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ESTIMATING THE INFRASTRUCTURE NEEDS AND COSTS FOR THE LAUNCH OF ZERO-EMISSION TRUCKS

Dale Hall, Nic Lutsey

icct
THE INTERNATIONAL COUNCIL
ON CLEAN TRANSPORTATION

www.theicct.org

communications@theicct.org

BEIJING | BERLIN | BRUSSELS | SAN FRANCISCO | WASHINGTON

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International Council on Clean Transportation
1500 K Street NW Suite 650
Washington DC 20005 USA

communications@theicct.org | www.theicct.org | @TheICCT

EXECUTIVE SUMMARY

The transition to zero-emission commercial trucks holds great promise. Although heavy-duty electrification is in the early stages, the pace of development could progress quickly. Innovation in battery technologies, cost reductions from potential economies of scale, and development of high-power charging stations can provide a foundation for commercial trucks to follow the path of electric passenger cars. Incremental growth is made further feasible by the ability of commercial fleets to incorporate fuel savings in purchasing decisions, as well as to precisely plan infrastructure for company-specific operations.

This report quantifies the infrastructure needs and associated costs for implementing battery electric and hydrogen fuel cell trucks in three applications: long-haul intercity tractor-trailers, drayage trucks, and medium-duty delivery trucks. We focus on vehicles operating from the greater Los Angeles, California, region, where interest in these technologies has been concentrated. We evaluate the amount of charging and hydrogen refueling infrastructure required to sustain low-, medium-, and high-volume deployments in each of these applications, we estimate the costs of this infrastructure for fleets or the public, and assess financial implications for the transition to zero-emission trucks.

Table ES-1 summarizes the charging requirements and costs as the number of trucks increases from 100 to 1,000 to 10,000 in each of the three applications. The total infrastructure costs are substantial, into the hundreds of millions of dollars to reach 10,000 electric trucks for each of the three applications. However, infrastructure costs per vehicle decline as truck volume grows. The last column shows that, even if fleets were to bear these associated infrastructure costs, the overall vehicle ownership cost of electric trucks in these applications will generally be lower than conventional vehicle costs by 2030. Public infrastructure funding or other fiscal incentives could further improve the cost of ownership proposition. Although we highlight only the electric truck findings in this table, equivalent findings for hydrogen fuel cell trucks are also assessed in the report.

Table ES-1. Charging infrastructure for increasing electric truck volume in three applications

Application	Case	Number of trucks	Charging outlets	Infrastructure cost per truck (thousand)	Vehicle ownership cost versus diesel
Delivery (Class 6, 9.75-13 tons)	Low volume	100	130	$82	0% to +5%
	Medium volume	1,000	820	$40	-15% to -10%
	High volume	10,000	6,300	$27	-25% to -20%
Drayage (Class 7-8, 13+ tons)	Low volume	100	100	$58	+10% to +25%
	Medium volume	1,000	810	$38	0% to +5%
	High volume	10,000	7,300	$28	-15% to -10%
Long haul (Class 8, 16.5+ tons)	Low volume	100	150	$189	+13% to +18%
	Medium volume	1,000	1,200	$114	+5% to +10%
	High volume	10,000	9,700	$71	-5% to 0%

From this analysis, we draw the following conclusions.

Declining technology costs are making zero-emission trucks increasingly cost-competitive with conventional diesel vehicles. Although zero-emission trucks are more expensive in the near-term than their diesel equivalents, electric trucks will be less expensive than diesel in the 2025–2030 time frame, due to declining costs of batteries and electric motors as well as increasing diesel truck costs due to emission standards compliance. This analysis identifies additional obstacles, such as charging time and reduced cargo capacity, which could also add costs for fleets; however, electric trucks are expected to be cost-competitive even with these costs. Fuel cell trucks will also become less expensive in upfront vehicle cost and total cost of ownership by 2030.

Infrastructure costs are significant, but do not fundamentally impede the viability of zero-emission trucks. Whether constructed by fleets, third parties, or public agencies, charging and hydrogen infrastructure for zero-emission trucks pose significant costs. As fleets deploy the technologies at greater scale, infrastructure costs add more than $70,000 per battery electric long-haul tractor-trailer and more than $25,000 per drayage truck or delivery truck, amounting to 7% to 9% of the lifetime operating cost in each application. If these infrastructure costs are excluded, electric fleets could see vehicle ownership cost parity with diesel in the early 2020s; including these infrastructure costs pushes parity five to 10 years later.

Initial infrastructure buildouts will be costly without careful planning and coordination. In the early zero-emission truck deployments, it will be essential to plan infrastructure for specific routes, applications, and duty cycles to minimize costs. For electric trucks, overnight and loading area charging can greatly reduce charging costs, and coordination among fleets and public agencies could help distribute the initial costs. Government-led programs and public-private partnerships would help coordinate and share such investments.

Policy will be needed to spur this transition to zero-emission trucks. This analysis is focused on the shift from hundreds to tens of thousands of zero-emission trucks in three freight applications. To move through these steps, new zero-emission truck models need to be developed and improved, with continued investments to bring the greater volume and lower costs that are assumed in this analysis. Policy changes, such as the zero-emission truck regulation that California is considering, as well as public support for infrastructure, could spur the changes assessed in this report to occur within 10 years; without such policy and support, it could take decades.

This analysis finds encouraging evidence for the feasibility of zero-emission trucks, but also an indication of the substantial scale of investment needed. The findings also indicate numerous opportunities for continuing research. Because duty cycles and vehicle fleets vary widely among and within countries, additional analyses will be needed to determine costs in different regions. Another type of zero-emission trucks, e-roads powered by catenary lines, could also be considered for applications with concentrated traffic and high power use. Despite substantial costs and uncertainties, it is evident that zero-emission trucks, and the many air quality and climate benefits they will bring, are on the way.

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INTRODUCTION

Increasingly, manufacturer announcements and fleet deployments are raising the prospects for zero-emission trucks. There are now more than 100 zero-emission truck models in commercial truck segments, and these are being deployed in increasingly larger numbers. Zero-emission technologies are being developed by a combination of different players, including established manufacturers and suppliers, start-ups, and newly formed partnerships between companies. Aligned with this activity, companies have announced commitments to high-volume purchase of these vehicles and the transition of their fleets toward zero emissions in the years ahead. Zero-emission heavy-duty truck technology is clearly emerging, in a similar way to electric passenger vehicle technology six to eight years earlier.

Freight activity from diesel-powered trucks continues to grow, posing air-quality risks and representing an increasing share of greenhouse gas emissions, as shown in Figure 1. By 2040, medium- and heavy-duty vehicles are expected to be the largest fraction of transport-sector emissions as activity grows and other sectors become more efficient and shift to alternative fuels (International Energy Agency, 2017). Furthermore, diesel-powered trucks disproportionately contribute to air pollution, especially nitrous oxides (NOx) and particulate matter (PM), which cause a wide range of health problems, including asthma and cancer. A recent study found that large trucks are the largest contributor to PM pollution in areas near roadways in North America (Wang et al., 2018).

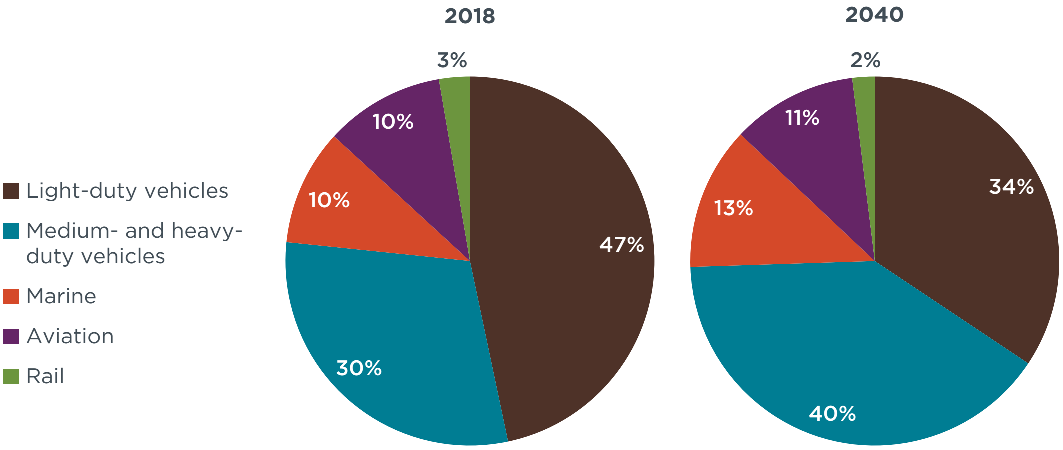

Figure 1. Global transport-sector greenhouse gas emissions by mode

Zero-emission trucks that could potentially reverse these emission trends are currently in the early stages of development, and research illustrates that these vehicles may soon become competitive with conventional alternatives. Moultak, Lutsey, and Hall (2017) found that the total cost of ownership (TCO) of zero-emission Class 8 trucks, including e-roads and hydrogen fuel cells, could fall below that of diesel trucks as soon as 2025 while also reducing emissions by 75%. A European Union-focused report finds that battery electric trucks with a range up to 300 miles (480 kilometers) are already competitive on a TCO basis with best-in-class diesel trucks, with future cost reductions expected (Earl et al., 2018). Other research projects that battery electric trucks for most freight applications will reach TCO parity with diesel in the 2030 range, with some smaller regional applications as soon as 2020 (Tryggestad, Charma, van de Staaij, & Keizer, 2017).

Major truck manufacturers are beginning to demonstrate and produce zero-emission trucks across the medium- and heavy-duty market. Figure 2 illustrates announced or in-production battery electric and hydrogen fuel cell freight trucks. The vertical axis shows the gross vehicle weight rating (GVWR) categories and corresponding U.S. vehicle classes 4 through 8. The horizontal axis shows the announced battery or hydrogen tank range in miles. Battery electric trucks are indicated by the blue markers, while the hydrogen fuel cell trucks are in green. Trucks of either technology that are in production or expected to be in 2019 are indicated as filled-in data points; those with expected production start dates beyond 2020, or not yet announced, are hollow data points. Additional details on these vehicles are listed in the Appendix.

Figure 2. Range and GVWR class of announced or in-production zero-emission trucks

This figure, although not exhaustive, indicates that there is significant activity in commercializing zero-emission trucks, both from established global truck manufacturers as well as from newer start-up companies. Based on company announcements, there are at least 10 heavy-duty (Class 7 or Class 8, 13+ tons) models of battery electric trucks with a range of up to 550 miles that are slated for commercial deployment by 2021. Several trucks will directly compete in terms of range and weight (for example, three Class 6 electric trucks have been announced with a 150-mile range). Although there has been more activity on battery electric trucks to date, large manufacturers are also exploring fuel cells for the most demanding truck segments as well. A number of these zero-emission trucks, including from BYD, emoss, Mitsubishi FUSO, and Hyundai, have already entered production and are serving in fleets. In addition to these two technologies, other truck manufacturers are working on e-roads capable of dynamically powering trucks through catenary lines, on-road rails, or induction. Siemens, Volvo, and Scania are among the major companies investing in e-road technology, and are experimenting with different vehicle configurations that include batteries and diesel, natural gas, or hydrogen range extenders.

