

Memorandum

TO: Leslie Fordjour, NYMTC

FROM: Ben Mandel, CALSTART; Chris Lamm, Cambridge Systematics, Inc.

DATE: 12/31/2020 (revised 3/19/2021)

RE: Clean Freight Corridors Planning Study Task 3 Draft Deliverable:
Alternative Fuel Vehicle Technology Scan and Projections

INTRODUCTION

NYMTC has initiated a Clean Freight Corridors Planning Study to facilitate increased adoption of high-efficiency, low-emission alternative technologies for freight transportation in the New York metropolitan region. As a component of the Regional Freight Plan contained in NYMTC's *Plan 2045* Regional Transportation Plan, this study will support deployment of alternative fuel medium- and heavy-duty (M/HD) vehicles for goods movement by identifying roadway corridors best suited for designation as Clean Freight Corridors to guide future investment in alternative fueling/electric charging infrastructure.

The task objective for the marketing projection analysis is to provide consultant support to assess opportunities for the development of the Clean Freight Corridors in the NYMTC planning area (including Connecticut, New Jersey, New York, and Pennsylvania) that are integrated within the larger Multi-State Metropolitan Region. *Task 3.1: Alternative Fuel Vehicle Technology Scan and Projections* aims to provide brief assessments of the present technological outlook for each alternative fuel technology, including regional adoption rates, the role of automated vehicle (AV) technology, and several brief case studies of fleets that have adopted these technologies for long-haul, warehouse, and delivery applications.

ALTERNATIVE FUELS TECHNOLOGY SCAN

While alternative fuel vehicle (AFV) options are continually expanding and the

underlying technologies are rapidly improving, these technologies still face fundamental barriers to adoption. Some of these barriers persist as constraints to adoption, including the characteristically higher upfront capital cost and the lack of adequate or accessible fueling infrastructure. Other barriers are more a function of perception than current reality, such as the belief that AFV technologies cannot provide needed levels of performance (e.g., driving range or payload capacity) or that AFV model availability is insufficient to support viable fleet operations.

To better assess the extent to which these barriers continue to impede fleet adoption, and how the technologies are evolving to overcome past shortfalls, it is necessary to understand the current market conditions of various alternative fuel vehicle types. The subsections that follow characterize the efficiency, performance, cost, manufacturer offerings, and infrastructure considerations for the vehicle propulsion technologies that use each of the major alternative fuel types covered by this study: battery electric vehicles, hydrogen fuel cell electric vehicles, liquefied petroleum gas vehicles, and compressed natural gas vehicles. This section closes with an assessment of the state of play for autonomous vehicle technology and its potential to improve overall truck freight efficiency.

BATTERY ELECTRIC VEHICLES

Recent advances in battery electric vehicle (BEV) technology have helped to highlight the benefits of electric charging as an alternative to diesel fueling, in turn raising commercial fleet demand for these products. One key factor is the high energy efficiency and low cost of fueling that BEVs offer. According to the U.S. Department of Energy (DOE), BEVs propulsion systems productively use 77% of the electricity consumed by their batteries, as opposed to conventional internal combustion engine (ICE) vehicles, which convert between 12-30% of the primary energy stored in gasoline.¹ In addition to the energy conversion factor, BEVs are able to recapture a significant amount of the energy they use through regenerative braking; depending on the drive cycle, this feature can further extend the driving

¹ U.S. Department of Energy Office of Energy Efficiency & Renewable Energy: All-Electric Vehicles. Retrieved from <https://fueleconomy.gov/feg/evtech.shtml>

range by 10-25%² and increase overall efficiency. The advantages in energy efficiency and fuel economy (measured in miles per gallon of diesel equivalent (MPGDE) or kilowatt-hours (kWh)) for BEVs relative to diesel vehicles can result in significant operating cost savings; the cost to operate a HD BEV is an average of \$0.24 (USD) per mile as opposed to the comparable diesel cost of \$0.50 (USD) per mile.³

EVs provide a quieter, smoother, and quicker acceleration compared to conventional ICE vehicles. Although EVs have higher upfront costs compared to conventional ICE vehicles, mostly attributed to battery cost, the total cost of ownership (TCO) is still lower for EVs in high-mileage applications and where electricity costs can be effectively managed. EVs also have fewer moving parts, which results in lower maintenance costs; the electrical systems of EVs typically require less attention and regenerative braking extends brake life, while the absence of fluids such as engine oil minimizes the need for scheduled maintenance.

² Jha, S. (2020, August 27). *Fast and Agile Regenerative Braking is Redefining Vehicle Dynamics*. Retrieved from <https://www.electronicdesign.com/markets/automotive/article/21140424/global-marketing-insights-fast-and-agile-regenerative-braking-is-redefining-vehicle-dynamics>

³ Welch, D., Facanha, C., Kroon, R., Jousma, F., & Weken, H. (2020). *Moving Zero-Emission Freight Toward Commercialization*. CALSTART. Retrieved from <https://globaldrivetozero.org/publication/moving-zero-emission-freight-toward-commercialization/>

Table 1. Comparison of alternative fuel types

FUEL TYPE	INFRASTRUCTURE COST	FUEL COST	PROS	CONS
EV	Level 3 (DC Fast Charging) material and installation costs can vary from \$14,000 to \$91,000.	Fuel costs are highly variable between states and utilities. Some utilities have produced special rate programs for commercial EVs to lower fuel costs.	- Cheaper TCO compared to ICE vehicles. - Zero tailpipe emissions and reduced lifecycle GHG emissions. - High energy efficiency.	- Long charging times. - Most public fast charging not designed for trucks. - High upfront vehicle cost. - Limited vehicle model availability for certain duty cycles.
H2	Average of ~\$4 million per filling station.	The average price for open retail hydrogen fuel is \$13.99/kg. Price parity is expected to occur when hydrogen is priced at \$8/kg assuming \$3.50/gasoline gallon.	- Lower TCO at high production volumes. - Zero tailpipe emissions and reduced lifecycle GHG emissions. - Significantly greater energy efficiency (compared to ICE vehicles) makes hydrogen fuel suitable for long-haul applications.	- Large fuel throughput needed to justify station costs. - Limited fueling availability currently. - Regulatory restrictions on transport and storage of compressed gases. - Limited vehicle model availability. - Most hydrogen is currently produced with fossil fuels.
LPG	Small propane station averages around \$65,000. Larger stations can cost up to \$2 million.	Fuel costs are variable but typically fall between the cost of regular gasoline and natural gas.	- Infrastructure can be relatively affordable. - Existing fueling network is already widespread.	- Produces tailpipe emissions. - Lower energy content per diesel gallon equivalent.
CNG	Costs of installation vary widely with CNG stations ranging from \$1 to \$4 million with fast-fill dispensers.	Heavy-duty CNG trucks can carry a 40 to 80% price premium over diesel alternatives.	- Despite higher premiums, heavy-duty trucks can save ~\$30,000 per year in fuel and maintenance costs in some applications. - Most common alternative fuel in the study area	- Tailpipe emissions. - Lower energy content per diesel gallon equivalent.

Furthermore, the batteries in BEVs are designed to last over the course of the lifetime of the vehicle (expected to be 7-10 years⁴ as opposed to diesel trucks which are often able to run 10-15 years), limiting the need for replacements which can be especially costly if the vehicle warranty has expired.⁵ Despite these benefits, a gap of BEV-specific training remains to be addressed in the automotive maintenance workforce.⁶ A lack of familiarity with BEV charging, maintenance, and operation remains a barrier to some fleet customers as they consider transitioning away from more familiar diesel systems to BEV technologies.

EVs are often promoted for their environmental benefits. The vehicle's battery provides all the energy necessary for the drivetrain and additional onboard accessories, resulting in zero tailpipe emissions. While the life cycle emissions of a particular vehicle will vary by region, vehicle type, and duty cycle among other factors, there is a mounting opportunity to create a 100% zero emissions energy supply through the investment in wind, solar, and other renewable electricity sources.

The upfront purchase premium of BEVs over comparable diesel vehicles, driven primarily by their large battery packs, is a significant hurdle for many commercial fleets. Economies of scale have helped offset this concern in some circumstances, but the market is still expanding and evolving to meet the needs of many kinds of fleets. In cases of on-road accidents or malfunctions, the cost to replace the battery itself can be prohibitive. And the wear and tear of the battery over time results in capacity degradation, which may prevent the vehicle from reliably performing to its duty cycle standard and this reduced range may turn fleets away from this technology. However, with a variety of automakers working to develop so-called "million-mile" batteries that will support many years of high mileage use, capacity degradation is expected to fade from being a significant deterrent to

⁴ <https://nacfe.org/emerging-technology/electric-trucks/>

⁵ *Alternative Fuels Data Center: Maintenance and Safety of Hybrid and Plug-In Electric Vehicles*. Retrieved from https://afdc.energy.gov/vehicles/electric_maintenance.html

⁶ Gilde, A., Norris, J., Scott, C., Okazaki, K., & Gordon, J. (2020). *Alternative Fuel Infrastructure Corridor Coalition (AFICC): Medium- and Heavy-Duty Alternative Fuel Infrastructure Strategic Development Plan*. CALSTART. Retrieved from <https://westcoastcollaborative.org/files/sector-fuels/wcc-aficc-mhd-infrastructure-development-plan-2020-03-12.pdf>

integration of BEV technology for freight vehicles.⁷

Model availability and performance for BEV truck technologies has rapidly improved in recent years and EV offerings and capabilities are poised to continue expanding. As of fall 2020, the North American market for M/HD BEVs covered a wide range of vehicle platforms, including: cargo vans, box trucks, straight trucks, step vans, and heavy-duty trucks including drayage trucks and regional-haul tractors. A range of original engine manufacturers (OEMs) and upfit/retrofit manufacturers (URMs) have seeded the incipient market with offerings throughout the commercial vehicle spectrum but more concentrated at the lighter end; these pioneering brands include BYD, Chanje, Envirotech, Lightning eMotors, Lion Electric, Motiv Power Systems, Phoenix Motorcars, SEA Electric, Unique Electric Solutions, and Workhorse. Additional brands, ranging from well-established truck OEMs to startups, are expected to launch commercial production for additional BEV truck products in North America between now and 2023, including Arrival, Avevai, Emiss, Freightliner, Hyundai, International, Kenworth, Mercedes-Benz, Meritor, Neuron EV, Nikola, Peterbilt, Phoenix Motorcars, Rivian, ROUSH CleanTech, SEA Electric,

