CALIFORNIA
AIR RESOURCES BOARD

Advanced Clean Trucks
Total Cost of Ownership Discussion Document

Preliminary Draft for Comment

Last Updated: February 22, 2019

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Executive Summary

The zero-emission truck market is beginning to grow rapidly with dozens of models commercially available today and many major manufacturers announcing plans for future commercialization of battery-electric and hydrogen fuel cell electric trucks and buses. Zero-emission vehicles are the cleanest option available and are a key part of California's strategies of meeting sustainability goals, reducing dependence on petroleum, and reducing NOx and PM emissions. The early electric truck market can be accelerated putting vehicles into the right duty cycles, new infrastructure and maintenance support, and finding applications suitable for their use. This paper presents an initial assessment of the costs of owning and operating zero-emission vehicles that are commercially available today compared to similar conventional diesel vehicles and projects how these costs are expected to change in the next 5 to 10 years. The analysis is intended to provide insight into which truck types and markets in California are most likely to become competitive on their own without rebates or grants.

This report assesses the cost of battery-electric and hydrogen fuel cell vehicles versus an equivalent diesel vehicle on a total cost of ownership (TCO) basis in applications or use cases where they are suitable to meet the daily needs of a fleet owner. Three vehicles are modeled – a Class 3 passenger van, a Class 6 walk-in stepvan, and a Class 8 day cab tractor used in regional operation – and represent vehicle types that are commercially available or are in pre-commercial demonstrations. This report is an assessment of key cost components that differ significantly between technologies including the purchase cost of the vehicle, ongoing fueling and maintenance costs, Low Carbon Fuel Standard (LCFS) revenue, infrastructure, and other assorted vehicle operating costs. The analysis does not include any vouchers, rebates, or grants for zero-emission vehicles to show how the costs compare without subsidies. The LCFS credit is a form of incentive, but is a market based mechanism that is part of a regulation to increase the use of low carbon transportation fuels in California. Please provide any comments and suggestions on the methodology or data sources to Mr. Paul Arneja, Air Resources Engineer, at Paul.Arneja@arb.ca.gov.

This analysis indicates that a wide range of battery-electric trucks are already becoming competitive with diesel fueled vehicles in the right application and are expected to have a favorable comparison to diesel vehicles by 2024. The TCO for fuel cell electric vehicles has the potential to be comparable to diesel vehicle by 2030 for hydrogen produced at scale. The following figures show the total cost of ownership for the three vehicle types modelled in 2018, 2024, and 2030

Figure 1: Total cost of ownership comparison of a passenger van – 15,000 mi. x 12 years

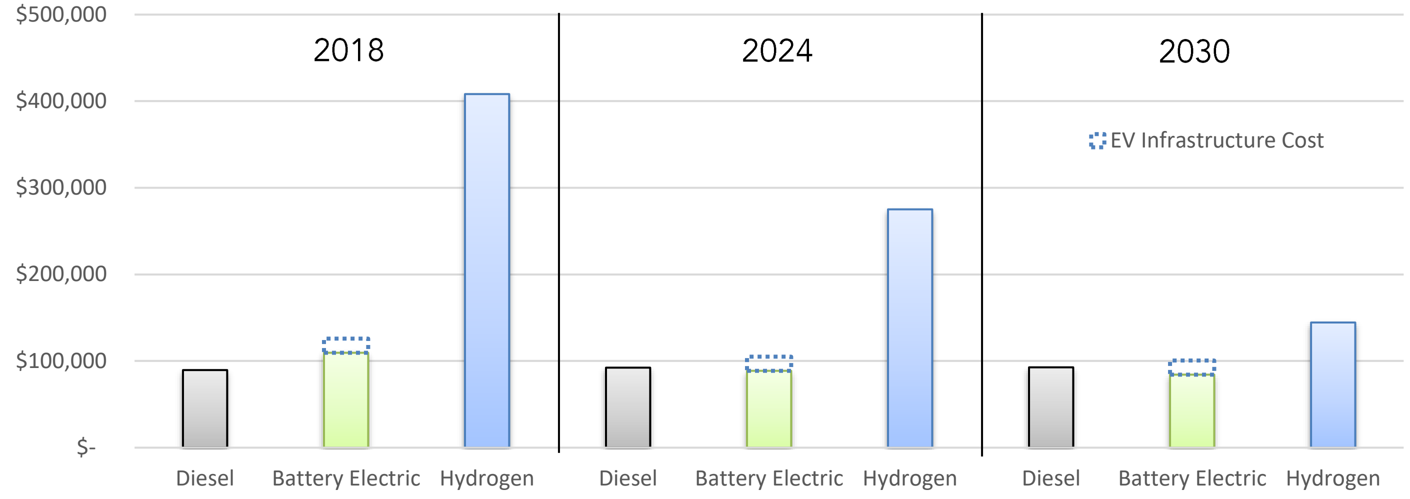


Figure 2: Total cost of ownership comparison of a walk-in stepvan – 24,000 mi. x 12 years

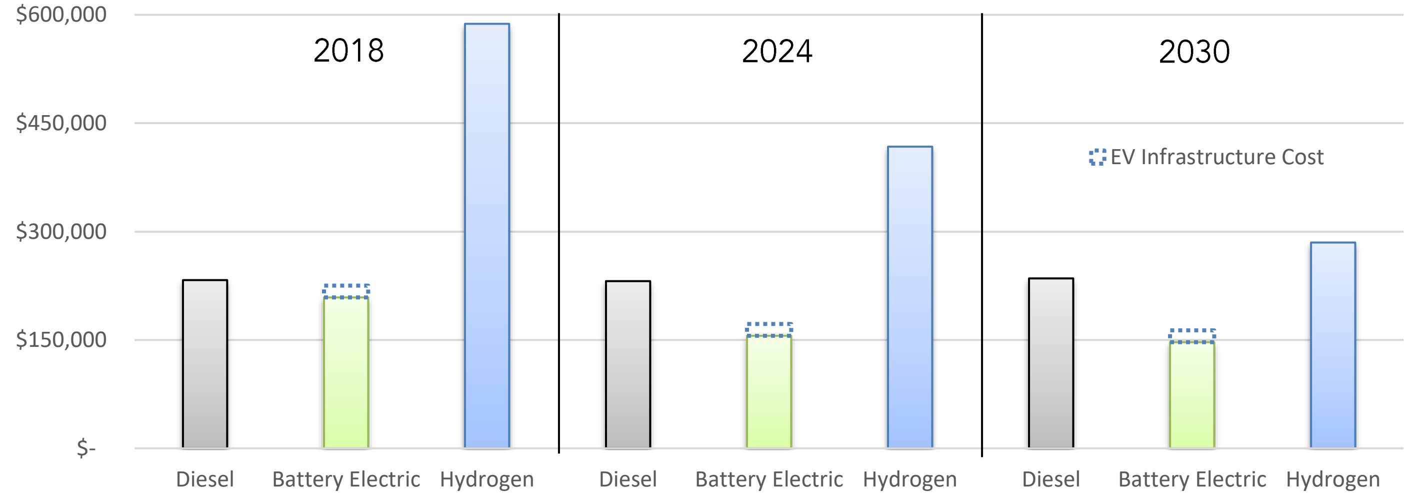
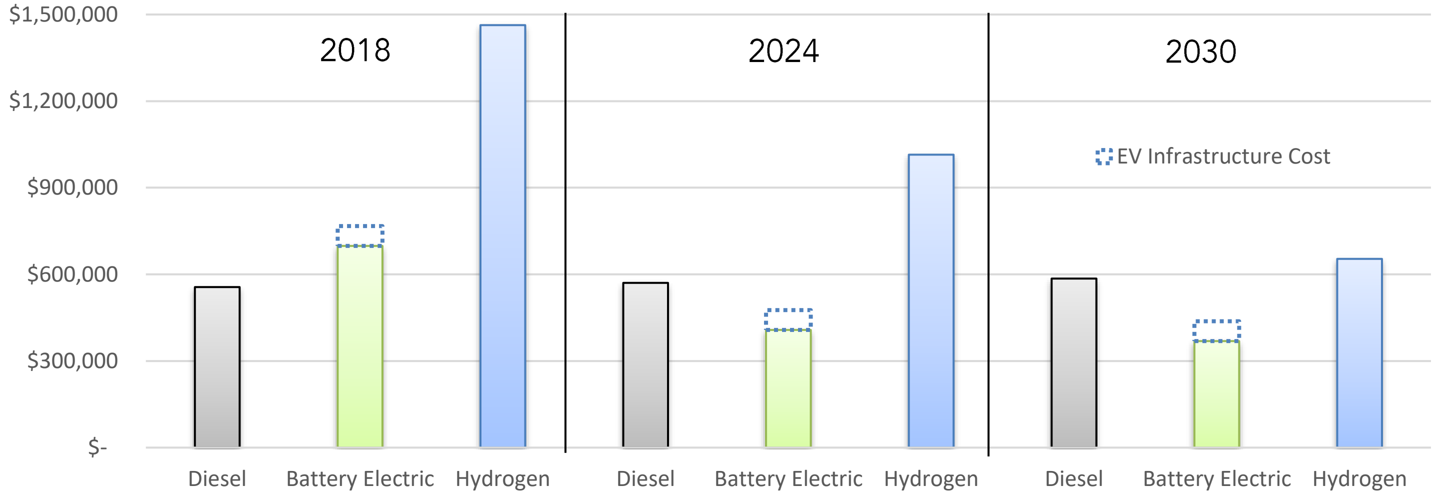


Figure 3: Total cost of ownership of a regional day cab tractor – 54,000 mi. x 12 years



Details on the assumptions and methodology used is described in further detail in this report. The key conclusions from this analysis suggests the following:

- Costs of batteries and fuel cell components are expected to decline substantially over the next decade and will bring down the incremental capital costs of zero-emission trucks and buses. This will improve their TCO compared to the diesel equivalent.
- Battery-electric trucks in a wide range of weight classes are likely to have a comparable TCO in local or regional applications around 2024.
- For the three vehicle types modelled, hydrogen fuel-cell technologies have the potential to approach TCO parity with diesel by 2030 assuming they have access to highly utilized stations. TCO parity will happen sooner if vehicle and fuel costs come down faster than assumed in this report.
- Electricity costs are dependent on how, when and where vehicles are charged with lower costs for charging overnight or morning during off-peak periods than fast charging during the day or during peak periods. Even including energy costs, demand fees, and fixed fees, electricity costs are expected to be lower on a per-mile basis than diesel in most cases.
- Credits from the LCFS program can eliminate or nearly eliminate electricity costs for battery electric vehicles that are charged overnight over extended periods in most utility service areas, and can still offset a substantial part of electricity costs for high power charging. Credits from the LCFS program can also reduce the estimated cost of dispensed hydrogen by 4 to 16 percent.
- Vehicle applications with lower diesel fuel economy due to stop and go driving or significant idle times and higher annual fuel usage are likely to have better operational cost savings opportunities than estimated in this analysis for battery-electric and fuel cell electric technology.
- Charging infrastructure costs will vary by fleet and application. For battery-electric vehicles, in many cases small vehicle deployments will not need site upgrades while deployments of 5 or more vehicles will likely require electrical service site upgrades. The upgrade costs will vary by site and charging solution needed by the fleet.

I. Introduction

Meeting California's criteria pollutant and greenhouse gas reduction goals will require emission reductions across all sectors. Widespread transportation electrification is a key part of the state's overall strategies – the Mobile Source Strategy, the State Implementation Plan, the 2030 Scoping Plan, and the Sustainable Freight Action Plan. The proposed Advanced Clean Truck regulation and fleet regulations are part of these plans and supports the state's electrification goals by accelerating the first wave of zero-emission trucks and fostering a self-sustaining market.

This report's purpose is to evaluate the total cost of ownership (TCO) of three technology options - diesel, battery-electric, and hydrogen fuel cell – to better understand the business cases for electrification of different truck types and uses. Today, there are funding programs in California that will offset incremental zero-emission vehicle costs, and will reduce infrastructure costs. As technology advances and the market matures, incremental costs are expected to decline. Manufacturers and fleets are more likely to pursue markets (trucks and applications) where the business case is most likely to become favorable without the need for incentives. Accelerating electrification in these early markets in California will result in local air quality benefits and GHG reductions.

Three representative vehicles have been selected to show cost scenarios across a variety of weight classes: a class 3 passenger van, a class 6 walk-in stepvan, and a class 8 day cab tractor used in regional service. These vehicles were selected because they are common vehicles in their weight class, zero-emission models are commercially available today, or because manufacturers have announced plans to commercialize them.

This report uses the TCO to compare costs between the three technology options at three different time periods: 2018, 2024, and 2030. The TCO is the discounted sum of all cash flows for a vehicle over its life. All values are shown using 2018 constant dollars meaning inflation is not modelled. All references for assumptions are listed in the paper or the appendix.

Note that this report only looks at the cost element of electrification; finding the right duty cycles for these vehicles and providing proper infrastructure support are separate discussion topics. This report does not look at catenary-electric systems or dynamic induction systems as the development of these technologies and infrastructure deployment place them beyond the timeframe of this report.

II. Vehicle Operation

Vehicle operations include the vehicle's annual mileage traveled as well as its expected lifetime. Higher distances travelled affects the capital cost by increasing battery or hydrogen storage requirements as well as creating opportunities for savings on fuel costs.

Operating years indicate a reasonable representation of how long the vehicle is expected to stay in use. This report assumes that a single fleet will own and operate a truck for a significant portion of its life and does not attempt to model fleets who replace trucks in 5 or less years as these tend to be high mileage operations that are not likely to be electrified for some time. For this report, an operating life of 12 years will be used. This represents a lower bound and reasonable estimate for how long a vehicle can be expected to operate – in reality, vehicles can last 20 or more years based on Department of Motor Vehicle (DMV) and EMFAC emission inventory survival rate data. Generally, the longer the timeframe used for this analysis, the better the TCO of the battery-electric vehicle due to their lower operating costs.

Table 1 shows the daily miles and operating years used in this report. These values are based CARB's EMFAC 2017 model which models the California vehicle inventory, activity, and associated emissions, as well as a CalHEAT study which broke the truck population into six main categories and estimated their annual vehicle miles traveled, fuel economy, and population.[1][2] These values are not reflective of any individual vehicle or fleet, but are a good estimate for that vehicle's typical duty cycle.

Table 1: Vehicle Operational Information

	Passenger Van	Stepvan	Regional Tractor
Daily Miles	50	80	180
Operating Days	300	300	300
Operating Years	12	12	12

III. Vehicle Purchase Price

This section covers the capital cost to for a fleet purchase the vehicle including taxes and financing costs. Today and for the foreseeable future, battery-electric and hydrogen vehicles cost more than their diesel equivalent. Declining battery and

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[1] California Air Resources Board, EMFAC 2017, 2017. https://www.arb.ca.gov/msei/categories.htm#emfac2017

[2] CalHEAT, CalHEAT Research and Market Transformation Roadmap for Medium- and Heavy-Duty Trucks, 2013. http://calstart.org/wp-content/uploads/2018/10/CalHEAT-Roadmap.pdf

component costs in addition to economies of scale are expected to lower the incremental costs of zero-emission vehicles as the market expands.

Vehicle price

Diesel vehicle prices are calculated using a 2018 diesel vehicle as a baseline and adding expected GHG Phase 2 compliance costs through 2030. Diesel vehicle prices today have been pulled from manufacturers' websites and other related websites. For battery-electric vehicles, we are able to look at the prices of vehicles available through HVIP and other programs today. But to estimate the cost of zero-emission vehicles in the future, both the battery-electric and fuel cell powered vehicle's costs are calculated by adding electric and fuel cell component costs and energy storage costs to a conventional glider vehicle. Numerous other studies in both light- and heavy-duty take a similar approach to modelling future costs of zero-emission vehicles. The price of the zero-emission vehicle is calculated by adding a 10% profit margin to the vehicle. This would result in higher profits for the manufacturer due to the higher vehicle cost.

