

CLEAN TRUCK TECHNOLOGY COMPARATIVE REPORT 2 Vehicle Technology Readiness, Market Acceptance, Commercial Availability and Estimated Costs

METRO GOODS MOVEMENT PLANNING



Metro

MAY 2022

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1 Background and Overview

This report provides an overview of Class 8 heavy-duty truck technology readiness and commercial availability as it relates to diesel, natural gas, battery electric vehicle (BEV), and hydrogen fuel cell electric vehicle (FCEV) powertrains. This report assesses both the current and projected availability of these technologies and the costs for each. The report begins with a summary of the baseline conditions of Class 8 truck use in Los Angeles County. Section 0 summarizes technology readiness and commercial availability for each truck technology across immediate-, short-, medium-, and long-term timeframes. Section 4 summarizes the current and projected total cost of owning and operating trucks of each technology. Finally, Section 0 discusses the future outlook for Class 8 truck technology readiness and costs.

2 Baseline Conditions

Historically, air pollution in LA County has been a public health concern, with increasing population and commercial and industrial activity creating worsening air quality conditions. However, LA County's air quality has improved significantly due largely by technological improvements that were triggered by stringent emissions standards. With that said, NO_x continues to be a cause for concern in certain regions of the County, such as the South Coast air basin, which is currently considered to be in Extreme ozone non-attainment for four standard classifications.¹ According to CARB's official emission inventory, Class 8 trucks are responsible for 17 percent of NO_x and 9 percent of diesel particulate matter emissions in the county (see Report 1).

As discussed in Report 1, the population of Class 8 trucks operating in the LA county is projected to increase by 40 percent by 2035, from 55,626 in 2022 to 77,954 in 2035. The five types of heavy-duty Class 8 trucks in LA County can be categorized as such: Out of State, California Registered Intrastate, California Registered Interstate, Drayage, and Single Unit. On average, Class 8 trucks in LA County travel between 60 and 300 miles per day, depending on the vocation. Long-haul trucks, such as Out of State and Interstate trucks, accrue the most VMT per day carrying payloads on highway roads. Though drayage trucks handle heavy payloads from the ports and railyards, their operations are much more localized compared to their long-haul counterparts. Other localized operations, such as those performed by single unit trucks, perform their work in cities and other non-highway roads.

CARB EMFAC2021 provides insight on the year-to-year vehicle population changes for each fuel type, as shown in Table 1. EMFAC2021 classifies both battery-electric and fuel cell electric vehicles as having Electricity fuel types, so there is not sufficient granularity in the data to say how the subpopulations of these different electric technologies are growing. In 2022, 90 percent of the Class 8 truck population are diesel trucks, with the other 10 percent of the population being made up by natural gas

¹ Ozone nonattainment classifications include: 2015 8-hour Ozone (70 ppb level), 2008 8-hour Ozone (75ppb), 1997 8-hour Ozone (80 ppb), and 1979 1-hour ozone (120 ppb).

counterparts. Assuming baseline conditions, which are the EMFAC21 outputs², the combined electric vehicle population is expected to grow rapidly, in some years nearly doubling from the previous year.³

Table 1 – EMFAC2021 Class 8 Projected Truck Population by Fuel Type in LA County

Calendar Year	Diesel	Electricity	Gasoline	Natural Gas
2020	47,736		92	4,532
2021	48,766		75	4,983
2022	50,253		63	5,310
2023	51,746	41	52	5,423
2024	53,754	163	44	5,714
2025	55,408	360	38	5,978
2026	56,774	626	32	6,229
2027	57,907	1,005	29	6,436

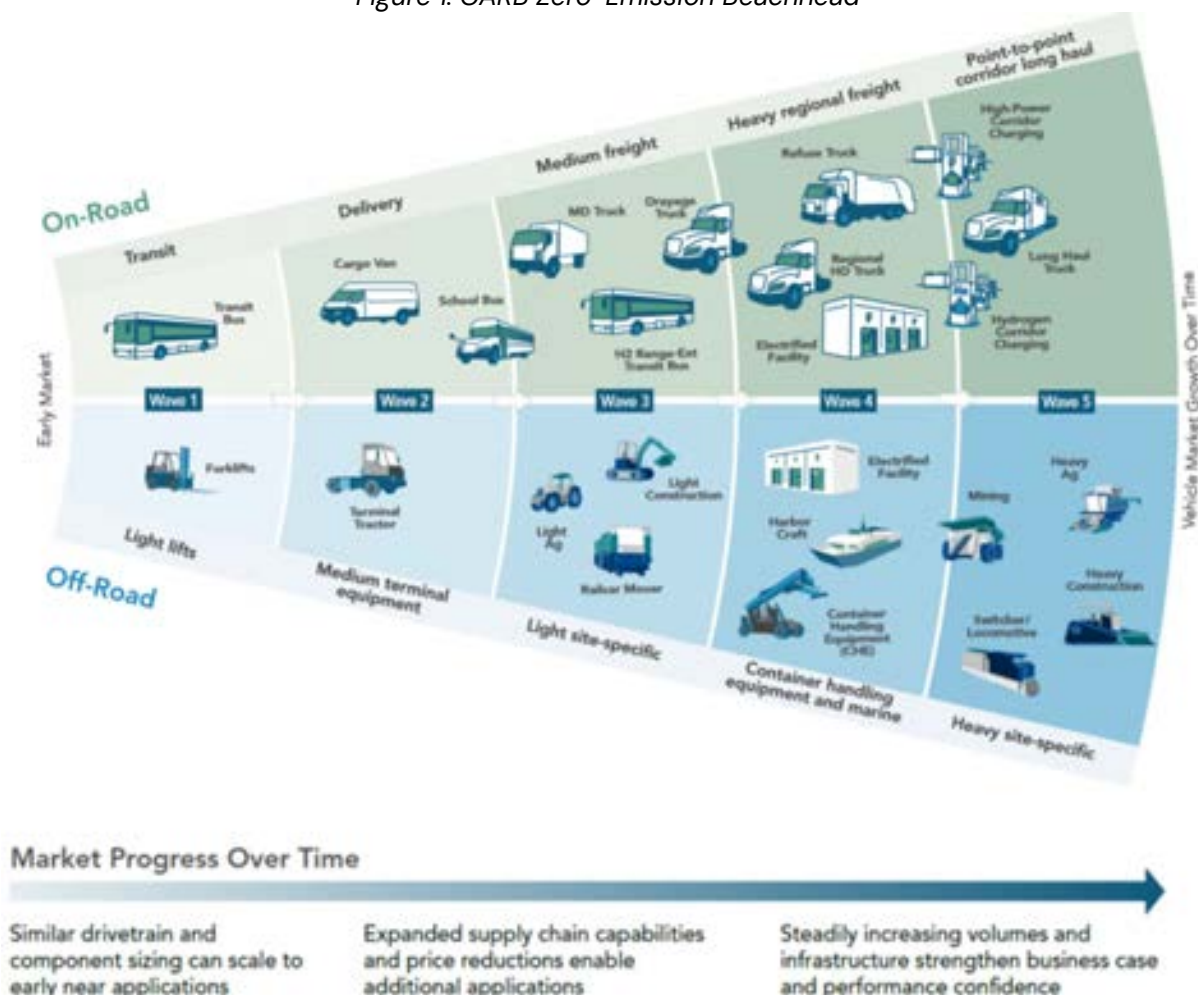
² EMFAC21 reflects: CARB's Advanced Clean Trucks Rule, Heavy-Duty Omnibus Regulation, Phase 1 & 2 GHG Standards for M/HD Engines and Vehicles, Truck and Bus Regulation.

³ Note that EMFAC2021 did account for the impact of the COVID-19 pandemic; however, it does not account for the current high gas prices, nor does it assume any economic recession in the horizon. The basis for the heavy-duty vehicle projections in the EMFAC2021 are from the California Statewide Travel Demand Model developed operated by Caltrans.

3 Current and Projected Technology Readiness and Commercial Availability of Class 8 Truck Technologies

Class 8 truck technologies which are in scope for this report include diesel, natural gas, hydrogen fuel cell, and battery electric. In terms of technology readiness, diesel and natural gas truck technologies are mature compared to battery electric and hydrogen fuel cell electric trucks. For zero-emission technologies (electric and hydrogen) it is expected that these technologies will commercialize systematically, with vehicles operating on predictable and shorter routes succeeding first, particularly those with access to overnight charging depots. Following these use cases, technology is expected to develop to serve longer and more complicated applications over time. CARB calls this projection of commercialization the Beachhead Strategy, and it is shown graphically in **Error! Reference source not found.** below.

Figure 1. CARB Zero-Emission Beachhead



Despite the zero-emission technology to be in early stages of commercialization, over the last three years, there has been plenty of announcements by major truck manufacturers on development and production of zero emission medium and heavy duty (MD/HD) vehicles (i.e., battery electric and fuel

cell trucks). According to ICF's EV Library⁴, there are approximately 170 models of electric MD/HD vehicles that are either available today or planned to be available in the next two years. These models are offered with different battery capacities and electric ranges making them suitable for various trucking vocations.

Aside from technology providers, there are also quite a bit of activity at state and federal level to transition MD/HD sector to zero emission. In 2020, California adopted the Advanced Clean Truck (ACT) regulation which sets the first in the nation ZEV sales requirements for MD/HD vehicle manufacturers to sell zero emission trucks starting with model year 2024. Upon the adoption of the ACT regulation in California, 15 states and the District of Columbia announced a joint memorandum of understanding (MOU), committing to work collaboratively to advance and accelerate the market, with the goal of reaching 100 percent of all new MD/HD vehicle sales to be zero emission vehicles by 2050 with an interim target of 30 percent zero-emission vehicle sales by 2030. California is also currently pursuing a new policy called the Advanced Clean Fleets (ACF) regulation which requires fleets operating in California to transition to zero emission technology between 2024 through 2042. Separately, the Zero Emission Drayage Truck regulation focuses specifically on heavy-trucks associated with goods movement by requiring all on-road diesel vehicles, including drayage trucks, to have a 2010 or newer engine by 2023.⁵ By 2050, almost two-thirds of the trucks operating in California are supposed to be zero emission. It will not be surprising to see other states follow California's footsteps and adopt similar requirements for their fleets.

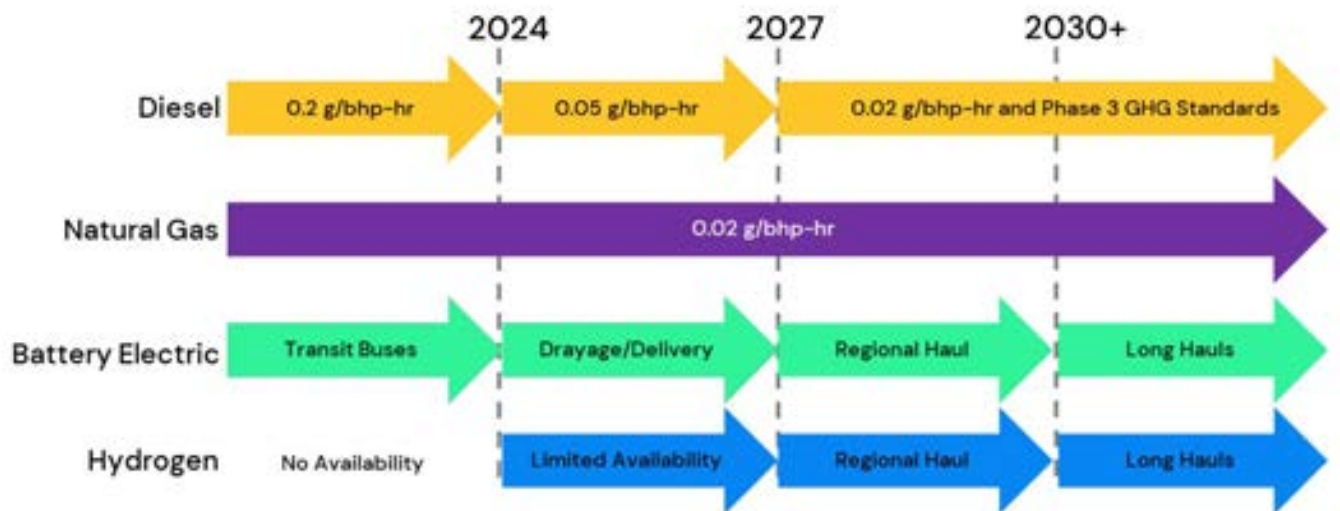
As it will be further described in the following subsections, the technology horizon varies significantly across these four fuel technologies. In the following subsection we will describe where the technology stands today, and how we envision it will evolve over the next 10 – 15 years considering upcoming regulatory actions, as well as industry announcements. A summary of this analysis is illustrated in

⁴ ICF's Electric Vehicle Library is a regularly updated database of EV makes and models along with key information about their specifications and estimated year of commercial availability

⁵ CARB. (2011, November 9). Drayage Truck Regulation. Retrieved from https://www2.arb.ca.gov/sites/default/files/classic/msprog/onroad/porttruck/finalregdrayage.pdf?_ga=2.201041255.816927322.1656456945-745151314.1653626725

Figure 2. More details can be found in section 3.1 through 3.4.

