂e. With incremental diesel efficiency technology improvements linked to efficiency standards (but without any zero emission vehicles) in the fleet from 2015 to 2050, CO₂ emissions in the 2050 fleet would decrease by 156 million tons—a 40% reduction from the base case in 2050. As shown in the efficiency scenario, CO₂ emissions begin to flatline after 2035, as the incremental efficiency gains slow and freight activity continues to increase. For the fuel cell-intensive scenario, emissions are estimated to peak around 2025 at 300 million metric tons of CO₂e and proceed to decrease through 2050, resulting in a 63% reduction in emissions relative to the base case in 2050. Finally, for the electric-intensive scenario, emissions are expected to peak around 2025 at 300 million metric tons of CO₂e and proceed to decrease through 2050, resulting in a 70% reduction in emissions relative to the base case in 2050.

Table 9. GHG emissions from EU tractor-trailers for baseline, fuel cell vehicle-intensive, and electric vehicle-intensive scenarios for 2050, with associated change in emissions

Scenario	Emissions by year (million ton CO ₂ e)			Change in emissions	
	2005	2015	2050	2015 to 2050	From 2050 base case
Base case	275	280	386		
Increased efficiency	275	280	230	-18%	-40%
Fuel cell intensive	275	280	145	-48%	-63%
Electric intensive	275	280	115	-59%	-70%

Both scenarios with substantial penetration of zero-emission vehicle technologies show substantial reduction in emissions relative to the base scenario and their overall CO₂ emissions in absolute terms. The fuel cell-intensive case results in 47% lower emissions in 2050 than in 2005. The electric-intensive case would cut emissions by 58%. Therefore, these scenarios underscore the great challenge at hand to decarbonize heavy-duty freight emissions. Advanced diesel efficiency technology and greatly accelerated penetration of zero emission vehicles will be required to achieve the 30% CO₂ emission reduction from the heavy-duty vehicle sector in 2030 and 60% reduction by 2050 relative to 2005 levels, as targeted by the European Commission.

Several recent analyses also help to estimate the potential and the implications for greater penetration of advanced heavy-duty vehicle electric drive technologies. A European Union analysis indicates that nearly 40% of highways could be electrified with overhead electric lines, up to 90% of new long-haul tractor-trailers could be electric, and up to 34% of heavy-goods vehicle activity could be powered by electric vehicles by 2050 (Ministry of the Environment, Energy, and Sea, 2016; Transport & Environment, 2016). A Germany-focused study on the increasing role of transport electrification includes a scenario for up to 80% tractor-trailer activity being powered by overhead catenary systems by 2050 (Renewbility, 2016). The IEA assesses technologies and freight-system improvements to decarbonize freight trucks and illustrates the importance of electrification to achieve deep carbon cuts (IEA, 2017). Essentially all of these studies agree with our findings that developing electric-drive pathways is key to being able to substantially decarbonize heavy-duty vehicles.

V. FINDINGS AND CONCLUSIONS

Decarbonizing heavy-duty vehicle activity by transitioning to zero-emission vehicle technologies, including electricity and hydrogen technologies, presents an immense challenge. Yet, there are many promising technologies that have been demonstrated and announced that prove the technical viability and suggest how these technologies could eventually be deployed on a large scale. Mass deployment of zero-emission vehicles can enable greater impact on reducing emissions and energy use, while helping to enable more renewable energy use. The ongoing zero-emission truck projects around the world in 2017 inform the vision forward on where the sector can go if motivated governments and companies act to deploy the technology beginning in 2020.

Table 10 summarizes our findings regarding the potential benefits, prevailing barriers to widespread adoption, and the relatively promising market segments for various zero-emission technologies for heavy-duty freight vehicles. The table summarizes findings for the three main technology areas that were analyzed: plug-in battery electric, dynamic electric charging (catenary or in-road), and hydrogen fuel cell vehicles. Each technology offers the prospect of lower climate emissions, no tailpipe pollutant emissions, lower fueling cost, greater renewable energy use, and higher on-vehicle energy efficiency.

Table 10. Summary of promising segments, benefits, and barriers for zero-emission heavy-duty freight vehicle technologies

Technology	Benefits	Prevailing barriers to widespread viability	Promising segments for widespread commercialization
Electric (plug-in)	<ul style="list-style-type: none"> • Reduce greenhouse gas emissions • Eliminate local air pollution • Reduce fueling costs • Reduce maintenance costs • Increase energy efficiency • Increase renewable energy use 	<ul style="list-style-type: none"> • Limited electric range • Vehicle cost (battery) • Charging time (unless battery swapping is utilized) • Cargo weight and size 	<ul style="list-style-type: none"> • Light commercial urban delivery vans • Medium-duty regional delivery trucks • Refuse trucks
Electric (catenary or in-road charging)	<ul style="list-style-type: none"> • Reduce greenhouse gas emissions • Eliminate local air pollution • Reduce fueling costs • Reduce maintenance costs • Increase energy efficiency • Increase renewable energy use • Enable regional travel 	<ul style="list-style-type: none"> • Infrastructure cost • Standardization across regions • Complete infrastructure network before vehicle deployment • Visual obstruction (catenary) 	<ul style="list-style-type: none"> • Medium-duty trucks and heavy-duty tractor-trailers on medium-distance routes with high freight use • Drayage trucks around ports
Hydrogen fuel cell	<ul style="list-style-type: none"> • Reduce greenhouse gas emissions • Eliminate local air pollution • Increase energy efficiency • Enable quick refueling time • Increase renewable energy use 	<ul style="list-style-type: none"> • Refueling infrastructure cost • Renewable hydrogen cost • Vehicle costs (fuel cell) 	<ul style="list-style-type: none"> • Heavy-duty tractor-trailers in long-haul operation • Drayage trucks around ports

The zero-emission vehicle technologies do present considerable challenges. They have a combination of near- and long-term barriers, issues, and questions that will have to be addressed before they can become widespread replacements for conventional trucks

and tractor-trailers that are typically diesel fueled. These challenges are somewhat different for the three different zero-emission vehicle technologies. As a result, the three technologies have different truck segments for which they offer the most promise for widespread commercialization, based on our assessment in 2017. We emphasize the high uncertainty in how these technologies could evolve over the long-term for 2030 and beyond. With sustained government and private industry investment, each of these various electric-drive technologies has the potential to overcome the various barriers faster than the others. Considering the vast scale of the problem of decarbonizing freight transport, it appears likely that many of the battery and fuel cell technologies will need to grow in parallel to meet medium- and long-distance freight demands as soon as they prove themselves.

The key barriers for plug-in battery electric vehicles include meeting the various freight vehicle specifications for daily travel range, initial vehicle cost, charging time, and maintaining vehicle cargo weight and volume capacity. The applications of light commercial urban vans, medium-duty regional vans, and other local vocational trucks (e.g., refuse trucks) offer higher potential for battery electric vehicles because they are more likely to have local usage and fleet operations that downplay or minimize the near-term technology limitations. Battery-swapping technology, although now only used in a couple isolated applications, has the potential to largely eliminate the charging time issue; however, it was not analyzed here due to lack of available information. Vehicles in urban delivery operation that offer a shorter radius from their base location, lower daily distances, less volume and mass constraints for cargo, and recharge in just one or two locations are suited for plug-in electric trucks. Many such vehicles are in local city government operations, short-distance urban cargo delivery, electric power utility service vehicles, and other applications in every major city. Several major automakers are adapting their electric car technology for light-commercial vans. The Deutsche Post StreetScooter is a recent example of the commercialization of electric truck technology for urban settings. Tesla's announced battery electric semi-tractor prototype is the only battery electric project we found in our assessment targeting long-haul heavy-duty applications without dynamic charging.

Electric vehicles that are dynamically charged—via overhead catenary transmission, on-road conductive tracks, or in-road inductive wireless charging—could play an important role in unlocking more potential advantages and market options for electric trucks. Dynamically charged trucks on dedicated e-roads could be implemented on a regional basis in a way that greatly reduces the battery electric truck barriers of battery cost, weight, size, and range. However, the dynamic electric truck charging systems have high infrastructure costs, for which only very early cost estimates are available. They also present an issue of needing some standardization of truck technology and infrastructure systems across regions (e.g., multiple countries in Europe) to be able to span long distance routes. Based on these technologies' relative advantages and barriers, promising applications include medium-duty trucks and heavy-duty tractor-trailers on short- and medium-distance routes with high freight use. This approach would require major infrastructure investments and could be rolled out initially on high-freight-traffic corridors, for examples for drayage trucks around shipping ports with key distribution to cities within several hundred miles. Examples of this technology already exist. Trolleybuses powered by overhead catenary wires are deployed in hundreds of cities worldwide, and prominent research projects in Germany and Sweden are demonstrating the technology for freight applications.

Hydrogen fuel cell heavy-duty vehicles could play a key role for low-carbon freight transport in several applications. As noted by the limitations above, an especially important opportunity for fuel cells is in applications for which plug-in and dynamic charging is difficult practically or from a cost perspective. Hydrogen fuel cell technology offers much faster refueling times compared with electric charging times, and this is of great importance to many truck fleets that cannot accommodate additional downtime within their freight activity patterns. The technology also offers the potential for much greater range from hydrogen than battery electric trucks with similar specifications. Especially strong potential is in urban fleets, where governments have prioritized hydrogen infrastructure deployment, and for long-haul tractor-trailer fleets with routes around and between those cities. A key challenge for fuel cells is in their fuel supply, specifically moving toward renewable hydrogen fuel supply, which is simultaneously lower carbon and lower cost. Perhaps the most prominent such projects in 2017 are the in-development Nikola and Toyota fuel cell hydrogen tractor-trailer demonstrations.

Based on the research analytical results and qualitative assessment of projects around the world, we close with several summary conclusions regarding emerging zero-emission technologies for heavy-duty vehicles.

