Title

Technology and Fuel Transition Scenarios to Low Greenhouse Gas Futures for Cars and Trucks in California

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Energy Futures
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SUSTAINABLE TRANSPORTATION ENERGY PATHWAYS
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Glossary

AEO	Annual Energy Outlook (of the Energy Information Administration)
BAU	Business as Usual
BEV	battery electric vehicle
CAFÉ	corporate average fuel economy (standards)
CARB	California Air Resources Board
CCST	California Council on Science and Technology
CI	carbon intensity, typically CO2e grams per megajoule of energy or similar energy unit
CO2e	carbon dioxide-equivalent emissions (including CH4 and N2O)
CNG	compressed natural gas
DGE	diesel gallons equivalent
DOE	U.S. Department of Energy
EATS	engine after treatment system
EV100	battery electric vehicle with 100 mile driving range
EV200	battery electric vehicle with 200 mile driving range
EDV	electric drive vehicle (includes battery electric, plug-in hybrid and fuel cell)
EMFAC	Emissions Factors (California Air Resources Board emissions inventory model)
EPA	U.S. Environmental Protection Agency
FCEV	fuel cell electric vehicle
H_2	hydrogen
HD	heavy-duty
HEFA	hydro-processed esters and fatty acids
HEV	hybrid electric vehicle
HDV	heavy duty vehicle (including medium and heavy-duty trucks)
ICCT	International Council on Clean Transportation
GGE	gasoline gallon equivalent
GHG	greenhouse gases (same as CO2e)
ICEV	internal combustion engine vehicle
LD	light-duty
LDV	Light-duty vehicles
LNG	liquefied natural gas
LCFS	Low Carbon Fuel Standard
MD	medium-duty
MPGGE	miles per gallon gasoline equivalent
NG	natural gas
OEM	original equipment manufacturer
P10	plug-in hybrid electric vehicle with 10 mile electric driving range
P40	plug-in hybrid electric vehicle with 40 mile electric driving range

PHEV	plug-in hybrid electric vehicle
RD	renewable diesel
RGC	reduced generalized cost
RNG	renewable natural gas
TCM	truck choice model
TCO	total cost of ownership
TTM	transportation transitions model
Voc	vocational
VMT	vehicle miles traveled
ZEV	zero emission vehicle (and name of scenario in this study)
ZEV+B	zero emission vehicle + biofuels (scenario in this study)

Abstract

This study examines potential changes in car and truck powertrain technology and fuel mix that could enable a transition to low carbon futures, out to 2050, in California. We consider combinations of battery-electric and plug-in hybrid electric vehicles, hydrogen fuel cells, and advanced biofuels, including ethanol, diesel biofuels, and renewable natural gas, for internal combustion engines that could lead to 80% GHG reductions compared to 1990. We consider two main low-carbon scenarios—a high ZEV adoption case (ZEV) and a mixed (ZEV and Biofuel) adoption case (ZEV+B)—both relative to a business-as-usual (BAU) case. We find that achieving an 80% reduction in CO_2 from cars and trucks (separately and together) appears feasible at relatively low cumulative cost, and with eventual likely net savings (as fuel savings exceed vehicle cost, mostly after 2030). However, the required rates of increase in sales of ZEV cars and trucks, and production volumes of advanced, low-carbon biofuels, will be quite challenging. Regarding ZEVs, we expect the greatest challenge to be for long-haul trucks, and we reduce the rate of sales increase for these as a result. In the ZEV scenario, all vehicle types reach 100% ZEV sales shares by 2050 (except long-haul trucks, which reach 80%). In the ZEV+B scenario, these targets are lower, but a strong ramp-up in advanced biofuel use is needed to achieve the 80% target, with commercial scale cellulosic production of ethanol and renewable diesel dominant by 2050. The net costs or savings of the scenarios are relatively low—on the order of ±$10-50 billion over the next 30 years—in relation to $4 trillion total spending in the BAU scenario. However, the additional costs of vehicle purchase run as high as $110 billion in the ZEV scenario, which will likely require substantial purchase incentives to overcome. Future research should examine how costs translate into policy needs (including generalized cost factors such as driving range) and the potential role, sourcing, and cost of advanced biofuels.

1 Executive Summary

California has adopted ambitious targets for greenhouse gas (GHG) reduction, including a target of 80% reduction in energy-related CO_2 emissions by 2050 relative to 1990, a statutory target of 40% reductions by 2030, and an executive order calling for state-wide carbon neutrality by 2045. Road transportation modes—including cars and light, medium, and heavy trucks—will have an important role to play.

In this study, we examine the costs and challenges of reducing road transportation GHG emissions to 80% below the 1990 level by 2050, through rapid uptake of advanced vehicle and fuel technologies. Reaching the 80% reduction target may also be helped by changes in travel patterns, land use, and personal transportation mode choice. However, in this report, we do not consider or model these additional factors. California's recently adopted target of carbon neutrality by 2045 seems even more ambitious than 80% reductions; we have not attempted to define road vehicle scenarios for this target as it is still unclear what levels of CO_2 they would need to reach by then to play their part in achieving this. The scenarios here suggest that even hitting the 80% reduction target by 2050 will be challenging. It will require major transformations in what consumers and businesses purchase and what vehicle manufacturers and fuels industries produce, as well as massive infrastructure deployment.

We modeled three market penetration scenarios for new technologies and fuels into both light-duty vehicles (LDVs) and medium/heavy duty vehicles (that for simplicity we refer to as simply "trucks" throughout this paper) with the following key features:

- **The business as usual (BAU) Scenario** reflects a continuation of current trends and certain "firm" policies—such as the current LDV ZEV mandate of 1.5 million light-duty zero-emission vehicles on California roadways by 2025—but does not extend any of them beyond existing targets. It results in relatively low CO_2 abatement through 2050 and provides a basis for comparison of the other scenarios.
- **The zero-emission vehicle (ZEV) scenario** includes very aggressive ZEV sales growth, reaching 100% sales share by 2050 for LDVs and most truck types, except long-haul heavy-duty trucks (typically Class 8, travelling 500 miles per day or more), which reach 80%. ZEV transit buses reach 100% by 2030.
- **The ZEV plus biofuels (ZEV+B) scenario** includes less aggressive ZEV sales growth, but still reaches over 80% sales share in 2050 for LDVs, close to 60% for most truck types, and a substantially lower 40% for long-haul trucks. However, this scenario couples this ZEV sales growth with large increases in advanced biofuel use (on the order of 60% cellulosic ethanol/gasoline blends and 100% advanced diesel biofuels blends by 2050).

The goal of the scenarios is to attempt to meet an 80% reduction in emissions in these sectors, not to provide the most likely path for decarbonization. The analysis is essentially a back-casting modeling approach where we determine what is needed to meet the 80% 2050 target and then work backwards to see what adoption rates are needed to get there, using two main scenarios. The analysis assesses needed rates of change and potential costs, and the implications for policy.

Figure 1-1 shows the sales fractions of each vehicle type in the second and third scenarios. The market share of ZEVs in the ZEV+B scenario is lower because non-ZEV vehicles can be partially decarbonized using biofuels.

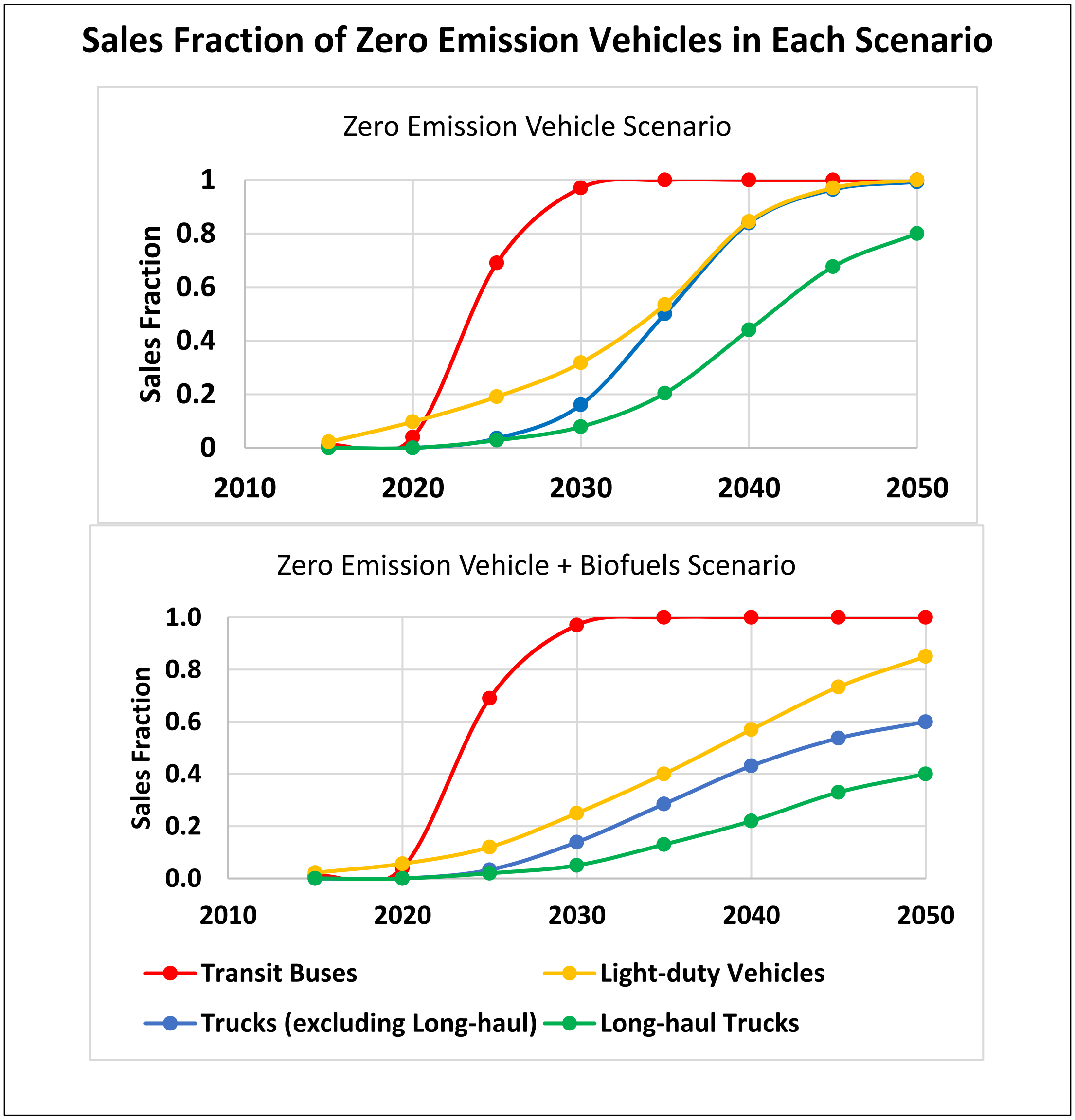


Figure 1-1. Sales fractions of zero emission vehicles among each vehicle type over time, as needed to achieve the 80% reduction target by 2050.

1.1 Major Findings

Both the ZEV and ZEV+B scenarios show significant promise in reducing GHGs and fossil fuel use but will be challenging to implement. Overarching results include:

- In the ZEV scenario, attaining an 80% reduction in GHGs from trucks will require a particularly rapid ramp-up in sales after 2025.
- Achieving deep GHG reductions in the ZEV scenario requires that energy for these vehicles, namely hydrogen and electricity, must eventually come from very low GHG sources.
- In the ZEV+B scenario, the ZEV sales targets will be easier to achieve (especially for long-haul trucks) than in the ZEV scenario, but the trade-off is a build up to very high, possibly infeasible or unsustainable, levels of advanced, very low-carbon biofuel use. A transition will be needed from today's dominant biofuels, from grains and oils, to predominantly cellulosic biomass-based fuels.
- The cumulative cost of the ZEV scenario from 2015 to 2050 for vehicles and fuels, aggregated across LDVs and trucks, is not significantly different than the cost of the BAU scenario. Higher vehicle costs are repaid through lower energy costs for electric compared to conventional vehicles. After 2030, these cost savings more than offset the higher capital costs. However, for some specific vehicle types (such as long-haul trucks) that are dominated by fuel cell vehicles, there are no fuel cost savings, so the overall costs are higher than the BAU.
- In our main scenarios, we estimate that the overall cost would be higher for the ZEV+B than the ZEV scenario, due to expected high advanced biofuel costs.
- However, the costs of each scenario vary substantially depending on a range of assumptions about technologies and fuels, particularly future petroleum, hydrogen, and biofuel prices. We explore this through a sensitivity analysis.
- Given higher vehicle purchase costs for ZEVs, policy incentives or mandates may be needed for many years to grow these markets. Vehicle purchase costs are approximately $115 billion higher in the ZEV and $75 billion higher in the ZEV+B scenarios than in the BAU scenario, over the 2015–2050 time frame. The extent to which subsidies would be needed to offset these higher costs, also taking into account fuel cost savings, is difficult to predict and we do not try to do this in the current study.
- Reducing total vehicle activity—through travel demand reduction, shared travel, mode shift, and changes in land use—could significantly reduce the ZEV and/or biofuels requirements, and possibly the costs, of attaining deep GHG emissions reductions from transportation. On the other hand, meeting air quality goals could require faster technology changes than shown here for GHG reduction. These aspects are beyond the scope of the research described in this report.
- In this report, we do not incorporate non-cost factors into the purchase decision analysis, which could add to the needed incentive levels. A separate report, being

prepared, will address these non-cost factors and how these may impact our estimated costs and needed policy strategies.

1.2 Projecting Technology Portfolios in Transportation

To meet the 80% GHG reduction target in 2050 in the ZEV scenario, most new LDVs and trucks in the state will eventually need to be ZEVs, either BEV or FCEV. Some PHEVs and some vehicles running on renewable natural gas or other biofuel may also co-exist, but these are minimized in our ZEV scenario. In ZEV+B these play a much bigger role. As shown in Figure 1-2, the resulting shares vary across vehicle type and scenario, though in 2030 ICE vehicles still dominate sales in most cases. By 2050, most vehicle types are dominated by some combination of electric and hydrogen vehicle. LDVs are mostly electric, non-long-haul trucks are mixed, and long-haul trucks are dominated by fuel cells (due to a strong match between their duty cycles and the projected range limitations of batteries). In the ZEV+B scenario, the penetration of ZEVs is far lower, with more diesel (and some gaseous fueled) trucks still sold in 2050. These trucks rely mainly on biofuels (renewable diesel and renewable natural gas, respectively).

