Zero Emission Long-Haul Heavy-Duty Trucking

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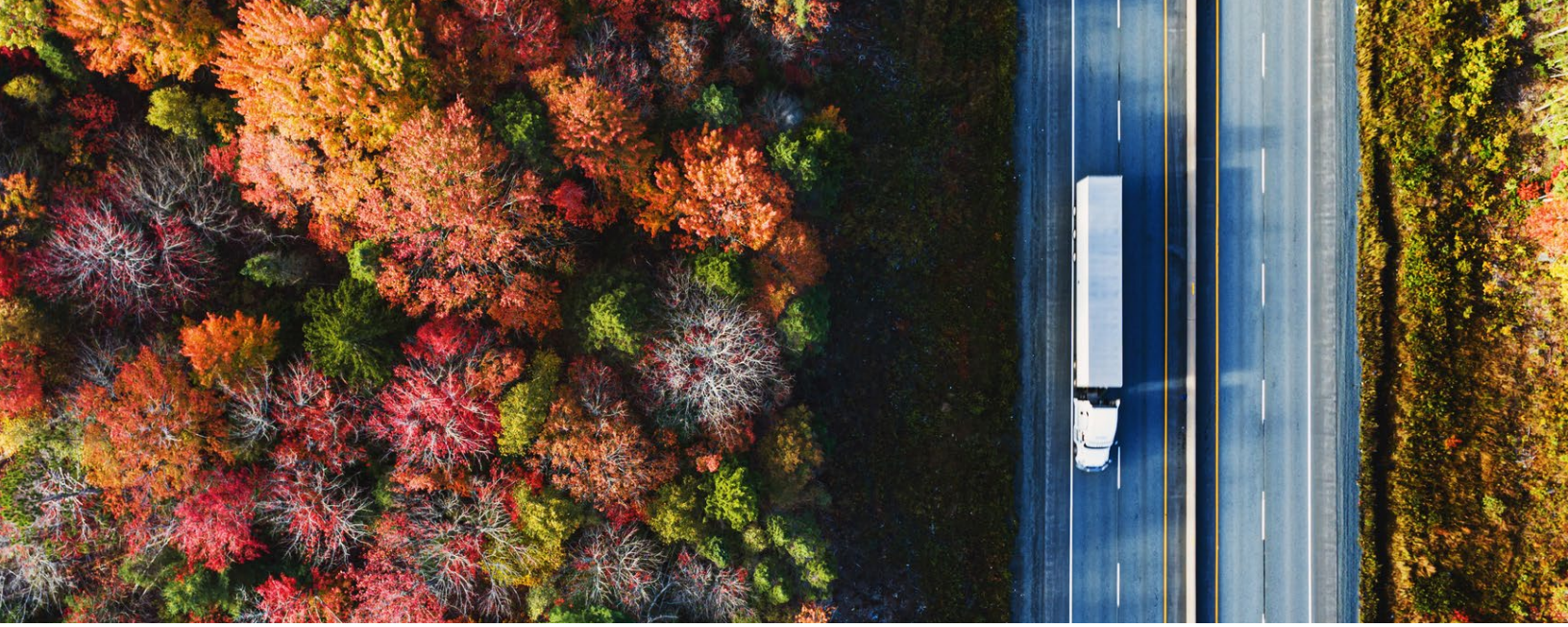


Executive Summary

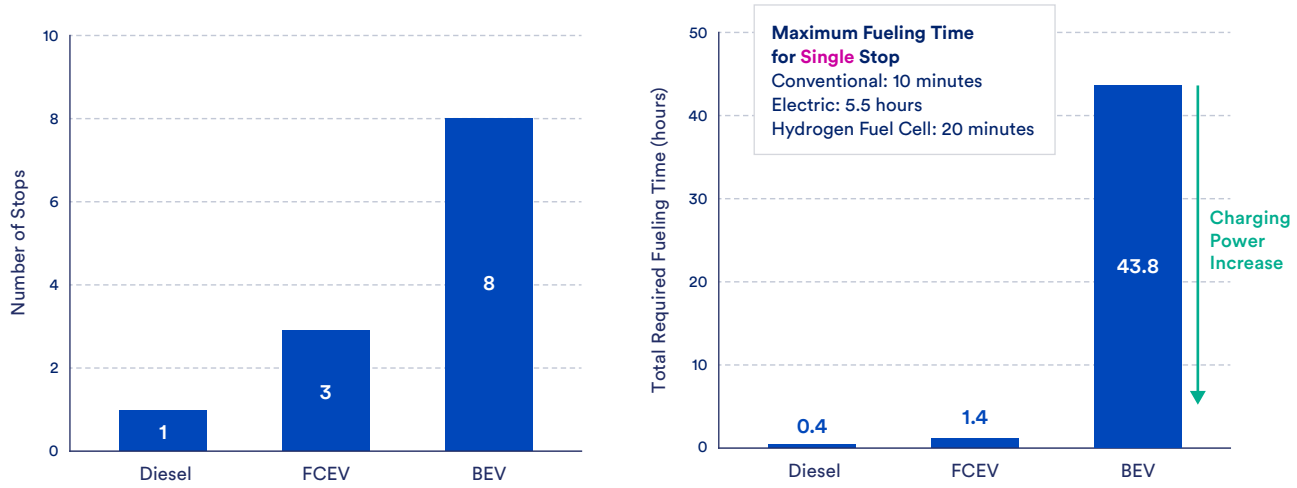
In order to achieve our climate goals, the global energy sector must reach net-zero emissions by 2050. Transportation is responsible for 15 - 20% of global CO_2 emissions, making it a critical area where we must develop wide-ranging decarbonization solutions for vehicles of all types and sizes, including everything from cars and trucks to airplanes. Heavy trucking is a transportation end-use case where, similar to marine vessels and airplanes and unlike passenger cars, vehicle size makes it difficult to decarbonize with on-board batteries. In particular, the over road range required by long-haul heavy-duty trucking, an end-use responsible for 49% of on-road diesel fuel consumption in the United States (U.S.), makes decarbonization particularly challenging. This work compares two alternative drivetrains, battery electric (BEV) and hydrogen fuel cell (FCEV) to diesel vehicles to determine which might provide the smoothest transition for long-haul operation.

The performance of a single truck on a long-haul route part of the 11th most popular trade corridor[1] between Los Angeles, the busiest U.S. port, to Newark, New Jersey, a key hub on the East Coast, was modeled. The simulation includes a diesel truck with a 240 gallon tank, a BEV with a 1000kWh battery, and a FCEV with 100 kg of hydrogen stored in on-board tanks. For both alternative drivetrains, this analysis assumes that the energy used to power the BEV and the FCEV has no or very low associated greenhouse gas emissions. Figure E.S.1 compares the number of stops required for each drivetrain to complete that route, as well as the total stop, or dwell time, noting on the right (in green) that for the BEV drivetrain dwell time will decrease as advances in charging technology result in increased charging power.

During the next phase of analysis, truck traffic flow between Los Angeles and Newark was simulated for the purpose of analyzing potential fueling or charging station infrastructure requirements. Specifically, the model was updated to allow for a varying number of trucks along the route, random truck departure locations, and a range of truck speeds. Each of these changes needed to approximate a realistic traffic pattern. The results, which assume that trucks are active all 24-hours each day of the week, show that in aggregate, a peak hydrogen dispenser flow rate of 2,700 kg per hour would be needed at a hydrogen station. For BEV, peak station power requirements would be approximately 22 MW. In addition, given the time it takes to charge, up to 121 BEV trucks are simultaneously charging, whereas for hydrogen stations, up to 17 FCEVs fuel at the same time.

In summary, the analysis shows that for long-haul trucking, the hydrogen fuel cell vehicle outperforms the battery electric vehicle in terms of number of stops required, total fueling time, and available room for cargo. Regarding infrastructure, switching a significant portion of heavy-duty trucks to BEVs requires a more robust buildout, in terms of size or number of stations, whereas the buildout for hydrogen, while still challenging, is comparatively more similar to diesel. Having said that, this analysis focuses on technical and operational merits and is not an exhaustive look at all the factors that may play into selecting a zero emission vehicle, which might include a comparison of projected total cost of ownership or detailing the specifics of well-to-wheels life cycle emissions. Specifically, total cost of ownership is an active discussion area with a number of recent analyses, many of which come to different conclusions regarding the levelized cost of hydrogen and how that may affect fuel cell vehicle market penetration in comparison to electric vehicles. This analysis, on the other hand, was carried out to better understand other relevant technical and operational parameters; concluding that while it is likely that battery-powered trucks will play a significant role in the transition to a zero-emission transportation sector, taking advantage of the merits of hydrogen FCEVs appears to be an important strategy for quickly and efficiently decarbonizing long-haul heavy-duty trucking.

Figure E.S.1: Number of Stops and Total Fueling or Charging Time



SECTION 1

Introduction

The Paris Agreement[2] charted a path to a substantial reduction of global emissions when 197 countries signed on in 2015, pledging to achieve a balance between emission sources and sinks by the second half of the century. After a report published by the Intergovernmental Panel on Climate Change (IPCC)[3] achieved a level of broad acceptance, the Paris Agreement is now generally considered a pledge to achieve net-zero emissions by 2050 as a way to prevent more than 1.5°C of surface warming over pre-industrial levels. However, progress since then has been slow and, according to a recent report from the International Energy Agency (IEA), the target will not be met if energy reform proceeds at the current pace. Considering the effect of all existing and stated energy policy for countries participating in the Paris Agreement, the IEA forecasts[4] CO_2 emissions to increase by approximately 5%, resulting in an increase in surface temperatures of around 2.7°C by 2100. Once announced pledges are counted in the projection, emissions decrease by approximately 35%, but that still results in a 2.1°C temperature increase. The IEA analysis, which is not unique in this space, shows that energy reforms are badly lagging and that a significant change is needed to prevent the worst effects of climate change.