First, we find that electric-drive technologies for heavy-duty vehicles will be essential to decarbonize the transport sector. Heavy-duty freight trucks are disproportionate contributors to pollution, with less than one tenth of all vehicles but roughly 40% of their carbon emissions, and their activity keeps growing. Electric-drive technologies, similar to those being commercialized in passenger cars, will be essential to decarbonize the heavy-duty sector and help meet climate stabilization goals. While the more efficient diesel technologies can reduce carbon emissions by about 40%, electric-drive technologies powered by renewable sources can achieve over an 80% reduction in lifecycle emissions. These technologies can be phased into the fleet through 2050. However, our analysis indicates that these technologies will be insufficient to achieve decarbonization of heavy-duty vehicles by 2050. This is largely a result of how long it takes the fleet to turn over as high-emission trucks are slowly retired over time. Decarbonization will also likely require broader freight sector strategies, including modal shift, logistics improvements, and demand management approaches.

Second, even though these electric-drive heavy-duty truck technologies are in their relative infancy in 2017, by 2030 these technologies are likely to offer cost-effective opportunities for deep emission reductions. Major projects involving heavy-duty electric and hydrogen fuel cell technologies show great potential as a result of their much greater efficiency and available low-carbon fuel sources. Compared with diesel heavy-duty vehicles in the approximate 2030 timeframe, when infrastructure costs are excluded, we find that overhead catenary results in 25%–30% lower costs, in-road induction results in 15%–25% lower costs, and hydrogen fuel cells result in 5%–30% lower costs to own, operate, and fuel. Key drivers for cost-effectiveness are battery pack costs dropping to below \$150 per kilowatt-hour and hydrogen fuel costs dropping to below the per-energy-unit cost of diesel (i.e., below \$4 per kilogram), as well as the deployment of supporting infrastructure. Beyond these cost-effectiveness considerations, any low-emission technology will have to prove that it meets the same utility, reliability, and safety demands as conventional combustion technologies.

Third, we find that different electric-drive technologies are suitable for different heavy-duty vehicle segments, but simultaneous massive infrastructure investments will be

needed for each of them. Advances in battery packs and other electrical components will enable shorter distance urban commercial vans to become plug-in electric, similar to passenger cars. By eliminating battery weight and volume constraints, overhead catenary or dynamic inductive grid technologies can enable electric zero-emission goods transport on and around heavily traveled freight corridors. Hydrogen fuel cell technology might be especially key for longer distance duty cycles. Both of these technologies will require sustained investments by government and industry. Electric highways will require extensive charging (at central stations, with overhead transmission, or inductive road charging). Investments in low-carbon and low-cost hydrogen pathways and refueling infrastructure will have to be made in parallel with vehicle technology advances.

Beyond this report's scope, there is the larger question about how to strategically develop a balanced freight system that includes the right mix of many technologies, including battery electric and fuel cells, in a system that develops over time. Eventually, in the 2020–2030 timeframe, governments and industry leaders will have to make more discrete decisions about infrastructure to serve various technologies of particular vehicle types (medium- and heavy-duty) and freight applications (medium- and long-distance). As technology solutions emerge, questions about how best to sequence the rollout of infrastructure in advance of vehicle deployment, and avoid technology lock-in or stranded assets, will become more important. For the next 5 years, there is minimal such risk, because the technologies analyzed here are all in research, exploratory, and early demonstration phases. Analyzing the expanding and evolving infrastructure systems from a longer term strategic perspective remains a rich area for future research. Studies like this and others (see IEA [2017] and Transport & Environment [2016]) will continue to help inform strategic policy development as technologies evolve.

Based on these conclusions, the challenge for decarbonizing freight transport is becoming clear. To stabilize global temperatures, many developed countries have set the goal of reducing greenhouse gas emissions 80% from 1990 levels by 2050. Efficiency improvements will be of great importance but transitioning to zero-emission vehicles and fuels will be required to achieve greenhouse gas emission reduction targets. To achieve such a transition, a large variety of policy actions will be needed to increase heavy-duty sector efficiency and advance the low-carbon fuel options. Government policies, incentives, and investments will be needed to help offset the increased technology costs until the costs are competitive with conventional vehicle technologies, as well as to set clear expectations for industry investments.

For the near term, the continued and strengthened promotion for drayage, bus, and urban delivery truck applications are important to identify the most appealing business cases for electric-drive trucks. The lessons learned from the uptake of zero emission vehicles in these heavy-duty applications and the resulting reduction in overall technology costs will help to ease the transition in the more demanding long-haul applications. While we are learning from these early projects, government-backed investments in infrastructure give fleets and manufacturers the confidence to more heavily invest in the development, production, and deployment of zero-emission heavy-duty vehicle technologies. The case of California's continued support for zero-emission buses is instructive. The state and local bus agencies continued to feed both hydrogen and electric buses with sustained infrastructure and incentives over the past decade, and now electric buses are demonstrating success and the potential become self-sustaining.

Governments have been acting in key ways to help spur this progress. Simultaneously exploring the bigger, bolder, and infrastructure-intensive options like hydrogen fuel cells and dynamic electric charging in major freight regions is necessary to better understand the costs, benefits, and viability of these technology options for widespread applications. Using available resources, for example from the Volkswagen settlement mitigation funding, for such infrastructure or demonstration projects would certainly be warranted. Key roles for governments are in setting a clear vision, making initial investments in the key technologies, and encouraging further industry development of the ultimate solutions (e.g., Brown, 2016). Because of the complexity of the freight sector, it seems highly likely that a mix of many technologies, likely including plug-in, charging systems, and fuel cells, will ultimately be needed for long-term decarbonization.

REFERENCES

- Akerman, P. (2016) eHighway Electrified heavy duty road transport. Siemens. Retrieved from https://www.iea.org/media/workshops/2016/thefutureoftrucks/7_Akerman_PA_eHighway_IEA_JRC_workshop.pdf
- Appel, F. (2013, May 21). Working together for climate protection. Deutsche Post DHL Group. Retrieved from <https://delivering-tomorrow.com/working-together-for-climate-protection/>
- Association of Electric Vehicles Québec (AVEQ) (2017, May 27). Le transport par camion léger: un beau créneau pour l'électrification. Retrieved from <http://www.aveq.ca/actualiteacutes/le-transport-par-camions-legers-un-beau-creneau-pour-lelectrification>
- BMW Group (2015, July 6). Travel through Munich in a vehicle that is 100% electric, clean and quiet. The BMW Group and SCHERM Group officially put an electric truck into service. Launch event with Bavaria's Minister for Economic Affairs, Ilse Aigner. Retrieved from <https://www.press.bmwgroup.com/global/article/detail/TO224983EN/travel-through-munich-in-a-vehicle-that-is-100-electric-clean-and-quiet-the-bmw-group-and-scherm-group-officially-put-an-electric-truck-into-service-launch-event-with-bavaria%E2%80%99s-minister-for-economic-affairs-ilse-aigner?language=en>
- Bradley, G. (2016, September 8). Green trash: NZ thinks big with electric rubbish trucks. NZ Herald. Retrieved from http://www.nzherald.co.nz/business/news/article.cfm?c_id=3&objectid=11705404
- Brown, E. G. Jr. (Governor of California). (2016, July) California Sustainable Freight Action Plan. Retrieved from http://www.casustainablefreight.org/documents/Main%20Document_FINAL_07272016.pdf
- Bundesministerium für Umwelt, Naturschutz, Bau and Reaktorsicherheit (BMUB). (2016a). BEAR. Batterieelektrische Abfallentsorgung mit Roboterunterstützung. Retrieved from <http://www.erneuerbar-mobil.de/projekte/bear>
- Bundesministerium für Umwelt, Naturschutz, Bau and Reaktorsicherheit (BMUB). (2016b). CitE-Truck. Retrieved from <http://erneuerbar-mobil.de/projekte/cite-truck>
- Bundesministerium für Umwelt, Naturschutz, Bau and Reaktorsicherheit (BMUB). (2016c). CO₂ GoGreen. Testing e-mobility in fleets—CO₂ free delivery in Bonn. Retrieved from <http://www.erneuerbar-mobil.de/projekte/co2-gogreenmobil.de/projekte/bear>
- Bundesministerium für Umwelt, Naturschutz, Bau and Reaktorsicherheit (BMUB). (2016d). ELANO. Elektrisch angetriebene Nutzfahrzeuge an Oberleitungen. Retrieved from <http://www.erneuerbar-mobil.de/projekte/elano>
- Bundesministerium für Umwelt, Naturschutz, Bau and Reaktorsicherheit (BMUB). (2016e). ENUBA. Elektromobilität bei Schweren Nutzfahrzeugen zur Umweltentlastung von Ballungsräumen. Retrieved from <http://www.erneuerbar-mobil.de/projekte/enuba>
- Bundesministerium für Umwelt, Naturschutz, Bau and Reaktorsicherheit (BMUB). (2016f). ENUBA 2. Elektromobilität bei schweren Nutzfahrzeugen zur Umweltentlastung von Ballungsräumen. Retrieved from <http://www.erneuerbar-mobil.de/projekte/enuba-2>
- Bundesministerium für Umwelt, Naturschutz, Bau and Reaktorsicherheit (BMUB). (2016g). Terminal truck. Retrieved from <http://erneuerbar-mobil.de/projekte/terminal-truck>