The transition to zero-emission commercial heavy-duty vehicles could take decades and potentially be considerably slower than for passenger cars due to the technology, operational, and infrastructure requirements. If the heavy-duty vehicles suffer from any volume or mass penalties, this would compromise the cargo-hauling capabilities. Many heavy-duty vehicles are driven 400 to 1,000 miles per day, which would require larger, more durable battery packs, adding to the cost and mass of the vehicle. In addition, they would require much faster charging options, battery swapping, on-road charging, or a network of hydrogen refueling solutions to accommodate their commercial operations.

Despite the issues outlined above, the pace of development could progress more rapidly. Innovation in battery technologies, cost reductions from potential economies of scale, and experience with high-power charging stations from electric bus adoption provide a foundation on which to build. Further, commercial fleets could incorporate fuel savings over a full vehicle ownership cycle in the vehicle purchase decision. In addition, fleet owners have the ability to provide their own charging infrastructure solutions for their company-specific operations with known parking locations. These factors make incremental growth increasingly possible for zero-emission commercial trucks to progress from pilot fleets, to niche operations, to medium-sized fleets with prescribed short-haul operations in the years ahead.

Although there is a strong research base for estimating the vehicle-level technologies, there is limited available research to quantify the infrastructure necessary for the operation of zero-emission trucks. This infrastructure—whether battery electric fast-charging stations, hydrogen refueling stations, or overhead catenary lines—has the potential to add significant costs and logistical hurdles for zero-emission trucks. The infrastructure needs are likely to vary widely depending on the vehicle type, drivetrain, duty cycle, typical cargo, and weight capacity of the trucks. Some early research estimates that the additional infrastructure costs for zero-emission trucks in Germany, if financed fully by the truck operators, could add 10% to 25% to the per-truck cost, raising the total cost of ownership above that of diesel (Kühnel, Hacker, & Görz, 2018). Deeper analysis is warranted on the specific infrastructure needs and associated costs for vehicles in different market segments and regions as zero-emission trucks are increasingly deployed.

This white paper seeks to address the gap in research by quantifying the infrastructure needed to supply freight trucks in three applications: long-haul tractor-trailers, drayage trucks operating out of a container port, and medium-duty delivery trucks. Although e-roads may play an important role in decarbonizing road freight, we found that data on the associated costs was less available, and we also view the technology as less applicable for medium-duty urban distribution applications. We therefore focus on battery electric and hydrogen fuel cell technologies. This analysis is tailored to the greater Los Angeles, California, region, where there is significant commercial interest in zero-emission vehicles to reduce both freight costs and air pollution. For each application, the zero-emission truck infrastructure needs are analyzed for small, near-term deployments up to large-scale commercialization. We then discuss the contribution of the infrastructure cost, whether borne by fleet operators or by government, to the overall cost of transitioning to zero-emission trucks.

METHODOLOGY

This paper considers the infrastructure needs for zero-emission vehicles operating in three vehicle applications in the greater Los Angeles area. The Los Angeles area geography helps to define the basis for all the technical specifications, fleet operation, route distances, and fueling costs, but the analysis could be roughly applicable for other areas with high-volume freight activity and zero-emission technology developments. For each application, we determine a representative vehicle, including powertrain specifications for battery electric and hydrogen variants, as well as multiple representative duty cycles and routes. Charging and refueling needs are assessed for trucks performing each of these duty cycles in terms of hours of charging per day at both ultra-fast and slower charging stations. This is then translated into the number of stations required for a fleet serving a mix of routes.

This analysis is performed for three cases: a low-volume case for an initial deployment of 100 trucks, a medium-volume deployment of 1,000 trucks, and a high-volume, longer-term deployment of 10,000 trucks. In keeping with the experience of light-duty vehicles, we assume that stations will see somewhat higher throughput and benefit from economies of scale in the higher volume cases (Nicholas & Hall, 2018). This section outlines the representative vehicles and duty cycles as well as additional assumptions used for each of these three applications.

VEHICLE AND ROUTE SPECIFICATIONS

Long-haul tractor-trailer. Long-haul, Class 8 tractor-trailers account for the highest share of fuel consumption and greenhouse gas emissions among heavy-duty vehicles, and therefore have great potential for fuel savings and emission reductions through a shift to zero-emissions technologies. However, the travel patterns of these vehicles present challenges; their routes involve multi-day intercity travel rather than frequent returns to a base location. To date, there are no zero-emissions intercity tractor-trailers in operation, although several prototypes have been demonstrated, including the Tesla Semi, Freightliner eCascadia, and Nikola Motors One.

Greater Los Angeles is a hub for freight activity and sees more than 720 million tons of road freight movements annually (Oak Ridge National Laboratory, 2018). Figure 2 displays the profile of road freight movements from the Los Angeles Combined Statistical Area according to the Freight Analysis Framework (FAF4), produced through a partnership between the Bureau of Transportation Statistics and the Federal Highway Administration. Each dot represents a destination region, either a metropolitan statistical area (brown) or a state with its metropolitan areas excluded (blue). Selected markets with high freight traffic from Los Angeles are labeled.

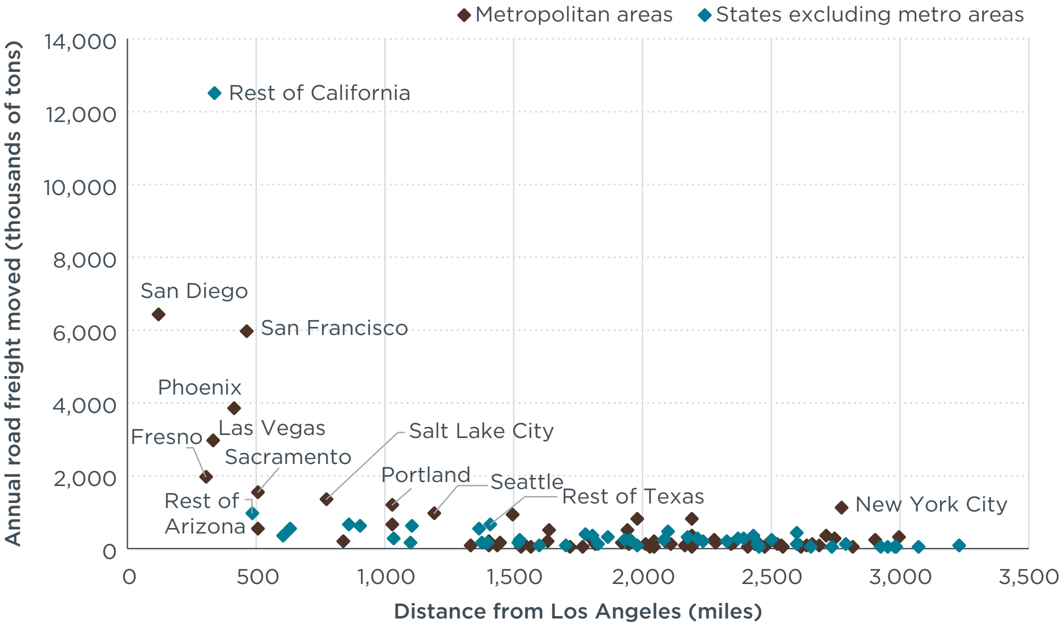

Figure 3. Road freight movement patterns to and from the Los Angeles metropolitan area in 2016 based on the FAF4 database

As shown in the figure, most shipments travel relatively short distances to destinations within California or to nearby cities such as Phoenix and Las Vegas; in fact, 66% of tons, a proxy for truck trips, go to destinations fewer than 1,000 miles away. However, 72% of ton-miles, a rough proxy for truck travel time and energy use, take place on journeys over 1,000 miles. In the near term, it is likely that zero-emission trucks will be concentrated on heavily trafficked, shorter-distance routes (those toward the left of the chart). However, in the long term, zero-emission trucks will need to be capable of much longer journeys.

We assess charging requirements on five routes of different lengths, as outlined in Table 1 below, represented by Los Angeles to San Diego, Las Vegas, Salt Lake City, Seattle, and Chicago. In addition to trip length, the table outlines the assumed distribution of trucks among routes similar to these in the three cases by truck-hours. To provide clear comparisons of how infrastructure needs will evolve with growing scale, we assume the same composition of trips in each case. In reality, initial deployments will likely concentrate on a few short routes where fleets can optimize infrastructure and demand, while later deployments will need to serve a much broader variety of routes.

Table 1. Specifications of selected long-haul routes and assumed breakdown of trips

Trip distance (miles)	100-200	200-500	500-1000	1,000-1,500	2,000 +
Destination from Los Angeles	San Diego	Las Vegas	Salt Lake City	Seattle	Chicago
Road freight (thousand tons, 2016)	7,672	5,893	1,334	930	802
Percentage of fleet driving time	10%	10%	25%	25%	30%

In this analysis, the long-haul tractor-trailer is assumed to be similar in general characteristics to a top-selling long-haul sleeper tractor-trailer in the United States.

Important specifications of the truck used in this analysis are listed in Table 2. Where possible, these values (and the underlying components) stem from the analysis of Moultak et al. (2017) or from announced zero-emission trucks in the same category. Vehicle performance specifications such as efficiency are uncertain given the lack of real-world experience and warrant further analysis. For simplicity, we assume that the vehicle attributes are the same among the three cases.

Table 2. Key specifications for zero-emission long-haul tractor-trailer

	Specification	Value	Notes
	Gross Combined Vehicle Weight Rating (GCVWR)	80,000 lbs	Maximum for Class 8
Battery electric	**Tare weight (truck and trailer)**	33,129 lbs	
	Total baseline battery size	600 kWh	80% available for use
	Electric motor power	550 kW	Equivalent to 700 HP diesel engine
	Energy consumption (without trailer)	1.9 kWh/mile	
	Range (no trailer)	250 miles	
	Range (fully loaded)	190 miles	
	Max fast charging speed	500 kW	
	Depot and overnight charging	50 kW	
Hydrogen fuel cell	**Onboard hydrogen storage**	60 kg	Stored at 70 MPa
	Energy consumption (without trailer)	13 miles/kg	
	Range (no trailer)	800 miles	
	Range (fully loaded)	585 miles	
	Hydrogen fueling rate	3.6 kg/minute	

We assume that these tractor-trailers will carry 75% of their maximum cargo capacity by mass on average, and that they are driven to the maximum extent allowed under U.S. Department of Transportation limits: up to 11 hours of driving or 14 hours of total active time, per day, 235 days per year (Federal Motor Carrier Safety Administration, 2015). We also assume that vehicles will charge at 50 kW overnight, either at a truck stop or at a loading destination. Furthermore, we assume that one-third of loading docks will have charging capability (also at 50 kW), and that the average turnaround time while loading and unloading is 90 minutes. Fast charging (at 500 kW) is used as much as necessary to maximize driving time in a day.