Figure 2. Progression of Technology Development over the next 10 years⁶



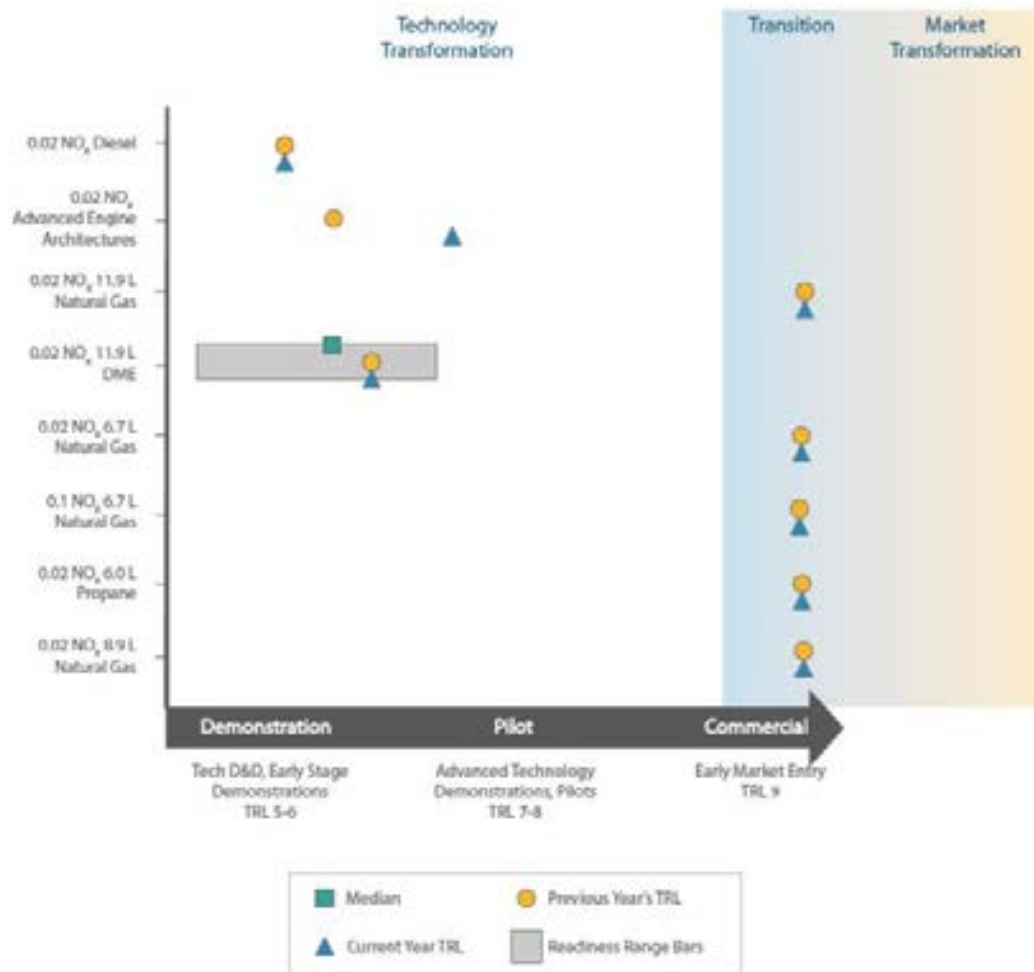
3.1 Diesel

Operating conventionally fueled diesel trucks has been the norm in heavy-duty trucking. However, diesel trucks have been a major source of local and regional air quality issue, toxics exposure especially in low income and disadvantage communities, and significant contributor to GHG emissions. In recent years, diesel trucks have improved with the introduction of emissions and efficiency standards, particularly those that reduce NO_x and particulate matter (PM) emissions. The introduction of new engine and aftertreatment systems combined with the use of renewable diesels have led to significant reductions in both criteria and GHG emissions. Today, all new diesel engines sold across the U.S. are meeting a national NO_x emission standard of 0.2 grams per brake horsepower hour (g/bhp-hr) and PM standard of 0.01 g/bhp-hr. Compared to 1998 standards (4 g/bhp-hr for NO_x and 0.1 g/bhp-hr) these standards are 20x more stringent for NO_x and 10x cleaner for PM emissions. In August 2020, CARB adopted its proposed amendments to the exhaust emissions standards and test procedures for 2024 and subsequent model year heavy-duty engines and vehicles (also known as the HD Omnibus regulation) that requires all California-certified heavy-duty engines of model year 2024–2026 to meet the 0.05 g/bhp-hr NO_x standard, with more stringent standards (0.02 g/bhp-hr) for the subsequent model years. Figure 3 shows CARB’s estimate for the readiness level of these cleaner combustion technologies, with the main takeaways being that low NO_x natural gas and propane engines are past demonstration and pilot phases and now entering early market commercialization, while low NO_x diesel, advanced engine architectures, and dimethyl ether⁷ (DME) technologies are still being demonstrated

⁶ Diesel and Natural gas emission rates indicate NO_x emission reductions due to engine improvements.

⁷ DME is a synthetically produced fuel that can be used in place of diesel in modified compression ignition diesel engines.

Figure 3. On-Road Combustion Technology Status Snapshot

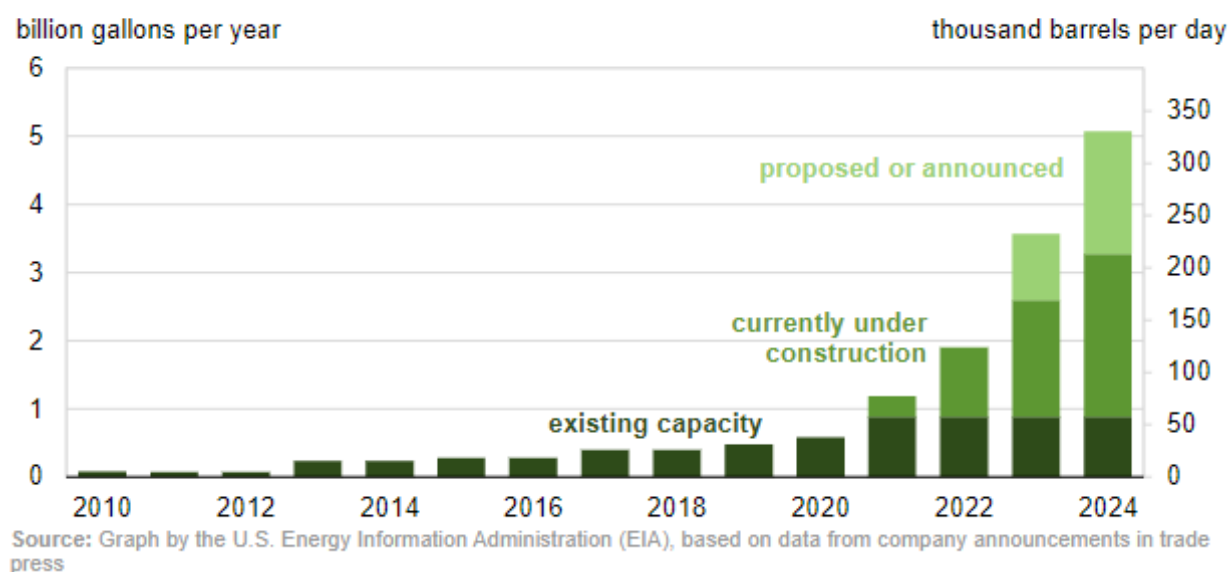


While CARB and EPA standards will reduce criteria pollutant emissions (NO_x and PM) and improve engine and vehicle efficiency (through Phase 2 GHG standards), curbing GHG emissions from diesel trucks may also necessitate the use of renewable diesel (more discussion on renewable diesel is included in Report 4). However, it should be noted that, when blended with diesel, biofuels when have been shown to increase NO_x emissions.⁸ The market for renewable diesel is growing in the U.S. and especially in California, as a result of the federal Renewable Fuel Standard as well as California's Low Carbon Fuel Standards Program. It is expected that production capacity could increase significantly through 2024, based on project announcements that either are currently under construction or could be in development soon (Figure 4). According to the U.S. Energy Information Administration (EIA), U.S. renewable diesel production capacity totaled nearly 0.6 billion gallons per year (gal/y), or 38,000 barrels per day (b/d) in 2020. A handful of projects currently under construction could increase production capacity by 2.4 billion gal/y; proposed and announced projects would add another 1.8 billion gal/y by 2024. U.S. renewable diesel production would total 5.1 billion gal/y by the end of 2024

⁸ O'Malley, J., & Searle, S. (2021, March 17). Air Quality Impacts of Biodiesel in the United States. In The International Council on Clean Transportation. Retrieved from <https://theicct.org/publication/air-quality-impacts-of-biodiesel-in-the-united-states/>

if all projects come online as intended. By 2024, it is expected that renewable diesel will make up about 5% of current U.S. diesel production capacity.

Figure 4. Existing and Expected U.S. Renewable Diesel Production Capacity (2010 – 2024)⁹



With most major U.S. truck manufacturers committing to transitioning their vehicle offerings to zero-emission technologies by 2040, new diesel vehicle sales are expected to significantly decrease in the next 15–20 years. However, considering that diesel trucks can have a lifetime of up to 18 years (or 800,000 miles per California Senate Bill 1)¹⁰, some existing diesel trucks, and those that will be sold in the near future are likely to stay in service beyond 2040. Therefore, more stringent efficiency standards for newer models and increased availability of renewable diesel production will be key in reducing emissions from these trucks. The role of regulatory and incentive policies will be further described in Report 6: Incentives and Regulation.

3.2 Natural Gas

Natural gas-powered trucks are another type of commercially available technology that, when compared to diesel trucks, can reduce criteria pollutants such as NO_x and PM, GHG emissions, and most importantly fully eliminate diesel PM, one of the key sources of public health issues in communities near major freight facilities. Further, lifecycle GHG emission reductions can be significantly improved when natural gas trucks are powered by renewable natural gas (RNG). In 2016, the first 0.02 g/bhp-hr certified natural gas engine was introduced by Natural gas engine developer Cummins Westport Inc. Today, there are more than 9 engine models and sizes that are available for sale in California. The list of 2020 and 2021 model year CARB certified 0.02 and 0.05 g/bhp-hr certified engines are shown in Table 2. Please note that this list includes engines for both medium and heavy duty vehicles. Engines that are specific to heavy duty applications are highlighted in light blue.

⁹ U.S. Energy Information Administration. (2021, July 29). U.S. renewable diesel capacity could increase due to announced and developing projects. In *Today in Energy*. Retrieved from <https://www.eia.gov/todayinenergy/detail.php?id=48916>

¹⁰ SB 1 Truck Provisions: <https://calstablog.files.wordpress.com/2017/04/sb-1-truck-provisions-q-and-a.pdf>

Table 2. CARB-Certified 0.02 and 0.05 g/bhp-hr Heavy-Duty Natural Gas Engines (As of February 2022)¹¹

Low NOx Engine	Engine Family	Displacement (Liters)	NOx Certification Standard (g/bhp-hr)	Percent NOx Reduction	Fuel ¹²	Intended Service Class ¹³
2021						
Agility Powertrains	MAGIE06.0CNG	6.0	0.02	90%	NG	HDO
Cummins 6.7	MCEXH0408BDA	6.7	0.02	90%	NG	MHDD
Cummins 8.9	MCEXH0540LDA	8.9	0.02	90%	NG	MHDD
Cummins 8.9	MCEXH0540LDB	8.9	0.02	90%	NG	UB
Cummins 8.9	MCEXH0540LDC	8.9	0.02	90%	NG	HHDD
Cummins 11.9	MCEXH0729XDA	11.9	0.02	90%	NG	HHDD-UB
PSI 8.8	MPSIE8.8LN1	8.8	0.02	90%	LPG	HDO
Roush 7.3	MRIIE07.3BL1	7.3	0.05	75%	LPG	HDO
2020						
PSI 8.8	LPSIE8.8LN1	8.8	0.02	90%	LPG	HDO
Cummins 6.7	LCEXH0408BBC	6.7	0.02	90%	NG	MHDD
Cummins 8.9	LCEXH0540LBN	8.9	0.02	90%	NG	HHDD
Cummins 8.9	LCEXH0540LBL	8.9	0.02	90%	NG	MHDD
Cummins 8.9	LCEXH0540LBM	8.9	0.02	90%	NG	UB
Cummins 11.9	LCEXH0729XBC	11.9	0.02	90%	NG	HHDD-UB
Roush (LPG) 6.8	LRRIIE06.8BW2	6.8	0.02	90%	LPG	HDO
Roush (LPG) 6.8	LRRIIE06.8BWL	6.8	0.05	75%	LPG	HDO

Natural gas vehicles have emerged as a popular alternative to diesel vehicles as fleets have sought to decrease their emissions. Much like diesel trucks, breakthroughs in low-NOx engine technologies have the potential to further decrease emissions in addition to renewable natural gas. While some truck

¹¹ California Air Resources Board. (2022, February 24). List of Optional Low NOx Certified Heavy-Duty Engines. Retrieved from https://www2.arb.ca.gov/sites/default/files/2022-03/Optional%20Low%20NOx%20Certified%20Heavy-Duty%20Engines-as%20of%2002242022-1_O.pdf

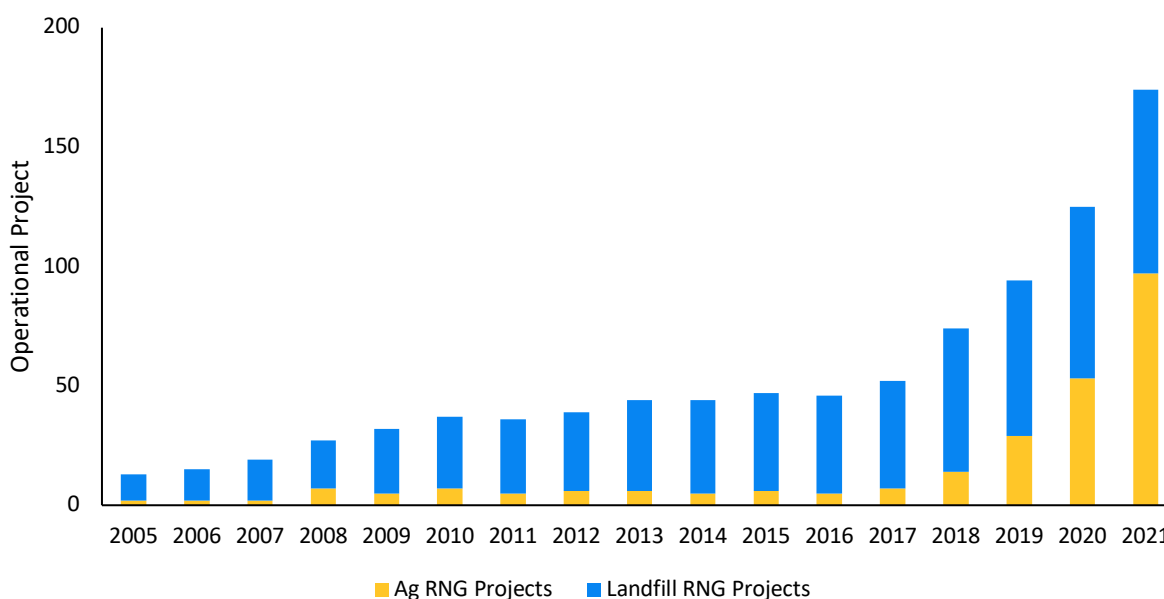
¹² Liquid petroleum gas (LPG) is considered an alternative fuel under the Energy Policy Act and can reduce lifecycle emissions compared to diesel fuel by 13 to 99 percent.

¹³ UB - Urban Bus, HDO - Heavy-Duty Otto-Cycle, MHDD - Medium-Heavy Duty Diesel Cycle, HHDD - Heavy-Heavy Duty Diesel Cycle, NG - Natural Gas, LPG - Liquefied Petroleum Gas (Propane). The cycle describes the engine ignition process; HDO is ideal for spark ignition engines and MHDD and HHDD is ideal for compression ignition engines.

manufacturers have made commitments to increase low-emission vehicle offerings, most manufacturers' climate commitments focus on zero-emission sales, signaling a decrease in natural gas truck offerings over the next 15–20 years.

