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Infrastructure to support a 100% zero-emission tractor-trailer fleet in the United States by 2040

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Introduction

To decarbonize the U.S. transportation fleet, policymakers cannot ignore heavy-duty tractor-trailers. These combination vehicles, consisting of a trailer pulled primarily by a Class 7 or Class 8 diesel semi-tractor, were approximately 13% of the on-road medium- and heavy-duty fleet in 2020 and generate approximately 60% of its greenhouse gas emissions and fuel consumption.[1] These vehicles are the workhorses of the U.S. transportation fleet, consuming large volumes of diesel fuel while pulling heavy payloads and traveling relatively long distances each year.

This year the U.S. government has made moves to address emissions from heavy-duty vehicles. On January 27, 2021, President Biden endorsed a greenhouse gas target of, “net-zero global emissions by mid-century or before,” and on April 22, 2021 announced a near-term target of a 50%–52% reduction in net economy-wide emissions from 2005 levels by 2030.[2] On August 6, 2021, President Biden directed the U.S. EPA Administrator to update greenhouse gas emission standards for heavy-duty engines ‘in consideration of the role that zero-emission heavy-duty vehicles might have in reducing

1 U.S. EPA and U.S. DOT. “Final Rule: Greenhouse Gas Emissions and Fuel Efficiency Standards for Medium- and Heavy-Duty Engines and Vehicles–Phase 2.” Federal Register / Vol. 81, No. 206, October 25, 2016. https://www.gpo.gov/fdsys/pkg/FR-2016-10-25/pdf/2016-21203.pdf.

2 United States Administration. “Executive Order on Tackling the Climate Crisis at Home and Abroad.” January 27, 2021 https://www.whitehouse.gov/briefing-room/presidential-actions/2021/01/27/executive-order-on-tackling-the-climate-crisis-at-home-and-abroad/and United States Administration. “FACT SHEET: President Biden Sets 2030 Greenhouse Gas Pollution Reduction Target Aimed at Creating Good-Paying Union Jobs and Securing U.S. Leadership on Clean Energy Technologies.” April 22, 2021. https://www.whitehouse.gov/briefing-room/statements-releases/2021/04/22/fact-sheet-president-biden-sets-2030-greenhouse-gas-pollution-reduction-target-aimed-at-creating-good-paying-union-jobs-and-securing-u-s-leadership-on-clean-energy-technologies

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emissions from certain market segments.'[3] The U.S. Congress recently voted on the adoption of significant new funding to support the electrification of heavy-duty vehicle fleets.[4] Incentives for the installation of privately owned infrastructure, publicly owned installations along federal, state, and tribal lands, as well as public guarantees along critical corridors, will jump start the deployment of this infrastructure before 2030 and set the long-term pace needed to meet national targets.

Zero-emission tractor-trailers, which replace an internal combustion engine with a dedicated electric motor, will significantly reduce greenhouse gas emissions through a combination of greater energy efficiency and the shift away from fossil fuels. Significant public health benefits will follow, particularly among disadvantaged communities historically exposed to the highest concentrations of diesel exhaust. Investments in new infrastructure will provide significant new economic development opportunities across the nation. In addition, a more efficient zero-emission truck fleet will be less costly to operate and maintain, and more reliant on domestic sources of energy. Public officials will find it useful in their decision making to understand the scale of investment needed to fully realize these benefits.

This paper estimates the order of magnitude in scale and pace of national infrastructure investment to meet the goal of 100% sales of zero-emission tractor-trailers by 2040. The installation of depot charging for battery-powered short-haul tractor-trailers is the starting point of this transition. By one estimate, 80% of tractor-trailers travel less than 200 miles per day.[5] These short-haul trips are characterized by predictable start-and-end points and long overnight dwell time. New owners of zero-emission short-haul tractor-trailers will purchase at least one charger and install this at the site where the vehicle parks overnight. Overnight charging at low power (100 kW) would deliver the full driving range needed by the start of the next day, minimizing energy costs for the vehicle owner and infrastructure costs for the electricity provider. Additional overnight charging points could be installed at other predictable and consistent points of pick-up or distribution.

This depot charging approach limits freedom of movement of the vehicle, so additional infrastructure investments will be necessary. Some trips will require more power than one overnight depot charging event can provide. In addition, a reasonable share of vehicle owners, particularly independent owner-operators, will not have the resources to install a private network of charging points and will depend on chargers installed by others. The solution is to establish a network of 'publicly accessible' charging points, which are publicly or privately owned charging points—including overnight (100 kW), fast (350 kW), and ultra-fast (1 MW or greater) speeds—that any vehicle owner can access when needed. For those applications carrying the heaviest loads the longest distances, a minimum number of hydrogen refueling stations may also be necessary to support a niche fleet of hydrogen fuel cell tractors. In summary, investments in publicly accessible infrastructure are an important factor in the growth of the zero-emission tractor-trailer market.

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3 Biden, J.R. 2021. *Executive Order on Strengthening American Leadership in Clean Cars and Trucks.* https://www.whitehouse.gov/briefing-room/presidential-actions/2021/08/05/executive-order-on-strengthening-american-leadership-in-clean-cars-and-trucks/.

4 At the time of writing, the bill had been approved by the U.S. Senate, but had not yet passed through the U.S. House of Representatives.

5 Borlaug, Brennan et al. 2021. "Heavy-Duty Truck Electrification and the Impacts of Depot Charging on Electricity Distribution Systems." *Nature Energy* 6(6): 673–82.

This briefing paper looks at the total annual and cumulative investment required over the next 30 years to construct a national network of publicly accessible charging and hydrogen refueling stations. The pace of infrastructure deployment in this paper is defined by the goal of achieving 100% zero-emission tractor-trailer sales nationwide by 2040. This target lines up with the goals or public positions taken by various actors as of this writing, including the U.S. House Select Committee on the Climate Crisis, the UK Department of Transport, Daimler Trucks, Walmart, FedEx and the Environmental Defense Fund.[6] For battery-electric trucks, the results include the number and type of charging stations needed in each year. For hydrogen fuel cell trucks, the results include the total number of hydrogen refueling stations needed in each year. The result is an estimate of the total up-front public and private sector investment needed to deploy this scale of charging and refueling infrastructure.