The extra mass of the battery has the potential to reduce the maximum cargo capacity of battery electric tractor-trailers, requiring additional vehicles to haul the same amount of freight. As data emerges from tractor-trailers that move from prototype to more rigorous testing in various conditions, all these assumptions can be further refined.

Drayage truck. Drayage trucks, which carry shipping containers within and around ports, often operate on congested surface streets, and have received intense scrutiny for their air quality and noise impacts in the Los Angeles area. These trucks are frequently identified as an early opportunity for zero-emission truck demonstrations due to their short routes and frequent stops; in fact, zero-emission drayage tractor-trailers are already in use in ports in California and China. Therefore, despite accounting for a relatively small share of greenhouse gas emissions, the electrification of this application can provide substantial benefits. Many trucks in drayage applications are purchased used, leading to lower costs for operators but higher emissions. However, the Port of Los Angeles and Port of Long Beach (which see about 15,000 trucks in drayage applications) have both enacted a Clean Trucks Program requiring the use of newer trucks; as of 2018, any new truck registered for use in the ports must be model year 2014 or newer (Clean Air Action Plan, 2018).

A study from the National Renewable Energy Lab on drayage truck activity around the Ports of Los Angeles and Long Beach provides a useful framework for assessing the infrastructure demands in this application (Prohaska, Konan, Kelly, & Lammert, 2016). The study found that the vast majority of drayage truck trips are short, low-speed trips within or near the port area; however, there are a substantial number of longer trips to railyards and the Inland Empire metropolitan area. The breakdown of truck trips used in the analysis is shown in Table 3. For all cases, our assumed breakdown matches the distribution observed for drayage trucks in the study by Prohaska et al. In reality, we would expect that initial demonstrations of zero-emission drayage trucks would be focused on near-dock applications where infrastructure needs are minimal.

Table 3. Typical drayage truck route profiles and frequency under different cases

Trip type	Port ↔ Near dock	Port ↔ Rail yards	Port ↔ Inland Empire	Port ↔ Beyond Inland Empire	Trip outside of port
Distance (miles)	5	20	50	80	30
Average speed (mph)	20	30	38	48	45
Percentage of truck trips	64%	10%	15%	2%	9%

The truck in the analysis was based on a popular Class 8 day cab, capable of carrying a 40-foot shipping container on a chassis trailer. Key specifications for the truck, as well as the battery electric and hydrogen fuel cell drivetrains, are listed in Table 4. This day cab truck has a smaller battery corresponding to its shorter trip lengths, enabling this battery electric truck to be slightly lighter than the diesel baseline. Again, we assume that the containers carried by these trucks average 75% of their maximum capacity by weight.

Table 4. Key specifications for zero-emission drayage truck

	Specification	Value	Notes
	GCVWR	60,700 lbs	
Battery electric	**Tare weight (truck and trailer)**	20,570 lbs	
	Total baseline battery size	500 kWh	80% available for use
	Electric motor power	500 kW	Equivalent to 670 HP diesel engine
	Energy consumption (without trailer)	1.9 kWh/mile	
	Range (no trailer)	212 miles	
	Range (fully loaded)	175 miles	
	Max fast charging speed	500 kW	
	Depot and port charging	50 kW	
Hydrogen fuel cell	**Onboard hydrogen storage**	50 kg	Stored at 70 MPa
	Energy consumption (without trailer)	13.6 miles/kg	
	Range (no trailer)	680 miles	
	Range (fully loaded)	530 miles	
	Hydrogen fueling rate	3.6 kg/minute	

As with long-haul tractor-trailers, we assume that battery electric drayage trucks have the opportunity to charge overnight, either at the port, a distribution center, or some other location. All trucks have the opportunity to charge during the port turnaround, at 50 kW for 20 of the 40 minutes between trips. Additionally, we assume that 33% of the non-port destinations will be equipped with 50-kW charging stations that can be used for 25 minutes between trips. For hydrogen fuel cell trucks, trucks are refueled when the hydrogen tank reaches 10%.

Delivery trucks. Delivery trucks are a broad, heterogeneous category, composed of medium- and heavy-duty trucks. They play an important role in the last mile of freight, supplying commercial, industrial, and residential addresses. Due to the wide diversity of vehicle types and applications, there is no uniform solution for infrastructure in this application. As an initial exploration, we consider the case of medium-duty Class 6 straight box trucks making regional deliveries and returning to a central depot. Larger, heavy-duty delivery trucks may behave similarly to the drayage trucks described above, and therefore have similar infrastructure needs.

As with other segments, we assume the same distribution of trips for each case. Table 5 outlines the breakdown of trips by distance in these three cases. The table also shows the driving time for each trip; we assume a 30-minute turnaround time at each end of the trip.

Table 5. Breakdown of delivery truck travel by distance

One-way trip distance	15 miles	30 miles	50 miles
Percentage of driving time	35%	35%	30%
Average trip time (minutes)	30	51	67

Although delivery trucks span many sizes, this analysis considers a Class 6 box truck based on a top-selling model in this segment. Key specifications for the delivery truck in this analysis are provided in Table 6 below. The truck is capable of carrying about 10,000 pounds of cargo.

Table 6. Key specifications for zero-emission delivery truck

	Specification	Value	Notes
	GCVWR	25,500 lbs	Class 6
Battery electric	**Tare weight**	10,564 lbs	
	Total baseline battery size	300 kWh	80% available for use
	Electric motor power	350 kW	Equivalent to 500 HP diesel engine
	Energy consumption (empty)	1.4 kWh/mile	Similar to Freightliner eM2
	Range (empty)	172 miles	
	Range (fully loaded)	164 miles	
	Max fast charging speed	350 kW	
	Depot charging	50 kW	
Hydrogen fuel cell	**Onboard hydrogen storage**	25 kg	Stored at 70 MPa
	Energy consumption (empty)	13 miles/kg	
	Range (empty)	330 miles	
	Range (fully loaded)	313 miles	
	Hydrogen fueling rate	3.6 kg/minute	

In each case, we assume that the vehicles perform out-and-back trips (leaving with cargo and returning empty) from a central depot; for battery electric vehicles, 50-kW charging is available at depots. We assume that charging is also available at 33% of the delivery docks outside of the depot. Turnaround time is 30 minutes at both ends, of which 23 minutes can be used for charging. The trucks are assumed to operate for 12 hours per day, representing multiple shifts. Additionally, we assume 50-kW charging is available overnight at depots. Fast charging at 350 kW accounts for the remainder of energy needs.

INFRASTRUCTURE ASSESSMENT

Fast charging needs assessment. We first assume that all trucks will receive a full charge overnight, using 50-kW charging at the home base or at a truck stop, as overnight depot charging is the first and most important component of fleet infrastructure provision (North American Council for Freight Efficiency, 2019). We determine the number of 50-kW charge points needed to provide sufficient overnight charging for the trucks, with additional chargers at a limited number of loading docks. For long-haul and delivery trucks, this requires a dedicated 50-kW overnight charge point for each truck in the low-volume case, with the high-volume case a more efficient ratio of one charge point for every 1.5 trucks, as trucks are not driving the same shift, and many will be able to use charge points in other settings for their overnight needs. For drayage trucks, we assume that most of the charging stations built at the port will also be used for overnight charging. We provide an additional 50-kW charge point for every two drayage trucks for overnight charging, meaning that in total there is about one 50-kW charge point for every 1.5 trucks.

Ultra-fast charging provides the remainder of the energy for the assumed travel requirements. For each vehicle route, we determine both the required number of fast charges and the amount of time needed for these charges, taking into account cases with and without charging available while loading. Charging time is optimized to maximize available driving time during the day. From this, we calculate the total amount of ultra-fast charging time required each day. This is translated into charge points through utilization in terms of average charging hours per day. As demonstrated in the light-duty sector, utilization increases with electric vehicle penetration; this is likely to be true in the heavy-duty sector as well, where routes are more defined and station locations can be carefully optimized (Nicholas & Hall, 2018). For drayage trucks, we use a similar methodology to calculate the number of 50-kW charging stations needed at the port, with utilization increasing over time.

Charging infrastructure costs. At this early stage of development, there is still considerable uncertainty around the specific technologies and costs for heavy-duty electric vehicle charging infrastructure. Currently, light-duty electric vehicle charging standards support up to 350-kW charging, but in practice there are very few charging stations capable of providing more than 140 kW, and few cars will be able to benefit from such power in the near term (Nicholas & Hall, 2018). Some electric buses are capable of charging at 500 kW using proprietary standards. However, industry stakeholders including Tesla and CharIN, developer of the combined charging system (CCS) standard, have stated that charging standards for heavy-duty vehicles should support power levels of at least 1 megawatt (CharIN, 2019; Tesla, 2018). As this technology has not yet been demonstrated, this analysis considers charging speeds of up to 500 kW; higher charging speeds could result in a need for fewer charging stations but at a higher cost per station.

Charging infrastructure costs consist of hardware cost for each individual station as well as the installation and grid connection costs per site. Estimates for these costs are illustrated in Figure 3 in terms of dollars per kilowatt. As seen by the blue and orange lines, the hardware costs for the two station types (50 kW or 350+ kW) do not vary by site size. The per-kW installation costs, however, decline as the total site power increases as grid connection and construction costs can be amortized over more stations. The installation and grid connection costs are based on the findings of a study in Ottawa, Canada (Ribberink, Wilkens, Abdullah, McGrath, & Wojdan, 2017).

