Title

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Evaluation of the Economics of Battery-Electric and Fuel Cell Trucks and Buses: Methods, Issues, and Results

Andrew Burke, Marshall Miller, Anish Sinha, Lew Fulton

STEPS+ Sustainable Freight Research Program Report
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Abstract

This study evaluates the economics of various types and classes of medium-duty and heavy-duty battery-electric and hydrogen fuel cell vehicles relative to the corresponding diesel-engine powered vehicle for 2020-2040. The study includes: large passenger vans, class 3 city delivery vans, class 4 step city delivery trucks, class 6 box trucks, class 7 box trucks, class 8 box trucks, city transit buses, long haul tractor trailer trucks, city short haul tractor trailer delivery trucks, inter-city buses, and HD pickup trucks. Typical designs were formulated for each vehicle type in terms of its road driving and load characteristics and powertrain and energy storage components. The performance and energy consumption of the electrified trucks were simulated for appropriate driving cycles using the ADVISOR simulation program. The vehicle design characteristics were varied over 2020-2040 to reflect expected technology improvements. The study then focused on estimating the initial cost and total cost of ownership (TCO) for each vehicle type over the initial 5-year period and the 15-year lifetime and calculating payback periods. Calculations were done for 2020, 2025, 2030, 2035, and 2040. The analysis particularly focuses on 2025 and 2030 since these are the most relevant years for initial market penetration.

For both battery and fuel cell vehicles, thanks to technology cost reductions, the initial cost generally decreases markedly in the period 2020-2030 and more modestly for 2030-2040. Assuming fairly constant electric prices, declining hydrogen prices, and slowly rising diesel prices, TCOs for the various electrified truck types typically become less than that of the corresponding diesel truck before the initial cost of the electrified trucks gets close to that for the diesel truck. For most battery-electric truck types, TCO competitiveness occurs by 2025. For that year, the payback time for most truck types is 4-6 years and is less than 4 years by 2030. Fuel cell vehicles take longer to pay back due mainly to hydrogen fuel costs remaining above diesel prices on an energy basis. Fuel cell truck payback times of 3-5 years by 2030 can be achieved if the cost of hydrogen in that year is reduced below $7/kg. Fuel cell buses have payback times of less than one year in 2030. By 2030, the purchase cost of most types of both battery-electric and hydrogen fuel cell trucks is close to that of the corresponding diesel vehicle and TCOs are competitive as long as battery costs and fuel cell costs drop per our expectations along with moderate electricity and hydrogen costs. The cost sensitivity results indicated these conclusions were not significantly changed by reasonable variations in the major cost inputs (battery, fuel cell, hydrogen, electricity and diesel fuel) assumed in the economic analyses.

Contents

Executive Summary

There is currently much activity concerned with the introduction of battery-electric and fuel cell trucks into the commercial market in California. California Air Resources Board (CARB) has established a ZEV (zero emission vehicle, including battery electric and fuel cell) truck sales mandate, starting in 2024. Truck manufacturers have begun announcing their plans for producing ZEV trucks regularly. Many fleets are considering or actively purchasing ZEV trucks and buses. A key issue is a large uncertainty surrounding the economics of ZEV trucks compared with the diesel or gasoline engine powered trucks with which they will compete.

The objective of this paper is to quantify the relative costs and address the uncertainty in both the initial cost of zero-emission trucks of various classes and their total ownership costs over different periods of ownership. We have developed cost models and specific estimates that are sufficiently detailed to make important comparisons over the near and longer term. In this paper, we present these and attempt to make our inputs and assumptions clear, including the sources and magnitudes of important uncertainties. Our short term estimates (2020-2025) and longer term (2030-2040) provide a sense of how vehicle costs may evolve, as battery-electric and fuel cell truck technologies mature and sales volumes increase.

Cost analysis structure and inputs

The economic decision factors evaluated in this study are straightforward. These cost factors are those that would be of interest to truck and bus buyers making decisions whether to purchase electrified trucks or to continue to purchase conventional engine-powered trucks. We consider four types of economic cost comparison:

- The initial purchase cost of the ZEV trucks and buses, compared to the conventional truck of the same types and size, and comparable utility (useable range).
- The total cost of operation (TCO) of the trucks, considering amortized purchase cost, fuel cost, and maintenance cost over a five-year ownership period, and with a specified resale value at the end of this period. This attempts to capture the typical fleet perspective.
- The TCO of the trucks over a 15-year time frame, with a low discount rate, attempts to capture the societal perspective on relative cost.
- The payback period for purchasing ZEV trucks is compared to the base diesel vehicle.

The purchase cost of ZEV trucks and buses will depend to a large extent on the required driving range of the truck and the battery cost ($/kWh) or fuel cell system cost ($/kW), both of which are expected to decrease between 2020 and 2030. Another key factor, which affects both the initial cost and the energy cost of vehicles is the energy efficiency (kWh/mi) in actual operation, which can vary depending on changes in the route, weather, and traffic. This factor is critical because the energy use cost ($/mi) of an electric vehicle typically is significantly less than that of an internal combustion engine (ICE) powered vehicle and that difference can be used to offset the higher initial cost of the electric vehicle. The TCO cost is the accumulated operating cost of the vehicle over its lifetime. We assume average values for vehicle maintenance costs ($/mi).

All four of these metrics provide insights into the economics of electrified vehicles. The relative importance to truck buyers of the initial cost and the ownership cost will vary depending on the size of their fleet and how they are planning to finance the purchase and operate the truck. Hence both the initial and total ownership costs are needed to evaluate the economics of electric truck purchases and operation. A further metric that we consider is payback time, which combines the effects of the initial cost difference and the operation costs. When the first is higher and the latter is lower than the comparative vehicle, the payback time (in years or miles) can be fairly low and encourage fleets to purchase the more expensive vehicle. All of these cost factors were evaluated in this study and are discussed for battery-electric and fuel cell trucks of various weight classes (2-8).

The economics of the various truck and bus classes have been analyzed using a set of spreadsheet models in which the characteristics of the battery-electric and fuel cell trucks were described in detail, along with the incumbent diesel truck technology projected into the future. The inputs for the models were varied systematically for 2020-2040 as the technologies matured and the battery and fuel cell costs decreased. We focus our results on 2020, 2030 and 2040, which are approximate dates reflecting current, medium term and long-term improvements and cost reductions in the various technologies.

We summarize five types of key inputs and assumptions in Table ES-1: battery system costs, fuel cell system costs, green (electrolytic) hydrogen costs, electricity (increasingly green) prices, and diesel fuel prices. In the main report, we consider low, medium (base) and high cost scenarios for each type of cost. Here we focus on the base cost results. The original equipment manufacturer (OEM) battery and fuel cell costs are modified with an integration factor to reflect the cost to the vehicle manufacturers to assemble/integrate the new electric drive components into the vehicle. All the input costs decline over time with learning and as the production volumes increase, given a successful introduction of battery electric and fuel cell trucks in each market class.

Table ES-1: Base case cost inputs to analysis for five key variables

Mid-range assumed values	2020	2025	2030	2035	2040
Battery costs (\$/kWh)	225	175	100	85	70
Fuel cell system costs (\$/kW)	525	193	118	95	78
Hydrogen costs (\$/kg)	12	8.5	7.5	6	5
Electricity costs (\$/kWh)	0.17	0.17	0.17	0.17	0.17
Diesel fuel cost (\$/gal)	3.25	3.30	3.75	4.00	4.00

One caveat related to the analysis (and to this table) is that a detailed analysis of the cost of refueling infrastructure for battery-electric and hydrogen fuel-cell trucks was not considered in the present analysis with simplified assumptions made and included in fuel price. Much better estimates of future delivered energy costs, especially for electricity in different situations, are needed. This will be important in determining the success of marketing battery electric trucks and also influence energy costs for fuel cell vehicles. Unlike light-duty vehicles that need to be refueled relatively infrequently, high-travel commercial medium and heavy-duty trucks will need to be refueled daily. This will put increased demands on the infrastructure for commercial vehicles.

Results and analysis

While the analysis includes results for the 2020-2040 timeframe, we focus here on the 2025 and 2030 results since these are most relevant to ZEV market penetration over the next decade. We also focus here on our purchase cost and TCO results, while payback times are also considered in the body of the paper.

The main results using our cost metrics are summarized in three figures below. First, the initial purchase cost results for transit buses and 5 types of trucks are summarized in Figure ES-1. This includes two types of long-haul trucks (300- and 500-mile range), short haul trucks, delivery trucks and heavy-duty pickups.

In 2025 for all the BEV and FCEV trucks, the initial purchase costs are much higher than the cost of purchasing a diesel truck. This reflects both an expected modest volume and a high component cost situation. However, by 2030 BEV and FCEV purchase costs drop considerably and become competitive with diesel for several truck types; fuel cells become nearly competitive with diesel for all truck types though still somewhat more expensive for the long haul. They also notably have a lower purchase cost than battery-electric trucks for all types except heavy-duty pickups. Heavy-duty trucks having a 150-mile range will be reasonably close in purchase cost to diesel but are still much higher for 300 and 500-mile long haul. Fuel-cell vehicles used in urban areas are also projected to be competitive with diesel vehicles and will have a small purchase cost advantage over battery-electric vehicles.

Figure ES-1: Purchase costs ($K) of diesel, fuel cell and battery electric trucks, 2025 and 2030

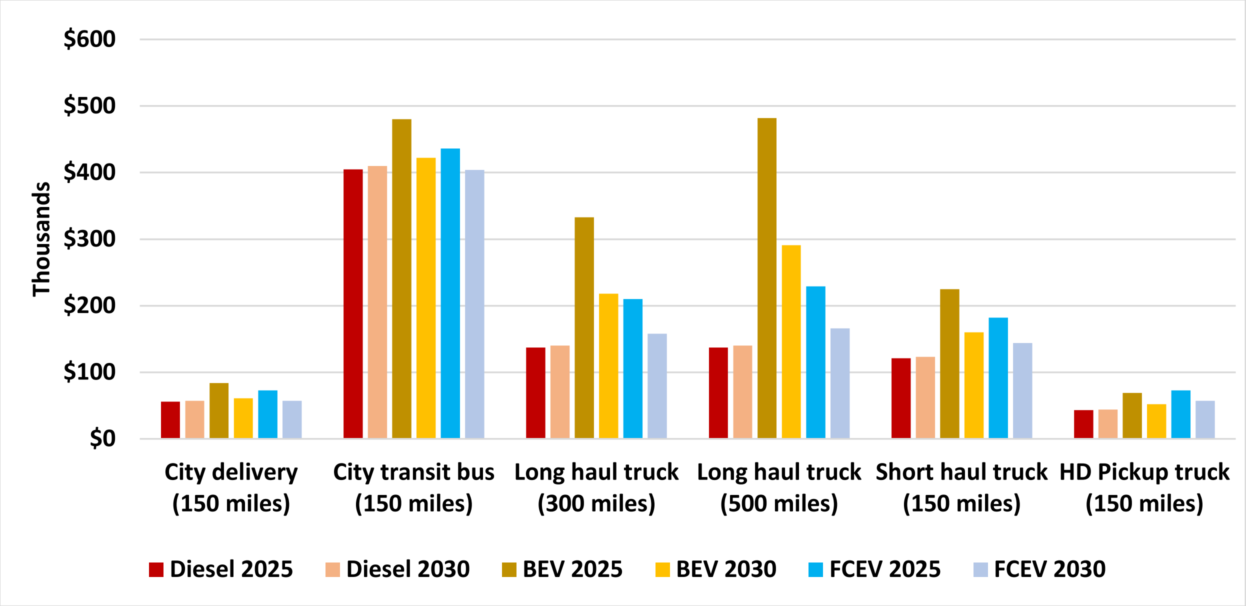
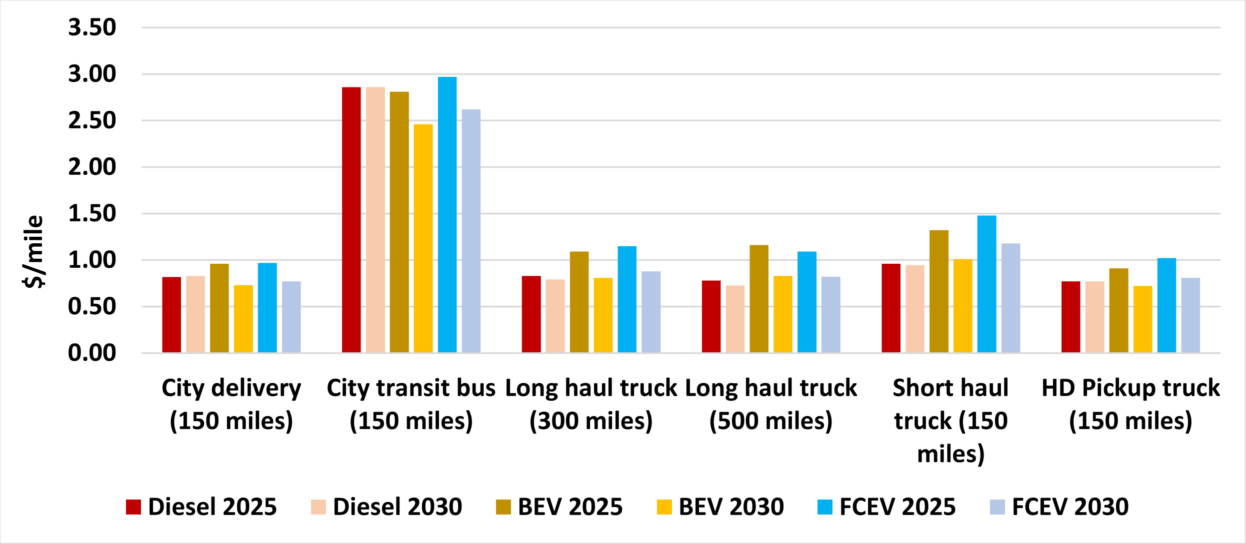


Figure ES-2 shows the total cost of ownership (TCO), on 5-year ownership and then resale basis. The story shifts with consideration of the full TCO. Battery-electric vehicles do much better given their lower energy costs than fuel cells, and are close to competitive across truck types by 2025 (and fully competitive with diesel buses). By 2030, the battery-electric trucks have lower TCO in city usage and only slightly higher for long distance usage. In 2030, the fuel-cell vehicles have higher 5 yr TCOs than the comparable battery-electric vehicles, but in most cases close to that of the diesel vehicles. Notably, for

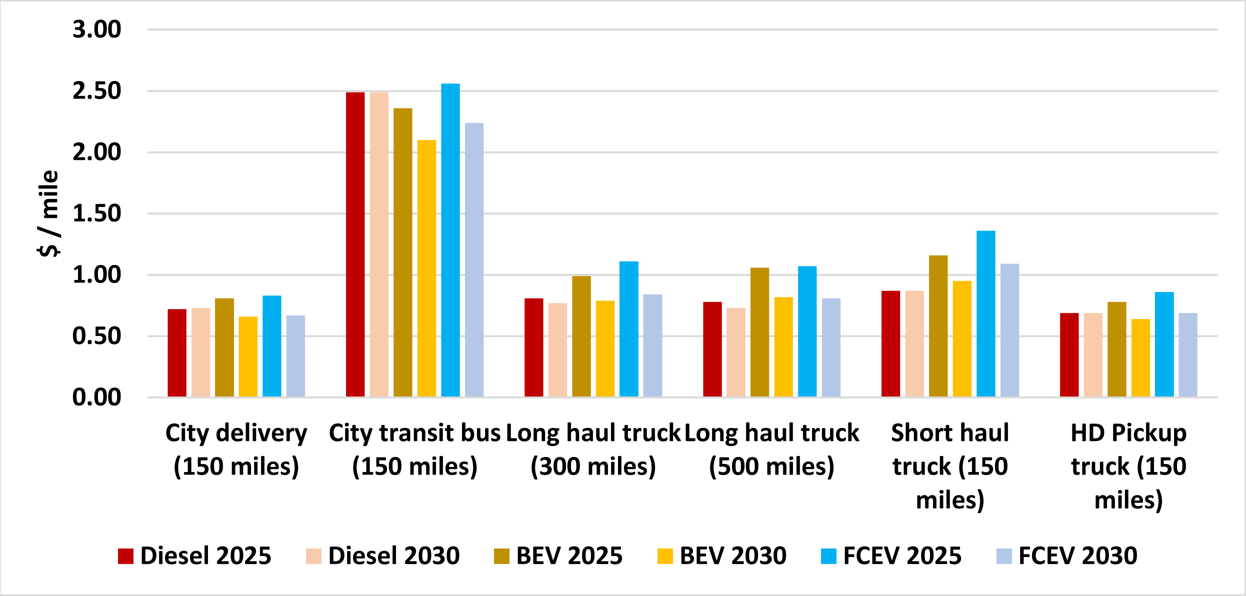
300 and 500-mile long-haul trucks, both BEVs and FCEVs are more competitive with diesel on a TCO basis than on initial cost.

Figure ES-2: TCO-5yr ownership costs for electrified trucks, 2025-2030



The study also considered a TCO case with 15-year ownership and no resale value (vehicle lifetime analysis). In this case, we used a 3% discount rate and declining travel per year as the truck aged. These results are closer to a "societal cost" estimation, taking into account all miles driven and social cost discounting. The results are shown in Figure ES-3. The 15-year ownership costs ($/mi) are slightly lower than the corresponding values for the 5 years, but the costs relative to the diesel vehicle are similar. By 2030, the lifetime TCO results for most of the battery-electric and fuel cell truck types are less than or close to those of the corresponding diesel truck. The highest 2030 cost increment is for fuel-cell trucks in short haul heavy-duty applications.

Figure ES-3: TCO-15yr ownership costs for electrified trucks, 2025-2030



Sensitivity analysis

The "base case" results shown above do not capture the wide range of variation that is possible in future costs. For all five of our main cost parameters, we have estimated low and high case values that are almost equally plausible as our central estimates (Table ES-2). We have no way to estimate the actual probability that any of these cases will play out in reality, but here we show an example for one truck type of how the relative cost per mile of TCO, in the 5 year case, could vary.

Table ES-2: Variation in key parameters by case, in 2025 and 2030

	Diesel ($/gal)			Electricity ($/kWh)			Hydrogen ($/kg)		
Year	Low	Base	High	Low	Base	High	Low	Base	High
2025	2.63	3.50	4.38	0.12	0.17	0.27	7.00	8.50	12.00
2030	2.81	3.75	4.69	0.12	0.17	0.27	6.00	7.00	9.00

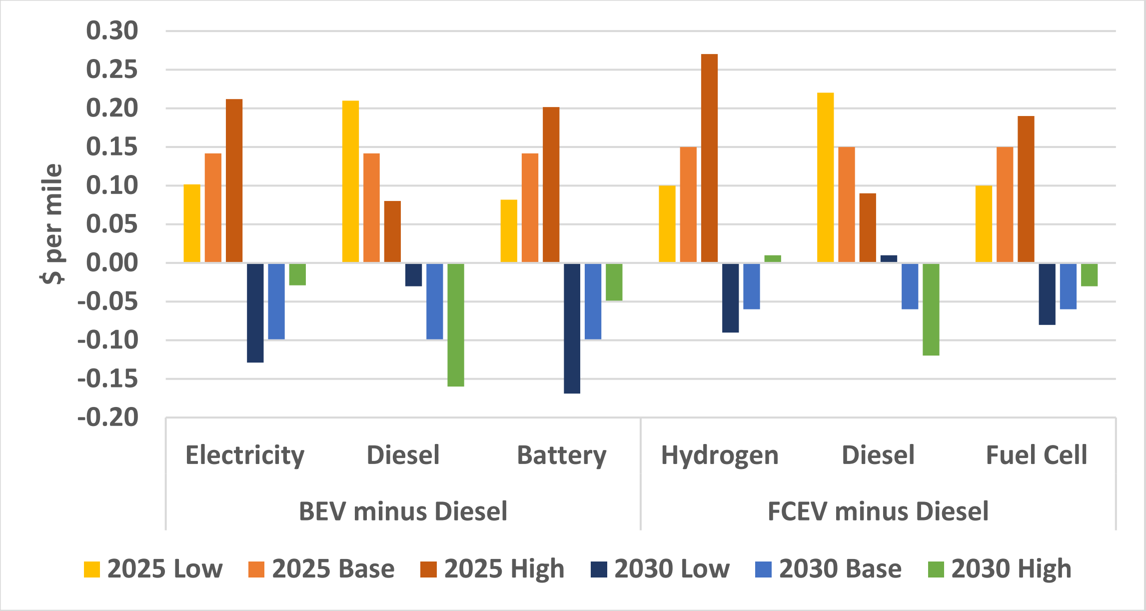
	Battery ($/kWh)			Fuel Cell ($/kW)		
Year	Low	Base	High	Low	Base	High
2025	150	175	200	145	193	240
2030	75	100	125	90	118	145

Figure ES-4 shows the variation in TCO across the low, mid, and high cost cases for BEV and FCEV delivery trucks. The yellow/orange bars show variations in 2025, while blue/green bars show 2030.

In 2025, BEV trucks have a base case TCO about $0.15 higher than diesel trucks, but this can range from about $0.10 to over $0.20. Fuel cells center at $0.18 more expensive but range from $0.12 to $0.30. By 2030, the central case for both technologies is cheaper than diesel (negative cost difference), with as much as a $0.15 advantage for BEVs and $0.09 for FCEVs, and as little as a $0.04 advantage for BEVs and up to $0.04 higher than diesel for FCEVs. If one were to combine low end or high end for multiple parameters, bigger ranges would result, but the probability of 2 or more low end or high-end outcomes together is typically much lower than other combinations.

Sensitivity cases for other truck and bus technologies, shown in the body of the report, indicate a similar result – there is variation across technologies but not big enough to dramatically alter their relative cost effectiveness in any given year.

Figure ES-4: Variations in TCO for delivery trucks, by technology and sensitivity case



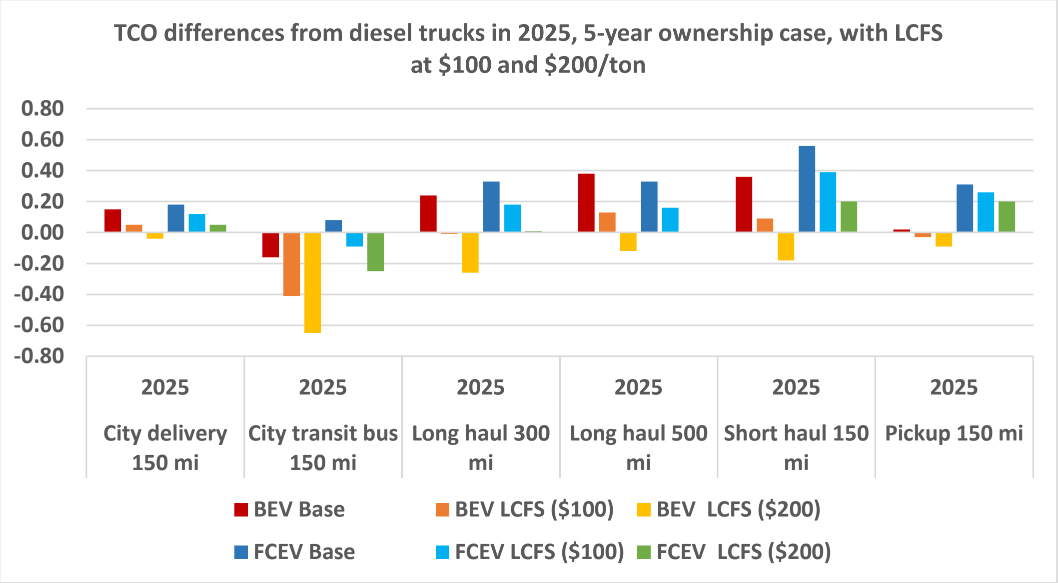
Note: As per the X-axis, sensitivity cases include varying electricity price, diesel price, battery price, hydrogen price and fuel cell vehicle price.