Methodology and assumptions

Vehicle sales and stock projections

To model the future growth and activity of the national heavy-duty tractor-trailer fleet, data on current and projected nationwide HDV stock, sales, and vehicle activity in the United States were obtained from the U.S. Environmental Protection Agency's Motor Vehicle Emission Simulator (MOVES3). We extracted detailed MOVES3 outputs by vehicle market segment, fuel, and model year for the years 2000, 2010, 2015, 2030, and 2050, and then estimated stock, sales, and activity values for each intermediate year using linear interpolation. Using sales estimates and reported vehicle stock by model year, we then calculated annual survival rates such that the number of vehicles sold in intermediate years aligned with the number of vehicles of that model year provided by MOVES3 in later years. Vehicle activity was calculated based on vehicle stock and total miles traveled for each vehicle from ages 0 to 30 years. Per-vehicle activity was linearly interpolated by vehicle age for each intermediate year. The resulting database generated by these steps contains current and projected annual vehicle stock, sales, and activity by vehicle market segment, fuel type, and model year from 2000 to 2050.

We then incorporated into this database a timeline for the transition of all new heavy-duty tractor-trailers to zero-emission powertrains. Table 1 gives the year in which we assume that 100% of heavy-duty truck sales are zero-emission. We expect this transition will first occur in California in response to Executive Order N-79-20 and the California Air Resources Board Draft 2020 Mobile Source Strategy.[7] We expect the remaining 50 U.S. states to follow California by 2040. An increase in the sales share of zero-emission vehicles does not affect the total level of vehicle activity. These sales shares and activity

Table 1. 100% Zero-emission sales targets for heavy-duty tractor-trailers

MOVES3 market segment	CA	Remaining U.S. states
Short-haul tractor trailers	2030	2040
Long haul tractor-trailers	2035	2040

6 House Select Committee on the Climate Crisis, "Solving the Climate Crisis: The Congressional Action Plan for a Clean Energy Economy and a Healthy, Resilient, and Just America," Majority Staff Report. 116th United States Congress, June 2020, https://climatecrisis.house.gov/report.

7 Office of the Governor of California. Executive Order N-79-20, (2020). https://www.gov.ca.gov/wp-content/uploads/2020/09/9.23.20-EO-N-79-20-text.pdf; Air Resources Board. "Revised Draft 2020 Mobile Source Strategy." Sacramento, CA: California Air Resources Board, (April 23, 2021). https://ww2.arb.ca.gov/sites/default/files/2021-04/Revised_Draft_2020_Mobile_Source_Strategy.pdf.

data were then used as inputs in version v1.6 of the ICCT Roadmap emissions model, aggregating the two types of tractor-trailers in MOVES3 into a single Roadmap vehicle category for tractor-trailers.

We made further projections for two zero-emission powertrains: battery-electric and hydrogen fuel cell electric. The share of vehicles allocated to each of these two powertrain types was determined based on the estimated daily range required of vehicles in each vehicle category. For the main findings of this analysis, we assumed that vehicles operating along routes with a daily distance up to 650 miles will be served by battery electric powertrains. This distance is informed by the vehicle specifications announced by manufacturers, by the Hours of Service limits set by U.S. regulations,[8] and by the possibility of charging during mandated rest periods. We assumed longer routes will be served by hydrogen fuel cell powertrains. Since there is uncertainty about future advances in battery technologies and the potential role of fast charging to extend existing range, we conducted a sensitivity analysis on this daily mileage cut-off. This allows us to estimate the scale of investments for hydrogen refueling stations under different levels of fuel-cell truck adoption.

Vehicle energy demand projections

To estimate the energy demand of internal combustion engines, we used the energy intensity estimates of individual vehicle categories in MOVES3 and consolidate these within the Roadmap model vehicle categories. The accuracy of the energy-intensity estimates was verified by comparing the model's output against ICCT vehicle simulation and published fuel consumption statistics, including from the International Energy Agency and the U.S. Energy Information Administration.[9] These estimates form the basis of estimated energy demand of zero-emission powertrains.

To estimate the energy demand of zero-emission powertrains, we used the average energy intensity of conventional internal combustion engines in each vehicle segment and model year, then adjusted these by weighting factors that reflect the higher energy efficiency of electric powertrains. We used energy intensity ratios from the California Air Resources Board comparison of heavy-duty battery electric and diesel vehicle energy efficiency over similar duty cycles.[10] The energy intensities we applied to zero-emission powertrains are shown in Table 2. We assume technology advances will deliver linear improvements in these values after 2021 with no further improvement after 2030.

Table 2. Average energy consumption for heavy-duty tractor-trailers, by powertrain

	2021	2030-2050
Battery-electric powertrain		
kWh/mi	2.3	1.9
MPGe*	16.6	20.1
Hydrogen fuel cell powertrain		
kg H2/100 mi	11.4	9.7
MPGe	9.9	11.7

**MPGe: Miles per gallon of diesel-equivalent*

8 Federal Motor Carrier Safety Administration, "Summary of Hours of Service Regulations," U.S. Department of Transportation, September 28, 2020, https://www.fmcsa.dot.gov/regulations/hours-service/summary-hours-service-regulations.

9 International Energy Agency, "Energy Efficiency Indicators," June, 2021, https://www.iea.org/data-and-statistics/data-product/energy-efficiency-indicators; and U.S. Energy Information Administration, "Annual Energy Outlook 2021," (February 3, 2021), https://www.eia.gov/outlooks/aeo/index.php.