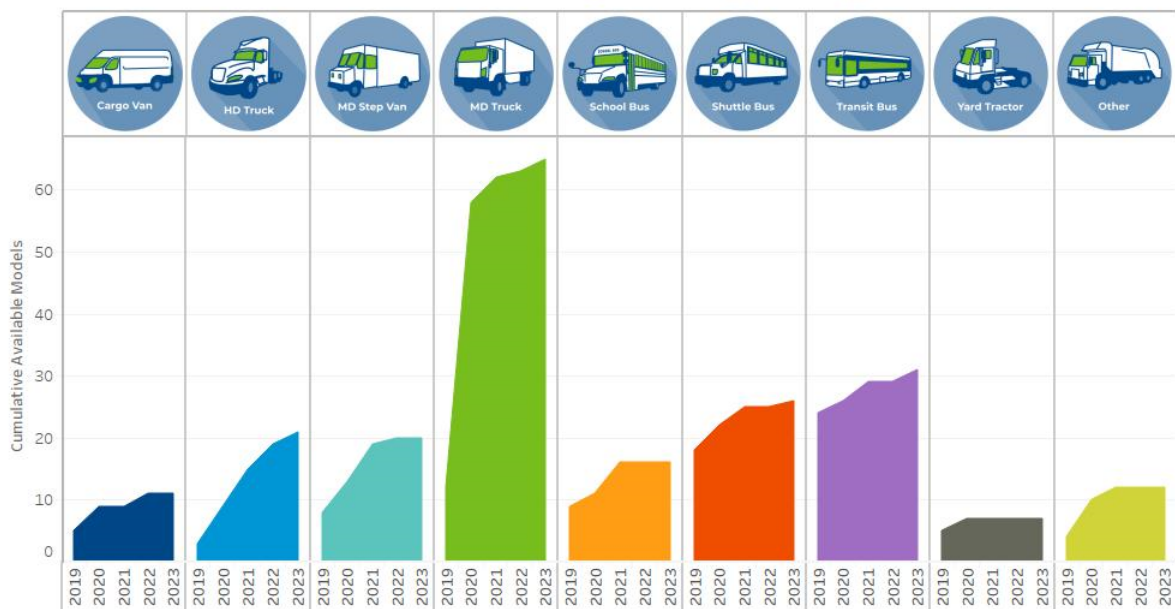


Figure 1. Zero-emission model availability by M/HD platform type, 2019-2023 (CALSTART Zero-Emission Technology Inventory)

⁷ See, e.g., <https://www.wired.com/story/what-happens-after-a-million-mile-battery-outlasts-the-car/>

Driving Deliveries of the Future

IKEA is a globally recognized retailer known for its ready-to-assemble furniture. Perhaps lesser known are IKEA's bold commitments to climate action and their vision of becoming "People & Planet Positive" by 2030. In addition to investments in renewable energy and installing electric vehicle charging stations for customers at every retail location worldwide, IKEA's environmental stewardship now extends to the technology it uses to deliver its goods to customers. In 2018, the Ingka Group, which owns the last-mile segment of IKEA's business, announced that 100% of its home deliveries globally will be made using zero-emission technology by 2025. It further identified New York, Los Angeles, Amsterdam, Paris, and Shanghai as its first priority markets for zero-emission truck deployments beginning in 2020.

In New York, the company has deployed ten battery electric vehicles (BEVs) thus far, including five Lightning eMotors Ford E-450 trucks and five Workhorse C1000 step vans, with plans for 34 more electric trucks to come later in 2021. Though these vehicles have been in service for just a few months as of this writing, the drivers of these BEVs have already indicated excitement and positive responses to the electrification transition. One challenge that IKEA has confronted is that it does not own its delivery vehicles.

Therefore, these vehicles are procured and operated by contract carriers on behalf of third-party logistics providers, and many of the contract carriers are small fleets that own just a few trucks. For many of these fleets, the high upfront investment associated with BEVs is prohibitive. To make good on its last-mile commitment while making BEV technology accessible to its operators, IKEA has partnered with Fluid Truck to offer BEVs for daily and weekly rental at reasonable rates for contract carriers on an app-based platform.

Having successfully navigated the difficulties surrounding vehicle acquisition, the next largest obstacle is providing sufficient charging infrastructure. Steven Moelk, IKEA's Fulfillment Project Implementation Manager for zero-emission delivery, notes that his team is in "a race against the clock on the infrastructure side." His objective is to provide dedicated charging for all 44 vehicles at IKEA's Staten Island Customer Distribution Center, so that operators aren't responsible for installing and maintaining their own charging equipment for the rented trucks. However, Mr. Moelk acknowledges that public fast charging along corridors would be useful for IKEA's contract carriers to enable them to more confidently complete longer routes using BEVs. Part of his infrastructure plan involves coordinating with other fleets, charging providers, utilities, and potential site hosts to share and optimize multi-use charging hubs near existing IKEA distribution centers. This will also offer a range of benefits and opportunities to decarbonize more of the transportation system around such charging hubs. According to Mr. Moelk, "The only way we get to 100% zero-emission is to think beyond IKEA."



Tesla, Volvo, and Xos.⁸ More OEMs are slated to join this market in the coming years as policy and legislation signal a more definitive transition toward zero-emission (ZE) technologies in coming years. As of year-end 2019, the leading M/HD platform type in terms of commercially available BEV models was transit bus. However, urban delivery applications also provide a conducive environment for BEV technology through a combination of short duty cycle, back-to-base operation, and fairly fixed-route service. As such, model availability for BEV delivery formats, including medium-duty trucks, medium-duty step vans, and cargo vans, is projected to grow most dramatically in the next 1-2 years (see Figure 1). Consistent with the formats dominating currently available BEV truck offerings, the maximum driving range for today's BEV trucks is clustered near or below 150 miles. As battery technology improves to become cheaper and lighter, longer-range models (particularly for heavy-duty tractors) have been slated for commercial production between 2021 and 2023 (see Figure 2).⁹

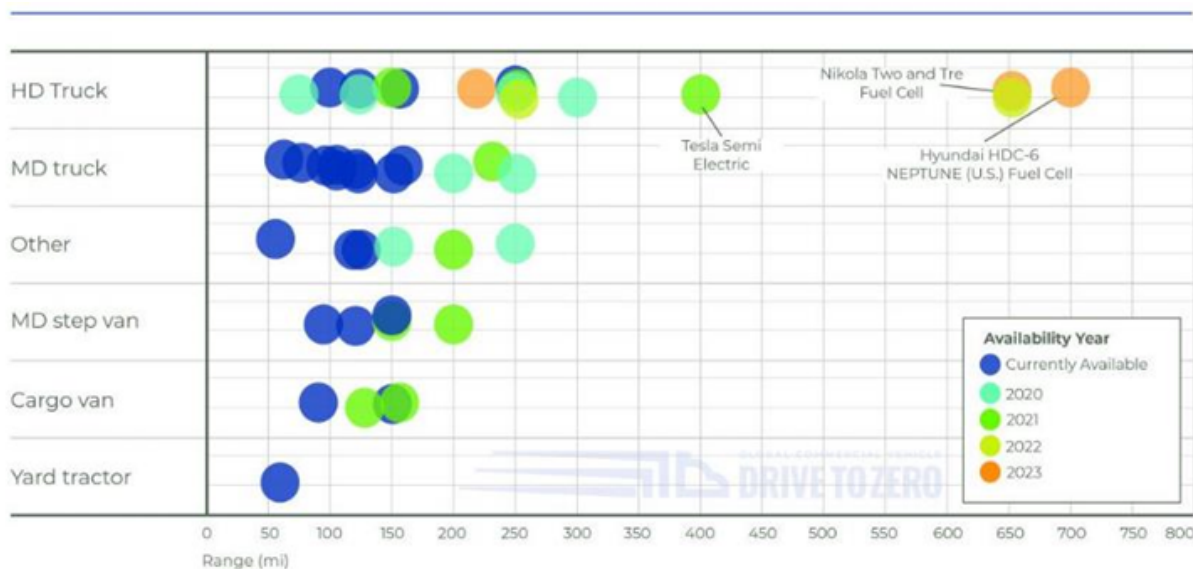


Figure 2. Zero emission truck model availability by truck type and estimated driving range (expected date of commercial availability indicated by color of dot) (CALSTART Zero

Many concerns surrounding BEV adoption—particularly for regional- and long-haul applications—can be eased with abundantly available high-power charging

⁸ Zero-Emission Technology Inventory. CALSTART. Retrieved from

<https://globaldrivetozero.org/tools/zero-emission-technology-inventory/>

⁹ The Zero-Emission Technology Inventory tracks commercial availability of both battery electric and hydrogen fuel cell electric commercial vehicle models; the vast majority of currently available models are BEV but Figures 1 and 2 characterize both technology types.

infrastructure located strategically along commercial or freight corridors. Even for urban freight vehicles, accessible high-speed public charging can supplement lower-speed depot charging and/or allow the purchase of lighter vehicles with smaller battery packs.¹⁰ Level 1 and Level 2 deliver alternating current (AC) from a charging station to the vehicle's internal charging equipment, which converts it to direct current (DC) needed to charge the vehicle's battery. Level 2 is most common and charges at between 6-20 kilowatts (kW). Level 3, or DC fast charging (DCFC), delivers direct current energy straight into the vehicle's onboard battery at 480 volts and anywhere from 25-350 kW and can be advantageous for vehicles without long uninterrupted stretches (at least 8-10 hours) of dwell time in which to charge large battery packs.¹¹ Depending on the fleet needs, battery size, charger type, and available charging windows, vehicles may take 3-12 hours to fully recharge.

Beyond charging speed, several other factors must be considered when configuring charging infrastructure projects. First is the upfront cost of equipment purchase and installation. Not including the EVSE material costs, DCFC stations are often the most convenient for commercial fleets needing to recharge quickly along their routes, but entail high upfront investments that can range between \$14,000 and \$91,000 including equipment and labor costs.¹² Another confounding variable is the lead time necessary for planning and obtaining permits. Depending on the location, electricity may or may not be available at the desired voltage for a charging station, or power service (maximum kW available) may be insufficient to add charging infrastructure without service upgrades. Fleet vehicles that return to depots for overnight storage may have longer charging windows that can be met with Level 2 chargers. Vehicles that operate around the clock may only have time for quick charges in-depot or along service routes and would be better suited to Level

¹⁰ *Supra* note 3

¹¹ Greene, D. L., & Baker, H. H., Jr. (2015, January). *Alternative Transportation Refueling Infrastructure in the U.S. 2014: Status and Challenges*. Retrieved from <https://energy.gov/epsa/downloads/alternative-transportation-refueling-infrastructure-us-2014-status-and-challenges>

¹² Smith, M., Castellano, J. (2015). *Costs Associated with Non-Residential Electric Vehicle Supply Equipment: Factors to consider in the implementation of electric vehicle charging stations*. Washington, D.C.: U.S. Department of Energy. Retrieved from https://afdc.energy.gov/files/u/publication/evse_cost_report_2015.pdf

3 charging. Grid and electrical upgrades require months of permitting approvals, preparation, and construction time before the chargers are commissioned. EVSE site hosts must also consider the financial impact of demand charges, a per-kilowatt charge based on the period of greatest power demand in a month.¹³ For fleet managers unaccustomed to managing utility bills, demand charges can be an unexpected cost element, though “smart charge” management software or onsite battery energy storage solutions may enable fleets to manage power demand and mitigate demand charge cost impacts to an extent.

HYDROGEN FUEL CELL ELECTRIC VEHICLES

The hydrogen fuel cell electric vehicle (FCEV) market is in a more nascent stage of commercialization compared to BEVs but shows promise to be as good a fit or better for specific commercial vehicle applications. Currently the only commercially available FCEV M/HD models are transit buses, though a handful of OEMs have announced that they will be bringing long-range FCEV tractors to market in the next 2-3 years. For example, Nikola Motors has announced multiple partnerships and raised over \$1 billion for the development and production of its HD fuel cell models, even securing a purchase commitment from Anheuser-Busch.¹⁴ Others entering the market include Hyundai, Hyzon Motors, Toyota/Kenworth, Unique Electric Solutions, and US Hybrid.¹⁵ Due to the novelty of the technology, with most companies still in the product development and prototyping phases of commercialization, and the lack of economies of scale in the use of fuel cells for vehicle propulsion, FCEVs are significantly more expensive than conventional diesel models.