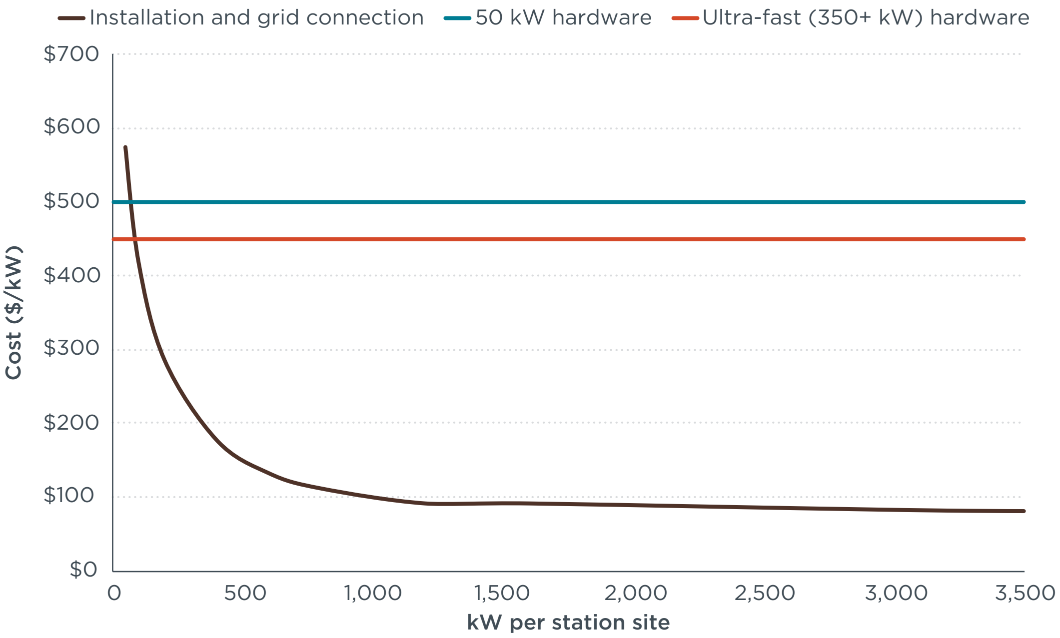

Figure 4. Estimated charging infrastructure hardware and installation costs, shown in dollars per kilowatt, for the low-volume case

This framework suggests that, for a given number of stations, it is generally less costly to build more stations at a few sites, rather than distributing the stations across many sites. For example, if one were to build 16 total 50-kW charging stations, it would cost $5.4 million to build these stations at two sites containing eight stations each, compared with $7.4 million at eight sites with two stations each. For any site with more than two charging stations, the charger hardware will represent the majority of the costs.

Based on experience with other innovations, we assume that the hardware costs of charging stations will decline over this period of analysis as a result of increasing scale and technology improvements. Specifically, we assume a 3% annual cost reduction for 350-kW and 500-kW stations and a 2% annual reduction for 50-kW stations, which are already produced at greater scale for light-duty electric vehicles. This translates to a 14% and 10% cost reduction at medium volume for ultra-fast and 50-kW stations respectively, and a 26% and 18% reduction at high volume. However, we do not reduce the installation costs, as greater scale and improved processes could be offset by the need to install in more challenging locations.

There are a number of tax credits or other incentives for electric vehicle charging stations. The California Electric Vehicle Infrastructure Project (CALeVIP) provides rebates for charging infrastructure in four California regions, with up to $80,000 available for DC fast-charging stations. Furthermore, there are additional innovative programs to generate funding for infrastructure. California's Low Carbon Fuel Standard (LCFS) provides higher credit accrual rates for heavy-duty vehicle charging, providing charging station operators with about $0.16 per kWh of electricity dispensed. This additional revenue could significantly improve the business case for building and operating charging infrastructure for trucks; however, we do not include these credits or incentives in our cost assessment.

Hydrogen fueling needs assessment. To evaluate the number of hydrogen fueling pumps required, we take a similar approach as with electricity. We first determine the energy, and corresponding amount of hydrogen fuel, required to enable our assumed travel patterns. Based on the fill rate, this is translated into average fueling time per truck per day. We then translate this into number of dispensers based on utilization in terms of active hours per day; as with charging stations, utilization increases over time, with large-scale deployment approaching the level seen at diesel fueling stations.

Hydrogen fueling station costs. As of early 2019, there were 39 retail hydrogen fueling stations open in California with more under construction, with at least 20 of these in the Greater Los Angeles area (California Fuel Cell Partnership, 2019). These stations are privately operated and have been supported by funding from the California Energy Commission, automakers, and other public and private sources (California Air Resources Board, 2018). Unlike electric vehicle charging infrastructure, hydrogen standards are similar for light-duty and heavy-duty vehicles, and many stations are already capable of serving both passenger and heavy commercial vehicles. Nonetheless, there has been some dedicated research into hydrogen fueling for heavy-duty vehicles, including the creation of the Heavy-Duty Refueling Station Analysis Model (HDRSAM) by Argonne National Lab, which provides best-available estimates of station capital and operational costs for a variety of configurations and operational profiles (see Argonne National Laboratory, 2017).

Capital costs for hydrogen fueling stations in this analysis are based (with some modifications) on the HDRSAM. Key assumptions on station attributes for the model are described in Table 7. All assumptions not listed in Table 7 use the default values in the model. The station sizes considered range from one to five dispensers, with larger stations becoming more common in the medium and high cases as utilization increases. The operational costs of the stations, which range from $0.43 to $1.07 per kg, are assumed to be integrated into the cost of hydrogen fuel.

Table 7. Station assumptions used to assess station capital costs

	Low volume (100 trucks)	Medium volume (1,000 trucks)	High volume (10,000 trucks)
Hydrogen delivery option	Tube truck delivery		
Production volume of components	Low	Mid	High
Hydrogen dispensing	Cascade, 700 bar		
Hydrogen fueling rate	3.6 kg/minute		
Start-up year	2020	2025	2030

As with electric vehicle charging, numerous programs have emerged to help fund hydrogen fueling stations. The LCFS in California includes provisions to provide credits based on the capacity of hydrogen fueling stations rather than the amount of fuel dispensed; this could make the operation of these stations more lucrative during early market stages. Public-private partnerships among the government, hydrogen manufacturers, and automakers have been crucial for building out the light-duty hydrogen network in California, a model that may also be useful for the heavy-duty market. A deeper analysis of how to fund infrastructure for these applications could be an area for future research.

Station sizing and distribution. Although this research does not attempt to suggest exact locations or sizes for charging or refueling stations, the relative distribution of stations of different sizes will impact infrastructure costs. Particularly in the early market, a less-concentrated network of stations enables greater flexibility in terms of charging, reducing unnecessary driving. Therefore, for each mode, our low-volume case assumes that stations are more widely distributed at smaller sites, while the stations are relatively more clustered with a greater average number of stations per site when considering higher volumes.

The experience with natural gas fueling stations for heavy-duty vehicles provides an example for how hydrogen fueling or ultra-fast charging networks could develop. Compressed natural gas (CNG) stations have many similarities in design and operation to gaseous hydrogen stations in particular but may bear resemblance in network design to ultra-fast charging stations as well. As of May 2019, there are 751 CNG public filling stations available for heavy-duty trucks in the United States with 1,477 dispensers (U.S. Department of Energy, 2019). Thirty-six percent of stations had a single dispenser, 43% had two, 10% had three, 10% had four, and the remaining 1% of stations had five or more dispensers. We assume that, in the high-volume case, hydrogen and ultra-fast charging station sites will be similarly distributed. In the low- and medium-volume cases, station size distributions are further skewed toward stations with one or two dispensers.

For 50-kW charging stations, which are used by battery electric trucks at distribution hubs, loading docks, and at port, we assume a greater concentration, with a large share of stations in the medium- and high-volume cases located at sites with 8 or more chargers. This reflects the likelihood that initial deployments of electric trucks will be concentrated in relatively few fleets using depot charging. However, we also incorporate many smaller sites with one or two chargers, potentially located at loading docks and truck stops, which would face higher per-charger installation and grid connection costs.

WEIGHT AND TIME PENALTY

Battery electric trucks could face additional challenges compared with diesel trucks due to the weight of batteries and the time spent charging. At a battery density of 0.2 kWh/kg, the 600-kWh battery would weigh 3,000 kg. Other components of the battery electric powertrain are estimated to weigh approximately 600 kg. However, the engine, transmission, and fluids in a conventional diesel truck also weigh approximately 3,000 kg (Sharpe, 2019). Therefore, the total loss in cargo capacity is approximately 600 kg, or 3% of the cargo capacity. If a 1-megawatt-hour (MWh) battery was used instead, the resulting loss in cargo capacity would rise to 11%. For delivery trucks, the added mass of the 300-kWh battery pack reduces the maximum cargo capacity of the battery electric truck by about 6% compared with the diesel version. The drayage truck in our scenario, with a 500-kWh battery, weighs slightly less than the diesel equivalent in our scenario. Hydrogen trucks in all applications weigh less than their diesel or battery electric counterparts.

For those segments in which the battery electric truck weighs more than a diesel equivalent, we assume that additional trucks will be needed, a cost which we incorporate into the per-truck analysis. We assume that 50% of trucks would be fully loaded and therefore face this penalty. For example, this means that a fleet operating delivery trucks, with an 11% lower cargo capacity, would need 5.5% more trucks, and therefore face 5.5% higher fleetwide costs. However, it is important to note that policies could reduce or negate this challenge. In California, Assembly Bill 2061, passed in 2018, increases the weight limit for zero-emission trucks by 2,000 pounds over the normal limit for diesel trucks of that class (California Legislative Information, 2018). This allowance negates the weight penalty for all applications in this analysis.

Additionally, battery electric trucks could face a disadvantage due to the amount of charging time required, which could cut into driving time. We assume that if a fleet loses driving time due to charging, additional trucks must be purchased, proportionally increasing fleetwide costs. This cost is calculated separately for each application to account for driving regulations for long-haul tractor-trailers. For drayage and delivery trucks, any time spent fast charging cuts in to active time; for both of these applications, we estimate the average daily fast-charging time at 30 minutes. Faster charging, such as the megawatt standards being developed, could reduce this penalty. Fueling with hydrogen requires a similar amount of time as diesel; therefore, we do not include a time penalty for hydrogen trucks in our analysis.

ANALYSIS

Using the above methodology, we estimate the amount of infrastructure, and the associated outlay, required to power fleets of zero-emission trucks. We do not attempt to site or determine the ideal spatial distribution of infrastructure outside of our assumptions about utilization and station size. Each application is analyzed separately without considering how multiple kinds of vehicles could use the same stations; this strategy could ultimately offer the potential for higher utilization in the near- to medium-term if multiple truck applications typically utilized the same stations. Where there is a time-dependent assumption for cost estimates, we assume that the low-volume case occurs in 2020, the medium-volume case in 2025, and the high-volume case in 2030.

BATTERY ELECTRIC CHARGING INFRASTRUCTURE

The charging infrastructure for electric trucks consists of both ultra-fast charging (350–500 kW) as well as slower (50 kW) charging used overnight and while stopped for loading or unloading. Figure 5 illustrates our estimates for the amount of charging infrastructure needed on a per-vehicle basis (lines and markers, plotted on the right axis), as well as the associated per-vehicle costs for that infrastructure (bars, plotted on the left axis). For both metrics, the results are separated into the 50-kW and ultra-fast infrastructure. The costs also include interest, assuming that these costs are amortized at a 5% interest rate over 80 months, adding 20% to the underlying capital costs.