10 California Air Resources Board, "Battery Electric Truck and Bus Energy Efficiency Compared to Conventional Diesel Vehicles," May 2018, https://ww2.arb.ca.gov/sites/default/files/2018-11/180124hdbevefficiency.pdf.

Infrastructure investment needs for battery-electric tractor-trailers

The methods for estimating infrastructure needs and costs for battery-electric vehicles are simplified in this analysis to achieve an order of magnitude estimate of scale and cost. The investment and charging infrastructure requirements of battery electric vehicles are contingent on a large number of factors. These include the number of battery electric trucks on the road , the average energy consumption of tractor-trailers, the daily vehicle miles travelled (VMT) by those vehicles, the charging power, the duration of the charging events, the utilization rate of the charging network, and the cost of individual chargers, among others. We avoid a micro-level analysis of each use case in each vehicle category in order to generate a macro-level analysis that can be useful for policy makers.

The previous sections described various inputs that inform the infrastructure analysis for battery-electric vehicles. These include vehicle stock and vehicle energy demand, by year. Daily VMT is based on annual VMT estimates provided by the MOVES3 model. We assume that daily VMT is lognormally distributed to estimate energy demand over a variety of use cases.[11] These data produce an estimate of the total number of battery-electric vehicles and their energy demand in each calendar year through 2050.

Heavy-duty vehicle applications require a range of charging capabilities based on operational and payload constraints, among other factors. To accommodate the range of potential charging needs, we assume direct current (DC) chargers must be available at a minimum of three nominal power levels: 100 kW (overnight chargers),[12] 350 kW (fast chargers), and 1,000 kW (megawatt chargers).[13] We assume the average effective charging power, which accounts for slower rates of charging required at the start and end of a charge cycle to preserve battery health, is 85% of nominal power. We assume the charging efficiency, which accounts for the resistive losses at various places in the charger, vehicle, and their interface, is 85%. These assumptions allow us to predict how much energy demand can be met in the future by chargers with charging speeds of 100 kW, 350 kW, and 1 MW. While power sharing on site will allow for greater flexibility in charging power and potentially lower cost, to capture the diversity in power needs that will be required by different use cases and the respective cost reduction potential, we assume the mix of charging powers outlined above.

Regarding charging duration, we assume the duration of overnight charging (100 kW) is 7 hours while fast (350 kW) and megawatt charging (1 MW) lasts 30 minutes. We set the initial utilization rate for public fast and megawatt chargers in 2021 at 1 vehicle per day but, as fleet scale grows and costs decline, we assume utilization grows logarithmically to 12 vehicles per day by 2050.[14] While we refer to the publicly accessible 100 kW chargers as overnight chargers, we take the view that these chargers will not only

11 Compared to other mathematical functions, lognormal distributions have been found to provide a robust fit of VMT, while featuring a higher probability for long-distance trips, as is the case in the vehicle segment analyzed. For more information see Plötz, Patrick, Niklas Jakobsson, and Frances Sprei. "On the Distribution of Individual Daily Driving Distances." Transportation Research Part B: Methodological 101 (July 1, 2017): 213–27. https://doi.org/10.1016/j.trb.2017.04.008.

12 While we assume that overnight needs to be met with 100 kW DC chargers, we recognize that the application of up to 133 kW AC charging enabled by the SAE J3068 standard may offer hardware cost reductions while increasing cost and weight onboard the vehicle. However, since there is not sufficient information on the deployment of this solution among heavy-duty vehicle manufacturers, it was not considered in the analysis.

13 While charging standards are under development that will enable over 1 MW of power, we consider that much of the charging time benefit is realized with 1 MW.

14 For more information on the logarithmic growth of charger utilization rates, see Hsu, Chih-Wei, Peter Slowik, and Nic Lutsey. Colorado Charging Infrastructure Needs to Reach Electric Vehicle Goals, (Washington, D.C.: ICCT, February 25, 2021), https://theicct.org/publications/colorado-charging-infra-feb2021.

be used for overnight charging, but also for day charging during long dwell periods, increasing the utilization rate of the infrastructure. Thus, for publicly accessible overnight chargers, we set the initial utilization rate at one charging event every 10 days, increasing logarithmically to 1.5 charging events per day by 2050. While there is room to reduce the cost of infrastructure by increasing the utilization of chargers, in this study we make a conservative assumption in the absence of reliable real-world data.

We assume that overnight charging will represent the most cost-effective charging approach among the three included in this analysis. This is due the lower charging power required, the full control over the infrastructure in the case of depot charging, and the possible lower demand charges during off-peak charging with time-varying tariffs.[15] For every battery electric truck deployed, we therefore assume a single depot overnight charger is also installed for each truck. This is a conservative assumption, as the number of depot chargers installed by large fleets will likely be optimized to account for the number of trucks these fleets are charging overnight in publicly accessible chargers during long-haul operation, extended periods of truck inactivity, and variability in the battery state of charge at the beginning of charging, among others.

For battery-electric trucks not returning to base for overnight charging, we estimated the required public overnight charging for those long-distance trucks. According to the Federal Highway Administration, in 2020 there were approximately 313,000 long-term parking spots for trucks, including spaces at both public and private truck stops, in the United States.[16] We assume that truck parking along U.S. highways expands with the growth in vehicle stock, and that the number of 100 kW chargers at those long-term truck parking stops increases proportionally with the fleet of battery-electric tractor-trailers. Based on current vehicle stock and overnight truck stops, we estimate that the average tractor-trailer spends 20% of nights out of base. This estimate is fixed in time and is used to estimate the number of parking spots at truck stops that need to be equipped with a 100 kW charger. While we recognize power sharing with other higher-power infrastructure at these locations can allow for greater flexibility and costs reductions while meeting the overnight charging needs, we consider individual 100 kW chargers per parking spot due to the variability in size of the resting areas. The total costs are expected to be similar, due to the strong dependence of hardware cost on charging power (see Table 3).