- Bundesministerium für Umwelt, Naturschutz, Bau and Reaktorsicherheit (BMUB). (2017a). Elektromobile Nutzfahrzeuge wirtschaftlich und nachhaltig einsetzen. Retrieved from <http://erneuerbar-mobil.de/projekte/en-win>
- Bundesministerium für Umwelt, Naturschutz, Bau and Reaktorsicherheit (BMUB). (2017b). Feldversuche Oberleitungs-LKW in Hessen und Schleswig-Holstein. Retrieved from http://www.bmub.bund.de/fileadmin/Daten_BMU/Download_PDF/Verkehr/feldversuche_o_lkw_bf.PDF
- Burnham, A. (2016, May). User Guide for AFLEET Tool 2016. Argonne National Laboratory. Retrieved from https://greet.es.anl.gov/afleet_tool
- BYD. (2016, June 10). State to award \$9 million for zero-emission trucks at two rail yards, one freight transfer yard in Southern California. Retrieved from <http://www.byd.com/usa/news-posts/state-to-award-9-million-for-zero-emission-trucks-at-two-rail-yards-one-freight-transfer-yard-in-southern-california/>
- California. (2016). California sustainable freight action plan. Retrieved from http://www.casustainablefreight.org/documents/PlanElements/FINAL_07272016.pdf
- California Air Resources Board (CARB). (2015a, November). Draft technology assessment: Medium- and heavy-duty battery electric trucks and buses. California EPA. Retrieved from https://www.arb.ca.gov/msprog/tech/techreport/bev_tech_report.pdf
- California Air Resources Board (CARB). (2015b, November). Draft technology assessment: Medium- and heavy-duty fuel cell electric vehicles. California EPA. Retrieved from https://www.arb.ca.gov/msprog/tech/techreport/fc_tech_report.pdf
- California Air Resource Board (CARB). (2015c, June 23). 2014–2015 grant solicitation. Air Quality Improvement Program and Low Carbon Transportation Greenhouse Gas Reduction Fund (GGRF) investments. Advanced technology freight demonstrations: Zero-emission drayage truck project. Mobile Source Control Division of California Air Resources Board. Retrieved from <https://www.arb.ca.gov/msprog/aqip/solicitations/msc1516solicit.pdf>
- California Air Resource Board (CARB). (2015d, October 1). Grant solicitation. Air Quality Improvement Program and Low Carbon Transportation Greenhouse Gas Reduction Fund (GGRF) investments. Zero-emission truck and bus pilot commercial deployment projects. Retrieved from <https://www.arb.ca.gov/msprog/aqip/solicitations/msc1524solicit.pdf>
- California Air Resource Board (CARB). (2016a, March 16). Zero-emission truck and bus pilot commercial deployment project applications. Retrieved from <https://www.arb.ca.gov/msprog/aqip/solicitations/tbpilotsumms.pdf>
- California Air Resources Board (CARB). (2016b, July 22). Zero-emission truck and bus pilot commercial deployment project selections. Retrieved from https://www.arb.ca.gov/msprog/aqip/solicitations/zetbpilot_prelim_selections.pdf
- California Air Resources Board (CARB). (2017, March 9). First of 27 electric trucks coming to Southern California freight and rail yards. Retrieved from <https://www.arb.ca.gov/newsrel/newsrelease.php?id=900>
- Center for Transportation and the Environment (CTE). (2016). CTE activity map. Retrieved from <http://www.cte.tv/projects-map/>

- Chandler, S., Espino, J., & O’Dea, J. (2016, October). Delivering opportunity: How electric buses and trucks can create jobs and improve public health in California. Union of Concerned Scientists and Greenlining Institute. Retrieved from <http://www.ucsusa.org/sites/default/files/attach/2016/10/UCS-Electric-Buses-Report.pdf>
- Connolly, D. (2016). eRoads: A comparison between oil, battery electric vehicles, and electric roads for Danish road transport in terms of energy, emissions, and costs. Aalborg University. Retrieved from http://vbn.aau.dk/files/237844907/David_Connolly_eRoads_2016.pdf
- Daimler. (2016a). Mercedes-Benz: First fully electric truck. Retrieved from <https://www.daimler.com/products/trucks/mercedes-benz/urban-etruck.html>
- Daimler. (2016b). The Mercedes-Benz Urban eTruck: Connectivity meets eMobility. Retrieved from <https://www.daimler.com/products/trucks/mercedes-benz/world-premiere-urban-etruck.html>
- Dalløkken, P. E. (2016, September 13). Askø elektrisk distribusjonsbil. Askø nye lastebil har to tonn batterier mellom akslingene. TU. Retrieved from <https://www.tu.no/artikler/askos-nye-lastebil-har-to-tonn-batterier-mellom-akslingene/351502>
- Davis, S. C., Williams, S. E., & Boundy, R. G. (2016). Transportation Energy Data Book. Edition 35. Retrieved from <http://cta.ornl.gov/data/index.shtml>
- Delgado, O. (2016, July 8). Stage 3 China fuel consumption standard for commercial heavy-duty vehicles. Washington, D.C.: The International Council on Clean Transportation (ICCT). Retrieved from <http://www.theicct.org/china-stage-3-fuel-consumption-standard-commercial-HDVs>
- Delgado, O., Miller, J., Sharpe, B., & Muncrief, R. (2016, November). Estimating the fuel efficiency technology potential of heavy-duty trucks in major markets around the world. Global Fuel Economy Initiative. Washington, D.C.: The International Council on Clean Transportation (ICCT). Retrieved from <http://www.globalfueleconomy.org/media/404893/gfei-wp14.pdf>
- Delgado, O. & Muncrief, R. (2015, July). Assessment of heavy-duty natural gas vehicle emissions: Implications and policy recommendations. Washington, D.C.: The International Council on Clean Transportation (ICCT). Retrieved from <http://www.theicct.org/assessment-heavy-duty-natural-gas-vehicle-emissions-implications-and-policy-recommendations>
- den Boer, E., Aarnink, S., Kleiner, F., & Pagenkopf, J. (2013, July). Zero emission trucks. An overview of state-of-the-art technologies and their potential. CE Delft. Retrieved from http://www.theicct.org/sites/default/files/publications/CE_Delft_4841_Zero_emissions_trucks_Def.pdf
- Die Bundesregierung & Government of Sweden (2017, January 31). Innovation and cooperation for a sustainable future. A German & Swedish partnership for innovation. Retrieved from <http://www.regeringen.se/490ab0/contentassets/a8f2545e3b6147ed8050ba060d8123c3/innovation-and-cooperation-for-a-sustainable-future.pdf>
- Electric Green Last Mile. (eGLM) (2017). Retrieved from <https://www.eglm.eu/>
- Electric Vehicles International (EVI). (2011, August 11). EVI and UPS announce the purchase of 100 zero-emission, all-electric, delivery vehicles. Retrieved from http://www.evi-usa.com/LinkClick.aspx?fileticket=WBadW_fSxM0%3D&tabid=80

- Elonroad. (2016). What if All traffic goes electric. Retrieved from <http://elonroad.com/>
- EMOSS. (2016). Eight e-Trucks complete Hytruck project. Retrieved from <http://www.emoss.biz/news/eight-e-trucks-complete-hytruck-project/>
- Eudy, L. Post, M., & Jeffers, M. (2016). Fuel Cell Buses in U.S. Transit Fleets: Current Status 2016. National Renewable Energy Laboratory. Retrieved from <https://www.nrel.gov/docs/fy17osti/67097.pdf>
- European Alternative Fuels Observatory (2017). E-bus city overview. <http://www.eafo.eu/vehicle-statistics/buses/cities>
- European Commission. (2011a). Energy roadmap 2050 impact assessment. Retrieved from https://ec.europa.eu/energy/sites/ener/files/documents/sec_2011_1565_part1.pdf
- European Commission. (2011b). Roadmap to a single European transport area—Towards a competitive and resource efficient transport system. Retrieved from <http://eur-lex.europa.eu/legal-content/EN/ALL/?uri=CELEX:52011DC0144>
- European Commission. (2017a). 2030 climate & energy framework. Retrieved from https://ec.europa.eu/clima/policies/strategies/2030_en
- European Commission. (2017b). 2050 energy strategy. Retrieved from <https://ec.europa.eu/energy/en/topics/energy-strategy-and-energy-union/2050-energy-strategy>
- Eurostat. (2017a, May 5). Gas prices for industrial consumers—bi-annual data (from 2007 onwards). Retrieved from <http://appsso.eurostat.ec.europa.eu/nui/submitViewTableAction.do>
- Eurostat. (2017b, May 8). Electricity prices for industrial consumers—bi-annual data (from 2007 onwards). Retrieved from <http://appsso.eurostat.ec.europa.eu/nui/submitViewTableAction.do>
- EV Sales (2017a). China buses and batteries 2016. Retrieved from <http://ev-sales.blogspot.pt/2017/01/china-buses-2016.html>
- EV Sales (2017b). China PHEV buses 2016. Retrieved from <http://ev-sales.blogspot.com/2017/02/china-phev-buses-2016.html>
- FREVUE. (2017a). Testing electric trucks in beverage distribution—Amsterdam & Rotterdam. Retrieved from <http://frevue.eu/demonstrators/testing-electric-trucks-in-beverage-distribution/>
- FREVUE. (2017b). Electric logistics in parcel services UPS—Rotterdam. Retrieved from <http://frevue.eu/demonstrators/electric-logistics-in-parcel-services-ups/>
- FREVUE. (2017c). Overcome grid restrictions to electric vehicles charging and roll-out plan for larger fleets Electric logistics—London. Retrieved from <http://frevue.eu/demonstrators/overcome-grid-restrictions-ev-charging-plan-roll-larger-fleets/>
- FREVUE. (2017d). EMOSS truck. Retrieved from <http://frevue.eu/vehicles/emoss-truck/>
- FREVUE. (2017e). Expansion of successful consolidation centre to new end-user types: Regent Street—London. Retrieved from <http://frevue.eu/demonstrators/expansion-of-successful-consolidation-centre-to-new-end-user-types-regent-street/>
- Frito Lay. (2016). Fleet sustainability. Retrieved from <http://www.fritolay.com/purpose/fleet-sustainability>