As discussed earlier, key to reduction of GHG emissions from the natural gas-powered engines is the use of RNG. Domestic production of RNG began around 2005 with the majority of projects being landfill gas (LFG). As of 2021 agricultural RNG and LFG projects each made up approximately 50% of domestic RNG projects, with other potential feedstocks on the horizon such as diverted green waste (**Error! Reference source not found.**). However, when it comes to the use of RNG, there are many sectors that will be competing for this fuel. Not only can RNG be used in decarbonizing the transportation sector, but it is also envisioned to facilitate reduction of emissions in hard to electrify sectors such as heavy industry as well as buildings. Later in Report 4, we will further elaborate on the availability of RNG, and their viability as vehicle fuels in the immediate-and short-terms.

Figure 5. U.S. Renewable Natural Gas Projects Operating by Year¹⁴

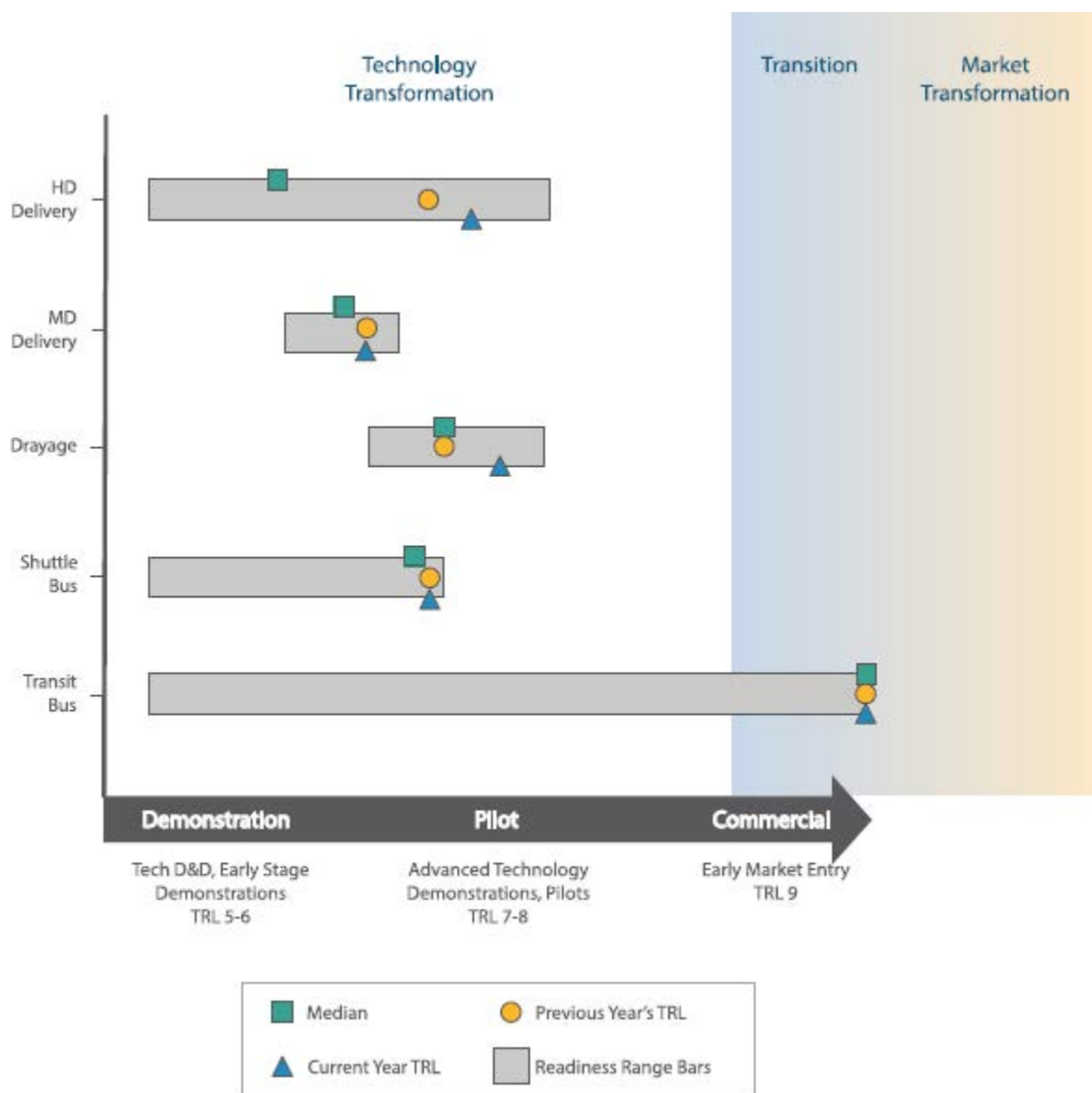


¹⁴ U.S. Environmental Protection Agency. (n.d.). Renewable Natural Gas. In *Landfill Methane Outreach Program (LMOP)*. Retrieved from <https://www.epa.gov/lmop/renewable-natural-gas>

3.3 Hydrogen

Hydrogen fuel cell vehicles are largely still in technology development stages with demonstrations and pilots still ongoing. Hydrogen fuel cell transit buses are fully commercially available, but other HD hydrogen vehicles are still being developed and automaker-announced models generally have later timeframes for release compared to battery electric vehicles. Figure 6 shows CARB's estimate for the technology readiness of hydrogen powered vehicles in various vehicle classes and truck vocations. As noted, transit buses are the only hydrogen application in the HD sector that has reached early market entry.

Figure 6. On-Road Fuel Cell Electric Vehicles Technology Status Snapshot¹⁵



¹⁵ CARB. (2020). Long-Term Heavy-Duty Investment Strategy. Retrieved from https://ww2.arb.ca.gov/sites/default/files/2020-11/appd_hd_invest_strat.pdf

Through their Global Commercial Vehicle Drive to Zero Program, CALSTART has collected heavy-duty trucks that are currently available and expected to be available within the next few years. As shown in Table 3, currently there are eight hydrogen heavy-duty truck models announced to be manufactured over the next 2 – 3 years, with Hyzon being the only manufacturer with current hydrogen heavy-duty truck offerings. Hydrogen powered models from Hyundai, Kenworth, Nikola and Toyota are expected to be released through 2024. As shown, the expected electric range for these vehicles spans between 150 miles for Kenworth T680 to 900 miles for Nikola Two FCEV.

Table 3. Heavy-Duty Hydrogen Fuel Cell Electric Trucks (Per the Global Commercial Vehicle Drive to Zero Program)¹⁶

Vehicle Type	Manufacturer	Model	Fuel Type	Estimated Range (miles)	Reported Availability Year
HD Truck	Hyundai	HDC-6 NEPTUNE	FCEV	800	2023
HD Truck	Hyundai	Xcient	FCEV	249	2023
HD Truck	Hyzon	FCET 8	FCEV	500	2021
HD Truck	Hyzon	FCET 6	FCEV	350	2021
HD Truck	Kenworth	T680	FCEV	150	2023
HD Truck	Nikola	Tre FCEV	FCEV	500	2023
HD Truck	Nikola	Two FCEV	FCEV	900	2024
HD Truck	Toyota	Beta	FCEV	300	2023

To further illustrate on the potential of hydrogen powered trucks in the future zero emission vehicle market,

Table 4 below illustrate various manufacturers commitment toward zero emission products. Of the 21 manufacturers with listed commitments, 18 companies did not limit the technologies they will produce to reach their zero-emission goals. This gives manufacturers the flexibility to increase investments in future hydrogen fuel cell truck offerings as well as battery electric offerings. As shown, most of the heavy-duty vehicle manufacturers continue to set ambitious zero-emission vehicle targets with manufacturers like Daimler, Volvo, and Paccar announcing climate targets or goals. Due to their on-board hydrogen storage, hydrogen fuel cell trucks have a longer range, require fewer stops on long routes, can be fueled much faster, and have less risk of lost cargo capacity. This makes them a suitable option for heavier and longer-range vehicles (e.g., interstate class 8 trucks). Importantly, there is currently a limited availability of hydrogen fueling stations in LA County which are capable of serving Class 8 trucks. Significant hydrogen fueling infrastructure, as well as electric vehicle charging

¹⁶ CALSTART. Zero-Emission Technology Inventory. Retrieved March 14, 2022, from <https://globaldrivetozero.org/tools/zero-emission-technology-inventory/>.

infrastructure, will need to be developed to accommodate future increases in the number of these trucks on the road. This topic is addressed in greater detail within Report 4 of this project.

*Table 4. MH/DV manufacturer commitments to ZEV sales and carbon neutrality (As of December 2021)*¹⁷

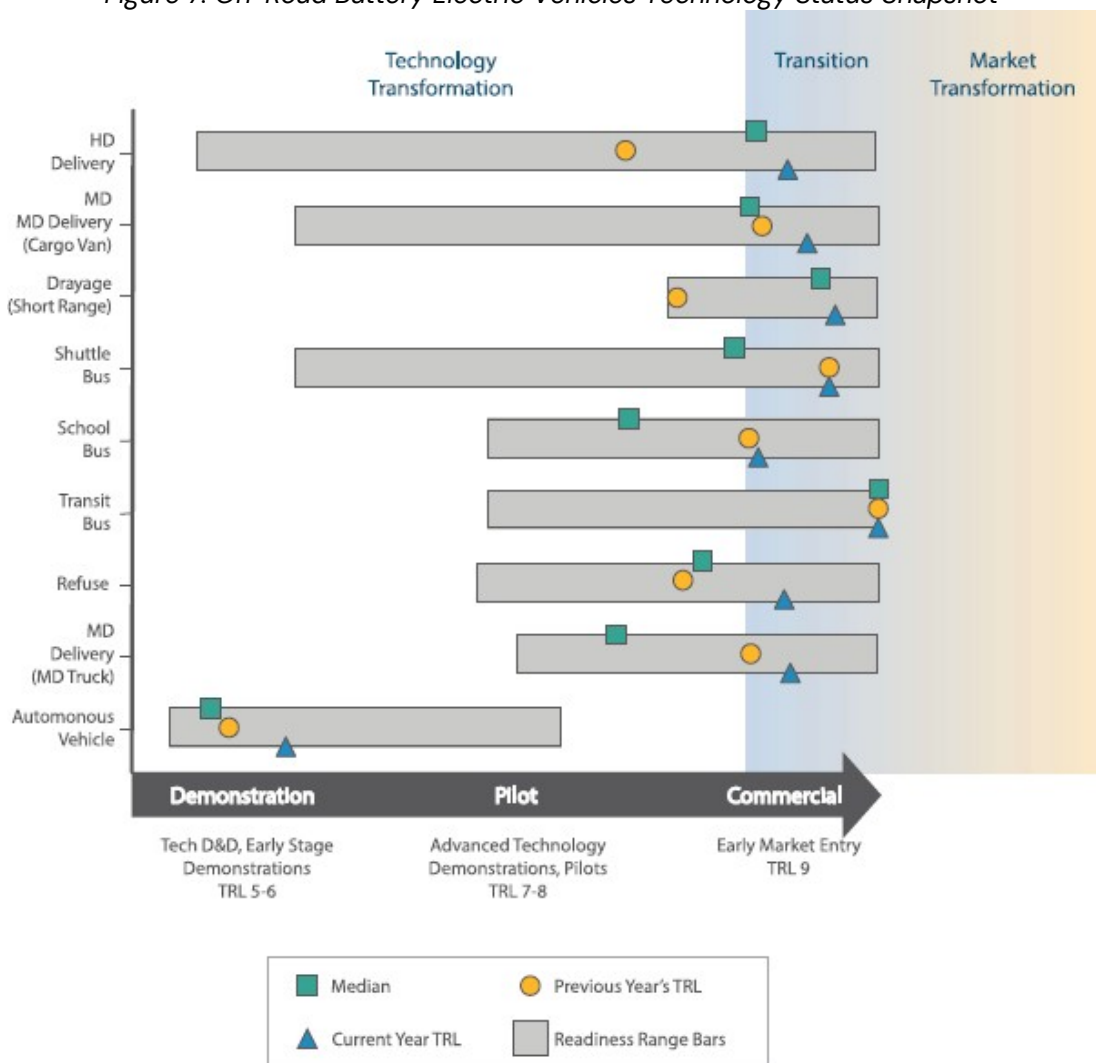
Manufacturer	Commitment	Date
Scania	At least 90% of zero-emission vehicle sales worldwide, with remainder powered by 100% fossil-free energy	2040
GM group	100% carbon neutral in global products and operations	2040
Stellantis	70% low-emission vehicle sales in Europe, and 40% in the US	2030
Ford Group	100% fossil free new vehicle sales	2040
Daimler Group	100% carbon neutral in driving operation in Europe, North America, and Japan	2039
Toyota Group	100% carbon neutral in lifecycle by 2050	2050
Changan	100% electric vehicle sales	2025
Great Wall Motor	100% carbon neutral with interim target of 80% new energy vehicle sales by 2025	2025
Mahindra & Mahindra	100% carbon neutral in operations	2040
VW Group	100% carbon neutral in operations	2050
Renault	100% carbon neutral worldwide, with interim target of 100% CO ₂ neutral in Europe by 2040	2050
Nissan	100% carbon neutral across operations and product lifecycle	2050
Mitsubishi	100% carbon neutral, with 50% EV sales by 2030	2050
Isuzu	100% carbon neutral in vehicle operation and plants sheet	2050
Paccar	100% fossil free new vehicle sales	2040
Suzuki	90% reduction in CO ₂ emissions in driving operation	2050
Volvo Trucks Group	100% fossil free new vehicle sales	2040
CNH Industrial	100% fossil free new vehicle sales	2040
Honda	100% battery-electric and fuel cell electric vehicle sales in North America, with interim targets of 40% by 2030 and 80% by 2035	2040
Mazda	90% reduction in CO ₂ emissions in driving operation and energy production	2050
Hyundai Kia	100% carbon neutral in all operations	2050

¹⁷ CALSTART. Review of Commitments for Zero-Emission Medium- and Heavy-Duty Vehicles. Retrieved May 24, 2022, from https://globaldrivetozero.org/site/wp-content/uploads/2021/12/Review-of-Commitments-for-Zero-Emission-Medium-and-Heavy-Duty-Vehicles_Dec_2021_Final-.pdf

3.4 Battery Electric

The technological readiness of Class 8 electric vehicles varies depending on the vehicle's duty cycle (see Report 1), range requirements, and general application. Transit buses are farther along in the market followed by drayage, refuse and delivery trucks. However, the technology is still under development for long-haul tractors. As described in Report 1, due to shorter trip distance, and more predictable routes, transit buses, refuse trucks, and to some extent drayage trucks are suitable candidates for early deployment electric vehicles. From one hand, these vocations do not need electric vehicles with significantly high ranges, and on the other hand, the return to base and local operations of these vehicles make the charging infrastructure deployment less complicated as compared to line haul and more energy intensive applications. With that said, as illustrated in Figure 7, all heavy-duty vehicles are in the early market entry stage of commercialization.