A subset of energy reforms is summarized in the IEA report highlighting the necessary scale as well as the difficulty of achieving net-zero emissions by 2050. For example: by 2030, 60% of global car sales must be electric and 1,020 GW of new wind and solar must be introduced; by 2035, 50% of heavy truck sales must be electric, no more internal combustion engine-equipped passenger vehicles can be sold, and the electricity grid in advanced economies must be net-zero emission; by 2050, almost 70% of electricity generation must be from wind and solar. That list, which is not exhaustive, shows that the next energy transition will require major advancements in technology, infrastructure, as well as changes to day-to-day behavior. To meet these targets there needs to be both research and development to prove out a range of potential new options as well as the willingness to move quickly.

As illustrated in those examples, one major challenge is decarbonizing the transportation sector, which at present is responsible for 15 - 20% of CO_2 emissions.[5] IEA projects that fossil fuel use in the transportation sector needs to be reduced 90% (100 EJ to 10 EJ) by 2050. This transition will require more than passenger vehicle electrification; specifically, difficult to abate

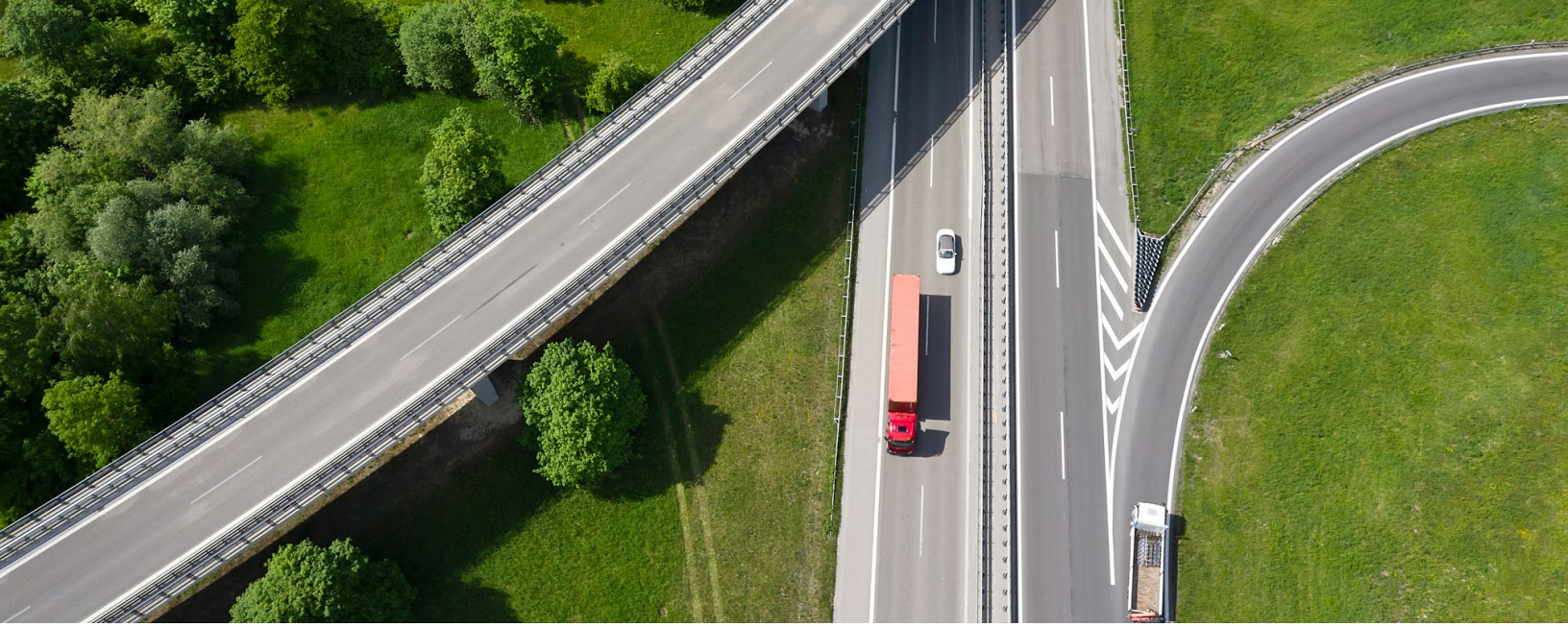
modes of transportation like aviation and marine shipping will need to be addressed as well. Given the size, cargo carrying, distance traveled, and operational requirements of these heavier vehicles, the main decarbonization challenge is related to the size and weight of the on-board batteries that would be needed for full electrification. In addition, airplanes and marine vessels are typically in service for 10 - 30 years and replacement vehicles have long development lead times.

The smaller vehicles used for on-road transportation, on the other hand, present a comparatively simpler decarbonization challenge. To that end, significant progress on electrification has been made in terms of technological advancements and development of supporting infrastructure in the passenger vehicle, or light-duty space. Those technologies have been successfully brought to market and will play a critical role in decarbonizing trucking, a transportation end-use case that falls between aviation and light duty on-road vehicles in terms of decarbonation difficulty. The heavy trucking sector, defined in the U.S. as vehicles weighing more than 26,000 pounds, is responsible for fewer total emissions than light-duty vehicles, but still is large enough of a sector to warrant significant concern and difficult enough of a problem to not have seen as much progress.

In the U.S., heavy trucking emits 24%[6] of all emissions from the transportation sector or around 450 million metric tons[7] of CO_2 each year. Of particular note are long-haul (e.g., sleeper) routes, defined by the National Renewable Energy Laboratory (NREL) as greater than 500 miles, as those make up approximately 49%[8] of diesel fuel consumption and represent trucking's biggest decarbonization challenge. For that reason, this work focuses on how to efficiently and effectively decarbonize long-haul heavy-duty trucking.

In order to understand the technology needed to decarbonize these longer routes, this analysis looked at how two state-of-the-art zero-emission vehicle (ZEV) drivetrain technologies — battery electric (BEV) and hydrogen fuel cell (FCEV) — performed on a hypothetical, cross-country truck freight route. For both drivetrains, implicit is the assumption that the energy used to power each vehicle has no or very low associated greenhouse gas (GHG) emissions. The fuel cell vehicle is assumed to use low-emission hydrogen, which includes both the commonly referred to "blue" hydrogen, derived from natural gas with carbon capture and sequestration (CCS), as well as "green" hydrogen, which is produced using water and renewable or other carbon-free electricity via a process called electrolysis. For the battery electric vehicle, the electricity used to charge is assumed to come from carbon-free sources such as wind, solar, hydro, geothermal, or nuclear.

Regarding performance, the two drivetrains were first assessed by analyzing differences in the number of stops required, total dwell time, and available room for cargo for a single truck. The potential effects on the infrastructure were then considered by assessing hydrogen station fuel flow rate, hydrogen storage, charging station power, and station size requirements using a custom-built simulation. By comparing the two drivetrains to on-road diesel vehicles, this analysis allows for a determination of which drivetrain — FCEV or BEV — would provide the smoothest transition to zero emission long-haul heavy-duty trucking.



SECTION 2

Background

In the U.S., trucks are classified by gross vehicle weight rating and separated into eight classes. The heaviest trucks, class 7 and 8, range from 26,001 to 80,000 pounds[9] and are often configured as combination trucks comprised of a truck-tractor and a trailer containing the cargo. Similarly, in the EU, trucks are organized by number of axels, where the heaviest classes include trucks with three or more axels with a maximum weight of 44 metric tons.[10] Most commonly, these heavy trucks are powered by diesel-fueled internal combustion engines (ICE), but as the necessity to reduce the climate impact of heavy trucking has become clear, a transition to alternative fuels has begun. Much of the early research into alternative fuels centered around the Alternative Motor Fuels Act of 1988 where vehicle manufacturers were offered incentives in the form of credits to build flexible fuel vehicles.[11] This led to the emergence of a wide range of fuel and drivetrain options over the past few decades, including renewable or bio-diesel, ethanol, both liquified natural gas (LNG) and compressed natural gas (CNG), propane, electricity, hydrogen, and ammonia.

Some of these fuels still require an ICE, but others like hydrogen use fuel cells to chemically convert the fuel to electricity that is then used to power an electric drivetrain. The goal of this work was to analyze climate beneficial alternative fuels that provide a substantial net reduction in emissions while being sourced from sustainable feedstocks; given that, neither fuels such as LNG, which still emit a significant amount of CO_2 when combusted, nor biofuels, which often have supply sustainability issues as well as direct and indirect land use issues, were considered. That left electricity, via either on-board batteries or hydrogen fuel cells.[i]

Before looking specifically at zero-emission heavy trucks that are powered by batteries or hydrogen, it is useful to frame the problem in terms of the ultimate goal, which is reducing GHG emissions. Rial and Perez carried out a comprehensive life-cycle analysis (LCA) that combined VECTO,[12] COPERT,[13] GREET,[14] and AFLEET[15] to evaluate production through end-of-life emissions for diesel trucks and found that for every kilometer driven, 0.94 kg

[i] Ammonia fueled combustion engines and fuel cells were not considered since the technology readiness level (TRL) of those drivetrains are low compared to battery electric and hydrogen fuel cell. Ammonia fueled trucking, in particular drivetrains powered by ammonia solid oxide fuel cells, is thought of as a potentially more convenient, longer-term solution.

of CO_2e (3.33 lb CO_2e per mile) is emitted.[16] The same paper also compared diesel to other fossil fuel options and found that in the best case, LNG only reduces GHG emissions by 4 – 6%. For particulate matter, diesel is responsible for 180 PM2.5e per kilometer (290 PM2.5e per mile) and LNG only offers a 10% improvement. As illustrated in an internal study,[17] particulate matter exposure can lead to negative health effects including death, making reducing these emissions another key part of this transition. This is why clean fuels that contain no carbon atoms, or zero-carbon fuels, battery electric vehicles, and related technology must be researched and developed. A different study that does include BEVs in the LCA carried out a comparison to diesel. That paper showed that diesel emissions range from 850 – 1,161 metric tons (937 – 1,280 short tons) of CO_2e over a vehicle's lifetime which is 0.71 – 0.97 kg per kilometer (2.51 – 3.43 lb per mile) assuming 1,200,000 lifetime kilometers (or 745,805 miles).[18] Whereas a BEV, assuming grid power is used for charging, emits 448 – 700 metric tons (494 – 772 short tons) of CO_2e, or approximately half as much as the diesel truck. Of this, depending on the specific process, between 13 – 30% of emissions occur during battery manufacturing due to the energy needed to process the lithium. While not explicitly discussed in the paper, increasing the amount of renewable energy used in this process will further improve the emission benefits seen when switching from diesel to BEV. Regarding hydrogen, a different analysis by Tahir and Hussain found that FCEV life cycle emissions match that of BEVs, assuming most of the energy used for electrolysis and battery charging is renewable, even with the conservative assumption that FCEV technology will largely remain unchanged through 2050. For that case, which is referred to by the authors as 2050 conditions, the FCEV emits 0.37 kg CO_2e per metric ton-kilometer (1.20 lb per short ton-mile) and the BEV emits 0.38 kg CO_2e per metric ton-kilometer (1.23 lb per short ton-mile).[19]

These life cycle analyses show that heavy duty truck diesel emissions can be effectively mitigated by both BEV and FCEV. However, climate benefits do not necessarily drive adoption, especially if vehicle costs and performance are not competitive with diesel. Several recent analyses examine FCEV and BEV performance as well as total cost of ownership (TCO) to better understand how that will affect vehicle adoption.