Paired with the high cost of the vehicle itself, as of 2018 hydrogen fuel carried an average open retail price of \$13.99/kilogram (kg).¹⁶ For reference, \$8/kg is believed to be the point at which FCEVs can reach total cost of ownership parity with diesel

¹³ *Ibid.*

¹⁴ Nikola. (2019). *Anheuser-Busch Completes First Zero-Emission Beer Delivery* [Press release]. Retrieved from https://nikolamotor.com/press_releases/anheuser-busch-completes-first-zero-emission-beer-delivery-69

¹⁵ *Supra* note 8

¹⁶ *Supra* note 6

for commercial vehicles.¹⁷ These factors, combined with the risks associated with earlier-stage technologies, has created a barrier to adoption for many fleets. While market barriers remain, several pilots and demonstration projects¹⁸ are underway to test and validate early deployments of FCEVs to continue developing the technology.

Despite the initial barriers to mass adoption of FCEVs, they offer notable vehicle energy efficiency and greenhouse gas (GHG) emission reductions benefits. To start, FCEVs have a significantly higher efficiency rating than conventional ICE vehicles. The energy density of hydrogen is approximately 120 megajoules per kilogram (MJ/kg) compared to the diesel energy density of 45.5 MJ/kg.¹⁹ These figures indicate that FCEVs may attain about twice the energy efficiency of a comparable diesel-fueled vehicle, which has implications for longer-range duty cycles. The U.S. DOE confirms that FCEVs are generally 40-60% energy efficient, compared to an average ICE vehicle's 25% efficiency.²⁰ Given these calculations, it is assumed that hydrogen will reach price parity with diesel when the price drops to \$8 per kg, which is projected to occur within the next decade.²¹

Similar to BEVs, FCEVs have additional environmental benefits. Hydrogen fuel cells themselves do not produce toxic emissions, thereby eliminating potential impacts on human health and atmospheric pollutants. A fuel cell itself is composed of a Proton Exchange Membrane (PEM) where hydrogen and oxygen combined to generate electricity and the only byproducts are water and heat.²² Fuel cells, like battery packs, are readily scalable as they can be stacked to create systems for larger vehicles. These units do not have any moving parts and operate reliably without excess noise.

¹⁷ California Fuel Cell Partnership. (n.d.). Cost to refill. In California Fuel Cell Partnership. Retrieved from <https://cafcp.org/content/cost-refill>

¹⁸ Zero- and Near Zero-Emission Freight Facilities (ZANZEFF) Shore to Store Project. Retrieved from https://sustainableworldports.org/wp-content/uploads/ZANZEFF_Factsheet_final.pdf

¹⁹ Molloy, P. (2019). Run on Less with Hydrogen Fuel Cell Vehicles (FCEVs). Retrieved from <https://www.act-news.com/news/fcevs-run-on-less/>

²⁰ Plug Power. 5 Things You Should Know About Fuel Cells. Retrieved from <https://www.plugpower.com/fuel-cell-power/fuel-cell-benefits/>

²¹ *Supra* note 6

²² *Supra* note 20

While over 99% of hydrogen is currently produced using fossil fuels (as of 2018),²³ it is possible to generate the fuel with renewable energy via electrolysis, a process that uses electricity to separate water into hydrogen and oxygen. Renewable, or “green,” hydrogen can be made with wind, solar, or hydropower energy inputs into electrolyzers, though it is a very costly process that has not been built to a critical scale. Despite that, projections of future renewable energy generation indicate a decline in cost which may create a business case for harnessing excess energy supply for green hydrogen production. One such outlook estimates that renewable hydrogen could be produced for \$0.7 to \$1.6 per kg in many parts of the world by the year 2050.²⁴

The FCEV operational experience is similar to conventional diesel vehicles in some ways. The experience at the fueling station is virtually identical, with a nozzle similar to a traditional gas or diesel pump used to fill the onboard hydrogen tank and the process is complete in less than 15 minutes.²⁵ Likewise, as with gas or diesel hydrogen refilling stations are likely to be at large multi-user sites rather than at dedicated depot fueling sites. This eases the burden on fleets to retrain their drivers and allows them to maintain their daily route schedules without much interruption. And because heat is one of the fuel cell byproducts, FCEV are better suited to cold-weather operation than BEVs because they can circulate waste heat for cabin conditioning. However, if a mechanical issue does occur, it may be difficult to service the vehicle due to the low numbers of FCEVs on roads and limited access to replacement parts.

Hydrogen fueling station projects are unique in many ways and thus require additional considerations during the planning process. First, hydrogen supply and storage require a large infrastructure investment. Hydrogen can either be transported to a refueling station via pipeline, truck, or is produced onsite via steam methane reformation (SMR) or electrolysis.²⁶ Oftentimes, existing pipeline

²³ *Hydrogen Economy Outlook: Key messages*. (2020, March 30). Retrieved from <https://data.bloomberglp.com/professional/sites/24/BNEF-Hydrogen-Economy-Outlook-Key-Messages-30-Mar-2020.pdf>

²⁴ *Ibid.*

²⁵ *Supra note 19*

²⁶ *Supra note 11*

infrastructure is not adequate to support the flow of hydrogen which may necessitate additional upgrades to the gas distribution system by the local utility company. There are many containers and physical states (e.g., gas, liquid, or solid state) in which hydrogen can be stored, but many of the low-cost options are bound by geographic or spatial limitations (e.g., salt or rock caverns, depleted gas fields, etc.).²⁷ The crucial point is that hydrogen must remain compressed on site and be ready to be dispensed through the proper equipment. The cost to build an average M/HD fueling station is estimated at approximately \$4 million, more than any one fleet can finance and therefore requires well-financed developers to construct the necessary fueling infrastructure.²⁸ This presents an additional risk in a market that is currently characterized by significant uncertainty in both supply and demand.

LIQUEFIED PETROLEUM GAS VEHICLES

Liquefied petroleum gas (LPG), otherwise known as propane, is a colorless, odorless liquid. It is produced during natural gas processing or crude oil refinement, or in some cases is generated from biomass (renewable propane).²⁹ It is the third most common transportation fuel type, after gasoline and diesel and is stored onboard vehicles in a pressurized tank. While it has been used in many different vehicle technologies, propane is commonly used in residential heating and cooking. Due to its widespread use in a range of applications, propane has a large and reliable supply network across the country, with more than 2,000 public or private vehicle fueling stations.³⁰

There are two types of propane-fueled vehicles, either available as models from OEMs or ones that have been converted from other fuel types. Dedicated propane vehicles have been built with the exclusive ability to fuel with propane, while bi-fuel

²⁷ *Supra note 23*

²⁸ *Supra note 6*

²⁹ *Alternative Fuels Data Center: Propane. Retrieved from <https://afdc.energy.gov/fuels/propane.html>*

³⁰ *Smith, M., & Gonzales, J. (2014, August). Costs Associated with Propane Vehicle Fueling Infrastructure. Retrieved from https://afdc.energy.gov/files/u/publication/propane_costs.pdf*

propane vehicles have two separate fuel tanks that enable it to run on propane and regular diesel or gasoline for added range.³¹

Similar to other alternative fuels, propane has environmental benefits. It is a cleaner burning, lower-carbon fuel than others derived from petroleum and Argonne National Laboratory's GREET model demonstrates that propane use can decrease GHG emissions by approximately 13%.³² Additionally, propane can reduce NO_x emissions by 15% compared to diesel.³³ It has a near-zero global warming potential (GWP), referring to the heat absorbed by GHGs in the atmosphere, unlike other GHGs such as CO₂ or methane.³⁴ These factors make propane an attractive option for commercial vehicles, particularly for operation in zones that have historically experienced poor air quality and disproportionate GHG emissions.

When compared to its diesel equivalent, propane offers some benefits and drawbacks. One benefit is that dispensing is relatively simple and comparable to traditional fueling. Oftentimes, propane dispensers are collocated at gas stations which makes them convenient stops for drivers. The national average retail fuel price for propane (April 2020) is \$2.73 per gallon compared to a diesel price of \$2.61/gal; however, when compared on an energy-equivalent basis, the cost of propane is \$4.20 per diesel gallon equivalent (\$/DGE).³⁵ Though the lower fuel economy presents some challenges to fleets hoping to save on fuel costs, some OEMs have mitigated this concern by developing optimized engines that capitalize on propane's high octane rating and significantly improve vehicle performance. Customers in small- or medium-sized fleets with a centralized fueling location may notice fuel cost savings benefits with particular vehicle types. Another benefit of propane vehicles is that they operate well in cold weather due to the fuel's gaseous form, thereby preventing cold start problems that often impede ignition in

³¹ *Supra* note 29

³² *Supra* note 29

³³ *GHG and Criteria Pollutant Emissions Analysis*. (2017). Retrieved from <https://propane.com/wp-content/uploads/2019/06/20890-GTI-GHG-Emissions-Analysis-Final-Report.pdf>

³⁴ Sloan, M. *2016 Propane Market Outlook: Key Market Trends, Opportunities, and Threats Facing the Consumer Propane Industry Through 2025*. Retrieved from https://afdc.energy.gov/files/u/publication/2016_propane_market_outlook.pdf

³⁵ *Clean Cities Alternative Fuel Price Report*. (2020, April). Retrieved from https://afdc.energy.gov/files/u/publication/alternative_fuel_price_report_april_2020.pdf

diesel-powered vehicles.³⁶ Finally, propane fleet owners can expect to save money in maintenance and repairs such as oil changes made necessary by an accumulation of diesel particulates in the engine.³⁷

In the past, the propane vehicle market was limited to a couple OEMs or vehicle conversion kits but has recently grown in popularity. Manufacturers such as ROUSH CleanTech, Blue Bird, Thomas Built Buses, IC Bus, and Freightliner Custom Chassis have quickly expanded the vehicle selection for fleets, particularly in box truck, school bus, and shuttle van platforms.³⁸ ICF projects that the expansion of propane vehicle applications offers long term potential for the fuel. For example, it estimates that annual new propane vehicle sales will increase from 12,900 (in 2014) to 52,000 per year by 2025 with 40% in light-duty and 60% in medium-duty platforms. Similarly, ICF projects that total propane fuel sales will grow by 9% between 2014 and 2025, mainly due to technology and fuel efficiency advancements.³⁹ This presents a significant opportunity for commercial fleets that operate class 3-6 vehicles.

While propane infrastructure is comparable to conventional fueling stations in some ways, there are still specific considerations to keep in mind. As previously stated, propane production occurs ubiquitously in many parts of the country and distribution networks are already in place. In sum, propane is shipped from these production facilities to a distribution center which then transports the fuel by rail, ship, or truck to propane marketers. This node is then responsible for delivering the propane to end-user filling sites.⁴⁰ Since an efficient supply chain (similar to diesel) is already established, propane filling stations generally require less make-ready work to make them functional for fleet use. Building a new station usually requires the buildout of end-user equipment such as an above-ground storage tank, pump, nozzle, and metering system. In many cases, fuel suppliers may offer a low-cost lease of the equipment which greatly reduces the financial burden on fueling station owners.