Figure 7. On-Road Battery Electric Vehicles Technology Status Snapshot¹⁸



¹⁸ CARB. (2020). Long-Term Heavy-Duty Investment Strategy. Retrieved from https://ww2.arb.ca.gov/sites/default/files/2020-11/appd_hd_invest_strat.pdf

While demonstrations and pilots of these technologies do continue, the technology has developed to a point in which multiple auto manufacturers are now offering these vehicles for commercial sale. A comprehensive list of available battery electric zero emission trucks is provided in Table 5. As illustrated, these electric models have ranges as low as 56 miles with BYD 8R refuse trucks to as high as 500 miles, as announced for Tesla Semi. While the reported availability years for some of these trucks are noted as 2021 or 2022, production of these vehicles may have been delayed due to supply chain issues caused by the pandemic or for other issues faced by the manufacturers.

Table 5. Heavy-Duty Battery Electric Trucks (Per the Global Commercial Vehicle Drive to Zero Program)¹⁹

Vehicle Type	Manufacturer	Model ²⁰	Estimated Range ²¹	Reported Availability Year ²²
HD Truck	BYD	8TT*	125	2021
HD Truck	Freightliner	eCascadia*	250	2022
HD Truck	Freightliner	EM2 106 – Class 7*	250	2022
HD Truck	Kenworth	T680E*	150	2021
HD Truck	Lion	Lion8*	180	2021
HD Truck	Mercedes	eActros	124	2021
HD Truck	Nikola	Tre BEV*	350	2021
HD Truck	Peterbilt	520EV Class 7*	90	2020
HD Truck	Peterbilt	579EV*	200	2020
HD Truck	Roush	Roush Ford F-750	N/A	2021
HD Truck	SEA Electric	Autocar ACMD Class 7 (Repower)	150	2020
HD Truck	SEA Electric	Autocar ACMD Class 8 (Repower)	150	2020
HD Truck	SEA Electric	Freightliner Cascadia (Repower)	150	2020
HD Truck	SEA Electric	Freightliner M2 105 (Repower)	150	2020
HD Truck	SEA Electric	Freightliner M2 106 (Repower)	150	2020
HD Truck	SEA Electric	Hino GH EV (Repower)	125	2020
HD Truck	SEA Electric	Kenworth T370 (Repower)	150	2020
HD Truck	Tesla	Semi	300-500	2022
HD Truck	Volvo	VNR Electric*	275	2021
HD Truck	XOS	HDXT	110-230	2022

As discussed in previous sections, MHDV manufacturers continue to set ambitious targets to increase zero-emission heavy-duty vehicle offerings over the next 20 years. While most manufacturer targets commit to fossil-free vehicles without prescribing to a specific technology, it is likely that manufacturers will provide more BEV offerings than hydrogen due to the size of the current and expected near-term BEV market (25 vehicle offerings) in comparison to the hydrogen vehicle market (8 vehicle offerings). With their competitive advantage and as BEV technology advances to increase efficiency, maximize range, and decrease the weight of the battery, manufacturers are likely to increase their BEV offerings to reach their climate targets.

¹⁹ CALSTART. Zero-Emission Technology Inventory. Retrieved March 14, 2022, from <https://globaldrivetozero.org/tools/zero-emission-technology-inventory/>.

²⁰ (*) indicates that the vehicle is available in the California HVIP catalogue. See: californiahvip.org/vehicles

²¹ Estimated range is reported by manufacturers and actual results may vary under real-world conditions.

²² Model availability dates are reported by manufacturers and are subject to change.

4 Estimated Total Cost of Ownership for Class 8 Truck Technologies

The total cost of ownership (TCO) framework for vehicles assesses the total cost to purchase, operate, maintain, and resell a vehicle. It provides a look at the economic lifecycle of a vehicle, as opposed to simply comparing the purchase price of different powertrain technologies. In this section we first analyze existing TCO studies by CARB, the National Renewable Energy Laboratory (NREL), and a report produced by ICF for the California Electric Transportation Coalition (CalETC). Additional information on the costs associated with Class 8 truck technologies is included in

Summary

This report summarizes the current and projected state of technology for alternative fuel Class 8 trucks. Innovations in conventional engine technologies, including low-NOx engines, are explored and the role these technologies may play in the transition of heavy-duty trucks in LA County is discussed. Also, increasing model offerings of hydrogen fuel cell electric and battery-electric trucks show promise as the industry begins to signal increasing interest in alternative fuel vehicles.

In addition to discussing vehicle technology readiness and availability, this report also includes a review of relevant literature on Class 8 truck costs. Four total cost of ownership (TCO) analyses were reviewed including those from CARB's ACF and ACT regulations, a CALETC report on heavy-duty vehicles in California, and from NREL. These TCO estimates shed light on the potential economics of alternative fuel trucks compared to conventional diesel trucks.

Key Takeaways

- Two significant regulations impacting Class 8 truck technology in California are already in place and proposed. These are expected to have substantial impacts on California emissions reduction efforts. The regulations include CARB's already-approved Advanced Clean Truck (ACT) regulation (2020), which requires medium- and heavy-duty vehicle manufacturers to sell zero emission trucks starting with model year 2024, and the proposed Advanced Clean Fleet (ACF) regulation. When adopted, the ACF regulation will require fleets operating in California to transition to zero emission technology vehicles between 2024 and 2042.
- Today, all new diesel engines sold across the U.S. must meet certain standards for NOx and PM emissions in compliance with regulations from California and the U.S. EPA.
- EPA's Renewable Fuel Standard and California's Low Carbon Fuel Standard Program are helping to increase the production of renewable diesel, as well as other alternative fuels. As we look into the future, however, new diesel vehicles sales are expected to significantly decrease in the next 15 – 20 years due to requirements in CARB's ACT and ACF regulations.
- When powered by renewable natural gas (RNG), natural gas-powered trucks can significantly reduce NOx and GHG emissions, and fully eliminate diesel PM. While promising as a means to reduce GHGs and eliminate diesel PM, the demand for RNG from sectors other than transportation, such as heavy industry and buildings, may present challenges. This competition poses uncertainty on RNG's availability and viability as a vehicle fuel in the immediate- and short-terms.
- The refueling process for hydrogen fuel cell trucks is similar to diesel trucks, and FCETs offer a few advantages over BEVs, including: fewer stops on long routes, faster refueling times, and potentially less risk for lost cargo capacity due to the weight of on-board energy storage (re: BET battery packs). However, hydrogen is relatively more expensive than electricity as a transportation fuel. These attributes make hydrogen FCETs a suitable option for heavier and longer range operations, as well as operations requiring fast refueling.
- The technological readiness of Class 8 battery-electric trucks varies depending on the vehicle's duty cycle, range requirements, and general applications. Long-haul BEV's tractors are still largely under development. However, shorter range trucks, such as drayage truck, have been developed and are commercially available. These types of operations are suitable candidates for early deployment of battery-electric Class 8 trucks because of shorter trips distances and more predictable routes. Over time, Class 8 truck models with longer range capabilities are expected to become commercially available.

- While the upfront purchase prices of battery electric and hydrogen Class 8 trucks are considerably higher than diesel and natural gas trucks, the potential for operating cost savings associated with these zero-emission trucks can lead them to have lower lifetime TCO compared to diesel and natural gas trucks, especially with the addition of incentive funding.

4.1 TCO Comparison

The total cost of ownership (TCO) framework is a useful tool, particularly in the short- and mid-term, to understand the economic lifecycle of a vehicle and not simply the upfront purchase costs. It is important to note, however, that TCO studies make a number of assumptions that influence the final results. Total cost of ownership is highly dependent on several factors, such as the type of truck purchased, daily mileage, fuel economy, fuel prices, and general operational characteristics for the truck. In the following section we outline four TCO analyses of heavy-duty trucks and highlight the primary differences between the examples. We also describe how varying assumptions can impact the TCO outcomes. In order to create a more simplified comparison between the four TCO analyses, we have listed only the TCO assumptions and results for a Class 8 short-haul truck. We focus on short-haul trucks (which includes drayage) since it is expected to be the first market for zero emission truck technologies along I-710 in LA County. Over time, truck zero emission technologies are expected to improve and range capabilities will increase.

Table 66 shows the TCO assumptions across the four reviewed studies and summarizes the TCO results. CALETC²³ represents ICFs TCO study, ACT²⁴ represents the Draft Advanced Clean Trucks Total Cost of Ownership Discussion Document, ACF²⁵ represents the Draft Advanced Clean Fleets (ACF) TCO Discussion Document, and NREL²⁶ represents a TCO study that focused on the TCO of Class 8 tractors and Class 4 parcel delivery trucks.

²³ CalETC and ICF. (2019, December). Comparison of Medium- and Heavy-Duty Technologies in California. Retrieved from https://caletc.aodesignsolutions.com/assets/files/ICF-Truck-Report_Final_December-2019.pdf

²⁴ CARB. (2019, February 22). Appendix H Draft Advanced Clean Trucks Total Cost of Ownership Discussion Document. Retrieved from <https://ww2.arb.ca.gov/sites/default/files/barcu/regact/2019/act2019/apph.pdf>

²⁵ California Air Resources Board. (2021, September 9). Draft Advanced Clean Fleets Total Cost of Ownership Discussion Document. Retrieved from https://ww2.arb.ca.gov/sites/default/files/2021-08/210909costdoc_ADA.pdf

²⁶ NREL. (2021, September). Spatial and Temporal Analysis of the Total Cost of Ownership for Class 8 Tractors and Class 4 Parcel Delivery Trucks. Retrieved from <https://www.nrel.gov/docs/fy21osti/71796.pdf>

Table 6. TCO Study Assumptions Summary based on a Class 8 Short-Haul Truck

Source	TCO Assumption	Diesel	NG	BEV	FCEV
Purchase Price	CALETC (2030 MY)	\$118,000	\$133,00	\$147,000	\$137,000
	ACT (2030 MY)	\$183,053	-	\$244,194	\$284,462
	ACF (2030 MY)	\$212,726	\$281,425	\$250,214	\$269,924
	NREL (2025 MY) ²⁷	\$163,000	\$155,000	\$223,000	\$214,000
Maintenance (\$/mi)	CALETC	\$0.19	\$0.19	\$0.17	\$0.17
	ACT	\$0.19	-	\$0.14	\$0.19
	ACF	\$0.198	\$0.198	\$0.149	\$0.149
	NREL	\$0.152	\$0.151	\$0.098	\$0.153
Infrastructure Costs ²⁸	CALETC	\$2,538	\$31,948	\$25,034	\$128,199
	ACT	\$0	-	\$68,698	\$0 ²⁹
	ACF	-	\$45,309	\$184,633	-
	NREL	-	-	-	-
Discount Rate	CALETC	5%			
	ACT	5%			
	ACF	Uses 2020 constant dollars and does not use discount rates.			
	NREL	7%			
Annual VMT (mi/year)	CALETC	50,000			
	ACT	54,000			
	ACF	50,000			
	NREL	60,000			

²⁷ Modeling assumed single shift and volume limited, which assumes no dwell time cost incurred nor are no payload capacity cost incurred

²⁸ Note that infrastructure costs can vary significantly project by project depending on charging and fueling needs and other factors. Data regarding infrastructure costs are expected to be published in future reports produced by utilities per California Senate Bill 350 requirements as transportation electrification projects are completed and data becomes available.

²⁹ Hydrogen stations were assumed to be available at strategic locations around ports or major distribution hubs where the infrastructure costs are included in the hydrogen fuel price rather than reflecting costs for stations installed in a depot.

Figure 88 provides a graphical representation of three of the four studies but leaves out NREL since exact dollar amounts were not given. These studies generally found that, despite higher vehicle capital, battery electric and natural gas vehicles to be less costly compared to diesel in the immediate timeframe due to regulations, incentives and subsidies, with continued TCO improvements for subsequent model years. Hydrogen trucks tend to cost more in the immediate, short- and medium-timeframes. CALETC/ICFs analysis showed a significant TCO reduction for both battery electric model years (2019 & 2030) compared to a diesel and natural gas truck. Hydrogen trucks, however, remained more expensive than diesel trucks for the duration of the study. CARBs ACT analysis showed similar results to CALETC, with battery electric trucks having a more favorable TCO for model years 2024 and 2030; hydrogen trucks remained more expensive for both model years. Results for CARBs ACF found battery electric and hydrogen trucks to be less expensive over their lifecycle for all model years (2025, 2030, and 2035) compared to diesel. We note that although the ACT and ACF analyses were developed by CARB, their results were different – particularly for FCETs. Changes in TCO assumptions, which can likely be due to there being a two-year gap between the analyses, included a difference in the initial purchase price, slightly different fuel efficiency assumptions, as well as slightly different VMT assumptions. NRELs analysis was conducted for 2018, 2025, and 2050 and found battery electric trucks to be less expensive across its lifecycle in two of the four scenarios (see scenario descriptions in section 4.1.4), while hydrogen vehicles tended to cost less only in the 2050 timeframe. The following sections will describe each TCO analysis in detail, illustrating how critical assumptions can impact the results.

Figure 8. Reviewed TCO Analysis Results



4.1.1 Advanced Clean Trucks Total Cost of Ownership Discussion Document

As part of the Advanced Clean Trucks regulation, CARB conducted a TCO assessment of Class 8 Day Cab Tractors. The aim of the report was to assess the cost competitiveness of zero emission

powertrain technologies versus a comparable diesel truck. Specifically, the TCO evaluated battery electric and hydrogen fuel cell electric Day Cab's for model years 2018, 2024, and 2030. Unlike CALETC's TCO, CARB sought to assess the affordability of zero-emission trucks without vouchers, rebates, or grants. Although, Low Carbon Fuel Standard (LCFS) revenue could be considered as a form of incentive, CARB included in the TCO analysis with the notion that it is part of a regulation to increase the use of low carbon transportation fuels in California. CARB staff assumed an LCFS credit price of \$125 based on the 2018 rulemaking. The ACT study does not include infrastructure costs separately for hydrogen and instead accounted for that in the cost of hydrogen fuel. Diesel vehicles are assumed to use existing retail refueling stations, and battery electric vehicle charging infrastructure is taken from battery-electric bus data from the Innovative Clean Transit (ICT) rulemaking documents.