To estimate the total cost of this infrastructure, we accounted for the cost of the charging hardware itself and for the additional costs of the hardware installation. However, we did not attempt to estimate the cost of any additional grid upgrades required by the increased power demand. The installation costs are aligned with those found in a previous ICCT study,[17] but are adjusted to account for planning and site selection based on recent discussions with industry. The installation costs per kW fall as a function of charger power and number of chargers installed per site. The dispensers and power cabinets of the charging infrastructure are assumed to have a limited lifetime, leading to hardware replacement costs 10 years after installation.

15 Borlaug, Muratori, Gilleran, Woody, Muston, Canada, Ingram, Gresham, and McQueen, "Heavy-Duty Truck Electrification and the Impacts of Depot Charging on Electricity Distribution Systems."

16 Federal Highway Administration (FHWA), "National Coalition on Truck Parking," Office of Freight Management and Operations, December 1, 2020. https://ops.fhwa.dot.gov/Freight/infrastructure/truck_parking/workinggroups/2020/mtg/nctptpwnmtg12012020.pdf.

17 Nicholas, Michael. Estimating Electric Vehicle Charging Infrastructure Costs across Major U.S. Metropolitan Areas, (Washington, D.C.: ICCT), August 12, 2019, https://theicct.org/publications/charging-cost-US.

Table 3. Assumptions used in the analysis of the infrastructure requirements for battery electric heavy-duty tractor-trailers.

Type of charger	Power (kW)		Charger cost (USD)		Installation costs (USD/kW)	Utilization (vehicles per day)		Charging duration (h)
	Average	Nominal	2021	2050	2021–2050	2021	2050	
Overnight	85	100	49,000	27,300	240	1 (depot) 0.1 (public)	1 (depot) 1.5 (public)	7
Fast	300	350	134,500	76,300	129	1	12	0.5
Megawatt	850	1000	336,000	190,800	77	1	12	0.5

Note: For comparison, a U.S. construction company reports the cost of a typical fuel station pump is $16,000-21,000, the average installation cost of each pump ranges from $2,500 to $3,000 per dispenser, and the average cost to install a complete fueling station is $500,000. Source: CommTank, "Gas Station Construction Company Services," accessed July 30, 2021, https://www.commtank.com/services/gas-station-construction-company/

We estimate the cost of chargers will decline based on a learning rate of 3% per year between 2021 and 2030, and 1.5% per year from 2030 onwards. The cost estimates of each charger type are summarized in Table 3.

The estimated total number of fast and megawatt chargers per battery-powered vehicle is based on an assumed lognormal distribution of daily VMT. Some battery electric trucks can satisfy their charging needs with overnight charging alone, while some will require additional en route charging to complete their daily trip. For the latter vehicles, we examined whether an additional 30-minute fast charging event with a 350-kW charger is sufficient to supplement overnight charging to satisfy the expected daily VMT. If that is not the case, we explored whether one or two megawatt charging events are required to meet the energy demands of the vehicle. We do not predict the optimal location of chargers, nor assume the additional energy demand to reach a charging point. The result of this analysis determines the number of charging points of each type that are needed per vehicle, across the different vehicle segments.

Infrastructure needs and cost assumptions for hydrogen fuel-cell heavy-duty tractor-trailers

The projected number of fuel-cell electric trucks on the road , the average hydrogen consumption of individual vehicle segments, the daily vehicle miles travelled by those vehicles, the utilization rate of the hydrogen refueling network, and the cost of individual refueling stations are all based on methods developed and applied for battery-electric vehicles.

We assume daily VMT is lognormally distributed, with a mean value consistent with the MOVES3 model. The number of fuel-cell electric vehicles deployed in a given year is a function of the adoption rate of zero-emission powertrains by market segment following a pre-determined timeline (see Table 1) and the number of these vehicles traveling more than about 650 miles daily. These fuel-cell vehicle stock projections, combined with hydrogen fuel cell consumption estimates in Table 2, produce an estimate of the hydrogen demand in each calendar year through 2050.

We assume that the average hydrogen refueling station will have the capacity to deliver 4,800 kg of hydrogen per day. We set that the initial utilization rate for hydrogen stations at 10% of this capacity, growing logarithmically to 75% of the average capacity by 2050. The assumed cost of such a hydrogen refueling station in 2020 is $6 million.[18] We estimate that this cost will decline based on a learning rate of 3% per year between 2021 and 2030, and 1.5% per year from 2030 onwards. These learning rates are in line with recent values published by the European Commission, who estimated the cost reduction to be 1% to 1.5% per year between 2020 and 2050.[19] These assumptions are summarized in Table 4.

The result of this analysis determines the number of hydrogen-refueling stations, with the aforementioned daily throughput, that are needed to supply the energy demand of hydrogen-powered vehicles.

Table 4. Assumptions used in the analysis of the infrastructure requirements for fuel cell trucks

Daily distance for fuel cell requirement	650 miles
Capacity of hydrogen refueling station	4,800 kg/day
Utilization rate, 2021	10% of total capacity
Utilization rate, 2050	75% of total capacity
Cost of hydrogen refueling station, 2021	$6,000,000
Cost of hydrogen refueling station, 2050	$3,300,000

Findings

Based on the U.S. fleet data and projections from MOVES3, the national fleet of Class 7 and Class 8 tractor-trailers is projected to grow by 3.5% in the next 30 years, totaling around 3 million tractor-trailers in 2050. Similarly, sales are projected to remain stable at around 145,000 units over the same period. Figure 1 shows the projected deployment of zero-emission tractor-trailers in comparison to internal combustion engine vehicles, assuming a transition to 100% zero-emission vehicle sales by 2040 as described in Table 1.