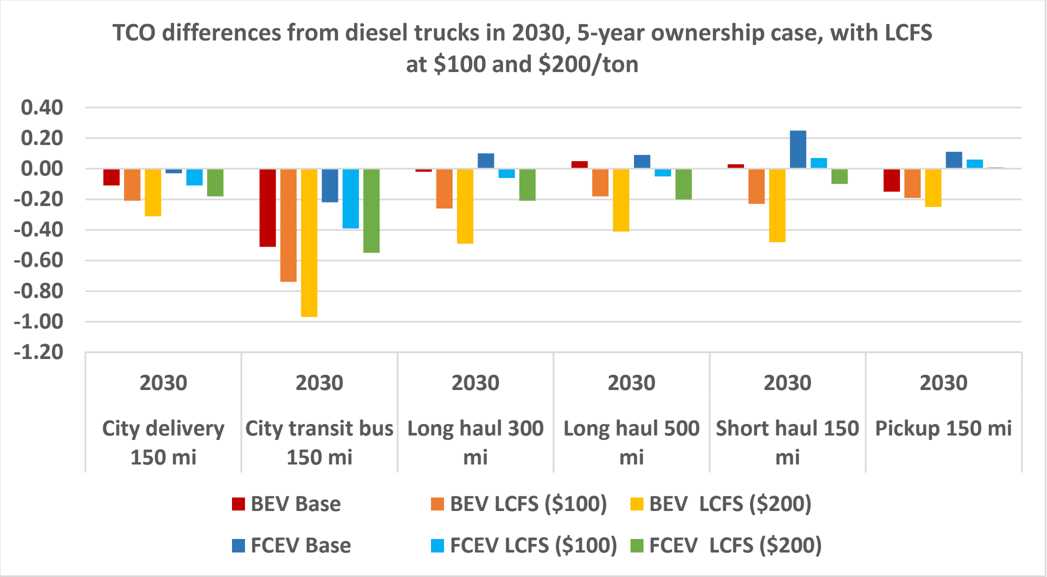
Effects of applying LCFS and carbon cost to TCO estimates

In addition to the sensitivity cases, we considered how the results change if the value of CO2 abatement is considered and included in the calculations. We did this two ways: first, by including the credit that would be received in the Low Carbon Fuel Standard (LCFS) program given the carbon intensities of different technologies in different years, and the values of those credits; second, by applying a straight dollar value to the CO2 emitted, as a cost per ton. We used the LCFS approach for the commercial (5-year) TCOs, where the fleets may see this policy's impact on price differences in the cost of fuel, and used the second approach in the societal cost (15 years) results, to estimate how carbon value affects those societal costs. The results are sown in the figures below.

For the LCFS results, using the 5-year TCO estimation methods, Figure ES-5 shows the results using base TCO estimates along with either a $100 or a $200 credit price case. Results for 2025 and 2030 are shown in separate figures. If these credits were fully passed through to fuel price, as shown here, their effects would be quite significant. With a $100 credit price, the TCO for BEV trucks becomes very close to diesel or becomes negative in 2025 and is negative for all truck types in 2030. For fuel cell trucks, with a $200 credit, some truck types become comparable in TCO with diesel in 2025, and nearly all do by 2030, with the TCO for some fuel cell truck types dropping well below diesel. Whether all costs would be passed through to fuel price is another question, especially when prices such as electricity prices become very low or even negative. That analysis is beyond the scope of this study.

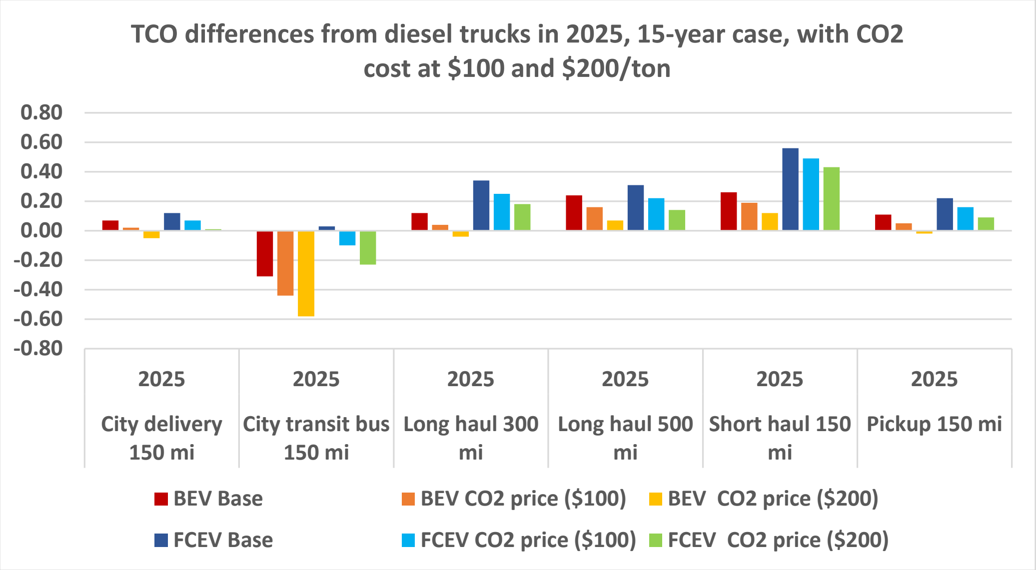
Figure ES-5: LCFS TCO Results for 2025 (top) and 2030 (bottom)

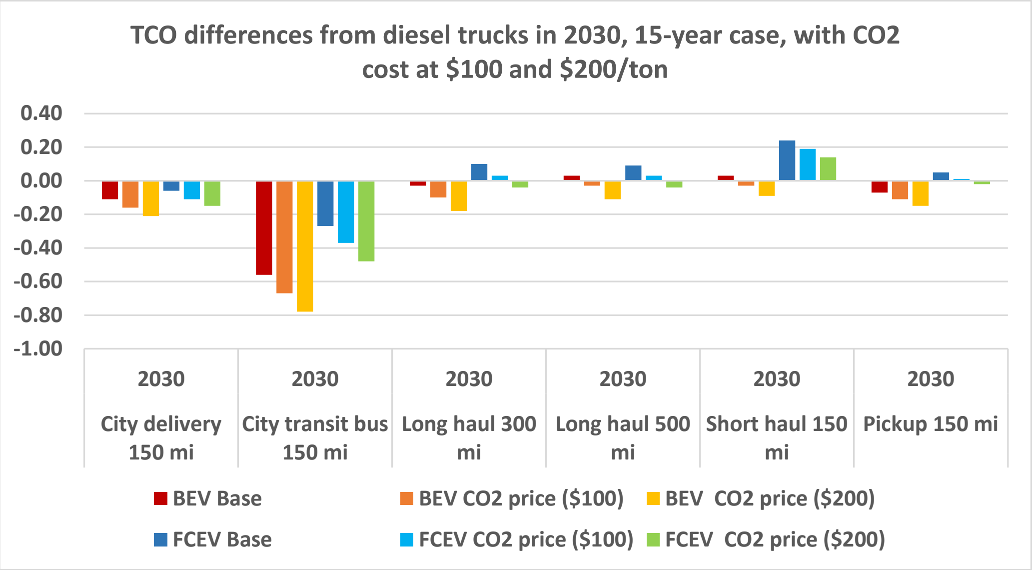




The carbon cost estimates applied to the 15-year case are shown in Figure ES-6. Given the prices used, these do not have as big an impact on the TCOs as the LCFS credit price cases, both given the longer time frame (and overall greater discounting of future costs) in this scenario, and due to the nature of the energy efficiency ratios (EERs) in the credit price system of LCFS differentiating from our estimated efficiencies of the vehicles. But they still make a significant difference, and have the general effect of making BEV trucks similar or lower cost than diesel in 2025, at least at $200/ton, and fuel cells generally similar or cheaper by 2030 at $200/ton (and in many cases at $100/ton).

Figure ES-6: Carbon Societal Cost TCO Results for 2025 (top) and 2030 (bottom)





Conclusions

In general, on a first cost basis, electric and fuel cell trucks will have a difficult time competing with diesel engine-powered trucks for the next 5 years, and in some cases over the next 10 years, particularly in the case of class 7 and 8 trucks. However, on a 5- or 15-year total cost of ownership (TCO) basis ($/mi), excluding all taxes and subsidies, battery-electric city trucks appear competitive with diesel trucks and buses even in 2025. This appears to be the case for the city delivery trucks for 5 years and the city transit buses for the 15 year lifetime of the bus. By 2035, the results indicate all the battery-electric trucks on a TCO basis, except for the 500-mile range long haul truck, will be able to compete with the engine-powered trucks. The calculated TCO values for the 5-year ownership period are in most cases only slightly higher than those for the 15 year lifetime of the trucks.

The cost results will vary with the assumptions made concerning the cost of the batteries and fuel cells and how those costs will vary with time (2020-2040), though not dramatically. The results indicate that the cost of batteries may need to be less than $100/kWh and fuel cells less than $120/kW before the electrified trucks can compete with the corresponding diesel truck on a first cost basis. The cost results also indicate that on a total ownership cost (TCO) basis, the electrified trucks and buses can compete with diesel vehicles before they reach initial cost parity because of their lower maintenance and energy costs. This should occur by 2025-2030 for most of the electrified trucks. In the case of battery-electric trucks, the payback time will be less than 3 years for most types of city delivery trucks. For the fuel cell trucks and buses, reducing the cost of hydrogen to $7.5/kg or lower is needed before they can compete on a TCO basis with diesel vehicles. In the present TCO calculation, it has been assumed that the batteries have a long lifetime (at least 10-12 years). This assumption does not influence the 5-year TCO, but it can have a strong effect on the 15-year TCO. Thus, both the initial cost of the batteries ($/kWh) and their lifetime (miles or years) can have a large effect on the economic attractiveness of electric trucks. The assumptions in the present calculations concerning the electricity cost ($.17/kWh including amortized charger cost) and the diesel fuel cost ($ 3.50/gal in 2025 and $3.75/gal in 2030) will also have a significant effect on the TCO.

Overall, the results suggest that battery electric and fuel cell trucks, produced at large volumes and with ongoing cost reductions from learning, will become cost competitive with diesel trucks in most cases by 2030, and in some cases much sooner. LCFS credit values can improve the TCOs and breakeven points significantly further, depending on credit prices. More empirical data will be needed to better understand battery life and various types of costs such as maintenance and repair. Taking into account the societal cost of CO2 and other externalities, and the effects of today's price-related policies on TCO will also be an important addition to the analysis. Finally, other non-cost factors that affect purchase decisions also need to be better understood and included in truck choice studies. These include driving range, risk, and refueling time, among others. These can vary both in magnitude and importance for different truck types and individual trucks and will evolve over time.

1. Introduction

There is currently much activity concerned with the introduction of battery-electric and fuel cell trucks into the commercial market. California Air Resources Board (CARB) has established a zero-emission truck (ZET) mandate [1] starting in 2024, and truck manufacturers [2, 3] and fleet leasing companies [4, 5] are announcing their plans for introducing electric trucks regularly. A key uncertainty surrounding this situation is the economics of ZETs compared with the diesel or gasoline engine powered trucks with which they will compete. Regardless, it seems clear that both the large truck manufacturers, like Freightliner and Volvo, and startup truck manufacturers, like Rivian [6], and Arrival [7], will be offering electric trucks for sale in the next few years.

The objective of this paper is to quantify the uncertainty in both the initial cost of ZETs of various classes as well as transit buses (together termed ZEVs), and estimate their total ownership costs over a typical period of ownership. The cost models developed are sufficiently detailed that the sources of the uncertainties are clear, and their magnitudes are estimated for both the short term (2025-2030) and the longer term (2035-2040) as the zero emission truck and bus technologies mature. This study provides more detailed estimates (truck types, technologies, years, decision factors) than previous detailed studies of the costs of medium- and heavy-duty trucks and buses [8-15] The analysis covers the timeframe 2020-2040, but we focus most of our attention on results for 2025 and 2030 since these are most relevant to ZEV market penetration.

2. Economic decision factors evaluated

The economic decision factors evaluated in this study are widely used, and typically of interest both to truck/bus buyers making decisions whether to purchase ZEVs or to continue to purchase conventional engine-powered vehicles, and to public agencies concerned with setting truck or bus regulations. One key factor is the initial purchase cost of the ZEV compared to the conventional vehicle of the same size and utility (useable range). The cost of the ZEV will depend to a large extent on its driving range and the needed battery or fuel cell capacity, and their cost per unit ($/kWh for BEVs, $/kW for fuel cell vehicles). These costs, and thus BEV and FCEV purchase costs, are expected to decrease during the period 2020-2030.

Another key factor is the energy use cost of the truck (typically measured as kWh/mi for BEVs or mi/kg for fuel cells). This cost is a function of both energy price and vehicle efficiency, which can vary depending on changes in the route, weather, and traffic. We attempt to take into account these “real world” factors in developing an average efficiency estimate for each vehicle type.

A third type of cost considered here is the maintenance cost of vehicles. We use recent estimates (and our own recent report [16]) on maintenance costs and apply these on a per-mile of driving basis. These costs can be a significant source of savings for ZEVs.

With the purchase cost, energy cost, and maintenance cost estimates, several further comparative metrics can be developed. These include the “total cost of ownership” (TCO), which adds these together, using a certain period of years of ownership to estimate total operating costs, and then add these to the purchase cost. Thus the TCO depends both on the purchase cost of the vehicle and the energy and maintenance costs, as well as a time-based discount rate (%) appropriate for type of calculation. The TCO also depends on how many miles are driven each year, and the decrease in driving over time as vehicles age. We also consider mileage points when it is necessary to replace the battery.

The residual values of both the aged components (battery pack or fuel cell) and the vehicle at various times during its life are important in the calculation of the TCO.

We estimate TCO costs for both a five year ownership period, with a vehicle resale value, and for a 15 year ownership case where the vehicle is then retired. Vehicles may achieve a lower TCO than others if they have a lower energy or maintenance cost, even if they also have a higher purchase cost.

The final metric we consider is payback time. Energy or maintenance cost savings can "pay back" the higher initial cost of a vehicle, which can be measured in terms of the time (years) or distance (miles) for this payback to fully occur, or when total costs reach a "breakeven" point with the conventional option. These breakeven times and miles are calculated in our cost model. Payback may not occur if there are no net operating cost savings, or if these do not fully compensate for higher purchase cost in the time frame considered. Conversely, if a ZEV has a lower purchase cost than a conventional vehicle, payback is instantaneous with net savings from day one.

The relative importance to vehicle buyers of the initial cost and the total cost of ownership will vary depending on the size of their fleet and how they are planning to finance the purchase and operation of the vehicle. Hence both the initial and ownership costs are needed to evaluate the economics of ZEV purchases and operation. The calculation of the initial vehicle cost and the ownership costs depends on many assumptions and input parameters which are identified and discussed in the following section.

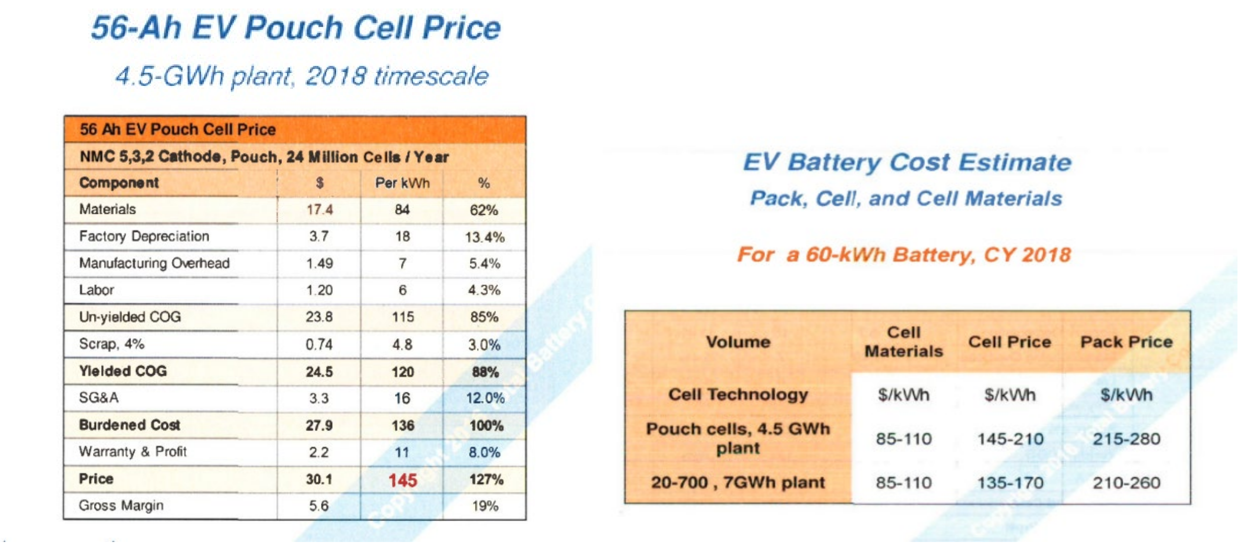
3. Vehicle design and cost issues to be considered

To evaluate the economics of a ZEV it is necessary to have in mind a "paper design" of the vehicle and its characteristics, including its range and energy use (kWh/mi or mi/kg hydrogen). The key elements of the design are the size (class) of the truck, the power (kW) of the electric powertrain, and the size (kWh or kW) of the battery or fuel cell. In the sections that follow, it is assumed that the design of the truck is known and that the minimum range requirement of the truck is specified. In addition, it is assumed that the battery characteristics (cell Wh/kg, Wh/L, pack weight and volume packaging factors) and fuel cell characteristics are also known.

3.1 Battery and powertrain cost factors

The major differences in the costs of battery-electric and engine-powered trucks and buses are related to the costs of the battery and powertrain components and their integration into the vehicle. The costs of the components are usually specified in terms of their purchase cost for an original equipment manufacturer (OEM), which must then assemble these parts into the final product. We assume an "integration factor" to mark up these parts cost to reflect this value added. In past work dealing with light-duty battery electric vehicles or hybrid-electric vehicles with small batteries [17], an integration factor of 1.2 was used to account for all aspects of the integration of new components. In this study for medium/heavy duty vehicles, we use an initial integration factor of 1.3 for the period 2020-2025, to reflect small production runs and non-optimized systems. The factor is then reduced over time to 1.1 in 2040.

The cost of batteries to the OEM (before integration costs) have been estimated by a range of studies, though most have focused on light-duty vehicles. The battery cost estimates by Anderman [18] and Bloomberg [19] are shown in Figures 1 and 2. It seems likely that both estimates of the battery costs refer to the costs/prices of the OEM.



56-Ah EV Pouch Cell Price

4.5-GWh plant, 2018 timescale

56 Ah EV Pouch Cell Price			
NMC 5,3,2 Cathode, Pouch, 24 Million Cells / Year			
Component	$	Per kWh	%
Materials	17.4	84	62%
Factory Depreciation	3.7	18	13.4%
Manufacturing Overhead	1.49	7	5.4%
Labor	1.20	6	4.3%
Un-yielded COG	23.8	115	85%
Scrap, 4%	0.74	4.8	3.0%
Yielded COG	**24.5**	**120**	**88%**
SG&A	3.3	16	12.0%
Burdened Cost	**27.9**	**136**	**100%**
Warranty & Profit	2.2	11	8.0%
Price	**30.1**	**145**	**127%**
Gross Margin	5.6		19%

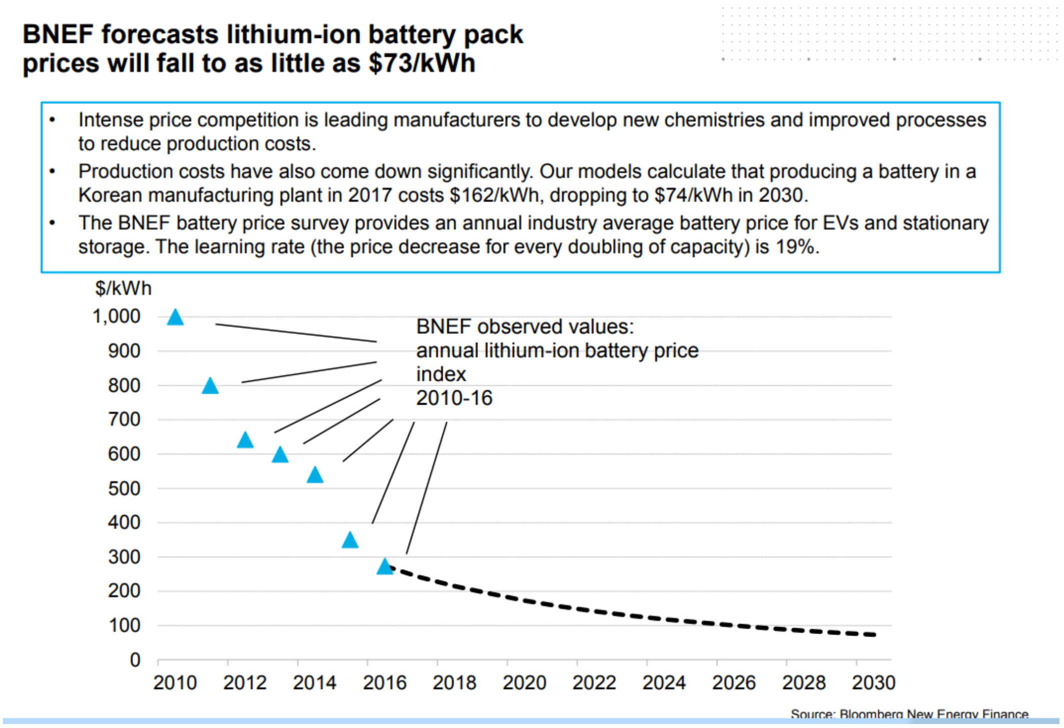
EV Battery Cost Estimate

Pack, Cell, and Cell Materials

For a 60-kWh Battery, CY 2018

Volume	Cell Materials	Cell Price	Pack Price
Cell Technology	$/kWh	$/kWh	$/kWh
Pouch cells, 4.5 GWh plant	85-110	145-210	215-280
20-700 , 7GWh plant	85-110	135-170	210-260

Figure 1: Battery cost forecasts by Anderman [18]



BNEF forecasts lithium-ion battery pack prices will fall to as little as $73/kWh

- Intense price competition is leading manufacturers to develop new chemistries and improved processes to reduce production costs.
- Production costs have also come down significantly. Our models calculate that producing a battery in a Korean manufacturing plant in 2017 costs $162/kWh, dropping to $74/kWh in 2030.
- The BNEF battery price survey provides an annual industry average battery price for EVs and stationary storage. The learning rate (the price decrease for every doubling of capacity) is 19%.