Diesel truck prices follow a similar price trajectory as the previous studies, with 2030 prices being roughly 10 percent more expensive compared to 2018 model years. 2030 battery electric trucks experience almost a 60 percent reduction in purchase price compared to 2018, while hydrogen trucks experience 64 percent reduction from 2018 to 2030 (

Table 7).

Table 7. Purchase Price for a Day Cab Tractor

Fuel Type	Diesel	Battery Electric	Hydrogen Fuel Cell
2018	\$134,000	\$474,930	\$629,189
2024	\$144,101	\$232,155	\$431,480
2030	\$146,442	\$195,960	\$227,570

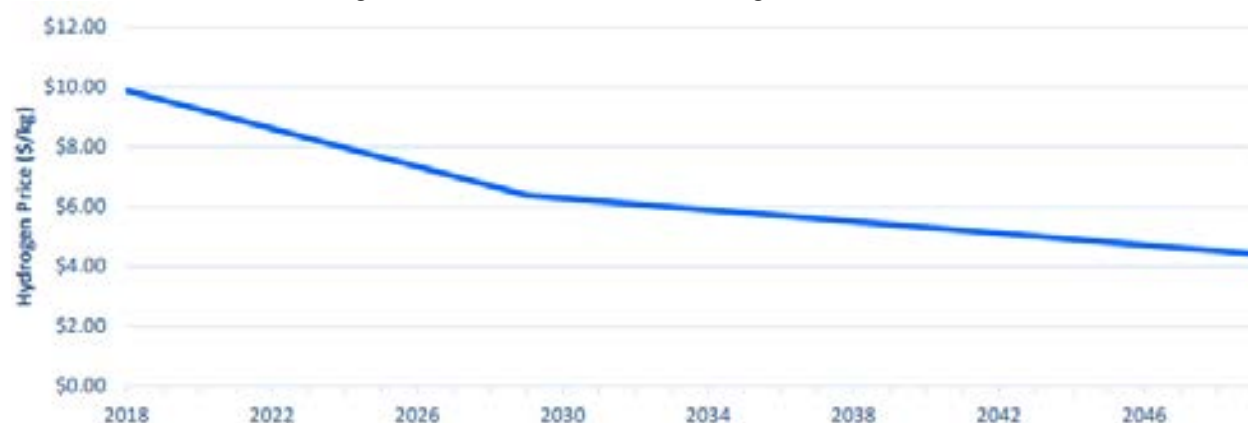
For maintenance costs, a diesel Day Cab tractor was used as a reference, where hydrogen fuel cell trucks were assumed to incur the same cost per mile, and battery electric trucks experience a 25 percent reduction (Table 8).

Table 8. Maintenance Cost Assumptions for a Tractor

Fuel Type	Regional Tractor
Diesel	\$0.19/mi
Battery-electric	25% lower than diesel
Hydrogen Fuel Cell	Equivalent to diesel

For this analysis, CARB assumed that hydrogen fueling infrastructure would be either publicly available around ports or at major distribution centers. Thus, the cost of stations would be represented in the cost of hydrogen fuel. To estimate the cost of hydrogen fuel overtime, CARB relied on industry information on current and future production volumes. CARB assumed that cost remains high in early years (i.e., 2018 for the time the analysis was conducted) due to low production volumes; in 2030, it is assumed that cost will fall as intermediate production volumes are achieved, and gradual cost reductions will continue through 2050 (Figure 9).

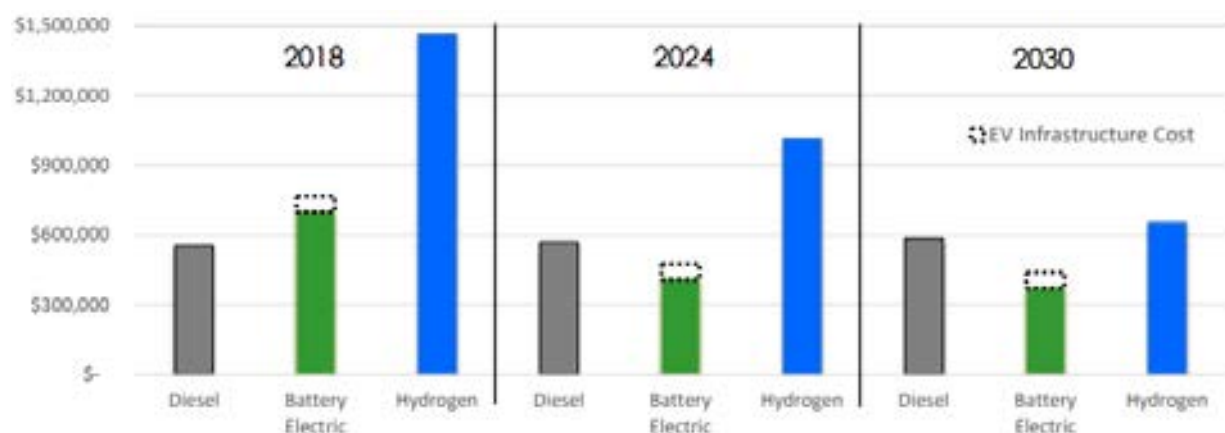
Figure 9. Estimated Cost of Hydrogen Over Time



TCO results were favorable for battery electric trucks for model years 2024 and 2030 but remained more expensive in 2018. Hydrogen fuel cell trucks remain more expensive than diesel trucks for the

duration of the study, although significant cost reductions for the 2030 model year almost closed the cost gap.

Figure 10. Day Cab Tractor Total Cost of Ownership Comparison



4.1.2 Draft Advanced Clean Fleets Total Cost of Ownership Discussion Document

As part of the Advanced Clean Fleets proposal, the California Air Resources Board conducted a comprehensive assessment comparing TCOs associated with diesel, natural gas, FCEV, and BEV heavy-duty trucks. TCOs were analyzed for 2025, 2030, and 2035.³⁰ The analysis assumes that Class 8 Heavy-duty trucks have a useful life of 12 years and 800,000 miles. Diesel vehicle prices are projected to increase moderately for all Class 8 duty cycles through 2030, while natural gas vehicle price remains steady for all model years. Battery electric and hydrogen fuel cell vehicles decrease in price for each model year but remain marginally more expensive than diesel for 2035 model years (

³⁰ No 2025 analysis is included for sleeper cab tractors since they do not face a requirement in the current Advanced Clean Fleets proposal until 2030.

Table 9). Note that this TCO does not include rebates, incentives, or grants in order to show the cost across powertrains without the impacts of subsidies.

Table 9. Initial Purchase Price forecast by Model Year

	Class 8 Duty-Cycle ³¹	Diesel	Natural Gas	Battery Electric	Fuel Cell Electric
MY 2025	Day Cab	\$143,862	\$195,607	\$201,999	\$212,353
	Sleeper Cab	\$153,862	\$240,607	\$304,629	\$251,403
MY 2030	Day Cab	\$149,865	\$198,263	\$176,028	\$190,155
	Sleeper Cab	\$159,865	\$243,263	\$247,638	\$226,272
MY 2035	Day Cab	\$150,920	\$198,457	\$176,028	\$190,155
	Sleeper Cab	\$160,920	\$243,457	\$247,638	\$226,272

For this analysis it is assumed that diesel and natural gas trucks have the same maintenance costs per mile. Battery electric and hydrogen trucks are also assumed to have the same maintenance costs per mile. Sleeper cab are assumed to have lower maintenance costs due to higher VMT (Table 10).

Table 10. Vehicle Maintenance Costs per Mile

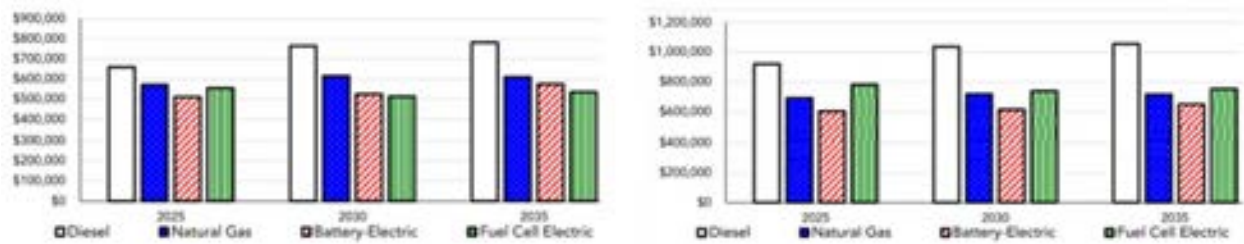
Class 8 Duty-Cycle	Diesel	Natural Gas	Battery Electric	Fuel Cell Electric
Day Cab	\$0.198	\$0.198	\$0.149	\$0.149
Sleeper Cab	\$0.159	\$0.159	\$0.119	\$0.119

An important distinction with this TCO analysis is that it assumes diesel and hydrogen vehicles are either using existing infrastructure or publicly accessible stations, therefore separate infrastructure costs are not included in the TCO. For battery-electric and natural gas vehicles infrastructure upgrades will normally be required and is included in the TCO calculation.

The TCO results for a Day Cab tractor with a short haul travel pattern show all non-diesel powertrains are cheaper across their useful life (12 years and 800,000 miles) for the three model years modeled (Figure 11). Refuse tractors showed similar results as the Day Cab Tractor. Battery Electric Refuse Tractors had the cheapest TCOs among the four powertrains.

³¹ Day Cab trucks are designed for short-haul duty-cycles; Sleeper Cab trucks for long-haul duty-cycles.

Figure 11 Total Cost of Ownership Estimates for Day Cab (Left) and Refuse (Right) Trucks



4.1.3 CALETC

CALETC's total cost of ownership analysis looked at the cumulative cost for the first owner of Class 2b through 8 vehicles. TCO results were conducted for diesel, natural gas, battery electric, and hydrogen vehicles for 2019 and 2030 model years. For the purposes of this report, we only show TCO results for Class 8 vehicles, specifically short-haul and long-haul. The CALETC report assessed the total cost of ownership for two Class 8 trucks: a short-haul BEV with an assumed energy storage of 250 kWh and a long-haul BEV with 500 kWh of energy storage.³² Table 11 shows initial purchase price assumptions for 2019 and 2030 model years.

Table 11. 2019 and 2030 Model Year Initial Purchase Price Assumptions in 2019\$³³

Class 8 Duty Cycle	Year	Diesel	Natural Gas	Electric	Hydrogen
Class 8 Short-Haul	2019	\$110,000	\$140,000	\$250,000	\$400,000
	2030	\$118,000	\$147,000	\$133,000	\$137,000
Class 8 Long-Haul	2019	\$160,000	\$190,000	\$375,000	\$480,000
	2030	\$172,000	\$200,000	\$191,000	\$197,000

Vehicle prices for diesel and natural gas powertrains were taken from CECs Revised Transportation Energy Demand Forecast 2018–2030 and outside literature. The analysis assumed that all natural gas engines will transition to low-NOx engines for 2030. ICF estimated the residual value to be 40% of the initial purchase price for diesel and natural gas vehicles based on conversations with OEMs. Future Class 8 electric vehicle prices were calculated by separating the battery and balance of truck price and applying a separate cost reduction curve to each portion of the truck. A Bloomberg New Energy Finance (BNEF) battery pack price of \$375/kWh was applied to 2019 electric trucks. ICF applied the BNEF price curves to the current estimated truck battery pack price of \$375/kWh which predicted a 58% price reduction from 2019 to 2030 in constant dollars. The results of the cost analysis projected price decreases between 35 percent and 40 percent for electric trucks in 2030. Lastly, hydrogen truck

³² Importantly, feedback from the Port of Long Beach indicates that these battery sizes may be low. In its feedback, the Port of Long Beach reported that, in its feasibility assessment for zero emission drayage trucks, it considered a short haul battery electric drayage truck with a 475 kWh battery.

³³ Importantly, feedback from South Coast Air Quality Management District indicates that the 2019 prices reported in the CalETC report cited here are likely lower than actual vehicle prices.

prices were calculated by assuming hydrogen trucks have the same relative price to electric trucks as hydrogen buses to electric buses.

The TCO analysis also considered current financial incentive programs including the Hybrid and Zero-Emission Truck and Bus Voucher Incentive Project (HVIP), the Low Carbon Fuel Standard (LCFS), and California investor-owned utility (IOU) programs for charging infrastructure. These programs can significantly impact TCO by decreasing the initial purchase price of a vehicle and decreasing capital costs for charging infrastructure. The CALETC report projects that incentives will provide considerable cost savings for the 2019 model year but offer minor cost savings for the 2030 model year (Table 12).

Table 12. 2018–2019 HVIP Truck Incentive Amounts (2019\$)

Vehicle Type	HVIP Voucher	Additional Disadvantaged Community Amount
Electric Class 8	\$150,000	\$15,000
Class 8 Hydrogen FCEV	\$300,000	\$15,000
Natural Gas – 11.9L	\$45,000	–

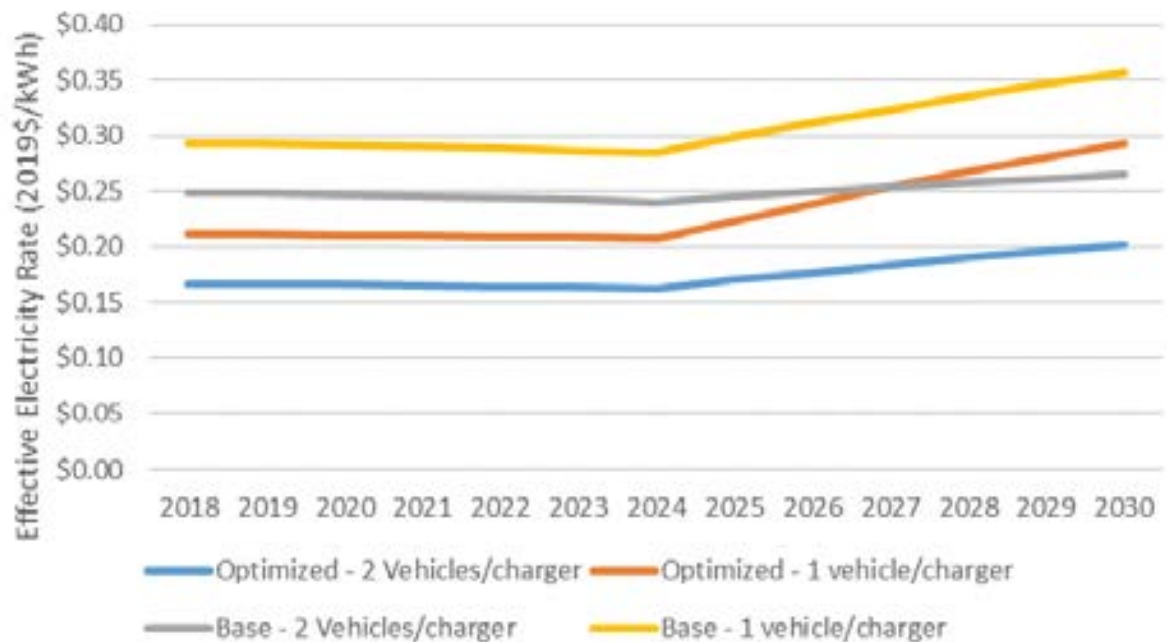
For maintenance costs, ICF applied data from Argonne National Laboratory’s Alternative Fuel Life-Cycle Environmental and Economic Transportation (AFLEET) tool for 2019 (Table 13). For 2030, O&M costs were reduced by 50% for electric trucks based on communication with OEMs.