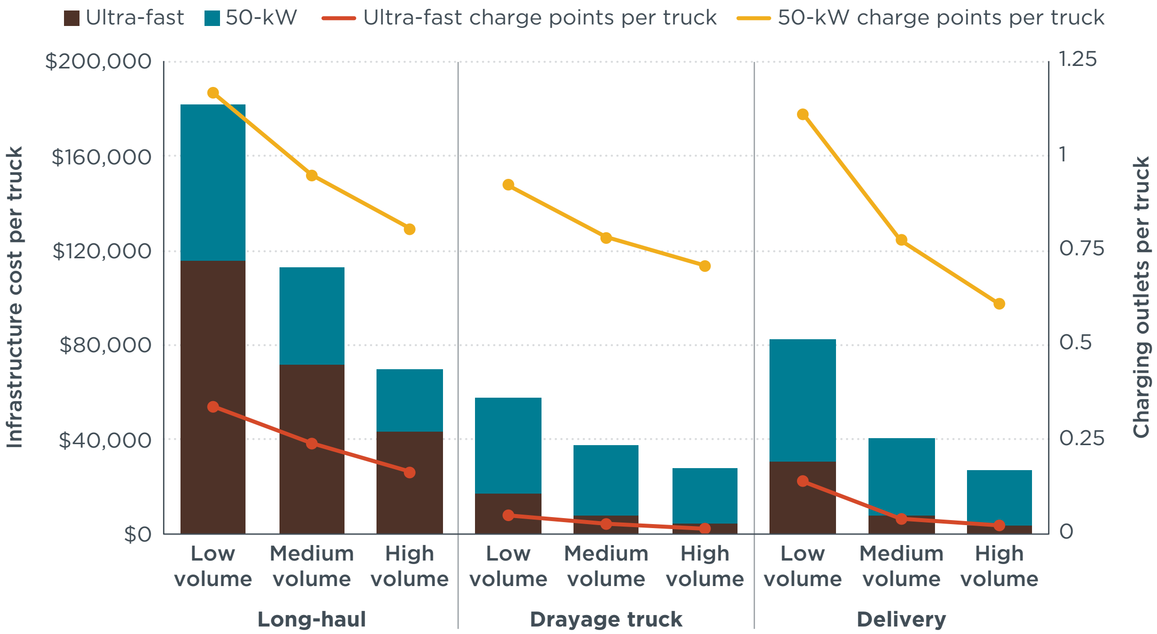

Figure 5. Charging infrastructure and associated capital costs required for battery electric trucks

A number of trends are visible from this chart. First, long-haul tractor-trailers have by far the highest associated infrastructure costs among the three applications, up to $180,000 per truck at low volumes and falling to $69,000 at high volumes. This is followed by delivery trucks ($27,000–$82,000); drayage trucks have the lowest charging infrastructure costs ($28,000–$58,000). This is due to the longer driving distances and heavier vehicle weight, and therefore greater energy consumption, of long-haul tractor-trailers, as well as a lower concentration of charging stations due to the need for a comprehensive, far-reaching network.

Second, there is a general trend of declining cost per truck as truck volumes increase, although this occurs less strongly for drayage and delivery trucks. These cost declines are due to a combination of factors, including falling hardware costs, higher station throughput, improving vehicle efficiency, and more efficient station network design with more chargers per site. This result, however, is sensitive to the truck travel patterns; increasing travel distance and route diversity at greater scale will result in higher total costs (but not necessarily cost per mile). This especially the case for drayage trucks: We estimate that drayage trucks operating on routes of up to 30 miles need no fast charging. Fast charging needs increase significantly as the trucks are deployed onto longer routes to the Inland Empire or beyond, driving up the cost per truck.

Third, ultra-fast charging stations account for a disproportionate share of the costs of charging infrastructure. Specifically, ultra-fast charging accounts for over 60% of infrastructure costs in the long-haul sectors, but 50-kW stations represent about 80% of the chargers by number. For delivery and drayage trucks, where ultra-fast charging plays a smaller role, 50-kW charging represents the majority of costs. For drayage trucks, we estimate that 30% to 45% of these chargers should be located at the port, with the remainder at overnight parking locations or other loading docks. In the case of delivery trucks, 50-kW charging also represents the majority of the cost, and most of this is located at overnight charging depots. For battery electric long-haul and delivery trucks, more than one 50-kW charger is required per truck in the early stages, as we consider chargers at both overnight depots and some loading docks.

In addition to the capital cost of infrastructure, transitioning to battery electric trucks could pose challenges in terms of the time spent charging, especially for long-haul trucking. Figure 6 displays the average time spent charging at ultra-fast chargers (up to 500 kW) per day for drivers on each of the five routes considered (using 2020, low-volume vehicle specifications). The brown bars represent the time required if 50-kW charging is available at the loading depots at each end, while the blue bars represent the time required if no such charging while loading or unloading is available. For all cases, it is assumed that the truck begins the day with a full charge.

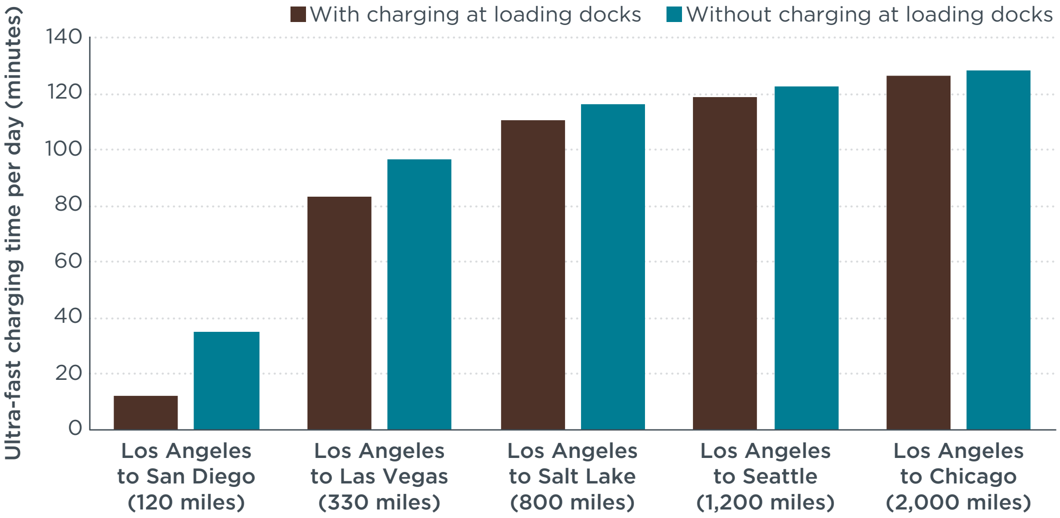

Figure 6. Daily ultra-fast charging time required on various routes from Los Angeles

As expected, the average daily time spent fast charging increases with the route length, up to 2 hours for a driver on the route to Chicago without charging available at depots. Although this is a significant amount of time, and much higher than is required to refuel a diesel- or hydrogen-powered vehicle, it does not significantly affect total daily driving time within legal limits. However, on the Los Angeles to Las Vegas route (and routes of similar length) where both charging and loading time are significant, drivers could lose over an hour of eligible driving time per day due to the charging requirements, reducing driving time by up to 15%. The reduced need for fast charging on short routes in the 100- to 200-mile range indicates that these routes could be an ideal test case for early deployments of battery electric trucks.

HYDROGEN FUELING STATIONS

Our estimates for the number of hydrogen fueling stations and the associated capital costs are presented in Figure 7. The brown vertical bars represent the infrastructure costs on a per-truck basis including interest costs. The lines represent the number of station locations (blue) and the number of dispensers (yellow) per truck; for example, in the medium-volume long-haul case, there is about one dispenser for every 25 trucks and one station site for every 40 trucks. The ratio between these two values indicates the number of pumps per station. As with natural gas fueling, the average number of pumps per site increases somewhat from about 1.5 in the low-volume case to 2 in the high-volume case.

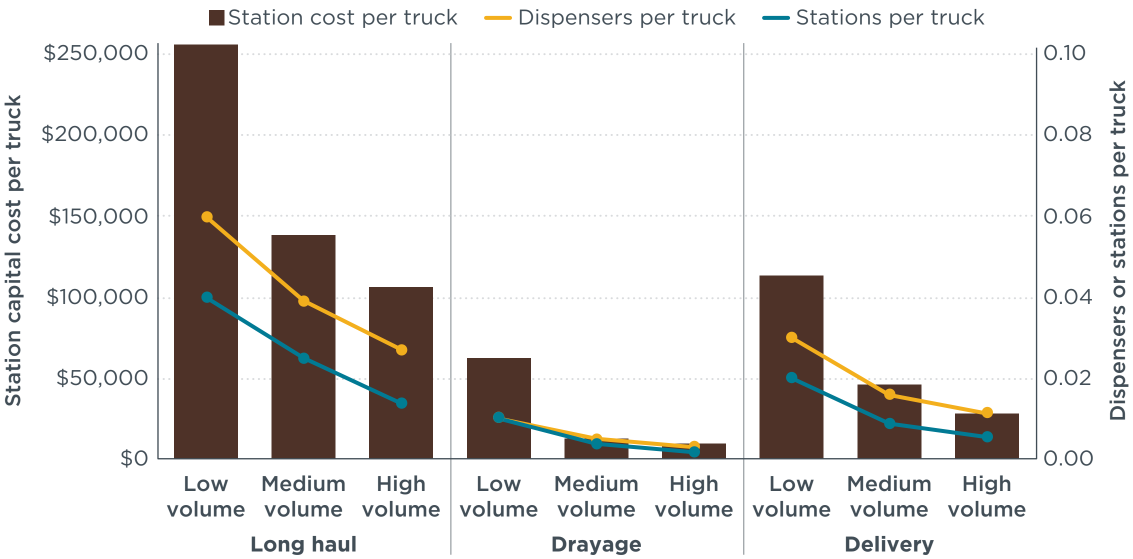

Figure 7. Hydrogen fueling infrastructure and associated capital costs for hydrogen fuel cell trucks

This figure offers insights about the deployment of fueling infrastructure for fuel cell heavy-duty trucks. First, long-haul tractor-trailers demand the most infrastructure investment by a large margin, followed by delivery trucks and drayage trucks. This is the same pattern as for electric charging infrastructure. Second, costs per truck decline significantly as scale increases, with large cost declines from the first 100 trucks to the first 1,000 trucks and more moderate declines afterward. This trend is consistent across each application. The cost reductions are attributable to the higher utilization of stations, as well as the increasing number of pumps per station and the falling component costs with increasing scale.

This analysis suggests that infrastructure for the hydrogen pathway is generally costlier than battery electric; however, the difference is far from uniform. For drayage trucks, battery charging infrastructure is more than twice as costly as hydrogen fueling infrastructure for the medium- and high-volume cases. Hydrogen faces the largest cost penalty in the near-term, when stations see low utilization. We note that there is significant uncertainty regarding infrastructure for all kinds of zero-emission heavy-duty vehicles. For example, grid connection costs for extremely high-power charging stations (upwards of 4 MW at a site) are not well-known and could result in higher costs.