Source: Bloomberg New Energy Finance

Figure 2: Battery price forecasts by Bloomberg [19]

The battery cost estimates in Figures 1-2 indicate a cost of $200-250/kWh in 2018, decreasing to $100/kWh by 2025 and $75/kWh by 2030. These cost estimates are all for batteries for light-duty vehicles, but as shown in Table 1, the same or similar cells can be used to assemble batteries for medium/heavy duty vehicles though the battery packs are typically much larger and set for higher voltages than for light duty. They also may be made with much smaller production runs.

Table 1: Comparison of the physical and working characteristics of the battery in light-duty and heavy-duty vehicles

Parameter	**Light-duty vehicle (Bolt)**	**Heavy-duty vehicle (short haul truck EV)**
Energy stored (kWh)	60	500
Pack voltage (V)	355	750
NCM Battery cell Ah (1.04 kg/cell)	56	56
Pack cell configuration	96s3p (288 cells)	192s13p (2500 cells)
Total weight of cells (kg)	300	2600
Cell energy density (Wh/kg)	200	200
Maximum Power (kW)	150	320
Power density (W/kg)	**500**	**123**
Miles per year	12000	85000
Battery deep disch cycles/yr	**50 (250 Wh/mi)**	**360 (2.1 kWh/mi)**
Average power (kW; W/kg)		
60 mph	15; 50	96; 37
City driving	5; 17	21; 8

The battery costs to the OEM (high and low cases) used in this study are shown in Table 2. They are based primarily on the data shown in Figure 2 from Bloomberg. These battery costs are multiplied by a vehicle integration factor in the economics calculations to get the cost of the battery pack onboard the vehicle. Battery cost projections are based on the time a battery manufacturer can meet a particular cost target. OEMs must integrate a battery into a new vehicle design, and the integration process might take 3-5 years. The battery cost from projections will then be valid for OEMs 3-5 years after the projection date. Our low-cost case below is based on Bloomberg's most recent projections. Our base case costs are higher than these cost projections and could include some delay in integrating the battery into vehicles.

Table 2: Battery pack costs for 2020-2040

Battery cost $/kWh	**2020**	**2025**	**2030**	**2035**	**2040**
Battery costs to OEMs					
- High cost case	250	200	125	100	75
- Base cost case	225	175	100	85	70
- Low cost case	200	150	75	70	65
Battery integration factor	1.5	1.5	1.5	1.5	1.4

The costs of the powertrain components (motor, power electronics, and DC-DC converters) will be given as $/kW of the system. As in the case of the batteries, the powertrain cost will be assumed to be the cost to the OEM and the retail vehicle cost will be calculated using a powertrain integration factor.

Information on the costs of the electric powertrains in the literature [20-22] shows a large variation as well as whether the cost is to the OEM or is the retail cost. The U.S. Department of Energy (DOE) has studied the present cost of the electric powertrains and has set long-term goals (2030). Based on the available information, the electric powertrain to the OEMs shown in Table 3 will be used in this study. It should be recognized that there is considerable uncertainty in the present costs and as a result, the costs shown for future years forecast significant cost decreases as the powertrain technology matures.

Table 3: Electric powertrain costs in the future

Year	\$/kW DOE HD	\$/kW DOE LD	\$/kW Heavy duty	\$/kW Medium duty	\$/kW Light-duty
2020	38	19	45	30	22
2030	14	6	25	20	10
2040	12	6	15	13	8
2050	12	6	15	13	8

3.2 Vehicle electricity use and battery oversize factors

Since the battery is the highest cost component in an electric vehicle, how the battery is sized (kWh) is a key factor in determining the initial cost of the vehicle. In some cost studies, the battery is sized simply by multiplying the energy consumption (kWh/mi) of the vehicle by its specified range (mi). Unfortunately, determining an appropriate "real world" value for the energy consumption of a particular electric vehicle design is not that simple. There are complications in assessing how much energy (kWh) should be utilized from a particular battery accounting for the loss of capacity due to degradation and limits set to preserve its health as it is used. In truck and bus applications, the battery pack will be deep discharged most days, which means that the cycles on the battery will not be much different than the number of days of vehicle operation. Hence sizing the battery (kWh) such that the electric vehicle will have a specified minimum range over the lifetime of the battery, for all seasons of the year and route conditions, requires particular consideration for MD/HD electric vehicles.

First, the actual in-use efficiency of the battery (and entire vehicle) must be assessed to derive an appropriate value for kWh/mi. The most direct approach is to measure the energy consumption for various routes and seasons using an electric vehicle of the vehicle class of interest. In the future that data will be available from commercial truck operations, but at present that is not the case. In the present study, the kWh/mi was calculated for the "paper design" vehicle using the simulation program ADVISOR [23-24]. Simulations can be run for various driving cycles over routes with variable grades and accessory loads. The selection of the appropriate driving cycle depends primarily on whether the vehicle will be used in the city in stop-go driving or on the highway at relatively constant speeds of 55-65 mph or higher. From these simulation results, an average value for kWh/mi can be determined and a reasonable "oversize" factor for the battery is estimated for particular types of vehicle operation. Test data for the energy consumption (kWh/mi) on real routes in Europe are given in [21]. Typical simulation results are given in Tables 4 and 5 for several types of electric vehicles. In Table 4, the energy consumption (kWh/mi) on level roads is given for various driving cycles. Note that there are large variations in energy use due to differences in the driving cycle for the same vehicle. In Table 5, the effect of the road grade is shown for city and highway driving. The effect of the grade on energy consumption is significant for even small grades and is greater for highway than city driving. Hence, the variation of kWh/mi for different routes and traffic conditions is important to consider. The simulation results indicate that the variations in energy consumption due to driving conditions and grade can be 20-30% for a specific electric vehicle. The effect of cold ambient temperatures will increase the energy consumption by an even greater factor [21].

A second reason to oversize the battery is battery degradation and the need to maximize the cycle life of the battery. The standard criteria for end-of-life of the battery is a loss of 20% in capacity (kWh). Hence to maintain a constant range over the lifetime of the battery, it will need to be oversized by 1/.8 or by a factor of 1.25. Otherwise, it will be necessary to reduce the expected range of the electric vehicle gradually as the battery ages. In addition, it is advisable not to discharge the oversized battery to zero state-of-charge (minimum cell voltage) at any time to maximize the range as the battery degrades. This means limiting the maximum energy discharged from the battery to less than 80% of that initially stored in the battery. This would result in an additional oversize factor of another 1.25. Otherwise, the battery cycle life will be less than projected by the manufacturer.

Table 4: Simulation results for example battery-powered trucks and buses (EVs)

Transit buses, 2030

Transit bus EV*	kWh/mi
Manhattan	2.2
NYcomp	1.8
ARB-TR	1.43
HHDT-CR	1.2

* C_D =.35, A_F =7.5, wt. =15,000 kg, f_r =.0075, 6 kW accessory load

City delivery-trucks, 2030

City delivery EV*	kWh/mi
Delivery cycle	.83
ARB-TR	.75
HHDT-CR	1.1
Non-FW 15mphav.	.83

* C_D =.75, A_F =7.8, wt. =6900 kg, f_r =.007, .8 kW accessory Load

Table 5: The increase in energy consumption (Wh/mi) for city and highway driving on grades for electric trucks of various types

Type of driving and grade	Vehicle type			
	City delivery	**Transit bus**	**Long haul truck**	**HD pick up**
City driving				
0	1.0	1.0	1.0	1.0
.5%	1.13*	1.2	1.24	1.19
1%	1.26	1.37	1.5	1.37
Highway driving				
0	1.0	1.0	1.0	1.0
.5%	1.23	1.15	1.39	1.25
1%	1.36	1.36	1.8	1.5

*Ratio = $(Wh/mi)_{grade}$ / $(Wh/mi)_0$

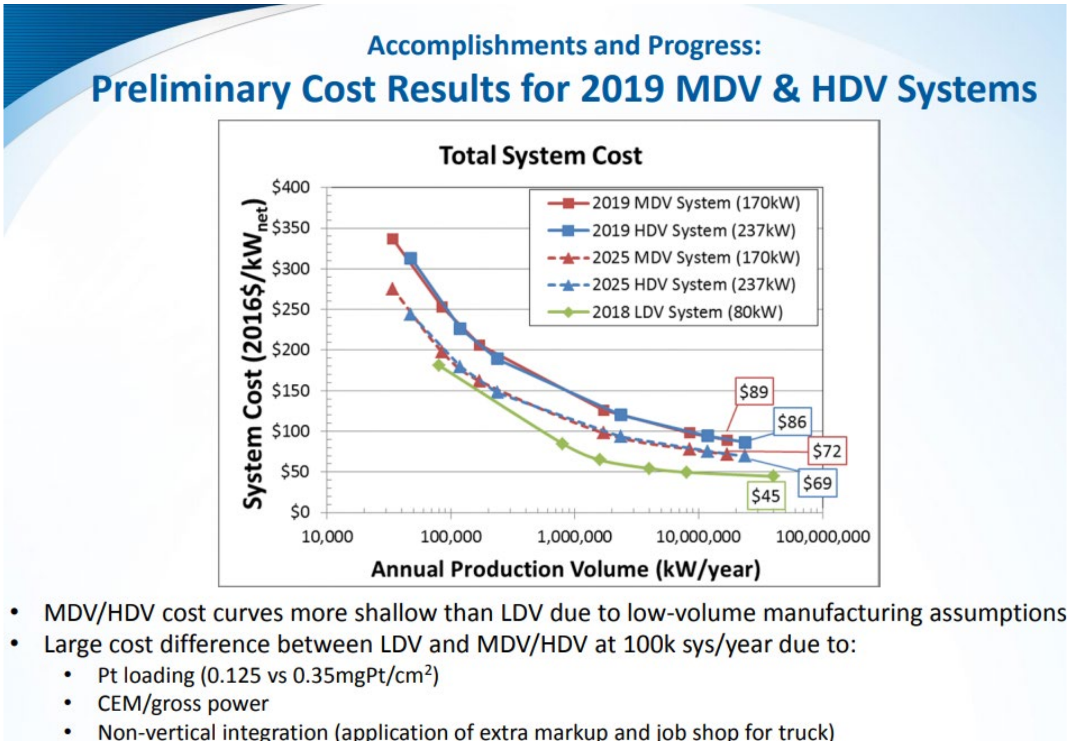
The lifetime of the battery will likely be determined by a combination of degradation due to calendar and operation (cycling mechanisms). Calendar degradation is minimized by controlling the temperature of the battery to less than 35 deg C and having the battery resting at higher than 75% state-of-charge [25]. Otherwise, the life (years or miles) of the battery could be determined by calendar degradation rather than the expected cycling effects. Hence, to experience battery lifetimes of 8-12 years, it will be necessary to manage carefully the temperature and charging patterns of the battery pack even when it is oversized.

In summary, to meet specified minimum range and calendar/cycle life expectations for an electric vehicle, the battery must be oversized in kWh than would be determined by simply multiplying the average kWh/mi on a level road by the specified range of the vehicle. The total oversize factor due to energy consumption and battery degradation effects could be as high as 2.0 (i.e. twice the nominally-derived size), but seems more likely to be in the range of 1.5-1.8 depending on the route variations and climate conditions expected. The average energy consumption on hilly terrain will be higher than that for operation on level roads (OEF) by a factor of 1.2-1.3. Another consideration is that older vehicles may have fewer vehicle miles traveled (VMT) per year and require less energy to meet their daily driving needs. Whether a fleet chooses to reduce VMT for older trucks depends on the truck application and fleet characteristics.

Assuming nominal oversize factors of about 1.2 for each of the three key factors (minimum state-of-charge), battery degradation, and on-road fuel economy adjustments, and assuming some overlap in these effects, we arrive at a combined oversize factor of 1.6 for the period 2020-2030 and some improvement thereafter, reaching a 1.5 factor after 2030, for our battery sizing calculations.

3.3 Fuel cell vehicle cost considerations

There is much less information available on the present and future costs of fuel cell systems than for batteries. This is especially true of fuel cells to be used in heavy-duty vehicles. DOE has funded studies on the cost of fuel cells for light-duty vehicles [26] and for heavy-duty vehicles [27, 28]. The DOE studies project the fuel cell costs shown in Figure 3 as a function of production volume for light-duty, medium-duty, and heavy-duty applications. The cost projections indicate a large reduction in cost ($/kW) with increasing production volume. Hence relating the projected costs to specific years in 2020-2040 requires some judgment concerning the size of the market for fuel cell trucks in each of the 5-year periods. The cost projections in Figure 3 indicate that the cost of MD and HD fuel cells will be significantly higher than those designed for light-duty vehicles. Light-duty fuel cells in passenger cars are being marketed by Toyota and Honda and in transit buses and trucks by Ballard [29]. Recent information on the cost of Ballard fuel cell systems for heavy-duty buses and trucks for 2020-2030 (Figure 4 taken from [29]) is much higher than those projected for light-duty vehicles. Discussions with Ballard have indicated the reasons for their higher cost ($/kW) are that in the HD vehicles the fuel cell operates at a much higher average power over its life and must be much more durable (at least 30,000 hr.). These requirements lead to increased costs, especially for the balance of the plant (air supply and cooling components). A summary of projections of fuel cell system costs for HD applications from several sources is given in Table 6. That information will be used to project the fuel cell costs used in the present analysis.



Accomplishments and Progress:

Preliminary Cost Results for 2019 MDV & HDV Systems

- MDV/HDV cost curves more shallow than LDV due to low-volume manufacturing assumptions
- Large cost difference between LDV and MDV/HDV at 100k sys/year due to:
  - Pt loading (0.125 vs 0.35mgPt/cm^2)
  - CEM/gross power
  - Non-vertical integration (application of extra markup and job shop for truck)

Figure 3: DOE (Strategic Analysis [28]) fuel cell cost projections as a function of production volume

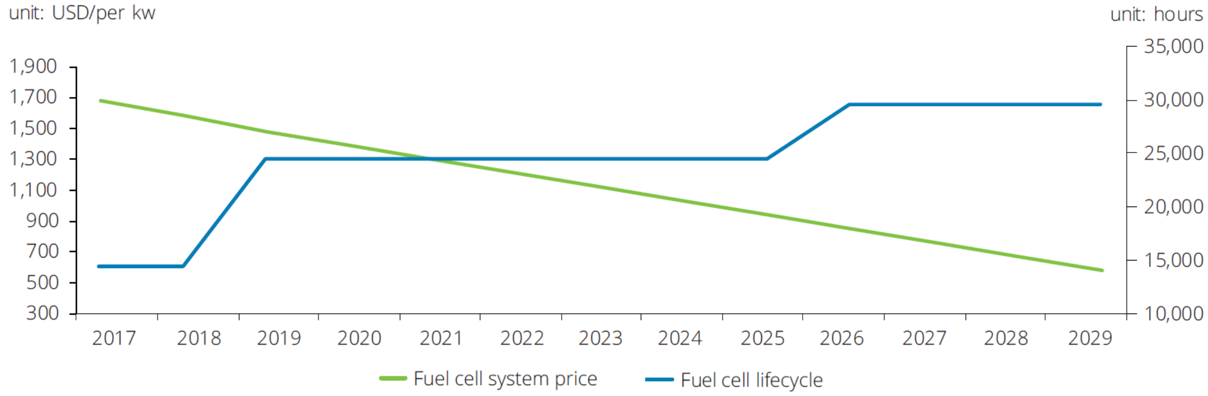


Figure 4: Ballard fuel cell cost projections for 2020-2029 [29]

The fuel cell costs cited in various references [28-32] are summarized in Table 6. When possible, the production volume associated with each cost is indicated.

Table 6: Projected fuel cell system costs for various production volumes for HD applications ($/kW)

Factors/estimates	Units	**2020**	**2025**	**2030**	**2035**	**2040**
Ballard (low volume) [29]	$/kW	1300	900	500		
ANL/DOE (high volume) [30]	$/kW	200	140	80	70	60
ANL/high vol. BAU	$/kW	200	185	175	170	160
		$/kW	$/kW			
Strategic Analysis [28]	Production volume/yr.*	2019	2025			
300 units/yr	300	350	280			
1000	1000	240	190			
3000	3000	180	145			
10000	10000	140	115			
30000	30000	120	90			
100000	100000	100	75			
300000	300000	85	65			
H2 Council/ McKinsey [31]						
2500 units/yr.			110			
20000 units/yr			75			

*1 unit is a 100-kW fuel cell

As shown in the studies, the costs can be expected to decrease significantly in the future as the fuel cell system and manufacturing technologies mature, much like has happened to lithium batteries in the last 10-15 years. Volume production is also shown to be an important factor, and unless fuel cell trucks reach large scale production rapidly, cost decreases may take longer than was the case for lithium batteries which have scaled tremendously in the past 10 years. In the case of batteries, the cost reduction was dominated by the rapid expansion of battery manufacturing capability in China and Korea and the successful efforts of the Chinese government to market very large numbers of electric passenger cars and buses over the last 5-10 years. It seems unlikely that these types of rapid capacity expansion events in China in connection with batteries will occur for fuel cells.

For the present study, three sets of fuel cell costs ($/kW) for 2020-2040 were used in the economic calculations. One projection, termed the high-cost projection, assumes a modest rate of market development for fuel cell trucks. The second is termed the low-cost projection based on the more rapid development of the market. The more optimistic projection infers a rapid development of both the light-duty and heavy-duty fuel cell vehicle markets much like the electric vehicle market led by China. A third set, termed the base case, intermediate between the high and low cases, is thought to be the most likely and is used for most of the fuel cell vehicle cost calculations.

The fuel cell costs used in this study are shown in Table 7 along with the associated production volumes needed to support the costs each year.

Table 7: Fuel cell cost projections for high and low cases

HD $/kW	**2020**	**2025**	**2030**	**2035**	**2040**
High cost case	700	240	145	115	90
Production volume (units/year)	<300	1000	3000	10000	30000
Base case	525	193	118	95	78
Low cost case	350	145	90	75	65
Production vol. (units/year)	300	3000	30000	100000	300000
Fuel cell system integration factor	1.5	1.5	1.5	1.5	1.4

3.4 Charging/fueling battery-electric and hydrogen fuel cell trucks

The purchase of battery-electric and hydrogen fuel cell trucks by fleets or an individual owner requires convenient charging/fueling facilities and, for positive TCOs, reasonable cost for the electricity and hydrogen such that the energy savings of the electrified trucks will off-set their higher purchase price.

It is recognized that the actual cost of electricity for battery charging for a particular application/fleet depends on many factors and thus can vary over a wide range. There are several approaches for charging the batteries for electric trucks. A simple approach is to charge the batteries overnight at a terminal using a dedicated charger. Present costs for high-power chargers (150 kW and 350 kW) seem to be about $1000 per kW. The power levels (kW) needed to charge the large batteries for the class 6-8 electric trucks can be high (up to several MW) and the cost of those chargers is less known. In the present study, the cost of the electricity was fixed at $.17/kWh. This includes $.02/kWh to offset the cost of the battery charger over its lifetime assuming the cost of the battery charger is $1000/kW for a 100 kW charger and its lifetime is 15 years. Over its lifetime, the charger will provide about $4.5\text{x } 10^{6}$ kWh to charge the batteries of vehicles. Hence the prorated cost of the charger is $100, 000/ $4.5\text{x}10^{6}$ = $.022/kWh. No demand charges were included in the cost of charging the batteries.

As discussed in [33], the Low Carbon Fuel Standard (LCFS) savings related to electricity could be significant. The LCFS credit can be estimated as follows. Assuming the use of renewable electricity to charge the batteries (near zero gmCO2/MJ) and 90 gmCO2/MJ for the diesel fuel used by the diesel trucks, the LCFS credit is given by

$$\text{LCFS credit (\$/kWh)} = ((\text{CI})_{\text{diesel}} \text{ x ERR} - (\text{CI})_{\text{elec.}}) \text{ x } 3.6 \text{ x } (\$/\text{tonne CO}_2) \text{x } 10^{-6}$$

For $(\text{CI})_{\text{diesel}} = 90$, $(\text{CI})_{\text{elec}} = 10$, ERR=5, $/tonne CO_2 = 150, the LCFS credit = $.24/ kWh. Hence the LCFS credit can be very important in the calculation of the TCO. In terms of offsetting the higher initial cost of the battery-electric cost, the annual cost saving for electricity can also be significant. For example, for a truck using 2 kWh/mi, the cost-saving due to the LCFS credit could be .24 x 2 x 50000 mi/yr = $24000/yr. Hence, even though the LCFS cost saving is uncertain in the future, it could be an important factor in the near term.

In the case of fueling the hydrogen fuel cell trucks, we reviewed several recent papers [29-32] on hydrogen fueling system development that provide estimates of the cost of producing, transporting, storing and dispensing hydrogen for vehicles. These reports vary considerably in their assumptions and focus with some focused on hydrogen from "blue" hydrogen (natural gas, with or without carbon capture, utilisation and storage (CCUS)) and some on "green" hydrogen from electrolysis and renewable electricity. The assumptions about electricity price, electrolyzer costs and load factors and the scale of vehicle refueling stations and their operating characteristics vary significantly. We attempted to find comparable, mid-case numbers (especially in terms of underlying electricity price and hydrogen scale). The station scale for truck stops will be much larger than stations for light-duty vehicles. The results of our comparisons are shown in Table 8. They indicate a rapid decrease in hydrogen cost ($/kgH$_2$) from $10 to $4 per kg delivered to vehicles in the 2020-2030+ time frame. In all cases, large systems and favorable economies of scale are assumed.

Table 8: Recent estimates of produced and delivered electrolytic H2 (production to refueling)

Study	**2020**	**2025-30**	**2030+**	**Notes**
US DOE targets [32]				Targets, but considered achievable in the time frame
- Low volume (higher cost)	16	10		
- High volume (lower cost)	13	5	4	For long term target, only a high volume one ($4)
H2 Council/McKinsey 2020 [31]	10.4	4.4		Mid-range electrolysis cost with trucking (pipeline very similar)
IEA (2019) [34]	12	7		Mid case, based on mid electricity price, electrolyzer cost, capacity factor
Ballard-Deloitte [29]	13	4		Not clear that the station cost includes all components of getting hydrogen from production to vehicle

Using the results in Table 8, high, base (average) and low estimates for the cost of H2 in 2020-2040 were made for use in the present economic calculations for fuel cell trucks. The cost of the hydrogen ($/kg) varied from 2020-2040 as shown in Table 9.