The cost of battery storage is the biggest factor in how much a battery-electric truck costs. Battery pack costs have dropped nearly 80 percent since 2010 and are projected to continue declining. The CARB discussion document "Battery Cost for Heavy-Duty Vehicles" was a literature review published in 2016 using data sources from 2013 and 2014 to assess battery costs for buses and heavy duty vehicles.[3] Battery pack cost for heavy duty applications are higher than for light cars due to smaller volumes and differing packaging requirements even though many use the same cells. However, this report is somewhat dated and does not reflect the current state of the battery market. At the December 4th, 2018 Advanced Clean Trucks workgroup meeting, a number of manufacturers suggested we use light-duty battery prices with a five-year delay to reflect battery-price projections that are applicable to heavy duty vehicles.

Figure 4 displays various battery prices projections and the suggested 5-year light-duty delay. The 5-year delay of light duty battery pack prices is similar to projections made in the CARB discussion document for 2018 and becomes similarly to the fairly recent projection made by ICCT after 2020.

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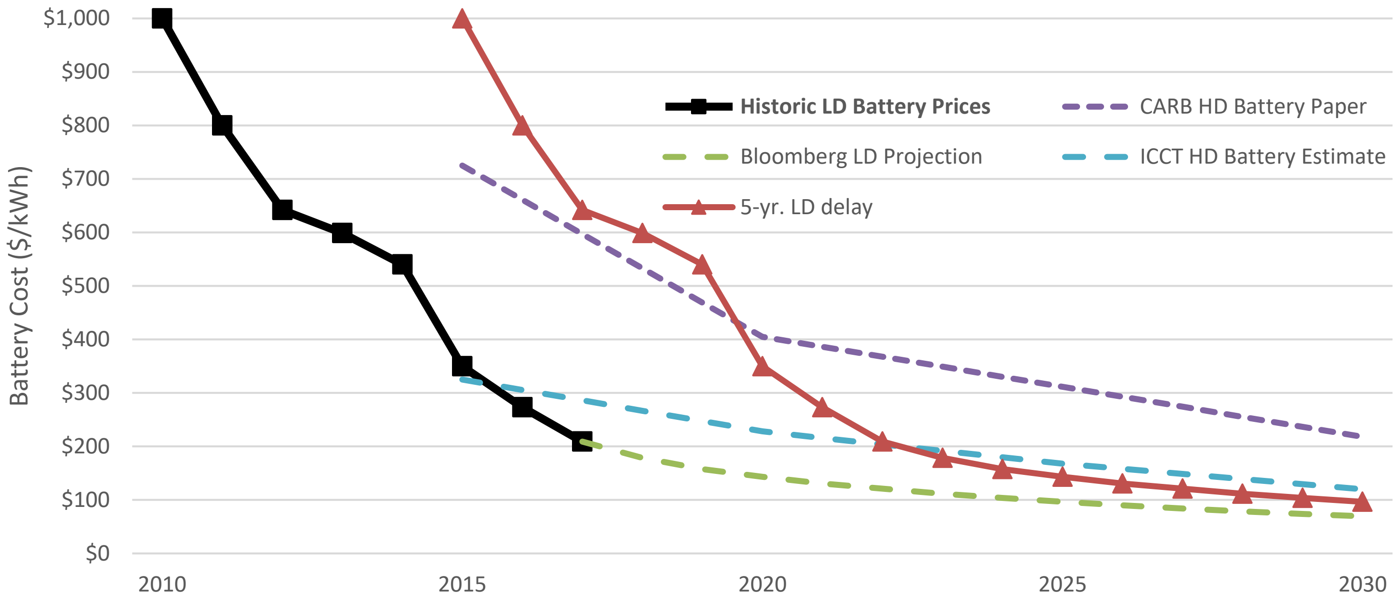
[3] California Air Resources Board, Battery Cost for Heavy-Duty Electric Vehicles, 2016. https://www.arb.ca.gov/msprog/bus/battery_cost.pdf

Figure 4: Battery price history and projections



The battery-electric vehicle costs in this analysis are calculated using electric vehicle component costs from the International Council on Clean Transportation whitepaper (ICCT), "Transitioning to Zero-Emission Heavy-Duty Freight Vehicles" and battery costs will use the Bloomberg light-duty battery prices with a five-year delay.[4][5] The ICCT whitepaper analyzed the feasibility of zero-emission technologies in the heavy-duty freight sector by looking at the technological feasibility and the total cost of ownership. This paper looked at battery-electric, catenary-electric, dynamic induction, and hydrogen fuel cell technologies through 2030.

Hydrogen fuel cell component costs are from an economic model by Ricardo called "Economic Models for Truck TCO and Hydrogen Refueling Stations".[6] This model estimated the cost of a hydrogen fuel cell tractor and walk-in stepvan in 2015 and 2030 based on a component-level analysis.

The battery-electric vehicle is modelled with using motors and electrical components in line with an existing diesel counterpart's power needs, and battery storage capacity based on the typical daily mileage, the fuel economy of the electric vehicle, and a 35% buffer to account for battery degradation and some operational variability.

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[4] International Council on Clean Transportation, Transitioning to Zero-Emission Heavy-Duty Freight Vehicles, 2017. https://www.theicct.org/sites/default/files/publications/Zero-emission-freight-trucks_ICCT-white-paper_26092017_vF.pdf

[5] Bloomberg, Better Batteries, 2019. https://www.bloomberg.com/quicktake/batteries

[6] Ricardo, Economic Models for Truck TCO and Hydrogen Refueling Stations, 2017.

The hydrogen fuel cell vehicle uses similar estimates for the motors and electrical components, but models the three types of vehicles slightly differently. For the passenger van and day cab tractor, the cost is modelled assuming the battery is 10 kWh and the fuel cell stack's power output is half the vehicle's peak power needs, while the stepvan is modelled with a 50 kWh battery and a fuel cell stack sized at a quarter of the vehicle's peak power needs. These assumptions are based on the specifications of hydrogen demonstration vehicles currently operating.

Based on the above information, we are using the following vehicle specifications for the zero-emission vehicles shown in Table 2.

Table 2: Specifications for zero-emission trucks

	Passenger Van	Delivery van	Regional tractor
Battery Size - BEV (kWh)	53	104	510
Battery Size – FC (kWh)	10	50	10
Fuel Cell Stack Size	80	60	175
Motor Size (kW)	160	240	350
Hydrogen Storage (kg)	10	20	40

The example shown in Figure 5 displays how the costs for diesel, battery-electric, and hydrogen fuel cell stepvans are projected to change over time. The final capital costs for all vehicles modeled are shown in Table 3 through Table 5. No incentives, rebates, or grants are assumed in these projections.

Figure 5: Stepvan Price over Time

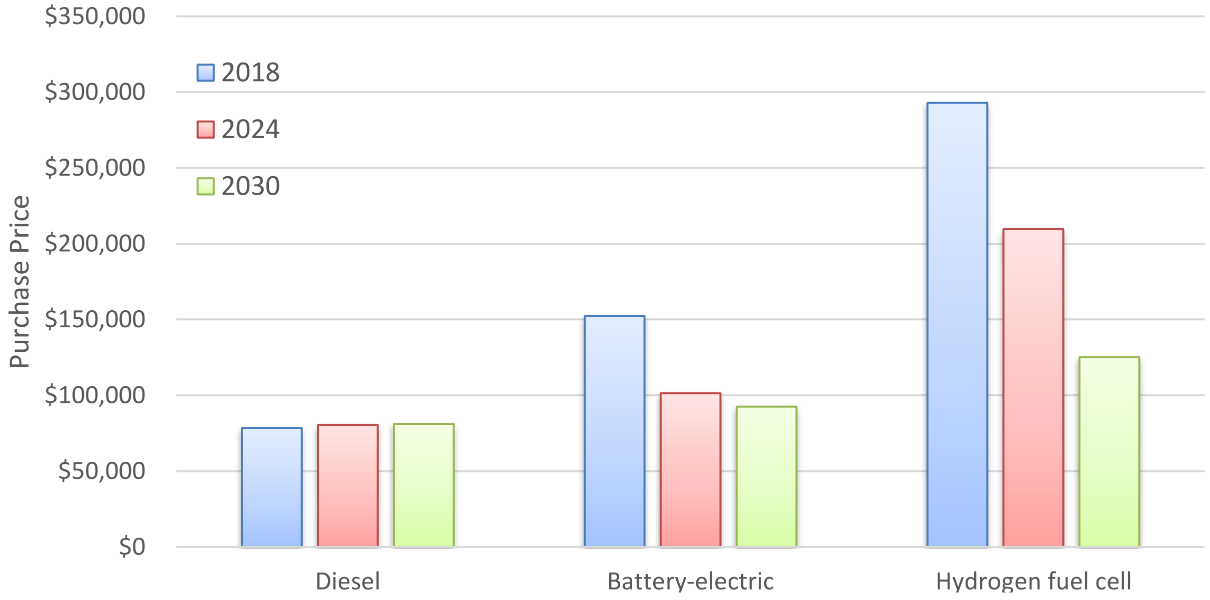


Table 3: Capital costs for a passenger van

Passenger Van	2018	2024	2030
Diesel	$47,000	$47,963	$48,364
Battery-electric	$76,609	$57,428	$53,654
Hydrogen fuel cell	$271,392	$178,664	$85,473

Table 4: Capital costs for a stepvan

Stepvan	2018	2024	2030
Diesel	$78,500	$80,522	$81,162
Battery-electric	$152,411	$101,336	$92,510
Hydrogen fuel cell	$292,892	$209,574	$125,116

Table 5: Capital costs for a tractor

Regional Tractor	2018	2024	2030
Diesel	$134,000	$144,101	$146,442
Battery-electric	$474,930	$232,155	$195,960
Hydrogen fuel cell	$629,189	$431,480	$227,570

Taxes

Taxes are additional costs levied on the purchase of a vehicle. Because they are based on the purchase price of the vehicle, they affect expensive vehicles more than cheaper vehicles.

Vehicles purchased in California must pay a sales tax on top of the vehicle's purchase price. The sales tax varies across the state from a minimum of 7.25% up to 10.25% in some municipalities; for this report, a value of 8% was used for this report. Class 8 vehicles are subject to an additional Federal Excise Tax which adds 12% to their purchase price.

Financing

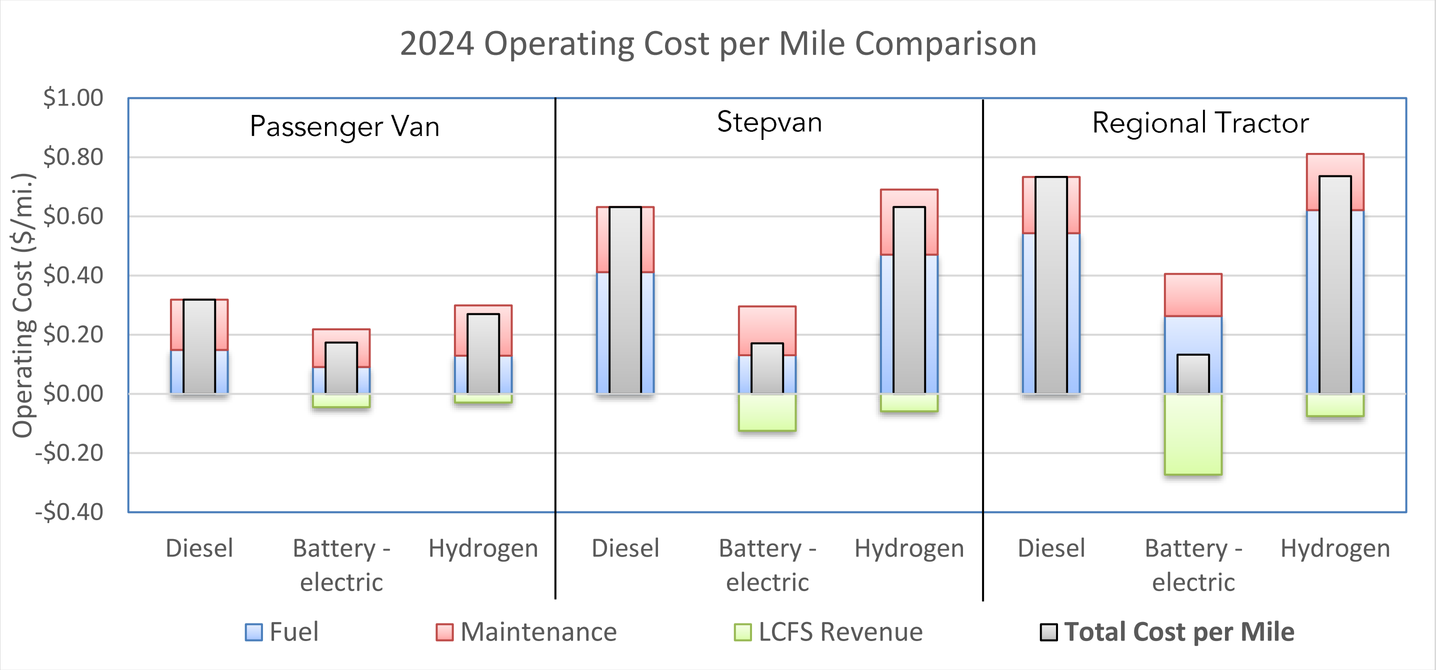
Most private companies finance their vehicles rather than purchase them outright. Financing allows companies to spread their costs out over time, but increases the vehicles cost due to interest payments. Because of this, the financing costs are greater for more expensive vehicles resulting in higher costs for zero-emission vehicles.

For this analysis, we are assuming that vehicles will be financed for 5 years at 5% interest. The interest rate will vary based on the creditworthiness of the fleet. We assume that most of the early market for zero-emission trucks will belong to larger companies who will have lower credit risk than smaller operators, resulting in lower interest rates.

IV. Operating Costs

Operating costs are dependent on how many miles a vehicle drives annually and the per mile costs of the vehicle. Three main operating costs are included: fuel, maintenance, and LCFS credit revenue. Figure 6 shows how the operating costs of the technologies and vehicles compare, and the rest of this section details how these numbers are calculated.