In 2015, one analysis authored by Kleiner et al. used the Transport Application based Cost Model (TACMO) to estimate TCO for both BEV and FCEV in several European countries (GER, AUT, TUR, UK). That study found that FCEV was as much as three times more expensive, €2.5 per kilometer compared to €0.8 for the BEV, due to high fuel cell system costs, hydrogen prices, and capital costs for hydrogen stations.[20] Although not discussed in the paper, in 2015 hydrogen was still a relatively new heavy truck fuel which likely led to the elevated projected costs. The more mature BEV technology compared well to diesel for the vehicle under study, an urban delivery truck. This was a small battery, short-range vehicle that needed to recharge every 69 kilometers (43 miles). In comparison, the FCEV vehicle in the study had a 223 kilometer (139 mile) range and the diesel vehicle an 852 kilometer (530 mile) range. This highlights the need to compare vehicles that have a similar range and use case.

A subsequent study from Transport and Environment does take range and use-case into account, finding that for long haul operation, defined as 1,200 kilometers (746 miles) in this particular analysis, a BEV with a large 1,150 kWh battery needs to make one stop for overnight charging while the FCEV can complete the full trip on 70 kg of compressed hydrogen gas.[21] It also identifies that high-power, 600 kW charging would be beneficial for any type of BEV operation as that would allow for 200 kilometers (124 miles) of range after charging for around 30 minutes. Finally, the battery would need to be very light for the BEV to have a competitive cargo carrying capacity. The analysis shows that a 3.14 kg (6.92 lb) per kWh battery leads to a loss of 1,216 kg (2,680 lb) of cargo capacity, a loss that can be adsorbed by the 2 metric ton[22] EU ZEV weight exemption.[ii] Overall, that analysis shows that while BEV may be useful for longer trips, FCEV has some advantages in terms of stops and refueling time.

The best comparisons, however, fixed the vehicle range for analysis across drivetrains rather than look at a specific duty cycle. Two recent studies from Argonne National Laboratory and NREL use this method as part of a very comprehensive TCO analysis. The NREL study[23] was carried out using FASTSim[24] and SERA[25] and included direct and indirect costs, regional fuel costs, hydrogen costs taken from demonstration data and Department of Energy targets, lost payload capacity

[ii] Weight exemptions allow zero-emission trucks to exceed otherwise strict weight restrictions by a set amount to account for the fact that batteries weigh more than diesel fuel combustion technologies. The exemption is applicable to all zero-emission heavy-duty trucks including hydrogen fuel cell vehicles.

costs, and dwell time costs, all considering both weight and volume limited scenarios. For an 805 kilometer (500 mile) range, weight-limited scenario in 2025, FCEV TCO is $1.80 per mile while BEV is $1.75. Parity with diesel at $1.30 per mile is reached by the FCEV in 2050 with the BEV slightly more expensive at $1.45. The authors identify battery cost and hydrogen fuel prices as keys to accelerating heavy-duty ZEV adoption and further note that for a 1207 kilometer (750 mile) range, FCEVs are the lowest-cost ZEVs regardless of scenario. Argonne conducted a similarly in-depth TCO analysis using a custom suite of tools developed in-house. That analysis shows that for the same 500-mile range in 2025, FCEVs cost $2.25 per mile while BEVs cost $2.10.[26] It should be noted that neither of these studies assess potential policy levers that can be used to more quickly bring ZEVs into parity with diesel. As an example, in the U.S., relevant new policies such as the clean hydrogen tax credit passed in the Inflation Reduction Act of 2022 may help FCEVs achieve cost parity.

While TCO varies slightly depending on the methodology, the research concludes that given recent and expected future advancements in BEV and FCEV technology, eventually parity will be reached with diesel vehicles. The actual timeline will depend on factors such as policy incentives and macro-economic market drivers, making it hard to accurately predict. The vehicles, however, are only one part of this equation. For zero-emission trucks to achieve a level of adoption necessary to affect climate benefits, infrastructure designed for heavy trucks with alternative drivetrains has to be made widely available, cost effectively.

The International Council on Clean Transportation (ICCT) analyzed infrastructure cost requirements on a per truck basis considering slow (50 kW) and fast (350 – 500 kW) charging, hydrogen station costs, as well as truck weight and time penalties.[27] Regarding the latter, ICCT's cost calculations assume that extra BEV trucks are purchased to cover for an increase in dwell time due to charging. The conclusion is that while there will be significant infrastructure costs, ultimately this will not fundamentally impede the viability of zero-emission trucks. On average, infrastructure costs are expected to add $70,000 per BEV and $105,000 per FCEV, amounting to 7% and 9% of TCO, respectively. At low truck volumes, infrastructure costs up to $180,000 per BEV and $250,000 per FCEV are projected, where FCEV costs are typically higher than BEV due to the price of hydrogen fuel and station buildout capital expense. That said, more variables are present in estimating those costs due to the relative newness of hydrogen in the heavy trucking market.

Research from Argonne used HDSAM[28] to show that capital costs likely will range from $0.75 million – $3.5 million[29] per hydrogen station. Including station operating costs, this resulted in fuel prices in the $3.5 – $6 per kg range with the potential to drop into the $2 – $4 per kg range if greater than 1000 kg are dispensed per day. Of that, 53% of the cost is due to hydrogen compression, one of the most challenging aspects of station design entirely unique to hydrogen. There is no consensus on fuel prices, however; for a similar station cost estimate, $1.5 million – $4.0 million, other research estimates $12 – $14 per kg for 100 – 300 kg dispensed per day.[30]

Data from different models will begin to agree as more hydrogen stations are built across the country. Additionally, costs are expected to come down with scale even if in the immediate future, they are likely to remain higher than the Department of Energy's target of $4 per kg[31] with their ultimate, aspirational goal being $1 per kg by 2031.[32] If the cost of hydrogen remains in the $10 - $17 range, as it is today,[33] there are scenarios where BEV adoption outpaces FCEVs to the point that fuel cell vehicle technology loses much of its relevancy. A recent paper from ICCT projects such a scenario, where FCEV truck market penetration is shown to be less than 1% in 2035.[34] That scenario seems most likely if FCEV TCO continues to be more than 20% - 30% greater than BEV for a number of years. Within that range, however, some of the operational advantages of FCEV may result in cost reductions large enough to offset the difference.

Furthermore, other research points to improving cost and performance for ZEVs and their related infrastructure over the next decade. A paper from M. Al-Alawi et al. looks at this landscape and projects that lower battery costs, improved fuel cell technology, policies like the Advanced Clean Trucks (ACT)[35] regulation, and other legislative forcers will add 756,000 ZEVs to the road by 2035.[36] Additionally, other recent analysis also predicts significant market adoption. NREL modeling used Transportation Energy & Mobility Pathway Options (TEMPO), a macro market model for exploring long term trends, to show that ZEV cost parity with diesel can be reached by 2035.[37] This analysis assumed $80 per kWh for batteries, $80 per kW for fuel cells, and hydrogen fuel prices that reach $4 per kg by 2035. This scenario playing out would result in ZEV sales reaching 42% of all medium and heavy-duty trucks in the same year. However, the work also notes that more conservative assumptions could result in a delay of ZEV parity of more than 10 years with ZEV sales as low as 7% in 2030. Ultimately, in 2050, the study in a handful of scenarios projects new ZEV sales to be 40% - 100%, where FCEV uptake is as high as 32%.

Many market analyses make the case that both BEV and FCEV will play a key role in decarbonizing transportation, and that significant market adoption is likely coming soon. This is a key development as the transition to zero-emission trucks will not only be powered by technological advances – it also needs to be driven by market forces. As the first step in the commercialization process, demonstration projects that feature both BEVs and FCEVs have begun or are in the planning stage. In 2018, a drayage truck demonstration project[38] was planned for the Port of Houston area. Three FCEV heavy trucks, each with a 38 kg tank capable of providing 321 kilometers (200 miles) of range, were proposed. The plan included a small fueling station, with an expected daily utilization of 40 - 50 kg per day, to supply the trucks. The project reported that no technical or regulatory barriers were identified, but economic concerns ultimately forced the project to conclude prematurely. In 2020, more success was seen in the South Coast air basin region of Southern California despite the project also facing a number of economic headwinds.[39] As part of the project, 11 trucks (BEV and diesel hybrids only), each with a 113 – 161 km (70 - 100 mile) range depending on the manufacturer, were proposed. Of these, 4 vehicles made it to the demonstration phase and in total amassed 64,360 kilometers (40,000 miles) of operation. However, fleet owners and operators cite range limitations as a significant technical barrier preventing them from fully adopting and deploying these trucks in drayage operations. In the same geographic area, but part of a different project, in 2021 five FCEVs and two hydrogen fueling stations successfully debuted in the port of Los Angeles.[40] The introduction of five more FCEVs and several pieces of battery electric off-road port equipment has already been proposed. A large heavy truck FCEV demonstration project planned for 2023 is slated to bring zero-emission heavy trucks to both northern and southern California.[41] Hyundai is planning to supply 30 FCEVs, each with an 805 kilometer (500 mile) range. In addition, a station is planned that will support up to 50 trucks and provide maintenance services, complete with hydrogen detection and ventilation equipment. Finally, a novel FCEV heavy truck concept has advanced to the prototyping stage. The truck, developed by Amogy and demonstrated in early 2023, uses a hydrogen fuel cell fed by ammonia dehydrogenated on-board the vehicle.[42] The system has a drivetrain efficiency of approximately 40%, similar to diesel, and might be able to solve a key challenge, low-cost fuel delivery. Overall, similar to the trends seen in technology development, infrastructure rollout, and market adoption, recent demonstrations have been much more successful and now are starting to show how the transition to zero emission heavy trucking might take place.