Table 9: Hydrogen costs ($/kg) for fuel cell trucks produced from electrolysis

	2020	**2025**	**2030**	**2035**	**2040**
High cost	17	12	9	7	6
Base (average)	12	8.5	7	6	5
Lower cost	10	7	6	5	4

In the spreadsheet cost calculations, the average base value for the cost of hydrogen was used as representative of the cost for each year.

As in the case of electricity for battery charging, there are possible LCS credits for hydrogen to consider especially in the near term. The approach to calculating the hydrogen credit is similar to that used for electricity.

$$\text{LCFS credit } (\$/\text{kgH2}) = ((CI)_{diesel} \times ERR - (CI)_{H2.}) \times 3.6 \times 33.3 \times (\$/\text{tonne } CO_2) \times 10^{-6}$$

For $(CI)_{diesel} = 90$, $(CI)_{H2} = 50$, ERR=3, \$/tonne CO_2 = 150, the LCFS credit = \$3.95/ kgH2, which is a significant fraction of the projected cost of hydrogen. For a fuel cell truck using .07 kgH2/mi and traveling 50000 mi/yr, the hydrogen credit could be 3.95 x .07 x 50000 = \$13825/yr, which would offset a significant fraction of the cost of the hydrogen needed to operate the fuel cell truck.

For all fuel costs, we do not include taxes. In addition, we assume that fuel costs change over time but that fuel costs for all truck types are the same. In other words, a long-haul truck in a given year will have the same electricity cost or hydrogen cost as a medium-duty delivery truck. We understand that electricity costs, for example, at truck stops in the early years could be different than the cost of electricity at a fleet depot, but we view that analysis as requiring a deeper dive and do not include any variation in this paper.

Another aspect of electricity costs that could affect TCO results is demand charges. If a truck charges at certain times of the day or a charging facility uses large excessive energy, the electricity cost could be higher due to these demand charges. For this paper we assume fleets attempt to minimize such charges by, for example, charging at night. We do not explicitly include possible effects due to demand charges, but we do a sensitivity analysis with the electricity cost at \$0.25/kWh. We feel this could be an average cost for a fleet that sometimes accrues demand charges. Our sensitivity analysis also includes a possible low cost for electricity of \$0.10/kWh. We add the \$0.02/kWh for the prorated cost of the charger to both of these costs.

A major issue in estimating electricity cost is the need for upgrades in the make-ready infrastructure. Make-ready infrastructure includes all hardware required to bring power from the electricity grid to a charging station. This hardware could include substations, conduits, and cabling. To upgrade the infrastructure to provide appropriate power to charging stations, utility companies must assess the charging needs and install the required hardware. In some cases, the cost could be quite high. At present, California PUCs (public utilities commissions) have allowed utilities to provide some make-ready infrastructure by increasing electricity costs on all rate payers. Fleets would then not see a significant increase in cost since that cost would be spread over a larger pool. We have decided not to attempt to include make-ready infrastructure costs in our analysis at this time.

Table 10 shows the variations we assumed for the costs of diesel, electricity and hydrogen and Table 11 for technology costs for batteries and fuel cell systems in five-year increments from 2020 to 2040.

Table 10: Low, base, and high fuel costs assumptions, 2020-2040

	Diesel ($/gal)			Electricity ($/kWh)			Hydrogen ($/kg)		
Year	Low	Base	High	Low	Base	High	Low	Base	High
2020		3.25		0.12	0.17	0.27	10.00	12.00	17.00
2025	2.63	3.50	4.38	0.12	0.17	0.27	7.00	8.50	12.00
2030	2.81	3.75	4.69	0.12	0.17	0.27	6.00	7.00	9.00
2035	3.00	4.00	5.00	0.12	0.17	0.27	5.00	6.00	7.00
2040	3.00	4.00	5.00	0.12	0.17	0.27	4.00	5.00	6.00

Table 11: Low, base, and high battery and fuel cell cost assumptions, 2020-2040

	Battery ($/kWh)			Fuel Cell ($/kW)		
Year	Low	Base	High	Low	Base	High
2020	200	225	250	350	525	700
2025	150	175	200	145	193	240
2030	75	100	125	90	118	145
2035	70	85	100	75	95	115
2040	65	70	75	65	78	90

3.5 Maintenance costs

Maintenance costs for diesel trucks are given in Table 12. The cost/mile for various truck types is taken from an ICF report [35]. In cases where they don't give values for a particular truck type, we use values for similar truck types. More details are given in the table. Maintenance values for battery electric trucks and fuel cell trucks are estimated using results from a recent UC Davis study on heavy-duty maintenance costs [16]. The paper looked at present costs and estimated how those costs would be reduced over time. Battery electric trucks are assumed to show a slight reduction in maintenance costs in 2020 and by 2035 be roughly 30% lower than diesel costs. Fuel cell truck maintenance is assumed to be roughly equal to diesel costs in 2020 and decrease 25% below diesel costs by 2035.

Table 12: Maintenance costs for various diesel truck types

Vehicle Type	$/mile	Comments
HD pickup	0.31	Assume ICF value of Class 2b van
MD delivery	0.2	
Transit bus	1.00	ICF gives value of 0.79
Intercity bus	1.00	
Short-haul	0.20	ICF gives value of 0.19 for short haul and 0.20 for drayage
Long-haul	0.20	Assume the same value as for short-haul
Passenger van	0.2	ICF gives value of 0.31
Class 3 delivery van	0.2	ICF gives value of 0.31
Step truck	0.2	Assume the same as for medium-duty delivery
Class 6 box truck	0.2	Assume the same as for medium-duty delivery
Class 7 box truck	0.2	Assume the same as for medium-duty delivery
Class 8 box truck	0.2	Assume the same as for medium-duty delivery

ICF: https://caletc.com/wp-content/uploads/2019/12/ICF-Truck-Report_Final_December-2019.pdf

3.6 Short and long-term ownership factors

Some truck buyers will be interested in ownership costs for short periods like 5 years and other buyers are interested in long-term ownership costs over the lifetime of the electric truck up to 15 years. When considering total costs over specified periods, the discounted value of the operating expenses is important and as a result, the discount rate (%) assumed in the analysis can be critical. In our analysis, we used 10% for the 5-year analysis and 3% for the 15-year analysis.

Another assumption that is important for the ownership analyses is the reduction in annual operating mileage as the truck ages. In our analysis, we assumed that the annual mileage decreased by 2-3% per year for the first 5 years and 8-9% per year for the next 10 years of the truck lifetime. Our first-year mileage estimates are shown in Table 13. The assumptions regarding the annual mileage for the first year and the rates at which the annual mileage decreases vary with truck type and application and are somewhat uncertain as detailed pertinent data are difficult to find.

Table 13: Assumed annual mileage for various types of buses and trucks

Vehicle/ Class	Miles/yr*
Passenger van	25000
Delivery truck	20000
Step van	25500
Class 6 Box trk	25500
Class 7 Box trk	30000
Class 8 Box trk	30000
HD pickup trk	20000
Class 8 Tractor 300 mi range	90000
Class 8 tractor 500 mi range	120000
Transit bus	40000
Intercity bus	60000
Short-haul	45000

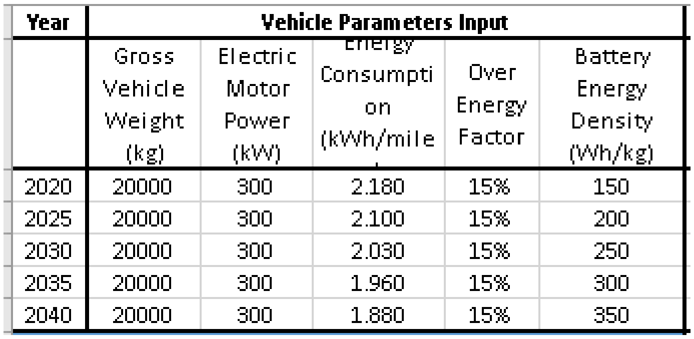
*annual mileage for year 1

4. Methods of economic analysis - model development

4.1 Basic inputs

The spreadsheet model is configured in many sheets. The sheets consist of the inputs and calculations for each of the battery-electric and fuel cell vehicle types being analyzed. An example of the vehicle inputs as they appear in the spreadsheet is shown in Table 14.

Table 14: Example vehicle inputs and directly related vehicle characteristics used in the spreadsheet model



Year	Vehicle Parameters Input				
	Gross Vehicle Weight (kg)	Electric Motor Power (kW)	Energy Consumption (kWh/mile)	Over Energy Factor	Battery Energy Density (Wh/kg)
2020	20000	300	2.180	15%	150
2025	20000	300	2.100	15%	200
2030	20000	300	2.030	15%	250
2035	20000	300	1.960	15%	300
2040	20000	300	1.880	15%	350

The inputs, and related quantities that are directly calculated from them, describe the baseline diesel, the various battery-electric, and fuel cell MD/HD vehicles in detail. The inputs also describe how the ZEVs are to be operated in terms of expected daily range and annual mileage. Some of the special parameters have been identified and explained in Section 3. There is a set of tables as shown in Table 15 for each of the ZEVs being analyzed and those values are used in the total operating cost calculations that are described in later sections of the report. The calculation of the initial cost of the ZEVs, their total operating cost (TCO) for the 5-year and 15-year time periods, and payback miles and years are discussed in detail in the remainder of Section 4.

4.2 Analysis of the initial (purchase) cost of the vehicles

Analysis of the initial cost of the BEV

The initial or purchase cost of the battery-electric trucks is estimated as shown below using the vehicle inputs in Tables 15.

$(\text{Vehcost})_{\text{BEV.}}$ = glider + Electric drive cost + battery cost

Glider = Price Diesel Vehicle – cost of engine and transmission of the diesel vehicle

Electric drive cost = \$/kW x kW of EM x system integration factor (IF_{pt}) for the driveline

Battery kWh = $(\text{kWh/mi})_{\text{level}}$ x bat. oversize factor $(\text{OSF})_{\text{bat}}$ x minimum range requirement (miles)

Battery cost = Battery kWh x $(\$/\text{kWh})_{\text{bat}}$ x system integration factor (IF_{bat}) for the battery pack

(IF_{bat}) and (IF_{pt}) used in the analysis are 1.3 in 2020 and decrease to 1.1 by 2040.

Analysis of the initial cost of the fuel cell vehicle

For the hydrogen fuel cell vehicles, the initial vehicle cost is given by

$(\text{Vehcost})_{\text{H2 FC.}}$ = glider + Electric drive cost + Power battery cost + fuel cell system cost

fuel cell cost = \$/kW x kW of fuel cell x integration factor

hydrogen storage cost = \$/kgH_2stored x kg stored H_2 x integration factor

kg stored H_2 = $(\text{kg/mi})_{\text{on level}}$ x H_2 oversize factor

fuel cell system cost = fuel cell cost + hydrogen storage cost

power battery cost =$(\$/\text{kWh})_{\text{powerbat}}$ x $(\text{kwh})_{\text{powerbat}}$ x integration factor

The fuel cell integration factor is the same as that used for batteries and power electronics. The H2 oversize factor is conceptually similar to the battery oversize factor and is a correction to the simplistic calculation of energy needed on a given drive cycle to drive a given range. The increase is due to vehicle hotel (accessory) loads, road grade, and other factors that can increase the power demands. The hydrogen oversize factor is lower than the battery oversize factor because there is no correction for degradation over time, or sizing to ensuring a minimum cycle life.

4.3 Calculation of the total ownership costs

The calculation of the total cost of ownership (TCO) for a specified period (5 or 15 years) requires the determination of operating expenses in each year of the period and then summing those annual expenses over the total period. Then at the end of the period, residual values of the vehicle and the batteries are needed. All the separate expenses must be discounted by the appropriate amount given by [$1/(1+d)^{n-1}$] where d is the discount percent and n is the year of the expense. In this study, the discount % used was 10% for the 5 years and 3% for the 15 years. At the end of the 15 years, the residual value of both the vehicle and the battery is taken as zero. At the end of the 5 years, it is assumed that the residual value of the diesel truck is 50% of its initial value and that of the battery-electric trucks is 50% of its initial cost minus the cost of the battery pack. It is further assumed that the residual value of the batteries after 5 years is 15% of their initial cost. We have assumed no battery replacement in 5 years. For 15 years, we would replace the batteries based on total mileage driven by the truck inferred from the equivalent deep (80%) discharge cycles. Cycle life of 1500 deep discharge cycles is assumed for the batteries. The size (kWh) and cost ($/kWh) of the replacement batteries are assumed to be the same as the initial battery pack.

The expense for the nth year of the battery-electric vehicle life is calculated as follows:

$$(\text{TCO})_n = [(\text{Energy})_{\text{elec}} + (\text{maint.})_{\text{BEV}}]/\ (1+d)^{n-1}$$

$$= [[(\text{kWh/mi}) \times (\text{OEF}) \times (\$/\text{kWh})_{\text{elec}}) + (\$/\text{mi})_{\text{maintBEV.}}] \times (\text{miles/yr.})_n]/(1-d)^{n-1}$$

The discounted total cost of ownership is then given by the following:

$$(\text{TCO})_{\text{total}} = (\text{Veh cost})_{\text{BEV}} + \sum_n (\text{TCO})_n + (\text{Residual- Veh +bat})/\ (1+d)^{N-1}\ ,\ N=n_{\text{max}}$$

$$(\text{TCO/mi})_{\text{total}} = (\text{TCO})_{\text{total}}\ /\ \sum_n (\text{miles/yr.})_n$$

The corresponding relationships for the baseline diesel vehicle are the following:

$$(\text{TCO})_n = [[(\text{mi/gal})_D \times (\$/\text{gal})_D + (\$/\text{mi})_{\text{maintD.}}] \times (\text{miles/yr.})_n]/(1-d)^{n-1}$$

$$(\text{TCO})_{\text{total}} = (\text{Veh cost})_{\text{Diesel}} + \sum_n (\text{TCO})_n + (\text{Residual- Veh})/\ (1+d)^{N-1}\ ,\ N=n_{\text{max}}$$

$$(\text{TCO/mi})_{\text{total}} = (\text{TCO})_{\text{total}}\ /\ \sum_n (\text{miles/yr.})_n$$

The relationships above for TCO apply to both the short 5-year and long 15-year periods of analysis. Both lifetime periods are considered in the model.

4.4 Calculation of the payback time and miles

The payback approach to assessing the economic attractiveness of the fuel cell and battery-electric vehicles relative to diesel vehicles is to calculate the time (in years) and/or mileage of operation to recover the higher initial purchase costs via energy and maintenance savings. This calculation only makes sense when the technology in question (fuel cell or battery electric) has a higher purchase cost and lower fuel/maintenance costs, so that payback is both needed and possible. This is usually, though not always, the case in our analysis. The payback analysis does not include vehicle depreciation. It can be specified as:

$$(\text{payback years}) = [(\text{veh cost})_{\text{BEV}} - (\text{veh cost})_{\text{Diesel}}]/[(\Delta\$/\text{mi})_{\text{fuel cost}} + (\Delta\$/\text{mi})_{\text{mainten cost}}]$$

$$(\text{payback miles}) = ([(\text{veh cost})_{\text{BEV}} - (\text{veh cost})_{\text{Diesel}}]/[(\Delta\$/\text{mi})_{\text{fuel cost}} + (\Delta\$/\text{mi})_{\text{mainten cost}}])\ /\ (\text{miles/yr.})_{n=1}$$

If the payback time or miles are deemed to be short by potential electric truck buyers in terms of their expected operation of the vehicle, the economics of their purchase will be attractive to them.

5. Model inputs and results for battery-electric and fuel cell buses and trucks

5.1 Data inputs for each vehicle type

The spreadsheets are set up to handle six vehicle types: transit bus, inter-city bus, city delivery truck, short-haul HD truck, long-haul HD truck, and HD pick-up truck or six classes (2b-8) of medium and heavy-duty trucks. For each vehicle type, the parameters shown in Tables 15 and 16 are provided for 2020-2040. Tables 15 are typical inputs for several battery-electric truck types and Tables 16 are typical inputs for several fuel cell truck types. A comparable study of class 8 long haul trucks using fuel cells and hydrogen can be found in [28. In that study both business-as-usual and the optimistic DOE cost and efficiency targets for HD fuel cell systems are used as inputs. Marketing plans for the use of fuel cells in trucks by truck manufacturers are discussed in [36-38.

Table 15: Data inputs for battery-electric vehicles

Table 15a: Vehicle inputs for a class 3 Delivery Van

	Vehicle Parameters Input				
Year	Vehicle Weight (kg)	Electric Motor Power (kW)	Energy Consumption (kWh/mile)	Over Energy Factor	Battery Pack Energy Density (Wh/kg)
2020	6900	150	0.83	0.15	150
2025	6900	150	0.791	0.15	200
2030	6900	150	0.754	0.15	250
2035	6900	150	0.739	0.15	300
2040	6900	150	0.703	0.15	350
	Results				
Year	Required Range (miles)	Battery Oversize factor	Battery capacity (kWh)	Battery Weight (kg)	Total Vehicle Cost ($)
2020	100	1.6	133	885	79894
	150	1.6	199	1328	99316
	200	1.6	266	1771	118738
2025	100	1.6	127	633	69267
	150	1.6	190	949	83664
	200	1.6	253	1266	98060
2030	100	1.6	121	483	54077
	150	1.6	181	724	61315
	200	1.6	241	965	68554
2035	100	1.5	111	370	50287
	150	1.5	166	554	55940
	200	1.5	222	739	61593
2040	100	1.5	105	301	46465
	150	1.5	158	452	50524
	200	1.5	211	603	54584

Cost Parameters Input									
Glider Cost ($)	Electric Drive ($/kW)	Electric Drive Integration Markup Factor	Energy Battery ($/kWh)	Electricity Cost ($/kWh)	Battery Integration Markup Factor	Maintenance Cost ($/mi)	Fuel Cost ($/mi)	Vehicle & Non-Battery Residual Value (%)	Battery Residual Value (%)
35200	30	1.3	225	0.17	1.3	0.18	0.16	0.5	0.15
35600	25	1.3	175	0.17	1.3	0.17	0.15	0.5	0.15
36000	20	1.2	100	0.17	1.2	0.16	0.15	0.5	0.15
36100	16	1.2	85	0.17	1.2	0.14	0.14	0.5	0.15
36200	13	1.1	70	0.17	1.1	0.14	0.14	0.5	0.15

Table 15b: Inputs for the diesel class 3 delivery van

Cost Parameters Input				
Maintenance Cost ($/mi)	Energy Consumption (mpgD)	Diesel Price ($/gal)	Fuel Cost ($/mi)	Vehicle Residual Value (%)
0.20	11.30	3.25	0.33	50%
0.20	12.00	3.50	0.34	50%
0.20	12.70	3.75	0.34	50%
0.20	13.30	4.00	0.35	50%
0.20	14.00	4.00	0.33	50%

Table 15c: Inputs for the battery-electric class 7 Box truck

	Vehicle Parameters Input				
Year	Gross Vehicle Weight (kg)	Electric Motor Power (kW)	Energy Consumption (kWh/mile)	Over Energy Factor	Battery Energy Density (Wh/kg)
2020	15000	300	1.76	0.3	150
2025	15000	300	1.7	0.2	200
2030	15000	300	1.64	0.15	250
2035	15000	300	1.58	0.15	300
2040	15000	300	1.52	0.1	350
	Results				
Year	Required Range (miles)	Battery Oversize factor	Battery capacity (kWh)	Battery Weight (kg)	Total Vehicle Cost ($)
2020	100	1.6	282	1877	178918
	150	1.6	422	2816	220102
	200	1.6	563	3755	261286
2025	100	1.6	272	1360	152580
	150	1.6	408	2040	183520
	200	1.6	544	2720	214460
2030	100	1.6	262	1050	119488
	150	1.6	394	1574	135232
	200	1.6	525	2099	150976
2035	100	1.5	237	790	110374
	150	1.5	356	1185	122461
	200	1.5	474	1580	134548
2040	100	1.5	228	651	101506
	150	1.5	342	977	110284
	200	1.5	456	1303	119062

Cost Parameters Input									
Glider Cost ($)	Electric Drive ($/kW)	Electric Drive Integration Markup Factor	Energy Battery ($/kWh)	Electricity Cost ($/kWh)	Battery Integration Markup Factor	Maintenance Cost ($/mi)	Fuel Cost ($/mi)	Vehicle & Non-Battery Residual Value (%)	Battery Residual Value (%)
79000	45	1.3	225	0.17	1.3	0.18	0.39	0.5	0.15
79000	30	1.3	175	0.17	1.3	0.17	0.35	0.5	0.15
79000	25	1.2	100	0.17	1.2	0.16	0.32	0.5	0.15
79000	20	1.2	85	0.17	1.2	0.14	0.31	0.5	0.15
79000	15	1.1	70	0.17	1.1	0.14	0.28	0.5	0.15

Table 16: Data inputs for fuel cell trucks

Table 16a: Inputs for the class 7 Box delivery truck

	Vehicle Parameters Input					
Year	Vehicle Weight (kg)	Electric Motor Power (kW)	Energy Consumption (kgH2/mile)	Over Energy Factor	Fuel Cell Power (kW)	Battery Capacity (kWh)
2020	15000	300	0.08	0.30	250	11
2025	15000	300	0.08	0.20	250	11
2030	15000	300	0.07	0.15	250	11
2035	15000	300	0.07	0.15	250	11
2040	15000	300	0.06	0.10	250	11

	Results			
Year	Required Range (miles)	H2 Oversize factor	H2 capacity (kg)	Total Vehicle Cost ($)
2020	100	1.3	10.8	297342
	150	1.3	16.3	304925
	250	1.3	27.1	320092
2025	100	1.3	10.2	167714
	150	1.3	15.4	171808
	250	1.3	25.6	179997
2030	100	1.3	9.4	130866
	150	1.3	14.0	132737
	250	1.3	23.4	136478
2035	100	1.3	9.0	121288
	150	1.3	13.4	122857
	250	1.3	22.4	125995
2040	100	1.3	8.3	110909
	150	1.3	12.4	112151
	250	1.3	20.7	114635

Cost Parameters Input										
Glider Cost ($)	Electric Drive ($/kW)	Electric Drive Integration Markup Factor	Fuel Cell ($/kW)	Fuel Cell Integration markup	H2 Storage ($/kgH2)	H2 Fueling Cost ($/kgH2)	Battery Cost ($/kWh)	Maintenance Cost ($/mi)	Fuel Cost ($/mi)	Vehicle Residual Value (%)
79000	75	1.3	525	1.3	1400	12	300	0.20	1.30	0.5
79000	40	1.3	193	1.3	800	8.5	200	0.18	0.80	0.5
79000	30	1.2	118	1.2	400	7	175	0.17	0.58	0.5
79000	25	1.2	95	1.2	350	6	150	0.15	0.48	0.5
79000	20	1.1	78	1.1	300	5	125	0.15	0.35	0.5