Figure 6: Cost per Mile vs. Technology Comparison

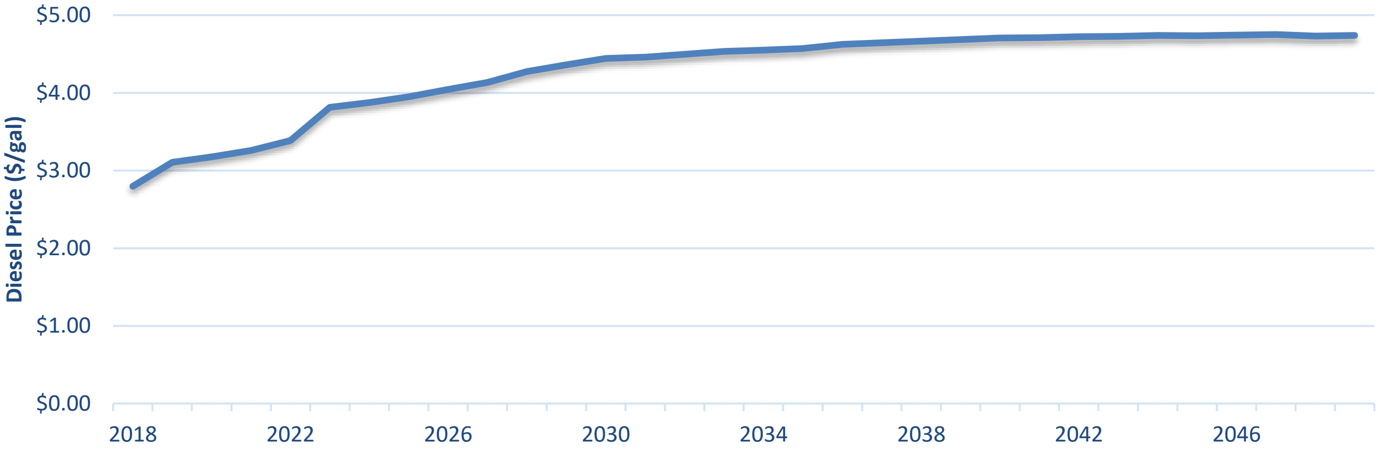


Fuel

The fuel cost represents the cost to fuel or recharge the vehicle and are a substantial component in the TCO. Battery-electric vehicles can have substantially lower electricity costs than diesel and can offset these costs with LCFS credits. Hydrogen fuel costs will vary by production method and volume but can become competitive with diesel due to the high efficiency of fuel cell systems and as hydrogen prices decline with increased production and highly utilized stations.

Diesel fuel price is taken from the Energy Information Administration (EIA) Annual Energy Outlook (AEO) 2018 for the Pacific region for transportation.[7] The diesel fuel price is then adjusted to include the costs of complying with the new 2018 Low Carbon Fuel Standard amendments are added to diesel fuel (more details in a later section). Figure 7 shows the diesel prices used for modeling.

Figure 7: Projected cost of diesel over time



Battery-electric fuel prices depend on how they are charged. Vehicles charged at high power or during peak periods will have higher electricity costs than if charging overnight over an extended period. Electricity prices are calculated using CARB's Battery-Electric Truck and Bus Charging Calculator and assumes a fleet of 20 vehicles will be depot charged overnight on a separate utility meter using a managed charging strategy with the applicable rate schedule.[8] The energy, demand, and fixed costs are all calculated using the Charging Calculator. Future electricity costs are modeled by adjusting the initial costs reflecting forecasted changes in the EIA AEO 2018 electricity cost projections. Electricity cost over time per utility and the statewide average are shown in Figure 8.

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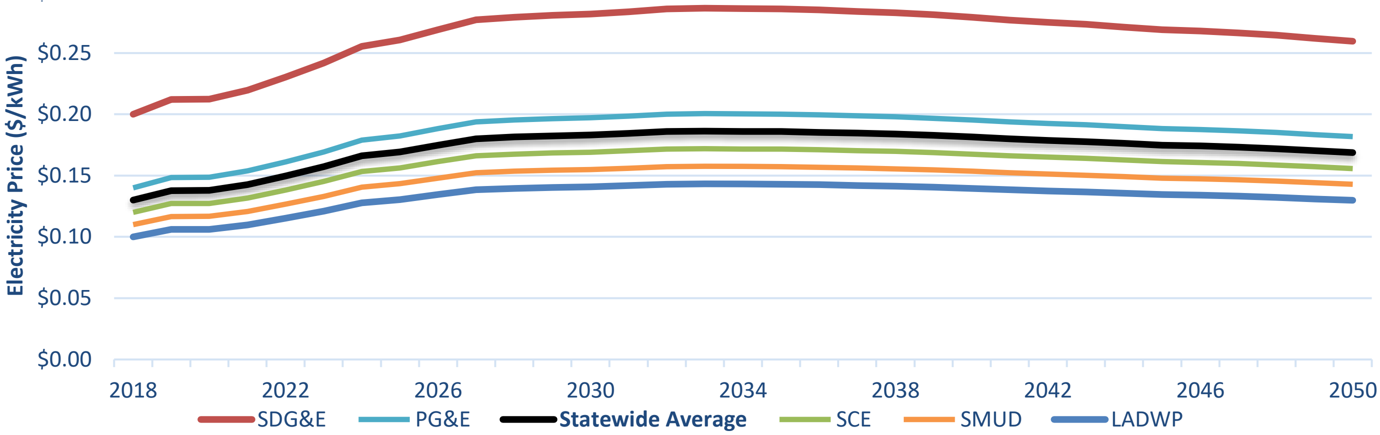
[7] Energy Information Administration, Annual Energy Outlook 2018. 2018. https://www.eia.gov/outlooks/aeo/data/browser/#/?id=3-AEO2019&cases=ref2019&sourcekey=0

[8] CARB, Battery-Electric Truck and Bus Charging Calculator, 2019. https://ww2.arb.ca.gov/resources/documents/battery-electric-truck-and-bus-charging-cost-calculator

Figure 8: Projected cost of electricity for a delivery van over time



For this analysis, 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. Hydrogen fuel costs are based of communication with Trillium CNG which estimated the cost of hydrogen at low, intermediate, and high volumes using different production methods.[9] This report uses their liquid hydrogen delivery numbers based on what Trillium presented as being most feasible for production at scale. The low volume cost will be used in 2018, the intermediate volume in 2030, and the high volume in 2050 with intermediate years being interpolated. These assumptions are based on expecting low volume production today, intermediate volume by 2030 when we would some moderate sized deployments but no complete conversions yet, and continuing price reductions out to 2050. Hydrogen costs over time are shown in Figure 9.

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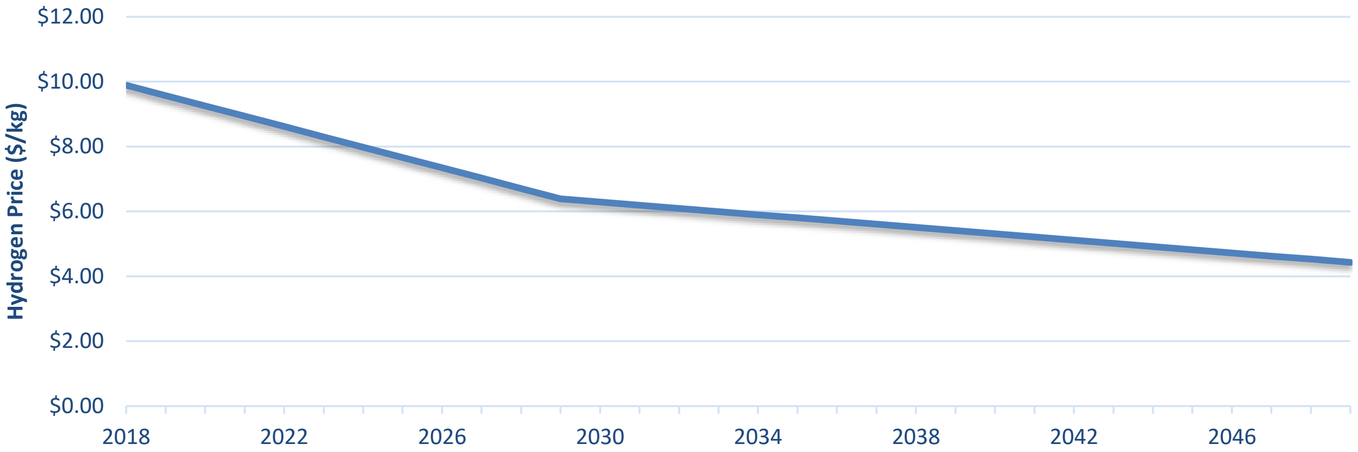
[9] Trillium CNG, Email Conversation, 2018.

Figure 9: Cost of hydrogen over time



Fuel economy numbers for diesel vehicles are calculated from the standards in GHG Phase 2. Battery-electric fuel economy is based on in-use data available. Hydrogen fuel cell fuel economy is calculated by applying LCFS Energy Economy Ratios to diesel fuel economies. Fuel economies are projected to improve over time due to regulatory requirements from GHG Phase 2 and technology improvements. More details on fuel economy calculations are shown in the appendix.

Table 6: 2018 Fuel economy values

Fuel Economy	Passenger van	Stepvan	Regional tractor
Diesel (mpg)	23.22	7.41	5.87
Battery-Electric (mi/kWh)	1.79	1.04	0.48
Hydrogen Fuel Cell (mi/kg)	58.04	14.08	11.15

Although not modelled in this report, there is a strong relationship between fuel economy and the duty cycle of a diesel vehicle. In a paper we wrote last year, CARB found the fuel economy for a tractor declines more than 40 percent at low speed versus high speed operations.[10] Because of this, the fuel economy for the passenger van and the regional tractor should be lower at lower mileage operation. The stepvan's fuel economy is specifically using an urban cycle so the lower efficiency should be accounted for.

Maintenance

Maintenance costs reflects the cost of labor and parts for routine maintenance, preventative maintenance, and repairing broken components. Maintenance costs for

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[10] CARB, Battery Electric Truck and Bus Energy Efficiency Compared to Conventional Diesel Vehicles, 2018. https://ww2.arb.ca.gov/sites/default/files/2018-11/180124hdbevefficiency.pdf

electric vehicles are generally assumed to be lower than for diesel in part due to their simpler design and less moving components. There is a lack of data on hydrogen fuel cell vehicles currently, but available data appears to show maintenance costs at parity with diesel. Table 7 shows the maintenance cost assumptions used in this report and more details are available in the appendix.

Table 7: Maintenance cost assumptions

Maintenance Costs	Passenger van	Stepvan	Regional tractor
Diesel	$0.17/mile	$0.22/mile	$0.19/mile
Battery-Electric	25% lower than diesel		
Hydrogen Fuel Cell	Equivalent to diesel		

Low Carbon Fuel Standard

The Low Carbon Fuel Standard (LCFS) regulation creates a market mechanism that incentivizes low carbon fuels by requiring California's transportation fuels to reduce their carbon intensity through the 2030 timeframe. Electricity and hydrogen are eligible to earn LCFS credits which can be sold and used to offset the costs of these fuels. Diesel is not eligible for LCFS credits.

Fleets who own and operate their infrastructure generate credits based on the amount of fuel they use. The following cash values assume a credit price of $125 as estimated by LCFS program staff in the staff report for the 2018 rulemaking.[11] An electric Class 2B-3 vehicle will earn roughly $0.08/kWh in 2018 using grid electricity while an electric Class 4-8 vehicle will earn roughly $0.13/kWh in 2018. For hydrogen, this report will assume the hydrogen is produced via steam methane reformation of landfill natural gas. This will result in Class 2B-3 vehicles earning $1.26/kg in 2018 and Class 4-8 vehicles earning $0.66/kg. LCFS credit revenue drops over time as the program standards tighten. Details on the calculations and numbers used are available in the appendix.

Table 8: Cumulative LCFS revenue in for a 2024 vehicle over a 12 year period

LCFS Revenue	Passenger van	Stepvan	Regional tractor
Diesel	$0	$0	$0
Battery-Electric	$10,564	$31,695	$163,129
Hydrogen Fuel Cell	$1,388	$5,781	$17,170

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[11] CARB, Public Hearing to Consider Proposed Amendments to the Low Carbon Fuel Standard Regulation and to the Regulation on Commercialization of Alternative Diesel Fuels. Staff Report: Initial Statement of Reasons, 2018. https://www.arb.ca.gov/regact/2018/lcfs18/isor.pdf

More information can be found on the LCFS webpage located here: https://www.arb.ca.gov/fuels/lcfs/lcfs.htm

V. Infrastructure

Infrastructure is necessary to refuel or recharge vehicles. All vehicles will need either dedicated infrastructure onsite or publically available retail stations. There are numerous ways infrastructure expenses can be accounted for which will affect the TCO in different ways. Infrastructure expenses are generally an upfront capital investment needed prior to vehicles being deployed, but infrastructure can last multiple vehicle lifetimes and generally is amortized over its life.

Diesel infrastructure

We assume the fleet is purchasing diesel from a retail station and the price for diesel infrastructure is included as a part of the diesel fuel cost. As a result, diesel infrastructure costs are not separately modeled.

Charging infrastructure

Fleets are responsible for two main cost components of installing charging infrastructure: the cost of the charger itself and the cost of upgrading the site to deliver power to the charger. The latter can include trenching, cabling, laying conduit, potential transformer upgrades and more.

Charger infrastructure costs for lighter trucks are taken from Pacific Gas and Electric's and Southern California Edison's SB350 MD/HD Infrastructure programs. Costs for heavier trucks are taken from battery-electric bus data and the Innovative Clean Transit rulemaking documents.

Table 9: Charging infrastructure costs

	Passenger van	Stepvan	Regional tractor
Charger info.	19 kW AC	19 kW AC	100 kW DC
Charger Cost	$5,000	$5,000	$50,000
Infrastructure Upgrade	$20,000	$20,000	$55,000

The cost of charging infrastructure is one of the biggest variables for battery-electric vehicles. Some locations will need minimal to no electrical site upgrades and as a result the fleet will only need to pay for the charger. Other sites will need significant trenching, cabling and conduit, new installation of transformers, and more. And as California's major Investor-Owned Utilities are proposing significant infrastructure investments, it is possible that fleets may not have to pay for infrastructure at all. Because of these factors, the infrastructure costs presented above represent an estimate as real costs will vary significantly. Infrastructure costs are spread out over a 20 year period.

Hydrogen Infrastructure

Hydrogen infrastructure costs are incorporated into the hydrogen fuel costs identified by Trillium and are not included here.

VI. Other Assorted Costs

Registration Fees

Vehicles operating and registered in California must pay an annual registration fee. The registration fee varies based on the vehicle’s cost, age, and weight. Additionally, the calculation is different for conventional HD vehicles and zero-emission HD vehicles.

Zero-emission vehicles have a higher Vehicle License Fee which based on the vehicle’s value. However, this is offset by lower weight fees for zero-emission vehicles compared to diesel. Most battery-electric vehicles will pay less in total registration fees as shown in Table 10. A more thorough analysis is included in the appendix.

Table 10: Registration fees of a 2024 vehicle over 12 years

Registration Fees	Passenger van	Stepvan	Regional tractor
Diesel	$10,603	$14,730	$35,405
Battery-Electric	$8,353	$11,455	$16,515
Hydrogen Fuel Cell	$13,342	$15,641	$24,227

Residual Values

Residual values represent the resale value of a truck at the end of its life. For this analysis, we are assuming that the initial purchaser will hold onto the truck for 12 years for all truck types as a simplification despite the expectation that some trucks will operate for more than 20 years.

The residual value for diesel trucks was calculated using TruckPaper.com. The value of Class 2B-3 vehicles, Class 4-6 box trucks, and Class 7-8 day cabs were measured model year to model year to develop a price curve for trucks as they age.

Due to a lack of data, we do not have projections for what the residual value of a battery-electric or fuel cell truck may be. A lower-bound calculation would look at the scrap value of the truck’s battery and the truck itself. The used battery value would be dependent on a number of factors including the health of the used battery and its suitability for second life applications. The value would be constrained below the value of new batteries. The sum of the truck value and used battery would be a lower bound of the residual value. For this analysis, we estimated the residual value of a battery-electric truck is one-half that of a diesel truck of the same age, and the residual value of a hydrogen fuel cell truck is one-fourth that of a diesel truck. Ultimately, the residual value of a 12 year old truck assumed in this analysis is a relatively small part of the total cost of ownership.

Midlife Costs

In this report, midlife costs are the cost of rebuilding or replacing major propulsion components due to wear or deterioration. For diesel vehicles, this would be a midlife rebuild, for battery-electric vehicles this would be a battery replacement, and for a hydrogen fuel-cell vehicle this would be a fuel cell stack refurbishment.