³⁶ *Supra note 29*

³⁷ *Ibid.*

³⁸ *Supra note 34*

³⁹ *Ibid.*

⁴⁰ *Supra note 29*

Additionally, many stations that already offer propane filling for residential use (e.g., grill tanks) may easily upgrade their dispensers to faster fill for vehicular use. The total cost to build a new propane station can range from approximately \$65,000 for a small station to up to \$2 million for larger stations.⁴¹ The range in cost can be attributed to the desired number of storage tanks and dispensers, in addition to fleet profile (size, vehicle type(s), and duty cycle).

A challenge presented to the Northeast and other colder regions of the country during the wintertime is the inconsistency of propane production and distribution patterns. For example, regionally sourced propane is produced from the Marcellus Shale Point Pleasant-Utica formations in the Appalachian Basin which reduces the need to import supply from other locations.⁴² Despite this advantage, cold weather sometimes forces changes in distribution schedules which may lead to supply constraints and potential fuel price volatility. Added capacity to existing storage sites will greatly reduce uncertainty in supply in the propane market and ensure the needs of commercial fleets can always be met.

COMPRESSED NATURAL GAS VEHICLES

Compressed natural gas (CNG) is an odorless gas composed primarily of methane (CH₄). Like propane, it is a fossil fuel-derived gas that is extracted from wells or produced through crude oil processing and is mainly supplied by facilities in North America. Renewable natural gas (RNG), otherwise referred to as biomethane, can be harvested from landfill waste, sewage, animal manure, and food waste and then cleaned so that it can operate in CNG engines; once cleaned, RNG is chemically identical to CNG.⁴³ CNG currently fuels approximately 175,000 vehicles in the U.S. alone and there are more than 1,000 fueling stations offering both compressed (900+) and liquefied natural gas (LNG) (50+) in many parts of the country.⁴⁴ CNG vehicles are widely available across vehicle class sizes and duty cycles but are especially common for heavy-duty tractors and transit and school buses. The

⁴¹ *Ibid.*

⁴² *Supra* note 34

⁴³ *Natural Gas Vehicle Basics* (2020, March). Retrieved from https://afdc.energy.gov/files/u/publication/natural_gas_basics.pdf

⁴⁴ *Ibid.*

technology cost of an average CNG vehicle can run 40-80% higher⁴⁵ than a comparable diesel alternative which may present a barrier to purchase for some fleets. In spite of this, natural gas vehicles (NGVs) are a suitable technology option for fleets operating within limited areas or routes and have a central fueling location.

Fleets seeking vehicle performance and experience that is comparable to diesel often choose NGVs for their convenience, reliability, environmental benefits, and low fuel cost. The fueling station experience consists of using a nozzle to fill a tank and requires about the same length of time as fueling a diesel vehicle. This factor is crucial to fleets with busy schedules that may operate full days of service. The tailpipe emissions from CNG-fueled vehicles are similar to or better than modern gas or diesel vehicles that are in compliance with the latest emissions requirements. Standard CNG has the potential to emit up to 10% lower GHGs and half the particulate matter that a diesel vehicle would.⁴⁶ Furthermore, depending on vehicle type and duty cycle, fleets powered by RNG can prevent an additional 84% of GHG emissions over the course of the fuel's lifecycle due to the reduction of methane release into the atmosphere at sites such as landfills and livestock facilities.⁴⁷ It is important to note that methane (CH₄) is a GHG with 25x more potent GWP than CO₂ and minimizing its release can result in significant environmental and community health benefits.

NGVs also offer similar driving experiences as diesel vehicles with respect to their power, acceleration, and speed but may have reduced range due to the lower energy content per diesel gallon equivalent. Some fleets compensate for this shortfall by adding more fuel storage tanks (CNG cylinders) to improve the driving range of larger vehicles. Fortunately, the cost of CNG fuel has trended downwards in recent years. A report published by the DOE Clean Cities in April 2020

⁴⁵ Dougherty, S.; Nigro, N. (2014). *Alternative Fuel Vehicle & Fueling Infrastructure Deployment Barriers & the Potential Role of Private Sector Financial Solutions*. Washington, D.C.: U.S. Department of Energy. Retrieved from https://afdc.energy.gov/files/u/publication/afv_fueling_infrastructure_deployment_barriers.pdf

⁴⁶ Natural Gas. Retrieved from <https://www.fueleconomy.gov/feg/bifueltech.shtml>

⁴⁷ Alternative Fuels Data Center: Natural Gas Benefits and Considerations. Retrieved from https://afdc.energy.gov/fuels/natural_gas_benefits.html

compared a national average retail fuel price of \$2.47/DGE compared to a diesel baseline of \$2.61/gal,⁴⁸ making NGVs an economically feasible option in terms of their total cost of ownership. Relative to maintenance, a key concern for NGVs is regularly scheduled service to ensure that the onboard pressurized storage tanks are in working condition and are undamaged. Even small accidents can pose a severe hazard to the safety of the vehicle and its operator, so it is essential to keep up to date on service requirements. Other maintenance costs for NGVs are lower compared to diesels due to the nature of a cleaner burning fuel which results in less particulate build up and necessary engine oil changes.⁴⁹

As with other alternative fuels, a challenge for CNG fleets is access to readily available fueling infrastructure at convenient rest stops. While all CNG fueling stations function similarly, there are different types of stations to be aware of. Fast-fill stations are the closest to conventional diesel pumps where drivers can fill their vehicle tanks within minutes. This is convenient for fleets that operate their vehicles throughout the day and operate within range of a fueling corridor. In contrast, time-fill stations fuel vehicles over an extended time period, such as the course of several minutes or even a few hours, but are more affordable compared to fast-fill stations. This fueling mechanism is best for fleets that return their vehicles to a centrally located depot or base for overnight fueling, and in this sense is analogous to Level 2 charging as compared to DC fast charging in the BEV charging context. Combination-fill stations offer both a quick on-demand or extended fueling option and are optimal for fleets with a variety of vehicle types and duty cycles.⁵⁰

In general, most CNG stations are connected to a utility pipeline that delivers depressurized gas which is then pressurized (i.e., compressed) onsite for fueling purposes.⁵¹ In some cases this pipeline infrastructure may be preexisting, or it may

⁴⁸ *Supra* note 35

⁴⁹ Alternative Fuels Data Center: Natural Gas Vehicle Maintenance and Safety. Retrieved from https://afdc.energy.gov/vehicles/natural_gas_maintenance_safety.html

⁵⁰ Smith, M., & Gonzales, J. (2014, September). *Costs Associated with Compressed Natural Gas Vehicle Fueling Infrastructure* (Rep.). Retrieved from https://afdc.energy.gov/files/u/publication/cng_infrastructure_costs.pdf

⁵¹ *Ibid.*

need to be installed, requiring collaboration with the local gas utility to ensure the appropriate upgrades are implemented.

A CNG Success Story

Manhattan Beer Distributors is a major beer supplier for 14 counties across lower New York State and an early adopter of CNG trucks. Manhattan Beer has a sizable heavy-duty delivery fleet, of which approximately 200 are CNG class 7-8 trucks from Volvo and International. Most of Manhattan Beer's CNG trucks operate out of its headquarters in Hunts Point, a neighborhood in the Bronx with some of the highest levels of air pollution in the nation owing to high volumes of freight activity. Juan Corcino, Director of Fleet Operations for Manhattan Beer, helped grow its CNG fleet over the past twenty years, starting with CNG conversions and expanding to purpose-built CNG delivery trucks. Manhattan Beer is replacing its diesel straight trucks with CNG tractor-trailer combination trucks to reduce the number of vehicles necessary to complete deliveries, replacing diesel vehicles at a ratio of two CNG trucks to three diesel trucks. In addition, Mr. Corcino has experienced that CNG trucks are easier and cheaper to maintain, are more reliable, and are less expensive to fuel than their diesel counterparts. The company operates its own fast-fill CNG dispensing station, which allows for quick refuels throughout the day at 10 diesel gallon equivalents per minute. Manhattan Beer proudly displays this progressive technology, which has even led to at least one new deal with a distributor that was impressed with the fleet's use of clean vehicles and that also prioritizes sustainability as a company policy. Manhattan Beer has utilized vehicle incentives available for CNG trucks in New York City and State to cover a substantial amount of the incremental costs for many of these vehicle orders. Its positive experience with CNG has encouraged Mr. Corcino to explore other types of emerging technologies for classes 7 and 8 including battery electric trucks.



Due to these factors and preferences for fast- or time-fill dispensers, the cost of installation for CNG stations can vary from \$1-4 million. In addition to the initial

build and installation, some stations require upgrades for compliance purposes (e.g., ventilation requirements per local fire codes), which can create an additional \$45,000 to \$100,000 in expenditures and can last 12-24 months, depending on the scale of the project.⁵²

AUTOMATED VEHICLE TECHNOLOGY

Automated vehicle technology is already active in mass market passenger and commercial vehicles and the technology is rapidly progressing from partial automation to more complete automation. Drivers already rely on automated features such as lane assist, backup sensors, blind spot detection, vehicle self-park, and others to get from point A to B in a safe and efficient manner. The development of these features has been intended to deliver greater safety benefits not only for the driver, but for pedestrians and cyclists as well in addition to improving the efficiency of transportation networks overall.

Automation takes on many forms and degrees of driver engagement, and has been defined in tiers by the Society of Automotive Engineers (SAE)⁵³:

- **Level 0:** No vehicle automation and the driver performs all driving tasks.
- **Level 1:** The vehicle is controlled by the driver but some driving assist features may be included.
- **Level 2:** The vehicle is partially automated but the driver must remain fully engaged and monitor the environment at all times.
- **Level 3:** Conditional automation in which the driver must be present but is not required to monitor the environment at all times.
- **Level 4:** High automation in which the vehicle is capable of performing all driving functions under certain conditions and the driver may have the option to control the vehicle.
- **Level 5:** Highest level of automation where the vehicle is capable of performing all driving functions under all conditions and the driver may not

⁵² *Supra note 6*

⁵³ *National Highway Traffic Safety Administration (NHTSA): Automated Vehicles for Safety. Retrieved from <https://www.nhtsa.gov/technology-innovation/automated-vehicles-safety>*

have the option to control the vehicle. In some cases, the driver is not present.

AV technology is based on a “sense-plan-act”⁵⁴ design where a combination of sensors (e.g., lidar, radar, cameras, ultrasonic, and infrared) and localization technology (e.g., Global Positioning System (GPS) and Inertial Navigation System (INS)) to interpret the vehicle’s immediate environment, compute appropriate actions for the present moment and near future, and execute accordingly. These vehicles are expected to quickly assess and respond to changing conditions in weather, traffic, topography, and obstacles to deliver a seamless driver and/or passenger experience.