Table 16b: Inputs for class 3 Delivery Truck

	Vehicle Parameters Input					
Year	Vehicle Weight (kg)	Electric Motor Power (kW)	Energy Consumption (kgH2/mile)	Over Energy Factor	Fuel Cell Power (kW)	Battery Capacity (kWh)
2020	6500	150	0.04	0.15	100	3
2025	6500	150	0.04	0.15	100	3
2030	6500	150	0.04	0.15	100	3
2035	6500	150	0.04	0.15	100	3
2040	6500	150	0.03	0.10	100	3

	Results			
Year	Required Range (miles)	H2 Oversize factor	H2 capacity (kg)	Total Vehicle Cost ($)
2020	100	1.3	5.2	127114
	150	1.3	7.9	130783
	250	1.3	13.1	138122
2025	100	1.3	5.1	73568
	150	1.3	7.6	75608
	250	1.3	12.7	79686
2030	100	1.3	4.8	57997
	150	1.3	7.2	58953
	250	1.3	11.9	60864
2035	100	1.3	4.7	53981
	150	1.3	7.0	54796
	250	1.3	11.6	56427
2040	100	1.3	4.2	49521
	150	1.3	6.3	50154
	250	1.3	10.6	51421

Cost Parameters Input										
Glider Cost ($)	Electric Drive ($/kW)	Electric Drive Integration Markup Factor	Fuel Cell ($/kW)	Fuel Cell Integration markup	H2 Storage ($/kgH2)	H2 Fueling Cost ($/kgH2)	Battery Cost ($/kWh)	Maintenance Cost ($/mi)	Fuel Cost ($/mi)	Vehicle Residual Value (%)
36000	30	1.3	525	1.3	1400	12	300	0.204	0.556452	0.5
36000	25	1.3	193	1.3	800	8.5	200	0.187	0.383333	0.5
36000	20	1.2	118	1.2	400	7	175	0.17	0.295956	0.5
36000	16	1.2	95	1.2	350	6	150	0.153	0.247312	0.5
36000	13	1.1	78	1.1	300	5	125	0.153	0.186688	0.5

Table 16c: Inputs for Transit bus

Vehicle Parameters Input						
Year	Vehicle Weight (kg)	Electric Motor Power (kW)	Energy Consumption (kgH2/mile)	Over Energy Factor	Fuel Cell Power (kW)	Battery Capacity (kWh)
2020	15000	250	0.10	0.15	200	9
2025	15000	250	0.09	0.15	200	9
2030	15000	250	0.08	0.15	200	9
2035	15000	250	0.08	0.15	200	9
2040	15000	250	0.08	0.15	200	9

	Results			
Year	Required Range (miles)	H2 Oversize factor	H2 capacity (kg)	Total Vehicle Cost ($)
2020	100	1.3	13.0	532025
	150	1.3	19.5	541125
	200	1.3	26.0	550225
2025	100	1.3	11.7	431090
	150	1.3	17.6	435770
	200	1.3	23.4	440450
2030	100	1.3	10.8	401711
	150	1.3	16.2	403869
	200	1.3	21.6	406027
2035	100	1.3	10.3	393745
	150	1.3	15.4	395542
	200	1.3	20.5	397339
2040	100	1.3	9.8	385335
	150	1.3	14.6	386798
	200	1.3	19.5	388260

Cost Parameters Input										
Glider Cost ($)	Electric Drive ($/kW)	Electric Drive Integration Markup Factor	Fuel Cell ($/kW)	Fuel Cell Integration markup	H2 Storage ($/kgH2)	H2 Fueling Cost ($/kgH2)	Battery Cost ($/kWh)	Maintenance Cost ($/mi)	Fuel Cost ($/mi)	Vehicle Residual Value (%)
360000	45	1.3	525	1.3	1400	12	300	1.00	1.38	0.5
360000	30	1.3	193	1.3	800	8.5	200	0.92	0.88	0.5
360000	25	1.2	118	1.2	400	7	175	0.83	0.67	0.5
360000	20	1.2	95	1.2	350	6	150	0.75	0.55	0.5
360000	15	1.1	78	1.1	300	5	125	0.75	0.43	0.5

5.2 Cost results for 2020-2040

The cost results are calculated for two scenarios:

1) A 5-year initial ownership period, with resale value of the vehicle at that time. This is meant to characterize the private financial decision of a vehicle owner, such as a fleet.
2) A 15-year period with a low discount rate over time, which is meant to reflect the societal value of the vehicle and its various costs over its lifetime. This calculation may show that in some cases, a new technology has lower 15-year societal costs and is a better solution from that point of view, regardless of whether it is lower cost to the owner over a five-year period.

As described in previous sections, our calculations are made including the initial cost of the vehicles and the TCO for the two time periods. Tabular and graphic forms of the vehicle costs and 5-year TCO for battery-electric and fuel cell trucks are shown in Figures 5 and 6 for the low projected costs of the fuel cells (see Table 7). The 15-year societal TCO results for 2020-2040 are shown in Figures 7 and 8.

For both heavy-duty pickup trucks and long-haul trucks, results are shown for two operating conditions. The long-haul truck analysis is given for both a 300 and 500-mile range. While fleets generally view a 500-mile range as a minimum for long-haul driving between refueling, the cost of a 500-mile range battery electric truck is quite high due to the large battery energy necessary. It's possible that some long-haul routes could be configured for trucks with a 300-mile range between refueling. That possibility would enable much less expensive battery electric long-haul trucks in the market.

Heavy-duty pickups are used in a variety of applications. Many trucks may only need to drive a maximum of 100-150 miles per day, but other trucks may require significantly longer ranges on certain days. In addition, heavy-duty pickups may tow significant loads and require higher power than vehicles that do not need to tow. We analyzed two heavy-duty pickup applications. The first has a 150-mile range and lower battery, fuel cell, and motor powers. The second has a 250-mile range and higher power battery, fuel cell, and motors. The two applications can be considered as bounds to possible future ZE (zero emission) pickups.

Figure 5: Cost results for battery-electric trucks in 2030

5 year TCO

Vehicle Type	BEV Capital Cost ($)	BEV TCO ($/mi)	Diesel Capital Cost ($)	Diesel TCO ($/mi)
Passenger Van	51000	0.38	44000	0.48
Class 3 City Delivery Truck	61000	0.73	57000	0.83
Class 4 Step Van	78000	0.55	81000	0.70
Class 6 Box Truck	108000	0.68	95000	0.81
Class 7 Box Truck	135000	0.85	110000	0.98
Class 8 Box Truck	157000	0.99	124000	1.11
Short Haul Truck	160000	1.01	123000	0.95
Long Haul 300 mi range	218000	0.81	140000	0.79

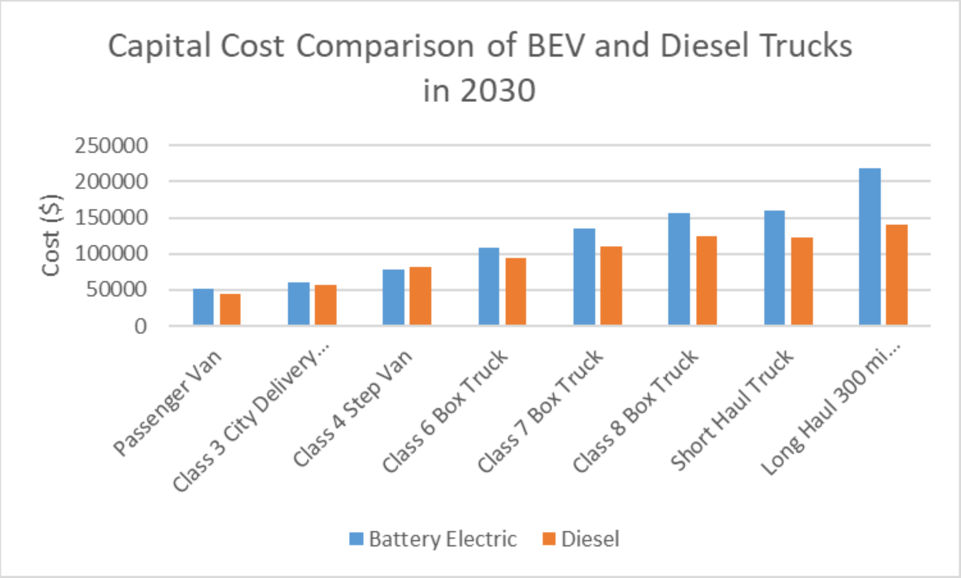


Figure 6: Cost results for fuel cell trucks in 2030

Capital cost and 5 year TCO in 2030

Vehicle Type	FCEV Capital Cost ($)	FCEV TCO ($/mi)	Diesel Capital Cost ($)	Diesel TCO ($/mi)
Passenger Van	54000	0.45	44000	0.48
Class 3 City Delivery Truck	57000	0.77	57000	0.83
Class 4 Step Van	79000	0.66	81000	0.70
Class 6 Box Truck	111000	0.81	95000	0.81
Class 7 Box Truck	133000	1.00	110000	0.98
Class 8 Box Truck	146000	1.13	124000	1.11
Short Haul Truck	144000	1.18	123000	0.95
Long Haul 300 mi range	158000	0.88	140000	0.79

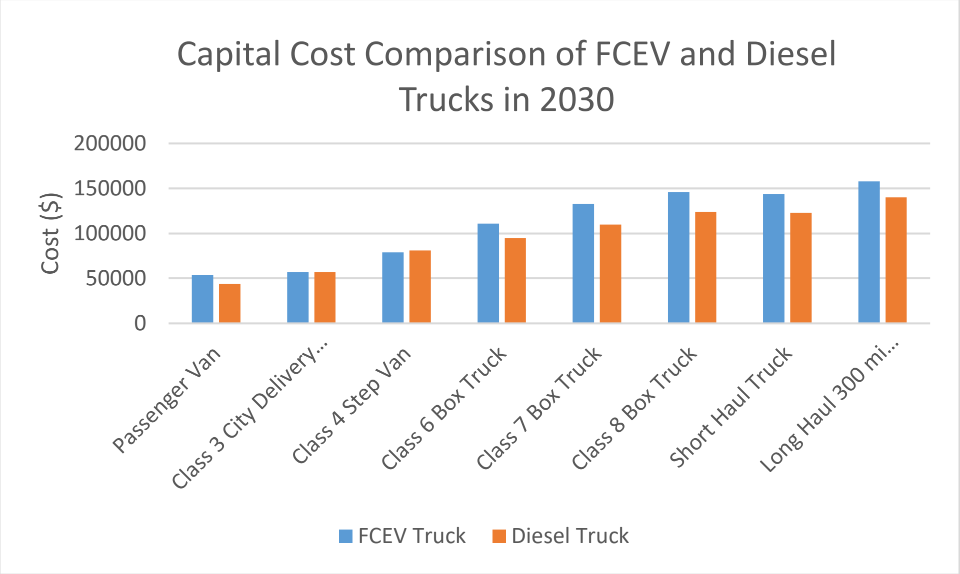


Figure 7: Societal (15 year) TCO for selected battery-electric vehicle types

Figure 7a: City delivery van

	Figure 7a: Class 3 Delivery Truck	
Year	BEV TCO ($/mile)	Diesel TCO ($/mile)
2020	0.99	0.71
2025	0.81	0.72
2030	0.66	0.73
2035	0.60	0.74
2040	0.57	0.72

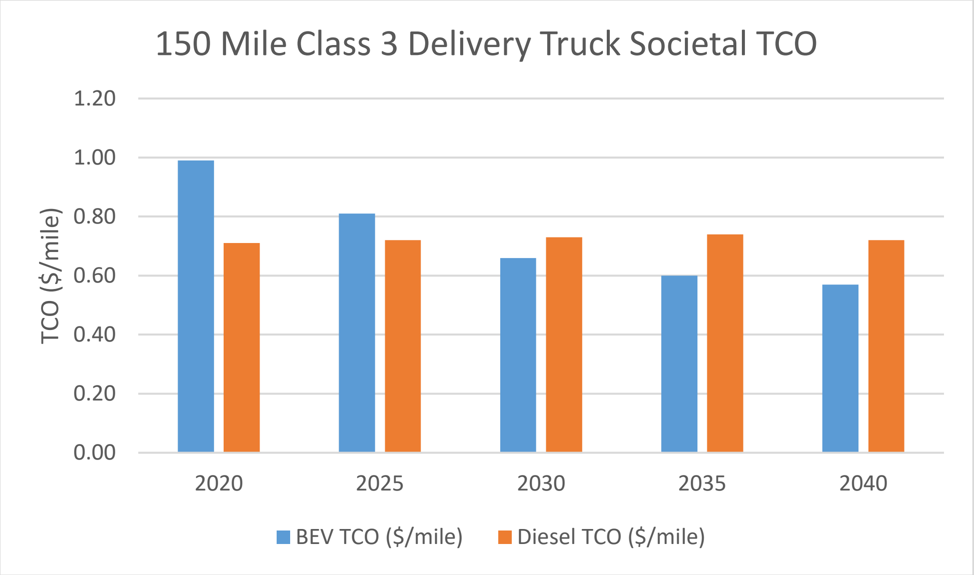


Figure 7b: 150 mi Class 7 Box truck

	Figure 7b: Class 7 Box Truck	
Year	BEV TCO ($/mile)	Diesel TCO ($/mile)
2020	1.15	0.88
2025	0.96	0.90
2030	0.80	0.92
2035	0.73	0.92
2040	0.68	0.90

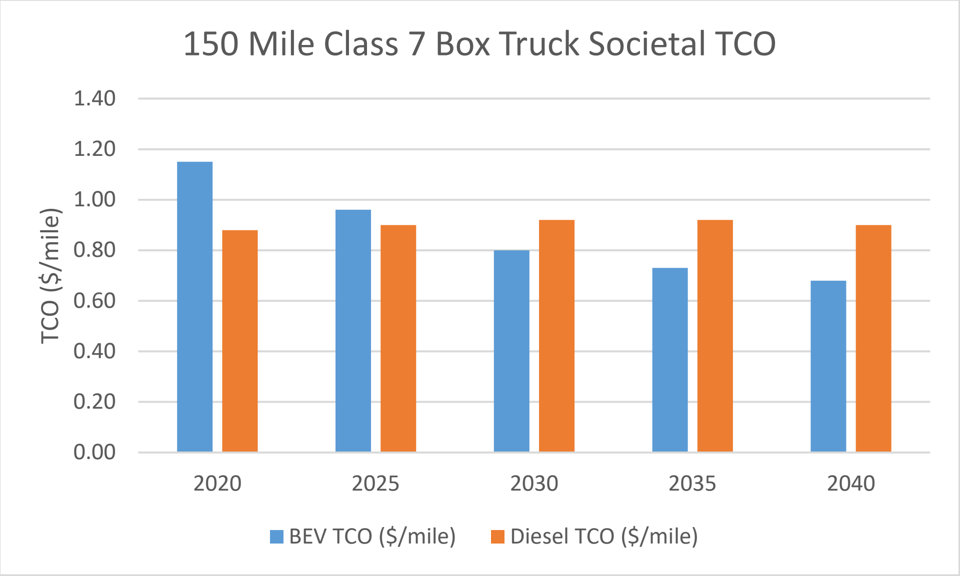


Figure 7c: 300 mi Long haul truck

	Figure 7c: Long-haul (300 mile)	
Year	BEV TCO ($/mile)	Diesel TCO ($/mile)
2020	1.24	0.82
2025	0.99	0.81
2030	0.79	0.77
2035	0.71	0.77
2040	0.67	0.69

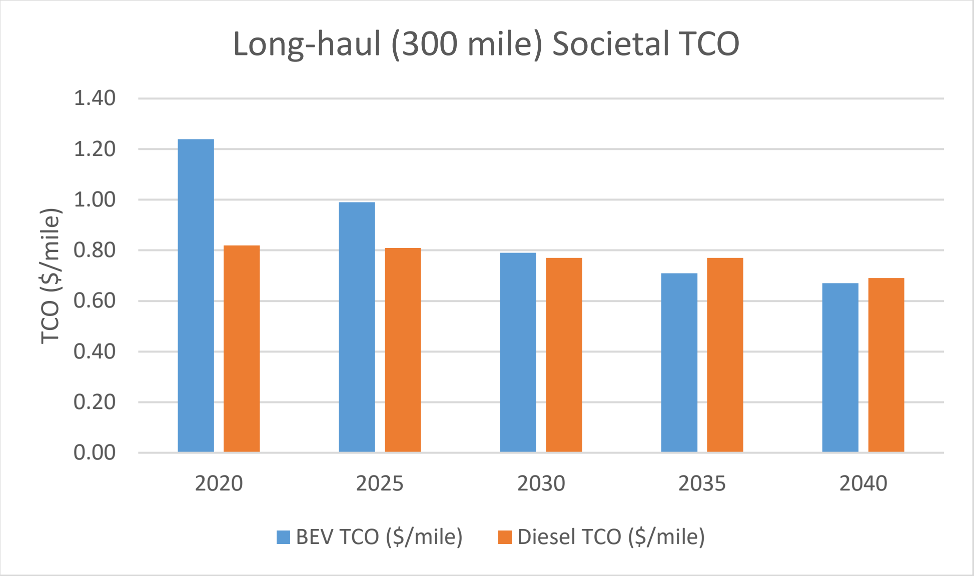


Figure 8: Societal (15 year) TCO for selected fuel cell trucks

Figure 8a: Class 3 fuel cell City Delivery Truck

	Figure 8a: Class 3 FCEV Delivery Truck	
Year	FCEV TCO ($/mile)	Diesel TCO ($/mile)
2020	1.23	0.71
2025	0.83	0.72
2030	0.67	0.73
2035	0.59	0.74
2040	0.52	0.72

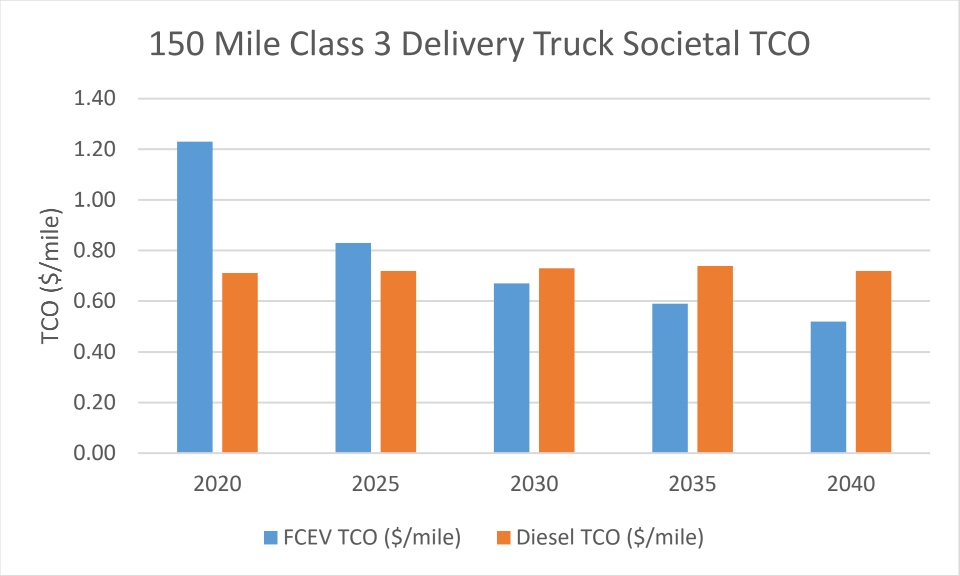


Figure 8b: Class 7 fuel cell Box truck

	Figure 8b: Class 7 FCEV Box Truck	
Year	FCEV TCO ($/mile)	Diesel TCO ($/mile)
2020	1.99	0.93
2025	1.24	0.94
2030	0.95	0.96
2035	0.82	0.96
2040	0.69	0.94

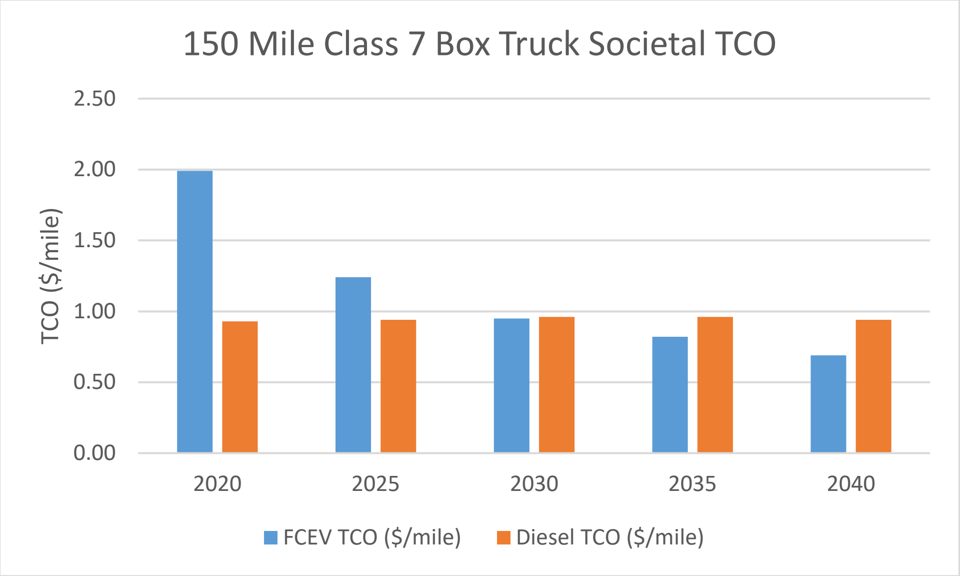


Figure 8c: City transit bus

	Figure 8c: Transit Bus	
Year	FCEV TCO ($/mile)	Diesel TCO ($/mile)
2020	3.30	2.50
2025	2.56	2.49
2030	2.24	2.49
2035	2.05	2.48
2040	1.93	2.45