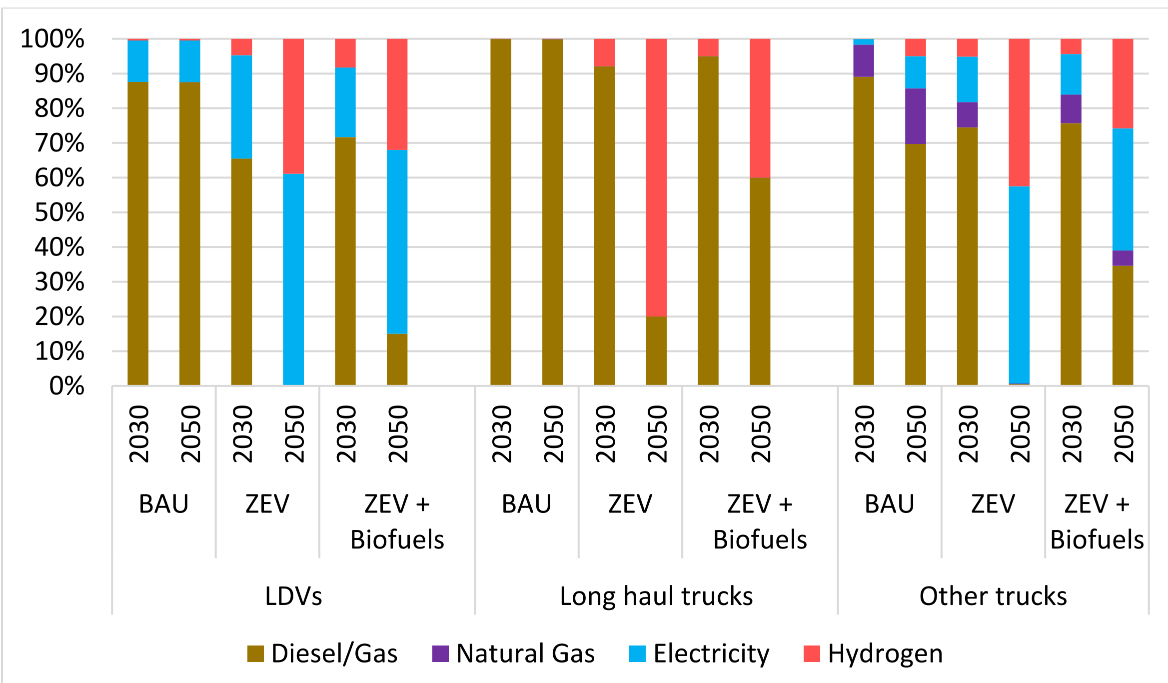


Figure 1-2. Vehicle sales shares across vehicle types, scenarios, technologies, and years. ("Natural Gas" includes compressed and liquefied natural gas.)

1.3 Impacts on Fuel Consumption and GHG emissions

As shown in Figure 1-3, even in the BAU there is a 30% reduction in fuel use between 2010 and 2050 due mainly to improved vehicle efficiency. In the ZEV scenario this reduction reaches 60%, with more than half the energy in 2050 coming from hydrogen and electricity, and with hydrogen accounting for a slightly higher share. A small amount of both gasoline and diesel fuel remain. In ZEV+B, energy use is higher (about a 50% reduction instead of 60% from 2010), but about half of energy use is biofuel: advanced renewable diesel and cellulosic ethanol. Very little gasoline and no diesel fuel remain in the mix.

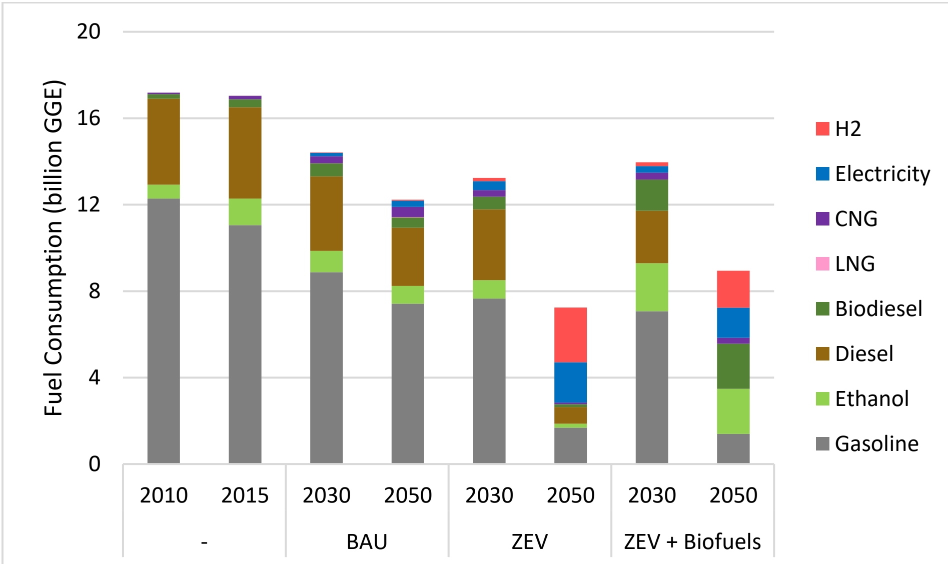


Figure 1-3. Fuel Consumption by Scenario – All Vehicles

Total (well-to-wheel) GHG emissions from LDVs, trucks, and combined for each scenario are shown in Figure 1-4. In the BAU scenario, LDVs achieve about a one-third reduction in GHGs from 2010 to 2050 due to improvements in fuel economy and some uptake of ZEVs and biofuels. For trucks however, the improvements in fuel economy are mostly offset by increased truck travel and the net effect is less reduction in GHGs.

By design, in both the ZEV and ZEV+B scenarios, LDVs and trucks achieve at least an 80% CO2e reduction in 2050 compared to 2010. On average the reduction is 83%, which is roughly consistent with an 80% reduction compared to 1990.

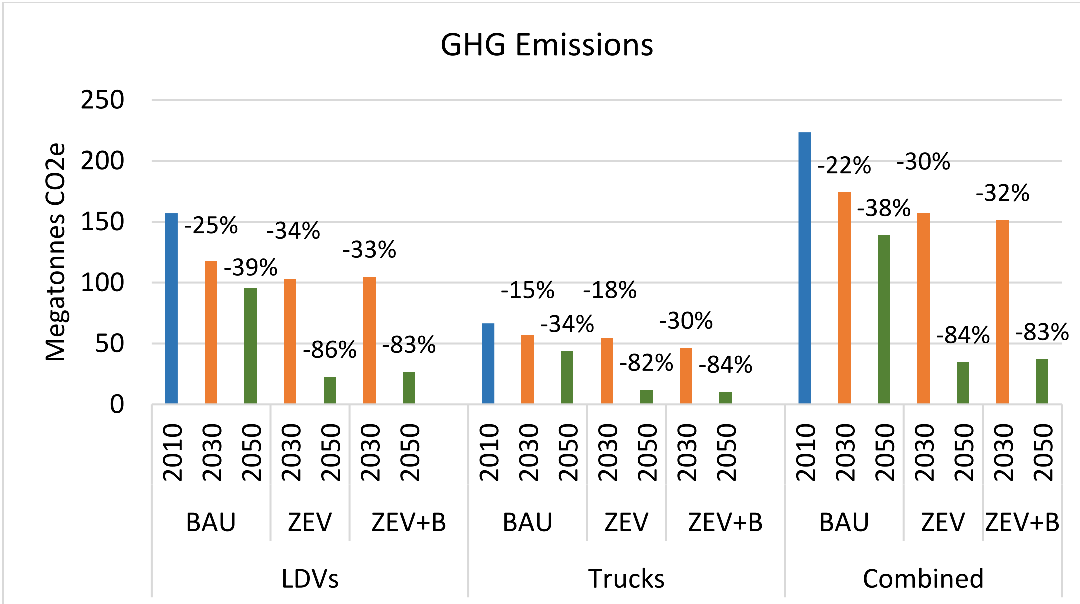


Figure 1-4. Greenhouse gas (GHG) emissions from LDVs and trucks for the BAU and ZEV scenarios (ZEV+B is similar to ZEV).

1.4 Impacts on Costs

This study includes estimates of the costs of purchasing and fueling cars and trucks with all costs projected to 2050 by technology and fuel type, with no discounting. This includes truck capital costs and fuel costs, as retail price equivalents. It does not include any subsidies or taxes.

Figure 1-5 shows the total state-wide costs of purchasing and fueling light-duty and trucks in terms of differences from a BAU. The total cost difference for LDVs is higher than for trucks, largely due to the significantly higher population. For both LDVs and trucks, there is a net increase in the cost of vehicles in the ZEV and ZEV+B scenarios, while there is fuel cost savings in all cases except the ZEV+B truck scenario. The main reason that vehicle costs are higher is the additional costs of battery electric and fuel cell technologies; the main reason for fuel savings is the lower cost per mile of electricity compared to gasoline and diesel fuel and the increased fuel economy of ZEVs. Long-haul fuel cell trucks do not exhibit cost savings due to the higher cost of hydrogen compared to diesel fuel outweighing the modest fuel economy increase. Biofuels costs, particularly advanced renewable diesel fuel, are expensive and take away fuel savings in the ZEV+B scenario.

Overall there is a net reduction of about $50 billion in the cost of light-duty vehicles and fuels in the ZEV scenario compared to the BAU, and a decrease of about $10 billion in the ZEV+B vs. BAU. For trucks there is a $15 billion increase in cost in ZEV vs. BAU, and $25 billion increase in ZEV+B vs BAU. However, these costs should be kept in context; they represent less than a 1%

change from the total expected public and private expenditure on vehicles and fuel over this period in the BAU (about $4 trillion over the 30 years).

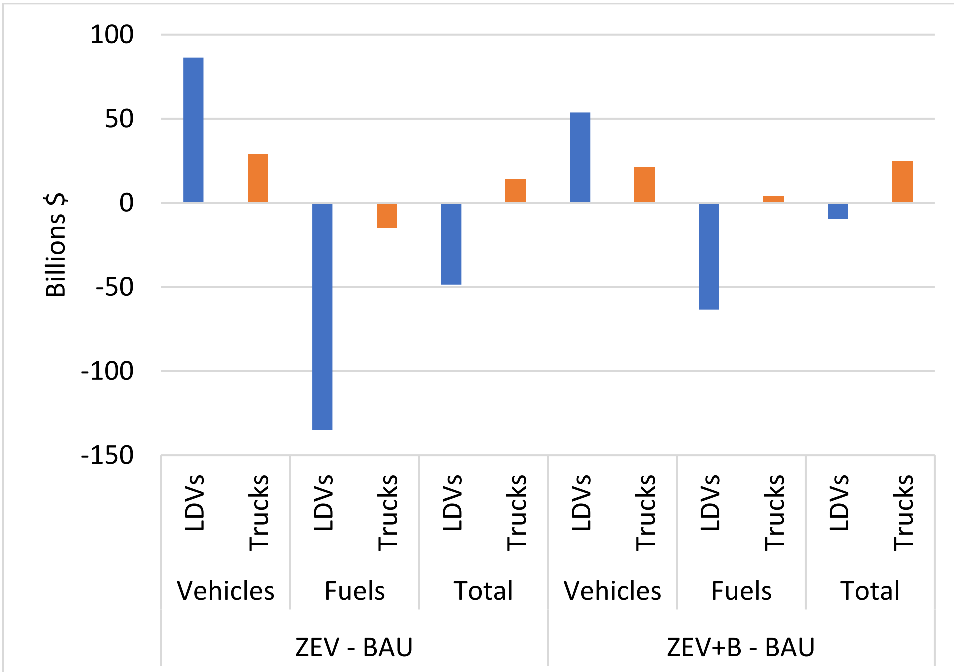


Figure 1-5. Cumulative costs from 2015-2050 for vehicles and fuels, ZEV and ZEV+B relative to BAU scenario.

Figure 1-6 also compares the ZEV and ZEV+B scenarios to the BAU but plots total costs over time, for vehicles, fuels, and total. These figures show that these scenarios have higher net costs than the BAU until at least 2030 and then eventually have lower net costs. The ZEV+B case takes considerably longer to achieve a breakeven point than the ZEV case. These breakeven dates can change considerably in sensitivity cases.

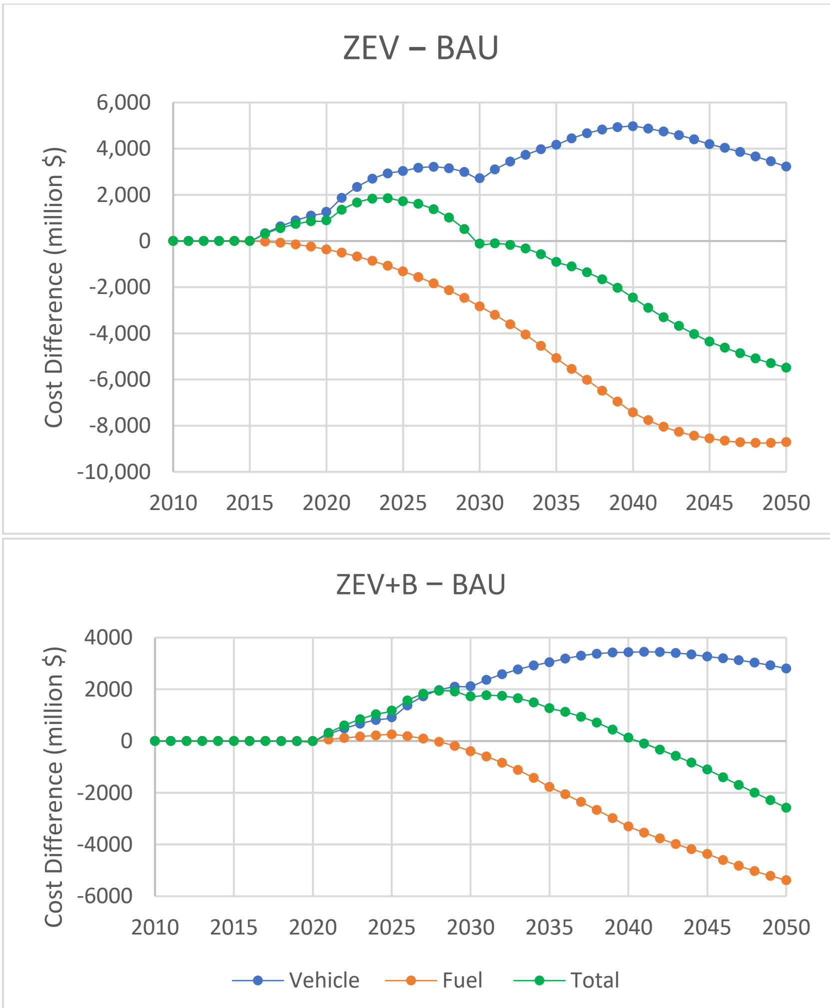


Figure 1-6. Vehicle and Fuel Cost differences (total, 2015 to 2050) for light-duty vehicles and trucks combined, ZEV vs. BAU and ZEV-B vs. BAU.