Overall, the research shows that climate beneficial zero-emission trucks and related infrastructure are viable, but depending on the end-use, total cost of ownership will change, potentially forcing difficult decisions from fleet operators. As mentioned in the introduction, one end-use of particular concern is long-haul heavy trucking. The goal of the analysis presented in this paper is to identify the merits of BEVs and FCEVs for that specific use case and determine each drivetrain's viability as a diesel replacement.

SECTION 3

Single Truck Analysis

3.1 Methodology and Assumptions

A long-haul route potentially relevant to today's freight context was created for analysis: Los Angeles, the busiest U.S. port, to Newark, New Jersey, a key hub on the east coast. To further constrain the route creation process, it was assumed that all stops were Pilot Flying J full-service truck stops, a proxy for a future alternative fueling network. This company's stations were chosen because Pilot Flying J is the largest U.S. truck stop operator. There are more of these full-service truck stops located in the southern part of the country; hence the shape of the 5,255 kilometer (3,266 mile) route pictured in Figure 1. Nonetheless, the route is still representative, as according to the Department of Transportation, the highways included in the route see on average 5,000 – 30,000 trucks per day[43] and freight mapping research carried out by A. Tomer and J. Kane, rank Los Angeles to New York/New Jersey as the 11th most popular trade corridor.[1] For ease of comparison, all drivetrains used the same route, but FCEV and diesel drivetrains skip some of the stops needed for BEV as those two configurations have a longer range. The NREL program FASTSim, an industry accepted vehicle design and diagnostic tool, was used to compute the range for all drivetrains.

The vehicle was assumed to be a fully loaded, class 8 truck, weighing 80,000 pounds. For drivetrains with lighter components, more cargo was added to reach this weight. Table 1 lists the detailed assumptions for each drivetrain.

Tesla 250 kW supercharger passenger vehicle charging data was extrapolated to estimate the charging time for the large 1000 kWh battery in the BEV. The fuel cell efficiency is based on recent data received from NREL. The hydrogen fueling rate was based on discussions with NREL and companies currently developing hydrogen fuel cell electric trucks. Five kilograms per minute is seen as readily achievable in the next few years.

Figure 1: Hypothetical Truck Route (Los Angeles, CA to Newark, NJ), With BEV Stops Shown

Table 1: Drivetrain Assumptions

	Diesel	BEV	FCEV
Tank Size	240 gallons (120-gallon tank on each side)	–	100 kg
Battery Size	–	1000 kWh	20 kWh
Drivetrain Power	310 kW	315 kW	300 kWh
Peak Efficiency (ICE/Battery/Fuel Cell)	52%	97%	63%
Fueling or Charging Time	10 minutes	330 minutes (250 kW charging)	20 minutes (5 kg per minute)

3.2 Analysis Results

At a high-level, for long-haul routes the FCEV configuration outperforms the BEV configuration in terms of number of stops required, total dwell time, and available room for cargo, potentially making it the more viable alternative drivetrain for this task. The reasoning behind this statement starts with a look at the range for each configuration. The diesel configuration has the longest range at 3,416 kilometers (2,123 miles), the FCEV in the middle at 1,640 kilometers (1,019 miles), and the BEV the shortest at 756 kilometers (470 miles).

In terms of fuel economy, the BEV was the best at 17.39 miles per diesel gallon equivalent[44] (mpdge), the fuel cell next at 11.31 mpdge, and the diesel truck the worst at 8.85 mpdg. These FASTSim results[iii] show that while the BEV boasts the best energy efficiency, the volumetric energy density of the storage medium, highest for diesel and lowest for the battery, does much to determine the overall range. The range for the BEV could be extended with a larger battery, but that would increase weight and adversely affect cargo capacity, a topic discussed in detail below.

For the case at hand, which assumes a 1000 kWh battery, the difference in range informs the first part of the high-level takeaway regarding the number of stops. The comparatively short range for the BEV means that 8 stops are required between Los Angeles and Newark at which point a significant portion of the

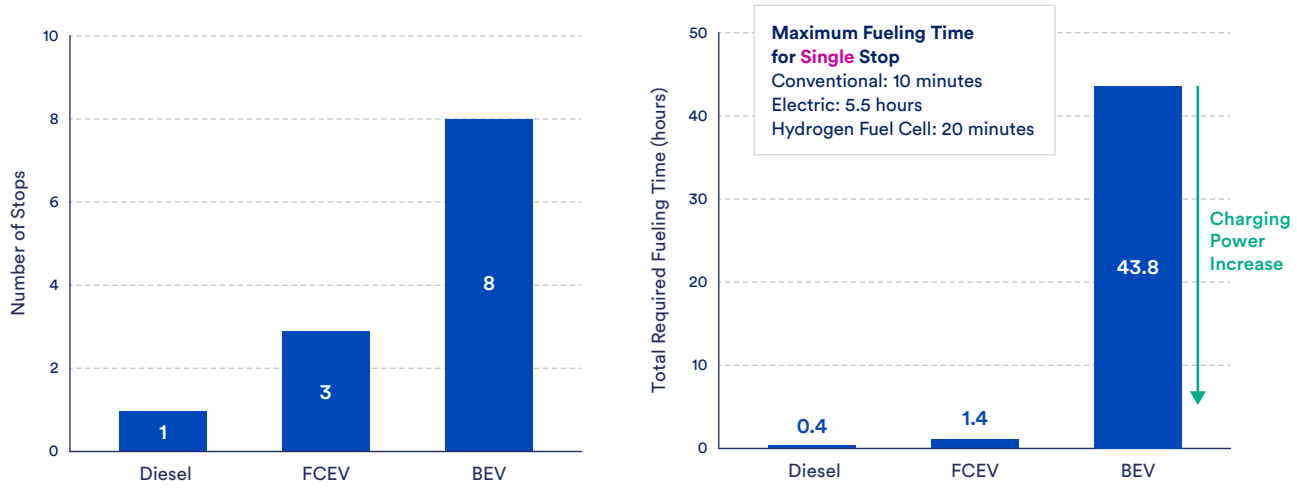
Table 2: Range and Fuel Economy for Each Drivetrain

Range		
Diesel	2123	miles
BEV	470	miles
FCEV	1019	miles

Fuel Economy		
Diesel	8.85	mpdge
BEV	17.39	mpdge
FCEV	11.31	mpdge

mpdge = miles per diesel gallon equivalent

Figure 2: Number of Stops and Total Fueling or Charging Time

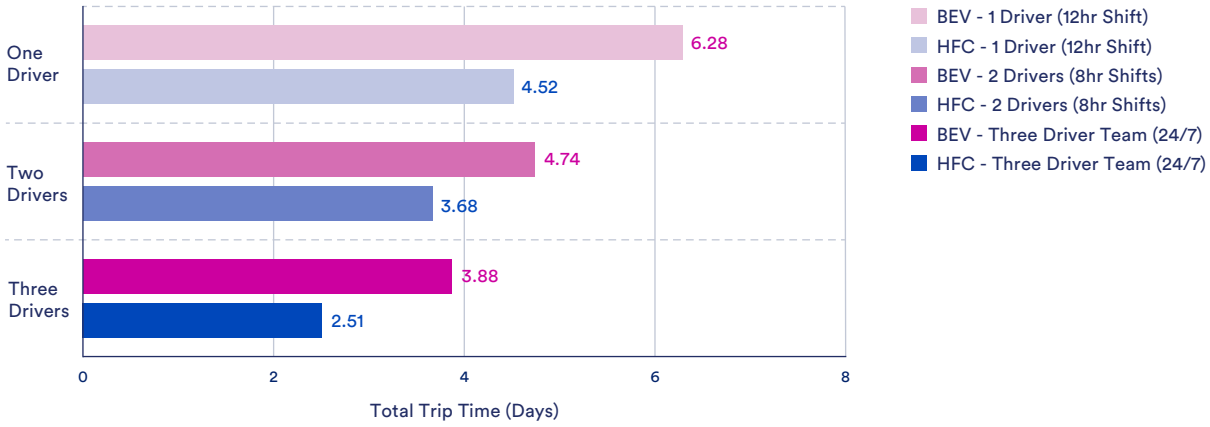


[iii] The FASTSim fuel economy results are theoretical, representative of a new truck on an idealized route. While these numbers are likely higher than actual on-road vehicles, the assumptions for each drivetrain are the same, allowing for the comparisons presented in this paper.

battery, 50 – 98%, must be charged. Along the same route, the FCEV requires 3 stops and typically needs to refuel three-quarters of the tank, and the diesel drivetrain only needs one stop. This increase when moving from the diesel drivetrain to the FCEV to the BEV is illustrated on the left of Figure 2.