- Fulton, L., & Miller, M. (2015). Strategies for transitioning to low-carbon emission trucks in the United States. UC Davis and National Center for Sustainable Transportation. Retrieved from <http://ncst.ucdavis.edu/wp-content/uploads/2014/08/06-11-2015-06-11-2015-STEPS-NCST-Low-carbon-Trucks-in-US-06-10-2015.pdf>
- FUSO. (2015). Zero emissions, one hundred percent electric: FUSO Canter E-CELL customer trials completed successfully. Retrieved from <http://www.fuso-trucks.com/fuso-europe/0-1179-1827328-1-1827329-1-0-0-0-1-18022-1578825-0-0-0-0-0-0-0.html>
- Gallo, J. B., & Tomić, J. T. (2013, August). Battery electric parcel delivery truck testing and demonstration. California Hybrid, Efficient and Advanced Truck Research Center (CalHEAT). Retrieved from http://www.calstart.org/Libraries/CalHEAT_2013_Documents_Presentations/Battery_Electric_Parcel_Delivery_Truck_Testing_and_Demonstration.sflb.ashx
- Gladstein, Neandross & Associates. (2012, March 8). Zero-emission catenary hybrid truck market study. South Coast Air Quality Management District. Retrieved from <http://www.gladstein.org/pdfs/ZETECHMarketStudy.pdf>
- Government of Québec. (2016, October 6). Projet mobilisateur en électrification des transports - Québec appuie le développement de quatre véhicules lourds 100% électriques. Retrieved from <http://www.fil-information.gouv.qc.ca/Pages/Article.aspx?aguillage=diffuseurs&listeDiff=45&type=1&idArticle=2410051237>
- Griffin, T. (2016, June). MT017: Medium duty parcel delivery truck. Retrieved from https://www.hydrogen.energy.gov/pdfs/review16/mt017_griffin_2016_o.pdf
- Hall, D., & Lutsey, N. (2017). Emerging best practices for electric vehicle charging infrastructure. Washington, D.C.: The International Council on Clean Transportation (ICCT).
- Hydrogenics. (2015, March 30). Hydrogenics awarded \$4.4 million in projects from the California Energy Commission. Retrieved from <http://www.hydrogenics.com/about-the-company/news-updates/2015/03/30/hydrogenics-awarded-%244.4-million-in-projects-from-the-california-energy-commission>
- International Council on Clean Transportation (ICCT). (2017). Global Transportation Roadmap Model. Washington, D.C.: Author. Retrieved from <http://www.theicct.org/global-transportation-roadmap-model>
- International Energy Agency (IEA). (2015). World Energy Outlook. Retrieved from <http://www.worldenergyoutlook.org/weo2015/>
- International Energy Agency. (2017). The future of trucks: Implications for energy and the environment. Retrieved from <https://www.iea.org/publications/freepublications/publication/TheFutureofTrucksImplicationsforEnergyandtheEnvironment.pdf>
- INTIS. (2016). Wireless power road—the future is wireless! Retrieved from <http://www.intis.de/mobility.html>
- Kasten, P., Mottschall, M., Köppel, W., Degünther, C., Schmied, M., & Wüthrich, P. (2016, November). Erarbeitung einer fachlichen Strategie zur Energieversorgung des Verkehrs bis zum Jahr 2050: Endbericht. Umweltbundesamt (Bundesministeriums für Umwelt, Naturschutz, Bau and Reaktorsicherheit). Retrieved from https://www.umweltbundesamt.de/sites/default/files/medien/377/publikationen/2016-11-10_endbericht_energieversorgung_des_verkehrs_2050_final.pdf
- Kelly, K. (2016). Medium- and heavy-duty vehicle duty cycles for electric powertrains. NREL. Retrieved from <http://www.nrel.gov/docs/fy16osti/66228.pdf>

- Kleiner, F., Özdemir, E. D., Schmid, S. A., Beerman, M., Çatay, B., Moran, B., ..., & Friedrich, H. E. (2015, March). Electrification of transport logistic vehicles: A technoeconomic assessment of battery and fuel cell electric transporter. EVS28. Retrieved from http://www.ieahev.org/assets/1/7/Task27-EVS28paper-Kleiner_et_al-2015.pdf
- La Presse. (2016, April 18). The ambitious plan of Alexandre Taillefer. Retrieved from <http://plus.lapresse.ca/screens/bd19e8f8-dc5b-4789-9a68-Odaa0ee8205b%7CNBK-UgHiLT1H.html>
- Lambert, F. (2017, May 3). Tesla Semi is using ‘a bunch’ of Model 3 electric motors, says Elon Musk. Electrek. Retrieved from <https://electrek.co/2017/05/03/tesla-semi-model-3-electric-motors-elon-musk/>
- Lawrence Berkeley National Laboratory (LBNL). (2014). Key China Energy Statistics 2014. China Energy Group. Retrieved from https://eetd.lbl.gov/sites/all/files/key_china_energy_statistics_2014_online.final_.pdf
- Lee, D.-Y., & Thomas, V. M. (2016, October). Parametric modeling approach for economic and environmental life cycle assessment of medium-duty truck electrification. *Journal of Cleaner Production*, 142, 3300–3321. doi:10.1016/j.jclepro.2016.10.139
- Li, X. (2015, November) Natural gas in China: A regional analysis. University of Oxford. The Oxford Institute for Energy Studies. Retrieved from <https://www.oxfordenergy.org/wpcms/wp-content/uploads/2015/11/NG-103.pdf>
- Löfstrand, S., Hellgren, J., Thulin, N., Engdahl, H., Pettersson, S., Williamsson, J., & Sandoff, A. (2013, April 8). Feasibility of electrifying urban goods distribution trucks. SAE International. Retrieved from <http://papers.sae.org/2013-01-0504/>
- Lutsey, N. (2015). Transition to a global zero-emission vehicle fleet: A collaborative agenda for governments. Washington, D.C.: The International Council on Clean Transportation (ICCT). Retrieved from <http://www.theicct.org/transition-global-zero-emission-vehicle-fleet-collaborative-agenda-governments>
- Lutsey, N. (2017). Integrating electric vehicles within U.S. and European efficiency regulations. Washington, D.C.: The International Council on Clean Transportation (ICCT). Retrieved from <http://www.theicct.org/integrating-EVs-vehicle-CO2-regs>
- Meszler, D., Lutsey, N., & Delgado, O. (2015, April). Cost effectiveness of advanced efficiency technologies for long-haul tractor-trailers in the 2020-2030 time frame. Meszler Engineering Services & The International Council on Clean Transportation (ICCT). Retrieved from http://www.theicct.org/sites/default/files/publications/ICCT_tractor-trailer_tech-cost-effect_20150420.pdf
- Miller, J., & Façanha, C. (2014, August). The state of clean transport policy—A 2014 synthesis of vehicle and fuel policy developments. Washington, D.C.: The International Council on Clean Transportation (ICCT). Retrieved from <http://www.theicct.org/state-of-clean-transport-policy-2014>
- Ministry of the Environment, Energy, and Sea. (2016, July). Projections de la demande de transport sur le long terme. Retrieved from <https://www.ecologique-solidaire.gouv.fr/sites/default/files/Théma%20-%20Projections%20de%20la%20demande%20de%20transport%20sur%20le%20long%20terme.pdf>
- Mohile, S. (2017, July 18). Ashok Leyland and Sun Mobility in alliance to develop electric mobility solutions. Retrieved from <http://www.livemint.com/Industry/GOvg1Ny4omwOSQ8MW0douM/Ashok-Leyland-and-Sun-Mobility-in-alliance-to-develop-electr.html>

- Motiv. (2014, September 16). First all-electric garbage truck in North America, developed by Motiv Power Systems, hits the road in Chicago. Retrieved from <https://motivps.com/pressreleases/>.
- Muncrief, R., & Sharpe, B. (2015, December 1). Overview of the heavy-duty vehicle market and CO₂ emissions in the European Union. Washington, D.C.: The International Council on Clean Transportation (ICCT). Retrieved from http://theicct.org/sites/default/files/publications/ICCT_EU-HDV_mkt-analysis_201512.pdf
- Musk, E. (2016, July 20). Master plan, Part Deux. Tesla Motors. Retrieved from <https://www.tesla.com/blog/master-plan-part-deux>
- Netherlands Enterprise Agency. (2016, January). 5 Years of 'hybrid and electric vehicles' living lab projects. Ministry of Economic Affairs. Retrieved from <https://www.rvo.nl/sites/default/files/2016/05/5%20Years%20of%20Hybrid%20and%20Electric%20Vehicles%20living%20lab%20projects.pdf>
- Nikola. (2016). Retrieved from <https://nikolamotor.com/>.
- Norsk elbilforening. (2017, February 9). Norges første elektriske søppelbil. Retrieved from <http://elbil.no/norges-forste-elektriske-soppelbil/>
- OECD/ITF. (2017). ITF transport outlook 2017. OECD Publishing. <http://dx.doi.org/10.1787/9789282108000-en>
- Phoenix Contact. (2013). Battery swapping for electric buses in Qingdao. Retrieved from https://www.phoenixcontact.com/assets/downloads_ed/local_gb/web_dwl_promotion/5733e.pdf
- Posada, F., Chambliss, S., & Blumberg, K. (2016, February). Costs of emission reduction technologies for heavy-duty diesel vehicles. Washington, D.C.: The International Council on Clean Transportation. Retrieved from <http://www.theicct.org/costs-emission-reduction-tech-hdvs>
- PR Newswire. (2017, June 13). California's first all-electric garbage truck headed to Sacramento, equipped with Motiv all-electric powertrain. Retrieved from <http://www.prnewswire.com/news-releases/californias-first-all-electric-garbage-truck-headed-to-sacramento-equipped-with-motiv-all-electric-powertrain-300472737.html>
- Prohaska, R., Ragatz, A., Simpson, M., & Kelly, K. (2016, June 27-29). Medium-duty plug-in electric delivery truck fleet evaluation. National Renewable Energy Laboratory (NREL). Retrieved from <http://www.nrel.gov/docs/fy16osti/66055.pdf>
- Renault Trucks. (2010, September 24). Maxity Electric: Renault Trucks presents the keys of the first Maxity electric 'zero emission' LCV to Tafanel. Retrieved from <http://www.en.renault-trucks.com/news/004-maxity-electrique.html>
- Renault Trucks. (2015, February 23). The French Post Office and Renault Trucks jointly test a hydrogen-powered truck running on a fuel cell. Retrieved from <http://corporate.renault-trucks.com/en/press-releases/2015-02-23-the-french-poste-office-and-renault-trucks-jointly-test-a-hydrogen-powered-truck-running-on-a-fuel-cell.html>
- Renewbility. (2016, November 21). Endbericht Renewbility III. Bundesministerium für Umwelt, Naturschutz, Bau, und Reaktorsicherheit. Retrieved from www.renewbility.de/wp-content/uploads/2016/11/Endbericht_III.pdf