Based on the mileage assumptions used in the Vehicle Operations section on page 3, the passenger van will travel roughly 150,000 miles over its life, the stepvan will travel roughly 300,000 miles, and the tractor will travel 600,000 miles. These numbers are underneath typical diesel engine rebuild mileage thresholds and as a result, no diesel overhaul is modeled.

We do not believe a battery replacement will be necessary over the 12 year period in this report. Today, zero-emission manufacturers are offering vehicles with eight or more years and up to 300,000 mile warranties on their products. Considering the 35% battery buffer used and the limited miles travelled, we are not modelling a battery replacement for the passenger van or stepvan. We are not aware of any batteries that are guaranteed to last for a 600,000 mile period so we will be modelling a battery replacement in year eight of the day cab's operation.

In their economic model, Ricardo estimates that a heavy-duty fuel cell system would need to be replaced after 7 years of operation and can be modelled at one third the cost of a fuel cell system at the time. The same assumption is used in this model.

Discount Rate

CARB's economic analyses generally use a discount rate of 2.5% to 5% for regulations with the assumption that private entities generally use a higher discount rate while public entities use a lower discount rate. This report assumes a discount rate of 5% for future years.

VII. Total Cost of Ownership Analysis

Based on the inputs above, the total cost of ownership (TCO) can be calculated for each vehicle. The components of the TCO modelled here are:

- Capital costs, including
    - Vehicle capital cost
    - Taxes associated with the vehicle purchase
    - Financing costs for the vehicle
- Fuel costs including
    - The cost of the fuel
    - LCFS credit revenue
- Other expenses, including
    - Maintenance cost
    - Midlife costs
    - Vehicle registration
    - Residual values at the end of the vehicle's operating life

Figure 10 through Figure 18 show the TCO comparisons between diesel, battery-electric, and hydrogen at in 2018, 2024, and 2030. Charging infrastructure is shown as a dotted line due to the variability of infrastructure costs as mentioned earlier in this report. All figures show the total cost of ownership which discounts all future cash flows using a 5% discount rate.

Figure 10: Total Cost of Ownership for a 2018 passenger van – 15,000 mi. x 12 years

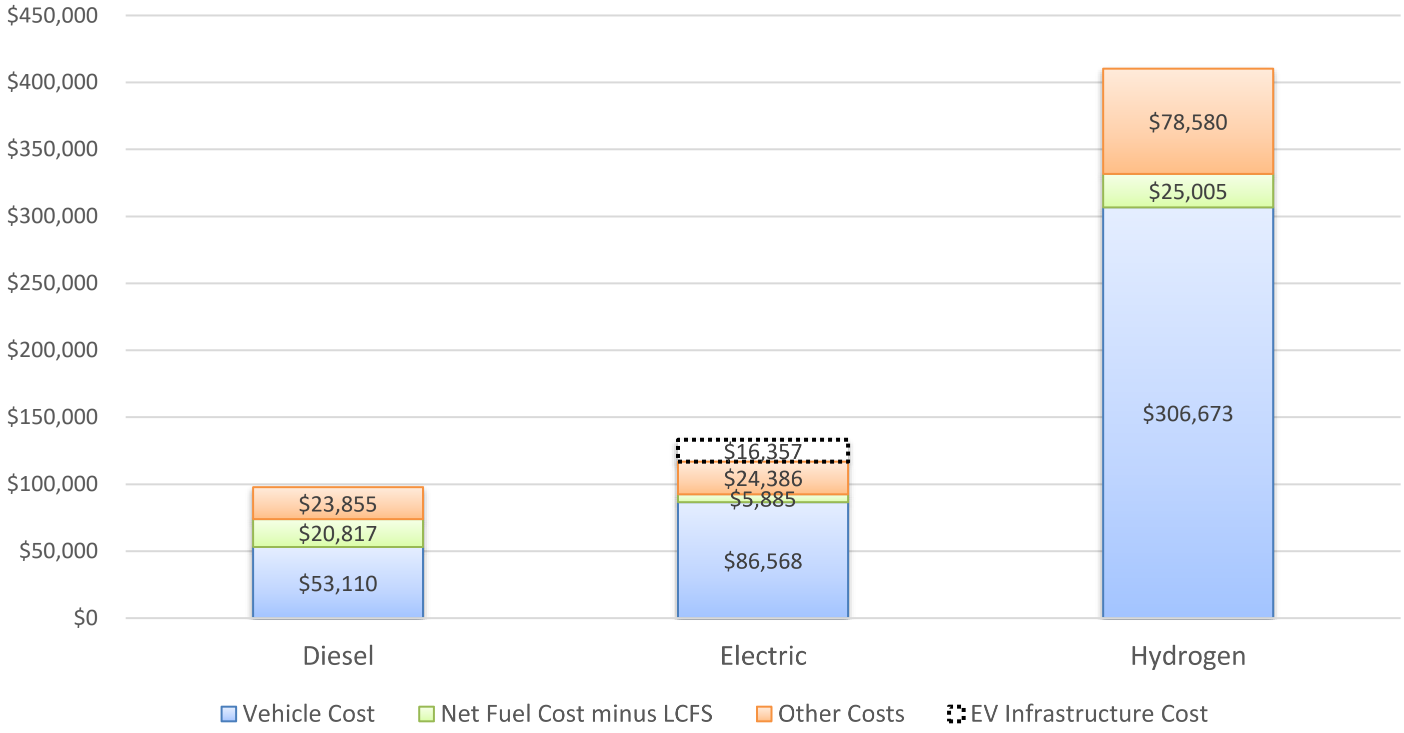


Table 11: Total cost of ownership assumptions for a 2018 passenger van

	Diesel	**Battery-electric**	**Hydrogen fuel cell**
Annual miles	15,000	15,000	15,000
Operating years	12	12	12
Energy storage	-	38 kWh	10 kWh/10 kg
Vehicle power	-	160 kW	160 kW/80 kW FC
Total Vehicle Cost	**$53,110**	**$86,568**	**$306,673**
Average fuel cost	$3.74/gal	$0.18/kWh	$8.00/kg
Average fuel economy	23.2 mpg	1.79 mi/kWh	58 mi/kg
Average LCFS revenue	0	$0.07/kWh	$1.03/kg
Total fuel cost	**$20,817**	**$13,142**	**$25,986**
Total LCFS revenue	**$0**	**($7,258)**	**($982)**
Lifetime maintenance cost	$23,731	$17,799	$23,731
Midlife cost	$0	$0	$42,982
Registration fees	$8,331	$7,509	$13,919
Residual values	($8,207)	($4,104)	($2,052)
Total Other Costs	**$23,855**	**$21,204**	**$78,580**
Total	**$97,782**	**$113,657**	**$410,258**
EV Infrastructure	$0	$16,357	$0

Figure 11: Total Cost of Ownership for a 2024 passenger van – 15,000 mi. x 12 years

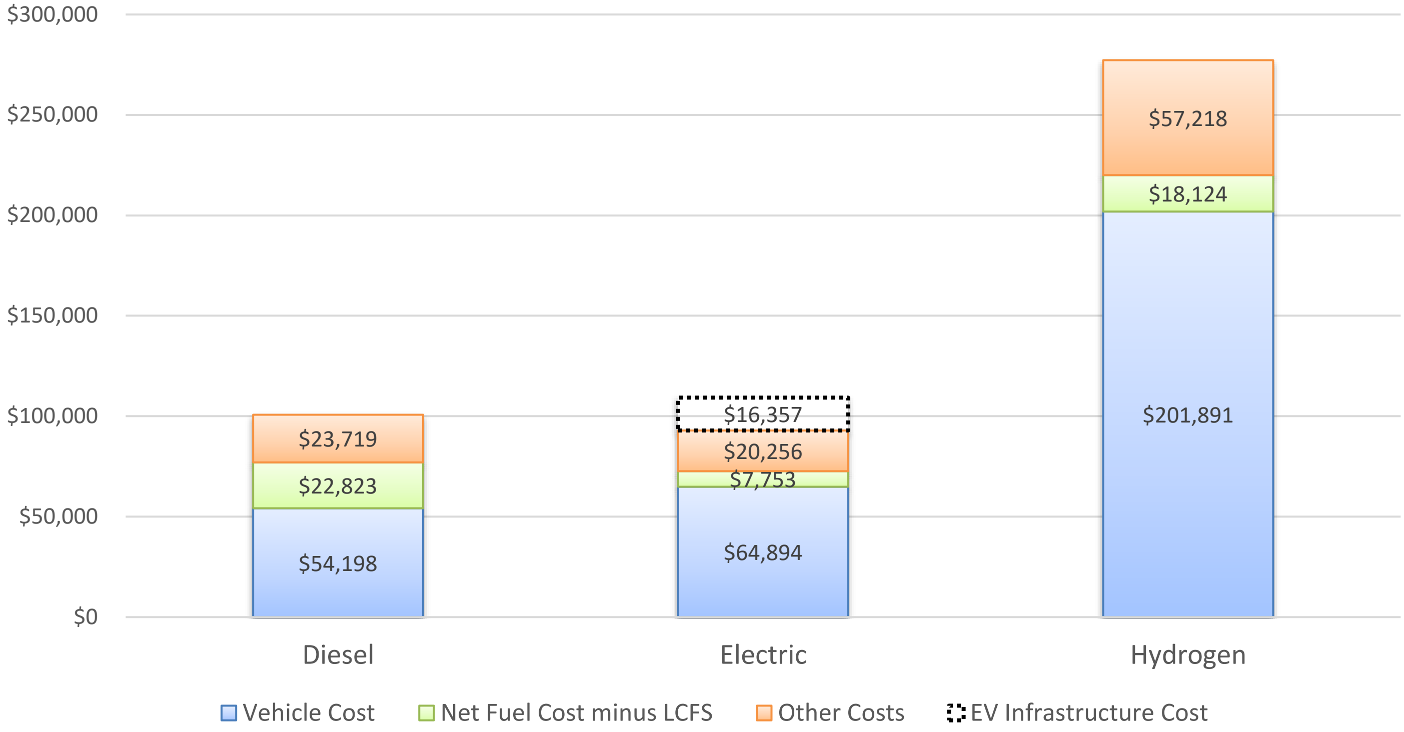


Table 12: Total cost of ownership assumptions for a 2024 passenger van

	Diesel	Battery-electric	Hydrogen fuel cell
Annual miles	15,000	15,000	15,000
Operating years	12	12	12
Energy storage	-	38 kWh	10 kWh/10 kg
Vehicle power	-	160 kW	160 kW/80 kW FC
Total Vehicle Cost	**$54,198**	**$64,894**	**$201,891**
Average fuel cost	$4.33/gal	$0.2/kWh	$6.55/kg
Average fuel economy	25.7 mpg	1.98 mi/kWh	64.2 mi/kg
Average LCFS revenue	0	$0.07/kWh	$0.88/kg
Total fuel cost	**$22,823**	**$13,650**	**$18,893**
Total LCFS revenue	**$0**	**($5,897)**	**($769)**
Lifetime maintenance cost	$23,731	$17,799	$23,731
Midlife cost	$0	$0	$24,713
Registration fees	$8,363	$6,645	$10,867
Residual values	($8,375)	($4,188)	($2,094)
Total Other Costs	**$23,719**	**$20,256**	**$57,218**
Total	**$100,740**	**$92,903**	**$277,233**
EV Infrastructure	$0	$16,357	$0

Figure 12: Total Cost of Ownership for a 2030 passenger van – 15,000 mi. x 12 years

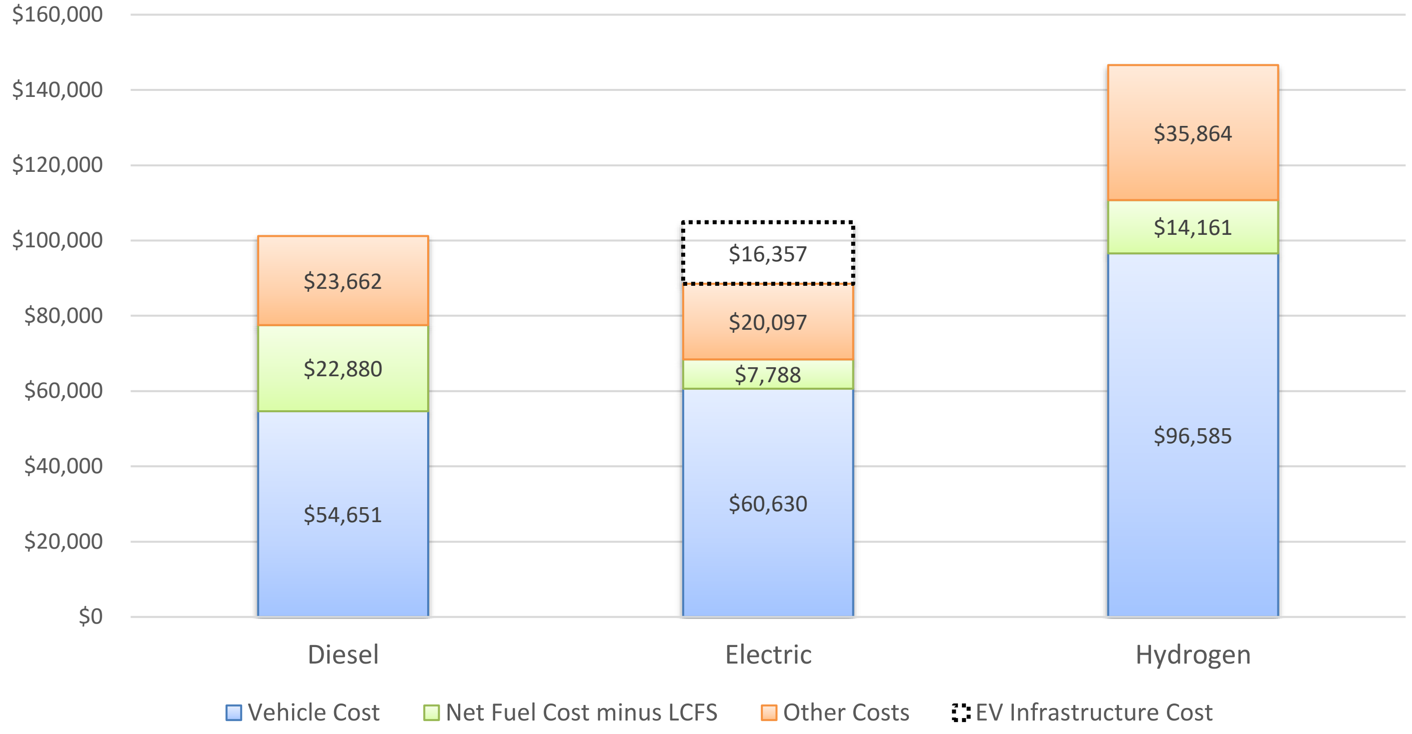


Table 13: Total cost of ownership assumptions for a 2030 passenger van

	Diesel	Battery-electric	Hydrogen fuel cell
Annual miles	15,000	15,000	15,000
Operating years	12	12	12
Energy storage	-	38 kWh	10 kWh/10 kg
Vehicle power	-	160 kW	160 kW/80 kW FC
Total Vehicle Cost	**$54,651**	**$60,630**	**$96,585**
Average fuel cost	$4.6/gal	$0.2/kWh	$5.70/kg
Average fuel economy	27.7 mpg	2.13 mi/kWh	69.3 mi/kg
Average LCFS revenue	0	$0.06/kWh	$0.84/kg
Total fuel cost	**$22,880**	**$12,993**	**$14,874**
Total LCFS revenue	**$0**	**($5,206)**	**($713)**
Lifetime maintenance cost	$23,731	$17,799	$23,731
Midlife cost	$0	$0	$6,444
Registration fees	$8,376	$6,521	$7,801
Residual values	($8,445)	($4,223)	($2,111)
Total Other Costs	**$23,662**	**$20,097**	**$35,864**
Total	**$101,193**	**$88,514**	**$146,610**
EV Infrastructure	$0	$16,357	$0