The more important measure of performance, however, is the required stop, or dwell, time for each configuration enroute. Total dwell time, also mentioned in the high-level takeaway, is considerably longer for the BEV because each stop to recharge takes hours. Accounting for the state of charge at each stop and summing it over the entire route shows the BEV charging for 43 hours and 48 minutes. This is time when goods are not moving, something that may negatively affect delivery times and overall fleet operation. In contrast, the total fueling time for the FCEV is 1 hour and 24 minutes, approximately 1 hour longer than the diesel drivetrain. High power fast charging, its potential illustrated in green, would reduce BEV dwell times, but that technology is still in the research phase, not expected to be commercially available for 5 – 10 years, with widespread availability likely occurring near the end of that window. Pre-charged battery swapping systems could also mitigate the issue, but the viability of swapping for trucking applications, where there will likely be significant truck-to-truck differences in drivetrain design, battery sizes, and chassis layout, remains unknown.

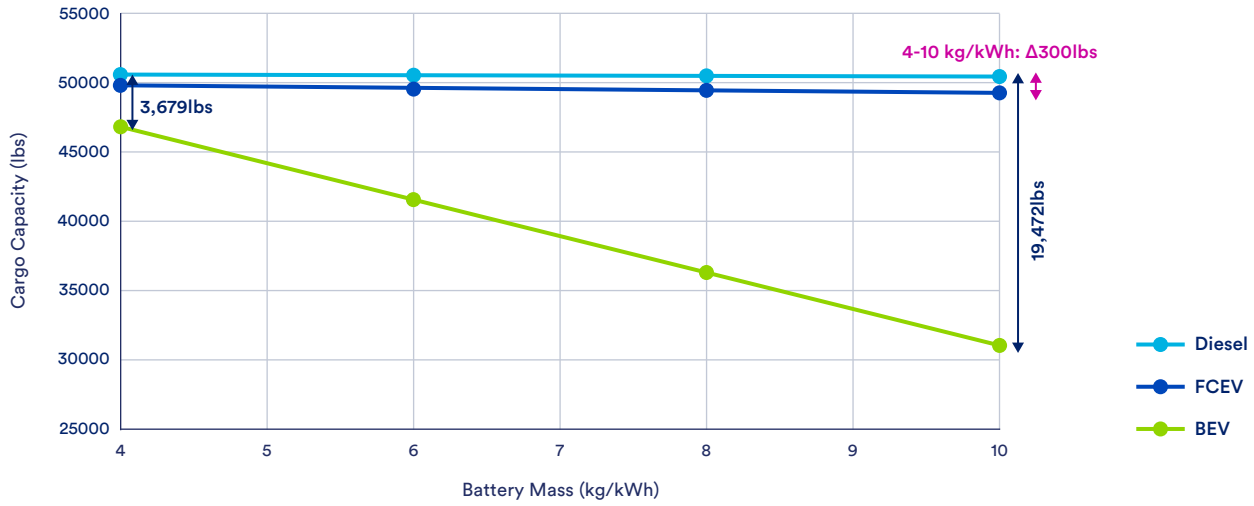
Figure 3: Total Trip Time Including Driver Rest



Another dwell time consideration is driver rest. The analysis in Figure 2 assumes a driver team working 24 hours a day. While this shift duration is sometimes completed, it is less common than a single driver doing a 10 – 12-hour shift or a pair of drivers each doing 8 – 10-hour shifts. In Figure 3, these two cases are compared against the driver team revealing a relative performance improvement for the BEV, since that vehicle can be charged while the driver rests. The case with the biggest difference is the driver team, where the BEV takes 56% longer (3.9 vs. 2.5 days) than the FCEV to complete the trip. For two drivers, the BEV takes 27% longer (4.7 vs. 3.7 days) while a single driver would take 40% longer in a BEV (6.3 vs. 4.5 days). In all cases the details of the rest profile determine the exact length of the trip. As such, even for these more common scenarios, in absolute terms the BEV takes significantly longer to complete the trip even if there is some relative improvement. It is important to consider driver rest, but that alone does not bring the BEV dwell times into parity for long-haul routes.

The last metric in the high-level takeaway is cargo capacity which, due to the incremental weight of the battery, also favors FCEV configurations. For a weight-limited scenario, taking into account the federal 2,000-pound[45] maximum gross weight exemption for plug-in electric vehicles, the 1000 kWh battery causes a 1,669 – 8,832 kilogram (3,679 – 19,472 pound) loss in cargo capacity depending on the assumption for battery weight (Figure 4). The FCEV configuration also

Figure 4: Cargo Capacity Sensitivity to Battery Weight for a Weight Limited Scenario



has a battery, but it is only 20 kWh and used for limited purposes (e.g., hill climbing, sudden acceleration, taking advantage of regenerative braking). That 20 kWh battery adds some weight, but only results in a few hundred-pound loss of cargo capacity relative to what can be carried on a diesel truck. Different FCEV designs may opt for a slightly larger battery, potentially up to 100 kWh, but since hydrogen functions as the main energy source, battery weight is not expected to become a major concern for FCEVs.

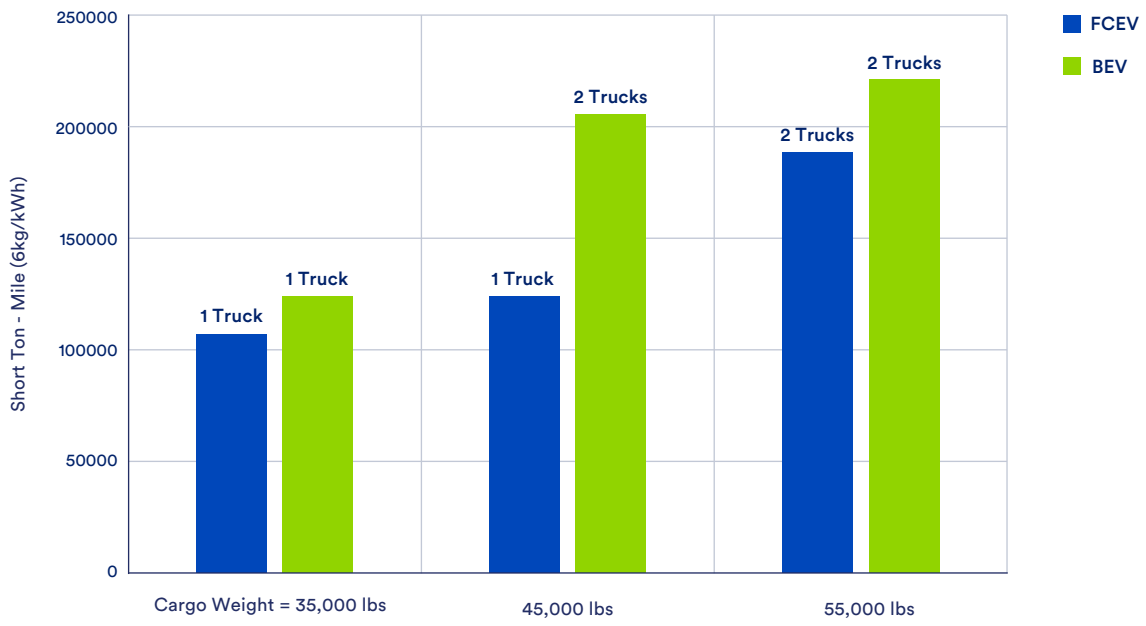
The ratio of battery mass to energy content is a key factor when projecting the impact battery weight will have on truck cargo capacity. Four kilograms per kilowatt hour has been achieved in passenger vehicles, but not for the large batteries and cooling systems needed in heavy trucks. The first Class 7 and 8 trucks to market may be closer to 5 – 6 kg/kWh, and given the uncertainty in this technology area, there is more risk of lost cargo capacity with the BEV.

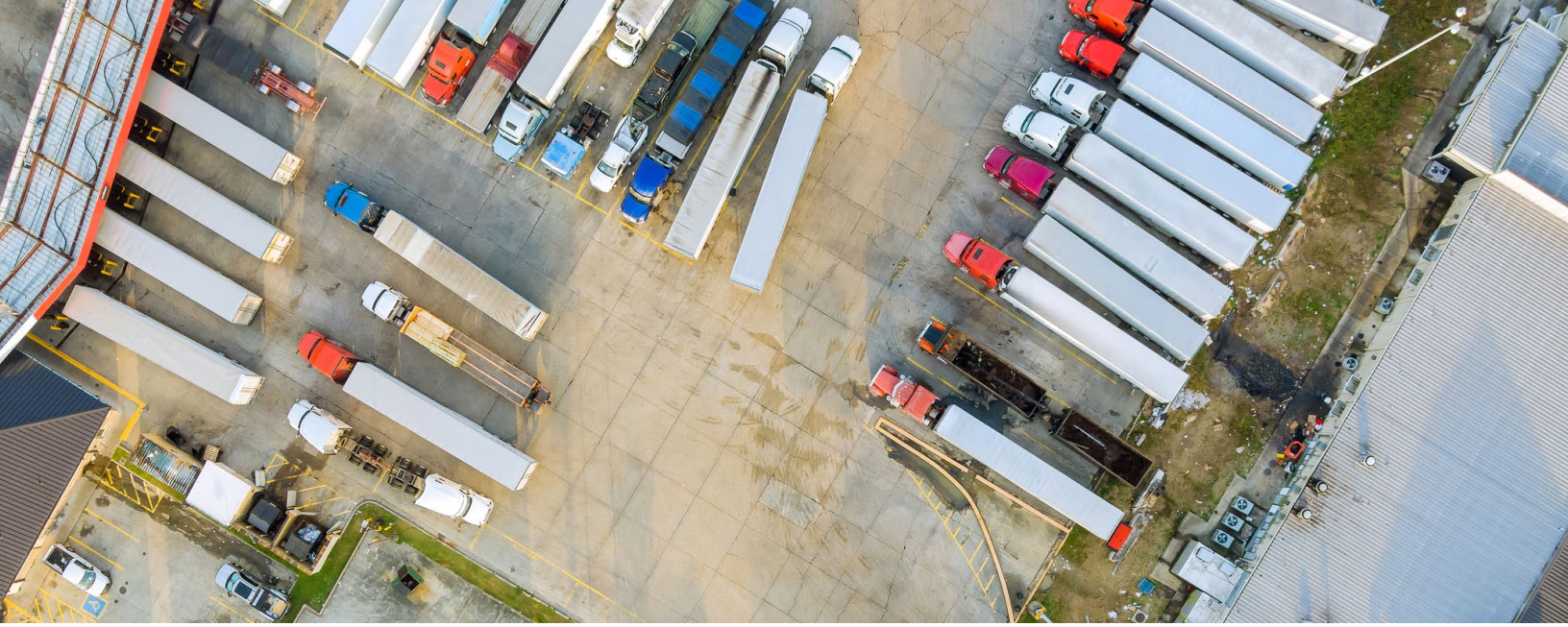
Lost cargo capacity has a demonstrable effect on fleet operations as illustrated by the difference in short ton-miles shown in Figure 5. Short ton-miles are a good proxy for overall fleet workload as carrying more freight over longer distances correlates with vehicle wear and tear which in turn means increased operating expenses (maintenance, labor, fuel). In each case shown in the figure, over the entire route the BEV results in more ton-miles than the FCEV. For the 15,876 kg (35,000 lb) and 24,948 kg (55,000 lb) cases, this is because the heavier BEV drivetrain increases the overall truck weight which over the same distance results in more ton-miles.