- Rodriguez, F., Muncrief, R., Delgado, O., & Baldino, C. (2017, May 5). Market penetration of fuel-efficiency technologies for heavy-duty vehicles in the European Union, the United States, and China. Washington, D.C.: The International Council on Clean Transportation (ICCT). Retrieved from <http://theicct.org/market-penetration-HDV-fuel-efficiency-technologies>
- San Joaquin Valley Air Pollution Control District (SJVUAPCD). (2016, June 16). Accept and appropriate \$25,550,900 in cap and trade funds from the California air resources board to implement four zero-emission truck and bus deployment projects in the San Joaquin Valley. Retrieved from http://www.valleyair.org/Board_meetings/GB/agenda_minutes/Agenda/2016/June/final/10.pdf
- Satyapal, S. (2014, March 23). Fuel cell technologies office overview. U.S. Department of Energy. Retrieved from http://www.energy.ca.gov/2014_energypolicy/documents/2014-04-23_workshop/presentations/08_Satyapal_DOE_Fuel_Cell_Technologies_Overview.pdf
- Scania. (2014, March 13). Scania tests next-generation electric vehicles. Retrieved from <https://www.scania.com/group/en/scania-tests-next-generation-electric-vehicles/>
- Scania. (2016, August 18). Scania and Asko test hydrogen gas propulsion. Retrieved from <https://www.scania.com/group/en/scania-and-asko-test-hydrogen-gas-propulsion/>
- Schmied, M., Wüthrich, P., Zah, R., Althaus, H., & Friedl, C. (2015, April). Postfossile Energieversorgungsoptionen für einen treibhausgasneutralen Verkehr in Jahr 2050: Eine verkehrsträger-übergreifende Bewertung. Umweltforschungsplan des Bundesministeriums für Umwelt, Naturschutz, Bau und Reaktorsicherheit. Retrieved from https://www.umweltbundesamt.de/sites/default/files/medien/378/publikationen/texte_30_2015_postfossile_energieversorgungsoptionen.pdf
- Sen, B., Ercan, T., & Tatari, O. (2016, May). Does a battery-electric truck make a difference? — Life cycle emissions, costs, and externality analysis of alternative fuel-powered Class 8 heavy-duty trucks in the United States. University of Central Florida. *Journal of Cleaner Production*, 141, 110–121. doi:10.1016/j.jclepro.2016.09.046
- Sharpe, B., Lutsey, N., Delgado, O., & Muncrief, R. (2016, August 25). U.S. efficiency and greenhouse gas emission regulations for model year 2018-2027 heavy-duty vehicles, engines, and trailers. Washington, D.C.: The International Council on Clean Transportation (ICCT). Retrieved from http://www.theicct.org/sites/default/files/publications/US%20HDV%20Phase%20%20FRM_policy-update_08252016_vF.pdf
- Siemens. (2014, August 6). Siemens tests eHighway system in California. Retrieved from [http://www.siemens.com/press/en/feature/2015/mobility/2015-06-eHighway.php?content\[\]=MO#event-toc-2](http://www.siemens.com/press/en/feature/2015/mobility/2015-06-eHighway.php?content[]=MO#event-toc-2)
- Siemens. (2016a, June 22). World's first eHighway opens in Sweden. Retrieved from [http://www.siemens.com/press/en/feature/2015/mobility/2015-06-ehighway.php?content\[\]=MO](http://www.siemens.com/press/en/feature/2015/mobility/2015-06-ehighway.php?content[]=MO)
- Siemens. (2016b, June 22). eHighway: solution for electrified road freight transport. Retrieved from <http://www.siemens.com/press/pool/de/feature/2016/mobility/2016-06-ehighway/background-ehighway-road-freight-transport.pdf>

- Silver, F., & Brotherton, T. (2013, February). CalHEAT research and market transformation roadmap for medium- and heavy-duty trucks. California Hybrid, Efficient and Advanced Truck Research Center. Retrieved from http://www.calstart.org/Libraries/CalHEAT_2013_Documents_Presentations/CalHEAT_Roadmap_Final_Draft_Publication_Rev_6.sflb.ashx
- Slowik, P. & Lutsey, N. (2016, October). Evolution of incentives to sustain the transition to a global electric vehicle fleet. Washington, D.C.: The International Council on Clean Transportation (ICCT). Retrieved from <http://www.theicct.org/evolution-incentives-electric-transition>
- South Coast Air Quality Management District (SCAQMD). (2014, December 4). Recognize and transfer revenue and execute contracts to develop and demonstrate fuel cell and plug-in hybrid heavy-duty trucks. Retrieved from <http://www.aqmd.gov/docs/default-source/Agendas/Governing-Board/2014/2014-dec5-003.pdf?sfvrsn=2>
- South Coast Air Quality Management District (SCAQMD). (2016a, May 4). State to award \$23.6 million for zero-emission trucks at seaports. Retrieved from <http://www.aqmd.gov/home/library/public-information/2016-news-archives/drayage-trucks>
- South Coast Air Quality Management District (SCAQMD). (2016b, October 7). Recognize revenue, transfer funds, and execute contract to develop and demonstrate fuel cell heavy-duty truck. Retrieved from <http://www.aqmd.gov/docs/default-source/Agendas/Governing-Board/2016/2016-oct7-003.pdf?sfvrsn=5>
- Stütz, S. (2015, March 19). Battery powered vehicles in urban distribution. Fraunhofer IML. Retrieved from http://www.ieahev.org/assets/1/7/Task_27_Workshop_Results.pdf
- Thiruvengadam, A., Thiruvengadam, P., Pradhan, S., Besch, M., Carder, D., & Delgado, O. (2014). Heavy-duty vehicle diesel engine efficiency evaluation and energy audit. Retrieved from <http://www.theicct.org/heavy-duty-vehicle-diesel-engineefficiency-evaluation-and-energy-audit>
- Toyota. (2017, April 19). Toyota opens a portal to the future of zero emission trucking. Retrieved from <http://pressroom.toyota.com/releases/toyota+zero+emission+heavyduty+trucking+concept.htm>
- Transport & Environment. (2016). Roadmap to climate-friendly land freight and buses in Europe. Retrieved from <https://www.transportenvironment.org/publications/roadmap-climate-friendly-land-freight-and-buses-europe>
- TransPower. (2015, March 26). \$16 million in new orders for TransPower trucks and tractors. Retrieved from <http://www.transpowerusa.com/press-releases/16-million-in-new-orders-for-transpower-trucks-and-tractors/>
- United Kingdom (UK) (2017). Low emission freight and logistics trial competition winners announced. Retrieved from <https://www.gov.uk/government/news/low-emission-freight-and-logistics-trial-competition-winners-announced>
- UPS. (2015, October 28). UPS deploys 18 new zero emission electric trucks in Texas. Retrieved from <https://pressroom.ups.com/pressroom/ContentDetailsViewer.page?ConceptType=PressReleases&id=1446039616630-395>
- UPS. (2017). The road to 1 billion miles. Retrieved from https://www.ups.com/media/en/green-fleet-infographic_FINAL2-for-UPS.pdf

- U.S. Energy Information Administration (U.S. EIA). (2017a). Annual Energy Outlook 2017 table: Electricity supply, disposition, prices, and emissions. Retrieved from <http://www.eia.gov/outlooks/aeo/data/browser/#/?id=8-AEO2017®ion=0-0&cases=ref2017&start=2015&end=2050&f=A&linechart=---ref2017-d120816a.63-8-AEO2017&ctype=linechart&sid=ref2017-d120816a.63-8-AEO2017&sourcekey=0>
- U.S. Energy Information Agency (U.S. EIA). (2017b). Annual Energy Outlook 2017 table: Use by sector: Transportation. Retrieved from <https://www.eia.gov/outlooks/aeo/data/browser/#/?id=13-AEO2017®ion=0-0&cases=ref2017&start=2015&end=2050&f=A&inechart=-ref2017-d120816a.19-13-AEO2017&ctype=linechart&sid=ref2017-d120816a.63-8-AEO2017&sourcekey=0>
- U.S. Environmental Protection Agency (U.S. EPA) & U.S. Department of Transportation (U.S. DOT). (2011, August). Final rulemaking to establish greenhouse gas emission standards and fuel efficiency standards for medium- and heavy-duty engines and vehicles. Regulatory impact analysis. Retrieved from <https://nepis.epa.gov/Exe/ZyPDF.cgi/P100EG9C.PDF?Dockey=P100EG9C.PDF>
- U.S. Environmental Protection Agency (U.S. EPA) & U.S. Department of Transportation (U.S. DOT). (2016, August 16). Greenhouse gas emission and fuel efficiency standards for medium- and heavy-duty engines and vehicles—Phase 2. Response to comments for joint rulemaking. Retrieved from <https://www.nhtsa.gov/sites/nhtsa.dot.gov/files/phase2-hd-fuel-efficiency-ghg-response-to-comments.pdf>
- Volvo Group. (2015). The Volvo Group sustainability report 2014: Efficiency. pp. 25. Retrieved from http://www3.volvo.com/investors/finrep/sr14/pdf/SR_2014.pdf
- Volvo Trucks. (2013). The road of tomorrow is electric. Retrieved from <pnt.volvo.com/e/getpdf.aspx?id=15979>
- Waste Management. (2016, September 8). Our move to electric trucks. Retrieved from <https://www.wastemanagement.co.nz/blog/news/our-move-to-electric-trucks>
- Weken, H. & Kroon, R. (2017, March 17). Heavy electric trucks feasible when jointly operated. FIER Automotive & Mobility. Retrieved from <https://www.fier.net/2017/04/10/sharing-makes-heavy-electric-truck-feasible/electric>
- Wolfe, C. (2015, July 7). Houston as a hydrogen haven? New York: Environmental Defense Fund (EDF). Retrieved from <http://blogs.edf.org/texascleanairmatters/2015/07/07/houston-as-a-hydrogen-haven/>
- Wolfram, P., & Lutsey, N. (2016, July 15). Electric vehicles: Literature review technology costs and carbon emissions. Washington, D.C.: The International Council on Clean Transportation (ICCT). Retrieved from <http://www.theicct.org/lit-review-ev-tech-costs-co2-emissions-2016>
- Wood, E., Wang, L., Gonder, J., & Ulsh, M. (2013, September 24). Overcoming the range limitation of medium-duty battery electric vehicles through the use of hydrogen fuel-cells. National Renewable Energy Laboratory. Retrieved from <https://www.nrel.gov/docs/fy14osti/60053.pdf>
- World Bank. (2017). Pump price for diesel fuel (US\$ per liter). Retrieved from http://data.worldbank.org/indicator/EP.PMP.DESL.CD?year_high_desc=true
- Zhao, H., Burke, A., & Zhu, L. (2013). Analysis of Class 8 hybrid-electric truck technologies using diesel, LNG, electricity, and hydrogen, as the fuel for various applications. University of California, Davis. Retrieved from <http://escholarship.org/uc/item/16p4244z - page-2>