Figure 13: Total Cost of Ownership for a 2018 walk-in stepvan – 24,000 mi. x 12 years

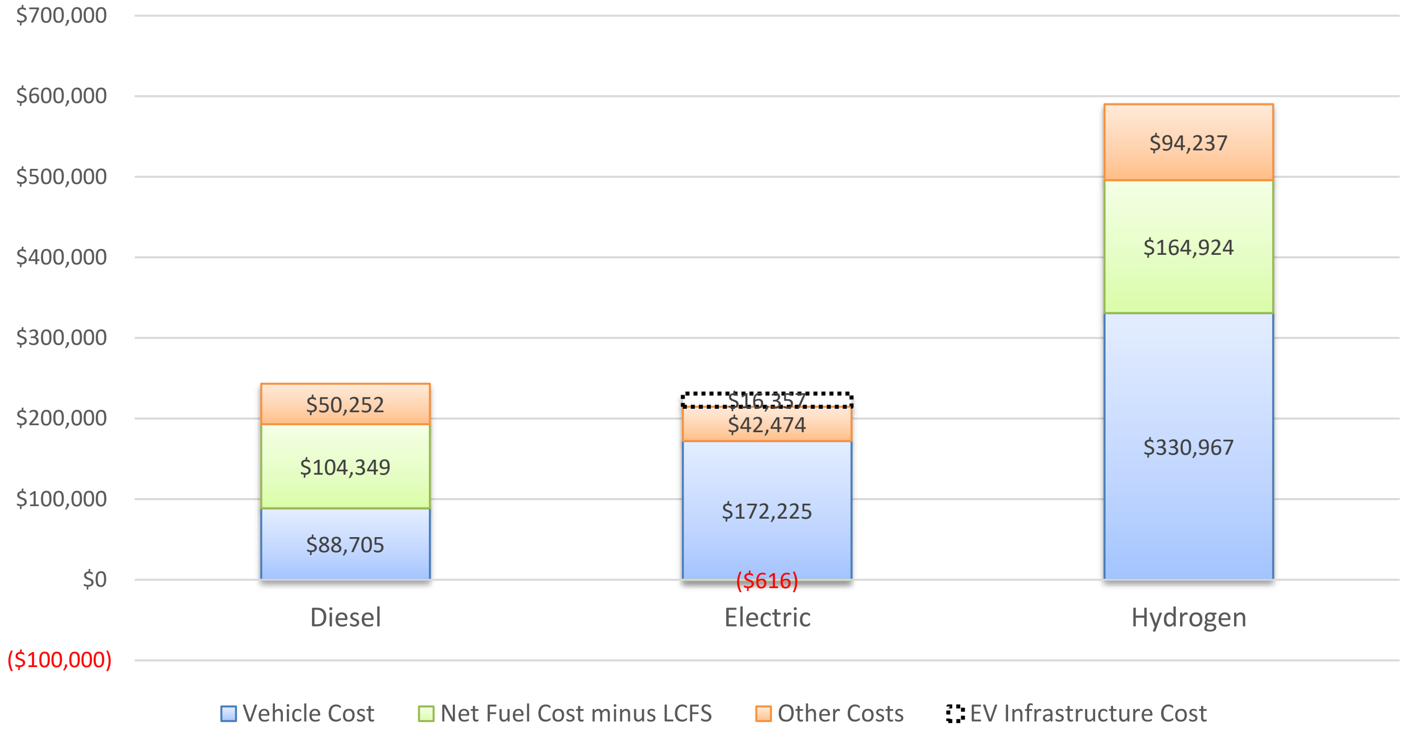


Table 14: Total cost of ownership assumptions for a 2018 walk-in stepvan

	Diesel	Battery-electric	Hydrogen fuel cell
Annual miles	24,000	24,000	24,000
Operating years	12	12	12
Energy storage	-	104 kWh	50 kWh/20 kg
Vehicle power	-	240 kW	240 kW/60 kW FC
Total Vehicle Cost	**$88,705**	**$172,225**	**$330,967**
Average fuel cost	$3.74/gal	$0.17/kWh	$8.00/kg
Average fuel economy	7.4 mpg	1.04 mi/kWh	14.1 mi/kg
Average LCFS revenue	0	$0.12/kWh	$0.43/kg
Total fuel cost	**$104,349**	**$33,472**	**$171,398**
Total LCFS revenue	**$0**	**($34,088)**	**($6,474)**
Lifetime maintenance cost	$49,138	$36,853	$49,138
Midlife cost	$0	$0	$32,237
Registration fees	$11,592	$10,860	$15,482
Residual values	($10,477)	($5,239)	($2,619)
Total Other Costs	**$50,252**	**$42,474**	**$94,237**
Total	**$243,306**	**$214,083**	**$590,129**
EV Infrastructure	$0	$16,357	$0

Figure 14: Total Cost of Ownership for a 2024 walk-in stepvan – 24,000 mi. x 12 years

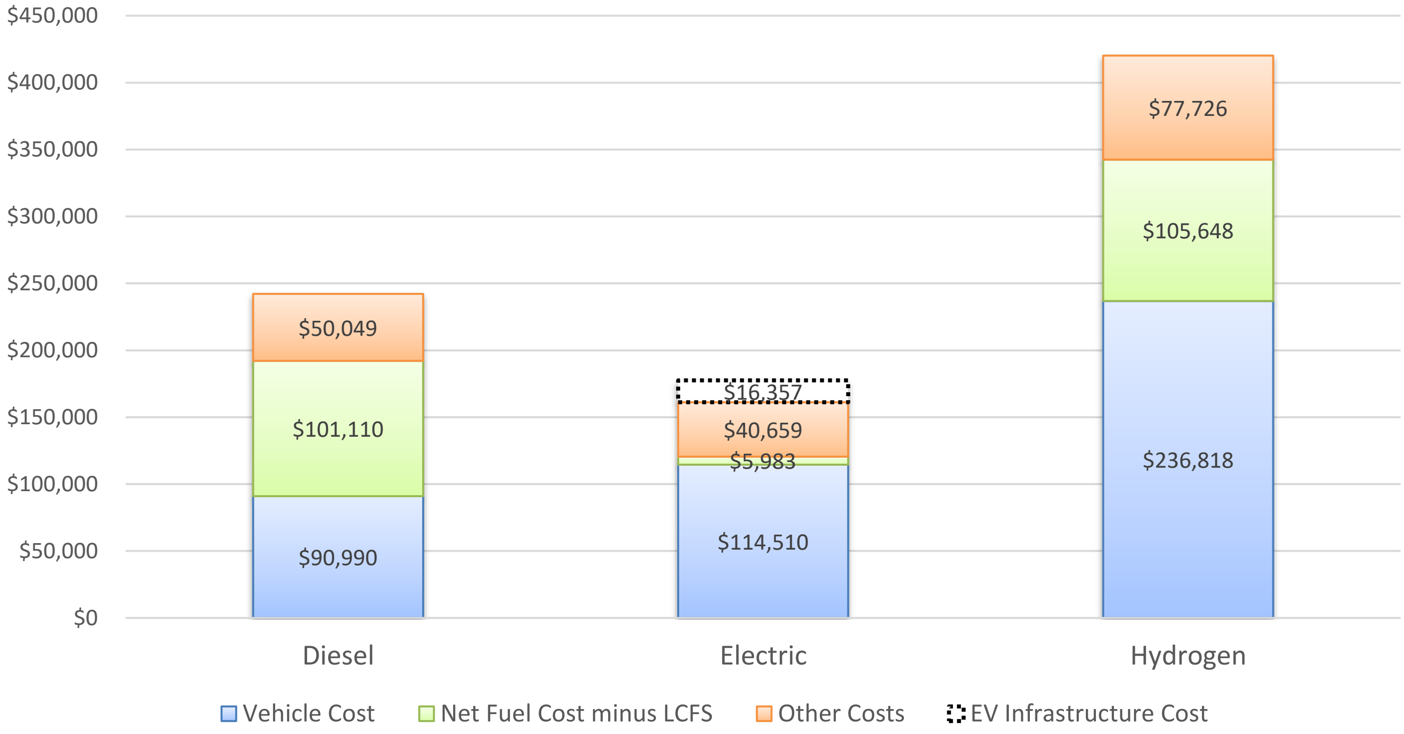


Table 15: Total cost of ownership assumptions for a 2024 walk-in stepvan

	Diesel	Battery-electric	Hydrogen fuel cell
Annual miles	24,000	24,000	24,000
Operating years	12	12	12
Energy storage	-	104 kWh	50 kWh/20 kg
Vehicle power	-	240 kW	240 kW/60 kW FC
Total Vehicle Cost	**$90,990**	**$114,510**	**$236,818**
Average fuel cost	$4.33/gal	$0.18/kWh	$6.55/kg
Average fuel economy	9.3 mpg	1.3 mi/kWh	17.6 mi/kg
Average LCFS revenue	0	$0.11/kWh	$0.32/kg
Total fuel cost	**$101,110**	**$30,725**	**$110,132**
Total LCFS revenue	**$0**	**($24,743)**	**($4,483)**
Lifetime maintenance cost	$49,138	$36,853	$49,138
Midlife cost	$0	$0	$18,535
Registration fees	$11,658	$9,179	$12,741
Residual values	($10,747)	($5,374)	($2,687)
Total Other Costs	**$50,049**	**$40,659**	**$77,726**
Total	**$242,148**	**$161,151**	**$420,193**
EV Infrastructure	$0	$16,357	$0

Figure 15: Total Cost of Ownership for a 2030 walk-in stepvan – 24,000 mi. x 12 years

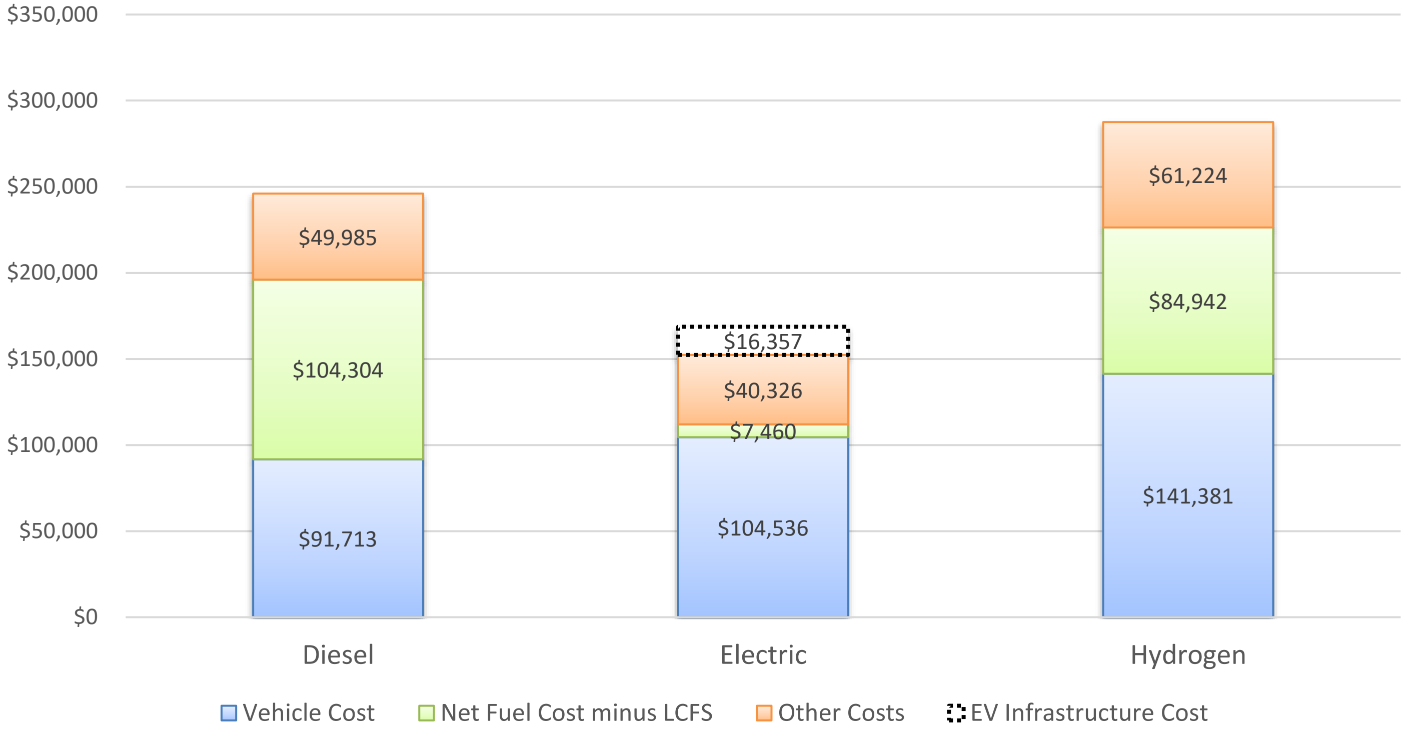


Table 16: Total cost of ownership assumptions for a 2030 walk-in stepvan

	Diesel	Battery-electric	Hydrogen fuel cell
Annual miles	24,000	24,000	24,000
Operating years	12	12	12
Energy storage	-	104 kWh	50 kWh/20 kg
Vehicle power	-	240 kW	240 kW/60 kW FC
Total Vehicle Cost	**$91,713**	**$104,536**	**$141,381**
Average fuel cost	$4.6/gal	$0.18/kWh	$5.70/kg
Average fuel economy	9.7 mpg	1.37 mi/kWh	18.5 mi/kg
Average LCFS revenue	0	$0.11/kWh	$0.28/kg
Total fuel cost	**$104,304**	**$30,096**	**$89,218**
Total LCFS revenue	**$0**	**($22,636)**	**($4,276)**
Lifetime maintenance cost	$49,138	$36,853	$49,138
Midlife cost	$0	$0	$4,833
Registration fees	$11,679	$8,889	$9,961
Residual values	($10,833)	($5,416)	($2,708)
Total Other Costs	**$49,985**	**$40,326**	**$61,224**
Total	**$246,002**	**$152,322**	**$287,547**
EV Infrastructure	$0	$16,357	$0

Figure 16: Total Cost of Ownership for a 2018 short-haul day cab tractor – 54,000 mi. x 12 years