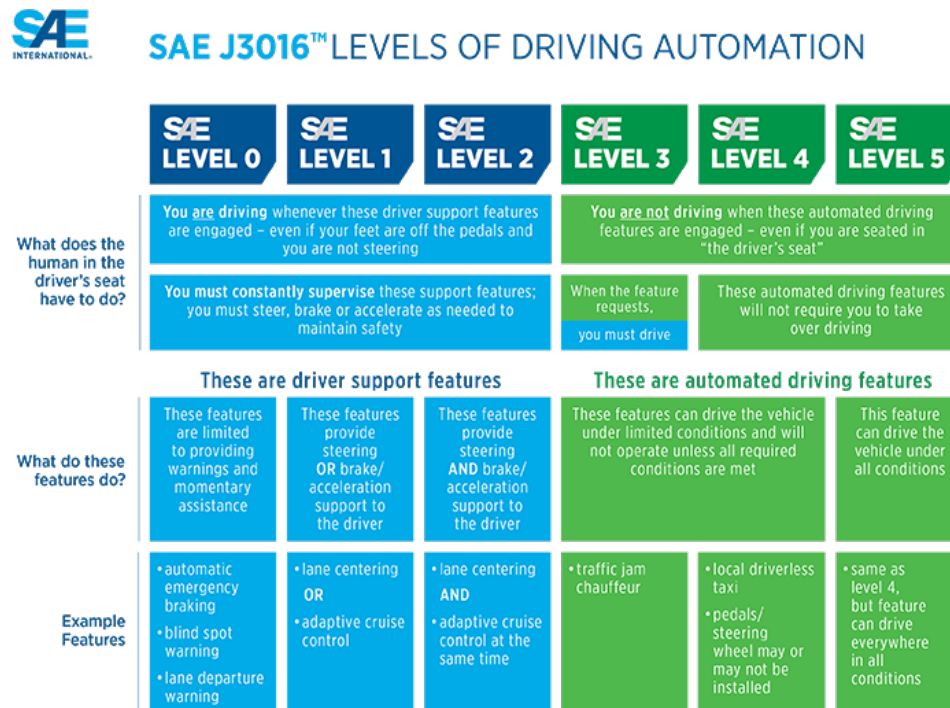


Figure 3. SAE-defined levels of driving automation⁵⁵

The emergence of AV technology is expected to lead to significant economic and social/safety benefits. A study by the National Highway Traffic Safety Administration (NHTSA) reported that vehicular accidents in 2010 caused a nationwide loss of

⁵⁴ Anderson, J., Kalra, N., Stanley, K., Sorensen, P., Samaras, C., & Oluwatola, O. (2016). *Autonomous Vehicle Technology: A Guide for Policymakers*. Retrieved from https://www.rand.org/content/dam/rand/pubs/research_reports/RR400/RR443-2/RAND_RR443-2.pdf

⁵⁵ SAE J3016 Levels of Driving Automation [Chart]. (2018). In SAE International. Retrieved from <https://www.sae.org/news/press-room/2018/12/sae-international-releases-updated-visual-chart-for-its-“levels-of-driving-automation”-standard-for-self-driving-vehicles>

\$242 billion in economic activity, including workplace productivity losses, quality of life losses due to injury, and deaths.⁵⁶ It is estimated that a staggering 94% of these accidents are caused by human error. AV researchers hope to mitigate this element by integrating machine learning and decision making into vehicles to ease traffic congestion and boost productivity across all relevant sectors.

For commercial fleets, one of the most important breakthroughs in AV technology is the concept of platooning, or “road trains.”⁵⁷ Vehicles equipped with automated driving systems (ADS) allow vehicle-to-vehicle information sharing and collection in order to coordinate movement and spacing. For example, platoon communications may affect a vehicle’s speed (slower or faster) or the distance at which it follows or is parallel to another vehicle. Platooning offers many advantages to the commercial sector, including higher energy efficiency and cost savings, right-sizing freight trips, and smoother traffic flows in cities.

This eco-driving technique is particularly compatible with BEVs due to the mechanical structure of the electric driveline and can be used to automate the vehicle docking and charging process.⁵⁸ By taking the driver out of the equation, AVs will not be required to locate a charge point that is en route to a convenient rest stop or destination and can be retrieved easily once fully recharged. The U.S. Energy Information Administration (EIA) forecasts that this technology will start increasing freight efficiency by 2025 and estimates a 10% reduction in fuel consumption attributable to automation of freight vehicles.⁵⁹

ALTERNATIVE FUEL VEHICLE ADOPTION PROJECTIONS

This section discusses forecasts for future sales of M/HD truck technologies in Connecticut, New York, New Jersey, and Pennsylvania to better understand the future need for fueling infrastructure to support vehicle demand across fuel types. Developing scenario forecasts for future fleet adoption of M/HD trucks is important

⁵⁶ *Supra* note 53

⁵⁷ *How an Automated Car Platoon Works*. Retrieved from <https://www.transportation.gov/connections/how-automated-car-platoon-works>

⁵⁸ *Taming the Autonomous Vehicle: A Primer for Cities*. (2017). Retrieved from <https://assets.bbhub.io/dotorg/sites/2/2017/05/TamingtheAutonomousVehicleSpreadsPDF.pdf>

⁵⁹ *Autonomous Vehicles: Uncertainties and Energy Implications* (2018, May). Retrieved from <https://www.eia.gov/outlooks/aeol/pdf/AV.pdf>

to inform strategic infrastructure planning by illustrating the likeliest range of possible penetration levels for various vehicle and fuel combinations, as well as the sensitivities and contingencies that drive these forecasts. Projections of future market behavior are, by definition, speculative and will depend on the data used as inputs. While making forward-looking market projections based on present conditions and technologies can reasonably approximate how the market may evolve, it is important to bear in mind that the freight vehicle technologies landscape is dynamic. The adoption of the emerging diesel-alternative technologies, as modeled for this study, is not deterministic, but rather subject to the influence of many factors discussed in the coming sections.

HEAVY-DUTY VEHICLE ADOPTION RATE MODEL (HDVARM)

The goal of these projections is to simulate the adoption behavior of freight vehicle fleets for various fuel types over the next 25 years (2020-2045). The market projection is based on CALSTART's Heavy-Duty Vehicle Adoption Rate Model (HDVARM). HDVARM is an input/output model which estimates the share of on-road vehicle adoption across fuel types in specific vehicle segments (e.g., class 6 regional truck) and regions of interest (e.g., U.S. states). HDVARM can be used to support policy and infrastructure planning by simulating fleet adoption decisions quantitatively and qualitatively. A diagrammatic depiction of HDVARM's input parameters and scoping conditions for this study is presented below in Figure 4.

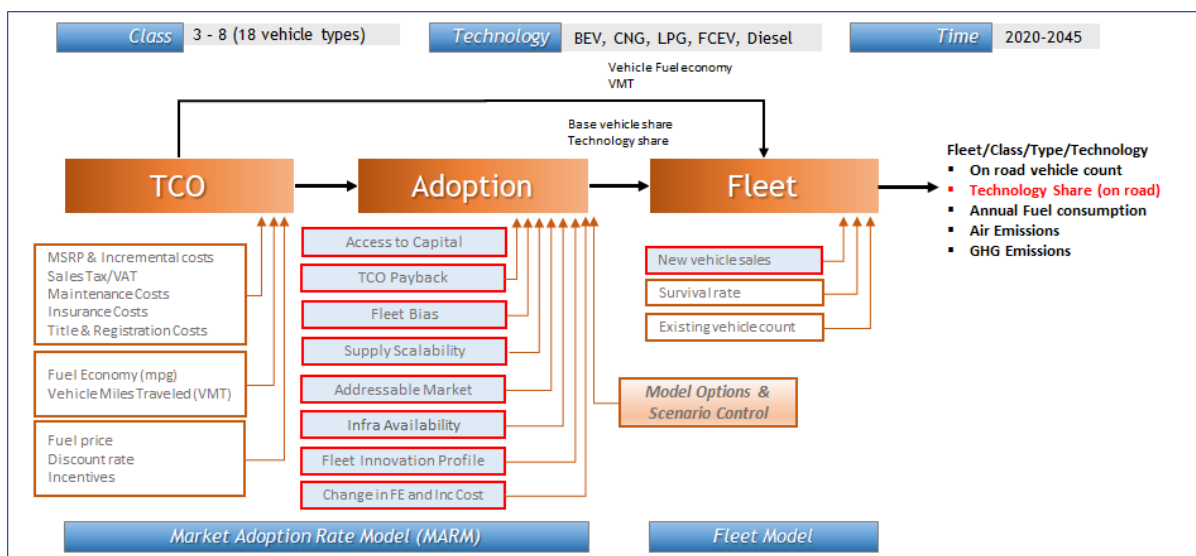


Figure 4. Overview of Heavy-Duty Vehicle Adoption Rate Model (HDVARM)

This modeling exercise includes 18 distinct types of on-road freight vehicles across gross vehicle weight rating (GVWR) classes 3-8 (i.e., >10,000 lbs).⁶⁰ The alternative fuel vehicle types modeled and compared to baseline (diesel) vehicles include battery electric (BEV), compressed natural gas (CNG), propane (LPG), and hydrogen fuel cell (FCEV). HDVARM projects fleet adoption decisions among these technology options based largely on total cost of ownership (TCO) simulations, which are determined on the basis of inputs that impact the upfront and ongoing costs associated with a designated vehicle-fuel combination.

As outlined in Figure 4, HDVARM simulates TCO for each vehicle-fuel combination and runs these intermediate results through a range of adoption profiles. Adoption profiles indicate how various fleets might respond to the TCO results; for instance, an early-adopter fleet adoption profile will have greater access to capital and allow alternative fuel vehicle technologies a longer payback period (relative to diesel vehicles), whereas a moderate or even a technology-averse profile will have less capital and be less patient with their required return on investment. These adoption profiles augment the purely financial TCO elements with more qualitative parameters that can determine how likely a fleet is to adopt a new truck technology through time. For instance, the addressable market for each vehicle segment in an adoption profile is a function of the suitability of various truck technologies for a fleet's operations; the more suitable a technology is assumed to be, the larger its addressable market and the more rapid the resulting adoption. The adoption profiles constructed for this modeling exercise are described in greater depth in a later section.

The results from the Market Adoption Rate Model (TCO simulation + adoption profiles) are then combined with a fleet model to determine how adoption decisions result in aggregate fleet purchases and overall fleet turnover, based on factors including existing vehicle counts and characteristic vehicle survival rates to gauge fleet turnover. These results provide a collective picture of the expected fuel

⁶⁰ Class 3 (cargo van, step van, regional truck), Class 4 (step van, regional truck), Class 5 (step van, regional truck), Class 6 (step van, regional truck), Class 7 (step van, regional truck, long haul truck, drayage), and Class 8 (long haul truck, regional truck, terminal tractor, drayage, heavy haul truck)

technology share for new sales of a selected vehicle segment in a selected state. The methodology and results from each model element are discussed in greater detail below and documented more thoroughly in the companion technical appendix.

TOTAL COST OF OWNERSHIP MODEL

CRITICAL TCO INPUTS

TCO represents a range of possible values depending on sensitivity to uncertain parameters. Two of the most influential and uncertain TCO inputs are fuel cost and incentive levels. Current and projected fuel prices (in real dollars) for each state are used to model fuel consumption costs, with three scenarios to cover a range of possible price paths. The reference scenario reflects states' current fuel prices with year-over-year trend projected in the U.S. Energy Information Administration's (EIA) Annual Energy Outlook 2020.⁶¹ Hydrogen fuel prices are assumed to follow the downward trajectory seen in Argonne National Laboratory's VISION model.⁶² The low and high fuel price scenarios apply different variations to the start at states' current average fuel prices but follow different trends. Under the "low" scenario, the diesel trend is ~50% lower, CNG and electricity are ~10% lower, and hydrogen is 40% lower. Under the "high" scenario, the diesel trend is ~50% higher, CNG is ~10% higher, and electricity and hydrogen are ~20% higher. Table 2 summarizes the fuel price trends for each scenario.