ANNEX

Table A1. Commercial medium-duty zero emission vehicles in development or production.

Company	Name	Technology	Current Status	Technology Specifications									Source
				Range (km)	Battery Chemistry	Max Speed (km/hr)	Recharge Time/ Refuel Time	Torque (Nm)	Power output (kW)	Battery kWh (or Hydrogen Storage kg)	Vehicle Gross Weight (ton)	Load Capacity (ton)	
BYD	T5	Electric Class 5 truck	Production	250	FePO4	97	1.5 h	550	150	145	7.3	3.8	BYD (2016b)
BYD	T7	Electric Class 6 truck	Production	200	FePO4	90	1.75 h	550	150	175	11	5.9	BYD (2016c)
Daimler	eCanter	All-electric light-duty truck	Small-scale production	>100	Li-ion		7 h (1 h = 80%)	380	185	70	7.5	4.6	Daimler (2016c)
Daimler Trucks	Canter E-CELL	All-electric light-duty truck	Replaced by the eCanter	>100	Li-ion	90	7 h (1 h)	650	110	48.5	6	3	FUSO (2014)
Deutsche Post DHL Group	StreetScooter Work	Battery electric delivery truck	Production	50-80	Li-ion	120			48	20.4	2.1		Deutsche Post DHL Group (2016)
EFA-S	P80-E	Electric medium-duty delivery truck	Production	80-130	Li-FeYPO4	80	8-10 h	300	91	62	7.5	3.5	EFA-S (2010)
EMOSS	DYNA EV200	Battery electric	Production	160	Li-FeYPO4	85	8 h	700	120	62	7.5	4.6	EMOSS (2016)
EVI	EVI-MD	Battery electric medium-duty truck	Production	145	LiFeMgPO4	105	6-12 h	900	200	99	7.3-10		GreenFleet (2016)
Iveco	Electric Daily 5t	Battery electric delivery truck	Production	90-130	ZEBRA (NaNi/Cl2)	70		300	80	63.6	5	2	Deutsche Post DHL Group (2013)
Motiv Power Systems & Rockport		Electric delivery truck	Production	109-161		97	8 h (2-3 h 50%)	1,200	150	85/106/127	6.6	3.6	Motiv (2016a)
ORTEN & EFA-S	ORTEN E 75 AT	Electric medium-duty truck	Production	100	LiFePO4	80	4 h (22 kW)	1,150	90	72.5	7.5	3.6	ORTEN (2016)
Paneltex		Electric delivery truck	Production	200	LiFePO4					80-120	7.5-11		Paneltex (2017)
Renault	Maxity	Electric with hydrogen-powered fuel cell	Field test 2015	200		90		270	47/20	42/45	3.5	1	Renault Trucks (2015)
Smith	Edison	Battery electric (chassis cab)	Production (except U.S.)	90-160	Li-ion	80	6-8 h (4 h fast)		90	40	3.5-4.6	1.2-2.1	Smith (2011a)
Smith	Newton	Battery electric (chassis cab)	Production	65-160	Li-ion	80	8 h	600	120	40-120	6.4-12	2.8-7.6	Smith, (2011b, 2011c)
Spijkstaal	Ecotruck 7500	Electric garbage truck		70-100	Li-ion	40	6-8 h		20		7.5	3.7	Spijkstaal (2016)
US Hybrid	eCargo	Battery electric cargo truck	Production	120	Li-ion (18650)	104			120	36	4.5		US Hybrid (2016a)
US Hybrid	H2 Cargo	Fuel cell plug-in cargo truck	Production	200	Li-ion	97	<5 min		120	28 (9.8 kg)	6.4		US Hybrid (2016c)
Workhorse	E-Gen	Electric delivery with range extender		96 (145)		108		2,200	200	60	8.8		Workhorse (2016)

Table A2. Commercial heavy-duty zero emission vehicles in development or production.

Company	Name	Technology	Current Status	Technology Specifications									Source	
				Range (km)	Battery Chemistry	Max Speed (km/hr)	Recharge Time / Refuel Time	Torque (Nm)	Power output (kW)	Battery kWh (or Hydrogen Storage kg)	Vehicle Gross Weight (ton)	Load Capacity (ton)		
Artisan		Battery electric Class 8 drayage		129-161							250			Artisan (2016)
BYD	Q1M	Electric terminal tractor (yard truck)	Production	15	FePO4	53	1-2 h	1,500	180	209	46	9	BYD (2016a)	
BYD	T9	Electric Class 8 truck	Production	148	FePO4	90	2.5 h	2,999	359	188	54	11	BYD (2016d)	
Charge		Electric truck	2017	160							3.5-26		Charge (2016)	
Daimler	Urban eTruck	Fully electric heavy-duty truck	Production 2020	200	Li-Ion			2 x 500	2 x 125	212	26		Daimler (2016a,2016b)	
Dennis Eagle, PVI, Phoenix		Electric refuse truck	Production	>150	Li-ion	90	6-8 h			170/255	26.8	9.7	Norsk elbilforening (2017)	
E-Force		Electric Class 8 truck	Production	300 (city) 200 (highway)	LiFePO4	87	6 h (44 kW)	630	300	240	18	10	E-Force (2015)	
EMOSS	CM 1212	Battery electric truck	Production	150	LiFePO4		2.8/5.5 h	950	150	120	12	6.6	EMOSS (2016)	
EMOSS	CM 1216	Battery electric truck	Production	200	LiFePO4		3.6/7.3 h	950	150	160	12	6	EMOSS (2016)	
EMOSS	CM 1220	Battery electric truck	Production	250	LiFePO4		4.5/9 h	950	150	200	12	5.4	EMOSS (2016)	
ESORO		Class 8 fuel cell truck	Production	375-400	LiFePO4		10 mins		250	120 (35 kg)	34 t		ESORO (2017)	
Ginaf	E 2114	Electric delivery truck	Production	105	LiFePO4			1,400 (3,400)	155 (280)	120	13.5 t	7.7	Ginaf (2017)	
Ginaf	E 2115	Electric delivery truck	Production	135	LiFePO5			1,400 (3,400)	155 (280)	156	13.5	7.7	Ginaf (2017)	
Ginaf	E 2116	Electric delivery truck	Production	150	LiFePO6			1,400 (3,400)	155 (280)	180	13.5	7.7	Ginaf (2017)	
Motiv Power. Cumberland		Electric Class 8 refuse truck		80-130		80	8 h (2.5 50%)	3,000	280	170/212	30	20	Motiv (2016b)	
Nikola Motor Company	NikolaOne	Hydrogen fuel cell electric semi-truck	Production 2020	1290-1930	Li-Ion		-	2,700	746	320	37-39	29	Nikola (2016)	
Renault	Midlum Truck	All-electric refrigerated truck		100	Li-Ion		8 h		103	150	16	5.5	Renault Trucks (2011)	
Renault	Trucks D	All-electric truck		120	Li-Ion		7 h		103	170	16.3	6	Kane (2014)	
Symbio FCell	Electric Dennis Eagle	Plug-in electric hydrogen waste truck		150	Li-Ion	80			40	85	26	17	Symbio FCell (2016)	
Toyota		Class 8 fuel cell drayage truck	Demonstration 2017	>320				1800	500	12	36		Toyota (2017)	
TransPower	Elec Truck	Electric drayage truck		110-160	Li-Ion (LFP)				300	215-270	36	26	TransPower (2015)	
US Hybrid	H2 Truck	Fuel cell electric drayage truck	Development	320	Li-ion	97	<9 min		320	30 (25 kg)	36		US Hybrid (2016d)	
US Hybrid	ETruck	Battery electric Class 8 truck	Development	161 (@27t)	Li-ion	97			320	240	36		US Hybrid (2016b)	

Table A3. Long-haul heavy-duty freight truck vehicle component cost breakdown for the different vehicle technologies. The values used are the best estimates from a variety of literature sources.