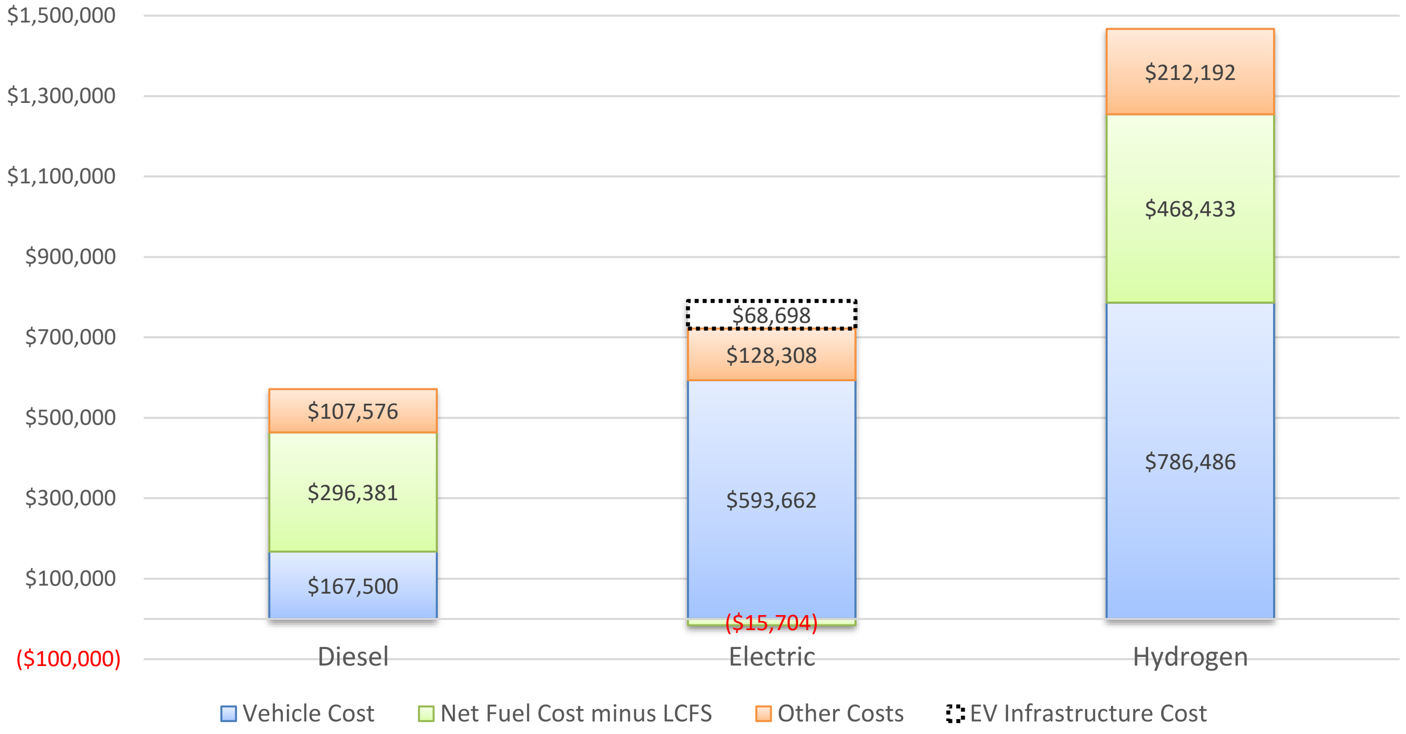


Table 17: Total cost of ownership assumptions for a 2018 regional day cab tractor

	Diesel	**Battery-electric**	**Hydrogen fuel cell**
Annual miles	54,000	54,000	54,000
Operating years	12	12	12
Energy storage	-	510 kWh	10 kWh/10 kg
Vehicle power	-	350 kW	350 kW/175 kW FC
Total Vehicle Cost	**$167,500**	**$593,662**	**$786,486**
Average fuel cost	$3.74/gal	$0.15/kWh	$8.00/kg
Average fuel economy	5.9 mpg	0.48 mi/kWh	11.2 mi/kg
Average LCFS revenue	0	$0.12/kWh	$0.43/kg
Total fuel cost	**$296,381**	**$152,074**	**$486,820**
Total LCFS revenue	**$0**	**($167,778)**	**($18,387)**
Lifetime maintenance cost	$95,484	$71,613	$95,484
Midlife cost	$0	$42,949	$94,023
Registration fees	$27,545	$21,472	$26,548
Residual values	($15,453)	($7,727)	($3,863)
Total Other Costs	**$107,576**	**$128,308**	**$212,192**
Total	**$571,456**	**$706,266**	**$1,467,111**
EV Infrastructure	$0	$68,698	$0

Figure 17: Total Cost of Ownership for a 2024 short-haul day cab tractor – 54,000 mi. x 12 years

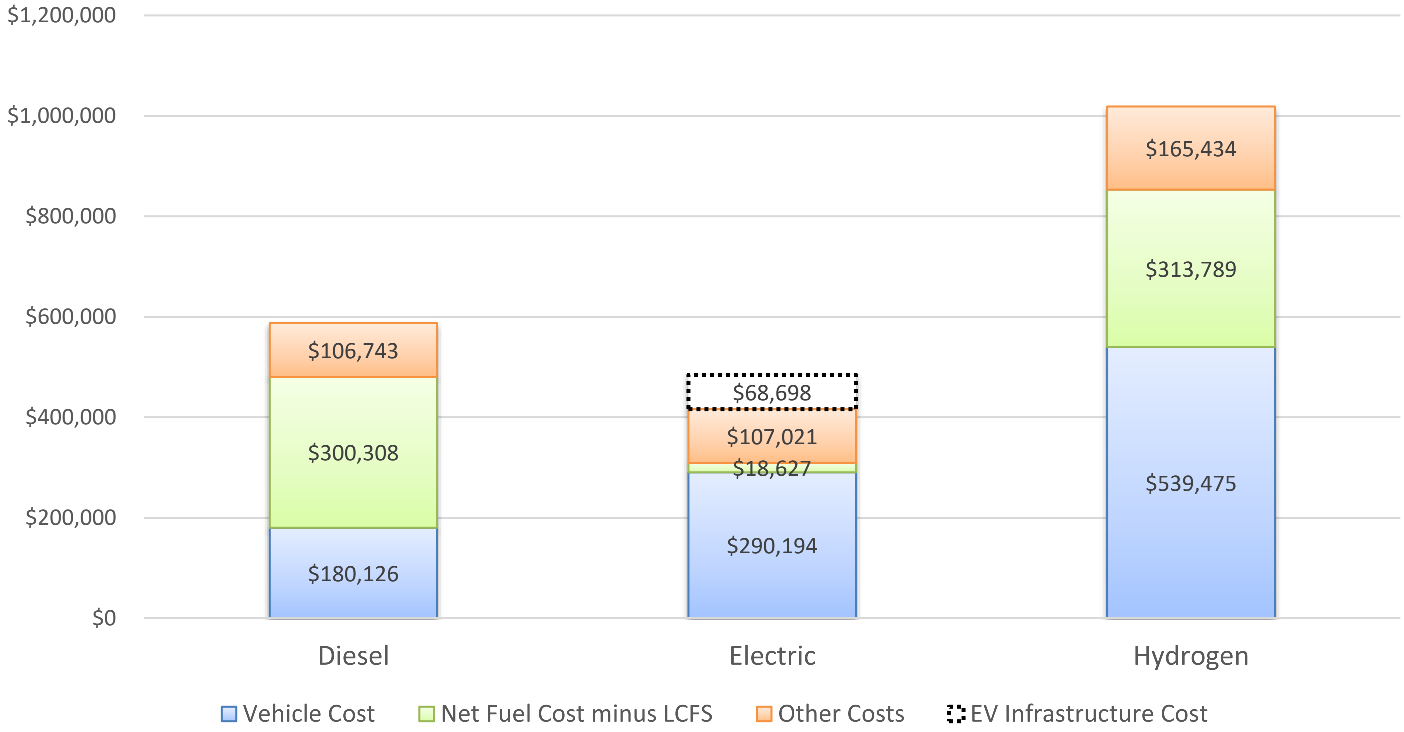


Table 18: Total cost of ownership assumptions for a 2024 regional day cab tractor

	Diesel	Battery-electric	Hydrogen fuel cell
Annual miles	54,000	54,000	54,000
Operating years	12	12	12
Energy storage	-	510 kWh	10 kWh/40 kg
Vehicle power	-	350 kW	350 kW/175 kW FC
Total Vehicle Cost	**$180,126**	**$290,194**	**$539,475**
Average fuel cost	$4.33/gal	$0.17/kWh	$6.55/kg
Average fuel economy	7 mpg	0.57 mi/kWh	13.4 mi/kg
Average LCFS revenue	0	$0.11/kWh	$0.32/kg
Total fuel cost	**$300,308**	**$145,975**	**$327,105**
Total LCFS revenue	**$0**	**($127,348)**	**($13,316)**
Lifetime maintenance cost	$95,484	$71,613	$95,484
Midlife cost	$0	$30,233	$54,059
Registration fees	$27,878	$13,484	$20,046
Residual values	($16,618)	($8,309)	($4,154)
Total Other Costs	**$106,743**	**$107,021**	**$165,434**
Total	**$587,178**	**$415,841**	**$1,018,699**
EV Infrastructure	$0	$68,698	$0

Figure 18: Total Cost of Ownership for a 2018 short-haul day cab tractor – 54,000 mi. x 12 years

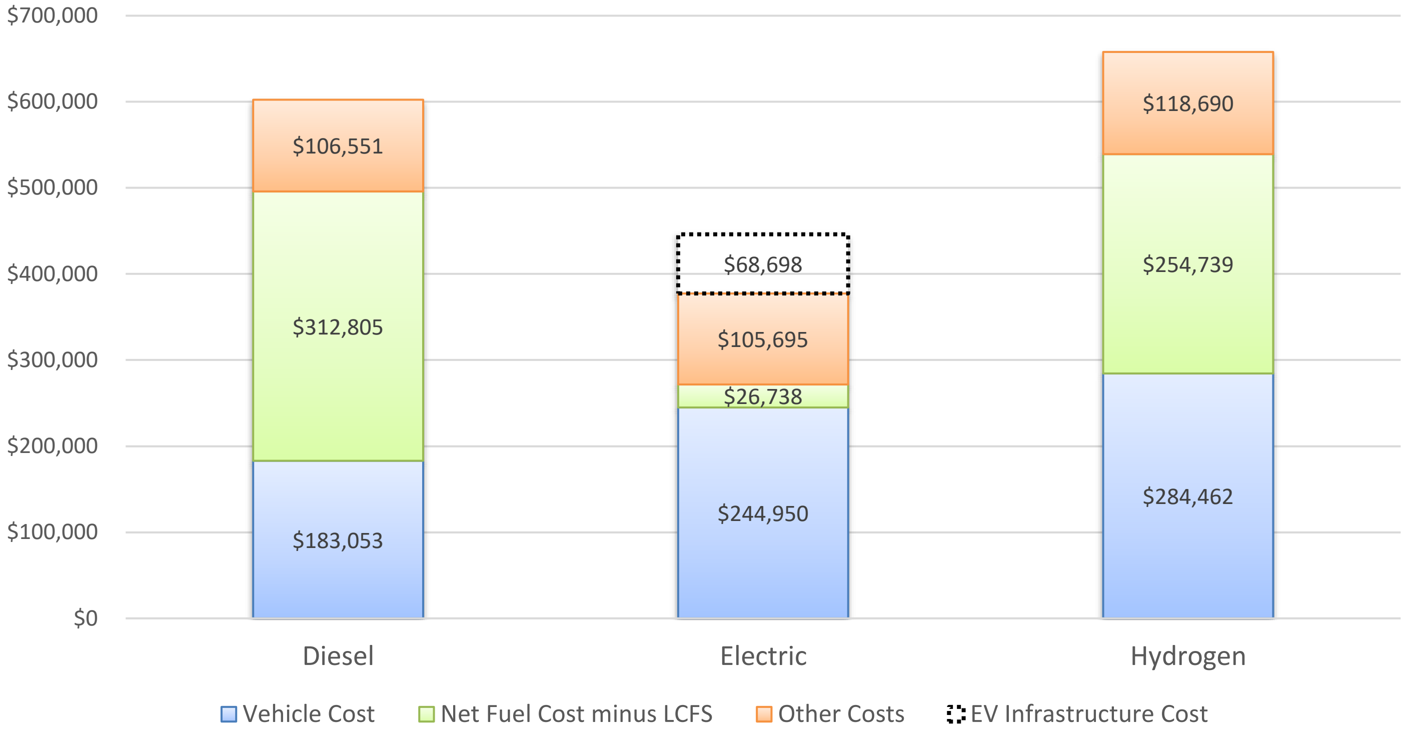


Table 19: Total cost of ownership assumptions for a 2030 regional day-cab tractor

	Diesel	Battery-electric	Hydrogen fuel cell
Annual miles	54,000	54,000	54,000
Operating years	12	12	12
Energy storage	-	510 kWh	10 kWh/40 kg
Vehicle power	-	350 kW	350 kW/175 kW FC
Total Vehicle Cost	**$183,053**	**$244,950**	**$284,462**
Average fuel cost	$4.6/gal	$0.17/kWh	$5.70/kg
Average fuel economy	7.3 mpg	0.59 mi/kWh	13.9 mi/kg
Average LCFS revenue	0	$0.11/kWh	$0.28/kg
Total fuel cost	**$312,805**	**$144,375**	**$267,562**
Total LCFS revenue	**$0**	**($117,637)**	**($12,823)**
Lifetime maintenance cost	$95,484	$71,613	$95,484
Midlife cost	$0	$30,233	$14,095
Registration fees	$27,955	$12,293	$13,333
Residual values	($16,888)	($8,444)	($4,222)
Total Other Costs	**$106,551**	**$105,695**	**$118,690**
Total	**$602,408**	**$377,383**	**$657,891**
EV Infrastructure	$0	$68,698	$0

Effects of daily miles on battery-electric payback

The TCO comparison between a battery-electric and diesel truck has a strong relationship with the duty cycle of the vehicle. Battery-electric vehicles cost more upfront but save money the more miles they travel. However, the trade-off exists where the more miles the BEV does, the larger the battery must be for it. The following figures show how the TCO of a 2024 battery-electric and diesel vehicle compare at different mileage thresholds.

This is a simplified analysis. A more comprehensive analysis would model battery replacements only for longer range vehicles, would reflect changing fuel economies at different mileages, and differing electricity rates under for different vehicle operations. Infrastructure costs are included in the figures below.