1.5 Policy Implications

Although we did not conduct a detailed policy analysis in this study, several policy implications are apparent, particularly related to costs and incentives:

- There is an ongoing need for policy support, particularly to address the vehicle price gap between ZEV and conventional trucks. This gap is commonly expected to decline over time, but further research is needed to determine whether the cost reductions by vehicles exceed the cost growth from deploying battery electric trucks in duty cycles less amenable to that technology type.

- These incentive policies will be more easily phased out once per-vehicle costs decline sufficiently to fully establish the market, but it is difficult to predict when that will be. It is also possible (especially for long-haul fuel-cell trucks running on hydrogen) that such a point will not be reached by 2050, depending on the future costs of vehicle as well as fuel technologies.
- If battery technology advances sufficiently to allow penetration into longer-range truck applications, that could fundamentally change the expected vehicle portfolio and obviate the need for more expensive fuel cell trucks.
- Without substantial penetration of ZEV technology into the truck sector, emissions reductions will likely have to be driven by biofuels, which may be challenging due to limited sustainable supply and would likely result in higher fuel costs.

More work is needed to better understand how costs may change over time and the level of policy support that may be needed depending on how the future unfolds.

This report will be soon be accompanied by a truck technology report and truck choice modeling report, which will both add detailed information and help point the way to additional research needs in the future. Our research over the coming 1-2 years will focus on improving the understanding of fleet behavior, non-cost decision factors, and the potential role, sourcing, and costs of advanced biofuels.

2 Introduction & Background

This study examines the vehicle technology mix that could enable a transition to a low carbon future out to 2050, in the car and truck sector. We estimate the potential penetration in the vehicle stock of new technologies—e.g., battery-electric vehicles (BEVs), plug-in hybrid electric vehicles (PHEVs), hydrogen fuel cell electric vehicles (FCEVs), and liquid and gaseous biofuels for internal combustion engine vehicles (ICEVs).

Multiple studies (e.g., CARB 2017, DOE 2016) show that fuel economy improvements alone will not be sufficient to attain 80% carbon reductions from 1990 levels by 2050, and transitioning from ICEVs to zero emission vehicles (ZEVs, consisting of BEVs and FCEVs) and near-ZEVs (consisting of PHEVs) will be necessary. In the absence of significant biofuels contributions, we estimate that essentially all new light-duty vehicle sales would need to be ZEVs to achieve the 2050 target.

A ZEV mandate, with a target of at least 16% of new sales as ZEVs with an additional requirement on PHEVs in 2025, exists in California for light duty vehicles (LDVs) (CARB 2018). In addition, the California Air Resources Board (CARB) has proposed a ZEV mandate for trucks which, if approved, would take effect in 2024 (CARB 2019a). Despite the relative success of ZEVs in some markets where policy support and incentives are strong, they have faced major challenges in displacing ICEVs. The key questions remain—how might transitions to ZEVs and low-carbon energy carriers (electricity, hydrogen, biofuels) take place over the next few decades and what would these transitions cost?

We estimate when future technologies and fuels might become competitive with incumbent petroleum fueled vehicles; and we evaluate what technologies and fuels could help achieve required reductions and at what cost. We investigate the possible market share of different vehicle technologies and the resulting implications for greenhouse gas (GHG) emissions and costs by vehicle type (LDVs or trucks), and vehicle category within these broad types.

3 Approach

3.1 General Approach

This study covers both LDVs and trucks in California. It disaggregates LDVs into two categories (cars and light-duty passenger trucks such as SUVs, minivans, and pickups), and disaggregates the freight truck sector into eight categories (Table 1). This provides additional granularity and captures some of the diversity of vehicle characteristics (application, size, fuel economy, drive cycle, refueling time). This division also helps separate the relative impacts of different vehicle categories on emissions. The trucking sector here consists of all vehicle classes from 2b through 8, including buses. For simplicity, in many cases we refer to this group of eight classes simply as "trucks."

We develop transitions in a "what-if" style, with multiple scenarios that can be compared in terms of their transition pathways and cost implications. Three scenarios through 2050 were developed:

- Business as Usual (BAU),
- Zero-emission Vehicle (ZEV), and
- ZEV+Biofuels (ZEV+B).

The ZEV and ZEV+B scenarios attempt to reach hypothetical ZEV sales targets in 2050, taking into account the realism of ramping-up ZEV sales for LDVs and different types of trucks, and ramping-up the blend percentage of gasoline and diesel biofuels. We test the sensitivity of results to fuel and component costs. And although we do not undertake detailed policy analysis, we consider the implications of the scenarios regarding the need for ongoing and possibly additional strong policies to achieve specific targets. We recognize that incentives in both the LDV and truck categories will likely be necessary to meet the desired emissions reductions.

3.2 Modeling Approach

We conduct the analysis using a transportation transitions model (TTM) to convert vehicle sales to vehicle stock and miles traveled in each technology, across the different vehicle categories. To generate the vehicle sales predictions used as inputs in the TTM, we use two different methods, one for LDVs and one for trucks. For LDVs, we use a method based on previous UC Davis studies, particularly on TIMES optimization modeling efforts for California, such as that documented in Yang et al (2016). For predictions of truck sales, we use the truck choice model (TCM).

In the TTM, the LDV group is segmented into cars and light-duty trucks (Table 1). These two categories are representative of the average vehicle across the numerous car and light-truck classes (e.g., subcompact, compact, midsize, full-size cars, and small and full-sized SUVs, pickups and vans). In both the TTM and TCM, the medium- and heavy-duty sectors are collectively treated as "trucks" and then segmented into eight categories (Table 1).

Table 1. LDV and truck categories in the TTM. The TCM includes only the truck categories.

Light Duty Categories	Truck Categories
• Cars • Light-duty trucks	• Long haul • Short haul • Heavy-duty vocational • Medium-duty vocational • Medium-duty urban • Urban bus • Other bus • Heavy-duty pickups and vans

Definitions:

- Light-duty trucks: a vehicle with a gross vehicle weight less than 8500 lbs. designed primarily for transporting property.
- Long-haul: a heavy-duty truck that generally travels greater than 250 miles per day and does not return to base each night.
- Short-haul: a heavy-duty truck that generally travels less than 250 miles per day and does return to base each night.
- Heavy-duty vocational: a heavy-duty truck that transports equipment or materials rather than cargo (e.g., refuse or mixers).
- Medium-duty vocational: a medium-duty truck that does not transport cargo (e.g., utility truck).
- Medium-duty urban: a medium-duty truck operating on urban drive cycles that generally transports cargo (e.g., delivery box truck).
- Urban bus: a transit bus operating primarily on urban drive cycles.
- Other bus: a coach often operating on highway drive cycles.
- Heavy-duty pickups and vans: a pickup truck or van with gross vehicle weight greater than 8500 lbs and less than 14,000 lbs.

3.2.1 Modeling Truck Choice

The TCM is fully documented in Miller et al (2017). This model allows generation of future truck sales shares by technology and fuel type for eight different truck classes. These resulting market shares can be combined with a truck sales and stock turnover model to calculate truck fleet numbers related to vehicle survival, total mileage, emissions, and fuel consumption for each truck type and from the fleet as a whole.

The TCM represents a discrete choice formulation that includes a number of important factors that will influence individual decision-makers' preferences among a suite of vehicle technology options. The model factors include:

- Private economic costs (vehicle purchase price, maintenance costs, and fuel costs)
- Incentives
- Carbon tax

- Green PR (Green Public Relations: the perceived monetary incentive due to environmental benefits of the technology)
- Refueling inconvenience (includes vehicle range, time to refuel, station availability)
- Uncertainty (maintenance issues, sales to secondary market, technology stability)
- Model availability (number of commercial models, number of original equipment manufacturers [OEMs] producing models)

The utility of each technology type is estimated for different truck purchase decision-makers (Miller 2017). It is currently calibrated to the market in California and includes "early adopter," "late adopter," and "in between," fleet types. The general flow of the model is shown in Figure 3-1.

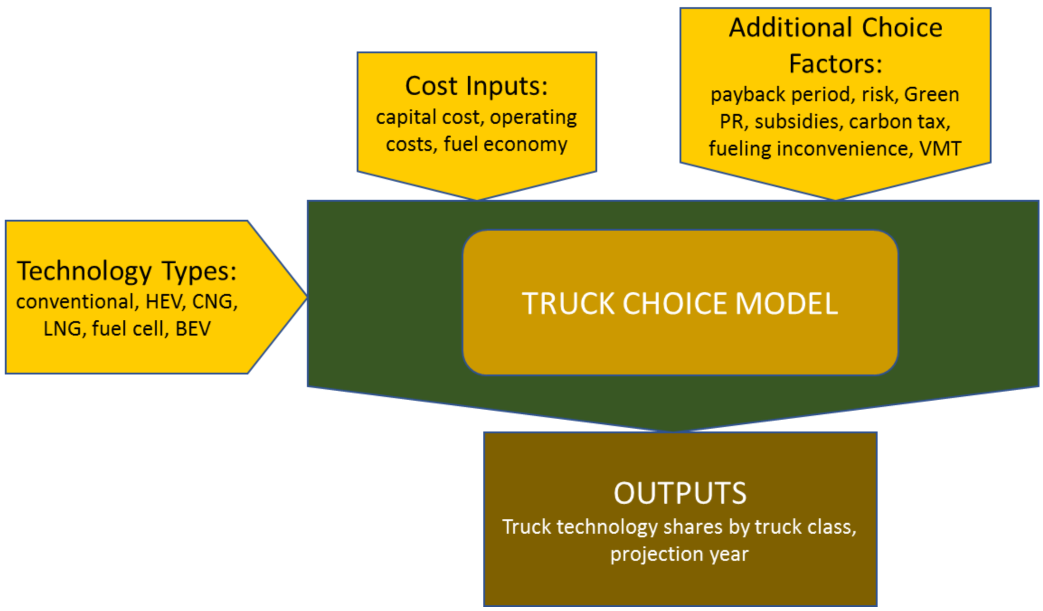


Figure 3-1. Truck Choice Model (TCM) Inputs and Outputs.
(HEV, hybrid electric vehicle; CNG, compressed natural gas; LNG, liquefied natural gas; BEV, battery electric vehicle; PR, public relations; VMT, vehicle miles travelled.)

The TCM is structured as a nested multinomial logit model in a Microsoft Excel spreadsheet. The basic nesting structure, shown in Figure 3-2, is similar to consumer choice models created for LDVs, such as LAVE-TRANS (NRC 2013). Nests represent groups of close substitutes for decision-makers as they consider the utility of various technology alternatives.

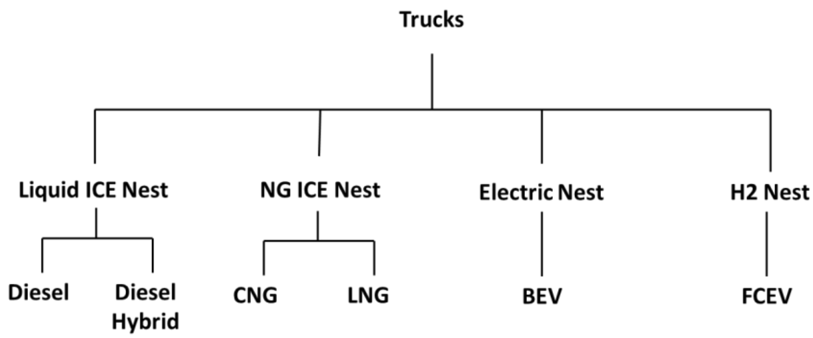
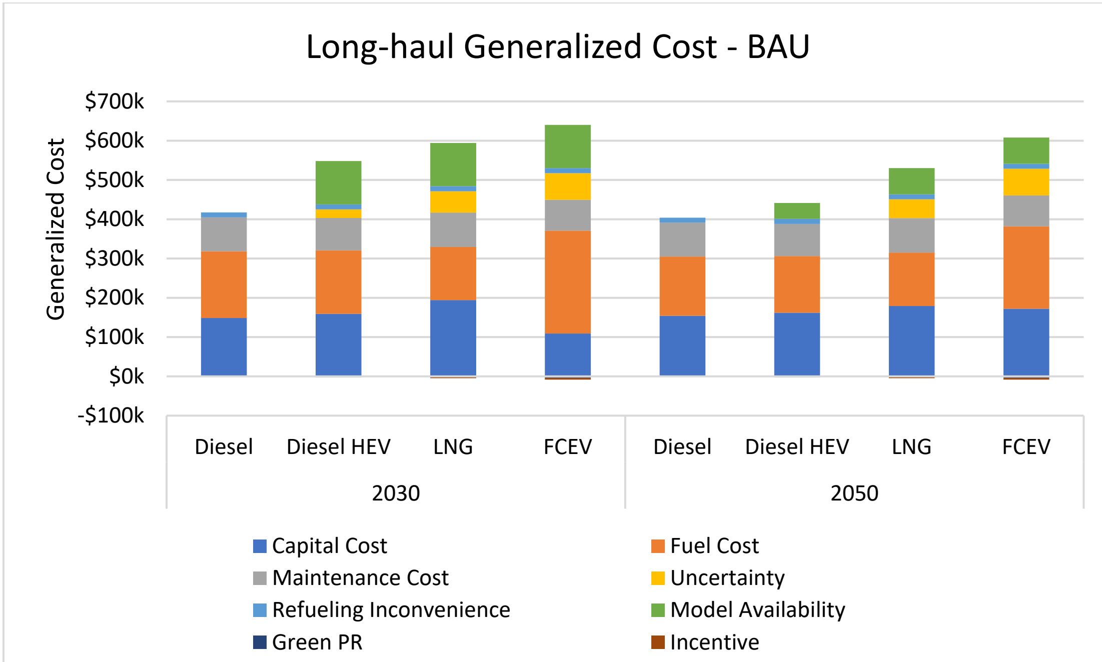


Figure 3-2. Nest structure for the TCM.