Vehicle component costs	2015	2020	2025	2030
U.S. base diesel tractor cost (\$)	135,000	135,000	135,000	135,000
EU base diesel tractor cost (\$)	135,000	135,000	135,000	135,000
China base diesel tractor cost (\$)	60,000	60,000	60,000	60,000
U.S. baseline trailer costs (\$)	25,000	25,000	25,000	25,000
EU baseline trailer costs (\$)	25,000	25,000	25,000	25,000
China baseline trailer costs (\$)	10,000	10,000	10,000	10,000
Number of trailers	3	3	3	3
U.S. base truck, "Glider" costs (\$)	78,300	78,300	78,300	78,300
EU base truck, "Glider" costs (\$)	78,300	78,300	78,300	78,300
China base truck, "Glider" costs (\$)	37,400	37,400	37,400	37,400
U.S. other efficiency improvements (\$)	2,790	9,580	7,140	26,500
EU other efficiency improvements (\$)	-	-	2,240	8,260
China other efficiency improvements (\$)	-	1,110	3,170	7,440
Diesel				
Engine power (kW)	350	350	350	350
Fuel tank (\$)	2,120	2,120	2,120	2,120
Battery (\$)	531	531	531	531
Aftertreatment (\$)	6,940	6,940	6,940	6,940
U.S. engine efficiency improvements (\$)	2,980	6,280	11,900	18,800
EU engine efficiency improvements (\$)	-	-	1,800	5,530
China engine efficiency improvements (\$)	-	883	4,270	5,330
U.S. total diesel/ICE vehicle cost (\$)	210,000	220,000	223,000	250,000
EU total diesel/ICE vehicle cost (\$)	204,000	204,000	208,000	218,000
China total diesel/ICE vehicle cost (\$)	90,000	91,500	95,100	99,800
Hybrid Battery Electric				
U.S. additional costs for hybrids (\$)	24,700	21,800	18,600	18,100
EU additional costs for hybrids (\$)	24,700	21,800	18,600	18,100
China additional costs for hybrids (\$)	11,000	9,680	8,270	8,050
U.S. total hybrid electric vehicle cost (\$)	235,000	242,000	242,000	268,000
EU total hybrid electric vehicle cost (\$)	229,000	226,000	227,000	236,000
China total hybrid electric vehicle cost (\$)	101,000	101,000	103,000	108,000
Natural Gas				
LNG SI tank (\$/DGE)	246	226	207	187
LNG SI tank capacity (DGE)	173	156	140	123
LNG SI tank cost (\$)	42,500	35,300	28,800	23,000
LNG CI tank (\$/DGE)	295	272	248	225
LNG CI tank capacity (DGE)	150	136	121	107
LNG CI tank cost (\$)	44,300	36,900	30,200	24,100
CNG SI tank (\$/DGE)	345	317	290	262
CNG SI tank capacity (DGE)	173	156	140	123
CNG SI tank cost (\$)	59,500	49,500	40,400	32,200
Battery cost (\$)	531	531	531	531
CI engine (\$)	68,900	68,900	68,900	68,900
SI engine (\$)	42,900	42,900	42,900	42,900
U.S. total LNG SI vehicle cost (\$)	242,000	242,000	233,000	246,000
EU total LNG SI vehicle cost (\$)	239,000	232,000	228,000	228,000
China total LNG SI vehicle cost (\$)	153,000	147,000	143,000	141,000

Vehicle component costs	2015	2020	2025	2030
U.S. total LNG CI vehicle cost (\$)	270,000	269,000	260,000	273,000
EU total LNG CI vehicle cost (\$)	267,000	260,000	255,000	255,000
China total LNG CI vehicle cost (\$)	118,000	116,000	115,000	117,000
U.S. total CNG SI vehicle cost (\$)	259,000	256,000	244,000	255,000
EU total CNG SI vehicle cost (\$)	256,000	246,000	239,000	237,000
China total CNG SI vehicle cost (\$)	113,000	110,000	108,000	109,000
Dynamic Induction Grid				
Battery (kWh)	165	155	143	133
Battery cost (\$)	53,800	35,300	24,000	15,900
Additional required BEV systems (\$)	19,300	18,100	16,000	14,300
Electric motor (kW)	350	350	350	350
Electric motor (\$)	7,960	6,370	5,720	5,080
Dynamic induction grid connection (\$)	16,700	11,800	11,500	10,800
U.S. total dynamic induction vehicle cost (\$)	254,000	234,000	218,000	226,000
EU total dynamic induction vehicle cost (\$)	251,000	225,000	213,000	208,000
China total dynamic induction vehicle cost (\$)	165,000	140,000	128,000	121,000
Overhead Catenary				
Battery (kWh)	165	155	143	133
Battery cost (\$)	53,800	35,300	24,000	15,900
Additional required BEV systems (\$)	19,300	18,100	16,000	14,300
Electric motor (kW)	350	350	350	350
Electric motor (\$)	7,960	6,370	5,720	5,080
Overhead catenary grid connection (\$)	71,700	49,600	21,200	21,200
U.S. total overhead catenary vehicle cost (\$)	309,000	272,000	227,000	236,000
EU total overhead catenary vehicle cost (\$)	306,000	263,000	222,000	218,000
China total overhead catenary vehicle cost (\$)	220,000	178,000	138,000	131,000
Fuel Cell				
Power (kW)	350	350	350	350
Fuel cell system (\$)	84,000	58,300	31,000	20,500
Compressed gaseous H2 tank (\$/kWh)	33	23	21	19
Compressed gaseous H2 tank capacity (kWh)	2,790	2,570	2,570	2,480
Compressed gaseous H2 tank price (\$)	92,000	59,100	54,000	47,200
Electric motor (kW)	400	400	400	400
Electric motor (\$)	9,080	7,270	6,530	5,800
Battery capacity (kWh)	12	12	12	12
Battery cost (\$)	3,910	2,740	2,020	1,430
Additional required FCHEV systems (\$)	13,300	11,900	10,800	9,670
U.S. total fuel cell cost—gaseous hydrogen (\$)	345,000	290,000	254,000	255,000
EU total fuel cell cost—gaseous hydrogen (\$)	342,000	281,000	249,000	236,000
China total fuel cell cost—gaseous hydrogen (\$)	256,000	196,000	164,000	150,000

Based on den Boer et al. (2013); Fulton & Miller (2015); Meszler et al. (2015); Posada et al. (2016); Sen et al. (2016)

Table A4. Annual vehicle distance traveled (in kilometers) for U.S., EU-28, and China long-haul heavy-duty vehicles.

Age	U.S. ^a	EU-28	China
1	130,832	126,332	153,175
2	119,001	114,908	139,324
3	108,164	104,444	126,636
4	97,441	94,090	114,082
5	87,476	84,467	102,415
6	78,930	76,215	92,409
7	70,940	68,500	83,055
8	63,474	61,291	74,314
9	56,865	54,909	66,576
10	50,887	49,137	59,577
10-Year Total	1,390,490	834,294	1,011,563

^a U.S. EPA & NHTSA, 2011

Table A5. Energy consumption (MJ/km) of each vehicle technology for vehicles purchased in 2015, 2020, 2025, and 2030.

	Region	2015	2020	2025	2030
Diesel	United States	14	13	10	9.3
	China	16	13	12	10
	EU-28	12	12	11	9
Diesel hybrid	United States	14	12	10	8.9
	China	15	13	11	10
	EU-28	11	11	10	8.8
Liquefied natural gas (compression ignition)	United States	16	14	11	10
	China	17	15	13	11
	EU-28	13	13	12	10
Liquefied natural gas (spark ignition)	United States	16	14	12	11
	China	18	15	14	12
	EU-28	14	14	12	11
Compressed natural gas (spark ignition)	United States	16	14	12	11
	China	18	15	14	12
	EU-28	14	14	12	11
Hydrogen fuel cell	United States	9.5	8.8	8.2	7.6
	China	9.5	8.8	8.2	7.6
	EU-28	9.5	8.8	8.2	7.6
Electric overhead catenary	United States	5.7	5.3	4.9	4.5
	China	5.7	5.3	4.9	4.5
	EU-28	5.7	5.3	4.9	4.5
Electric dynamic induction	United States	9.0	8.2	7.5	6.9
	China	9.0	8.2	7.5	6.9
	EU-28	9.0	8.2	7.5	6.9

Diesel conversion: 36.66 MJ/l

Table A6. Fuel cost projections from 2015 to 2040

Vehicle	Region	Fuel Prices					
		2015	2020	2025	2030	2035	2040
Diesel (\$/gallon)	United States	2.14	3.42	4.27	4.83	5.15	5.47
	China	2.53	4.00	5.00	5.73	6.03	6.40
	EU-28	3.72	5.94	7.43	8.40	8.95	9.51
CNG (\$/MMBTU)	United States	15.08	17.12	16.28	15.71	15.18	14.94
	China	7.22	7.59	7.22	6.97	6.73	6.63
	EU-28	13.92	14.65	13.94	13.44	12.99	12.79
LNG (\$/MMBTU)	United States	17.62	18.54	17.64	17.01	16.44	16.19
	China	7.82	8.23	7.83	7.55	7.30	7.18
	EU-28	15.06	15.87	15.10	14.57	14.08	13.86
Hydrogen from Natural Gas (\$/dge)	United States	6.00	5.46	4.93	4.39	3.85	3.32
	China	6.00	5.46	4.93	4.39	3.85	3.32
	EU-28	6.00	5.46	4.93	4.39	3.85	3.32
Hydrogen from Renewable Pathways (\$/dge)	United States	11.00	9.66	8.31	6.97	5.63	4.28
	China	11.00	9.66	8.31	6.97	5.63	4.28
	EU-28	11.00	9.66	8.31	6.97	5.63	4.28
Electricity (\$/kWh)	United States	0.10	0.12	0.13	0.14	0.13	0.13
	China	0.09	0.10	0.11	0.12	0.13	0.14
	EU-28	0.14	0.19	0.21	0.22	0.22	0.21