Table 2. Year-over-year fuel cost price change assumptions by scenario

	Fuel Type				
Scenario	Diesel	CNG	LPG	Electricity	Hydrogen
Low	1.60%	1.50%	3.20%	2.20%	-1.50%
Reference	3.10%	1.70%	3.60%	2.40%	-2.50%
High	4.70%	1.90%	4.00%	2.90%	-3.00%

The analysis assumes that all four states will put in place strong purchase incentives to catalyze sales of cleaner alternatives to diesel trucks by 2025 and to varying levels through 2040. While New York already has point-of-sale voucher

⁶¹ *Annual Energy Outlook 2020*. (2020). Retrieved from <https://www.eia.gov/outlooks/aeo/>

⁶² Argonne National Laboratory: VISION Model. Retrieved from <https://www.anl.gov/es/vision-model>

incentives in place for all four fuel types,⁶³ assumptions regarding incentive levels and timing of introduction and step-down/phase-out for incentives were constructed based on each state's policy signals and input from the study Technical Advisory Committee (see Table 3 for an overview of the assumed incentive levels across states and fuel types over time). It is assumed that incentive levels will decline gradually as market acceleration programs boost vehicle production volumes and allow these technologies to progress down the technology cost curve and require progressively less capital support through time.

Class	Year	BEV / FCEV				CNG/LPG	
		CT	NJ	NY	PA	NY	PA
3	2020	\$ -	\$ -	\$ 60,000.00	\$ -	\$ -	\$ -
	2025	\$ 40,000.00	\$ 40,000.00	\$ 60,000.00	\$ 40,000.00	\$ -	\$ -
	2030	\$ 20,000.00	\$ 20,000.00	\$ 40,000.00	\$ 20,000.00	\$ -	\$ -
	2035	\$ 20,000.00	\$ 20,000.00	\$ 20,000.00	\$ 20,000.00	\$ -	\$ -
	2040	\$ 10,000.00	\$ 10,000.00	\$ 10,000.00	\$ 10,000.00	\$ -	\$ -
	2045	\$ -	\$ -	\$ -	\$ -	\$ -	\$ -
4	2020	\$ -	\$ -	\$ 100,000.00	\$ -	\$ 30,000.00	\$ -
	2025	\$ 75,000.00	\$ 75,000.00	\$ 100,000.00	\$ 75,000.00	\$ 15,000.00	\$ 15,000.00
	2030	\$ 50,000.00	\$ 50,000.00	\$ 75,000.00	\$ 50,000.00	\$ -	\$ 7,500.00
	2035	\$ 50,000.00	\$ 50,000.00	\$ 50,000.00	\$ 50,000.00	\$ -	\$ -
	2040	\$ 25,000.00	\$ 25,000.00	\$ 25,000.00	\$ 25,000.00	\$ -	\$ -
	2045	\$ -	\$ -	\$ -	\$ -	\$ -	\$ -
5	2020	\$ -	\$ -	\$ 110,000.00	\$ -	\$ 40,000.00	\$ -
	2025	\$ 80,000.00	\$ 80,000.00	\$ 110,000.00	\$ 80,000.00	\$ 20,000.00	\$ 20,000.00
	2030	\$ 60,000.00	\$ 60,000.00	\$ 80,000.00	\$ 60,000.00	\$ -	\$ 10,000.00
	2035	\$ 60,000.00	\$ 60,000.00	\$ 55,000.00	\$ 60,000.00	\$ -	\$ -
	2040	\$ 30,000.00	\$ 30,000.00	\$ 30,000.00	\$ 30,000.00	\$ -	\$ -
	2045	\$ -	\$ -	\$ -	\$ -	\$ -	\$ -
6	2020	\$ -	\$ -	\$ 125,000.00	\$ -	\$ 50,000.00	\$ -
	2025	\$ 90,000.00	\$ 90,000.00	\$ 125,000.00	\$ 90,000.00	\$ 30,000.00	\$ 30,000.00
	2030	\$ 65,000.00	\$ 65,000.00	\$ 90,000.00	\$ 65,000.00	\$ -	\$ 15,000.00
	2035	\$ 65,000.00	\$ 65,000.00	\$ 65,000.00	\$ 65,000.00	\$ -	\$ -
	2040	\$ 40,000.00	\$ 40,000.00	\$ 40,000.00	\$ 40,000.00	\$ -	\$ -
	2045	\$ -	\$ -	\$ -	\$ -	\$ -	\$ -
7	2020	\$ -	\$ -	\$ 150,000.00	\$ -	\$ 55,000.00	\$ -
	2025	\$ 110,000.00	\$ 110,000.00	\$ 150,000.00	\$ 110,000.00	\$ 35,000.00	\$ 35,000.00
	2030	\$ 80,000.00	\$ 80,000.00	\$ 110,000.00	\$ 80,000.00	\$ -	\$ 17,500.00
	2035	\$ 80,000.00	\$ 80,000.00	\$ 80,000.00	\$ 80,000.00	\$ -	\$ -
	2040	\$ 55,000.00	\$ 55,000.00	\$ 55,000.00	\$ 55,000.00	\$ -	\$ -
	2045	\$ -	\$ -	\$ -	\$ -	\$ -	\$ -
8	2020	\$ -	\$ -	\$ 185,000.00	\$ -	\$ 60,000.00	\$ -
	2025	\$ 140,000.00	\$ 140,000.00	\$ 185,000.00	\$ 140,000.00	\$ 40,000.00	\$ 40,000.00
	2030	\$ 105,000.00	\$ 105,000.00	\$ 140,000.00	\$ 105,000.00	\$ -	\$ 20,000.00
	2035	\$ 105,000.00	\$ 105,000.00	\$ 105,000.00	\$ 105,000.00	\$ -	\$ -
	2040	\$ 80,000.00	\$ 80,000.00	\$ 80,000.00	\$ 80,000.00	\$ -	\$ -
	2045	\$ -	\$ -	\$ -	\$ -	\$ -	\$ -

Table 3. Vehicle purchase incentive assumptions by state and fuel type over time

⁶³ New York Truck Voucher Incentive Program. Retrieved from <https://nyserda.ny.gov/truck-voucher-program/>

Importantly, while all four states are signatories to the July 2020 Memorandum of Understanding on Medium- and Heavy-Duty Zero-Emission Vehicles,⁶⁴ and therefore it is reasonable to assert that BEV and FCEV incentives will be introduced and remain in place for several years, only Pennsylvania, as a major producer of natural gas, is assumed to keep purchase incentives for CNG and LPG in place through 2030. Because other states are expected not to have incentives for CNG and LPG past 2025, New Jersey and Connecticut—where no such incentives already exist—are assumed not to introduce CNG/LPG vehicle incentives during the study period as those states focus their market animation activities on zero-emission technologies.⁶⁵ It is plausible that as time goes on, states will transition vehicle purchase assistance from upfront cash grants to an alternative format such as a tax credit or a revolving loan structure, but for the time being the analysis assumes that states will apply the most direct form of assistance to address the persistent barrier to adoption, which is the more expensive purchase price.

TCO RESULTS

HDVARM evaluates the fixed and operational costs of each M/HD technology over a ten-year lifetime and compares the cost and payback period to that of the applicable base diesel vehicle. Four advanced vehicle technologies used in each M/HD vehicle type across each state are compared. Figure 5 illustrates the total cost of owning and operating each M/HD vehicle fuel technology in dollars per mile (\$/mi) over the course of the vehicle's lifetime. This is the blended average TCO for all included vehicle types across the study region (CT, NJ, NY, and PA). The TCO is further segmented into insurance and licensing costs, maintenance costs, fuel costs, and the base vehicle purchase cost to demonstrate which components are driving TCO disparities between the fuel types across time, through 2045; despite variations across fuel types in purchase/capital cost, the greatest driver of

⁶⁴ *Multi-State Medium- and Heavy-Duty Zero Emission Vehicle Memorandum of Understanding* (2020, July). Retrieved from <https://www.nescaum.org/documents/multistate-truck-zev-governors-mou-20200714.pdf/>

⁶⁵ *NJ Energy Master Plan*: https://nj.gov/emp/docs/pdf/2020_NJBPU_EMP.pdf; *CT Electric Vehicle Roadmap*: [http://www.dpuc.state.ct.us/DEEPEnergy.nsf/c6c6d525f7cdd1168525797d0047c5bf/f7ed4932eec438d0852585520001c81b/\\$FILE/EV%20Roadmap%20for%20Connecticut.pdf](http://www.dpuc.state.ct.us/DEEPEnergy.nsf/c6c6d525f7cdd1168525797d0047c5bf/f7ed4932eec438d0852585520001c81b/$FILE/EV%20Roadmap%20for%20Connecticut.pdf)

TCO differences at a given point in time appears to be the total lifetime fueling cost.

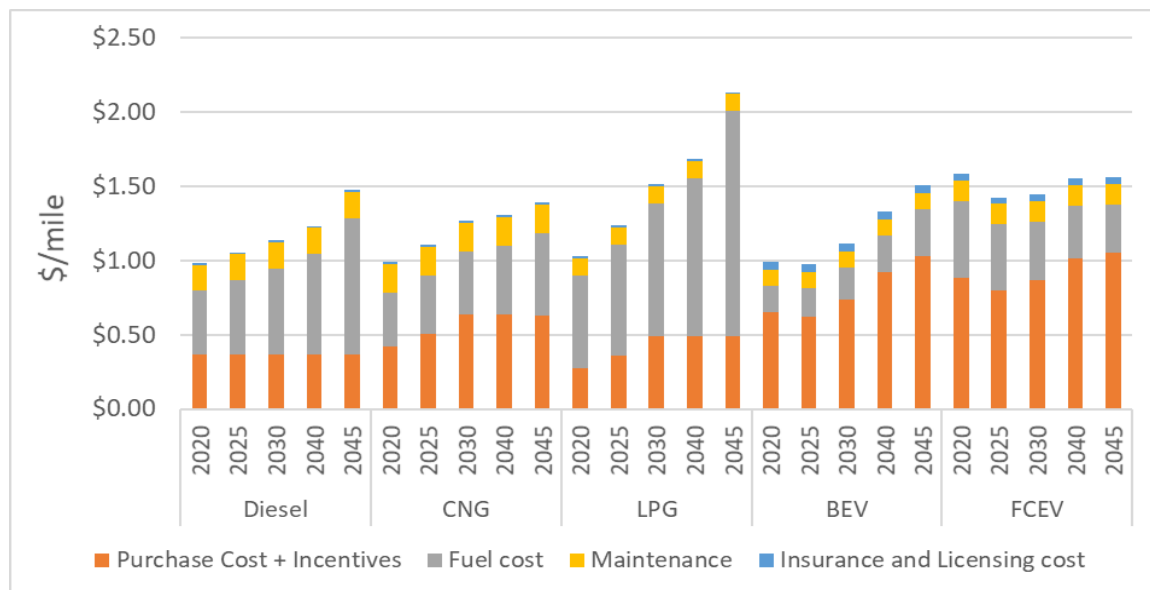


Figure 5. TCO composition (\$/mi) across fuel types by year, class 6 regional truck in New York

Figure 6 demonstrates how the overall TCO for each alternative fuel vehicle type compares to diesel vehicles over time and across states in each of vehicle classes 3-8 (assuming reference case pricing for fuel costs); note that a negative TCO indicates that the vehicle in question is more costly to own and operate than a diesel vehicle. At a high level, these results reflect whether the upfront cost premiums of alternative fuel trucks above comparable diesel trucks are offset by lower operating and maintenance (O&M) costs during a vehicle's service life. This is a function of several factors, including not only the magnitude of the purchase premium and the amount of O&M savings on a per-mile basis, but also (and importantly) the duty cycle of the vehicle in question and therefore how quickly ongoing savings can offset upfront costs. Because CNG, BEV, and FCEV technologies are all assumed to have lower O&M costs than diesel trucks, the ultimate TCO for a given vehicle segment and in a particular model year in these fuel types is a matter of whether the assumed duty cycle entails sufficient mileage to offset the upfront cost premium. Broadly, the TCO advantages relative to diesel for CNG, BEV, and FCEV technologies trend upward as model years progress, a function of both declining vehicle costs (in some cases aided by incentives) and

fueling costs that either fall outright (in the case of hydrogen) or that rise more slowly than diesel under the reference case scenario (in the case of CNG and BEV; see Table 2). Because LPG vehicles are assumed to have higher operating costs than diesel, they generally result in more expensive TCO compared to diesel despite characteristically very small vehicle cost premiums.