Table 13. Vehicle Maintenance Cost (2019\$/mi)

Vehicle Type	Diesel	Natural Gas	Electric	Hydrogen
Class 8 SH & Tractor	0.19	0.19	0.17	0.17
Class 8 Refuse	2.89	2.91	2.83	–
Class 8 Drayage	0.20	0.22	0.17	0.17

In order to develop an electricity rate for the TCO study, a weighted average based on existing and upcoming EV rate structures, and different charging regimes was conducted. Load profiles were developed to account for average daily electricity consumption, charger load, and off-peak charging opportunities (Figure 12). Considering the cost reductions for fleet operators by charging during low- or off-peak periods, ICF assumed electricity costs would not reflect a large degree of on-peak charging.

Figure 12. Effective California Average Electricity Rate Comparison



BEV infrastructure and installation costs that were used in the TCO analysis were based on data gathered from CARB's Innovative Clean Transit (ICT) rulemaking,³⁴ CARB's ACT rulemaking, and filings in the California Public Utility Commission's SB 350 proceedings.³⁵ Table 14 shows station costs and annual operation and maintenance costs for a range of power levels including 19 kW, 40 kW, 100 kW, and 200 kW. Costs are reflective of behind the meter costs and do not include potential utility costs.

Table 14. Electric Charger and Installation Costs in 2019\$ with Estimated Charging Time for Reference

Charger Capacity	Charger Cost	Installation Cost ³⁶	Annual O&M	Approximate Charging Time (20–80%) assuming a 350-kWh BEV
19 kW	\$5,000	\$20,000	\$500	11 hours
40 kW	\$8,000	\$20,000	\$ 800	5 hours
100 kW	\$40,000	\$48,000	\$4,000	2 hours
200 kW	\$50,000	\$55,000	\$5,500	1 hour

³⁴ CARB. (2017). ICT Transit Fleet Cost Model. Retrieved from <https://ww2.arb.ca.gov/resources/documents/transit-fleet-cost-model>

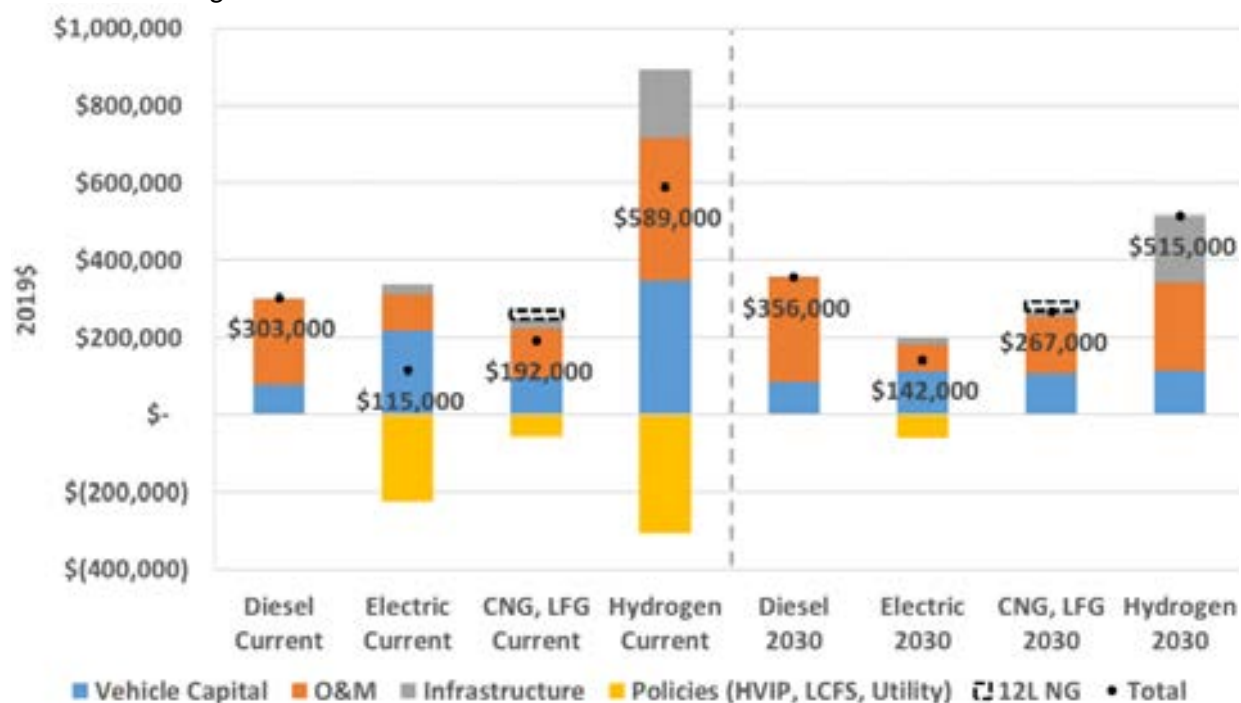
³⁵ CARB. (2019, April 18). California Air Resources Board Staff Current Assessment of the Technical Feasibility of Lower NOx Standards and Associated Test Procedures for 2022 and Subsequent Model Year Medium-Duty and Heavy-Du. Retrieved from https://ww2.arb.ca.gov/sites/default/files/classic/msprog/hdlnnox/white_paper_04182019a.pdf

³⁶ Although not explicitly shown here, per-charger installation costs can decrease when more than one charger is installed at once, due to economies of scale.

Figure 13 illustrates the results of the TCO analysis for Class 8 short-haul trucks. It shows positive improvements for all Class 8 battery electric and natural gas duty cycles in the mid- and intermediate timeframe. Hydrogen truck prices fall substantially for all duty cycles but tend to not reach price parity with diesel vehicles in the study timeframe.

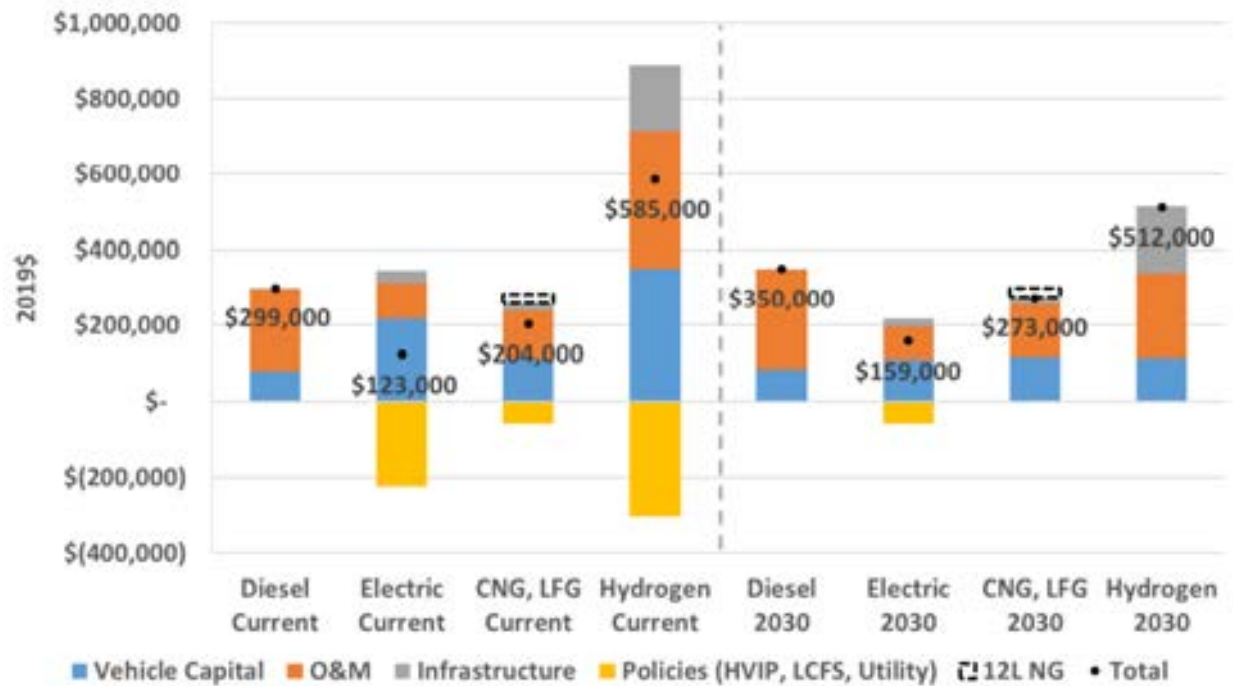
For a Class 8 short haul truck with an annual VMT of 50,000 miles per year and a first-owner life of seven years, the battery electric truck had a favorable TCO when including financial incentives and moderately more expensive when financial incentives are not accounted for. Hydrogen trucks were considerably more expensive in 2019. In 2030, the battery electric truck is projected to be considerably less expensive than the diesel truck, while hydrogen remains more expensive than diesel.

Figure 13. Class 8 Short Haul TCO Results (2019 and 2030 Model Year)



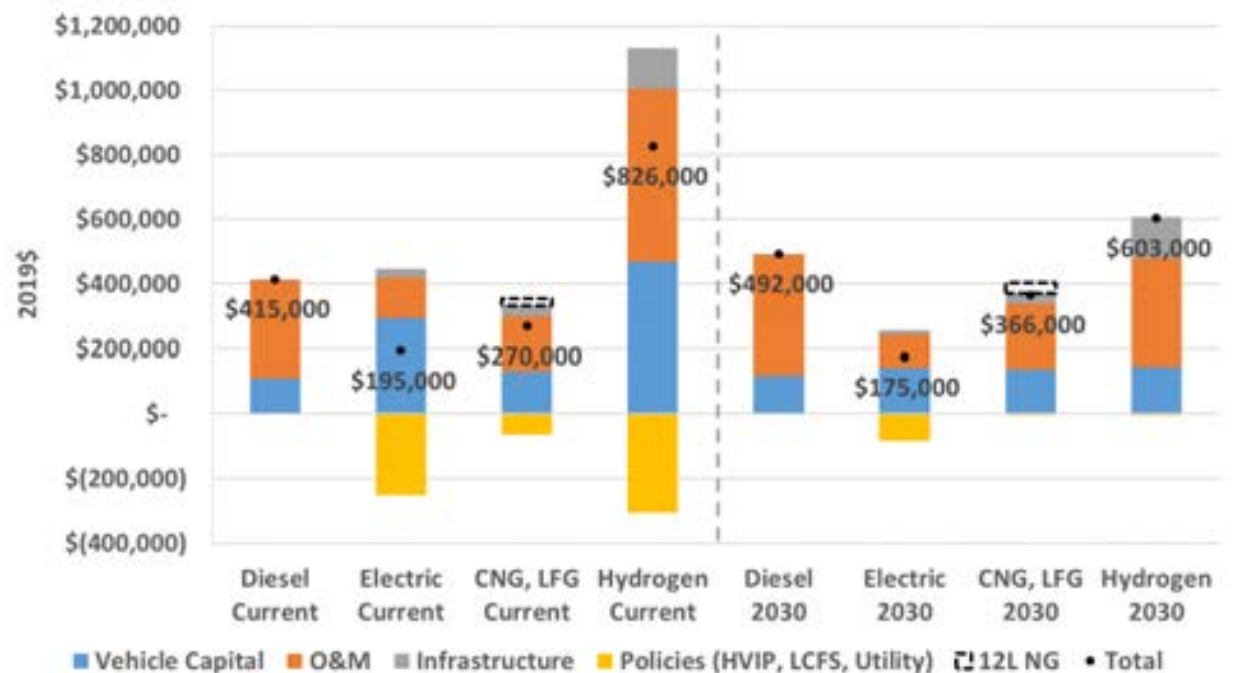
For a Class 8 drayage truck with an annual VMT of 45,000 miles per year and a first-owner life of twelve years (Figure 14), the battery electric truck was less expensive with the inclusion of incentive funding, while hydrogen is considerably more expensive compared to diesel trucks in 2019. In 2030, the electric truck is considerably less expensive than the diesel truck. Hydrogen does not reach price parity with diesel, but vehicle price falls substantially.

Figure 14. Class 8 Drayage TCO Results



For a Class 8 tractor with an annual VMT of 85,000 miles/year and a first-owner life of five years (Figure 15), the battery electric truck was cheaper, largely due to financial incentives, while hydrogen is considerably more expensive in 2019. In 2030, the electric truck is expected to remain less costly than the diesel truck even with the sunsetting of certain incentive programs.. Hydrogen Is not expected to reach price parity with diesel, but vehicle price is expected to fall substantially.