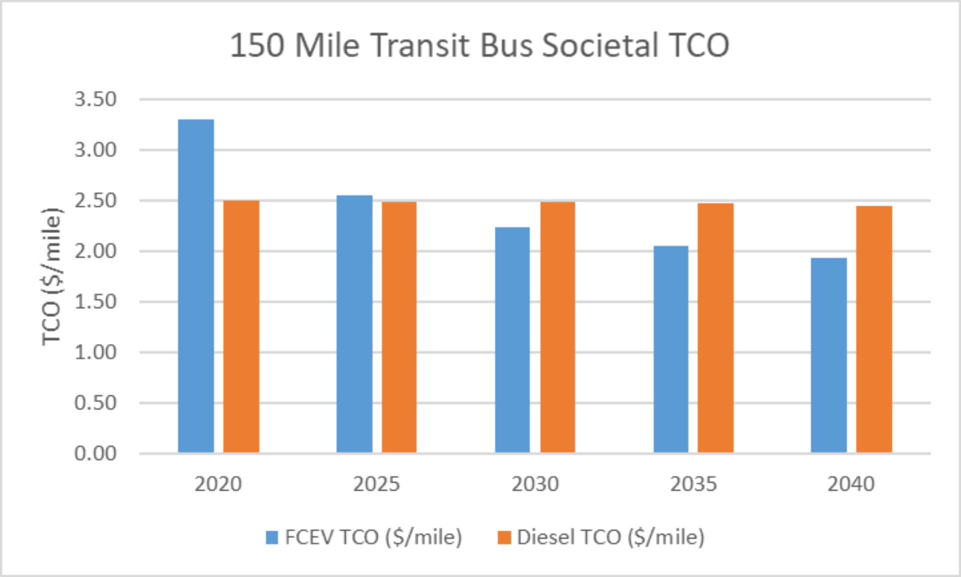
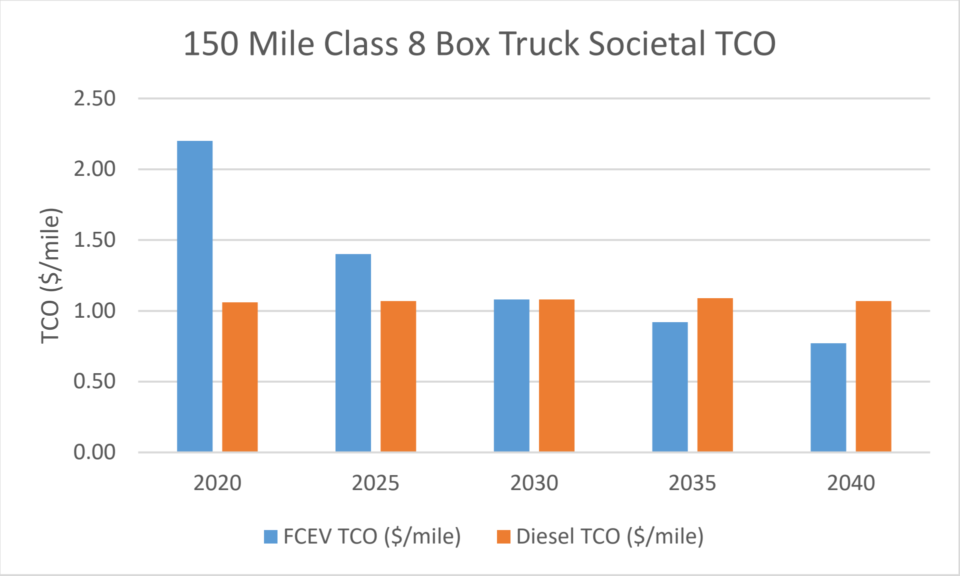


Figure 8d: Class 8 Large Box Delivery truck

	Figure 8d: Class 8 Box Truck	
Year	FCEV TCO ($/mile)	Diesel TCO ($/mile)
2020	2.20	1.06
2025	1.40	1.07
2030	1.08	1.08
2035	0.92	1.09
2040	0.77	1.07



5.3 Discussion of the cost results

Battery-electric trucks and buses

The cost results for the various types of trucks and buses are summarized in Tables 17 and 18 for the high, base, and low battery costs. The driving range of the city trucks considered was 150 miles. Results are shown for the initial vehicle cost and the TCO costs for the 5-year and 15-year periods of analysis. First, all of the battery electric trucks have a much higher initial cost/price than the comparable diesel engine truck in 2020 and even with the projected reductions in the cost of batteries and electric drive components, it will be at least 2030 before most of the battery-electric trucks have a purchase price close to the diesel-engine powered trucks even the cases of the low battery cost projections. Hence on a first cost basis, battery electric trucks will have a hard time competing in the market with engine-powered trucks in terms of the initial cost for at least 10 years. In the case of class 7 and 8 city trucks, it will be 5 years longer. A second conclusion from the results is that on the total cost of ownership (TCO) basis ($/mi), some of the types of battery-electric city trucks will be able to compete with engine-powered trucks/buses even in 2025 and certainly by 2030 using base battery costs. This appears to be the case for the city delivery trucks and passenger vans for 5 years and the buses for the 15-year lifetime of the bus. By 2035, the results indicate all the battery-electric trucks on a TCO basis will be able to compete with the engine-powered trucks. The calculated TCO values for the 5-year ownership period are in most cases only slightly higher than those for the 15-year lifetime of the trucks.

In the present TCO calculation, it has been assumed that the batteries have a very long lifetime (at least 10-12 years). This assumption does not influence the 5-year TCO, but it can have a strong effect on the 15-year TCO. Thus, both the initial cost of the batteries ($/kWh) and their lifetime (miles or years) could have a large effect on the economic attractiveness of electric trucks. The assumptions in the calculations concerning the electricity cost ($.17/kWh) and the diesel fuel cost (up to $ 4.0/gal by 2040) will also have a significant effect on the TCO. The sensitivity of the cost projections to variations in the electricity cost will be treated in a later section.

Consider next, the battery-electric long-haul truck and inter-city bus applications. These vehicles have ranges of 300-500 miles. Even for the low cost battery cases, the projected initial cost of the electric long haul trucks in 2040 is still slightly higher than the corresponding diesel-engine vehicles for a 300-mile range and significantly higher for the 500-mile electric vehicle. However, by 2035 the TCO costs of all the long-haul electric trucks are less than that of the diesel engine trucks. In the case of the inter-city bus, the initial cost of the electric bus is close to that of the diesel bus by 2035 and the TCO of the bus is less than that of the diesel bus by 2030.

Table 17: Summary of the cost results of battery-electric vehicles for various types for 2020-2040

	Diesel Truck			Electric truck								
Truck type	**Initial cost $K**	**TCO 5 yr. $/mi**	**TCO 15 yr. $/mi**	**Initial cost $K**			**TCO 5 yr. $/mi**			**TCO 15 yr. $/mi**		
				high	**base**	**low**	**high**	**base**	**low**	**high**	**base**	**low**
City delivery 150 mi												
2020	55	0.81	0.71	106	99	93	1.18	1.12	1.06	1.06	0.99	0.92
2025	56	0.82	0.72	90	84	77	1.10	0.96	0.90	0.87	0.81	0.75
2030	57	0.83	0.73	67	61	56	0.78	0.73	0.68	0.70	0.66	0.62
2035	58	0.84	0.74	59	56	53	0.70	0.67	0.64	0.63	0.60	0.58
2040	58	0.83	0.72	51	50	50	0.62	0.61	0.60	0.58	0.57	0.56
City transit bus 150 mi												
2020	400	2.86	2.50	539	522	506	3.14	3.07	2.99	2.71	2.62	2.54
2025	405	2.86	2.49	496	480	464	2.88	2.81	2.73	2.43	2.36	2.28
2030	410	2.86	2.49	435	422	409	2.52	2.46	2.40	2.15	2.10	2.05
2035	415	2.87	2.48	417	409	402	2.39	2.35	2.32	2.02	1.99	1.96
2040	420	2.84	2.45	399	397	395	2.30	2.29	2.28	1.97	1.95	1.94
Intercity bus 250 mi												
2020	400	2.18	1.96	583	562	541	2.49	2.42	2.36	1.21	2.14	2.06
2025	405	2.16	1.94	526	506	487	2.25	2.19	2.13	1.96	1.90	1.83
2030	410	2.17	1.95	453	436	419	1.97	1.91	1.86	1.74	1.69	1.65
2035	415	2.17	1.93	425	416	408	1.82	1.79	1.76	1.59	1.57	1.55
2040	420	2.16	1.92	401	399	396	1.73	1.72	1.71	1.53	1.52	1.51
Long haul 300 mi												
2020	134	0.84	0.82	464	429	394	1.41	1.33	1.26	1.32	1.24	1.15
2025	137	0.83	0.81	364	333	301	1.16	1.09	1.02	1.06	0.99	0.92
2030	140	0.79	0.77	245	218	191	0.87	0.81	0.75	0.84	0.79	0.75
2035	145	0.80	0.77	204	189	174	0.76	0.73	0.70	0.74	0.71	0.69
2040	149	0.77	0.74	169	164	160	0.68	0.67	0.66	0.69	0.67	0.66
Long haul 500 mi												
2020	134	0.78	0.78	698	640	581	1.55	1.45	1.36	1.46	1.36	1.25
2025	137	0.78	0.78	535	482	428	1.25	1.16	1.08	1.14	1.06	0.97
2030	140	0.73	0.73	337	291	245	0.90	0.83	0.75	0.88	0.82	0.77
2035	145	0.74	0.73	268	244	220	0.77	0.73	0.69	0.76	0.73	0.70
2040	149	0.71	0.70	212	205	198	0.67	0.66	0.65	0.70	0.69	0.67
Short haul 150 mi												
2020	119	0.95	0.87	291	273	254	1.62	1.54	1.46	1.48	1.39	1.30
2025	121	0.96	0.87	242	225	207	1.39	1.32	1.24	1.24	1.16	1.09
2030	123	0.95	0.87	175	160	145	1.08	1.01	0.95	1.00	0.95	0.90
2035	127	0.94	0.84	151	143	135	0.95	0.92	0.88	0.89	0.86	0.84
2040	130	0.85	0.75	128	126	124	0.83	0.82	0.81	0.79	0.78	0.77
Pickup 150 mi												
2020	42	0.77	0.70	86	82	77	1.10	1.06	1.01	0.97	0.92	0.87
2025	43	0.77	0.69	73	69	65	0.96	0.91	0.87	0.82	0.78	0.73
2030	44	0.77	0.69	56	52	49	0.76	0.72	0.69	0.67	0.64	0.62
2035	45	0.78	0.70	49	47	46	0.67	0.66	0.64	0.60	0.58	0.57
2040	46	0.77	0.68	44	44	43	0.62	0.61	0.61	0.56	0.55	0.55
Pickup 250 mi												
2020	42	0.77	0.70	110	103	97	1.36	1.29	1.22	1.21	1.13	1.06
2025	43	0.77	0.69	93	86	80	1.18	1.11	1.04	1.01	0.94	0.88
2030	44	0.77	0.69	67	61	56	0.88	0.82	0.76	0.79	0.74	0.70
2035	45	0.78	0.70	58	55	52	0.77	0.76	0.70	0.69	0.67	0.64
2040	46	0.77	0.68	49	48	47	0.67	0.66	0.65	0.63	0.61	0.60

Table 18: Summary of the cost results of battery-electric trucks of various classes for 2020-2040

	Diesel Truck			Electric truck								
Truck type	**Initial cost $K**	**TCO 5 yr. $/mi**	**TCO 15 yr. $/mi**	**Initial cost $K**			**TCO 5 yr. $/mi**			**TCO 15 yr. $/mi**		
				high	**base**	**low**	**high**	**base**	**low**	**high**	**base**	**low**
2b pass. Van 150 mi												
2020	42	0.46	0.44	84	80	75	0.56	0.54	0.52	0.52	0.50	0.48
2025	43	0.47	0.45	72	68	63	0.49	0.47	0.45	0.45	0.43	0.41
2030	44	0.48	0.46	55	51	47	0.40	0.38	0.37	0.38	0.36	0.35
2035	45	0.48	0.46	49	47	45	0.36	0.35	0.35	0.34	0.34	0.33
2040	46	0.48	0.45	43	43	42	0.33	0.33	0.33	0.32	0.32	0.31
3 City delivery van 150 mi												
2020	55	0.55	0.52	107	100	94	0.69	0.66	0.63	0.65	0.61	0.58
2025	56	0.56	0.53	90	84	78	0.60	0.57	0.54	0.54	0.52	0.49
2030	57	0.56	0.54	67	61	56	0.48	0.45	0.43	0.45	0.43	0.42
2035	58	0.57	0.54	59	56	53	0.43	0.42	0.41	0.41	0.40	0.39
2040	58	0.56	0.53	51	50	49	0.39	0.39	0.38	0.38	0.38	0.37
4 Step delivery truck 150 mi												
2020	79	0.68	0.64	135	127	119	0.83	0.80	0.76	0.77	0.74	0.70
2025	80	0.69	0.64	115	107	99	0.72	0.69	0.65	0.65	0.62	0.58
2030	81	0.70	0.65	85	78	71	0.57	0.55	0.52	0.54	0.52	0.49
2035	82	0.70	0.65	75	71	67	0.52	0.50	0.48	0.48	0.47	0.46
2040	83	0.69	0.64	66	64	63	0.47	0.46	0.46	0.45	0.45	0.44
6 Med. Box delivery truck 150 mi												
2020	90	0.78	0.73	178	168	158	1.03	0.99	0.95	0.94	0.90	0.85
2025	92	0.80	0.74	153	143	134	0.90	0.85	0.81	0.80	0.75	0.71
2030	95	0.81	0.75	116	108	99	0.72	0.68	0.65	0.66	0.63	0.60
2035	98	0.82	0.76	104	99	94	0.65	0.63	0.61	0.60	0.58	0.57
2040	100	0.81	0.75	92	91	89	0.59	0.58	0.58	0.56	0.55	0.54
7 Large Box delivery truck 150 mi												
2020	105	0.94	0.88	234	220	206	1.34	1.28	1.22	1.22	1.15	1.09
2025	107	0.96	0.90	197	184	170	1.14	1.08	1.03	1.01	0.96	0.90
2030	110	0.98	0.92	147	135	123	0.90	0.85	0.80	0.84	0.80	0.76
2035	112	0.99	0.92	129	122	116	0.81	0.78	0.75	0.75	0.73	0.71
2040	115	0.97	0.90	112	110	108	0.72	0.71	0.71	0.69	0.68	0.67
8 city box delivery truck 150 mi												
2020	120	1.08	1.01	278	261	244	1.58	1.51	1.44	1.45	1.37	1.29
2025	122	1.09	1.02	233	216	200	1.35	1.28	1.21	1.20	1.13	1.06
2030	124	1.11	1.03	172	157	143	1.06	0.99	0.93	0.98	0.93	0.88
2035	127	1.12	1.05	150	142	134	0.95	0.91	0.88	0.88	0.85	0.83
2040	130	1.10	1.02	130	127	125	0.84	0.83	0.82	0.80	0.79	0.78

Note that in Tables 17 and 18 that the TCO of the battery-electric city trucks becomes significantly less than that of the corresponding engine vehicle many years before its initial cost is close to that of the diesel vehicle. It is of interest to some potential buyers of the electric trucks as to how long it would take them to pay off the cost difference from savings in energy and maintenance costs. The payback years and miles for the various truck classes using the base cost batteries are shown in Table 17 for 2025 and 2030. Those periods were selected for the payback calculations because the TCOs of almost all of the electric trucks are less than that of the diesel truck and the initial cost of the electric trucks are all higher than that of the diesel trucks by varying amounts. The results in Table 17 indicate that except for the buses, the payback times for all the battery-electric vehicles are greater than 5 years in 2025, but by 2030, the payback times for all the BEVs except the long haul trucks are less than three years and, in many cases under two years. The payback times for the 300 mi and 500 mi long-haul trucks, as well as the 250 mile range heavy-duty pickup, are greater than 4 years.

This study indicates the development of the battery-electric truck and bus market could be relatively fast from 2020 to 2030. It should be noted, however, that these projections of battery-electric truck markets assume that the development of the market starts soon after 2020 and the sales/production of the electric trucks increases steadily up to 2040. Otherwise, the decreases in the costs projected will not occur. It is also assumed that the infrastructure needed to charge the batteries in the trucks will be developed as the market for electric trucks is established.

Table 19a: Payback miles and years for battery-electric trucks of various classes and types in 2025

		Cost Difference					
Vehicle	Mileage/ year	Capital ($)	Maintenance ($/mile)	Fuel ($/mile)	Operating ($/mile)	Payback Miles	Payback Years
Pass. Van	25000	25000	0.03	0.12	0.15	166995	6.7
Class 3 Delivery	20000	28000	0.03	0.13	0.16	172475	8.6
Class 4 Step Van	25500	27000	0.03	0.16	0.19	140170	5.5
Class 6 Box	25500	51000	0.03	0.20	0.24	216408	8.5
Class 7 Box	30000	77000	0.03	0.26	0.29	266724	8.9
Class 8 Box	30000	94000	0.03	0.29	0.32	295667	9.9
HD Pickup 150 mi	20000	26000	0.06	0.13	0.18	140894	7.0
HD pickup 250 mi	20000	43000	0.06	0.13	0.18	233016	11.7
Long-haul 300 mi	90000	196000	0.04	0.20	0.24	832963	9.3
Long-haul 500 mi	120000	345000	0.04	0.20	0.24	1466185	12.2
Transit Bus	40000	75000	0.18	0.41	0.59	126975	3.2
Intercity Bus	60000	101000	0.18	0.24	0.42	240428	4.0

Table 19b: Payback miles and years for battery-electric trucks of various classes and types in 2030

		Cost Difference					
Vehicle	Mileage/ year	Capital ($)	Maintenance ($/mile)	Fuel ($/mile)	Operating ($/mile)	Payback Miles	Payback Years
Pass. Van	25000	7000	0.04	0.13	0.17	40168	1.6
Class 3 Delivery	20000	4000	0.04	0.15	0.19	20891	1.0
Class 4 Step Van	25500	-3000	0.04	0.18	0.22	-13395	0.0
Class 6 Box	25500	13000	0.04	0.23	0.27	48108	1.9
Class 7 Box	30000	25000	0.04	0.29	0.34	74023	2.5
Class 8 Box	30000	33000	0.04	0.32	0.37	89701	3.0
HD Pickup 150 mi	20000	8000	0.07	0.13	0.20	39747	2.0
HD pickup 250 mi	20000	17000	0.07	0.13	0.20	84462	4.2
Long-haul 300 mi	90000	78000	0.05	0.17	0.21	364011	4.0
Long-haul 500 mi	120000	151000	0.05	0.17	0.21	704688	5.9
Transit Bus	40000	12000	0.23	0.43	0.66	18137	0.5
Intercity Bus	60000	26000	0.23	0.26	0.49	52548	0.9

Trucks and buses using fuel cells

The spreadsheet cost results for the various classes of trucks and buses using fuel cells are summarized in Tables 20 and 21. Cost results are shown in the tables for the high, base, and low fuel cell cost projections (see Table 7). The fuel cell cost ($/kW) has a greater effect on the initial cost of the fuel cell vehicles than on the ownership costs ($/mi). The hydrogen costs ($/kg) assumed are the base costs shown in Table 9. The fuel cell vehicle cost results are discussed in this section in detail. First, all of the trucks using fuel cells have a much higher cost/price than the comparable diesel engine truck in 2020. Even with the projected large reductions in the cost of fuel cells and the electric drive components, it takes until 2030 for the initial cost of class 3-6 trucks using fuel cells to be essentially equal to that of the conventional engine vehicles. In the case of class 7 and 8 trucks, it takes until 2035 for the initial costs to be nearly the same. Both the lifetime 15-year TCO and the 5-year TCO of the fuel cell trucks becomes lower than that of the corresponding engine vehicle by 2030 except for heavy-duty and pickup trucks. The results indicate that the cost of the fuel system will need to decrease to about $120/kW and/or the cost of hydrogen will need to be less than $5/kg for fuel cell vehicles to be cost competitive in most urban applications. According to Table 6, this would require a production volume of at least 20,000 units per year.

Table 20: Summary of the cost results for fuel cell vehicles of various types for 2020-2040

	Diesel Truck			**Fuel cell truck**								
Truck type	**Initial cost $K**	**TCO 5 yr. $/mi**	**TCO 15 yr. $/mi**	**Initial cost $K**			**TCO 5 yr. $/mi**			**TCO 15 yr. $/mi**		
				high	**base**	**low**	**high**	**base**	**low**	**high**	**base**	**low**
City delivery 150 mi												
2020	55	0.81	0.71	145	122	99	1.64	1.47	1.31	1.34	1.23	1.12
2025	56	0.82	0.72	79	73	66	1.01	0.97	0.92	0.86	0.83	0.80
2030	57	0.83	0.73	60	57	54	0.80	0.77	0.75	0.68	0.67	0.65
2035	58	0.84	0.74	56	53	51	0.71	0.69	0.68	0.60	0.59	0.58
2040	58	0.83	0.72	50	49	48	0.63	0.62	0.61	0.53	0.52	0.52
City transit bus 150 mi												
2020	400	2.86	2.50	587	541	496	3.96	3.80	3.63	3.41	3.30	3.19
2025	405	2.86	2.49	448	436	423	3.01	2.97	2.92	2.59	2.56	2.53
2030	410	2.86	2.49	410	404	397	2.65	2.62	2.60	2.25	2.24	.2.22
2035	415	2.87	2.48	400	396	391	2.45	2.44	2.42	2.06	2.05	2.03
2040	420	2.86	2.45	389	387	384	2.33	2.32	2.31	1.94	1.93	1.92
Intercity bus 250 mi												
2020	400	2.18	1.96	597	551	506	3.08	2.97	2.86	2.74	2.67	2.60
2025	405	2.16	1.94	453	441	429	2.36	2.33	2.30	2.11	2.09	2.07
2030	410	2.17	1.95	413	406	400	2.07	2.06	2.04	1.83	1.82	1.81
2035	415	2.17	1.83	402	398	393	1.90	1.88	1.87	1.65	1.64	1.64
2040	420	2.16	1.92	391	388	385	1.79	1.78	1.78	1.55	1.54	1.54
Long haul 300 mi												
2020	134	0.84	0.82	445	377	309	1.98	1.87	1.76	1.85	1.78	1.70
2025	137	0.83	0.81	228	210	191	1.18	1.15	1.12	1.13	1.11	1.09
2030	140	0.79	0.77	168	158	148	0.89	0.88	0.86	0.86	0.84	0.83
2035	145	0.80	0.77	152	145	138	0.76	0.75	0.73	0.72	0.71	0.70
2040	149	0.77	0.74	136	132	128	0.64	0.64	0.63	0.61	0.60	0.60
Long haul 500 mi												
2020	134	0.84	0.82	483	415	347	1.85	1.76	1.68	1.76	1.71	1.65
2025	137	0.83	0.81	247	229	210	1.11	1.09	1.07	1.08	1.07	1.05
2030	140	0.79	0.77	176	166	156	0.83	0.82	0.81	0.82	0.81	0.80
2035	145	0.80	0.77	159	152	145	0.70	0.69	0.69	0.68	0.68	0.67
2040	149	0.77	0.74	141	137	133	0.59	0.59	0.58	0.57	0.57	0.57
Short haul 150 mi												
2020	119	0.95	0.87	368	312	255	2.51	2.32	2.14	2.23	2.10	1.98
2025	121	0.96	0.87	198	182	167	1.53	1.48	1.43	1.39	1.36	1.33
2030	123	0.95	0.87	152	144	135	1.20	1.18	1.15	1.10	1.09	1.07
2035	127	0.94	0.84	139	133	127	1.04	1.02	1.00	0.94	0.93	0.92
2040	130	0.89	0.80	126	123	119	0.90	0.89	0.87	0.80	0.80	0.79
Pickup 150 mi												
2020	42	0.77	0.69	146	123	100	1.74	1.55	1.37	1.40	1.27	1.15
2025	43	0.77	0.69	79	73	66	1.07	1.02	0.97	0.89	0.86	0.83
2030	44	0.77	0.69	60	57	53	0.84	0.81	0.79	0.71	0.69	0.67
2035	45	0.78	0.69	55	52	49	0.74	0.72	0.70	0.62	0.61	0.60
2040	46	0.77	0.68	49	47	46	0.67	0.66	0.65	0.56	0.55	0.55
Pickup 250 mi												
2020	42	0.77	0.69	242	196	151	2.53	2.16	1.79	1.93	1.68	1.43
2025	43	0.77	0.69	113	101	88	1.35	1.25	1.15	1.08	1.01	0.95
2030	44	0.77	0.69	79	72	66	0.99	0.94	0.89	0.81	0.78	0.74
2035	45	0.78	0.69	69	64	59	0.86	0.82	0.78	0.70	0.68	0.65
2040	46	0.77	0.68	59	56	53	0.75	0.73	0.71	0.62	0.60	0.59