Beyond these general features of the TCO comparisons, the specific results hinge on tradeoffs between purchase price and operating cost. For low-mileage duty cycles, namely class 7 drayage, alternative fuels can only overtake diesel in TCO terms when purchase premiums are slim (as with CNG trucks). For more costly vehicle technologies like BEV and FCEV, the low-mileage duty cycle does not allow for operating savings to offset the upfront cost disadvantage. By contrast, these initially costlier vehicle technologies fare better in high-mileage duty cycles, in particular class 3 cargo van, class 4 regional truck, and class 8 long-haul, and do even better through time as successive model years bring diminished purchase costs which can be offset even more quickly and compellingly. In many instances, the TCO for CNG, BEV, and FCEV is negative relative to diesel toward the beginning of the period but crosses into positive TCO at some point during the study period.

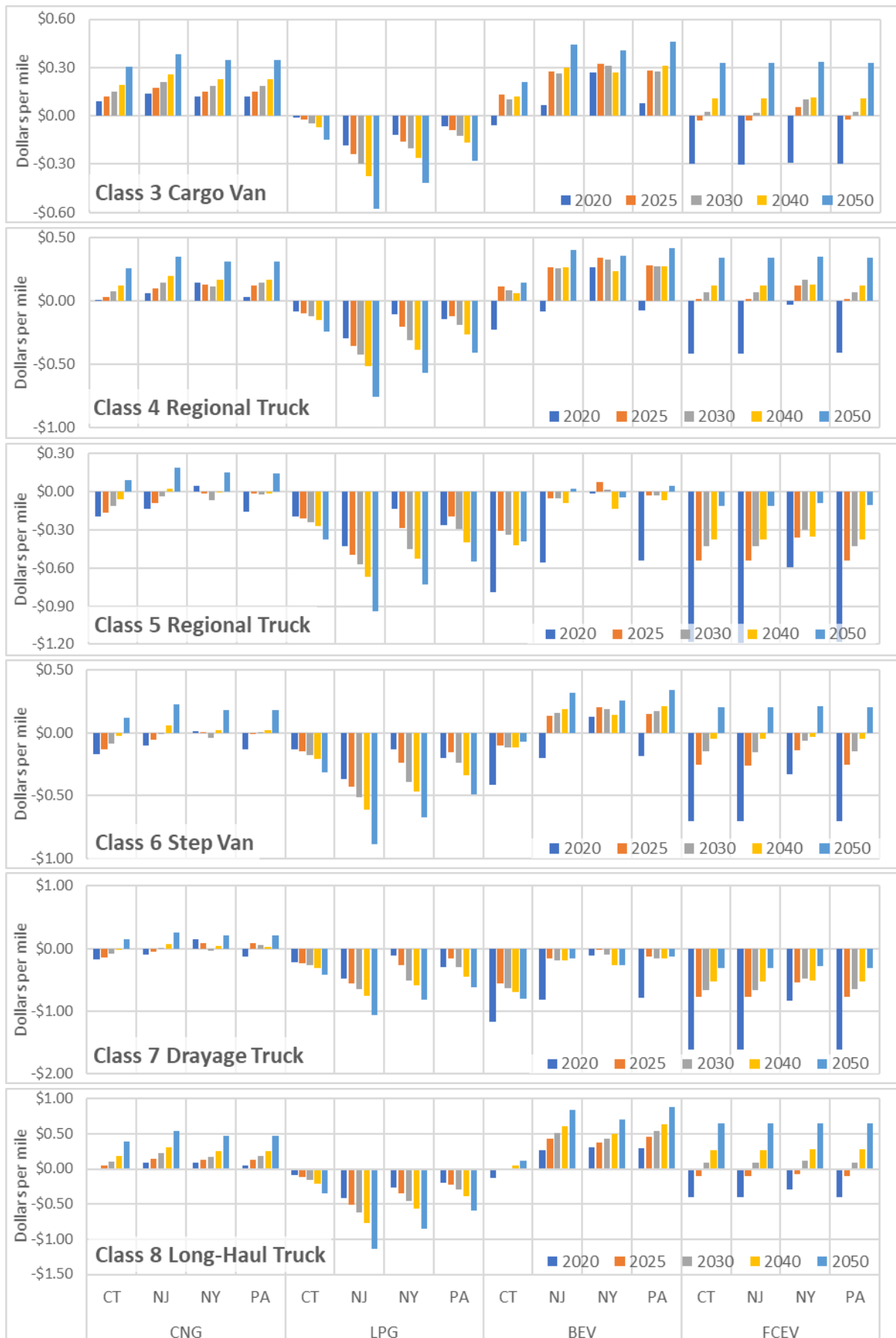


Figure 6. TCO advantage over diesel across states and fuel types for selected truck segments

MODELING SCENARIO CONSTRUCTION

In addition to the uncertain elements of TCO, the interactions between TCO and fleet adoption are subject to significant uncertainty. Exogenous factors such as fleets' purchasing power, fleets' preferences and the technology-policy environment can evolve in a variety of ways ranging from those more conducive to aggressive uptake of high-efficiency technologies to those more consistent with low uptake of newer freight vehicle technologies. To capture the inherent uncertainty in how fleets will respond to the range of TCO results across time, adoption profiles were constructed from differing permutations of the following six parameters (discussed in greater detail in the technical appendix):

- Fleets' **access to capital** (ability to pay more upfront for vehicles)
- Fleets' tolerance for **payback period**
- Fleets' affinity toward new technology (**preference factor**)
- Size of **addressable market** for a vehicle type based on technology, location, and duty cycle
- Fleets' sensitivity to **refueling availability**
- **Technological improvement** (fuel economy and price decline over time)

Three adoption profiles—Aggressive, Moderate, and Slow—were developed to account for a range of possible preferences and adoption-influencing conditions, as captured by different values assigned to each of the above parameters. The values assigned to each parameter in each profile are summarized below in Table 4.

Table 4. Composition of adoption profiles used in scenario modeling

Profile	Access to Capital	Payback Period	Preference Factor	Addressable Market	Refueling Availability	Technological Improvement
Aggressive	Excellent	≤4 years	Accelerated	Full	Accelerated	Advanced
Moderate	Great	≤3 years	Average	Moderate	Average	Above Average
Slow	Good	≤2 years	Slow	Niche	Slow	Average

Table 5. Overview of model runs used in HDVARM to project vehicle adoption rates of various fuel types for each vehicle segment

Model Run	Fuel Price Scenario	Adoption Profile
1A	Low	Aggressive
1B	Low	Moderate
1C	Low	Slow
2A	Reference	Aggressive
2B	Reference	Moderate
2C	Reference	Slow
3A	High	Aggressive
3B	High	Moderate
3C	High	Slow

To capture a representative range of prospective adoption rate results, a total of nine model runs were developed, with each of the adoption profiles detailed in Table 4 matched with each of the fuel price scenarios outlined in Table 2. All nine model run permutations are shown in Table 5. However, the discussion of results will be confined to the subset of model runs using the reference fuel price inputs (i.e., 2A, 2B, and 2C); while varying the adoption profile (for a given fuel price scenario) drives significant differences in

the sales shares across fuel types, varying the fuel price scenario (for a given adoption profile) does not drive significant differences in sales share.

ADOPTION RATE MODELING RESULTS

Figure 7 demonstrates an average regional outlook on uptake of alternative fuel vehicles, across all vehicle segments included in the study and over the entire study region through 2050. Under the aggressive run (2A, top panel), diesel drops under 50% of sales in 2029 as first BEV, then FCEV and later CNG technologies surpass diesel sales between 2031 and 2036. In this run, the alternative fuel technologies benefit from a more aggressive and patient fleet adoption profile to outperform diesel. CNG, BEV, and FCEV each settle in between 28-38% of sales by 2050, though the LPG share remains negligible throughout. Diesel ends the period with a sales share around 0.5%.

Under the midpoint run (2B, middle panel), diesel retains the majority of sales share a bit longer than in 2A (until 2032) but is shortly thereafter overtaken by BEV as the leading technology in sales share. BEV trucks settle just above 50% of sales after 2040, supported by declining costs and improving technology (e.g., greater fuel economy). The diesel sales share temporarily rebounds after 2040 at the expense of BEV sales share as purchase incentives—a critical determinant of BEV truck sales share—are assumed to cease after this date. The sales share for

FCEV trucks grows slowly but steadily beginning after 2030, as hydrogen fuel costs decline and the technology continues to improve, before ending the period around a 33% sales share. The CNG share also ramps up slowly beginning around 2035 and ending the period under 15%. As in 2A, the LPG share remains negligible throughout the study period. Diesel ends the period below a 1.5% sales share.

Finally, run 2C (bottom panel) reflects highly volatile responses to changing incentive levels, with large swings between diesel and BEV in particular. Diesel is not overtaken by any fuel type until 2034 and ends the period with a higher share than in the other two runs at 6%. Likewise, BEV ends the period with its highest share of the three runs at 60%, while the shares for FCEV and CNG are far lower than under other runs. As in the others, LPG's share remains negligible throughout.