(ICE, internal combustion engine; NG, natural gas; H2, hydrogen; CNG, compressed natural gas; LNG, liquefied natural gas; BEV, battery electric vehicle; FCEV, fuel cell electric vehicle.)

The utility of each vehicle type is determined by creating a generalized cost from all the decision factors (outlined above). Non-monetary factors such as uncertainty or model availability are monetized and added to the monetary costs to produce the generalized cost. The generalized cost for each technology is then used to calculate the relative purchase probabilities for each technology.

Specific examples of the process used to calculate generalized costs for two truck types (long-haul and short-haul) for the fleet type “in-between” are shown in Figure 3-3. The figure panels show the generalized cost in 2030 and 2050 for each technology type. The generalized costs in these figure panels are used in the BAU scenario for long-haul and the ZEV scenario for short-haul, and only a modest incentive is assumed for technologies other than diesel. In the long-haul BAU case, costs for liquefied natural gas (LNG) vehicles and FCEVs decrease modestly in 2050 but remain much higher than the diesel and hybrid costs. In the short-haul ZEV case the generalized cost for new technologies such as hybrid, CNG, battery electric, and fuel cell vehicles decreases significantly due to reductions in factors such as capital cost, model availability, and refueling inconvenience. For the long-haul BAU scenario the fuel cell vehicles’ generalized cost remains too high to see more than trivial market penetration, but in the short-haul ZEV case, the market penetration for both battery electric and fuel cell trucks is significant.



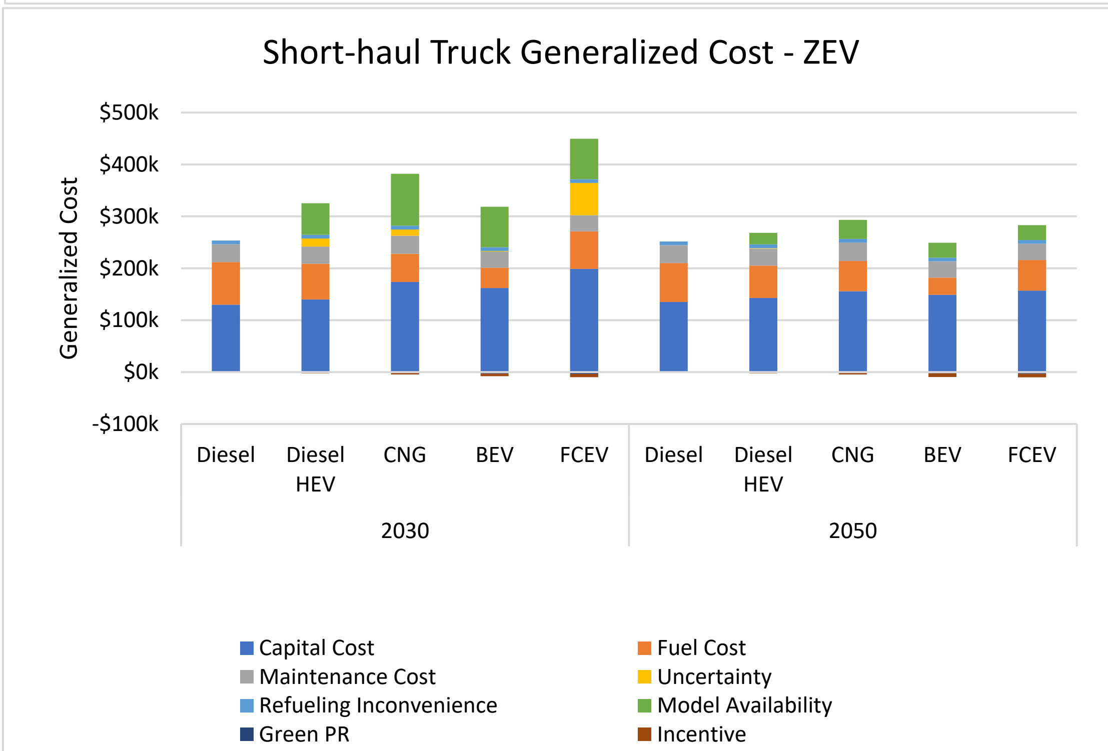


Figure 3-3. The generalized cost for the "in-between" fleet type for long-haul trucks in the BAU scenario and short-haul trucks in the ZEV scenario for both 2030 and 2050.

(HEV, hybrid electric vehicle; CNG, compressed natural gas; BEV, battery electric vehicle; FCEV, fuel cell electric vehicle.)

Over time, the capital cost for new technologies such as fuel cell, battery electric, or natural gas vehicles decreases. The non-monetary factors (uncertainty, model availability, and fueling inconvenience) decrease for technology types other than diesel.

3.2.2 Modeling ZEV targets

CARB has proposed a ZEV mandate for trucks in classes 2b-8 (CARB 2019a) The mandate would have ZEV truck sales reaching 15% by 2030 for Class 2b-3 and Class 7-8 tractors. ZEV sales would reach 50% in 2030 for Class 4-8 vocational trucks. The mandate would include a system where credits could be traded, banked, and used to satisfy requirements in other truck classes. We generate a ZEV and ZEV+B scenario for trucks from the TCM by adding an appropriate incentive to ZEV vehicles. The incentive is increased until the sum of the battery electric and fuel cell truck sales reaches the specified percentage for each year.

The TCM projected ZEV sales shares for transit buses rise far above our ZEV mandate without any incentive needed. Transit buses are unusual in that buses are highly subsidized by the federal government. Due to federal programs, transit agencies typically pay only a small part of their bus capital cost (CRS 2018). In addition, recent data suggests that battery electric buses could have a significant maintenance cost savings (CARB 2016). Given the steeply falling cost of batteries, the federal subsidy, and the maintenance savings, several California transit agencies have announced that they will convert their fleet to all-electric buses by 2030 and some market estimates suggest battery electric buses could dominate sales shares as early as 2030 (APTA 2018, Bloomberg 2018). Transit bus sales share in the BAU scenario reach 56% by 2030 and 97% by 2050.

The LDV ZEV and ZEV+B scenarios were constructed by increasing the sales shares from the present values to 100% (85%) in 2050 for the ZEV (ZEV+B) scenario. The LDV sector consists of cars and light-duty trucks with slightly different ZEV sales shares. ZEVs presently have lower penetration in the light-duty truck than the car market, but ZEVs reach the same sales share target in both markets in 2050. The goal of these scenarios was to reduce GHG emissions by 80% below 2010 values by 2050. The scenarios were modified slightly for minor reasons, and the final GHG emissions reductions are a little more than 80%.

Figure 3-4 shows ZEV sales shares through 2050 for both LDVs and trucks. The LDV sales shares include plug-in hybrids, battery electric, and fuel cell vehicles. The LDV shares are an average of cars and light-duty truck shares. The truck figure includes separate sales share curves for long-haul, transit buses, and all other truck types. Figure 3-5 shows the sales shares for the ZEV+B scenarios for LDVs and trucks.

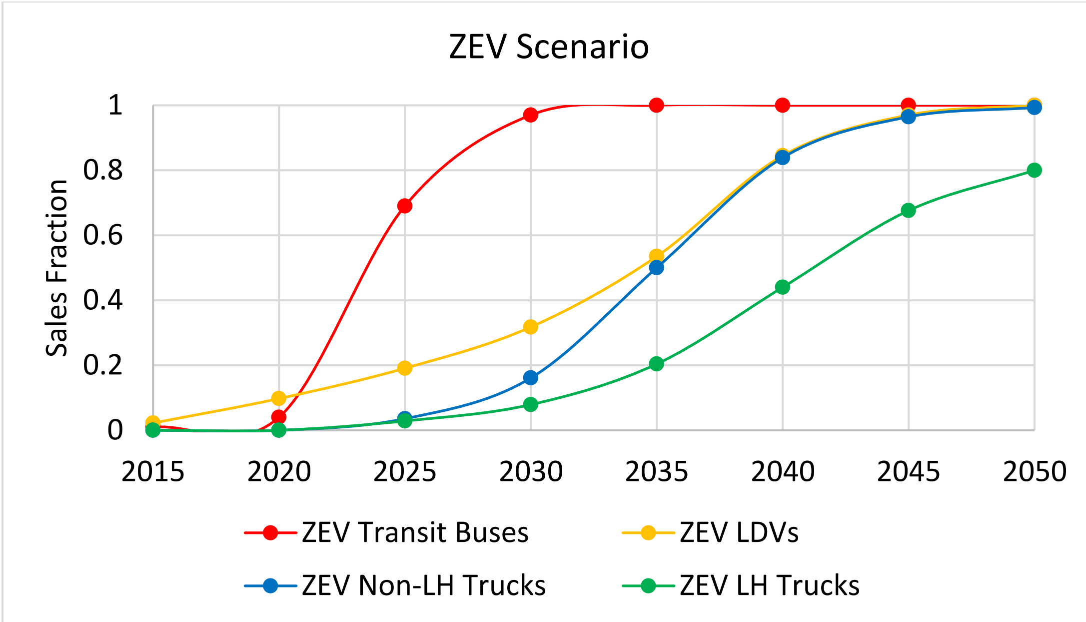


Figure 3-4. ZEV sales shares for the ZEV scenario for trucks and LDVs. The LDV curve is an average of the sales shares for cars and light-duty trucks.
(ZEV, zero emission vehicle; LH, long-haul.)

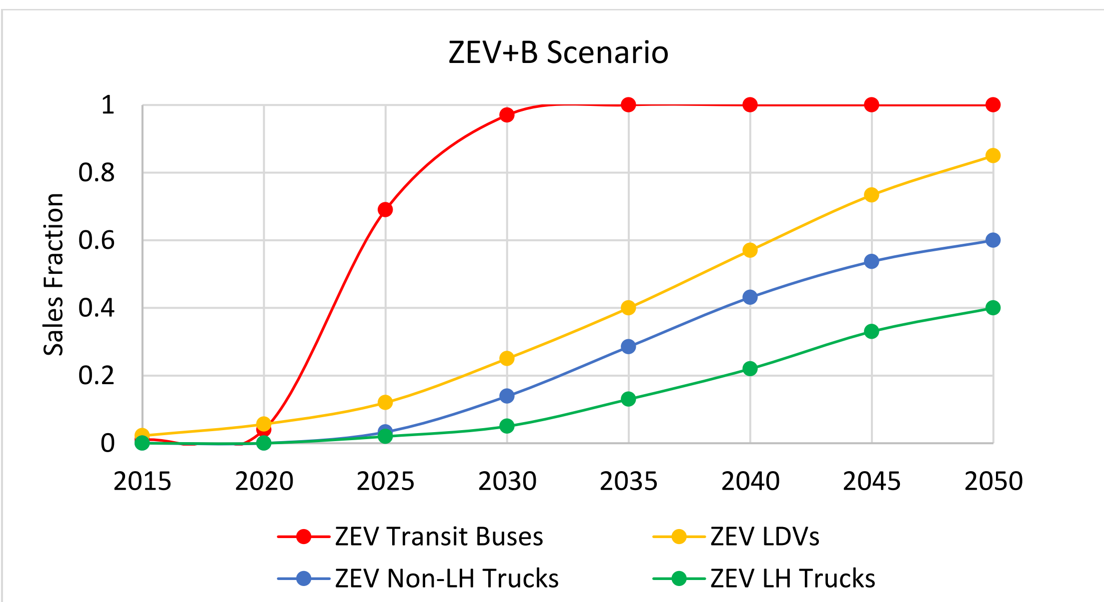


Figure 3-5. ZEV sales shares for the ZEV+B scenario for trucks and LDVs. The LDV curve is an average of the sales shares for cars and light-duty trucks.
(ZEV, zero emission vehicle; LH, long-haul.)

Truck sales shares are generated directly from the TCM outputs for the BAU scenario. Some purchase decision factors are calibrated such that the sales shares roughly match actual sales shares for 2010–2017. A first-pass set of sales shares for the ZEV and ZEV+B scenarios were generated for trucks from the TCM outputs, and the sales shares were adjusted to meet the goal of 80% reductions in GHG emissions in 2050 from the 2010 value.

The TCM provides the probability of truck purchase for a given set of truck purchasers. These can be translated into market share and then into an absolute number of trucks, giving the mix of truck types adopted for each application. The TTM then assesses the potential for advanced vehicle technology and fuels to reduce GHGs in the California on-road transportation sector while also estimating the total cost for deployment of these technologies. The TTM incorporates detailed 2010-2015 information on California vehicles including fleet stock, capital costs, fuel costs, vehicle miles traveled, and fuel economy; and the model projects these through 2050.

3.2.2.1 Modeling Vehicle and Fuel Transitions

The TTM is a spreadsheet-based model that projects into the future both vehicle sales/stocks and fuel/feedstock pathways in California. This model allows us to explore a broad range of scenarios and input assumptions and estimate the magnitude of the investments and subsidies required.

Based on the Argonne VISION model modified by CARB, the TTM includes relevant economic costs associated with these vehicles based on a detailed component level analysis for key technologies, such as fuel storage, batteries, fuel cells, and electric drivetrains. As in the rest of this analysis, the model is disaggregated into different categories (Figure 3-6). This level of disaggregation enables the determination of which vehicle and fuel technologies may be appropriate for specific vehicle types (e.g., BEVs as unsuitable for long-haul trucks, but possible for short-haul trucks).

The TTM comprises a vehicle module and a fuel module, outlined in Figure 3-6. The fuel module calculates fuel costs and carbon intensities. This fuel module provides a representation of economic costs and includes a detailed representation of fuel infrastructure deployment and scale required to adequately assess the full impacts of shifting to low-carbon fuels and vehicles. The fuel module provides a representation of all the necessary resource, production, transport, and refueling station elements in the TTM. The fuel module includes four primary elements of a generic fuel pathway. These elements include:

- **Resources supplies:** energy resources that are used in the production of the alternative fuel, plus the prices, and quantities of these resources.
- **Production/conversion facility:** production facilities are modeled with information about resource inputs, conversion efficiency, and facility costs.