For the middle case with 20,412 kg (45,000 lb) of cargo, due to the class 8 weight limit of 80,000 pounds, two BEVs are needed, compared to just one FCEV, to deliver all the goods. The extra truck causes a large increase in ton-miles; and additionally, affects fleet operations. Future zero-emission fleets relying on BEVs may need to purchase additional vehicles to compensate for this issue. It should be noted that volume-limited scenarios are also common so this issue will affect some freight loads differently. In general, however, a heavier drivetrain means less cargo flexibility and potentially allocating more capital expense to a larger fleet – and the heaviest drivetrain belongs to the BEV.

To summarize the single truck analysis on a cross country, long-haul heavy-duty truck route, the FCEV is able to make fewer stops than the BEV, needs less time to fuel, and has more room for cargo, performing well compared to diesel in all key parameters. For these reasons, the FCEV configuration proves to be the more viable alternative drivetrain for long-haul trucking.

Figure 5: U.S Ton-Miles Over Entire Route for Three Different Cargo Weight Scenarios





SECTION 4

Infrastructure Analysis

4.1 Methodology and Assumptions

In order to model the requirements for an alternative fueling infrastructure, a simulation of freight traffic between Los Angeles and Newark was designed to better understand potential fueling or charging station workloads. That design includes multiple trucks, where each truck's starting location and speed, limited to a number between 45 and 65 mph, is randomized to approximate a realistic traffic pattern. Starting location was set as a variable to ensure that trucks are present along the entire route and varying speed allows for different drive times between stations. Other vehicle parameters, such as drivetrain efficiency and the route profile, are included via the vehicle range computed with FASTSim. As with the single truck analysis, it is assumed that trucks are active 24 hours a day, seven days a week.

Diving into the details, the route was set up as a roundtrip that only includes the minimum number of stops required for each drivetrain: five stations for the FCEV (three stops and the two end points of Los Angeles and Newark) and 10 stations for the BEV (eight stops, two end points). Each truck will always stop at the same set of stations, but as explained above the starting point for each truck is randomized so all trucks will not be in the same place at once. As an example, Truck A might start in Los Angeles, travel to Newark, and then return to Los Angeles, while five minutes after Truck A started in Los Angeles, Truck B might start at a fueling station in El Paso, Texas, travel to Los Angeles, drive across the country to Newark, and return to EL Paso to complete the round trip. Truck C might start five minutes after Truck B at another random station, and so on. Time spent at a given station is related in a linear fashion to the fueling or charging requirement. For example, an empty hydrogen tank would take all 20 minutes to refuel whereas a half tank would only take 10 minutes. A Monte Carlo simulation, a computational technique that repeats tens of thousands of times varying a small subset of variables in a random fashion in order to compute event likelihoods, was selected given the large solution set caused by the number of trucks needed to approximate a realistic traffic pattern. Using this technique, given enough repetitions, even unlikely occurrences will be seen in the modelling.

The Monte Carlo simulation was run for truck counts ranging from 5 to 3,500 which helped to gain insight into how the number of trucks on the road affects infrastructure. A parameter called the density ratio (DR_{truck}) was created to understand those results.

Equation 1 $$DR_{truck} = \frac{Num_{truck}}{Num_{station}}$$

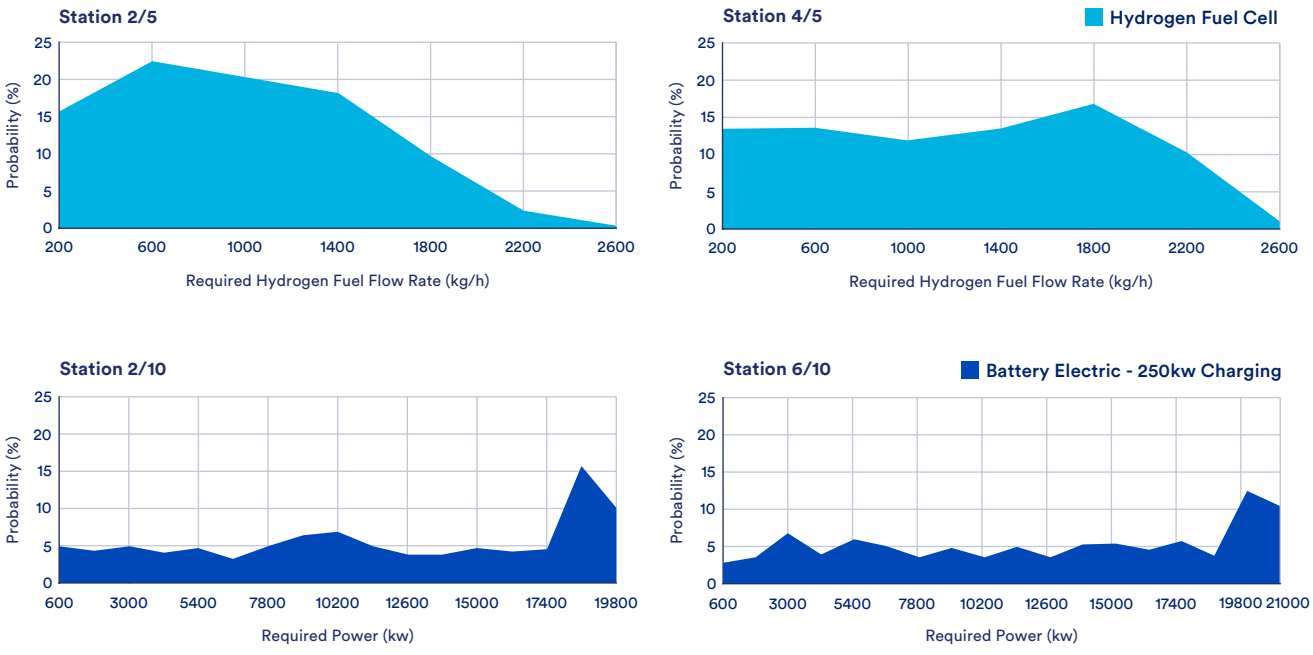
The simple parameterization in equation 1 allows for comparison across drivetrains, which have a different number of stations, as well as allows for comparison to the situation today. For example, if there are 10 trucks and 10 stations (DR_{truck}) = 1), stations likely will be idle most of the time. The situation would be similar if there were 1000 trucks serviced by 1000 stations. However, if you had 1000 trucks with only 10 stations (DRtruck = 100), each station would be very busy. In this way, regardless of the number of trucks or stations in a given scenario, this ratio can be used to compare the effect of like traffic densities.

Bearing that in mind, this method can also be used to compare simulation results to the situation on the road today. Currently, there are 2,746,882 combination trucks[46] on the road and 8,284 truck stops,[47] a density ratio of 332. While it is not feasible to simulate the movement of 2.7 million trucks, by running the simulation at a density ratio in the 300 - 350 range and given that the analysis assumes that trucks are always active regardless of the time of day, the results can be used to estimate the upper bound of the load on future transportation infrastructure if all diesel trucks on the road were replaced by a FCEV or BEV.

4.2 Analysis Results

At a high level, switching a significant portion of long-haul heavy-duty trucks to a battery electric drivetrain will require a more robust infrastructure, in terms of size or number of stations – whereas the equivalent infrastructure for hydrogen, while still challenging, is comparatively more similar to diesel. In both cases, however, significant infrastructure work will be needed to meet the requirements of a predominately zero-carbon, long-haul heavy-duty truck fleet. To reach this conclusion, station peak hydrogen fuel flow rate or peak power, as well as station average daily hydrogen or electric energy usage were analyzed. To compute either set of numbers, first the Monte Carlo simulation had to be discretized into one-hour time segments. For daily hydrogen or electric energy usage, the values were computed by summing the hourly results and averaging out the day-to-day differences. For station peak hydrogen flow rate or power, the values were computed from simulation results similar to the ones shown in Figure 6.