IMPLICATIONS FOR COST OF OWNERSHIP

This analysis indicates that the infrastructure for zero-emission heavy-duty trucks will require significant funding, particularly for long-haul tractor-trailers and in early phases of deployment. However, it is important to place these expenses in the context of the total cost of ownership (TCO) of these powertrain options. This section outlines how infrastructure contributes to the TCO for each application, adding these infrastructure costs to vehicle purchase, fuel or energy, and maintenance expenses. Because we expect higher numbers of each truck to be deployed as technology improves, we have assigned cost estimates accordingly: The low-volume (100 trucks) case is assigned 2020 cost estimates, the medium-volume (1,000 trucks) case is estimated at 2025 costs, and the high-volume (10,000 trucks) case uses 2030 costs. We assume that the trucks deployed in each case perform similar duty cycles over their 10-year initial lifetime, and that annual miles decline 2% each year.

These results are applied to the TCO analysis framework in Moultak et al., tailored for the three applications. The previously described battery electric and hydrogen fuel cell trucks (using either methane-derived or renewable hydrogen) are compared with conventional diesel trucks. Selected component costs such as batteries and electric motors have been updated based on new research (see Lutsey & Nicholas, 2019). Details on the assumptions used for cost projections can be found in the Appendix. Diesel prices are based on the U.S. Energy Information Administration's reference case estimates for the Pacific region, with updated California tax rates (Energy Information Administration, 2019). Electricity prices are based on Southern California Edison's industrial customer rates, with 2% projected annual increase; ultra-fast charging is assumed to cost 57% more than overnight 50-kW charging as a result of demand charges. We derive maintenance costs from the AFLEET model by Argonne National Laboratory (see Burnham, 2018). Vehicle and infrastructure capital costs are amortized over an 80-month period at a 5% interest rate, and a 4% discount rate is used for future fuel and maintenance expenses.

Long-haul tractor trailer. This is the largest, most expensive vehicle type, and also consumes the most fuel due to the long journeys. Figure 8 illustrates how battery electric and hydrogen fuel cell tractor-trailers compare with conventional diesel in terms of TCO over a 10-year lifetime, including infrastructure costs. The bars represent the four primary cost drivers: vehicle capital cost, maintenance, fuel or energy, and the infrastructure per vehicle. The vehicle cost includes the tractor and three trailers, which are identical for each powertrain. In most cases, fuel or energy costs make up the largest portion of TCO. The green bars represent the cost of additional tractor-trailers due to the "weight penalty" from batteries, which means that fleets would have to be approximately 1% larger to carry the same cargo, although recent regulations negate this issue for zero-emission trucks in California. The tan bars represent an added "time penalty" representing increased fleet size required to make up for lost driving time spent charging. For 2020, this is estimated to be about a 3% penalty across the fleet (with some routes being higher), with later years seeing lower penalties due to greater efficiency. Hydrogen tractor-trailers do not face weight or time penalties as their weight and refueling times are comparable to diesel.

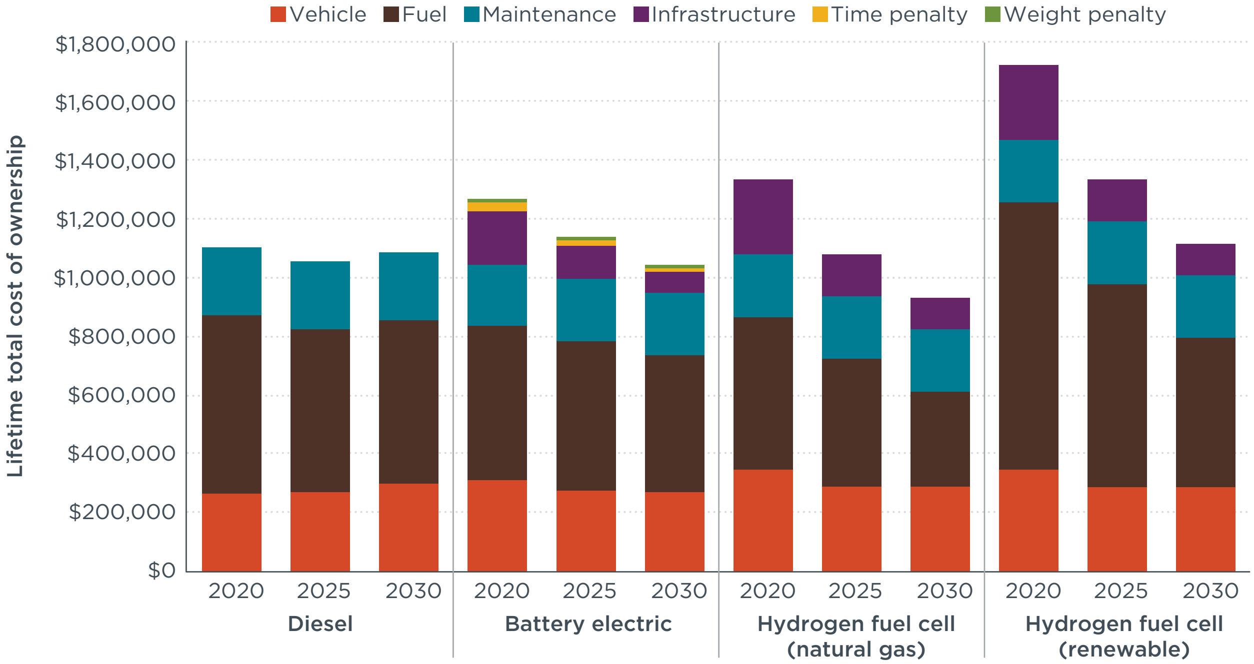

Figure 8. Total cost of ownership for diesel, electric, and hydrogen fuel cell long-haul tractor-trailers

This figure indicates that infrastructure costs can represent a significant increase to TCO for zero-emission tractor-trailer trucks, generally representing between 10% and 20% of the TCO but decreasing over time. In the 2025 case, charging infrastructure adds over $110,000 per battery electric long-haul tractor-trailer, amounting to 10% of the lifetime operating cost, which includes vehicle, fuel, maintenance, and infrastructure. At greater scale in 2030, charging infrastructure costs add about $70,000 per battery electric long-haul tractor, amounting to 7% of the lifetime operating cost. Hydrogen infrastructure for the fuel cell tractors is estimated at $105,000 per tractor by 2030, or 9% of the lifetime operating cost.

In terms of vehicle cost in Figure 8, a battery electric tractor-trailer costs $49,000 more upfront than a comparable diesel tractor-trailer in 2020. Diesels remain the least expensive through approximately 2026, when battery electric tractor-trailers become less expensive. Hydrogen fuel cell tractor-trailers are projected to be less expensive than diesel by 2028. By 2030, battery electric tractor-trailers are expected to be $26,000 less expensive than diesel in purchase price, and fuel cell tractor-trailers will cost approximately $13,000 less than diesel.

The figure illustrates that zero-emission tractor-trailers can offer lower costs than traditional diesel equivalents. Battery electric tractor-trailers meet TCO parity with diesel tractor-trailers by 2030. Fuel cell tractor-trailers using hydrogen derived from natural gas through steam methane reformation (SMR) reach cost parity with diesel counterparts between 2025 and 2028, while operating those tractor-trailers with renewable hydrogen suggests a 3% TCO penalty versus diesel even in 2030. Nonetheless, fuel cell tractor-trailers could remain compelling for their operational benefits relative to battery electric options, considering their short refueling times and lighter tractors.

The lifetime ownership cost of each zero-emission option is expected to steadily decline from 2020 to 2030 as a result of falling vehicle costs and improved efficiency, as well as less expensive hydrogen fuel for fuel cell vehicles. On the other hand, increasing fuel and vehicle costs are projected to outweigh savings from efficiency improvements for diesel tractor-trailers in the 2025 to 2030 time frame, resulting in a higher lifetime cost for a truck purchased in 2030 than in 2025. This suggests that the TCO and upfront price savings for zero-emission tractor-trailer options will only accelerate after 2030.

Acknowledging the many assumptions required in modeling the costs associated with these technologies, a simple sensitivity analysis was performed on key assumptions around battery electric long-haul tractor-trailers. We find that TCO is relatively insensitive to the vehicle's battery size; increasing or decreasing battery capacity by 50% increases TCO by only 1% in the 2030 time frame. For a larger battery, higher vehicle cost is offset by reduced infrastructure and time penalty costs. Total ownership costs are sensitive to vehicle efficiency; a 15% increase or decrease in energy consumption per mile results in a 9% increase or decrease respectively in lifetime cost. Further details on the sensitivity analysis are reported in the Appendix. We report numbers for our 2030 high-volume case, but effects in the 2025 medium-volume case are very similar.

Drayage trucks. Drayage trucks typically see much lower mileage than long-haul tractor-trailers, significantly altering the composition of their lifetime costs and providing different prospects for zero-emission variants. Figure 9 provides an overview of the TCO for each technology option for new drayage trucks. The color scheme and layout are the same as in Figure 8 above. Electric drayage trucks also face a small "time penalty," assumed to equal the percentage of the day dedicated to fast charging (compared with an assumed 5 minutes spent fueling); this increases fleetwide cost by less than 1% in our analysis. Vehicle costs represent a much higher share of the TCO for drayage trucks than for other applications. As with the long-haul sector, vehicle costs include the tractor as well as three container trailers.

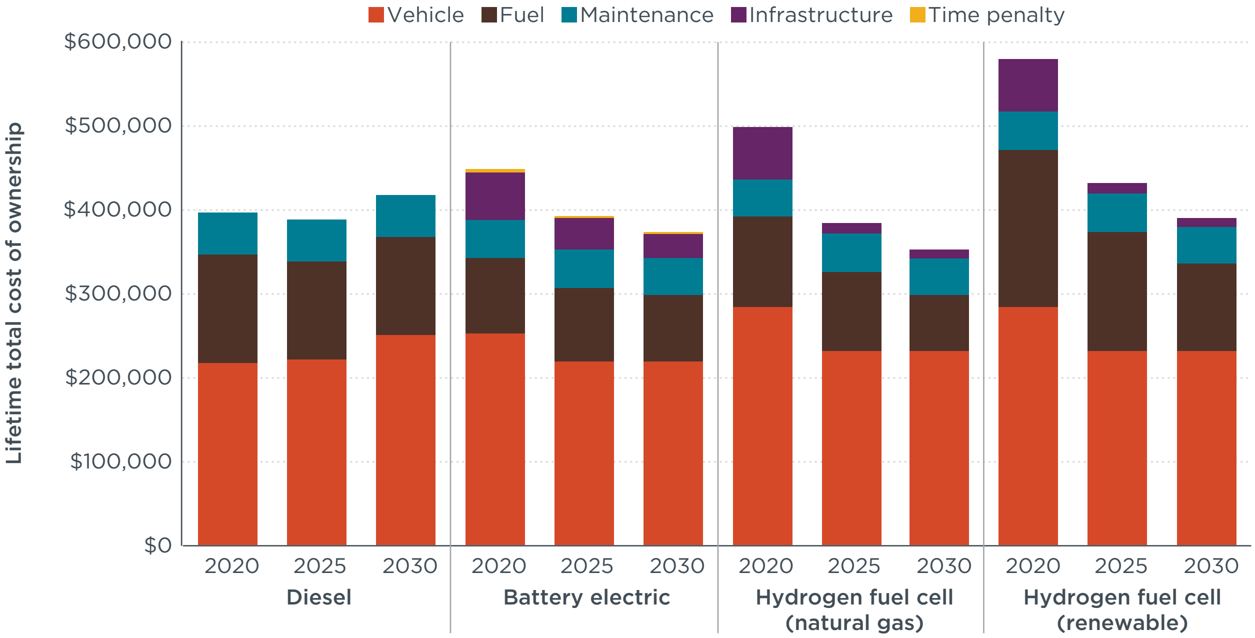

Figure 9. Total cost of ownership for diesel, electric, and hydrogen fuel cell Class 8 drayage trucks

For the drayage truck application, infrastructure needs for battery electric and hydrogen trucks alike are far less complex and represent only a small share of TCO. In the 2025 case, charging infrastructure adds $38,000 per battery electric drayage tractor, amounting to 10% of the lifetime operating cost. At greater scale in 2030, charging infrastructure costs add approximately $28,000 per battery electric drayage truck, amounting to 7% of the lifetime operating cost. Hydrogen infrastructure for the fuel cell drayage trucks is estimated at $10,000 per truck by 2030, or 3% of the lifetime operating cost.