- **Fuel transport**: finished transportation fuels must be transported to the refueling stations and this process is modeled from a cost and energy input perspective.
- **Refueling stations**: the cost and energy inputs of building refueling infrastructure is modeled.

The fuel module receives fuel demand and number of vehicles from the vehicle module and outputs fuel costs and fuel carbon intensities.

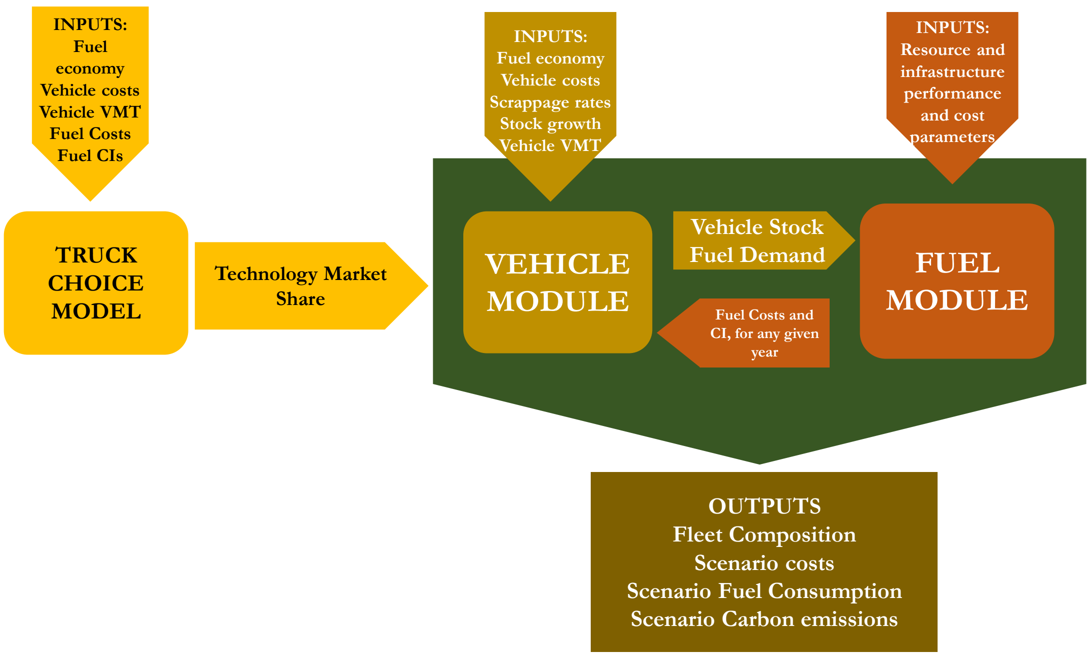


Figure 3-6. Basic modeling flow in the transportation transitions model (TTM). (VMT, vehicle miles travelled; CI, carbon intensity.)

3.3 Development of Scenarios

For this study, scenarios of technology and fuel adoption are developed that examine the impact of new vehicle sales for each vehicle type through 2050. These scenarios can be used to compare possible future technology deployment on a cost and GHG reduction basis.

The scenarios specify the percentage of new vehicle sales for every vehicle type and technology, year by year through 2050. The light-duty technology penetration inputs are derived from previous TIMES modeling by our group (Yang et al, 2016). However, both the LDV and truck scenarios are best thought of as “what if” specifications of market penetration used to understand potential effects and costs of new technologies and fuels entering the marketplace. For trucks, the ZEV scenario is intended to “push the boundaries” on the rate of increase of ZEVs, and their ultimate sales shares by 2050, to explore how much GHG reduction results. By limiting the mass market introduction of ZEVs in trucking to no earlier than 2025, this gives only about 15 years (until 2040) to achieve a high sales share, and thus a high stock share in 2050—a very fast rate of penetration.

3.4 Costs of Owning and Operating the Vehicle

From the capital cost of vehicles and the projection of new vehicle sales, we can calculate the total capital cost for new vehicles each year to 2050. Similarly, using fuel cost, vehicle efficiencies, and yearly vehicle miles traveled (and thus fuel use), we can calculate the cost of fuel each year.

However, there are certain caveats here. We do not discount future costs, partly due to the challenges of having vehicle sales in one future year generate fuel use in succeeding years. We also do not include fuel costs after 2050, even though we include vehicle purchase costs to 2050—thus the fuel use of these vehicles is not properly accounted for. We also allocate the entire vehicle capital cost to the year it enters the market, which often is not the case, since loans are taken out and vehicle capital costs are often paid for over time. Nonetheless, it is useful to compare the total yearly cost of BAU scenarios with other scenarios and conduct sensitivity analysis to see how these various cost factors affect the resulting scenario costs.

One sensitivity explored is fuel cost. We ran the analysis with three gasoline and diesel costs based on the US Energy Information Administration Annual Energy Outlook 2019. We used their reference cases for diesel and gasoline and constructed high and low fuel price cases. The high price case is the reference case plus 20%; the low price case is the reference case minus 20%. The prices used are shown in Table 7. All prices are given in $/gasoline gallon equivalent (GGE). We also varied the costs for electricity, hydrogen, and batteries.

3.5 Key Inputs

Many of the key technology assumptions and projections used in these scenarios are described in our accompanying technology documentation report (Miller 2019), but key assumptions are also described in sections below.

Table 2. Key Inputs and Outputs in the models.

Model	Module	Inputs	Outputs
Truck Choice Model (TCM)		• Capital cost • Operating Cost • Fuel Economy • Payback Period • Non-monetary factors • Subsidies • Carbon tax • Vehicle miles travelled (VMT)	• Market Shares of Vehicle Technologies for trucks (to TTM)
Transportation Transition Model (TTM)	Fuel module	• Feedstock information and prices • Production and conversion facility prices • Fuel distribution information • Fuel demand • Number of vehicles	• Fuel costs • Fuel carbon intensities (CIs) (to Vehicle Module)
	Vehicle module	• Vehicle Cost • Vehicle fuel economy • Vehicle survival rate • Initial stock numbers • VMT • Vehicle market shares	• Fuel demand • Number of vehicles (to Fuel Module) • Total mileage by technology and vehicle category • Total emissions (carbon footprint) • Total fuel consumption • Vehicle and fuel cost

NOTE: While carbon tax is an input to the TCM, we did not include it in this analysis.

3.5.1 Input #1: Technology Market Share (percentage of sales by technology)

An output of the TCM (for trucks) and input into the TTM, the evolution of vehicle technology penetration in each of the vehicle types by year, is shown in Figure 3-7 for cars and light-duty trucks for the BAU, ZEV, and ZEV+B scenarios.

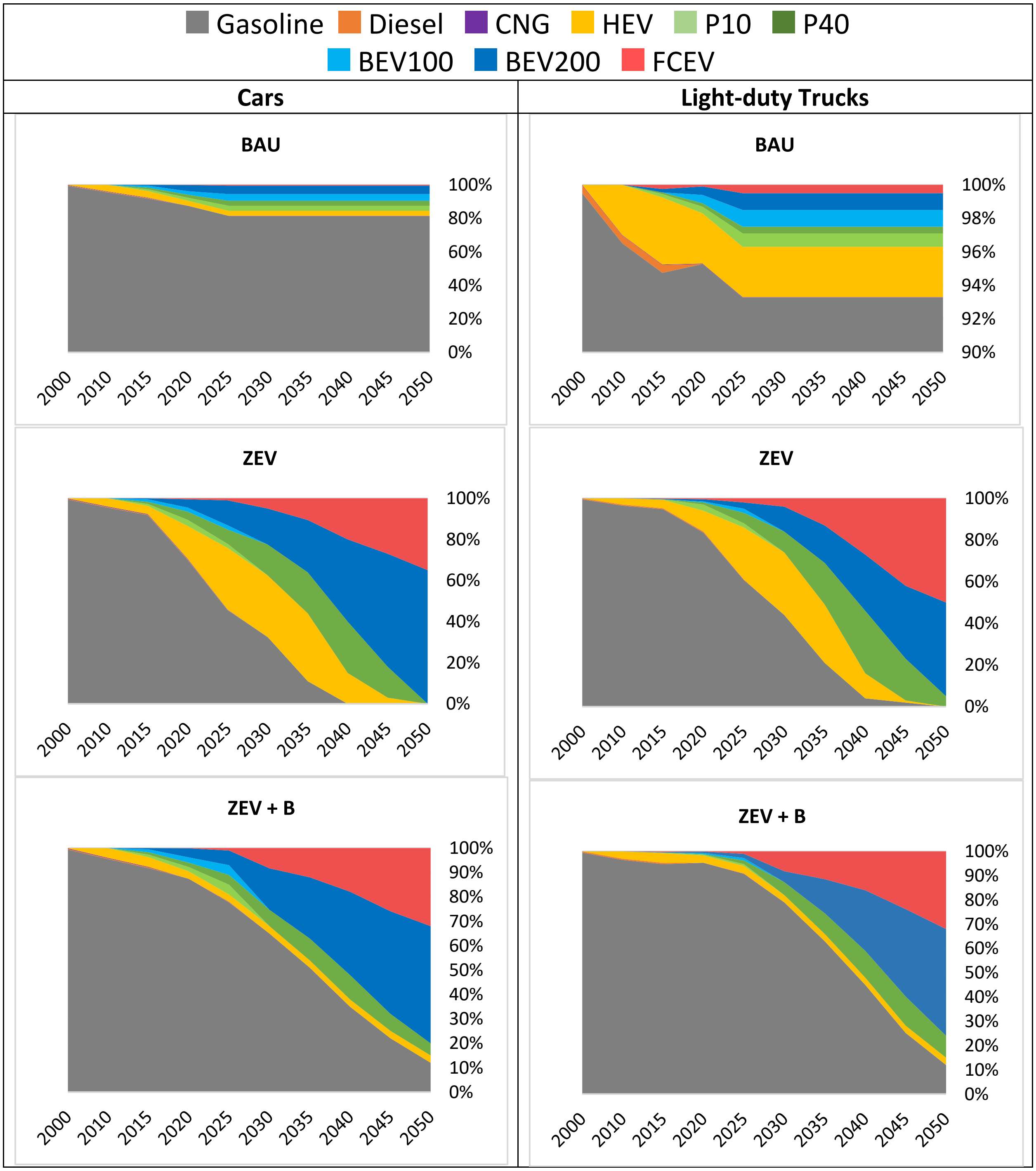


Figure 3-7. The sales percentages for cars and light-duty trucks in the BAU, ZEV and ZEV+ B scenarios.

(Abbreviations: CNG, compressed natural gas; HEV, hybrid electric vehicle; P10, plug-in hybrid electric vehicle with 10 mile electric driving range; P40, plug-in hybrid electric vehicle with 40 mile electric driving range; BEV100, battery electric vehicle with a 100-mile driving range; BEV200, battery electric vehicle with a 200-mile driving range; FCEV, fuel cell electric vehicle.)

3.5.1.1 LDV sales in BAU scenario (Figure 3-7, top)

The BAU scenario is designed to meet the existing CAFE standard to 2025 and California ZEV mandate to 2030 but does not assume any increase in ZEV vehicle sales beyond this level. It also does not assume any increase in biofuels from today's level. Note that in the BAU panels in Figure 3-7 there is an offset in the vertical scale for the BAU scenario to better show the percentages.

Our BAU scenarios are not what might be expected based on all policies presently discussed or in place, but rather an extension of the present trajectory of market share. For example, CARB has a transit bus rule that requires 100% market share of transit buses to be ZEVs by 2030, but our BAU scenario only has the market share at roughly 56%.

3.5.1.2 LDV sales in ZEV scenario (Figure 3-7, middle)

In contrast, the ZEV scenario shows marked increases in ZEVs (battery electric and fuel cell) and plug-in hybrids into the future, beyond the levels needed for the ZEV mandate, and reaching 100% of ZEV sales by 2050 for cars and light-duty trucks. The market is assumed to co-evolve these three technologies. The ZEV scenario was constructed to produce at least an 80% reduction in GHGs from 2010 values by 2050.

3.5.1.3 LDV sales in ZEV+B scenario (Figure 3-7, bottom)

The LDV ZEV+B scenario also shows aggressive ZEV market penetration, but ZEVs make up a smaller percentage of sales than in the ZEV scenario. ZEVs reach 85% of car sales and light-duty truck sales by 2050. In the ZEV scenario there are no sales of ICEV or HEV cars or trucks by 2050, but in the ZEV+B scenario ICEVs and HEVs make up 15% of sales for cars and light-duty trucks. This scenario is also constructed to produce at least an 80% reduction in GHGs from 2010 values by 2050.

To meet this target, the percentage of ethanol in the gasoline blend is increased to 60% by 2050. In the BAU and ZEV scenarios the ethanol percentage remains at 10% from 2015 through 2050. There is some concern that higher blends of ethanol can lead to technical problems such as increased emissions due to higher catalyst temperatures, corrosion of materials in engines and fuel systems, degradation of materials leading to fuel leaks, and reduced range (ICCT 2014). If these issues cannot be overcome, increased production and use of flex fuel vehicles (FFVs), which can use either ethanol or gasoline blends, could effectively increase the percentage of ethanol usage in LDVs.

3.5.1.4 Truck sales in BAU scenario

The truck BAU scenario is created from the TCM. In this scenario, there are almost no ZEV sales until after 2040, with sales remaining below 10% in 2050 except for transit buses and heavy-duty pickups and vans. Hybrids and natural gas vehicles reach a significant percentage of sales by 2050 in all truck types except transit buses. As mentioned above, federal subsidies and maintenance savings result in a very high BEV market share for transit buses (97% in 2050). ZEV sales shares of heavy-duty pickups and vans reach 14% by 2050.

3.5.1.5 Truck sales in the ZEV scenario

The truck ZEV scenario is created from the TCM BAU scenario by adding a ZEV mandate. Each truck type, except transit buses, is required to meet this mandate starting with 2% ZEVs in 2025 and reaching 100% ZEVs in 2050. Long-haul trucks reach 80% market share for ZEVs in 2050. An incentive is added to the generalized cost such that the model produces the specified ZEV market share every year. The incentive is the same for battery electric and fuel cell trucks. The model determines what percentage of the specified ZEV mandate market share is met with battery electric and with fuel cell trucks. Transit bus technology market shares in the ZEV scenario reach 100% by 2030.