Table 21: Summary of the cost results of fuel cell trucks in various classes for 2020-2040

	Diesel Truck			Fuel Cell truck								
Truck type	**Initial cost $K**	**TCO 5 yr. $/mi**	**TCO 15 yr. $/mi**	**Initial cost $K**			**TCO 5 yr. $/mi**			**TCO 15 yr. $/mi**		
				high	**base**	**low**	**high**	**base**	**low**	**high**	**base**	**low**
2b pass. Van 150 mi												
2020	42	0.46	0.46	146	123	100	0.95	0.88	0.80	0.87	0.82	0.77
2025	43	0.47	0.48	76	70	63	0.59	0.57	0.55	0.56	0.54	0.53
2030	44	0.48	0.48	57	54	51	0.46	0.45	0.43	0.44	0.43	0.42
2035	45	0.48	0.49	52	50	47	0.40	0.40	0.39	0.38	0.38	0.37
2040	46	0.48	0.48	47	45	44	0.35	0.35	0.34	0.33	0.33	0.33
3 City delivery van 150 mi												
2020	55	0.55	0.55	154	131	108	1.13	1.06	0.98	1.07	1.02	0.97
2025	56	0.56	0.56	82	76	69	0.71	0.69	0.67	0.69	0.68	0.67
2030	57	0.56	0.56	62	59	56	0.56	0.54	0.53	0.54	0.54	0.53
2035	58	0.57	0.57	57	55	52	0.49	0.48	0.47	0.47	0.47	0.46
2040	58	0.56	0.55	51	50	49	0.42	0.41	0.41	0.40	0.40	0.40
4 Step delivery truck 150 mi												
2020	79	0.68	0.67	217	183	149	1.47	1.36	1.25	1.35	1.28	1.21
2025	80	0.69	0.67	112	102	93	0.88	0.85	0.82	0.85	0.83	0.81
2030	81	0.70	0.68	83	79	74	0.67	0.66	0.64	0.65	0.64	0.63
2035	82	0.70	0.68	76	73	69	0.59	0.57	0.56	0.56	0.55	0.54
2040	83	0.69	0.67	68	66	64	0.50	0.50	0.49	0.47	0.47	0.46
Class 6 Box delivery truck 150 mi												
2020	90	0.78	0.76	293	248	202	1.82	1.67	1.52	1.64	1.54	1.44
2025	92	0.80	0.78	154	142	129	1.09	1.05	1.01	1.01	0.98	0.96
2030	95	0.81	0.79	118	111	104	0.84	0.81	0.79	0.78	0.77	0.75
2035	98	0.82	0.79	108	103	98	0.73	0.72	0.70	0.67	0.66	0.65
2040	100	0.81	0.78	97	95	92	0.63	0.62	0.61	0.57	0.57	0.56
Class 7 Box delivery truck 150 mi												
2020	105	0.94	0.93	362	305	248	2.32	2.14	1.95	2.11	1.99	1.86
2025	107	0.96	0.94	187	172	156	1.36	1.31	1.26	1.28	1.24	1.21
2030	110	0.98	0.96	141	133	124	1.03	1.00	0.97	0.96	0.95	0.93
2035	112	0.99	0.96	129	123	117	0.90	0.88	0.86	0.83	0.82	0.81
2040	115	0.97	0.94	115	112	109	0.76	0.75	0.73	0.69	0.69	0.68
Class 8 Box delivery truck 150 mi												
2020	120	1.08	1.06	378	321	264	2.52	2.34	2.15	2.32	2.20	2.07
2025	122	1.09	1.07	201	186	170	1.51	1.46	1.41	1.43	1.40	1.36
2030	124	1.11	1.08	154	146	137	1.16	1.13	1.10	1.09	1.08	1.06
2035	127	1.12	1.09	141	135	129	1.00	0.98	0.96	0.93	0.92	0.91
2040	130	1.10	1.07	127	124	121	0.85	0.84	0.83	0.78	0.77	0.76

The payback years and miles for the various fuel cell truck classes are shown in Table 22 for 2025 and 2030. In the case of the fuel cell trucks and buses, the initial vehicle cost and TCO relative to the diesel engine powered vehicles decrease together because both the vehicle component and hydrogen costs are decreasing from 2020 to 2040. Both the vehicle and TCO costs approach that of the diesel vehicles by 2030 and the TCO is significantly less by 2035. In 2025 fuel cell trucks don't ever payback because the hydrogen fuel cost is so high that there are no operating savings. In 2030 some of the trucks do see reasonable payback periods (5 years or less), but the operating cost savings are relatively modest due to the cost of hydrogen. In the section on LCFS below, we calculate payback periods with LCFS credits reducing the price of hydrogen, and the results are more promising.

Table 22a: Payback miles and years for fuel cell trucks of various classes in 2025

		Cost Difference					
	Mileage/	Capital	Maintenan	Fuel	Operating	Payback	Payback
Vehicle	year	($)	($/mile)	($/mile)	($/mile)	Miles	Years
Pass. Van	25000	27000	0.02	-0.03	-0.01	-2095200	NA
Class 3 Delivery	20000	20000	0.02	-0.11	-0.09	-218182	NA
Class 4 Step Van	25500	22000	0.02	-0.14	-0.12	-185263	NA
Class 6 Box	25500	50000	0.02	-0.13	-0.11	-447848	NA
Class 7 Box	30000	65000	0.02	-0.20	-0.18	-355124	NA
Class 8 Box	30000	64000	0.02	-0.23	-0.21	-299777	NA
HD Pickup 150 mi	20000	30000	0.03	-0.04	-0.01	-2764477	NA
HD pickup 250 mi	20000	58000	0.03	-0.04	-0.01	-5344656	NA
Long-haul 300 mi	90000	73000	0.02	-0.28	-0.26	-278268	NA
Long-haul 500 mi	120000	92000	0.02	-0.28	-0.26	-350694	NA
Transit Bus	40000	31000	0.08	-0.07	0.01	3611650	90.3
Intercity Bus	60000	36000	0.08	-0.20	-0.11	-318232	NA

NA = Operating cost difference is negative so there is no payback ever.

Table 22b: Payback miles and years for fuel cell trucks of various classes in 2030

		Cost Difference					
	Mileage/	Capital	Maintenan	Fuel	Operating	Payback	Payback
Vehicle	year	($)	($/mile)	($/mile)	($/mile)	Miles	Years
Pass. Van	25000	10000	0.03	0.05	0.08	121991	4.9
Class 3 Delivery	20000	2000	0.03	0.00	0.03	61250	3.1
Class 4 Step Van	25500	-2000	0.03	0.01	0.04	-50008	0.0
Class 6 Box	25500	16000	0.03	0.03	0.06	256168	10.0
Class 7 Box	30000	23000	0.03	0.04	0.07	333571	11.1
Class 8 Box	30000	22000	0.03	0.03	0.06	363506	12.1
HD Pickup 150 mi	20000	13000	0.05	0.03	0.08	157059	7.9
HD pickup 250 mi	20000	28000	0.05	0.03	0.08	338281	16.9
Long-haul 300 mi	90000	18000	0.03	-0.10	-0.07	-251382	NA
Long-haul 500 mi	120000	26000	0.03	-0.10	-0.07	-363107	NA
Transit Bus	40000	-6000	0.17	0.12	0.28	-21231	0.0
Intercity Bus	60000	-4000	0.17	-0.02	0.14	-28124	0.0

NA = Operating cost difference is negative so there is no payback ever.

5.4 Comparisons of the economics of battery-electric and fuel cell vehicles of various classes

The cost results in Tables 16-22 indicate that the battery-electric and fuel cell MD/HD vehicles become close to cost competitive with the engine powered vehicles around 2030. In both cases, those times correspond to the battery and fuel cell technologies becoming mature and large volumes of both technologies being manufactured. It is of interest to compare the relative economic attractiveness of electrified vehicles in 2030. These comparisons are made in Table 23 for various classes/types of trucks.

First, consider vehicles for urban applications that do not require long ranges. The results in Tables 18 and 21 indicate that for vehicle ranges of 150 miles, the battery and fuel cell vehicles of each class (2-8) have essentially the same projected cost except for long-haul trucks where fuel cell trucks are significantly less expensive due to the high cost of the large batteries in battery electric trucks. The 15-year TCO ($/mi) of the fuel cell trucks is higher than those of the corresponding battery-electric vehicles primarily because the cost of hydrogen was assumed to be $ 7.5 /kg in the calculations. The battery electric trucks have a significantly lower TCO than diesel vehicles except in the case of long-haul trucks. Fuel cell trucks have similar or lower TCO costs than diesel except for long-haul trucks. These results indicate that when the battery-electric and fuel cell technologies become mature, both of them should be competitive with the majority of engine vehicle technologies. Hence selecting one technology over the other for urban applications will not be made primarily based on vehicle economics. The availability of convenient and cost-effective infrastructure is likely to be the determining factor for city applications.

Table 23: Comparison of the economics of battery-electric and fuel cell vehicles of various types for mature technologies in 2030

Vehicle	**BEV 2030***			**FCV 2030****		**Diesel**	*******
	Initial cost K$	TCO 15 yr. $/mi		Initial cost K$	TCO 15 yr. $/mi	Initial cost K$	TCO 15 yr. $/mi
Class 2b Van 150 mi. range	51	.36		54	.43	44	.48
Class 3 Delivery trk. 150 mi. range	61	.66		57	.67	57	.73
Class 4 Step van 150 mi. range	78	.55		79	.64	81	.65
Class 6 Box 150 mi. range	108	.63		111	.77	95	.75
Class 7 Box 150 mi. range	135	.80		133	.95	110	0.96
Class 8 Box 150 mi. range	157	0.93		146	1.08	124	1.03
Transit bus 150 mi. range	422	2.10		404	2.24	410	2.49
Inter-city bus 250 mi range	436	1.69		406	1.82	410	1.95
Long Haul trk. 300 mi range	218	.79		158	.84	140	.73
Long Haul trk. 500 mi range	291	.82		166	.81	140	.76

*In 2030, the battery cost is $100/kWh and the electricity cost is $.17/kWh

**In 2030, the fuel cell system cost is $118/kW and the cost of renewable hydrogen is $7/kg

*** diesel fuel is $3.75/gal.

Next, consider longer-range applications involving inter-city travel. These applications utilize class 8 long haul trucks and inter-city buses (like Greyhound). The cost results in Tables 18 and 21 indicate that applications requiring ranges of 250-500 miles favor the use of fuel cells rather than batteries. The costs of the fuel trucks are significantly less than the battery-electric trucks and when the cost of hydrogen becomes $5/kg their TCO will also be significantly lower. This is the case because increasing the range of a fuel cell truck only requires carrying additional hydrogen onboard the vehicle and the cost of hydrogen storage is $350/kgH2 ($10.5/kWh) compared to $80/kWh for batteries. Hydrogen also has a large advantage in weight and volume of energy storage. For a range of 500 miles, the battery pack would weigh 4280 kg compared to 1050 kg for the hydrogen tanks. In terms of volume, the battery would be 2125 L compared to 1620 L for the hydrogen tanks. The breakpoint between the battery and fuel cell vehicles for long distance applications seems to be a range of about 200-250 miles.

5.5 Sensitivity Analysis

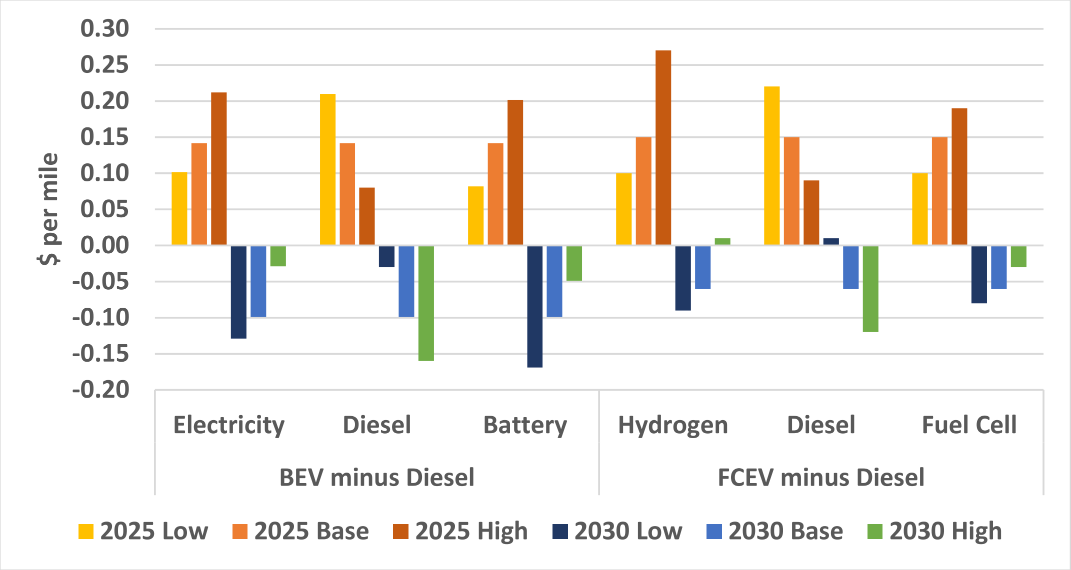
The "base case" results shown in Tables 15, 16, 18, and 19 provide a guide to the potential relative costs of BEV and FCEV vehicles to diesel vehicles over the next 20 years, but they do not capture the wide range of variation that is possible in future costs in any given year. We try to provide a sense of this variation through a simplified sensitivity analysis. For our five main cost parameters, we have estimated low and high case values (Table 24 and Table 25) that are almost equally plausible as our base values (Table 9). We have no way to estimate the probability of these cost cases in reality, but they will show the sensitivity of TCO to the cost inputs.

The Excel models were organized with the low, base, and high inputs shown in the tables. The results are shown in Tables 24-28 and Figures 9-13 for several vehicle types for 2025 and 2030. The tables show the actual TCO values for each of the inputs. The figures show differences between the calculated TCO and the base TCO for the diesel vehicle for the BEV and FCV trucks. Positive differences indicate the electrified vehicle has a higher TCO than the diesel vehicle and a negative value on the plot indicates a lower TCO than the diesel vehicle.

Table 24. Variation of TCO for sensitivity cases for BEV and FCEV City Delivery trucks in 2025 and 2030

		2025			2030		
		Low	Base	High	Low	Base	High
BEV	Electricity	0.92	0.96	1.03	0.70	0.73	0.80
	Battery	0.90	0.96	1.02	0.66	0.73	0.78
FCEV	Hydrogen	0.92	0.97	1.09	0.74	0.77	0.84
	Fuel Cell	0.92	0.97	1.01	0.75	0.77	0.80
Diesel	Diesel fue	0.75	0.82	0.88	0.76	0.83	0.89

Figure 9: The sensitivity of TCO differences for BEV and FCEV City Delivery Trucks in 2025 and 2030



For the city delivery trucks in 2025, BEV trucks have a base case TCO about $0.15/mi higher than diesel trucks, but this can range from about $0.08/mi to over $0.20/mi due to variations in the inputs. The base TCO of a fuel cell truck is $0.15/mi higher than the base diesel truck and ranges from $0.09/mi to $0.27/mi as the inputs are varied. By 2030, the base TCO for both truck technologies is less than for the diesel (negative cost difference). For BEVs, varying the inputs results in an advantage between $.03/mi and $.17/mi and for FC trucks, the relative TCO ranges from an advantage of $.12/mi to a disadvantage of $.01/mi. Overall these sensitivities show that the relative costs of technologies are not dramatically altered by varying key inputs within a reasonable range. The variation in hydrogen cost in 2025 results in the biggest range in TCOs of any variable. Varying the inputs within the ranges chosen results in around a $0.10-0.15/mi variation in TCO from low to high. The maximum variations in 2030 are smaller for the FCV cases than the BEV cases primarily because the variation in the electricity price percentage-wise is greater than for hydrogen.

The sensitivity results for several other vehicle types and transit buses are given in Tables 25-28. The overall trends and broad results are similar to those for the delivery trucks just discussed. Varying the inputs over reasonable ranges does not dramatically alter relative TCO results between BEV, FCEV and diesel technologies.

Table 25: Variation of TCO for BEV and FCEV short-haul trucks in 2025 and 2030

		2025			2030		
		Low	Base	High	Low	Base	High
BEV	Electricity	1.22	1.32	1.51	0.92	1.01	1.20
	Battery	1.24	1.32	1.39	0.95	1.01	1.08
FCEV	Hydrogen	1.35	1.48	1.79	1.09	1.18	1.34
	Fuel Cell	1.43	1.48	1.53	1.15	1.18	1.20
Diesel	Diesel fue	0.85	0.96	1.06	0.86	0.95	1.05

Figure 10: Sensitivities of differences in the TCO for short-haul trucks in 2025 and 2030

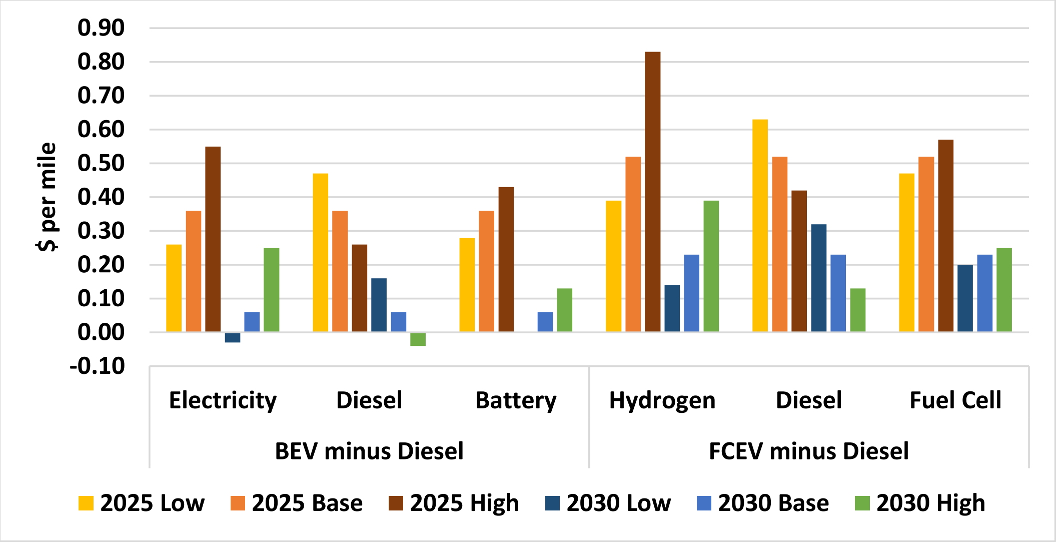


Table 26:

Table 26: Variation of TCO for BEV and FCEV 500 mi long-haul trucks in 2025 and 2030

		2025			2030		
		Low	Base	High	Low	Base	High
BEV	Electricity	1.07	1.16	1.34	0.74	0.83	0.99
	Battery	1.08	1.16	1.25	0.75	0.83	0.90
FCEV	Hydrogen	0.97	0.97	1.37	0.75	0.75	0.96
	Fuel Cell	1.07	0.97	1.12	0.81	0.75	0.83
Diesel	Diesel fue	0.66	0.78	0.88	0.63	0.73	0.84

Figure 11: Sensitivities of differences in the TCO for the 500 mi long haul truck in 2025 and 2030

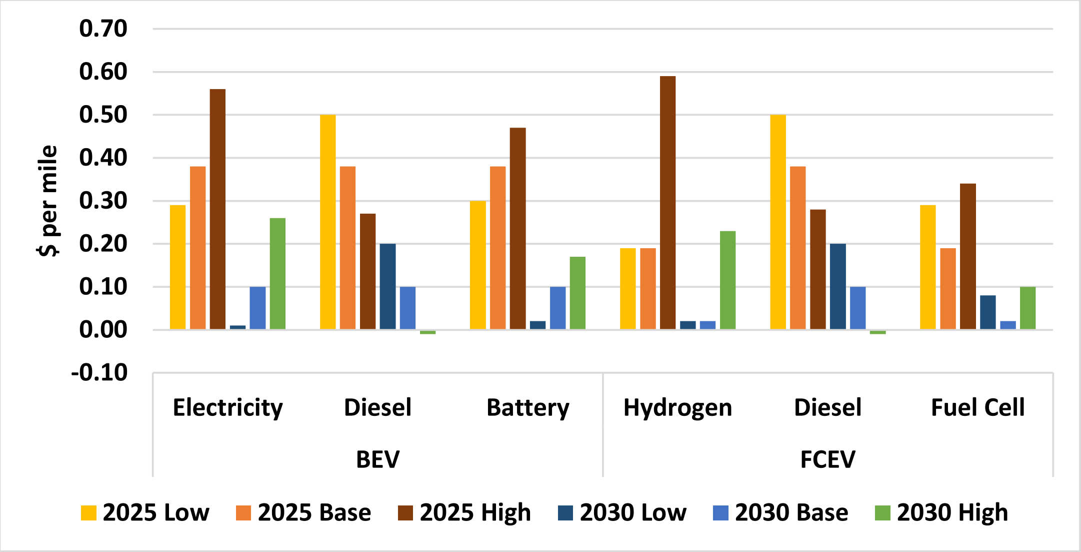


Table 27: Variation of TCO for BEV and FCEV HD pickup trucks in 2025 and 2030

		2025			2030		
		Low	Base	High	Low	Base	High
BEV	Electricity	0.89	0.91	0.96	0.70	0.72	0.77
	Battery	0.87	0.91	0.96	0.69	0.72	0.76
FCEV	Hydrogen	0.98	1.02	1.10	0.79	0.81	0.86
	Fuel Cell	0.97	1.02	1.07	0.79	0.81	0.84
Diesel	Diesel fue	0.72	0.77	0.81	0.73	0.77	0.82

Figure 12: Sensitivities of differences in the TCO for the HD pickup trucks in 2025 and 2030