Figure 19: TCO of a 2024 passenger van versus daily mileage

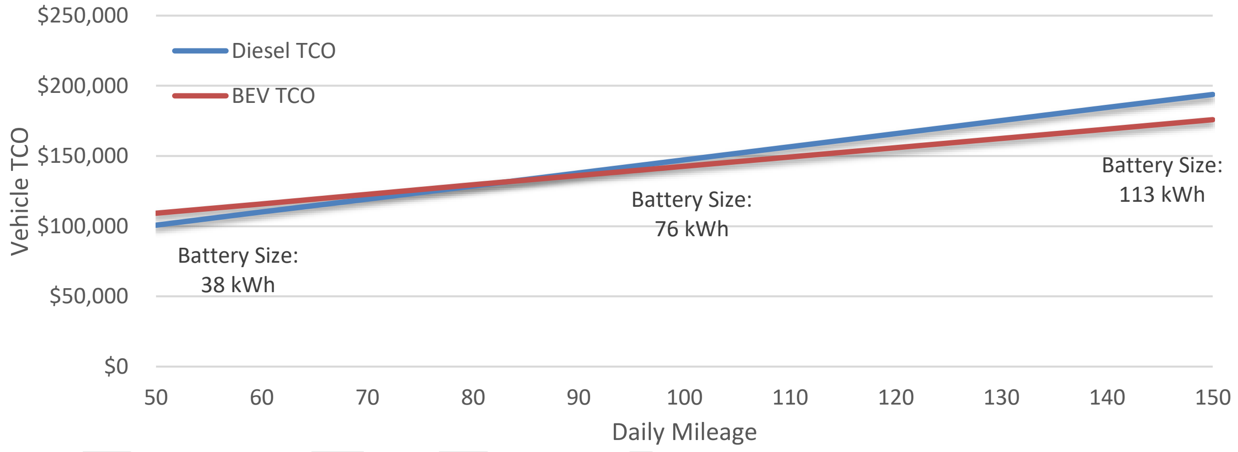


Figure 20: TCO of a 2024 walk-in stepvan versus daily mileage

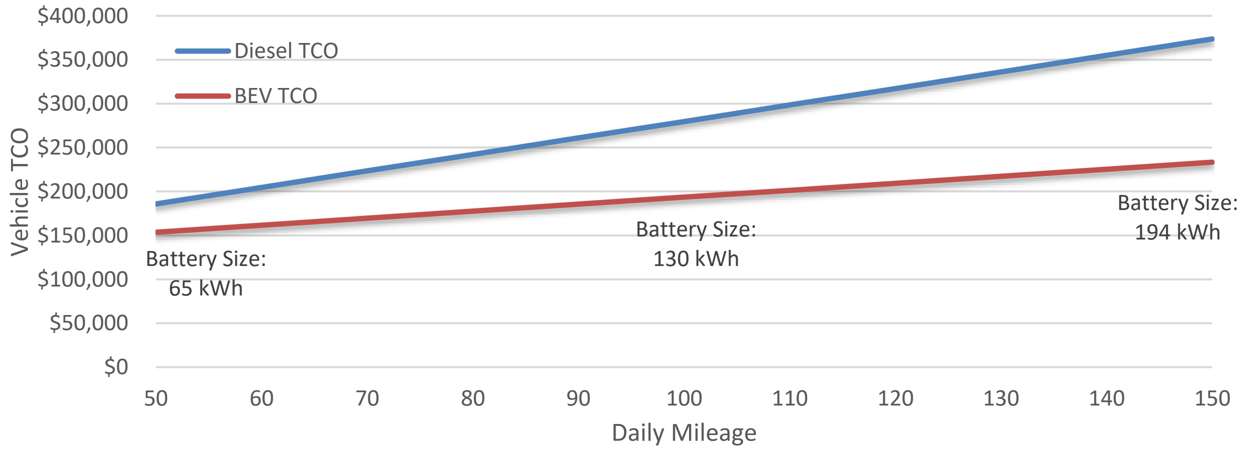
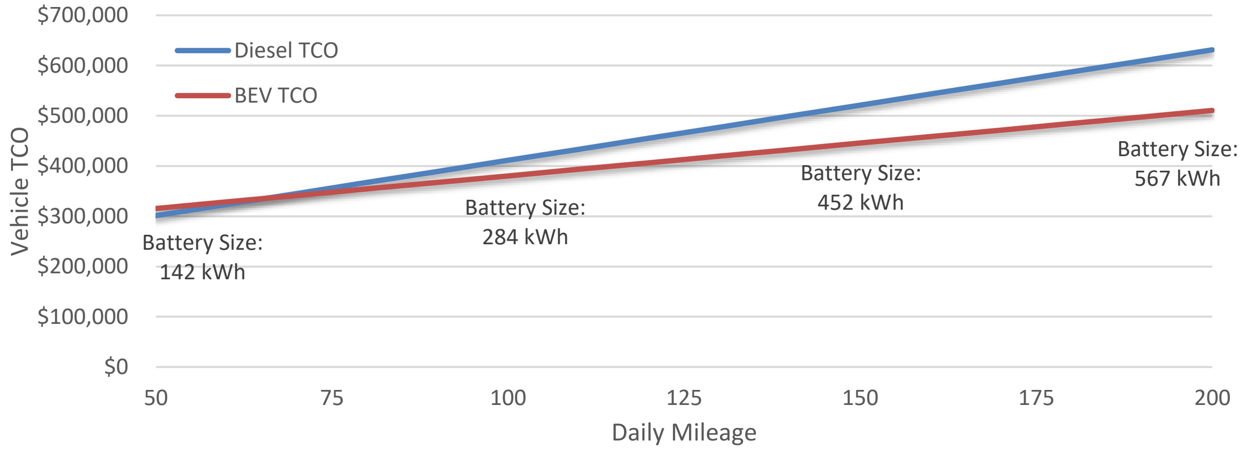


Figure 21: TCO of a 2024 regional day cab versus daily mileage



Summary

The TCO comparisons for the different technologies and vehicle types show several trends across technologies and vehicle types.

- Battery-electric technologies appear to achieve TCO cost parity with diesel powered vehicles by the 2024 timeframe for both the stepvan and the regional tractor example. For passenger vans, TCO parity may occur later.
- Charging infrastructure is a major variable for battery-electric vehicles. Each vehicle, fleet, and site will have different conditions that affect the cost of infrastructure and as a result, the total cost of ownership. Taking advantage of utility programs and deploying vehicles at sites with advantageous conditions will minimize infrastructure costs.
- Hydrogen fuel cell vehicles cost more upfront and may pay more for fuel than their diesel counterparts. But with reductions in capital cost and with declining hydrogen prices, TCO parity may be achievable by the 2030 timeframe. If costs for the vehicle and fuel decline faster than projected in this report, TCO parity may happen quicker than projected.
- TCO for heavier vehicles appear to have good economic opportunities for zero-emission vehicles. Their lower diesel vehicle fuel economy and higher fuel use presents the potential for greater operational savings for battery-electric and fuel cell electric vehicles.
- Lighter trucks are more fuel efficient and generate less LCFS credits, so the opportunities for net fuel savings are somewhat lower.
- The LCFS program is a key driver for zero-emission technology as it greatly decreases the fuel cost for battery-electric vehicles. For hydrogen fuel cell vehicles, the LCFS program provides benefits that can be increased by using low carbon intensity feedstocks for hydrogen production.

Appendix

Diesel fuel economy

Diesel fuel economy is calculated using standards from NHTSA & EPA's GHG Phase 2 Final Rule and will change over time.[12] GHG Phase 2 sets fuel economy in two equivalent standards, one of which is $\frac{gal.}{1{,}000\ ton-mile}$. This is converted to fuel economy with the following formula:

$$Fuel\ Economy\ \left(\frac{mi.}{gal.}\right) = Efficiency\ Standard\ \left(\frac{gal.}{1000\ ton - mi.}\right)^{-1} * Standard\ Payload\ (ton)$$

- Standard Payload is defined as:
  - 2.85 tons for Vocational - LHD
  - 5.6 tons for Vocational – MHD
  - 7.5 tons for Vocational – HHD
  - 12.5 tons for Tractors – Class 7
  - 19 tons for Tractors – Class 8
  - 43 tons for Tractors – Heavy Haul
- The passenger van meets standards equivalent to be a Ford Transit passenger van with GVWR of 10,360 lb., payload capacity of 3,520 lb., and GCWR of 11,200 lb.[13]
- The delivery van meets light heavy-duty vocational vehicle standards on an urban test cycle.
- The regional tractor was assumed to be a Class 8 low roof day cab.
  - From the GHG Phase 2 Regulatory Impact Analysis, "The short-haul combination tractors were evaluated using a day cab sales distribution assumption of 7 percent Class 7 low roof, 10 percent Class 7 high roof, 40 percent Class 8 low roof, 35 percent Class 8 high roof, and 8 percent vocational tractors, based on the information used in the HD Phase 1 analysis." Based on this, the most common configuration for a regional tractor is a low roof day cab, although it does not make up a majority of trucks.

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[12] EPA, Final Rule for Greenhouse Gas Emissions and Fuel Efficiency Standards for Medium- and Heavy-Duty Engines and Vehicles - Phase 2, 2016. https://www.gpo.gov/fdsys/pkg/FR-2016-10-25/pdf/2016-21203.pdf

[13] Ford, Transit, 2018. https://www.ford.com/services/assets/Brochure?bodystyle=Van&make=Ford&model=Transit&year=2018

Table 20 shows the calculated fuel economies based on the assumptions above:

Table 20: Calculated diesel fuel economies

	Passenger van (mpg)	Delivery van (mpg)	Regional tractor (mpg)
2018-2020	23.22	7.41	5.87
2021	23.80	8.42	6.66
2022	24.44	8.42	6.66
2023	25.01	8.42	6.66
2024	25.70	9.28	7.03
2025	26.33	9.28	7.03
2026	27.02	9.28	7.03
2027+	27.72	9.73	7.30

Electric fuel economy

Fuel economy data is gathered from a number of sources including dynamometer testing and in-use data. We are assuming efficiency will improve at the same rate as GHG Phase 2.

- The UC Riverside report, "Performance Evaluation of TransPower All-Electric Class 8 On-Road Truck", noted that the TransPower truck was significantly more efficient than previous trucks tested. [14]
- Daimler Trucks North America President and CEO Roger Nielsen stated, "Customers aren't expecting to change their trade cycle…Just like [the trucks and engines designed to meet] diesel exhaust emissions, they should expect an improvement in energy consumption year over year." in a 2018 interview.[15]

Table 21 shows the assumptions used for electric efficiency:

Table 21: Electricity efficiency assumptions

	Passenger van (mi./kWh)	Delivery van (mi./kWh)	Regional tractor (mi./kWh)
2018-2020	1.79[16]	1.04[17]	0.48[18]
2021	1.83	1.18	0.54
2022	1.88	1.18	0.54
2023	1.92	1.18	0.54
2024	1.98	1.30	0.57
2025	2.03	1.30	0.57
2026	2.08	1.30	0.57

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[14] University of California, Riverside, Performance Evaluation of TransPower All-Electric Class 8 On-Road Truck, 2014.

[15] TruckingInfo, Daimler Deals with Booming Market, Preps Electric Trucks, 2018. https://www.truckinginfo.com/317878/dtna-deals-with-booming-market-preps-electric-trucks

[16] San Diego Airport Parking Company, Communication with SDAPC, 2017.

[17] Information received from fleet regarding a Class 6 parcel delivery van, 2017.

[18] University of California, Riverside, 2014.

2027+	2.13	1.37	0.59

<u>Hydrogen fuel economy</u>

Currently, there is limited to no information available on the efficiency of hydrogen vehicles. Due to this lack of data, a simplified calculation using LCFS EER values is used. The LCFS program assigns an Energy Efficiency Ratio for alternate fuels as compared to a reference fuel – either gasoline or diesel. A Class 2B-3 vehicle has a ratio of 2.5 and a Class 4-8 vehicle has a ratio of 1.9. This ratio is applied to the diesel fuel economies shown in table to estimate the hydrogen fuel economy as shown in Table 22.

Table 22: Estimated Hydrogen Fuel Cell Fuel Economy

	Passenger van (mi./kg)	Delivery van (mi./kg)	Regional tractor (mi./kg)
2018-2020	58.1	14.1	11.2
2021	59.5	16.0	12.7
2022	61.1	16.0	12.7
2023	62.5	16.0	12.7
2024	64.3	17.6	13.4
2025	65.8	17.6	13.4
2026	67.6	17.6	13.4
2027+	69.3	18.5	13.9

<u>Electricity fuel cost</u>

Electricity cost is determined using CARB's Battery Electric Truck and Bus Charging Cost Calculator (Charging Calculator).[19] Inputs for the charging calculator are listed in the Table 23.

Table 23: Electric vehicle charging assumptions

	Passenger Van	Delivery Van	Regional Tractor
Number of vehicles	20 vehicles		
Charger Rating	19 kW	19 kW	80 kW
Charger Efficiency	90%		
Daily Miles	100 mi.	100 mi.	150 mi.
Energy Efficiency	0.56 kWh/mi.	0.96 kWh/mi.	2.1 kWh/mi.
Local Taxes and Fees	3% taxes and other fees		

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[19] CARB, Battery Electric Truck and Bus Charging Calculator, 2018. https://ww2.arb.ca.gov/resources/documents/battery-electric-truck-and-bus-charging-cost-calculator

Charging Period	Late evening charging period(9 PM – 6 AM)		
Charging Strategy	Managed Charging		
LADWP Rate	A-2(B)	A-2(B)	A-2(B)
PG&E Rate	CEV-L @ 350 kW	CEV-L @ 400 kW	CEV-L @ 1,200 kW
SMUD Rate	GS-GSS_T	GS-GSS_T	GS-TOU2
SDG&E Rate	AL-TOU2, EECC-CPP-D	AL-TOU2, EECC-CPP-D	AL-TOU2, EECC-CPP-D
SCE Rate	EV-8	EV-8	EV-9

Weights for the statewide average are determined from the California Energy Commission's Energy Consumption Database for Electricity Consumption in 2016 and are shown in Table 24.[20]

Table 24: Energy consumption by utility

Utility Provider	Total Usage (GWh)
Los Angeles Department of Water and Power	23,495
Pacific Gas and Electric	83,408
Sacramento Municipal Utility District	10,485
San Diego Gas and Electric	19,169
Southern California Edison	85,448

These inputs are used with the charging calculator to generate the expected electricity prices and the statewide average as shown in Table 25.

Table 25: Cost per kWh per utility and statewide average

	Passenger van ($/kWh)	Delivery van ($/kWh)	Regional tractor ($/kWh)
LADWP	$0.10	$0.10	$0.10
PG&E	$0.15	$0.14	$0.13
SMUD	$0.14	$0.11	$0.11
SDG&E	$0.21	$0.20	$0.19
SCE	$0.13	$0.12	$0.11
Weighted Average	**$0.14**	**$0.13**	**$0.12**

Electricity prices are expected to change over time. The US Energy Information Administration (EIA) has modeled potential electricity cost changes out to 2050 in their Annual Energy Outlook (AEO) "Energy Prices by Sector and Source" table, Pacific region. [21] These changes are displayed in Table 26.

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[20] California Energy Commission, California Energy Consumption Database, 2018. http://www.ecdms.energy.ca.gov/

[21] Energy Intelligence Agency, 2018.

Table 26: Cumulative electricity price growth per year

Year	Cumulative Electricity Cost Growth
2019	100%
2020	106%
2021	106%
2022	110%
2023	115%
2024	121%
2025	128%
2026	130%
2027	134%
2028	138%
2029	140%
2030	140%
2031	141%
2032	142%
2033	143%
2034	143%
2035	143%
2036	143%
2037	143%
2038	142%
2039	141%
2040	141%
2041	140%
2042	138%
2043	137%
2044	137%
2045	136%
2046	134%
2047	134%
2048	133%
2049	132%
2050	131%

Hydrogen fuel cost

Trillium projected hydrogen costs at different volume thresholds using four different production methods.[22] Trillium provided updated numbers in an email conversation with CARB afterwards, shown in Table 27.[23]

Table 27: Trillium Projected Hydrogen Costs

H_2 Volume	Gaseous Delivery ($/kg)	Liquid Delivery ($/kg)	On-site SMR ($/kg)	On-site Electrolysis ($/kg)
Low Volume 150 kg/day	$11.49	$10.21	$10.43	$11.05
Intermediate Volume 1,000 kg/day	$7.67	$6.39	$5.81	$6.46
High Volume 6,000 kg/day	$5.72	$4.43	$4.21	$4.90

This report uses their liquid hydrogen delivery numbers based on what Trillium presented as being most feasible for production at scale. The low volume cost will be used in 2018, the intermediate volume in 2030, and the high volume in 2050 with intermediate years being interpolated. These assumptions are based on expecting low volume production today, intermediate volume by 2030 when we would some moderate sized deployments but no complete conversions yet, and continuing price reductions out to 2050.

Low Carbon Fuel Standard

The Low Carbon Fuel Standard (LCFS) program requires fuel producers to lower the carbon intensity (CI) of their fuel or purchase credits from low carbon intensity (CI) fuel producers.

Fossil fuels are deficit generators while fleets using low CI fuels such as electricity or hydrogen are eligible to earn LCFS credits to be sold for revenue. Credit revenue to 2030 were calculated using the LCFS Credit Price Calculator.[24] Due to differing Energy Economy Ratio (EER) values and reference fuels, the credits generated for Class 2B-3 and Class 4-8 vehicles are different.