3.5.1.6 Truck sales in ZEV+B scenario

The ZEV+B scenario is created from the TCM in a similar manner to the ZEV scenario. Fuel cell and battery electric vehicles penetrate the fleet in significant numbers but with a slower ramp-up than for the ZEV scenario. By 2050, ZEV sales shares for all truck types except transit buses and long-haul trucks reach 60%. Long-haul trucks shares reach 40% in 2050. Transit bus technology market shares in the ZEV+B scenario are identical to the ZEV scenario. There is also a rapid ramp-up of diesel biofuels for ICEV trucks in the ZEV+B scenario. The blend of diesel replacement biofuels in diesel fuel ramps up to 100% by 2050. The details on these biofuels are provided below (in Sections 3.5.4 & 3.5.5).

The truck ZEV and ZEV+B scenarios are constructed such that GHG emissions are reduced by at least 80% in 2050 from 2010 levels. Table 3 summarizes the LDV and truck BAU, ZEV, and ZEV+B scenarios.

Table 3. Description of Scenarios

Category	BAU	ZEV	ZEV+ Biofuel
LDV	• Federal CAFE standards through 2025 and plateauing after that. • California ZEV mandate through 2030 and plateauing after that. • Biofuels are maintained at current levels of consumption.	• ZEV shares keep growing after 2030 and constitute 100% of new LDV sales by 2050. • No new HEVs and ICEVs are sold by 2050. • GHG emissions reductions reach more than 80% in 2050 from 2010 levels.	• ZEVs reach 85% of market share by 2050. • Ethanol increases to 60% blend in gasoline by 2050. • GHG emissions reductions reach more than 80% in 2050 from 2010 levels.
Trucks	• Market shares determined by TCM outputs. • ZEVs reach less than 15% of market share in 2050 for all truck types except transit buses (97% share).	• All truck types subject to ZEV mandate starting at roughly 3% in 2025 and reaching 100% in 2050. • Transit buses reach 100% market share in 2030.	• All truck types subject to ZEV mandate starting at roughly 3% in 2025 and reaching 60% for all trucks in 2050, except long-haul trucks (40%). • Transit buses have same market share as ZEV scenario. • Diesel biofuels reach 100% blend in 2050.

3.5.2 Input #2: Fuel Economy

A key assumption and projection to 2050 is the fuel economy and energy use per mile of various vehicle types and applications.

LDV fuel economy estimates and projections (elaborated in Appendix C. Fuel Economy Tables) are based on projections from the Autonomie vehicle simulation model from Argonne National Laboratory (ANL 2019). These fuel economy numbers were embedded within the MA3T model from Oak Ridge National Laboratory (Lin and Greene 2011). We extracted them for two primary categories, cars and light-trucks. These projections assume that engine efficiency and road load improvements continue to be applied to reducing fuel consumption of vehicles (even conventional ICEVs) through 2050.

For trucks, diesel, gasoline, and natural gas vehicle fuel economies were estimated using present values from EMFAC 2014 and information from available literature (Miller 2019). Fuel cell, battery electric, and hybrid vehicle fuel economies were estimated using dynamic vehicle simulations using the Advisor program and tying the results to present EMFAC values for diesel vehicles (Burke and Zhao 2015). The fuel economies for trucks are given in Appendix C. Fuel Economy Tables.

3.5.3 Input #3: Vehicle Costs

Vehicle costs were calculated by considering the total cost as a sum of component costs. The components for vehicles included are shown in Table 4.

Table 4. Components included in vehicle cost estimates

- Glider
- Engine
- Transmission
- Engine after treatment system (EATS)
- Fuel storage
- Fuel cell
- Battery
- Motor/controller

Vehicle costs are built up by summing the cost of the vehicle glider and various components. The components, such as batteries, motors, fuel cells, and hydrogen storage are sized for each technology and multiplied by a component cost factor (e.g., $/kWh of battery or $/kW of fuel cell system). Component sizes for LDVs are based on the National Research Council (NRC) study median scenario (NRC 2013). Component sizes are kept constant over time, but the costs of components change due to advances in technology or manufacturing. Truck component sizes for advanced technologies were determined using the Advisor dynamic vehicle model (Burke and Zhao2015. The cost for engines, aftertreatment, and transmissions was identified from published sources. More detail on all aspects of the vehicle cost can be found in the model documentation (Miller 2019).

Two components of interest are fuel cells and batteries, as costs for both components have come down significantly over time and are expected to continue to decrease through volume sales. Bloomberg New Energy Futures has very aggressive projections for battery costs through 2030 (BNEF 2019). The International Council on Clean Transportation (ICCT) has less aggressive projections (Moultak 2017). For LDVs, we extrapolate Bloomberg's projections, assuming relatively little reduction in cost through 2050. For trucks, we use costs that are roughly midway between the Bloomberg and ICCT projections extrapolated out through 2050. These costs are to the original equipment manufacturer (OEM) from battery manufacturers. We assume an integration cost factor of 1.4 for both LDVs and trucks to get a final component cost in the vehicle.

Table 5 shows, for LDVs and trucks, the costs in $/kWh for the batteries from the battery manufacturer, as a function of year. The values include the cost to integrate the battery into the vehicle design. Figure 3-8 shows a plot with the same costs.

Table 5. Battery costs for LDVs and trucks both with integration costs and without them.

Year	LDV ($/kWh)	LDV + Integration ($/kWh)	Truck ($/kWh)	Truck + Integration ($/kWh)
2015	294	412	300	420
2020	143	200	180	252
2025	96	134	120	168
2030	70	98	95	133
2035	67	94	83	116
2040	65	91	78	109
2045	64	90	76	106
2050	63	88	75	105

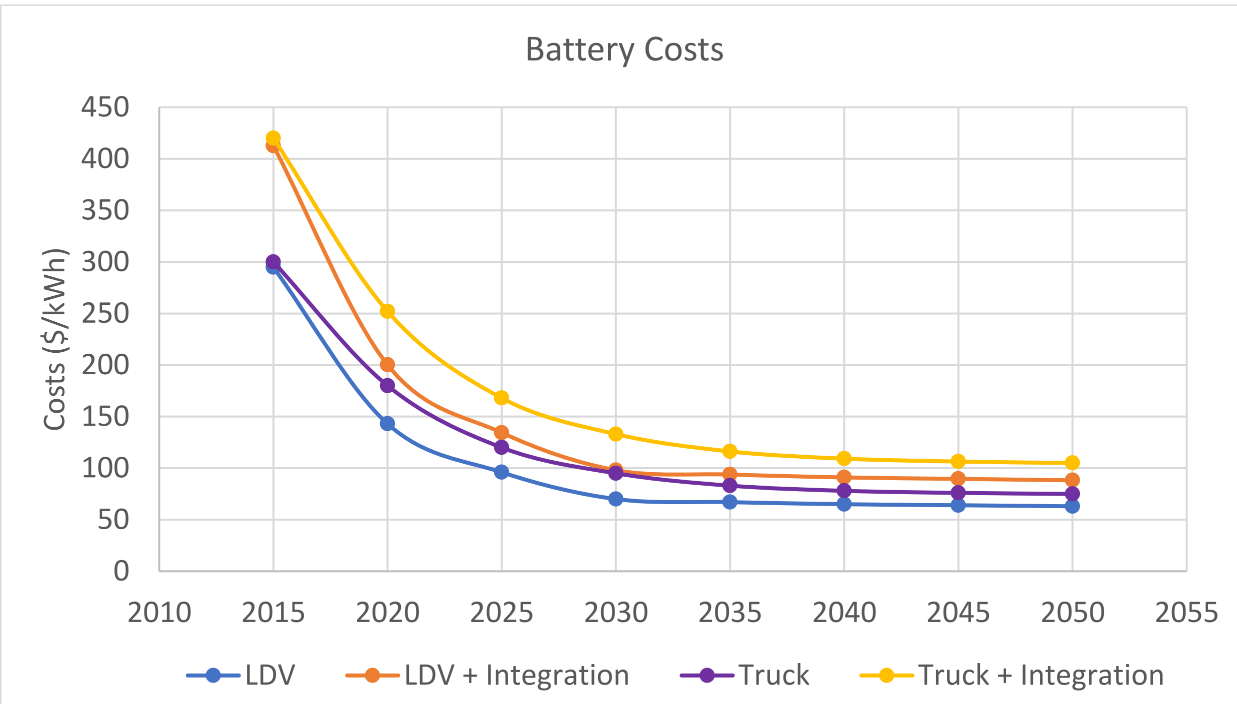


Figure 3-8. Battery costs to OEMs for LDVs and trucks.

The cost of fuel cells for LDVs and trucks was taken from an analysis by Strategic Analysis (Strategic Analysis 2016). The analysis estimated fuel cell costs as a function of volume sales. The volume sales costs were compared to expected sales in the ZEV scenario to determine costs as a function of year. The truck numbers only included volume sales up to 1000 units/yr. Costs for higher volumes are extrapolated using ratios of volume sales costs for LDVs. These costs include internal markups for components but do not include final OEM integration. The integration cost factor is assumed to be 1.4.

Table 6 shows the costs for the fuel cells for both LDVs and trucks without the integration factor.

Table 6. Costs for fuel cells for LDVs and trucks.

Year	LDV ($/kW)	Trucks ($/kW)
2015	164.8	1000.0
2020	98.9	473.0
2025	69.6	161.0
2030	58.5	110.0
2035	51.0	95.0
2040	45.0	85.0
2045	45.0	79.0
2050	45.0	75.0

Figure 3-9 shows vehicle costs for multiple vehicle categories through 2050 for each technology type.

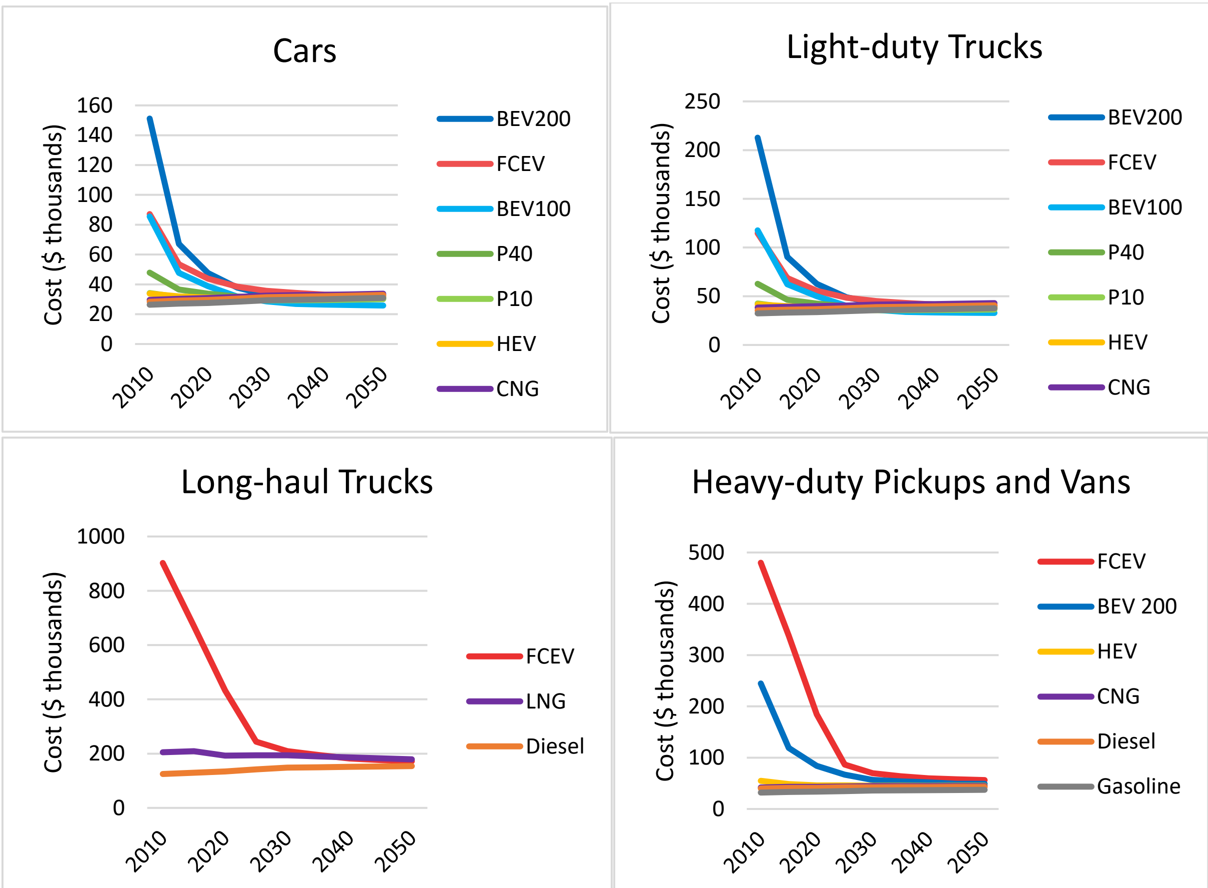


Figure 3-9. Cost of cars and light duty trucks, long haul trucks, heavy-duty pickups and vans a function of technology cost projections through 2050.

(Abbreviations: BEV200, battery electric vehicle with 200 mile driving range; FCEV, fuel cell electric vehicle; BEV100, battery electric vehicle with 100 mile driving range; P10, plug-in hybrid electric vehicle with 10 mile electric driving range; P40, plug-in hybrid electric vehicle with 40 mile electric driving range; HEV, hybrid electric vehicle; CNG, compressed natural gas; LNG, liquefied natural gas.)

3.5.4 Input #4: Biofuel Blends and Use in BAU

Biofuel use levels are projected as a function of many factors: the blend level and use levels of conventional fuels (gasoline and diesel), limits to those blend levels (such as a historical 10% blend wall for ethanol in gasoline), the projection of biofuels use under the Low Carbon Fuel Standard dynamics to 2030, and levels of biofuels that are consistent with reaching CO_2 targets in the two low CO_2 scenarios. There is also the breakdown of biofuels types and feedstock/fuel pathways, which are roughly determined by trends and expected future carbon intensity (CI) levels and costs.

Here we focus on the historical and BAU projections of biofuels as inputs. The biofuel blend levels and pathways used in the ZEV and ZEV+B scenarios are determined as part of the overall scenario development and described in Section 4.4 Result #4: Fuel Consumption by Fuel Type.