These results illustrate the lag between changes in new vehicle sales and changes in the in-use fleet. When sales shares are low but rapidly increasing, such as we see from 2030 to 2035, a relatively short lag time of about five years exists between a specified sales share and the equivalent stock share. Later, when sales shares are saturated, such as from 2040 to 2050, the remaining lifetime of internal combustion engine vehicles will control the pace at which the fleet reaches an equivalent stock share. For example, if zero-emission vehicles reach 100% of sales in 2040 and account for roughly four in five in-use vehicles by 2050, the remaining internal combustion engine fleet will consist of vehicles that are more than ten years old. This inertia in the system helps explain why the early and rapid transit to high sales shares of zero-emission tractor-trailers is necessary to meet greenhouse gas mitigation targets.

18 CALSTART, "Alternative fuel infrastructure corridor coalition (AFICC), Medium- and heavy-duty alternative fuel infrastructure strategic development plan," March 2020, https://westcoastcollaborative.org/files/sector-fuels/wcc-aficc-mhd-infrastructure-development-plan-2020-03-12.pdf.

19 European Commission, "Proposal for a Regulation of the European Parliament and of the Council on the Deployment of Alternative Fuels Infrastructure, and Repealing Directive 2014/94/EU of the European Parliament and of the Council," Impact Assessment, July 14, 2021, https://ec.europa.eu/info/sites/default/files/revision_of_the_directive_on_deployment_of_the_alternative_fuels_infrastructure_with_annex_0.pdf.

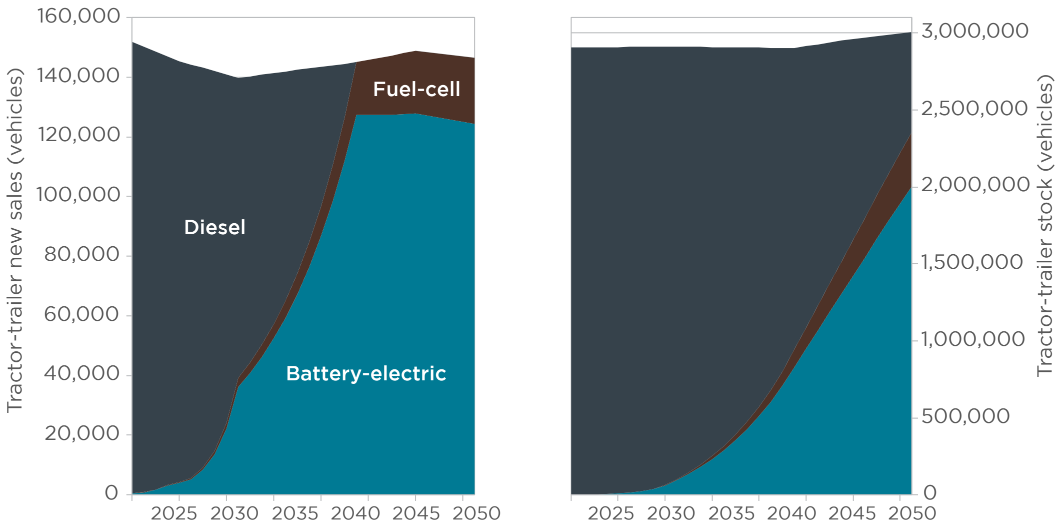

Figure 1. U.S. tractor-trailer sales and stock, assuming a transition to 100% zero-emission vehicle sales by 2040

These vehicle sales and stock projections lead to the findings on the magnitude of the required infrastructure roll-out shown in Figure 2.

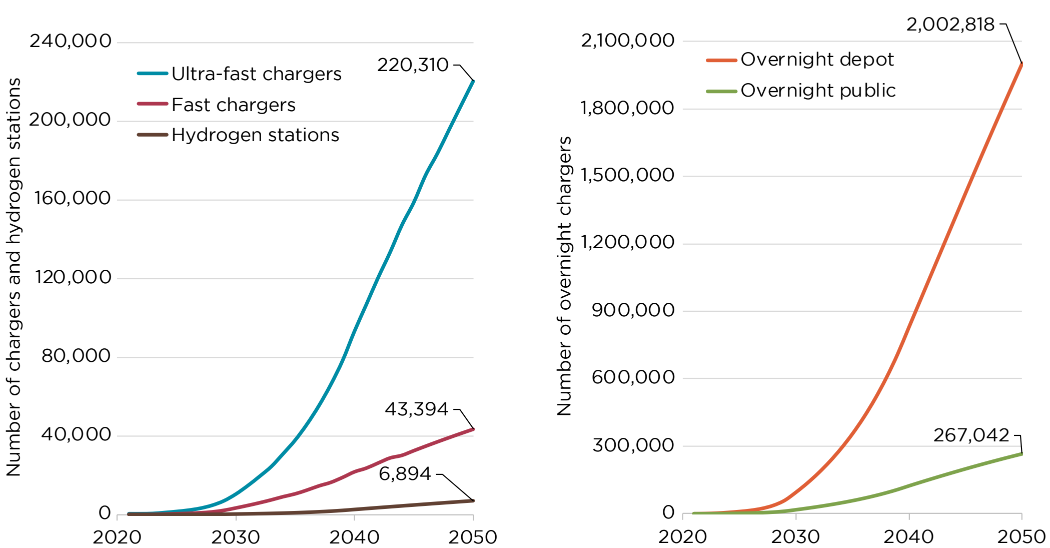

Figure 2. Number of chargers and hydrogen refueling stations needed to support 100% zero-emission tractor-trailer sales from 2040

By 2030, approximately 100,000 zero-emission tractor-trailers will require approximately 127,000 charging points and over 220 hydrogen refueling stations. Around 75% of charging points will provide overnight private depot charging, an additional 14% will provide overnight publicly accessible depot charging, and 11% will provide publicly accessible charging speeds of 350 kW or greater. In 2030, internal combustion engines will continue to power 96% of tractor-trailers operating in the United States.