The lower annual mileage in this application reduces the potential savings in fuel and maintenance, as compared with the long-haul tractor-trailer case. We estimate that battery electric trucks in the 2020 case are costlier over their lifetime than their diesel counterparts by $69,000, with an upfront cost premium of $35,000. By 2030, however, the TCO of a battery electric truck is 11% lower than diesel, and the truck purchase price is $31,000 less. Although we estimate that hydrogen trucks are costlier in the near term, they too become less expensive than diesel from a TCO standpoint: in about 2025 for hydrogen from SMR and around 2028 for hydrogen from renewable sources. We also anticipate that the upfront costs of both battery electric and fuel cell trucks will fall below that of diesel trucks in this application before 2030.

Many trucks used in drayage applications are purchased used rather than new. Even within the model year constraints imposed by the San Pedro Bay Ports, a 5-year-old truck can cost up to two-thirds less than a new truck with similar specifications. This in turn would reduce the 10-year TCO for the diesel truck by about 45% (although fuel and maintenance expenses could increase somewhat), eliminating any TCO benefit for a new battery electric or fuel cell truck even in 2030. This reveals a complexity for converting drayage trucks to zero emissions, despite the other promising benefits of zero-emission trucks in this application. Further tightening the Clean Trucks Programs at the ports could help to reduce this disparity in the future; in the long run, a second-hand market for zero-emission trucks could also emerge to serve this application.

Delivery trucks. Delivery trucks lie between long-haul tractor-trailers and drayage trucks in terms of travel distances and infrastructure requirements; these smaller trucks also have lower vehicle costs and higher efficiency than the Class 8 trucks in previous examples. Figure 10 below displays a similar TCO calculation, including infrastructure, for these trucks under the cases described above. Once again, the colored bars represent the cost of each component of ownership costs over the lifetime of the truck in 2018 dollars. As with long-haul tractor-trailers, the green bars illustrate the penalty that fleets would face due to the reduced cargo capacity of battery electric trucks assuming that 50% of trips are carrying the maximum cargo weight.

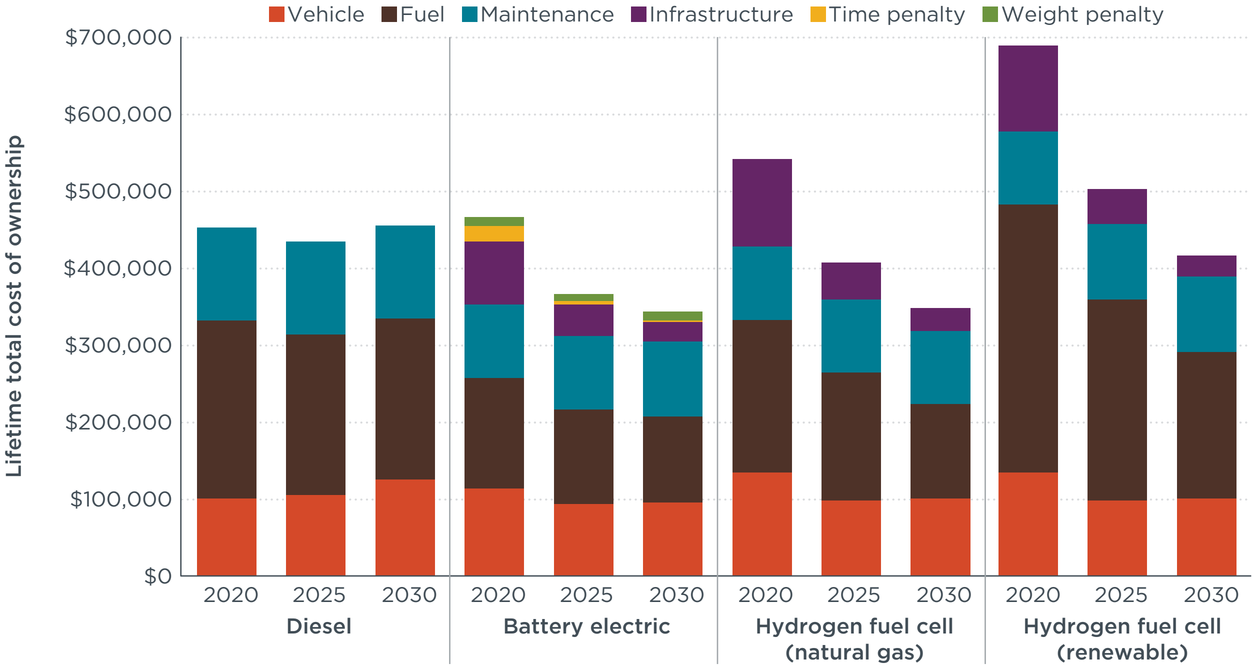

Figure 10. Total cost of ownership for diesel, electric, and hydrogen fuel cell Class 6 delivery trucks

In this analysis, delivery trucks present the most favorable cost picture for zero-emission technologies. Battery electric trucks, even when including the cost of overnight and fast-charging stations, cost approximately 3% ($14,000) more to operate over their lifetime in 2020; the upfront purchase price of the vehicle is about $12,000 more. By 2030, the vehicle upfront cost is $30,000 lower, while the lifetime savings are over $100,000. Hydrogen fuel cell trucks are also economically attractive with higher volumes: Fuel cell trucks using natural gas-derived hydrogen reach TCO parity with diesel in the early 2020s, and even renewably derived hydrogen reaches TCO parity with diesel in 2028 and upfront vehicle cost parity in 2024.

In terms of the infrastructure costs for the delivery trucks, charging infrastructure adds over $40,000 per battery electric in the 2025 case, amounting to 13% of the lifetime operating cost. At greater scale in 2030, charging infrastructure costs add approximately $27,000 per battery electric delivery truck, amounting to 9% of the lifetime operating cost. Hydrogen infrastructure for the fuel cell delivery applications are estimated at $29,000 per truck by 2030, or 7% to 8% of the lifetime operating cost.

Summary of infrastructure and ownership costs. Table 8 summarizes the principal quantitative findings of this analysis. The table illustrates the amount of infrastructure, associated infrastructure capital cost (on a total and per-vehicle basis), and TCO comparison (as percentage difference from diesel) for each of the applications and cases analyzed. The infrastructure counts shown are for the number of electric chargers at 50 kW and higher or the number of hydrogen fueling dispensers; the number of charging and fueling sites will be lower. The TCO incorporates all infrastructure capital costs and associated financing, for which the truck operators may not be fully responsible. For hydrogen vehicles, the ownership cost assumes using renewable hydrogen; using methane-derived hydrogen results in significantly lower costs, but much higher CO_2 emissions.

Table 8. Charging and hydrogen infrastructure for increasing truck volume in three applications

Technology	Application	Case[a]	Number of trucks	Charging outlets needed	Infrastructure cost (million)	Infrastructure cost per truck (thousand)	Vehicle ownership cost difference from diesel
Electric	**Delivery** (Class 6, 9.75-13 tons)	Low volume	100	130	$8	$82	0% to +5%
		Medium volume	1,000	820	$40	$40	-15% to -10%
		High volume	10,000	6,300	$270	$27	-25% to -20%
	Drayage (Class 7-8, 13+ tons)	Low volume	100	100	$6	$58	+10% to +25%
		Medium volume	1,000	810	$38	$38	0% to +5%
		High volume	10,000	7,300	$280	$28	-15% to -10%
	Long haul (Class 8, 16.5+ tons)	Low volume	100	150	$18	$182	+13% to +18%
		Medium volume	1,000	1,200	$113	$113	+5% to +10%
		High volume	10,000	9,700	$700	$70	-5% to 0%
Hydrogen fuel cell	**Delivery** (Class 6, 9.75-13 tons)	Low volume	100	3	$11	$113	+50% to +55%
		Medium volume	1,000	16	$46	$46	+15% to +20%
		High volume	10,000	112	$290	$29	-10% to -5%
	Drayage (Class 7-8, 13+ tons)	Low volume	100	1	$6	$62	+40% to +50%
		Medium volume	1,000	5	$13	$13	+10% to +15%
		High volume	10,000	33	$100	$10	-10% to -5%
	Long haul (Class 8, 16.5+ tons)	Low volume	100	6	$26	$255	+50% to +60%
		Medium volume	1,000	39	$139	$139	+20% to +30%
		High volume	10,000	271	$1,060	$106	0% to +5%

[a] Low volume applies to 2020; medium volume to 2025; high volume to 2030

CONCLUSIONS

This paper builds on previous analyses of the costs and feasibility of zero-emission heavy-duty freight trucks by assessing the infrastructure needs and related costs for the transition to zero-emission trucks operating in three applications in the Los Angeles, California, area. Specifically, we estimate the number and cost of charging stations for battery electric trucks, and of hydrogen refueling stations for fuel cell trucks, operating in long-haul tractor-trailer, port drayage, and local delivery applications. From this analysis, we draw the following conclusions.

Falling technology costs are making zero-emission trucks increasingly cost-competitive. Cost declines in batteries and electric motors in particular make battery electric trucks less expensive than diesel trucks in purchase price between 2025 and 2030. Obstacles such as charging time and reduced cargo capacity could add complications and costs for electric fleets beginning the transition. Fuel cell trucks could also become less expensive in upfront cost before 2030. As demonstration projects scale up and learning from other sectors continues, cost declines in hydrogen fueling stations and ultra-fast charging infrastructure will be important in transitioning the long-range applications that account for the greatest share of truck fuel use and emissions.