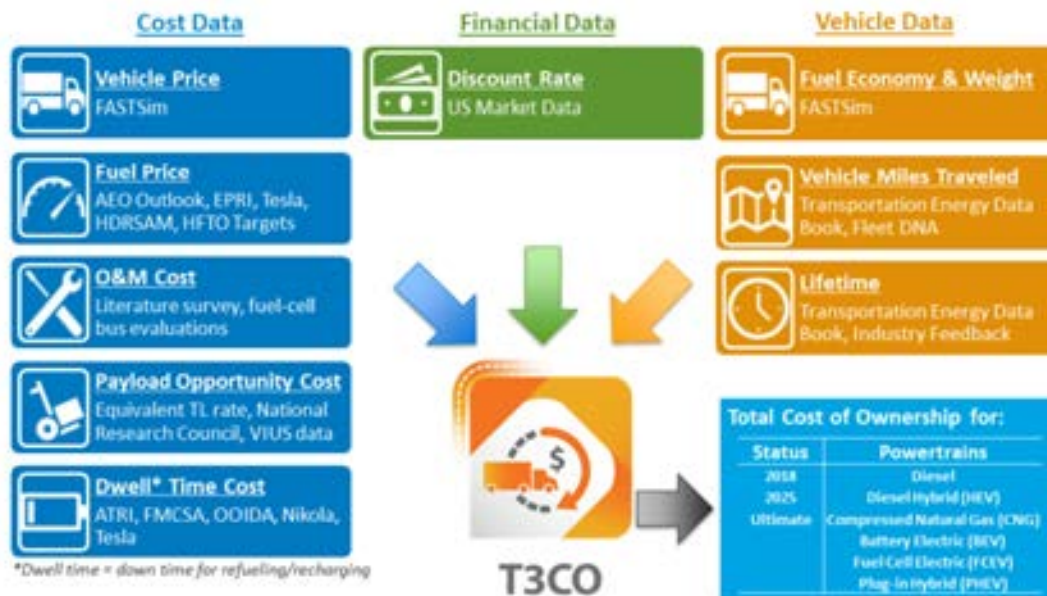
Figure 15. Class 8 Tractor TCO Results



4.1.4 National Renewable Energy Laboratory

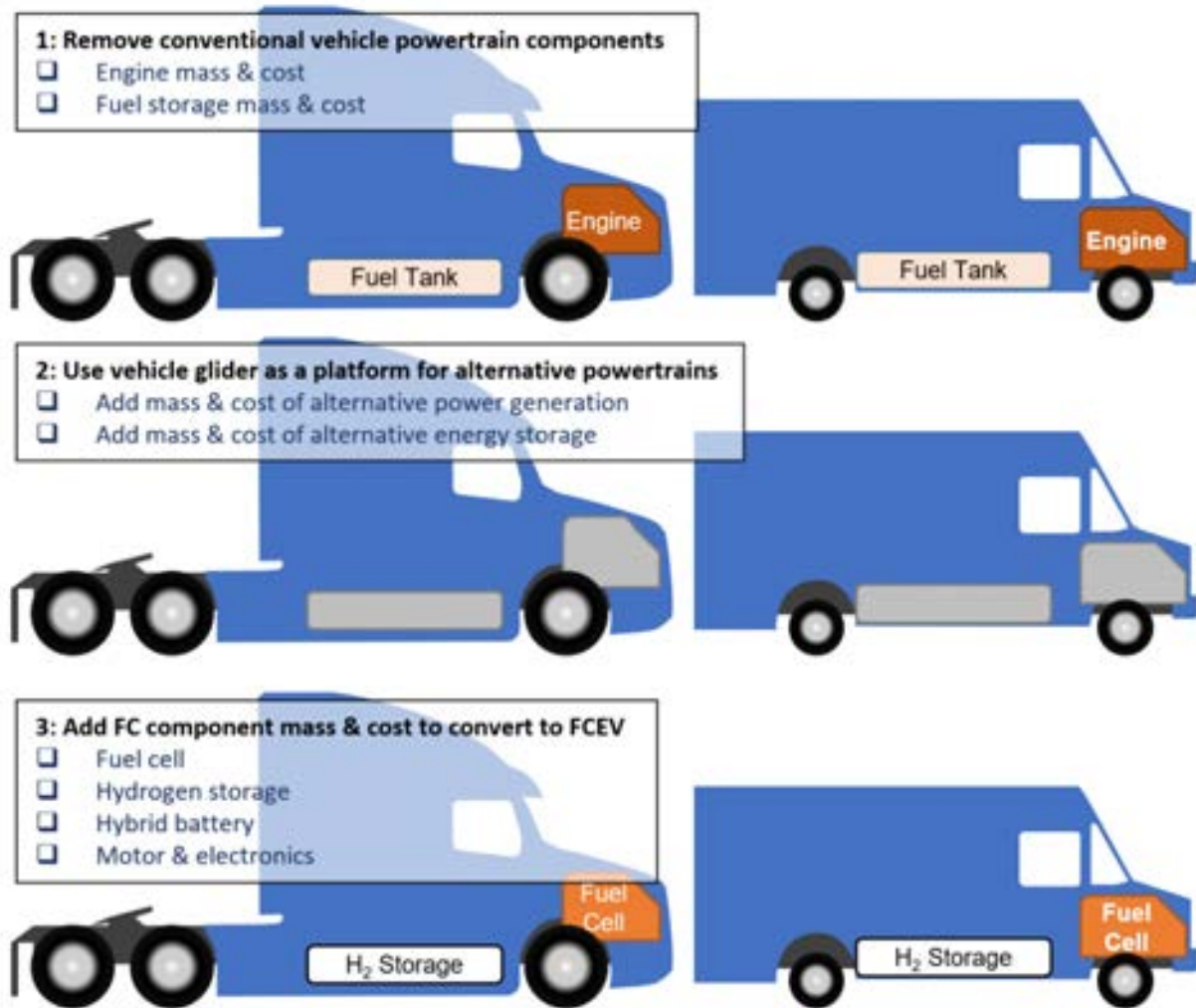
NREL utilized the Transportation Technology Total Cost of Ownership (T3CO) model, which integrates NREL's FASTSim and Scenario Evaluation and Regionalization Analysis (SERA) model into a TCO modeling framework which assumes a full vehicle lifetime. The model considers the combination of annual VMT (miles/year) and the powertrain's design mileage. It was assumed that a Class 8 tractor engine is designed for 1 million miles. The TCO results were for 2018, 2025, and 2050. It applies two discount rates 3% and 7 to discount the future costs back to present value 2021 dollars. NREL's TCO modeling data flow in the T3CO model is summarized in Figure 16.

Figure 16. Summary of the T3CO M/HDT stock model flow and output



Vehicle costs were estimated using the FASTSim model by modeling a conventional truck as the sum of the masses, performance, and cost of relevant components. For alternative powertrains, FASTSim strips the conventional vehicle leaving only the glider and matches the performance required depending on the duty cycle for battery electric, natural gas, or hydrogen vehicles. Vehicle estimation schematic using FASTSim Model is provided in Figure 17. Outputs from the model include vehicle designs with their respective upfront cost, performance, and weight.

Figure 17. FASTSim Model Vehicle Estimation Schematic



The O&M costs were gathered from external literature and were not assumed to decrease over time, but that the lower bound represents cost reductions due to technology improvements and more effective labor practices (Table 15).

Table 15. NREL Class 8 Tractor Maintenance Costs (\$/mile)

Vehicle	Bound	Diesel	Natural Gas	Battery Electric	Hydrogen
Class 8 Tractor	Low	\$0.075	\$0.064	\$0.060	\$0.060
	Mid	\$0.152	\$0.151	\$0.098	\$0.153
	High	\$0.301	\$0.298	\$0.143	\$0.349

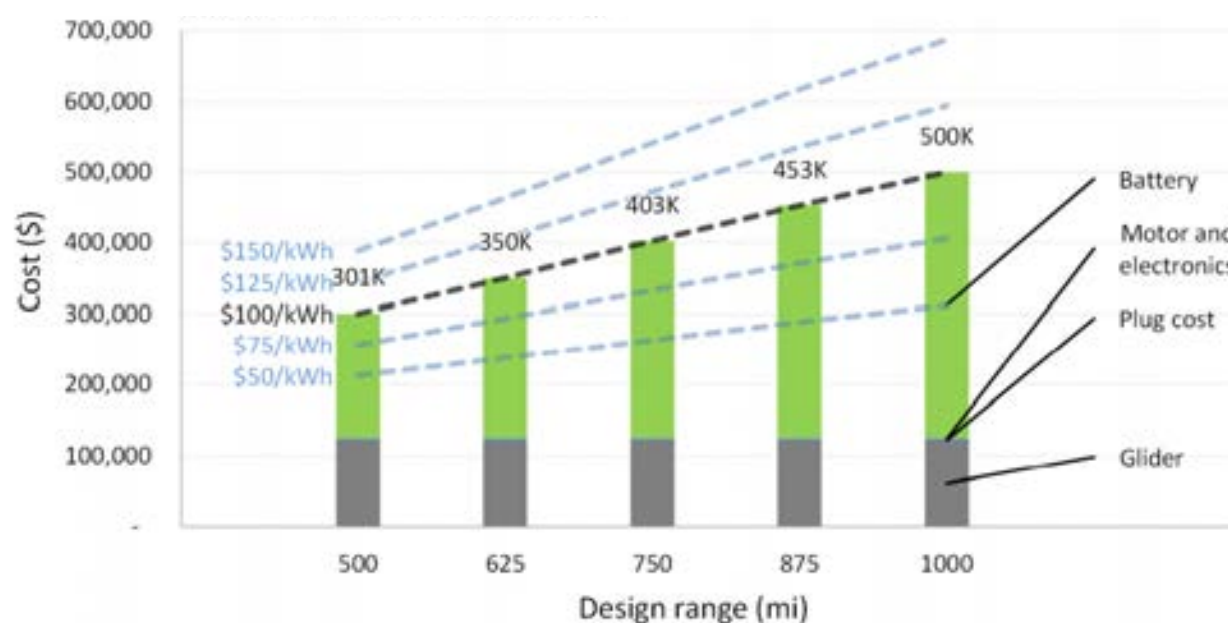
This analysis goes one step further and takes into account the costs associated with payload capacity and dwell time costs. The results found that all alternative powertrain technologies had favorable TCOs

depending on the business operating conditions and what the fuel price was. The business case for BEVs is better in relatively short-range applications when compared to FCEVs (which are best for long-haul). It should be noted that observation is relative, because as range increases, the opportunity for a BEV to generate savings on fuel and maintenance costs (measured per mile) increases. FCEVs tend to not become cost competitive with diesel trucks irrespective of dwell time and payload associated costs.

5 Outlook for BEV and Hydrogen Class 8 Trucks

Looking at the long-term timeframe, the market for zero-emissions Class 8 heavy-duty trucks appears to be growing with increases in model availability and with decreases in BEV Class 8 truck upfront costs largely coming from battery pack price reductions (Figure 18). In the immediate timeframe, the literature suggests that BEVs may result in lower TCO than diesel, natural gas, and FCEV trucks in certain applications.

Figure 18. Impact of battery cost on Class 8 BEV MSRP in 2025 frame³⁷



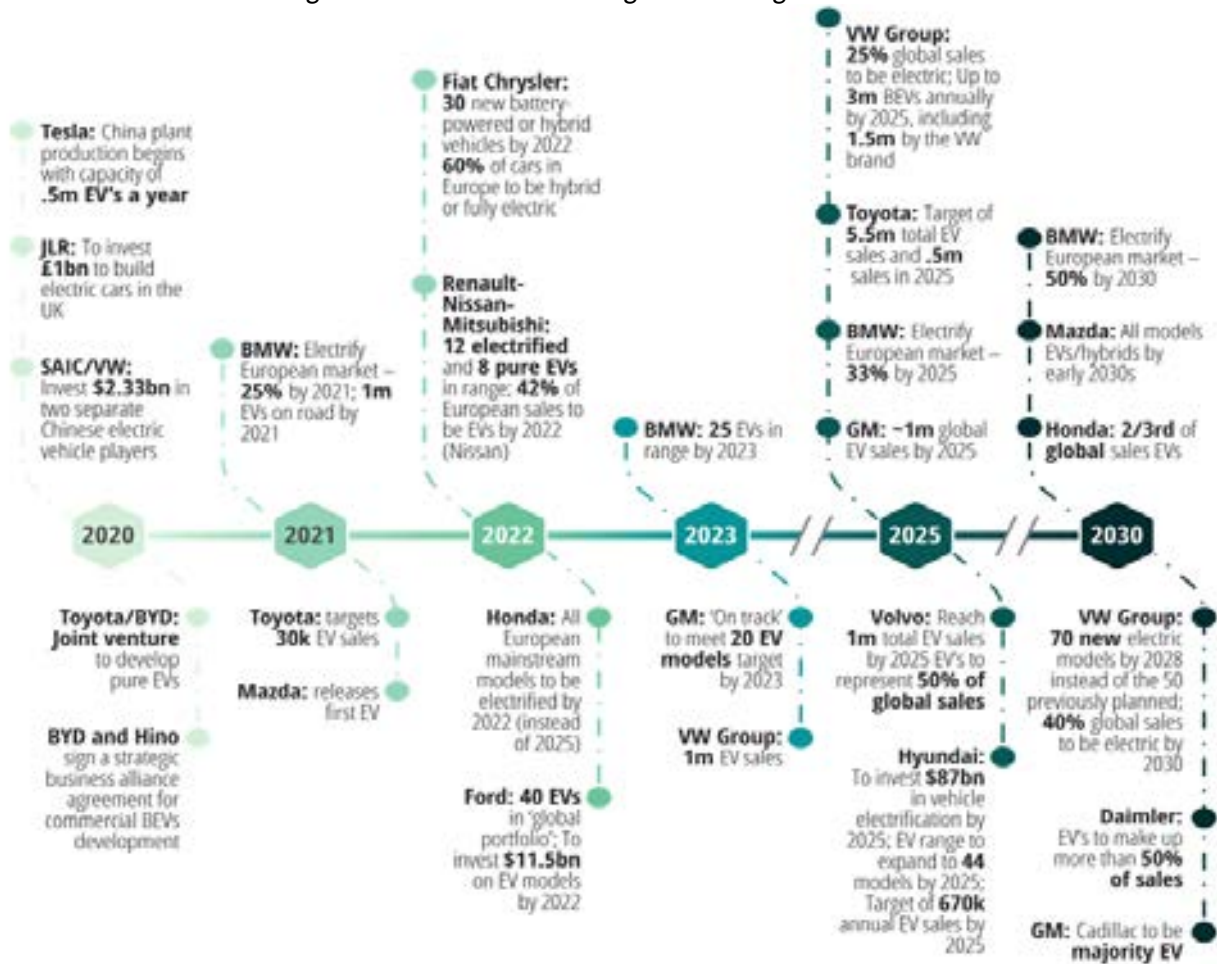
The outlook for zero emission trucks appears to be one of gradual market penetration in the long-term timeframe. Recently numerous battery electric truck manufacturers have announced Class 8 tractor models with ranges of 150–500. At the same time fuel cell electric truck manufacturers have announced ranges of 300–900 miles for hydrogen fuel cell models.

Hydrogen truck costs are expected to continue to fall as production—both of vehicles and fuel—increases. Due to their similar fueling patterns and range as diesel trucks, hydrogen is poised to replace diesel in long-haul duty cycles as costs continue to fall. The U.S. DOE’s Energy Earthshots Initiative has a target of reaching a price of clean hydrogen of \$1/kg by 2031.³⁸ Automotive original equipment manufacturers (OEM) are responding to this pending transition by accelerating EV targets, focusing largely on light-duty vehicles, but also medium- and heavy-duty models as outlined in Figure 19.