The picture shifts in 2040 when our scenario implies no internal combustion engines will be sold. In this year, approximately 950,000 zero-emission tractor-trailers will require 1.1 million charging points and close to 3,000 hydrogen refueling stations. Private overnight depot charging continues to be the dominant charging strategy, accounting for 77% of all charging points, while an additional 12% will provide publicly accessible overnight depot charging and 11% will provide publicly accessible charging speeds of 350 kW or greater. In this year, we expect zero-emission trucks to constitute 37% of all tractor-trailers operating on U.S. roadways.

After nearly a decade without new internal combustion engines entering the U.S. truck fleet, we estimate that by 2050, the 2.4 million zero-emission tractor-trailers operating on U.S. roads will constitute 78% of the entire tractor-trailer fleet. These zero-emission trucks will require 2.5 million charging points and almost 7,000 hydrogen fueling stations. Publicly accessible fast and ultra-fast charging points with a capacity of 350 kW or greater will account for 10% of the truck charging network. Publicly accessible overnight depot charging will comprise 11% of all charging points, while private overnight depot charging will provide the remaining charging opportunities.

To achieve this level of infrastructure deployment, a cumulative investment of $122 billion is necessary. Figure 3 summarizes the cumulative investments needed to support each type of publicly accessible infrastructure.

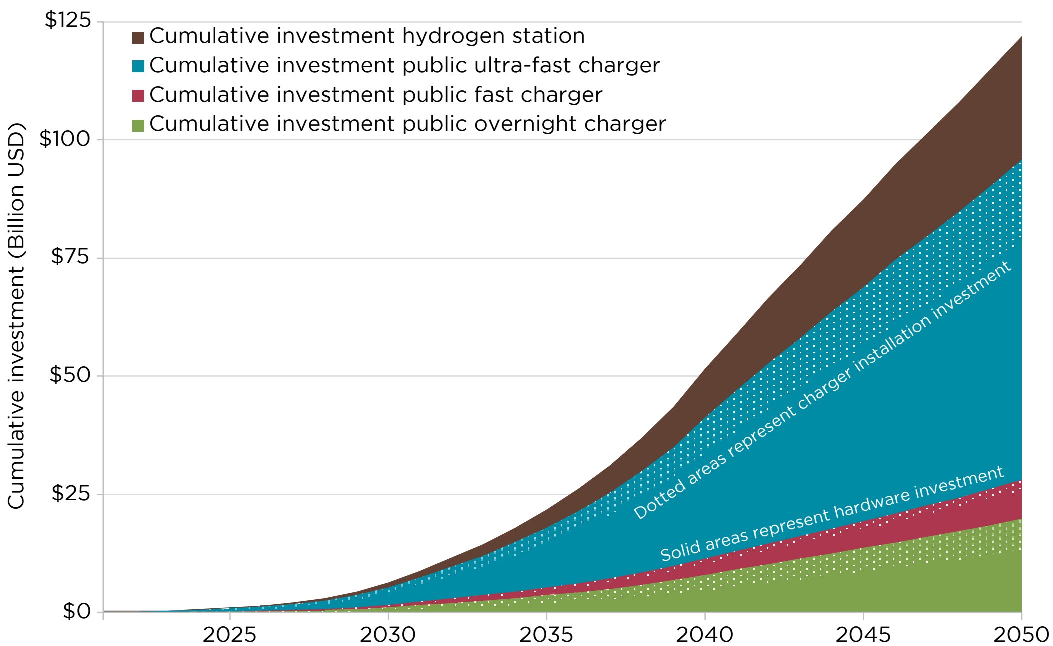

Figure 3. Cumulative investment needed to provide publicly accessible infrastructure to support the U.S. zero-emission tractor-trailer fleet, by infrastructure and expenditure type, from 2020 to 2050

We estimate that the deployment of 267,000 overnight chargers in publicly accessible truck stops by 2050 will require a cumulative investment of approximately $20 billion, with hardware costs accounting for 68% of the expenditures and installation costs for the remainder. We estimate that 2 million overnight chargers in privately owned and operated depots will be needed by 2050, requiring a cumulative investment of $116 billion for both hardware and installation expenditures.

The deployment of 220,000 ultra-fast chargers and of 43,000 fast chargers by 2050 will require a cumulative investment of $76 billion. Given the larger energy throughput of these chargers, installation costs only account for around 25% of the expenditure. Given the high energy demands of battery-electric tractor-trailers, ultra-fast chargers dominate these infrastructure expenditures, accounting for nearly $68 billion. The cumulative investment in fast chargers amounts to just over $8 billion.

Lastly, the cumulative investment required for the construction of 6,900 hydrogen stations is estimated to be $26 billion. This figure includes all hardware, construction, and installation costs.

The cumulative investments summarized above will require continuous efforts as the pace of electrification of tractor-trailers accelerates. We estimate that, on average, an investment of $4 billion per year from 2021 to 2050 will be required to roll-out the needed publicly accessible charging and refueling infrastructure. However, we estimate that the most significant investments will be needed after 2038, with an average annual investment of $7 billion until 2050, peaking at $8 billion in 2040. These results are shown in Figure 4.