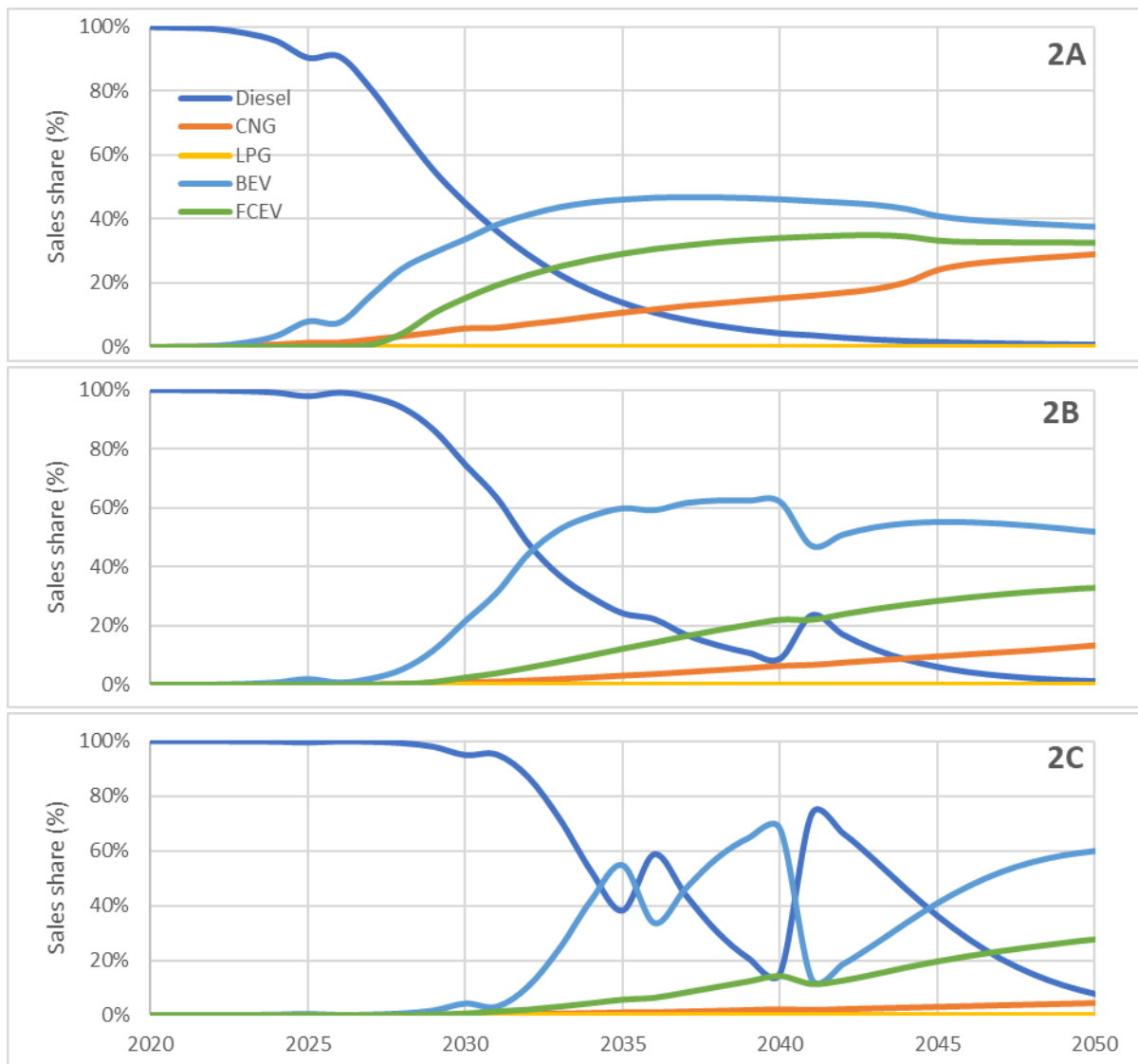


Figure 7. Overall sales share for all vehicle types in the entire study region under runs 2A-2C

Individual state results under the midpoint run (2B) are illustrated in

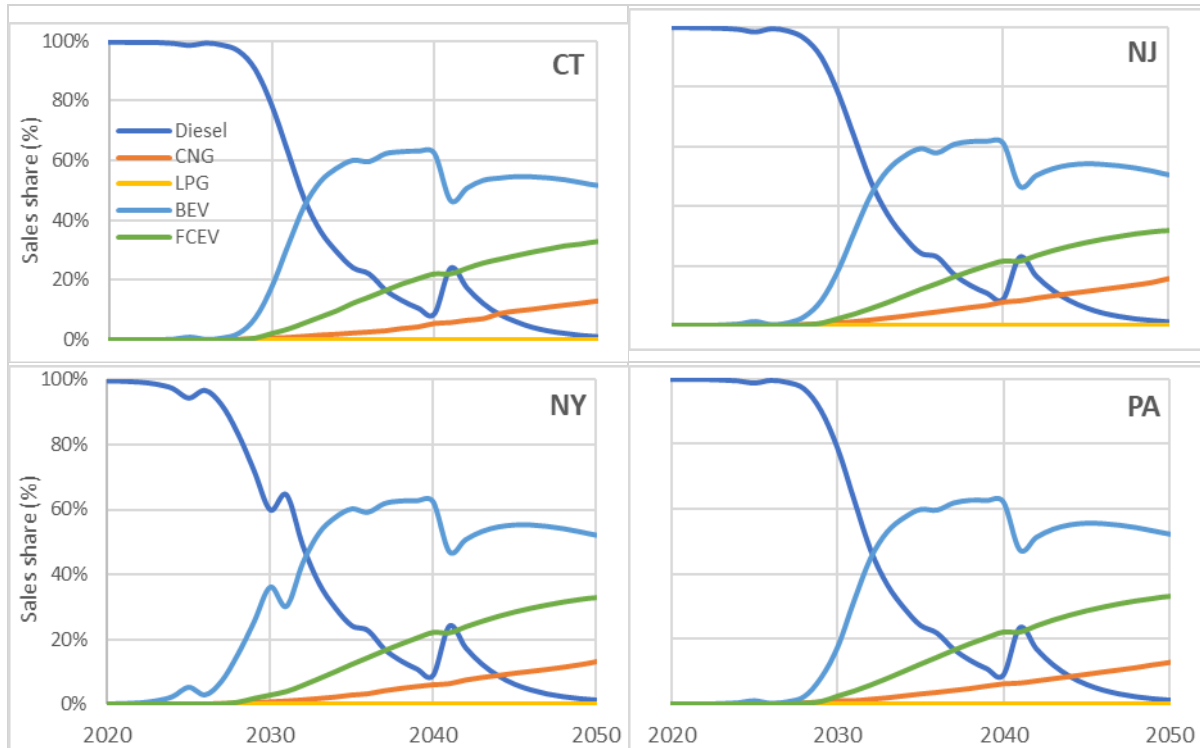


Figure 8 below; while all states show broadly similar shapes and end the study period in broadly similar positions, the diesel sales share remains effectively at 100% until states introduce purchase incentives for other fuel-type vehicles, which takes longer in CT and PA than in NY and NJ. The short-duration variations seen in 2025, 2030, and 2035 are primarily a function of assumptions regarding incentive step-downs for various alternative fuel vehicle types, which allows diesel to momentarily rebound before being overtaken by other market forces (namely fuel price and continued technological improvement for alternative fuel vehicles). In all jurisdictions, BEV is projected to be the dominant fuel type for class 3-8 freight vehicles before 2035 and to end the period with a majority of sales, while FCEV is projected to rise steadily and capture roughly 30% of sales and CNG rises more slowly to just roughly 15%.

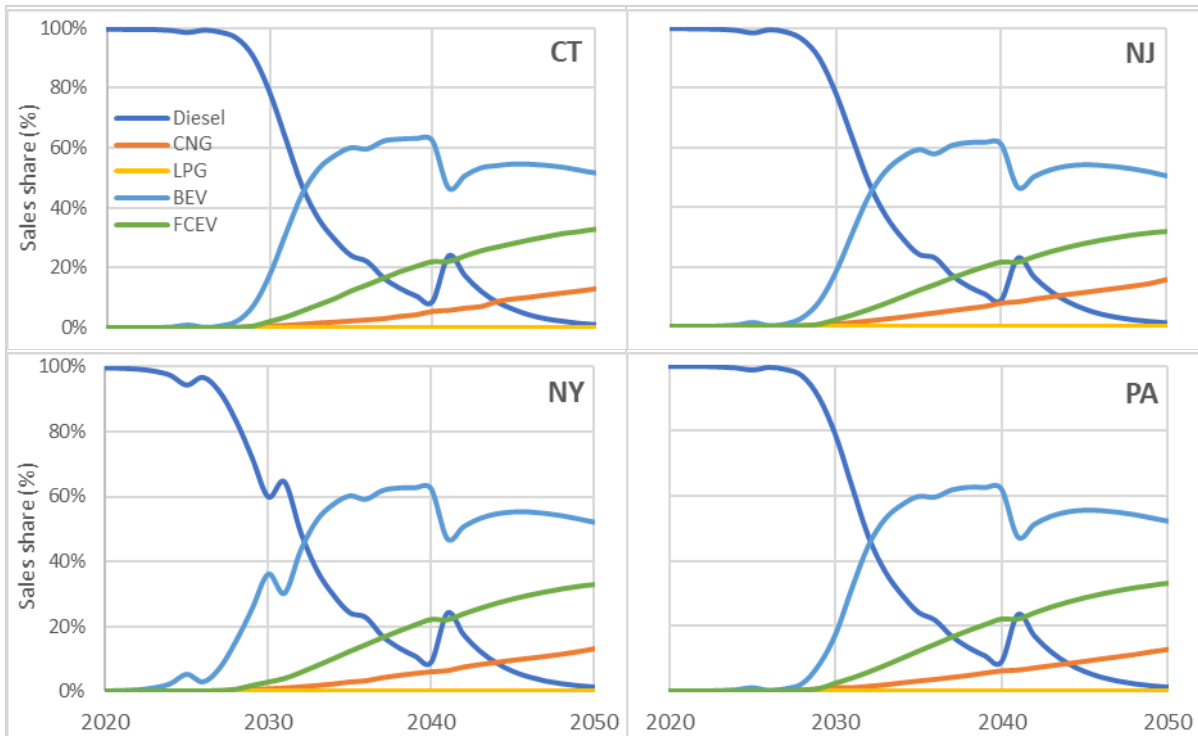


Figure 8. Overall sales share over time across vehicle types by state (run 2B)

CONCLUSION

While diesel is the near-universal fuel used in trucks currently, its market share will be eroded significantly and irrevocably beginning as soon as the middle of this decade through 2050 and beyond. As alternative fuel vehicle technologies improve, operating costs decline, and cities and states promulgate decarbonization and air quality policies that favor cleaner fuels, diesel alternatives—especially BEV and FCEV propulsion systems—will become increasingly favored by freight fleets. Although the pace and extent to which freight operators transition from diesel to the variety of cleaner options discussed above is highly subject to the policy conditions and adoption environment, the directional outlook for these technologies is clear.

This technical memo uses a proprietary model, HDVARM, to project how sales of freight vehicles, across 18 distinct vehicle segments in classes 3-8, will change through time based on their TCO and how aggressive or slow fleets are to adopt alternative technology. The modeling demonstrates that the TCO for the various alternative fuel vehicle types relative to diesel is a function of purchase price, O&M costs, and duty cycle. CNG, BEV, and FCEV technologies can be more affordable

than diesel throughout the study area as long as the duty cycle has enough miles to allow the O&M savings to offset the upfront cost premiums; this benefit will occur earlier in states that have robust incentives to shorten payback periods further. LPG trucks are slightly costlier to purchase but more expensive to operate than diesel, and this disparity in operating costs is projected to grow through time. Accordingly, the TCO for LPG vehicles struggles across vehicle platforms and states as well as worsens with time.

Under a range of projections for vehicle adoption in the study area across vehicle segments, diesel is projected to hold the largest sales share until the early 2030s and follow a downward trajectory to less than 10% by 2050 (and likely less than 2%). In its place, BEV, FCEV, and CNG will compete for market share with BEV taking the largest proportion by 2050 (38-60%), followed by FCEV (28-33%) and CNG (4-29%). Because of the poor TCO of LPG, this model does not project significant levels of LPG adoption in any vehicle segments or states.

Once these sales share projections are applied to existing inventories of freight vehicles in the study area, a more granular assessment can be conducted as to where particular fuel types are likeliest to agglomerate through time. This information, in turn, can support infrastructure planning so that publicly accessible alternative fuel infrastructure can be added where it will not only support and enable the projected levels of vehicle adoption, but where it will also face the best likelihood of robust utilization. This synthesis of vehicle technology adoption projections with mapping information will be presented as part of a later memo in Task 3.