³⁷ NREL. (2021, September). Spatial and Temporal Analysis of the Total Cost of Ownership for Class 8 Tractors and Class 4 Parcel Delivery Trucks. Retrieved from <https://www.nrel.gov/docs/fy21osti/71796.pdf>

³⁸ U.S. DOE. (2021). Hydrogen Shot Overview. Retrieved from <https://www.energy.gov/eere/fuelcells/hydrogen-shot#:~:text=The%20first%20Energy%20Earthshot%2C%20launched.%22%201%201%2022%20>

Figure 19. Timeline of Strategic OEM Targets for EVs³⁹



³⁹ Deloitte. (2020, July 28). Electric vehicles Setting a course for 2030. Retrieved from <https://www2.deloitte.com/us/en/insights/focus/future-of-mobility/electric-vehicle-trends-2030.html>

6 Summary

This report summarizes the current and projected state of technology for alternative fuel Class 8 trucks. Innovations in conventional engine technologies, including low-NOx engines, are explored and the role these technologies may play in the transition of heavy-duty trucks in LA County is discussed. Also, increasing model offerings of hydrogen fuel cell electric and battery-electric trucks show promise as the industry begins to signal increasing interest in alternative fuel vehicles.

In addition to discussing vehicle technology readiness and availability, this report also includes a review of relevant literature on Class 8 truck costs. Four total cost of ownership (TCO) analyses were reviewed including those from CARB's ACF and ACT regulations, a CALETC report on heavy-duty vehicles in California, and from NREL. These TCO estimates shed light on the potential economics of alternative fuel trucks compared to conventional diesel trucks.

Key Takeaways

- Two significant regulations impacting Class 8 truck technology in California are already in place and proposed. These are expected to have substantial impacts on California emissions reduction efforts. The regulations include CARB's already-approved Advanced Clean Truck (ACT) regulation (2020), which requires medium- and heavy-duty vehicle manufacturers to sell zero emission trucks starting with model year 2024, and the proposed Advanced Clean Fleet (ACF) regulation. When adopted, the ACF regulation will require fleets operating in California to transition to zero emission technology vehicles between 2024 and 2042.
- Today, all new diesel engines sold across the U.S. must meet certain standards for NOx and PM emissions in compliance with regulations from California and the U.S. EPA.
- EPA's Renewable Fuel Standard and California's Low Carbon Fuel Standard Program are helping to increase the production of renewable diesel, as well as other alternative fuels. As we look into the future, however, new diesel vehicles sales are expected to significantly decrease in the next 15 – 20 years due to requirements in CARB's ACT and ACF regulations.
- When powered by renewable natural gas (RNG), natural gas-powered trucks can significantly reduce NOx and GHG emissions, and fully eliminate diesel PM. While promising as a means to reduce GHGs and eliminate diesel PM, the demand for RNG from sectors other than transportation, such as heavy industry and buildings, may present challenges. This competition poses uncertainty on RNG's availability and viability as a vehicle fuel in the immediate- and short-terms.
- The refueling process for hydrogen fuel cell trucks is similar to diesel trucks, and FCETs offer a few advantages over BEVs, including: fewer stops on long routes, faster refueling times, and potentially less risk for lost cargo capacity due to the weight of on-board energy storage (re: BET battery packs). However, hydrogen is relatively more expensive than electricity as a transportation fuel. These attributes make hydrogen FCETs a suitable option for heavier and longer range operations, as well as operations requiring fast refueling.
- The technological readiness of Class 8 battery-electric trucks varies depending on the vehicle's duty cycle, range requirements, and general applications. Long-haul BEV's tractors are still largely under development. However, shorter range trucks, such as drayage truck, have been developed and are commercially available. These types of operations are suitable candidates for early deployment of battery-electric Class 8 trucks because of shorter trips distances and more predictable routes. Over time, Class 8 truck models with longer range capabilities are expected to become commercially available.

- While the upfront purchase prices of battery electric and hydrogen Class 8 trucks are considerably higher than diesel and natural gas trucks, the potential for operating cost savings associated with these zero-emission trucks can lead them to have lower lifetime TCO compared to diesel and natural gas trucks, especially with the addition of incentive funding.

Appendix A: Vehicle Technology Costs by Fuel Type

Diesel

Table 16. Diesel Vehicle Purchase Prices – from AFLEET 2020, customized to Los Angeles, CA⁴⁰

Vehicle Type	AFLEET
Single-Unit Short Haul	\$70,000
Single-Unit Long-Haul	\$75,000
Combination Short-Haul	\$130,000
Combination Long-Haul	\$150,000

Table 17. Class 8 Diesel Truck Maintenance Cost⁴¹

Vehicle Type	Cost (\$/mi)	Data Source
Tractor	\$0.14	Fleet Advantage
Long-haul Freight	\$0.19	Argonne NL AFLEET 2019
Drayage	\$0.19	Bloomberg
Refuse	\$0.80	M.J. Bradley and Associates

Natural Gas

Table 18. Class 8 Natural Gas Vehicle (LNG) Purchase Prices – from AFLEET 2020, customized to Los Angeles, CA⁴²

Vehicle Type	Purchase Price
Refuse Truck	\$325,000
Single-Unit Short Haul	\$100,000
Single-Unit Long-Haul	\$105,000
Combination Short-Haul	\$160,000
Combination Long-Haul	\$200,000

Table 19. Class 8 Compressed Natural Gas Vehicle Purchase Prices – from AFLEET 2020, customized to Los Angeles, CA⁴³

Vehicle Type	Purchase Price
Refuse Truck	\$335,000
Single-Unit Short Haul	\$110,000
Single-Unit Long-Haul	\$115,000
Combination Short-Haul	\$170,000
Combination Long-Haul	\$215,000

Table 20. Natural Gas Station Costs⁴⁴

Station Capacity	Station Equipment Cost	Installation Cost
1 million DGE/year	\$1,000,000	\$1,000,000

⁴⁰ ANL. (2020). *Alternative Fuel Life-Cycle Environmental and Economic Transportation (AFLEET) Tool*. Retrieved from <https://greet.es.anl.gov/index.php?content=afleet>

⁴¹ California Air Resources Board. (2021, September 9). Draft Advanced Clean Fleets Total Cost of Ownership Discussion Document. Retrieved from https://ww2.arb.ca.gov/sites/default/files/2021-08/210909costdoc_ADA.pdf

⁴² ANL. (2020).

⁴³ ANL. (2020).

⁴⁴ ICF. (2019, December).

Battery Electric

Table 21. Estimated Heavy-Duty Electric Vehicle Purchase Prices⁴⁵

Vehicle Type	Low	Average	High
Yard Tractor	\$199,000	\$145,615	\$242,000
Bucket Truck	\$480,000	\$504,500	\$550,000
Truck Tractor	\$150,000	\$483,833	\$550,000
Refuse Truck	\$395,000	\$447,500	\$500,000
Straight Truck	\$226,445	\$335,921	\$400,000

Table 22. Heavy-Duty Electric Vehicle Maintenance Costs⁴⁶

Class	Battery Electric (\$/mile)	Diesel (\$/mile)	Savings per Mile
Class 8 Refuse Packer	\$0.708	\$0.943	\$0.235
Class 8 Day Cab	\$0.149	\$0.198	\$0.049
Class 8 Sleeper Cab	\$0.119	\$0.159	\$0.040

Table 23. Estimated Range of EVSE Hardware Costs

EVSE Type	Approximate Output Power Range (kW)	Low-Cost Estimate	Medium-Cost Estimate	High-Cost Estimate
Level 1	1 – 3	\$375	\$400	\$475
Level 2	3 – 20	\$575	\$4,000	\$8,500
DCFC	20 – 360+	\$12,500	\$50,000	\$130,000+ ⁴⁷

Based on:

- EVSE Retail Websites, such as clippercreek.com and smartchargeamerica.com
- A California Electric Transportation Coalition (CalETC) report titled “Comparison of Medium- and Heavy-Duty Technologies in California” prepared by ICF.⁴⁸
- A 2015 Report from the US DOE titled “Costs Associated with Non-Residential EVSE”⁴⁹
- A 2019 Report from the Rocky Mountain Institute titled “Reducing EV Charging Infrastructure Costs”⁵⁰
- A 2019 Report from the International Council on Clean Transportation (ICCT) titled “Estimating Electric Vehicle Charging Infrastructure Costs Across Major U.S. Metropolitan Areas”⁵¹

Table 24. Estimated Range of Per-EVSE Installation Costs⁵²

Station Type	Minimum Per Charger Cost	Average Per Charger Cost	Maximum Per Charger Cost
Level 1	\$0	\$1,500	\$3,000
Level 2	\$600	\$3,000	\$12,700
DCFC	\$4,000	\$21,000	\$51,000+

⁴⁵ ICF. (n.d.). EV Model Library. (Unpublished Proprietary Database)

⁴⁶ CARB. (2021, September).

⁴⁷ Costs above \$130,000 exist for DCFC, and Output Power Rating is not the only factor that determines EVSE hardware costs. For example, the FreeWire Boost Charger is a 150 kW charger with 160 kWh of integrated, on-board energy storage, and it is estimated to cost over \$210,000. See: <https://www.eclipsesolar.ca/store/FreeWire-Boost-Charger-p234250063>

⁴⁸ ICF. (December 2019).

⁴⁹ Smith, M., Castellano, J. (November 2015). *Costs Associated with Non-Residential Electric Vehicle Supply Equipment*. U.S. Department of Energy. https://afdc.energy.gov/files/u/publication/evse_cost_report_2015.pdf

⁵⁰ Nelder, C., Rogers, E. (2019). *Reducing EV Charging Infrastructure Costs*. Rocky Mountain Institute. <https://rmi.org/insight/reducing-ev-charging-infrastructure-costs/>

⁵¹ Nicholas, M. (August 2019). *Estimating Electric Vehicle Charging Infrastructure Costs Across Major U.S. Metropolitan Areas*. The International Council on Clean Transportation.

https://theicct.org/sites/default/files/publications/ICCT_EV_Charging_Cost_20190813.pdf

⁵² U.S. DOE VTO. (November 2015). *Costs Associated with Non-Residential Electric Vehicle Supply Equipment*. Retrieved from https://afdc.energy.gov/files/u/publication/evse_cost_report_2015.pdf.

Table 25. Electricity Rates

Utility	Rate Schedule	Eligibility
SCE ⁵³	TOU-EV-8	Is available for customers with charging demands above 20 to 500 kW
	TOU-EV-9	Is available for customers with charging demands exceeding 500 kW
LADWP ⁵⁴	TOU A-2B	Large Commercial and Multi-Family Service (4.8kV)
	TOU A-3	Large Commercial and Multi-Family Service (34.5 kV)

Hydrogen

Table 26. Estimated Average Hydrogen Fuel Cell Vehicle Purchase Price

Vehicle Class	Purchase Price (MY 2021)
Class 8 Truck (Tractor and Straight Truck)	\$560,000

Purchase price estimates shown in Table 26 were developed using multiple data sources, including the following:

- Price Digest⁵⁵
- Tag prices extracted from the California Department of Motor Vehicles Registration database
- A California Electric Transportation Coalition (CalETC) report titled “Comparison of Medium- and Heavy-Duty Technologies in California” prepared by ICF.⁵⁶ In this study, ICF conducted an extensive literature review of prices for various truck classes and fuel technologies.
- Vehicle price data embedded in Argonne National Laboratory’s Alternative Fuel Life-Cycle Environmental and Economic Transportation (AFLEET) tool⁵⁷
- Vehicle price determinations made under a project conducted by H-D Systems⁵⁸
- Data from California’s Hybrid and Zero-Emission Truck and Bus Voucher Incentive Project (HVIP)⁵⁹
- Other sources such as manufacturers’ websites, zero emission truck and bus deployment reports

Table 27. Hydrogen Fuel Cost Estimates^{60,61}

Trillium H2 Projections	Gaseous Delivery \$/kg (\$/GGE)	Liquid Delivery \$/kg (\$/GGE)	On-Site SMR \$/kg (\$/GGE)	On-Site Electrolysis \$/kg (\$/GGE)
Low Volume (150 kg/day)	\$11.49 (\$11.28)	\$10.21 (\$10.02)	\$10.43 (\$10.24)	\$11.05 (\$10.84)
Intermediate Volume (1,000 kg/day)	\$7.67 (\$7.53)	\$6.39 (\$6.27)	\$5.81 (\$5.70)	\$6.46 (\$6.34)
High Volume (6,000 kg/day)	\$5.72 (\$5.61)	\$4.43 (\$4.35)	\$4.21 (\$4.13)	\$4.90 (\$4.81)

⁵³ SCE. (n.d.). Business Rate Basics. Retrieved from <https://www.sce.com/evbusiness/sites/default/files/evcharging/TOU-EV-7%208%209%20Rate%20Fact%20Sheet%20WCAG.pdf>

⁵⁴ LADWP. (n.d.). Business Rate Basics. Retrieved from https://www.ladwp.com/ladwp/faces/wcnav_externalId/a-fr-er-stcommindrates?_adf.ctrl-state=a2ngmjowz_37&_afLoop=411447447178707&_afWindowMode=0&_afWindowId=kgImbbmiz_72#%40%3F_afWindowId%3DkgImbbmiz_72%26_afLoop%3D411447447178707%26_afWindowMode%3D0%26_adf.ctrl-state%3DkgImbbmiz_104

⁵⁵ PriceDigests. (n.d.). PriceDigests. In PriceDigests. Retrieved from <https://pricedigests.com/>

⁵⁶ ICF. (December 2019).

⁵⁷ Argonne National Laboratory. (n.d.). Alternative Fuel Life-Cycle Environmental and Economic Transportation (AFLEET) Tool. In Argonne National Laboratory. Retrieved from https://greet.es.anl.gov/afleet_tool

⁵⁸ H-D Systems. (2019, June 14). Vehicle Attribute Forecasts. In California Energy Commission. Retrieved from https://www.energy.ca.gov/sites/default/files/2019-12/2-Gopal%20Duleep_Vehicle%20Attribute%20Forecasts_ada.pdf

⁵⁹ California Air Resources Board. (n.d.). California HVIP. In California HVIP. Retrieved from <https://californiahvip.org/>

⁶⁰ CARB. (2020, December).

⁶¹ CARB’s document reported values in \$/kg. ICF converted \$/kg to \$/GGE using the following conversion factor per the US DOE: GGE = H₂ kg X 1.019. United States Department of Energy. (n.d.). Fuel Conversion Factors to Gasoline Gallon Equivalents. In United States Department of Energy. Retrieved from <https://epact.energy.gov/fuel-conversion-factors>

Table 28. Hydrogen Fuel Cell Maintenance Cost by Duty-Cycle⁶²

Class	Fuel Cell Electric (\$/mi)	Diesel (\$/mi)	Savings (\$/mi)
Class 8 Refuse Packer	\$0.708	\$0.943	\$0.235
Class 8 Day Cab	\$0.149	\$0.198	\$0.049
Class 8 Sleeper Cab	\$0.119	\$0.159	\$0.040

⁶² CARB. (2021, September).