Figure 6: Typical Results From the Monte Carlo Simulation



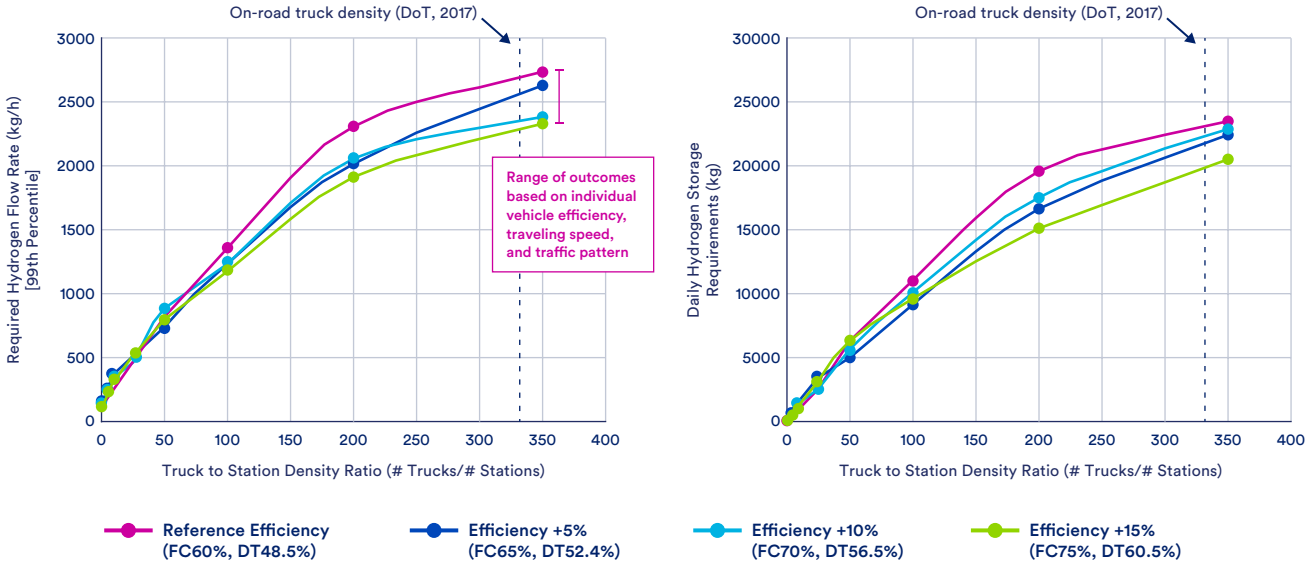
The simulation outputs a range of potential outcomes organized by percentage of occurrence on the vertical axis and the required electric power or hydrogen fuel flow rate on the horizontal. These results were interpolated to compute the 99th percentile which represents the hydrogen fuel flow rate or amount of electric power a station would need to cover 99% of operations. This is considered peak operating capacity for a given station. In real world terms, this means that 1% of the time, or 3 - 4 days of total time per year, a queue would form at a station.

The two charts shown in the upper half of figure 6 are for two of the five hydrogen fueling stations for a case with a DR_{truck} equal to 200, or 200 times more trucks on the road than available stations. The most likely outcome at 20% probability is that for any given hour, 600 kg of hydrogen fueling capability is needed, but to cover 99% of operations the station would need to maintain the ability to fuel 2,220 kg per hour. Looking at charging station number 2, bottom left of Figure 6, the peak power required would be 19,602 kW (19.6 MW). In this way, in addition to the averages, the peak requirements for both station types can be computed. This was carried out for eight density ratios (1, 5, 10, 25, 50, 100, 200, 350), where an on-road density of 350 represents a situation where every diesel truck currently on the road is replaced by a BEV or FCEV. On the other hand, the smaller density ratios provide modeling data that may be useful during the transition to alternative drivetrains. Specifically, the data could help with determining station design and demand for renewable electricity or low-emission hydrogen, or for reliably estimating the number of zero-emission trucks along a corridor that can be efficiently serviced.

Figure 7 shows the results for different density ratios for hydrogen stations. The left is the peak hydrogen flow rate, and the right is the average daily hydrogen storage. In addition, fuel cell efficiency was varied between 60 – 75% to study how infrastructure requirements might change as vehicle technology progresses. First, as the density ratio approaches levels similar to ones seen today, a peak aggregate dispenser flow rate of 2,700 kg per hour and 24,000 kg daily storage would be needed at a hydrogen station assuming today's fuel cell efficiencies.

Second, increasing drivetrain efficiency results in a small reduction in fuel storage requirements and peak flow rates, where the exact reduction depends on vehicle efficiency, traveling speed, and traffic pattern. Also, note that the curves flatten for higher density ratios. This occurs because at low density ratios the stations are often idle; thus, increasing the number of trucks on the road sharply increases station requirements. However, at higher truck densities the stations approach max capacity causing the change in slope.

Figure 7: Fuel Flow Rate and Storage Required at H_2 Stations Assuming All Combination Trucks on the Road are FCEV



Similar plots for charging stations are in Figure 8, a key difference being that the effect of station charging power, a key area of research and development, was examined rather than parameterizing battery efficiency, which already exceeds 90%. The four lines represent 250 kW, 500 kW, 1 MW, and 1.5 MW charging power, where 250 kW is the technology available today and the latter three represent the possibility of higher power charging in the future.

First, as the density ratio approaches levels similar to ones seen today, peak power requirements for a 250 kW charging station would be approximately 22 MW and the station would use on average 290 MWh daily. A similar change in slope, as seen with the hydrogen stations, also occurs at charging stations, most prominently for the cases with the longest dwell time. This is because a longer dwell time means fewer on-road trucks are required to max out station capacity.

Second, as charging power increases, dwell time decreases from 330 minutes (250 kW) to 50 minutes (1.5 MW), which increases the required peak station power in a non-linear fashion creating a range from 22 – 27 MW. The total energy usage increases slightly from 290 MWh to 340 MWh. The non-linear effect is due to the increase in charging power pushing up instantaneous power requirements while also reducing dwell time, or in other words, increased power means fewer trucks simultaneously charging but at a higher power level. These competing effects help to limit the overall increase in peak power and daily energy usage such that doubling the charging power from, for example, 500 kW to 1 MW does not act to double the energy requirements.

The last key station requirement that can be derived from the calculation is the number of hydrogen fuel dispensers or battery chargers needed at each truck station. This was computed by tracking the time needed to fuel or charge individual trucks while also considering the distance between each station. These two pieces of data were then used to create an individualized truck schedule containing the date, time, and location of each vehicle. Finally, using that schedule, as well as shifting to the station frame of reference, resulted in the number of trucks that need to use the chargers or fuel dispensers concurrently. This is summarized in Figure 9 for the eight density ratios, both for FCEV and BEV assuming the same 250 kW – 1.5 MW range of charging power. Each point in the figure represents the most likely station requirement at a given set of conditions as determined by the Monte Carlo simulation.

With the BEV, charging power is the main parameter that determines station requirements. For the 250 kW case at a density ratio of 350, 121 trucks need to charge simultaneously, primarily due to a charging cycle lasting up to 330 minutes. This requirement drops quickly, from

Figure 8: Power and Energy Required at Charging Stations Assuming All Combination Trucks on the Road are BEV

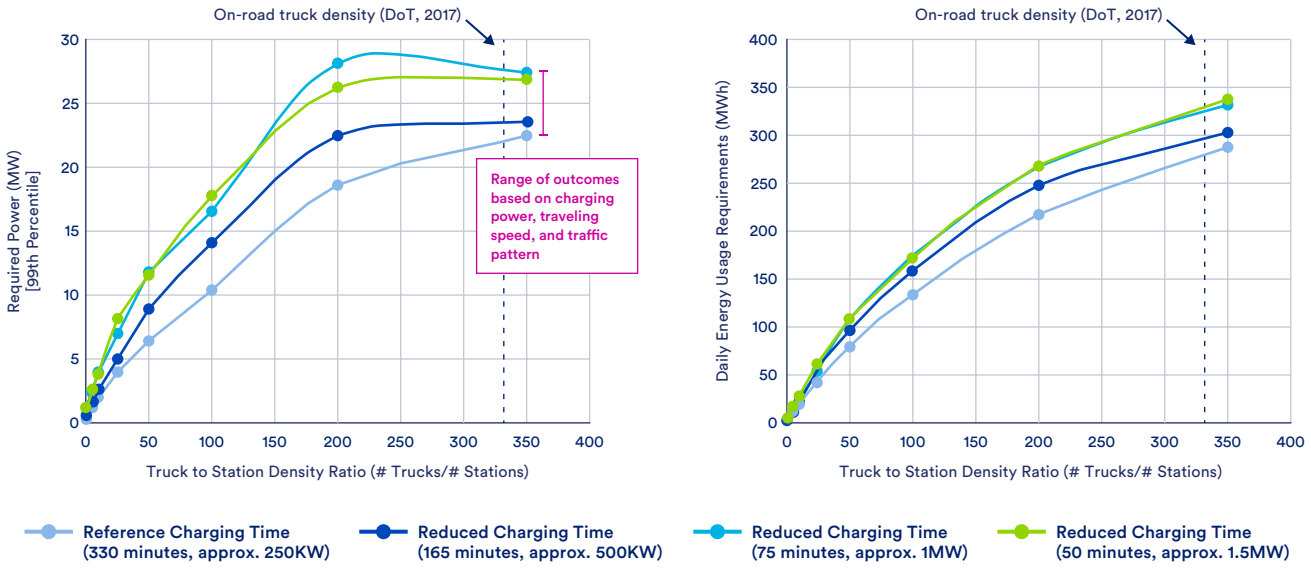
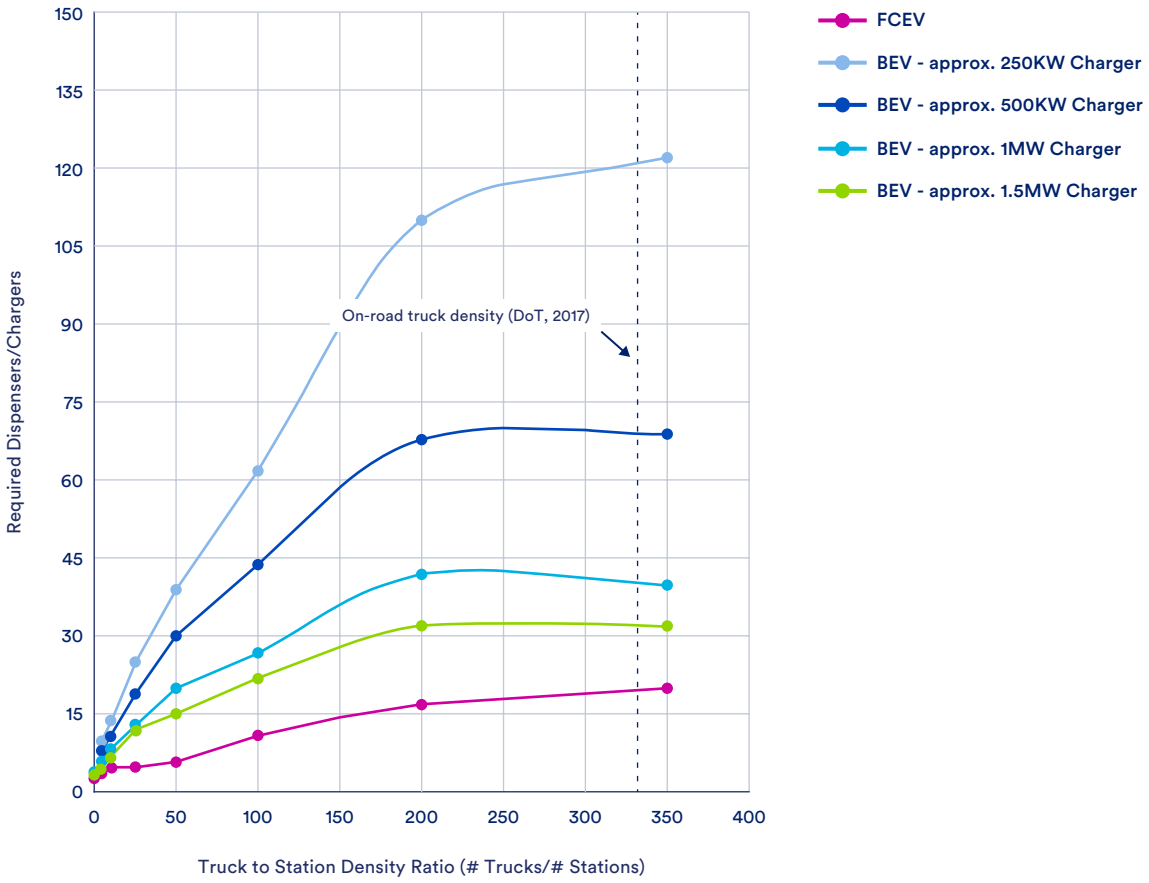