The development of ethanol, biodiesel fuel, and renewable natural gas historically and in the BAU scenario is shown in Figure 3-10. The historical trends show that nearly all ethanol and biodiesel have been conventional, i.e., starch based and oil based respectively. While ethanol use rose rapidly from 2010 to 2015, it has flattened out; biodiesel and renewable natural gas use has since risen rapidly. Biodiesel (including fatty acid methyl esters [FAME] and hydrotreated renewable diesel fuel) spiked after 2018 and may nearly reach 1 billion GGE by 2020. Our BAU projection has biodiesel returning to lower levels out to 2030 and beyond. However, this is uncertain since the Low Carbon Fuel Standard may keep it at higher levels and some CARB scenarios have it rising above 1 billion gallons GGE by 2030 (CARB 2019b).

In this BAU future, advanced fuels, such as cellulosic ethanol or biomass-based diesels (e.g., those made using pyrolysis or Fischer-Tropsch to get from cellulose to diesel replacement fuels) do not make significant inroads. Rather, most biofuels in the BAU future are conventional, though there is more hydro-treated renewable diesel and less FAME biodiesel. Renewable natural gas (RNG) grows relative to fossil natural gas but does not displace it.

This BAU future, as with the full set of assumptions in the BAU, is intended to avoid major shifts in trends and provide a "straw man" scenario to compare our other scenarios to. It does not assume a major impact from the Low Carbon Fuel Standard in 2030 beyond on-going ramp-ups in current fuels. Much more advanced forms of these biofuels are used in the other two scenarios, as described in Section 4.4 Result #4: Fuel Consumption by Fuel Type.

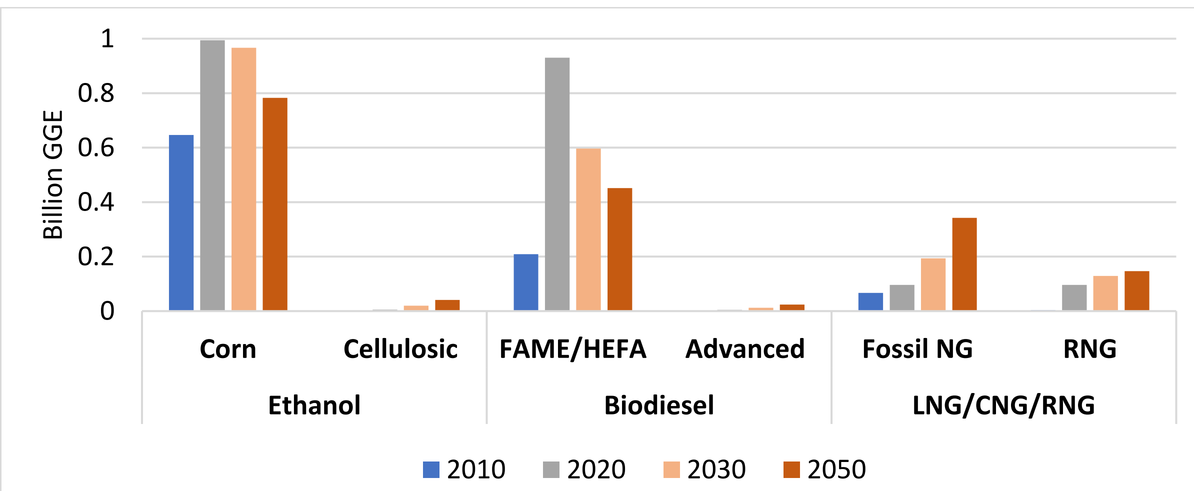


Figure 3-10. Biofuel projections for BAU scenario.

(Abbreviations: GGE, gasoline gallon equivalent; FAME, fatty acid methyl esters; HEFA, hydroprocessed esters and fatty acids; NG, natural gas; LNG, liquefied natural gas; CNG, compressed natural gas; RNG, renewable natural gas.)

3.5.5 Input #4: Fuel Costs

The present and projected fuel prices for gasoline and diesel fuel are taken from the Energy Information Administration Annual Energy Outlook 2018 (EIA 2018). The carbon intensities for gasoline and diesel are 13,300 gCO_2e/GGE and 13,200 gCO_2e/GGE (diesel gallon equivalent), respectively (CARB 2017). Gasoline and diesel fuel are blended with ethanol and diesel biofuels, respectively. The carbon intensity for the blend fuel depends on the biofuel carbon intensity and the blend percentage. Both of these vary with time. The fuel price and carbon intensity for all other fuels are either calculated from the fuels module portion of the TTM (Miller 2019) or estimated from recent studies.

Figure 3-11 shows the fuel cost as a function of time with no taxes added. The upper panel shows costs for gasoline, diesel, diesel biofuels, and ethanol, and. The diesel biofuels, ethanol, and the diesel blend costs are shown for a high biofuels scenario where diesel biofuels make up 50% of the diesel blend by 2050. The lower panel shows CNG, electricity, and hydrogen costs for the low CI scenario. The hydrogen cost is very high during early years because volume demand is very low. Initially hydrogen is produced from natural gas. Over time the percentage of low CI pathways increase significantly to produce very low CI hydrogen. The cost drops as demand increases but then starts increasing around 2030 due to the increased cost of low CI hydrogen from pathways such as electrolysis.

We assume ethanol will be produced originally from corn. In 2030 cellulosic ethanol is produced in small quantities, growing to 98% of all ethanol by 2050. Figure 3-12 shows the cost of diesel biofuels from the two pathways—hydro-processed esters and fatty acids (HEFA) and Fischer-Tropsch. Initially all diesel biofuels come from HEFA pathways, but over time Fischer-Tropsch pathways constitute an increasing percentage until 2050, when 50% of the diesel biofuels come from Fischer-Tropsch pathways.

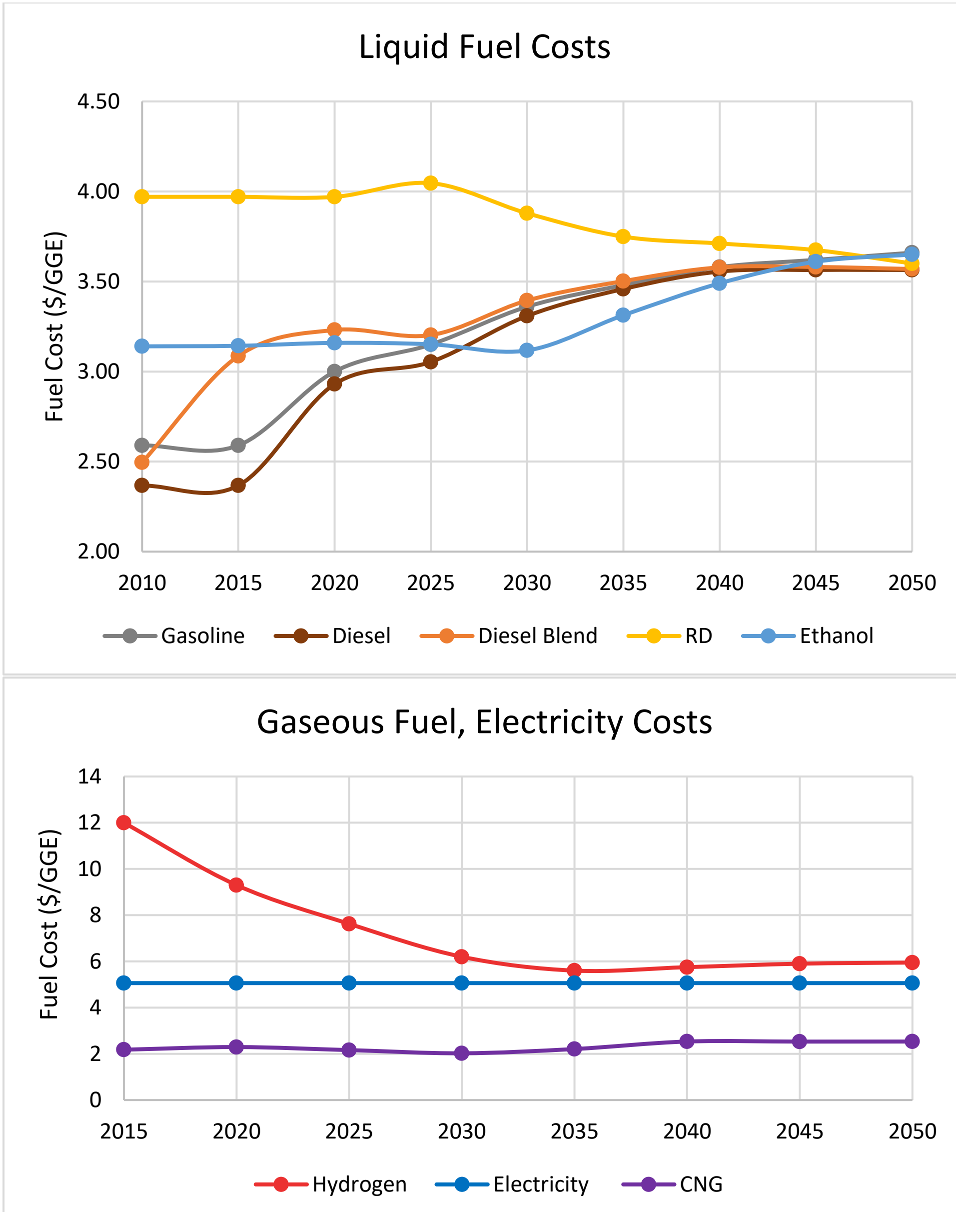


Figure 3-11. Fuel costs for liquid fuels (top) and other fuels (bottom). All costs are in $/GGE. (RD, renewable diesel; CNG, compressed natural gas)

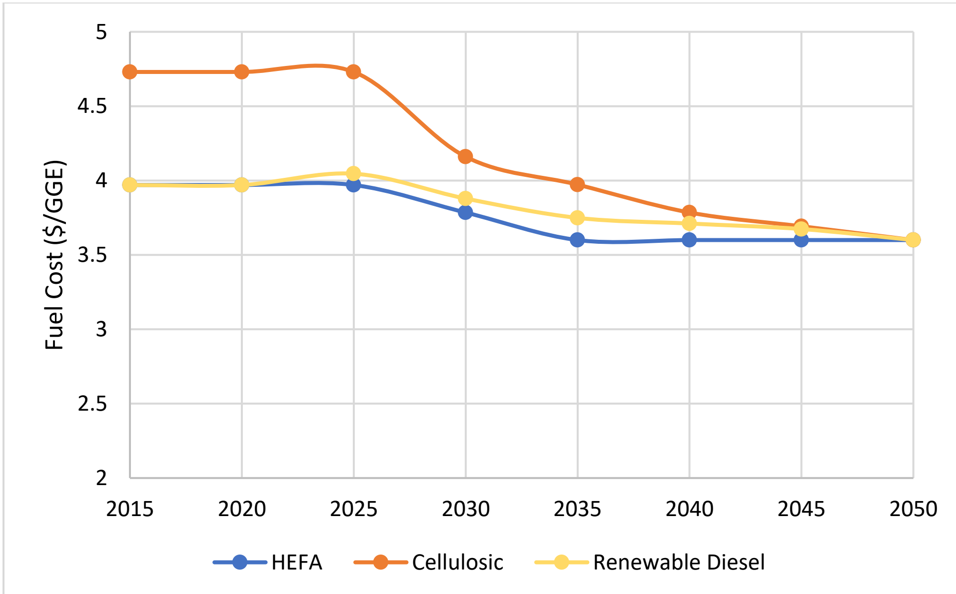


Figure 3-12. Price of diesel biofuels.
(HEFA [hydroprocessed esters and fatty acids], Fischer-Tropsch biofuels, and the blend prices.)

The main sensitivity explored is fuel cost. We ran the analysis with three cases for gasoline and diesel cost based on the US Energy Information Administration Annual Energy Outlook 2018. We used their reference cases for diesel and gasoline and constructed high and low fuel price cases. The high price case is the reference case plus 20% while the low-price case is the reference case minus 20%. The prices used are shown in Table 7. Diesel prices are given in $/DGE and gasoline prices are given in $/GGE.

Table 7. US EIA reference case gasoline and diesel prices (AEO 2018) and high and low fuel price cases. Diesel price units are $/DGE, and gasoline prices units are $/GGE.

Reference Fuel Case	2015	2020	2025	2030	2035	2040	2045	2050
Diesel	$2.69	$3.33	$3.47	$3.76	$3.93	$4.04	$4.05	$4.05
Diesel (low)	$2.69	$3.33	$2.78	$3.01	$3.14	$3.23	$3.24	$3.24
Diesel (high)	$2.69	$3.33	$4.16	$4.51	$4.72	$4.85	$4.86	$4.86
Gasoline	$2.59	$3.00	$3.15	$3.36	$3.48	$3.58	$3.62	$3.66
Gasoline (low)	$2.59	$3.00	$2.52	$2.69	$2.78	$2.86	$2.90	$2.93
Gasoline (high)	$2.59	$3.00	$3.78	$4.03	$4.18	$4.30	$4.34	$4.39

3.5.6 Input #5: Carbon Intensity of Fuels

Figure 3-13 shows the fuel CI for diesel, gasoline, ethanol, and diesel biofuels (top) and for CNG, electricity, and hydrogen (bottom). The diesel biofuels and ethanol CIs come from the high biofuels truck scenario, and the hydrogen and electricity come from the low CI fuel scenario. The CNG CI decreases due to increasing percentage of RNG in the fuel mix.