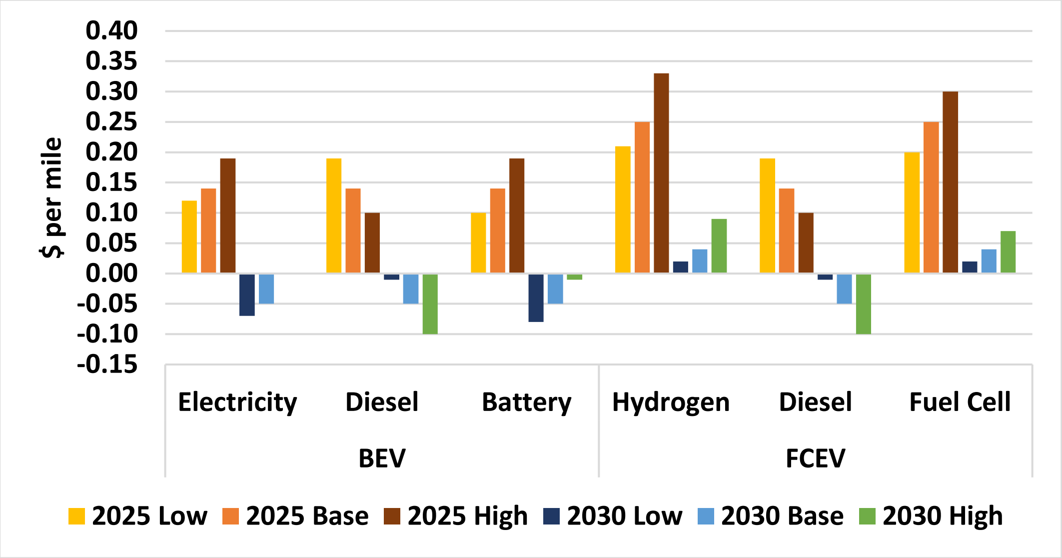
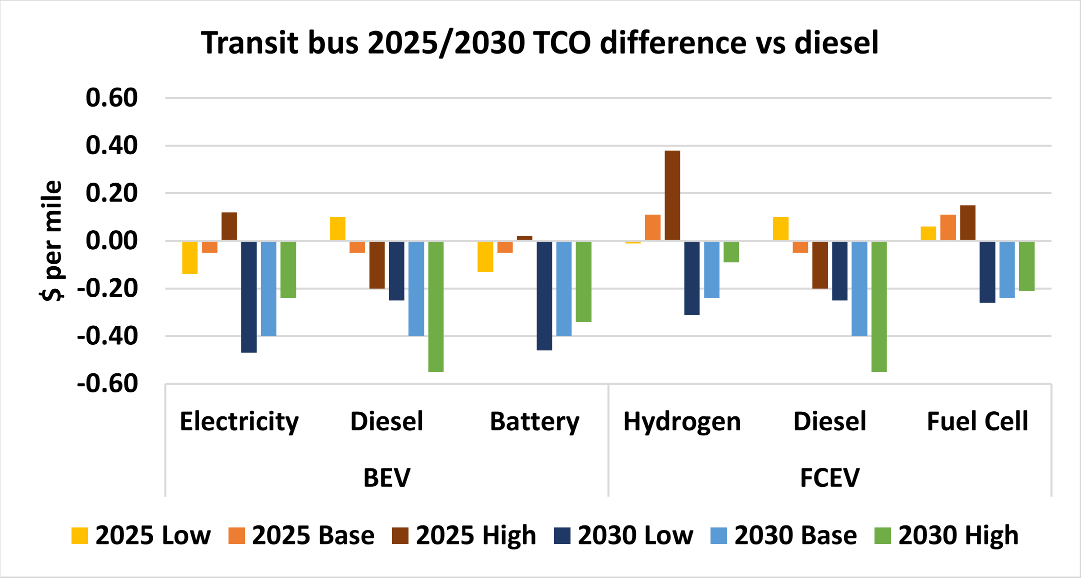


Table 28: Variation of TCO for BEV and FCEV Transit Buses in 2025 and 2030

		2025			2030		
		Low	Base	High	Low	Base	High
BEV	Electricity	2.72	2.81	2.98	2.39	2.46	2.62
	Battery	2.73	2.81	2.88	2.40	2.46	2.52
FCEV	Hydrogen	2.85	2.97	3.24	2.55	2.62	2.77
	Fuel Cell	2.92	2.97	3.01	2.60	2.62	2.65
Diesel	Diesel fue	2.71	2.86	3.01	2.71	2.86	3.01

Figure 13: Sensitivities of differences in the TCO for the city transit buses in 2025 and 2030



5.6 LCFS and Carbon Cost

Battery electric (BEV) and fuel cell (FCEV) trucks have lower greenhouse gas (GHG) emissions than conventional diesel trucks, and their emissions will decline over time as the production of electricity and hydrogen shifts to renewables. The benefits of lower GHG emissions do not show up in the TCO analysis described above. To include the value of lower GHG emissions, we did two things. In the private cost analysis, we calculated truck TCO by adding the effects of the California Low Carbon Fuel Standard (LCFS) regulation (LCFS reg) and the estimated effect of this on fuel prices, given truck GHG emissions per mile by technology. The LCFS regulation potentially increases or lowers the cost of fuels to truck operators based on the fuel carbon intensity (gCO2e/MJ), as scored within the LCFS system.

In the societal cost analysis, we considered a straight value of CO2 abatement. Various studies and agencies have estimated the societal or social cost of carbon (e.g. EPA, 2017, CARB, 2017, Stanford, 2015). These estimates typically range from about $15 to over $200 per tonne of CO2e, depending on the time frame, discount rate, and other factors. If a carbon tax were implemented, fuel costs would change as well, raising the cost of higher carbon-intensity fuels relative to lower-intensity fuels.

The LCFS regulation could directly affect truck fuel prices so we included that effect in the private 5-year TCO analysis. We included the effect of truck carbon emissions and a straight carbon price in the societal 15-year societal cost-oriented TCO analysis.

LCFS TCO Analysis

The LCFS is designed to promote the utilization of low-carbon transportation fuels in California and encourage the increased production of those fuels. The regulation is intended to encourage reductions in GHG emissions and shifts to lower carbon fuels in the transportation sector. We calculated the impact of LCFS cost adjustment on truck TCOs in 2025 and 2030 by modifying the baseline fuel costs for diesel, electricity, and hydrogen based on expected fuel carbon intensities, for sample LCFS carbon prices. We also selected target carbon intensities, which affect the relative fees or rebates on fuels, but do not affect the relative costs placed by the LCFS.

As shown in Table 29, based on CARB projections, the target carbon intensities we used are 86 gCO2e/MJ in 2025 and 80 gCO2e/MJ in 2030 [39]. The fuel carbon intensities are converted within the LCFS system to carbon intensities per vehicle mile using energy efficiency ratios (EERs). The vehicle EERs we use match the system's scoring; *i.e.* on a miles per gallon basis we use a 2.5 multiplier for FCEVs, 5 for Class 4-8 BEVs, 3.4 for Class 2b-3 BEVs, and 1 for diesel trucks (CARB calculation). We then multiplied through to a fuel cost adjustment per mile of driving, using assumed values of LCFS credits of $100 and $200.

The results are identical to the private 5-year analysis described above with the prices of diesel fuel, electricity, and hydrogen, but with fuel costs modified by the LCFS. We assumed diesel blends would use the same percentage of biomass-based diesel (BBD) as currently (~16%).

Table 29. Values used in the LCFS fuel price calculation with $100 LCFS credits.

		gCO2e/MJ					Price Change	
Year	Fuel	CI	Target	Target*EER	(MJ/GGE)	$/GGE	$/unit	(unit)
2025	Diesel	100.45	86.00	86.00	121.36	$0.18	$0.20	$/gal
	BBD	30.00	86.00	86.00	121.36	-$0.68	-$0.77	$/gal
	Diesel blend	89.20	86.00	86.00	121.36	$0.04	$0.04	$/gal
	Electricity	67.80	86.00	430.00	121.36	-$4.40	-$0.14	$/kWh
	Hydrogen	52.84	86.00	215.00	121.36	-$1.97	-$2.01	$/kg
2030	Diesel	100.45	80.00	80.00	121.36	$0.25	$0.28	$/gal
	BBD	28.00	80.00	80.00	121.36	-$0.63	-$0.72	$/gal
	Diesel blend	88.90	80.00	80.00	121.36	$0.11	$0.12	$/gal
	Electricity	47.66	80.00	400.00	121.36	-$4.28	-$0.13	$/kWh
	Hydrogen	39.88	80.00	200.00	121.36	-$1.94	-$1.98	$/kg

Notes: "BBD" is biomass based diesel, typically hydrotreated vegetable oil or "renewable diesel". Diesel fuel is 100% fossil fuel based diesel without blends of BBD. Diesel blend is 16% BBD, 84% diesel.

Table 30 shows the effect of the LCFS regulation on trucks purchased in 2025 and 2030. We included an LCFS credit price scenario of both $100 and $200. The LCFS price changes increase the diesel truck TCO very slightly, but the BEV and FCEV TCOs are significantly reduced. In some cases for the $100 credit, the LCFS fuel price change reduces the BEV or FCEV TCO below the diesel TCO when the base BEV or FCEV TCO was above the diesel TCO. Examples are the 2025 BEV TCO and the 2030 FCEV TCO for a 300-mile long-haul truck. An LCFS credit price of $200 results in an electricity price reduction of $0.27/kWh. The base electricity price is only $0.17/kWh so the price of electricity to fleets would be below zero. We assumed a price of exactly $0.0/kWh in this case.

Table 30. Truck Private 5-Year TCO with the effect of LCFS regulation on diesel, electricity, and hydrogen prices.

Truck type	Diesel			BEV			FCEV		
	Base	Base + LCFS ($100)	Base + LCFS ($200)	Base	Base + LCFS ($100)	Base + LCFS ($200)	Base	Base + LCFS ($100)	Base + LCFS ($200)
City delivery 150 mi									
2025	0.82	0.82	0.82	0.96	0.86	0.84	0.97	0.90	0.83
2030	0.83	0.84	0.85	0.73	0.64	0.62	0.77	0.71	0.65
City transit bus 150 mi									
2025	2.86	2.87	2.87	2.81	2.57	2.51	2.97	2.81	2.65
2030	2.86	2.88	2.90	2.46	2.25	2.19	2.62	2.48	2.34
Intercity bus 250 mi									
2025	2.16	2.17	2.17	2.19	2.01	1.97	2.33	2.20	2.07
2030	2.17	2.19	2.20	1.91	1.75	1.70	2.06	1.94	1.81
Long haul 300 mi									
2025	0.83	0.84	0.85	1.09	0.84	0.78	1.15	0.99	0.84
2030	0.79	0.80	0.82	0.81	0.59	0.53	0.88	0.74	0.60
Long haul 500 mi									
2025	0.78	0.78	0.79	1.16	0.92	0.86	1.09	0.93	0.77
2030	0.73	0.75	0.76	0.83	0.60	0.54	0.82	0.68	0.54
Short haul 150 mi									
2025	0.96	0.96	0.97	1.32	1.05	0.78	1.48	1.30	1.13
2030	0.95	0.97	0.98	1.01	0.77	0.52	1.18	1.01	0.85
Pickup 150 mi									
2025	0.77	0.77	0.77	0.91	0.85	0.83	1.02	0.97	0.92
2030	0.77	0.78	0.79	0.72	0.66	0.64	0.81	0.77	0.73

The payback period for battery electric trucks in 2025 is in the 5-12 year range except for buses. That period is significantly reduced by 2030 when the periods are in the 0-3 year range except for 250-mile pickups (4.22 years) and long-haul trucks (4-6 years). Fuel cell trucks do not payback in 2025 because the hydrogen cost is assumed to be $8.50/kg for renewable hydrogen. With the hydrogen cost at that price, there are no fuel savings and no overall operating cost savings. By 2030 the assumed cost of hydrogen drops to $7/kg, and there are fuel savings for all trucks except long-haul. The payback periods for passenger vans, class 3 delivery trucks, and class 4 step vans fall below 5 years with other trucks generally above 10 years. The cost of hydrogen in the 2025-2030 time period remains a significant barrier for fuel cell trucks to become economically competitive.

The LCFS program can reduce the cost of electricity and hydrogen and significantly lower the payback period. Table 31 shows the payback periods in 2025 and 2030 for battery electric trucks for the case with no LCFS (BEV), the case with an LCFS credit price of $100 (BEV 100), and the case with an LCFS credit price of $200 (BEV 200). In 2025 for the $200 credit price, many payback periods are reduced by roughly a factor of 2. In 2030, the already low payback periods are further reduced.

Table 31. Battery electric truck payback periods (years) in 2025 and 2030. The values are calculated for no LCFS (BEV), LCFS credit price of $100 (BEV 100), and LCFS credit price of $200 (BEV 200).

	2025			2030		
Vehicle	BEV	BEV 100	BEV 200	BEV	BEV 100	BEV 200
Pass. Van	6.68	4.08	3.69	1.61	1.06	0.95
Class 3 Delivery	8.62	4.74	4.23	1.04	0.60	0.53
Class 4 Step Van	5.50	2.93	2.61	0.00	0.00	0.00
Class 6 Box	8.49	4.52	4.02	1.89	1.10	0.96
Class 7 Box	8.89	4.47	3.94	2.47	1.37	1.19
Class 8 Box	9.86	4.67	4.10	2.99	1.57	1.35
HD Pickup 150 mi	7.04	4.75	4.36	1.99	1.38	1.25
HD pickup 250 mi	11.65	7.85	7.21	4.22	2.93	2.66
Long-haul 300 mi	9.26	3.86	3.34	4.04	1.66	1.40
Long-haul 500 mi	12.22	5.10	4.41	5.87	2.41	2.03
Transit Bus	3.17	2.05	1.87	0.45	0.31	0.28
Intercity Bus	4.01	2.54	2.32	0.88	0.59	0.54

Table 32 shows the payback periods in 2025 and 2030 for fuel cell trucks for the case with no LCFS (FCEV), the case with an LCFS credit price of $100 (FCEV 100), and the case with an LCFS credit price of $200 (FCEV 200). In 2025 there was no payback due to the high hydrogen price. With an LCFS credit price of $200, the payback periods for several trucks are under 10 years. By 2030 for the $100 credit price, payback periods fall to 3 years or lower for many truck types, and the $200 credit price, most trucks have payback periods of less than 2 years.

Table 32. Fuel cell truck payback periods (years) in 2025 and 2030. The values are calculated for no LCFS (FCEV), LCFS credit price of $100 (FCEV 100), and LCFS credit price of $200 (FCEV 200).

	2025			2030		
Vehicle	FCEV	FCEV 100	FCEV 200	FCEV	FCEV 100	FCEV 200
Pass. Van	NA	20.74	9.23	4.88	2.80	1.97
Class 3 Delivery	NA	156.75	9.58	3.06	0.70	0.42
Class 4 Step Van	NA	226.58	6.83	0.00	0.00	0.00
Class 6 Box	NA	62.06	11.22	10.05	3.16	1.87
Class 7 Box	NA	154.17	10.26	11.12	3.03	1.76
Class 8 Box	NA	116.39	8.53	12.12	2.62	1.47
HD Pickup 150 mi	NA	26.45	12.07	7.85	4.41	3.07
HD pickup 250 mi	NA	51.14	23.34	16.91	9.51	6.61
Long-haul 300 mi	NA	NA	4.83	NA	NA	0.61
Long-haul 500 mi	NA	NA	4.57	NA	NA	0.66
Transit Bus	NA	3.42	1.75	0.00	0.00	0.00
Intercity Bus	NA	9.01	2.44	0.00	0.00	0.00

NA = Operating cost difference is negative so there is no payback ever.

Carbon Cost TCO Analysis

For the 15-year ownership analysis, we re-calculated the truck TCO by including the cost of its yearly carbon emissions (gCO2e). We used the same assumed carbon intensities as for the LCFS example above. We valued carbon at both $100 and $200/ tonne CO2e. Table 31 shows the effect of carbon emissions on trucks purchased in 2025 and 2030. The results vary by truck type but generally indicate that at $100/ton, the TCO for BEV trucks typically drops below that for diesel, even in 2025 and can be much lower by 2030. For FCEVs, a $200/ton value produces similar effects as $100 for BEVs.

Table 31. Truck Societal 15-Year TCO with the effect of valuing carbon emissions on diesel trucks, BEVs, and FCEVs.

Truck type	Diesel			BEV			FCEV		
	Base	Base + carbon ($100)	Base + carbon ($200)	Base	Base + carbon ($100)	Base + carbon ($200)	Base	Base + carbon ($100)	Base + carbon ($200)
City delivery 150 mi									
2025	0.72	0.79	0.87	0.81	0.83	0.84	0.83	0.85	0.87
2030	0.73	0.79	0.85	0.66	0.67	0.68	0.67	0.68	0.70
City transit bus 150 mi									
2025	2.49	2.67	2.85	2.36	2.41	2.45	2.56	2.61	2.66
2030	2.49	2.63	2.77	2.10	2.13	2.16	2.24	2.28	2.31
Intercity bus 250 mi									
2025	1.94	2.06	2.18	1.90	1.94	1.97	2.09	2.13	2.17
2030	1.95	2.04	2.14	1.69	1.71	1.72	1.82	1.85	1.87
Long haul 300 mi									
2025	0.81	0.94	1.06	0.99	1.04	1.08	1.11	1.15	1.20
2030	0.77	0.87	0.97	0.79	0.82	0.84	0.84	0.87	0.90
Long haul 500 mi									
2025	0.78	0.91	1.04	1.06	1.11	1.15	1.07	1.11	1.16
2030	0.73	0.82	0.92	0.82	0.85	0.87	0.81	0.84	0.87
Short haul 150 mi									
2025	0.87	0.99	1.11	1.16	1.21	1.26	1.36	1.41	1.47
2030	0.87	0.96	1.05	0.95	0.98	1.01	1.09	1.13	1.17
Pickup 150 mi									
2025	0.69	0.77	0.85	0.78	0.80	0.81	0.86	0.88	0.89
2030	0.69	0.74	0.78	0.64	0.65	0.65	0.69	0.70	0.71

6. Summary and conclusions

The primary objective of this study was to evaluate the economics of various types and classes of medium-duty and heavy-duty battery-electric and hydrogen fuel cell vehicles relative to the corresponding diesel-engine powered vehicle for 2020-2040. The study included the following vehicles types and classes: large passenger vans, class 3 city delivery vans, class 4 step city delivery trucks, class 6 box trucks, class 7 box trucks, class 8 box trucks, city transit buses, long haul tractor trailer trucks, city short haul tractor trailer delivery trucks, inter-city buses, and HD pickup trucks. Typical "paper" designs of each of the vehicles were formulated in terms of its road load characteristics and powertrain and energy storage components. The vehicle performance and energy consumption were simulated for appropriate driving cycles using the ADVISOR simulation program. The vehicle design characteristics were varied over 2020-2040 to reflect expected technology improvements.

In this study, the cost and variation over time of the driveline and energy storage components, especially the batteries and fuel cell system, were of particular importance. Expected improvements in the performance and cost of the components were studied and suitable projections in the performance and cost of batteries and fuel cells were developed as inputs to Excel cost models. A spreadsheet was prepared to describe the economics of each of the vehicle types being analyzed. Every attempt was made to determine real-world values for the energy consumption (kWh/mi, kgH_2/mi) for the vehicles to account for the effects of road grade, traffic, and variations of the accessory loads. The simulations were interpreted to be the energy consumption on a level road under ideal conditions. In the analysis, those values were multiplied by factors of 1.15-1.3 to account for the real-world operation of the vehicles. The inputs used in the present study are given in detail in the report for future reference because the results and conclusions of the study are very dependent on the inputs used to make the economics calculations.

High, base, and low sets of values for the costs of the lithium batteries and polymer electrolyte membrane (PEM) fuel cell systems in 2020, 2025, 2030, 2035, and 2040 were developed from the literature. These base values and associated variations each year were used for the economics calculations. The energy cost inputs are also important. The energy situation over the next twenty years, and the likely retail energy prices (including diesel, electricity and hydrogen) is fairly uncertain. In the case of electricity, more and more electricity will be renewable being generated from photovoltaic cells. The cost of renewable electricity can vary over a wide range from day-to-day. In this study, the base electricity cost was fixed at $.15/kWh with an addition of $0.02/kWh for the amortized value of the charging system. The effects of the large variations in electricity cost were also considered in a sensitivity study. The cost of hydrogen is presently high ($10-15/ kg), but as shown in the table, it is expected to decrease markedly in the next twenty years. A key issue is how soon the cost of hydrogen will approach $5/kg. The effects of this uncertainty on fuel cell truck and bus operating costs were evaluated in a sensitivity study of hydrogen costs ($/kg$H_2$).

The initial purchase cost and total cost of ownership (TCO) were estimated for the initial 5-year period and the 15-year lifetime for the various vehicle types/classes using batteries and fuel cells. Calculations are done for 2020, 2025, 2030, 2035, and 2040. For both battery and fuel cell vehicles, both the initial cost and TCO decrease markedly in the period 2020-2030 and more modestly for 2030-2040.

The analysis of the cost results shows consistently that the TCO for the various electrified trucks is significantly less than that of the corresponding diesel truck before the initial cost of the electrified truck/ bus is close to that of the initial cost of the diesel truck. For the battery-electric trucks, this occurs by 2030 for the base cases. In 2030, the payback time for the city battery-electric trucks is 3 years or less. By 2030, the base cost results for fuel cell trucks indicate payback times are longer. The payback times for transit buses are much shorter than for trucks for both 2025 and 2030. By 2030, the initial costs of both battery-electric and hydrogen fuel cell trucks are approaching that of the corresponding diesel vehicle. In 2030 and beyond, whether the TCOs of the electrified trucks are less than the diesel trucks depend primarily on the energy costs – electricity, hydrogen, and diesel fuel. As noted previously, those energy costs from renewable sources are uncertain at present especially when LCFS credits are considered. The effect of the energy costs on the TCOs can be significant as shown in the sensitivity study results, but the differences do not significantly affect the conclusions concerning the relative economics of the battery-electric and fuel cell technologies for reasonable variations in the input costs.

For inter-city applications requiring long ranges of 300 miles and greater, the cost results indicate that the initial cost of trucks using fuel cells will be significantly less than those using batteries. In addition, the weight of the hydrogen storage will be much less than the batteries. As for city electrified trucks and buses, the energy costs will be critical in comparing their TCOs with diesel vehicles for inter-city applications.

The cost of the “make ready” infrastructure required for the battery-electric and hydrogen fuel trucks was not considered in the present analysis, but it will be critically important in determining the success of marketing electrified trucks and which technology is preferred by the market. Unlike light-duty vehicles that need to be refueled infrequently, the commercial medium- and heavy-duty trucks will need to be refueled daily. This will put increased demands on the infrastructure for commercial vehicles.

Another area needing more attention is valuing the non-cost attributes of these different vehicles, such as the value of different levels of driving range and refueling time. UC Davis will publish a follow on paper to this one in the coming months that adds these types of considerations into the analysis. UC Davis also will soon publish a comparison of this study and a range of other recent truck TCO type studies, and assess how various assumptions and treatment of different inputs affects estimates, and what that can tell us about improving consistency and reliability of these types of studies. That study will also be released during 2022.

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