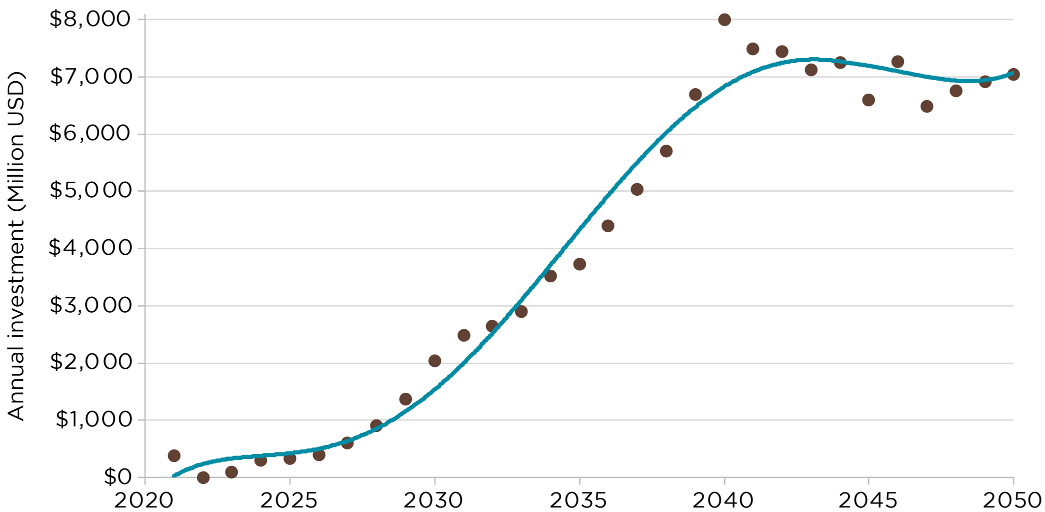

Figure 4. Total annual investments in publicly accessible charging and refueling infrastructure for zero-emission tractor-trailers

Sensitivity analysis of hydrogen infrastructure rollout

We also estimated the magnitude of the infrastructure rollout needed under various scenarios with different rates of fuel-cell truck adoption. That is, we varied the daily distance after which battery-electric tractor-trailers are not considered feasible, requiring the deployment of fuel-cell powertrains. The results for the vehicle and infrastructure rollout, as well as the cumulative investments in 2050, are shown in Figure 5.

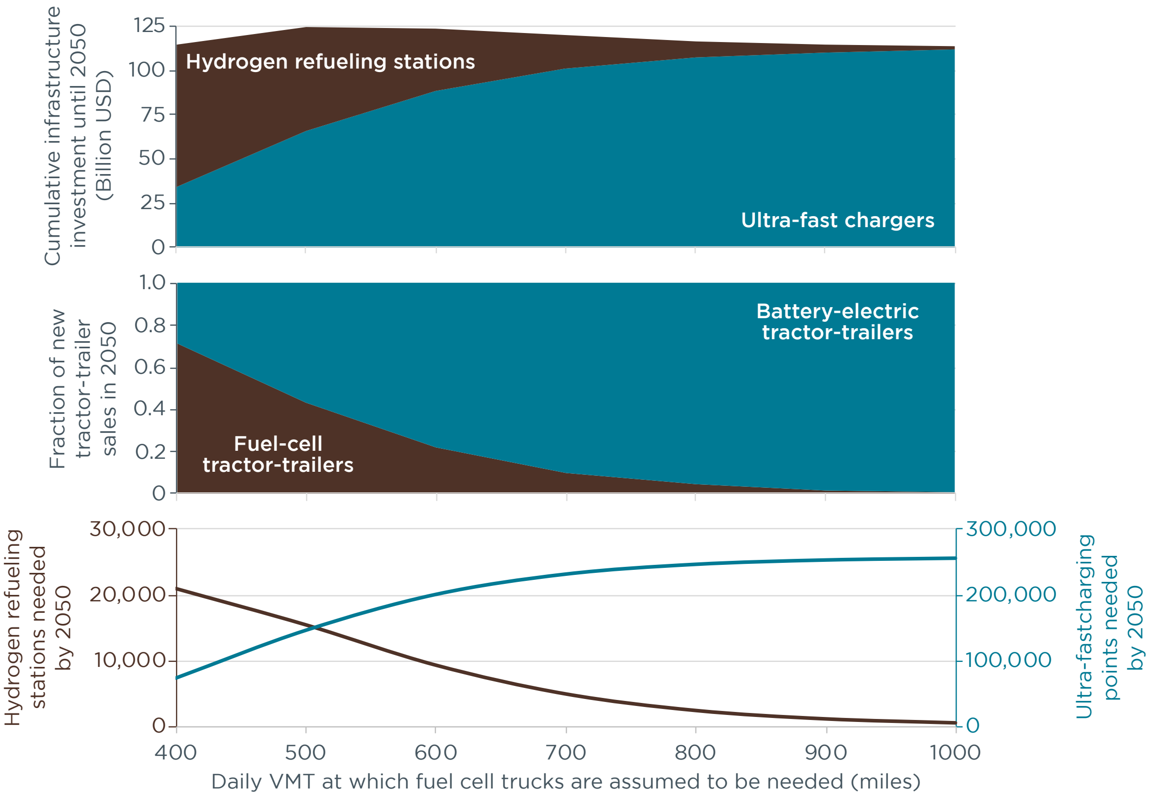

Figure 5. Sensitivity analysis on the hydrogen infrastructure rollout

The total investments in recharging and refueling infrastructure for zero-emission tractor-trailers is largely insensitive to the assumptions on the deployment of hydrogen fuel-cell vehicles. In a scenario where no deployment of fuel-cell tractor-trailers occurs, investment in hydrogen refueling stations would be displaced entirely by battery-electric charging infrastructure for a total cumulative investment of $112 billion by 2050, an 8% reduction from the base scenario.

In this battery-electric only scenario, we estimate that by 2050, 2.4 million battery-electric tractor-trailers would require 3 million charging points. Publicly accessible overnight chargers needed would amount to 314,000, fast chargers to 51,000, and megawatt chargers to 260,000. These estimates are 18% higher than in the base scenario including fuel-cell trucks.

Overnight chargers at publicly accessible truck stops by 2050 would require a cumulative investment of approximately $23 billion, 16% higher than in the base scenario. The investment in fast and ultra-fast chargers would require a cumulative investment of $89 billion, 17% higher than in the previous scenario. We estimate that the 2.4 million overnight chargers in privately owned and operated depots will require cumulative investment of $136 billion, also 17% higher than in the base scenario.