Figure 9: Required Hydrogen Fuel Dispensers or Battery Chargers at Truck Stations



121 down to 31, as charging power is increased and as the density ratio is reduced. Hydrogen stations, on the other hand, only need to have 17 dispensers available since it takes at most 20 minutes to complete the fueling process, allowing vehicles to leave before others arrive.

Station size is an important factor in determining where fueling stops can be located, especially near urban areas, and it is an issue that needs to be considered if alternative fueling stations are to replace their conventional counterparts. To that end, the number of fuel dispensers or chargers computed as part of the previous analysis can be used to estimate the footprint of both station types for comparison to a typical diesel station. However, while that is sufficient for charging stations, more information is needed to size a hydrogen station since much of the other critical infrastructure (storage tanks, compressors) is typically located aboveground. This differs from electrical lines needed for charging or liquid storage needed for diesel, both of which are typically buried.

The National Fire Prevention Association (NFPA)[48] is a key governing body that plays a large role in determining the regulations for compressed hydrogen gas stations, including deciding on hydrogen asset offset distances from the curb, surrounding buildings, and other supporting infrastructure. These regulations are discussed in detail in a paper from Sandia National Laboratories[49] as part of their work that models the size of several different types of hydrogen stations. One type of station discussed includes buried hydrogen storage tanks. NFPA regulations

do allow for hydrogen tanks to be buried, however those regulations also specify that the tanks cannot be located under buildings and must be set back from other buried utilities. In addition, valves, controls, and instrumentation must be located aboveground, meaning that unlike the tanks, compressors are not allowed to be buried. Due to these limitations, the report goes on to show that for a small, four dispenser hydrogen station, underground hydrogen tanks only reduce station area by approximately 4%, and at a significant increase to station capital costs. For this reason, the following analysis assumes that all hydrogen station infrastructure is located aboveground.

Hydrogen station size is primarily a function of how many fuel dispensers are needed and how much hydrogen must be delivered to trucks each day, as those two data points determine the size and number of the storage tanks, number of compressors, and footprint of the fueling island. The number of dispensers and daily hydrogen requirement, both of which are outputs from the infrastructure analysis, are used as inputs into HDRSAM,[50] a tool developed by Argonne National Laboratory. HDRSAM computes the area needed for the fueling island and related infrastructure, ignoring additional space that would be needed for other amenities like parking, a convenience store, or a rest area. Diesel and charging station calculations, however, don't require a model. Station size was computed assuming the fueling or charging island footprint equals the total area of all combination trucks simultaneously in the station plus an extra 50%, where 50% is assumed to be enough space to cover the size of the dispenser or charger as well as any walkways needed around each vehicle. All charging and diesel infrastructure except the island was assumed to be buried and as before, other amenities are not considered. Figure 10 shows the results of this comparison relative to the size of a representative, 12-dispenser diesel highway truck station.

The results show that charging stations would need to be 10 times larger because compared to diesel dispensers, ten times as many chargers are required. Hydrogen stations would be smaller at 5.26 times diesel, but that is still a significant station footprint. It is important to note, however, that hydrogen is a relatively new transportation fuel and regulations regarding it may be updated as new data becomes available. In 2020, after the most recent version of HDRSAM was published, NFPA updated their regulations and reduced some of the most stringent safety distances. These updated regulations do need to be adopted by local governments and thus would need to be considered on a case-by-case basis as part of the station permitting process; however, using the Sandia report to compute the relative change in area and applying that to the HDRSAM (2017) results, hydrogen stations could be 53% smaller if the new regulations are adopted (figure 11). With this, hydrogen stations would be a more reasonable 2.80 times larger than diesel stations, marking a clear advantage over charging stations – if still challenging compared to what exists today.

Figure 10: Station Size Relative to 12-Dispenser Diesel (2016 NFPA Hydrogen Regulations)

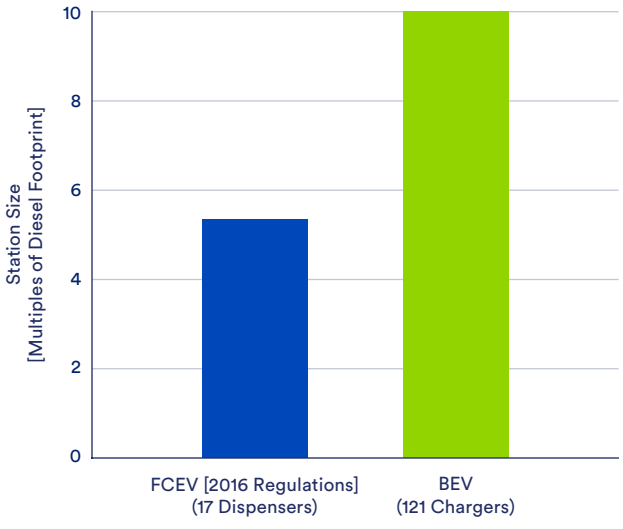
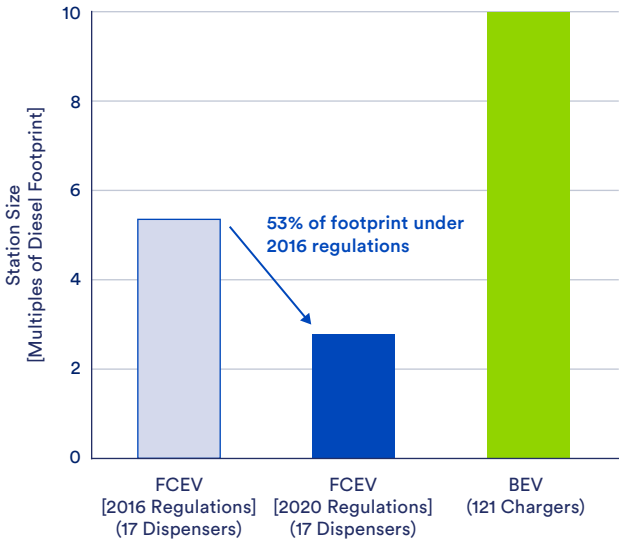


Figure 11: Station Size Relative to 12-Dispenser Diesel (Updated NFPA Hydrogen Regulations)



SECTION 5

Conclusion

For long-haul heavy-duty operation, the hydrogen fuel cell vehicle (FCEV) outperforms the battery electric vehicle (BEV) in terms of number of stops required, total fueling time, and available room for cargo. Furthermore, switching a significant portion of heavy-duty trucks to a battery electric drivetrain requires a more robust infrastructure buildout, in terms of size or number of stations, whereas the buildout for hydrogen, while still challenging, is comparatively more similar to diesel. BEV likely will close the gap with FCEV on several of these metrics if 1 – 2 MW class high-power charging becomes widely available.

Significant challenges remain both for BEV and FCEV. Stations for either alternative drivetrain require infrastructure changes and investments in order to deliver the necessary power or hydrogen, and both station types would use more land than diesel stations today. Unique to BEVs, the charging station electric power requirements are high enough to cause concern about the negative effects on the grid as well as the possibility of not being able to secure enough clean electricity. For FCEVs, more research and development is needed to achieve fueling times equal to those of diesel, and either a reduction in drivetrain component or glider weight is needed to eliminate any potential cargo capacity limitations. In addition, this analysis did not evaluate total cost of ownership for either alternative drivetrain. That type of analysis would likely highlight other key hurdles, such as how the cost to produce, transport, and dispense hydrogen might adversely affect fleet operation expenses and how the large battery needed for BEVs might mean capital expenses two to three times more than diesel trucks or show a need to increase fleet size to make up for the cargo capacity shortfall. Furthermore, both the electricity and hydrogen must have little to no associated greenhouse gas emissions, another factor that increases costs.

To summarize, long-haul heavy trucking contributes to nearly half of all heavy trucking emissions in the United States. It is one of the most difficult areas to decarbonize due to the distance traveled, duty-cycle, and cargo capacity required. Plus, a robust charging and fueling network needs to be built out in a way that works with the trucking industry while not disrupting current energy infrastructure. And all of this work must begin soon if the sector's substantial emissions are to be abated by midcentury. Battery-powered trucks will play a significant role in the transition to a zero-emission transportation sector. With that being said, taking advantage of the merits of hydrogen fuel cell vehicles is likely the best way to quickly and efficiently decarbonize long-haul heavy-duty trucking.

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