ANNEX REFERENCES

- Artisan. (2016, March). Electric Class 8 truck. Retrieved from <http://artisanvs.com/electric-class-8-truck/>
- Charge. (2016, November 3). Delivering in your city from 2017 British auto tech company charge reveals new electric truck. Retrieved from https://charge.auto/imgs/Charge_Truck_03112016.pdf
- BYD. (2016a, August). Heavy duty performance Class 8 - 15 hours - Up to 102,000 lbs GCWR. 100% battery-electric Class 8 terminal tractor. Retrieved from <http://www.byd.com/usa/wp-content/uploads/2016/08/Q1M-final.pdf>
- BYD. (2016b, August). Long-range battery electric Class 5 - cab chassis - 16,000 lbs GVWR. 100% battery-electric Class-5 truck. Retrieved from <http://www.byd.com/usa/wp-content/uploads/2016/08/T5-final.pdf>
- BYD. (2016c, August). Long-range battery electric Class 6 - cab chassis - 23,600 lbs GVWR. 100% battery-electric Class-6 truck. Retrieved from <http://www.byd.com/usa/wp-content/uploads/2016/08/T7-final.pdf>
- BYD. (2016d August). Long-range battery electric Class 8 - 120,000 lbs GCWR. 100% battery-electric Class 8 tractor. Retrieved from <http://www.byd.com/usa/wp-content/uploads/2016/08/T9-final.pdf>
- Daimler. (2016a). Mercedes-Benz: First fully electric truck. Retrieved from <https://www.daimler.com/products/trucks/mercedes-benz/urban-etruck.html>
- Daimler. (2016b). The Mercedes-Benz Urban eTruck: Connectivity meets eMobility. Retrieved from <https://www.daimler.com/products/trucks/mercedes-benz/world-premiere-urban-etruck.html>
- Daimler. (2016c). The new Fuso eCanter. E-Pioneer among light trucks. Retrieved from <https://www.daimler.com/products/trucks/fuso/ecanter.html>
- den Boer, E., Aarnink, S., Kleiner, F., & Pagenkopf, J. (2013, July). Zero emission trucks. An overview of state-of-the-art technologies and their potential. CE Delft. Retrieved from http://www.theicct.org/sites/default/files/publications/CE_Delft_4841_Zero_emissions_trucks_Def.pdf
- Deutsche Post DHL Group. (2013, May). Fact & figures: Alternative drive vehicles: Iveco Electric Daily. Retrieved from <http://www.dpdhl.com/content/dam/dpdhl/presse/veranstaltungen/co2frei/factsheets-alternative-drive-vehicles.zip>
- Deutsche Post DHL Group. (2016, April). Fact & figures: Alternative drive vehicles: the StreetScooter. Retrieved from <http://www.dpdhl.com/content/dam/dpdhl/presse/veranstaltungen/co2frei/factsheets-alternative-drive-vehicles.zip>
- E-Force. (2015). E-FORCE 18t electric truck. Retrieved from http://eforce.ch/wp/wp-content/uploads/2016/06/E_FORCE_Fact_Sheet_E_2015.pdf
- Electric Vehicles Schwaben GmbH (EFA-S). (2010). UPS P80-E Spec's & Facts. Retrieved from <http://efa-s.de/Eigene%20Dateien/UPS%20Datenblatt%20englisch.pdf>
- EMOSS. (2016). CM12 series - 12 tonne electric truck. Retrieved from <http://www.emoss.biz/electric-truck/12-tonne-electric-truck/>
- ESORO. (2017). The world's first fuel cell heavy goods vehicle able to fulfill Coop's logistics requirements. Retrieved from http://www.esoro.ch/deutsch/content/aktuelles/images/Factsheet_Lastwagen_E.pdf

- Fulton, L., & Miller, M. (2015). Strategies for transitioning to low-carbon emission trucks in the United States. UC Davis and National Center for Sustainable Transportation. Retrieved from <http://ncst.ucdavis.edu/wp-content/uploads/2014/08/06-11-2015-06-11-2015-STEPS-NCST-Low-carbon-Trucks-in-US-06-10-2015.pdf>
- FUSO. (2014). Zero emission and quiet as a whisper: eight new FUSO Canter E-CELL in customer trials. Retrieved from http://www.fuso-trucks.com/press-and-media_press-releases/the-new-Canter-E-CELL
- Ginaf. (2017). E 2114 DuraTruck. Retrieved from http://www.ginaf.nl/fileadmin/inhoud/Trucks/specblad_euro6/E2114_NL.pdf
- GreenFleet. (2016). Medium duty truck zero emissions. Electric Vehicles International. Retrieved from http://www.fpgreenfleet.net/images/EVI-MD_Fact_Sheet_Print.pdf
- Kane, M. (2014). The Electric Renault Truck D on the streets of Paris. InsideEVs. Retrieved from <http://insideevs.com/the-all-electric-renault-trucks-d-on-the-streets-of-paris/>
- Meszler, D., Lutsey, N., & Delgado, O. (2015, April). Cost effectiveness of advanced efficiency technologies for long-haul tractor-trailers in the 2020-2030 time frame. Meszler Engineering Services & The International Council on Clean Transportation (ICCT). Retrieved from http://www.theicct.org/sites/default/files/publications/ICCT_tractor-trailer_tech-cost-effect_20150420.pdf
- Motiv. (2016a, June). Electrify your delivery van. Retrieved from http://motivps.com/wp-content/uploads/2016/06/Rockport_1Sheet.pdf
- Motiv. (2016b, June). Electrify your refuse truck. Retrieved from http://motivps.com/wp-content/uploads/2016/06/Cumberland_1Sheet_vF.pdf
- ORTEN. (2016). ORTEN E 75 AT. Retrieved from http://www.electric-trucks.de/images/files/Datenblaetter_Englisch/ORTEN_E_75_AT.pdf
- Paneltex. (2017, April). Electric vehicles. Retrieved from <https://s3-eu-west-2.amazonaws.com/paneltex.co.uk/wp-content/uploads/2017/04/Paneltex-Electric-Vehicles-Brochure.pdf>
- Posada, F., Chambliss, S., & Blumberg, K. (2016). Costs of emission reduction technologies for heavy-duty diesel vehicles. International Council on Clean Transportation (ICCT). Retrieved from <http://www.theicct.org/costs-emission-reduction-tech-hdvs>
- Renault Trucks. (2011, October 13). The world's largest electric-powered truck undergoing tests with Carrefour. Retrieved from <http://corporate.renault-trucks.com/en/press-releases/the-world-s-largest-electric-powered-truck-undergoing-tests-with-carrefour.html>
- Renault Trucks. (2015, February 23). The French post office and Renault Trucks jointly test a hydrogen-powered truck running on a fuel cell. Retrieved from <http://corporate.renault-trucks.com/en/press-releases/2015-02-23-the-french-poste-office-and-renault-trucks-jointly-test-a-hydrogen-powered-truck-running-on-a-fuel-cell.html>
- Sen, B., Ercan, T., & Tatari, O. (2016, May). Does a battery-electric truck make a difference? – Life cycle emissions, costs, and externality analysis of alternative fuel-powered Class 8 heavy-duty trucks in the United States. University of Central Florida. *Journal of Cleaner Production*, 141, 110-121. doi:10.1016/j.jclepro.2016.09.046

- Smith. (2011a). Smith Edison: The world's favourite all-electric light commercial vehicle. Retrieved from http://www.smithelectric.com/wp-content/uploads/2016/02/SmithEdisonSpecSheet_OUS_2011.pdf
- Smith. (2011b). Smith Newton: The world's best-selling all-electric truck. Retrieved from http://www.smithelectric.com/wp-content/uploads/2016/02/SmithNewtonSpecSheet_OUS_2011.pdf
- Smith. (2011c). The Newton. Retrieved from http://www.smithelectric.com/wp-content/uploads/2016/02/SmithNewtonUS_SpecSheet_2011.pdf
- Spijkstaal. (2016). Ecotruck 7500. Electric garbage truck. Retrieved from http://www.spijkstaal.nl/cms/bestanden/cms_dir/editor/bestanden/Spijkstaal%20Productsheet%20EN%20Ecotruck%207500.pdf
- Symbio FCell. (2016). Waste truck-cleaning truck. Retrieved from <http://www.symbiofcell.com/vehicles/waste-truck/>
- Toyota. (2017, April 19). Toyota opens a portal to the future of zero emission trucking. Retrieved from <http://pressroom.toyota.com/releases/toyota+zero+emission+heavyduty+trucking+concept.htm>
- TransPower. (2015, May 14). Electric drayage truck. Featuring the ElecTruck Drive System. Retrieved from <http://www.transpowerusa.com/downloads/ElecTruck-Data-Sheet-5-14-15.pdf>
- US Environmental Protection Agency and National Highway Traffic Safety Administration (US EPA and NHTSA) (2011). Final rulemaking to establish greenhouse gas emissions standards and fuel efficiency standards for medium- and heavy-duty engines and vehicles: Regulatory impact analysis. Retrieved from <https://nepis.epa.gov/Exe/ZyPDF.cgi/P100EG9C.PDF?Dockey=P100EG9C.PDF>
- US Hybrid. (2016a). eCargo. Retrieved from <http://www.ushybrid.com/documents/PDF/2/eCargo.pdf>
- US Hybrid. (2016b). eTruck. Retrieved from <http://www.ushybrid.com/documents/PDF/2/eTruck.pdf>
- US Hybrid. (2016c). H2 cargo fuel cell plug-in step van. Retrieved from <http://www.ushybrid.com/documents/PDF/2/H2Cargo.pdf>
- US Hybrid. (2016d). H2 truck. Retrieved from <http://www.ushybrid.com/documents/PDF/2/H2Truck.pdf>
- Workhorse. (2016). Step vans: Introducing the extended range E-GEN. Retrieved from <http://workhorse.com/stepvans>