Infrastructure costs are significant, but do not fundamentally impede the viability of zero-emission trucks. Whether constructed by fleets, third parties, or public agencies, charging infrastructure and hydrogen refueling infrastructure pose significant costs for zero-emission trucks, particularly in the early stages of deployment. The per-tractor charging infrastructure costs for electric long-haul tractor-trailers range from $113,000 at lower volumes in the 2025 time frame, to $70,000 at higher volumes in the 2030 time frame. For long-haul fuel cell tractor-trailers, hydrogen infrastructure costs could be as much as $140,000 at low volumes, declining to around $105,000 at larger scale. As scale increases, infrastructure represents a decreasing portion of total operating expenses. In 2025, at the scale of about 1,000 trucks, infrastructure represents about 10% to 14% of the total cost of ownership, whereas this share drops to 7% to 10% in the 2030 time frame with tens of thousands of trucks.

When including these infrastructure costs in overall operating costs, both battery electric and hydrogen fuel cell long-haul tractor-trailers have the potential to be less expensive than diesel trucks in the 2030 time frame at a scale of about 10,000 trucks. Delivery trucks offer even more promising reductions, with total cost of ownership for battery electric trucks falling below that of diesel trucks in the early 2020s and even renewable-powered hydrogen trucks reaching lifetime cost parity before 2030.

If infrastructure costs are excluded from TCO calculations, fleets would see lifetime ownership benefits from zero-emission long-haul tractor-trailers in the early 2020s, five to 10 years earlier than if the fleets cover the infrastructure costs directly. As a result, sharing the infrastructure costs with some combination of governments, utilities, and other providers could enable much faster adoption of zero-emission trucks. Innovative programs such as California's Low Carbon Fuel Standard could help to provide funding needed to build infrastructure in the early stages of the market. Drayage trucks require much less costly infrastructure, making them an ideal case for early demonstration projects, but face additional market barriers, as the fleets are typically comprised of older, less expensive trucks.

Initial infrastructure buildouts will be costly without careful planning and coordination. Early deployments of zero-emission trucks, at the scale of 100 vehicles, would mean high infrastructure expenditures with low utilization to build a network capable of supporting vehicles' duty cycles. It is therefore especially important to plan these initial deployments to specific fleet operation routes and applications where duty cycles are dependable and less onerous, such that a relatively small number of stations can serve all of the recharging or refueling needs. For battery electric trucks, providing charging overnight and at loading and unloading locations can reduce ultra-fast charging needs and total costs. Additionally, coordination among different fleets and operators could help to distribute the high initial costs by enabling multiple types of vehicles to share the same infrastructure. Government-led programs and public-private partnerships could help to coordinate investments. As the market grows, infrastructure should see higher utilization and expansions can be concentrated at a smaller number of sites, eventually leading to a business case for construction and operation of charging or refueling networks.

Policy will be needed to spur this transition to zero-emission trucks. This analysis was focused on the shift from hundreds to tens of thousands of zero-emission trucks in three freight applications. To move through these steps, new zero-emission truck models need to be developed and improved, with continued investments to bring greater volume and lower costs. With policy and government support, such as the zero-emission truck regulation that California is considering, the scale of the changes assessed in this report could happen within 10 years, but without such policy it could take decades (California Air Resources Board, 2019). Regulations, coupled with financial incentives and public funding or sharing of infrastructure costs, could enable a more rapid shift toward zero-emission vehicles. Additionally, other agencies such as ports and electric utilities can play crucial roles in building infrastructure and overcoming the many barriers that zero-emission trucks face.

This analysis offers both encouraging findings for the feasibility of introducing zero-emission trucks as well as an indication of the scale of investment and planning that will be needed to build the infrastructure associated with this transition. The findings also indicate numerous opportunities for further research. Because vehicle fleet operations and duty cycles vary widely among and within countries, similar analyses could estimate how charging needs and cost dynamics might differ elsewhere. Quantifying the impact of ultra-fast charging on the electric distribution grid, as well as evaluating opportunities for smart charging in these applications, could help to guide utility planning and minimize grid upgrade costs. The topic of coordination and cross-use of infrastructure for different types of fleets, including usage of infrastructure by both light- and heavy-duty vehicles, requires additional study. A third type of zero-emission trucks, e-roads powered by catenary lines in-road dynamic charging, could also be considered for applications with concentrated traffic and high power use. Despite substantial costs and uncertainties, it is evident that zero-emission trucks, and the many air quality and climate benefits they will bring, are on the way.

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APPENDIX

DETAILS ON ANNOUNCED AND PRODUCTION ZERO-EMISSION TRUCKS

Table A1. Announced or in-production battery electric medium- and heavy-duty trucks

Make	Model	Range (miles)	Battery capacity (kWh)	Vehicle class	First demonstration	Start of regular production
Eforce	EF18 SZM	310	630	8 (Tractor-trailer)	2016	2017
Eforce	EV26	310	630	8 (Straight truck)	2016	2017
Thor	ET-One	300	800	8 (Tractor-trailer)		2019
Volvo	FL Electric	186	300	7		2019
BYD	Day Cab	167	435	8 (Tractor-trailer)		2018
emoss	EMS 18 Series	155	240	8 (Straight truck)	2017	2018
emoss	EMS 16 Series	130	200	8	2015	2018
emoss	EMS 12 Series	124	200	7	2013	2018
BYD	Class 6 Truck	124	221	6		2018
Cummins	AEOS	100	140	7	2018	2019
emoss	EMS 10 Series	93	120	6	2014	2018
Mitsubishi FUSO	eCanter	62	83	4	2017	2019
Tevva	eTruck	93	75	4-6		2018
Tesla	Semi	550	1000	8 (Tractor-trailer)	2018	2020
Nikola	Two	400	1000	8 (Tractor-trailer)	2019	
Freightliner	eCascadia	250	550	8 (Tractor-trailer)	2018	2021
Lion	Lion8	250	480	8	2018	2020
Freightliner	eM2 106	230	325	5	2018	2021
Mercedes-Benz	eActros	125	240	7-8 (Straight truck)	2018	2021
MAN	eTGM	124	150	7-8 (Straight truck)	2018	
Volvo	VNR	124	300	8	2019	2020
Volkswagen	e-Delivery	124	200	4	2018	2020
Peterbilt	e220	100	148	6	2019	
Xos	MDV	50	60	6	2018	2020
Eforce	EF18 SZM	310	630	8 (Tractor-trailer)	2016	2017
Eforce	EV26	310	630	8 (Straight truck)	2016	2017
Thor	ET-One	300	800	8 (Tractor-trailer)		2019
Volvo	FL Electric	186	300	7		2019
Volkswagen	e-Delivery	124	200	4	2018	2020
Peterbilt	e220	100	148	6	2019	
Xos	MDV	50	60	6	2018	2020

Table A2. Announced or in-production hydrogen fuel cell medium- and heavy-duty trucks

Make	Model	Range (miles)	Vehicle class	First demonstration	Start of regular production
Nikola	One	1000	8 (Tractor-trailer)		2022
Toyota	Beta	300	8 (Tractor-trailer)	2018	
Kenworth	T680	300	8 (Tractor-trailer)	2019	
Hyundai	XCient	238	8 (Straight truck)		2019
Dongfeng	Special Vehicle	205	4	2017	

VEHICLE AND INFRASTRUCTURE SPECIFICATIONS

Table A3. Additional technical assumptions used in infrastructure and TCO analysis

Value	Long-haul tractor-trailers			Drayage truck			Delivery truck		
	2020	2025	2030	2020	2025	2030	2020	2025	2030
Diesel price ($/gallon)	$3.75	$4.07	$4.71	$3.75	$4.07	$4.71	$3.75	$4.07	$4.71
Electricity price ($/kWh)	$0.14	$0.16	$0.17	$0.14	$0.16	$0.17	$0.14	$0.16	$0.17
Ultra-fast charging price ($/kWh)	$0.23	$0.24	$0.26	$0.23	$0.24	$0.26	$0.23	$0.24	$0.26
Hydrogen from natural gas ($/kg)	$5.12	$4.64	$4.17	$5.12	$4.64	$4.17	$5.12	$4.64	$4.17
Hydrogen from renewable sources ($/kg)	$9.26	$8.07	$6.88	$9.26	$8.07	$6.88	$9.26	$8.07	$6.88
Diesel maintenance cost ($/km)	$0.118	$0.118	$0.118	$0.118	$0.118	$0.118	$0.127	$0.127	$0.127
Battery/fuel cell maintenance cost ($/km)	$0.107	$0.107	$0.107	$0.107	$0.107	$0.107	$0.101	$0.101	$0.101
Battery electric annual efficiency improvement	2.1%								
Hydrogen fuel cell annual efficiency improvement	2.5%								
Diesel annual efficiency improvement	4%								
Annual vehicle miles traveled	140,653	141,859	142,435	30,193	30,193	30,193	68,647	68,647	68,647
Electric drive power (kW)	700			600			450		
Battery density (kWh/kg)	0.2								
Battery pack cost ($/kWh)	$152	$106	$74	$152	$106	$74	$152	$106	$74
50-kW charging station hardware cost	$25,000	$22,598	$20,427	$25,000	$22,598	$20,427	$25,000	$22,598	$20,427
Ultra-fast charging station hardware cost	$225,000	$193,215	$165,920	$225,000	$193,215	$165,920	$ 140,000	$ 120,223	$165,920
Single-dispenser H_2 station cost*	$4,971,061	$3,351,993	$2,882,217	$4,971,061	$2,149,144	$2,447,139	$3,239,012	$2,203,899	$2,046,555
Ultra-fast charging station utilization (hours/day)	5.4	7.2	9	6	7.2	9	4.5	5.4	9
H_2 station throughput (kg/dispenser/day)	1,000	1,350	1,700	570	1,000	1,340	720	1,000	1,100

*Hydrogen stations are sized to store and dispense the necessary amount of hydrogen required for that application, so station costs are not directly comparable across years.

SENSITIVITY ANALYSIS RESULTS

Table A4. Sensitivity of infrastructure and TCO cost estimates for long-haul electric tractor-trailer to key assumptions

Scenario	Impact on infrastructure cost	Impact on total cost of ownership
Battery size: From 600 kWh to 900 kWh	-18.4%	0.4%
Battery size: From 600 kWh to 400 kWh	12.2%	1.1%
Efficiency: 15% higher energy consumption	14.4%	9.4%
Efficiency: 15% lower energy consumption	-15.0%	-9.2%
Opportunity charging: No loading dock charging	-2.6%	1.2%
Opportunity charging: Charging at 66% of loading docks	2.6%	-1.2%

Note. All numbers reported in terms of difference from baseline scenario for 2030 (high-volume case).