Summary

This analysis estimates the number of public and private charging points and hydrogen refueling points needed to enable a national transition to 100 percent sales of zero-emission Class 7 and Class 8 tractor-trailers by 2040. The policy of the Biden Administration is to reduce net economy-wide greenhouse gas emissions to 50%–52% below 2005 levels by 2030 and to net zero by 2050. Class 7 and Class 8 tractor-trailers, which generate 60% of the greenhouse gas emissions of the heavy-duty fleet and use primarily fossil diesel fuels, are a critical target for decarbonization. Zero-emission powertrains entering the U.S. market can deliver the decarbonization needed, but only if publicly accessible charging and refueling infrastructure is available. The key findings are summarized in Table 5.

By 2030, approximately 127,000 charging points and 220 hydrogen refueling stations will be necessary to support a fleet of 100,000 zero-emission tractor-trailers. The cumulative investment needed to install publicly accessible charging infrastructure is $6.4 billion, beginning in 2021. Of the installed chargers, 32,000 will need to be publicly accessible And of the publicly accessible chargers, 14,000 will require a charging speed of 350 kW or greater.

By 2050, the network of national charging points will need to support a fleet of 2.4 million zero-emission tractor-trailers. This will require 2.5 million charging points and almost 7,000 hydrogen fueling stations, while the additional cumulative investment in publicly accessible charging infrastructure will need to equal approximately $122 billion. These investments, spread out over the next 30 years, amount to half of the annual health damages associated with exposure to transportation attributable PM2.5 and ozone pollution in the United States in a single year (2015).[20]

This national zero-emission infrastructure network consists of three key investment areas. Most of the investments will be required to satisfy overnight charging needs. These predominantly 100 kW depot chargers in both public and private settings will be the foundation of the national zero-emission truck fleet. Most of these overnight depot chargers will be packaged with the purchase of the vehicle and paid for by the vehicle owner, meaning access to these chargers will be limited to the vehicle owner. The cumulative private investment in this limited-access depot charging infrastructure will amount to approximately $116 billion through 2050.

Due to the nature of long-distance operations of Class 7 and Class 8 tractor-trailers, many publicly accessible chargers at trucks stops and other driver rest areas will be required. These trucks do not return to base every night, or they have daily energy needs greater than what can be supplied by overnight charging alone. The cumulative investment needed for this publicly accessible infrastructure through 2050 is $96 billion. Of this cumulative investment, 20%, equal to $20 billion, will support the installation of 80% of the necessary publicly accessible chargers, with an equal share of overnight and fast chargers. These publicly accessible fast chargers will be necessary to shorten dwell time and enable high mileage operation. Of the cumulative infrastructure investment to 2050, these 350 kW and 1MW chargers represent $76 billion, or 62% of the total. For the longest-range tractor-trailers, a network of hydrogen refueling stations at a cumulative cost of $26 billion, or 21% of the total, may be necessary, although we project just 12% of the fleet would utilize them.

20 Anenberg, Susan C., Joshua Miller, Daven K. Henze, Ray Minjares, and Pattanun Achakulwisut. "The Global Burden of Transportation Tailpipe Emissions on Air Pollution-Related Mortality in 2010 and 2015." *Environmental Research Letters 14,* no. 9 (September 2019): 094012. https://doi.org/10.1088/1748-9326/ab35fc.

Under an alternative infrastructure scenario where battery-electric tractor-trailers satisfy all the operational and performance requirements of the fleet and no investments are made in hydrogen infrastructure, the cumulative investments needed in all publicly accessible infrastructure are $10 billion lower than the scenario with hydrogen infrastructure. Conversely, the investments in chargers in privately owned and operated depots increase to an estimated $136 billion. The combined, cumulative infrastructure investments in private depots and publicly accessible locations until 2050 is insensitive to the assumptions on the deployment of fuel-cell electric tractor-trailers.

Public investment in this infrastructure will accelerate its deployment. Most of the estimated investment cost, particularly after 2030, can come from the private sector. However, government incentives for the purchase and installation of infrastructure, as well as public guarantees along critical corridors, will jump start the deployment of this infrastructure before 2030. The sooner this support arrives, the faster the market for zero-emission tractor-trailers will develop.

This paper does not include all of the necessary infrastructure costs, such as upgrades to grid infrastructure, as some uncertainty around the magnitude of these investments exists. For example, the demand charges utilities set for zero-emission trucks could limit the uptake of fast and ultra-fast publicly accessible chargers. Greater power sharing and optimization of charger installation within fleets could reduce charger installation and energy consumption costs. Coordinated siting of power infrastructure for light-duty and heavy-duty vehicles could also lower overall costs to utilities. Despite these gaps, these estimates provide an important and timely outline of the magnitude of infrastructure needed to ensure a sufficient pace of market growth to deliver on climate goals both domestically and internationally.

Table 5. Infrastructure needs of a 100% zero-emission tractor-trailer fleet in the United States

	2030	2040	2050
Size of zero-emission tractor-trailer fleet	103,000	950,000	2.4 million
Share of combustion engine tractor-trailers	96.4%	67%	21%
Share of battery-electric tractor-trailers	3.3%	29%	67%
Share of fuel-cell tractor-trailers	0.3%	4%	12%
Overnight private chargers (100 kW)	95,000	830,000	2 million
Overnight public chargers (100 kW)	18,000	125,000	267,000
Fast chargers (350 kW)	3,200	22,000	43,000
Ultra-fast chargers (1 MW)	10,500	93,000	220,000
Hydrogen refueling stations (4,800 kg/day)	220	2,500	6,900
Median annual investment in publicly accessible infrastructure over the previous decade	$0.4 billion	$4 billion	$7 billion
Cumulative investment in publicly accessible infrastructure from 2021	$6 billion	$52 billion	$122 billion
Cumulative investment in private overnight depot chargers from 2021	$6 billion	$49 billion	$116 billion
Total cumulative public and private investment	$12 billion	$101 billion	$238 billion