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[22] Trillium, APTA's Fuel Cell Electric Bus Infrastructure Webinar, 2018. https://www.apta.com/resources/standards/quarterly-webinar-series/Documents/APTA%20Webinar%20on%20Fuel%20Cell%20Electric%20Bus%20Infrastructure%20for%20100-Bus%20Fleet%209-20-18%20FINAL.pdf

[23] Trillium, Email conversation with Trillium, 2018.

[24] CARB, LCFS Credit Price Calculator, 2018, https://www.arb.ca.gov/fuels/lcfs/dashboard/creditpricecalculator.xlsx

The LCFS revenue for a battery-electric vehicle depends on the vehicle and the electricity used. For this report, we are assuming vehicles will be charged using grid electricity at a CI of 93.75. The EER for a battery-electric Class 2B-3 vehicle is 3.4 and the value for a battery-electric Class 4-8 vehicle is 5.0. For fleets using electricity as a transportation fuel, Table 28 shows the expected credit revenue per kWh used:

Table 28: LCFS revenue generated for a battery-electric vehicle at $100/credit

Year	Class 2B-3 ($/kWh)	Class 4-8 ($/kWh)
2018	$0.081	$0.141
2019	$0.080	$0.136
2020	$0.079	$0.133
2021	$0.077	$0.131
2022	$0.076	$0.129
2023	$0.074	$0.127
2024	$0.073	$0.124
2025	$0.071	$0.122
2026	$0.070	$0.120
2027	$0.068	$0.118
2028	$0.067	$0.115
2029	$0.065	$0.113
2030 and beyond	$0.064	$0.111

Note: the CI for electricity is projected to drop due to requirements of SB 100 which will result in a lower CI than 93.75. This will result in higher revenues than those depicted above.

The LCFS revenue for a hydrogen fuel cell vehicle depends on the production method for the hydrogen. Liquefied hydrogen from landfill gas steam methane reformation was selected for this analysis because 1) it is one of the two liquefied hydrogen pathways with a lookup value in the LCFS rulemaking, and we are assuming liquid delivery of hydrogen and 2) state law (SB 1505) requires one-third of the statewide hydrogen is renewable, and the state's hydrogen community have made clear that renewable hydrogen is a key part of the future hydrogen economy.[25] This fuel has a CI of 129.09. The EER for a hydrogen fuel cell Class 2B-3 vehicle is 2.5 and the value for a battery-electric Class 4-8 vehicle is 1.9. For fleets using hydrogen as a transportation fuel, Table 29 shows the expected credit revenue per kg used:

Table 29: LCFS revenue generated for a hydrogen fuel cell vehicle at $100/credit

Year	Class 2B-3 ($/kg)	Class 4-8 ($/kg)
2018	$1.257	$0.660
2019	$1.248	$0.598

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[25] California Fuel Cell Partnership, The California Fuel Cell Revolution, 2018. https://cafcp.org/sites/default/files/CAFCR.pdf

2020	$1.210	$0.569
2021	$1.173	$0.541
2022	$1.136	$0.512
2023	$1.099	$0.484
2024	$1.061	$0.455
2025	$1.024	$0.426
2026	$0.987	$0.398
2027	$0.949	$0.369
2028	$0.912	$0.340
2029	$0.875	$0.312
2030 and beyond	$0.837	$0.283

<u>Maintenance</u>

The maintenance cost reflects the cost of labor and parts for routine maintenance, preventative maintenance, and fixing broken components. Table 30 shows all data sources we are aware of that estimates maintenance cost per mile for a variety of vehicles.

Table 30: Maintenance cost sources

Cost ($/mi.)	Vehicle Studied	Data Source
Passenger/Cargo Van		
$0.16	ADA Minivan – CNG	Access LA Report[26]
$0.20	ADA Minivan – Gasoline	Access LA Report
$0.140	Diesel SUV	CEC Presentation[27]
Pickup		
$0.16	1/2 Ton Pickup – 4x2 and 4x4	Utilimarc Report[28]
$0.068	Compact Pickup – Gasoline	CEC Presentation
$0.062	Midsize Pickup – Gasoline	CEC Presentation
$0.083	1/2 Ton Pickup	AAA Brochure[29]
Stepvan		
$0.223	Class 4 Diesel	2011 NREL Report[30]
$0.206	Class 4 Hybrid Gasoline	2011 NREL Report

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[26] Access LA, Access LA Fleet Design, 2017. https://www.sacog.org/sites/main/files/file-attachments/access_la_life_cycle.pdf

[27] California Energy Commission, Maintenance Cost Attributes for Light Duty Vehicles, 2015. https://efiling.energy.ca.gov/getdocument.aspx?tn=206183

[28] Utilimarc, ½ Ton Pickup Truck Data, 2015. http://fleetanswers.com/sites/default/files/Pickup%20Article%20Jan%202015%20%281%29_0.pdf

[29] AAA, Driving Costs: 2017 Update, 2017. http://exchange.aaa.com/wp-content/uploads/2017/08/17-0013_Your-Driving-Costs-Brochure-2017-FNL-CX-1.pdf

[30] National Renewable Energy Laboratory, FedEx Express Gasoline Hybrid Electric Delivery Truck Evaluation: 12-Month Report, 2011. https://www.nrel.gov/docs/fy11osti/48896.pdf

$0.130	Class 4 Diesel	2012a NREL UPS Study[31]
$0.141	Class 4 1st Gen Hybrid Diesel	2012a NREL UPS Study
$0.168	Class 6 Diesel	2012b NREL UPS Study[32]
$0.219	Class 6 2nd Gen Hybrid Diesel	2012b NREL UPS Study
$0.22	Class 6 Diesel	Fleet estimate
$0.236*	Class 4 Diesel	2002 NREL UPS Study[33]
$0.263*	Class 4 CNG	2002 NREL UPS Study
Cutaway Shuttle		
$0.290	Class A,B,C Cutaway	Access LA Report
Straight Truck/Box Truck		
$0.140	Class 7 Straight Truck – Hybrid	2012 NREL Coca-Cola Study[34]
$0.290	Class 7 Straight Truck – Diesel	2012 NREL Coca-Cola Study
$0.31	Straight Truck	2017 ATRI Report[35]
Tractor Trailer		
$0.19	Class 8 Tractor – LTL	2018 ATRI Report[36]
$0.22	Class 8 Tractor – Specialized	2018 ATRI Report
$0.13	Class 8 Tractor – TL	2018 ATRI Report
$0.144	Class 8 Tractor	Fleet Advantage[37]
$0.28	Class 8 Diesel	Manufacturer estimate
$0.19	Class 8 Drayage	Bloomberg[38]
Refuse Truck		
$0.799	Class 8 Diesel	M.J. Bradley and Associates[39]

*Data from 2002 has been adjusted using CPI

Based on the above data sources, we will be using the following maintenance cost numbers for this report

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[31] National Renewable Energy Laboratory, Thirty-Six Month Evaluation of UPS Diesel Hybrid-Electric Delivery Vans, 2012. https://www.nrel.gov/docs/fy12osti/53503.pdf

[32] National Renewable Energy Laboratory, Eighteen-Month Final Evaluation of UPS Second Generation Diesel Hybrid-Electric Delivery Vans, 2012. https://www.nrel.gov/docs/fy12osti/55658.pdf

[33] National Renewable Energy Laboratory, UPS CNG Test Fleet, 2002. https://www.nrel.gov/docs/fy02osti/31227.pdf

[34] National Renewable Energy Laboratory, Coca-Cola Refreshments Class 8 Diesel Electric Hybrid Tractor Evaluation: 13-Month Final Report, 2012. https://www.nrel.gov/docs/fy12osti/53502.pdf

[35] American Truck Research Institute, An Analysis of the Operational Costs of Trucking: 2017 Update, 2017. http://atri-online.org/wp-content/uploads/2017/10/ATRI-Operational-Costs-of-Trucking-2017-10-2017.pdf

[36] American Truck Research Institute, 2018.

[37] Fleet Advantage, Mitigating Rising M&R Costs for Class-8 Truck Fleets, 2018. http://info.fleetadvantage.com/mitigating-rising-fleet-maintenance-and-repair-costs-for-class-8-trucks

[38] Bloomberg, What Tesla's Big Rig Must Do to Seduce Truckers, 2017. https://www.bloomberg.com/news/articles/2017-11-15/what-tesla-s-semi-truck-must-do-to-seduce-truckers

[39] M.J. Bradley & Associates, New York City Commercial Refuse Truck Age Out Analysis, 2013. https://www.mjbradley.com/sites/default/files/EDF-BIC-Refuse-Truck-Report-2013.pdf

- For passenger vans, we are averaging the three sources since none of them are a perfect match for a diesel passenger van. This ends up being $0.17/mi.
- For delivery vans, we will be using the fleet estimate of $0.22/mi. as this number is testimony from a major fleet and matches up with the other data sources well.
- For the regional tractor, we will be using the Less than Truckload (LTL) value of $0.19/mi. from the ATRI report. LTL operations generally perform the most stop-and-go travel of the three and, as a result, represent shorter haul the best.

We are estimating a 25% maintenance cost reduction for battery-electric HD vehicles.

- A paper by Propfe, B. et. al. estimates based on a component level analysis that a battery-electric light-duty vehicle will have maintenance costs 20% lower than a comparable ICE vehicle while an extended-range electric vehicle could see maintenance savings of nearly 30%.[40]
- A paper by Taefi, T. et. al. found an estimated 20%-30% maintenance savings on electric freight vehicles based on feedback from fleets operating these vehicles.[41]
- A whitepaper by the Electrification Coalition estimated a battery-electric car have 28% reduced maintenance costs compared to a gasoline car, and a plug-in hybrid would have 6% reduced maintenance costs.[42]
- A CARB study analyzed data available on the maintenance cost of battery-electric buses versus diesel and CNG buses. It found the maintenance cost of a battery-electric bus was $0.60/mi. versus $0.85/mi. for a diesel or $0.79/mi. CNG bus, reflecting a 30% maintenance cost reduction.[43]
- A report by Gladstein, Neandross, and Associates cites a 50% maintenance cost reduction for battery-electric trucks based on feedback from manufacturers.[44]
- Numerous electric vehicle manufacturers that staff has spoken to are seeing an 80% reduction in maintenance costs, although this is based on limited data.

We are estimating hydrogen fuel cell vehicles to have equivalent maintenance cost to diesel.

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[40] Propfe, B. et.al. Cost analysis of Plug-in Hybrid Electric Vehicles including Maintenance & Repair Costs and Resale Values, 2012. http://www.mdpi.com/2032-6653/5/4/886

[41] Taefi, T. et.al. Comparative Analysis of European examples of Freight Electric Vehicle Schemes, 2014. http://nrl.northumbria.ac.uk/15185/1/Bremen_final_paperShoter.pdf

[42] Electrification Coalition, State of the Plug-in Electric Vehicle Market, 2013. https://www.pwc.com/gx/en/automotive/industry-publications-and-thought-leadership/assets/pwc-ec-state-of-pev-market-final.pdf

[43] California Air Resources Board, Literature Review on Transit Bus Maintenance Cost, 2016. https://www.arb.ca.gov/msprog/bus/maintenance_cost.pdf

[44] Gladstein, Neandross, and Associates, Draft 2018 Feasibility Assessment for Drayage Trucks, 2018. http://www.cleanairactionplan.org/documents/draft-drayage-truck-feasibility-assesment.pdf/

- Ballard recommends estimating a fuel cell bus's maintenance costs as the same as a battery-electric bus plus $0.20/mi. for fuel cell maintenance. This adjustment will put a fuel cell bus in line with a diesel or CNG bus.[45]

The maintenance cost assumptions used in this report are summarized in Table 31.

Table 31: Maintenance Cost Estimates

	Passenger van	Delivery van	Regional tractor
Diesel Cost	$0.17/mile	$0.22/mile	$0.19/mile
Electric Cost	25% lower than diesel		
HFC Cost	Equivalent to diesel		

<u>Registration Fees</u>

Vehicles operating and registered in California must pay an annual registration fee. The registration fee has a fixed portion and portions that depend on the vehicle's cost, age, and weight. Additionally, the calculation is different for conventional HD vehicles and zero-emission HD vehicles. Note that all zero-emission trucks have the same fee schedule; there is no explicit difference between battery-electric and hydrogen fuel cell trucks.

For this analysis, the registration is broken into four main components:

- Fixed fees: identical for all vehicles modeled in this report
- Vehicle License Fee: based on the cost and age of the vehicle
- Weight Fee: based on the registered weight of the vehicle
- Transportation Improvement Fee: based on the vehicle's cost

The fixed fee is the sum of all fees that stay constant across all vehicles we model. These fees vary slightly from county to county; the ones shown here are specifically for Sacramento County.[46] . They are displayed in Table 32.

Table 32: Fixed registration fees

Fee Name	Amount
Diesel	$247
Zero-emission	$95

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[45] Ballard, Fuel Cell Electric Buses: Proven Performance and the Way Forward, 2018. https://info.ballard.com/fuel-cell-electric-buses-proven-performance-white-paper?hsCtaTracking=ab0058ba-1240-4ab6-a4e6-0032faf329b7%7Cd0616627-31ce-416a-bbe8-d036529a4d75

[46] California Department of Motor Vehicles, Vehicle Registration Calculator, 2018. https://www.dmv.ca.gov/wasapp/FeeCalculatorWeb/newVehicleFees.do

The Vehicle License fee is calculated by multiplying the cost of the vehicle by 0.65%. This amount decreases over time based on a schedule from 100% in year one to 15% in year 11 and beyond.[47] This is the same for diesel and zero-emission trucks.

Diesel and zero-emission trucks pay different weight fees which result in savings for the zero-emission trucks.[48] Table 33 shows the assumptions we are making for weight fees.

Table 33: Vehicle Weight fee assumptions

	Passenger van	Delivery van	Regional tractor
Registered Weight	15,000 lb.	26,000 lb.	80,000 lb.
Diesel Weight Fee	$332	$546	$2,064
Zero-emission Weight Fee	$266	$358	$358

The Transportation Improvement Fee is based on the value of the vehicle at purchase. It is the same for both diesel and zero-emission vehicles. For vehicles with a price between $35,000 and $59,999, the fee is $150 annually. For vehicles with a price above $60,000, the fee is $175 annually.

Based on the above values, the cumulative registration costs for these vehicles are shown in Table 34 through Table 36.

Table 34: Cumulative lifetime registration fees for a 2018 vehicle

2018	Diesel	Battery-Electric	Hydrogen Fuel Cell
Passenger Van	$8,331	$7,509	$13,919
Stepvan	$11,592	$10,860	$15,482
Day Cab Tractor	$27,545	$21,472	$26,548

Table 35: Cumulative lifetime registration fees for a 2024 vehicle

2024	Diesel	Battery-Electric	Hydrogen Fuel Cell
Passenger Van	$8,363	$6,645	$10,867
Stepvan	$11,658	$9,179	$12,741
Day Cab Tractor	$27,878	$13,484	$20,046

Table 36: Cumulative lifetime registration fees for a 2030 vehicle

2030	Diesel	Battery-Electric	Hydrogen Fuel Cell
Passenger Van	$8,376	$6,521	$7,801

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[47] California Legislative Analyst's Office, A Primer on the Vehicle License Fee, 1998. https://lao.ca.gov/1998/061798_vlf_primer/061798_vlf.html

[48] California Department of Motor Vehicles, Registering Commercial Vehicles and PTI Trailers, 2014. https://www.dmv.ca.gov/portal/wcm/connect/3f3a5df8-3db5-42ba-b3c4-f6b92ae032c9/ffvr27.pdf?MOD=AJPERES&CVID=

Stepvan	$11,679	$8,889	$9,961
Day Cab Tractor	$27,955	$12,293	$13,333