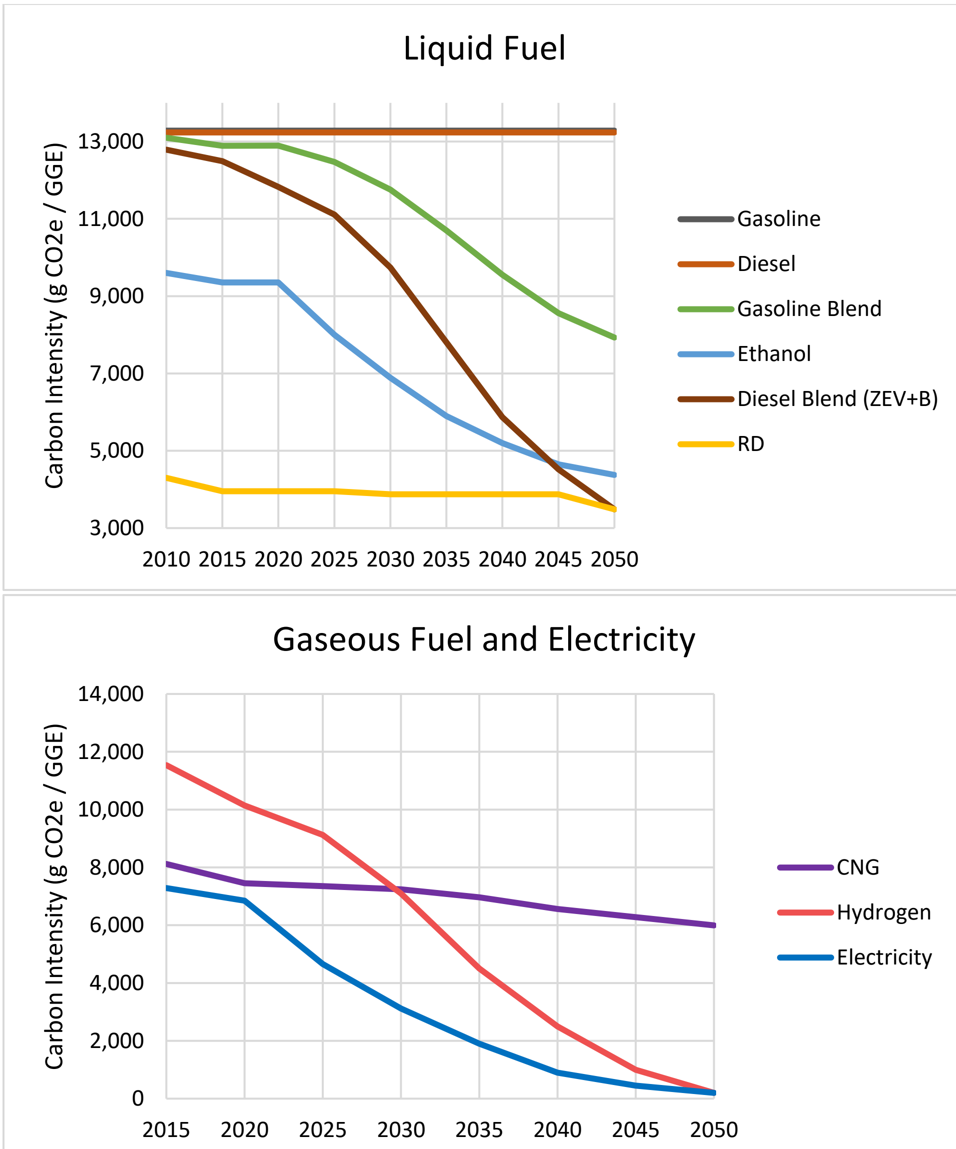


Figure 3-13. Carbon intensity (CI) through 2050 for all fuels.

The model calculates GHG emissions each year based on vehicle stock, fuel economies, vehicle miles traveled, and the fuel carbon intensities. Input #6: Vehicle Stock and Scrappage Values

We use CARB's projections for vehicle stock out through 2050 and their vehicle scrappage values to calculate new vehicle sales for each year through 2050. The LDV stock values come from Vision 1.0 (Vision 2012). For trucks we extract initial vehicle stock by technology type (diesel, CNG, gasoline, etc.) and total stock each year through 2050 from EMFAC2014 (EMFAC 2014). Scrappage rates come from Vision 1.0 (Vision 2012). The initial stock numbers by age were smoothed so that new vehicle sales costs do not show significant variation from year to year. The projected fleet stock numbers are independent of the scenario modeled.

3.5.7 Input #7: VMT

The average annual VMT per vehicle for each vehicle type is taken from CARB's Vision 2.0 model (CARB 2015). The VMT is a function of vehicle age with the miles traveled decreasing each year. Battery electric and fuel cell vehicles have the same VMT as conventional vehicles independent of range. Future versions of the model may limit VMT for low-range vehicles.

Table 8. VMT in the first year for each vehicle type.

Vehicle Type	VMT (thousand miles)
Cars	20.2
Light-duty Trucks	20.8
Heavy-duty Pickups and Vans	26.1
Medium-duty Urban Trucks	29.9
Transit Buses	46.1
Other Buses	42.5
Medium-duty Vocational Trucks	8.3
Heavy-duty Vocational Trucks	50.2
Short-haul Heavy-duty Trucks	60.0
Long-haul Heavy-duty Trucks	117.0

4 Results

Market share (% sales by technology) projections for trucks to 2050 were generated with the TCM in this study, while LDV market share projections were taken from a previous UC Davis study (Yang et al 2016). Together these were used in the TTM to generate projections of vehicle stocks, VMT, energy use, and GHG emissions. Major results are shown in this section; Appendix A – Market Share includes tables showing the market share and other results for each truck type and technology for the three scenarios.

4.1 Result #1: Market Share (Percentage of New Sales)

Figure 4-1 and Figure 4-2 show the market share for long-haul trucks and HD pickups and vans for each of the three scenarios. These two truck types use more than half of the total fuel used by trucks in California. Further results sections report on the impacts of these sales scenarios and provide additional detail on the factors that drive these scenarios, and how the sales shares by technology/fuel vary by truck type.

Among long-haul trucks, in the BAU, no ZEV trucks are sold before 2045 and the shares of both ZEV and CNG do not rise above 0.1% by 2050. Hybrid sales exceed 16% in 2050. In the ZEV scenario the share of ZEV (all fuel cell) trucks reaches 80% in 2050, and diesel sales fall to 20%. As described in our technology report, we do not consider BEV for long-haul applications due to technical challenges in this application. In the ZEV+B scenario, the percentage of ZEVs drops to 40% in 2050 and diesel trucks, to 60%.

In contrast, for HD pickup trucks, new technology vehicles have significant market share. ZEVs reach 14% market share by 2050, split about equally between BEVs and FCEVs. ZEVs reach a 100% total market share in the ZEV scenario by 2050 and 60% in the ZEV+B scenario.

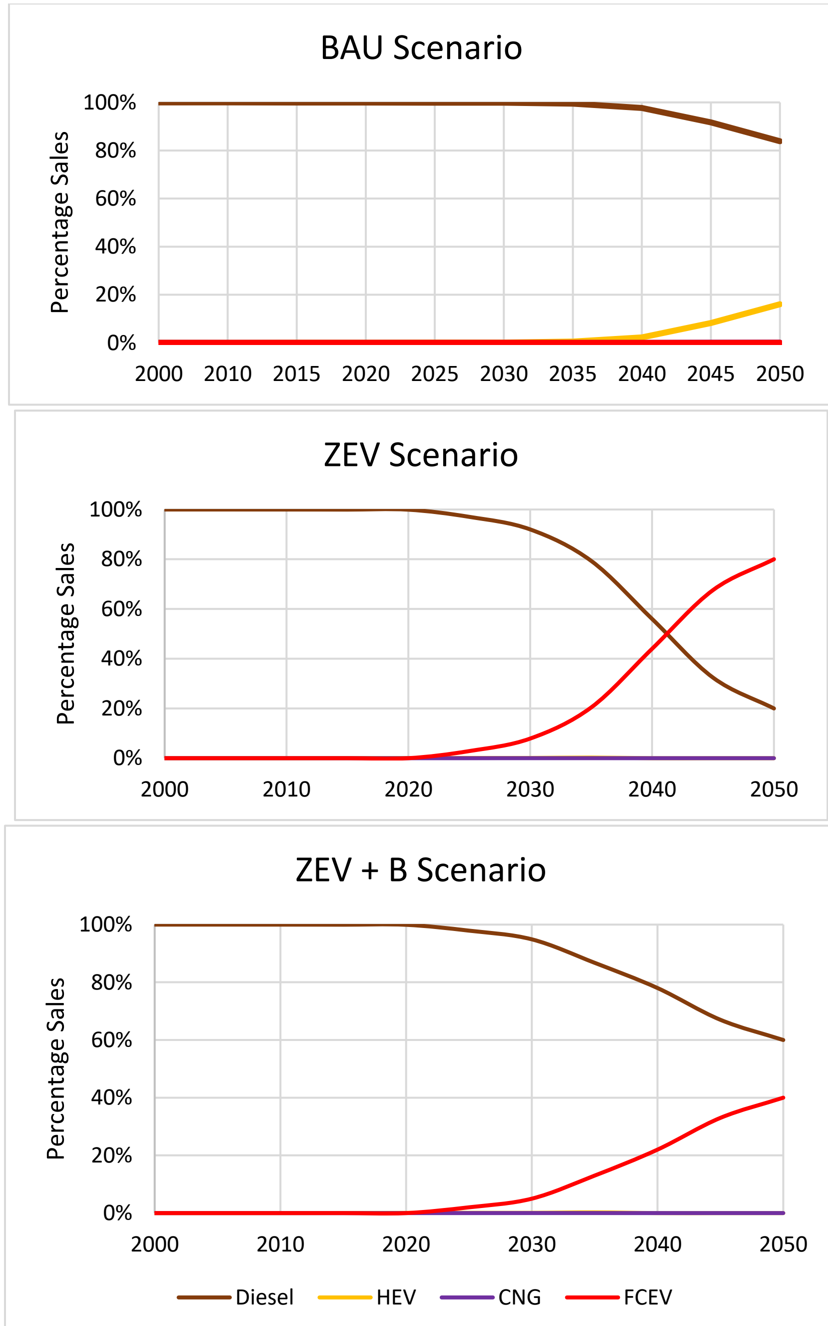


Figure 4-1. Market share for long-haul trucks through 2050 in each of the scenarios.
(HEV, hybrid electric vehicle; CNG, compressed natural gas; FCEV, fuel cell electric vehicle)

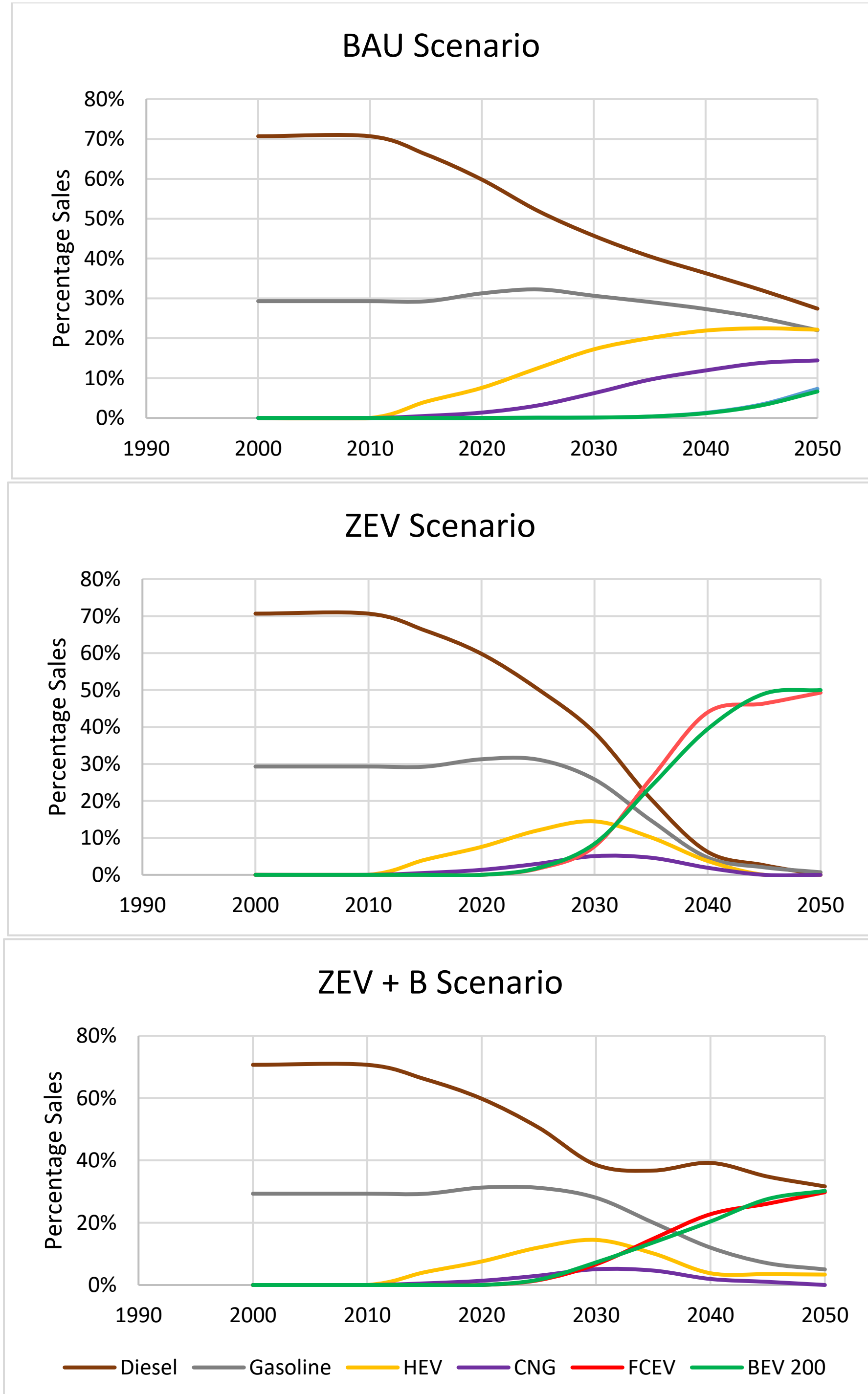


Figure 4-2. Market share for heavy-duty pickups and vans through 2050.
(HEV, hybrid electric vehicle; CNG, compressed natural gas; FCEV, fuel cell electric vehicle)

Figure 4-3 shows the 2030 and 2050 percentages of vehicle sales by technology type for each of the 10 vehicle types, for the BAU, ZEV, and ZEV+B scenarios. The 2050 shares of ZEVs in the

BAU are very low, with the major exception of transit buses. This reflects an expectation that BEV transit buses will be highly competitive by 2030 or well before.

In the ZEV scenario, ZEV (and near-ZEV, [i.e., PHEV]) LDVs achieve a 100% market share by 2050. Similarly, all truck classes achieve a 100% share except long-haul trucks which reach 80%. In most cases both BEVs and FCEVs contribute market share, but ZEVs are exclusively FCEVs in long-haul trucks and BEVs in transit buses and heavy-duty vocational trucks.

In the ZEV+B scenario, the 2050 ZEV market shares are lower than in the ZEV scenario. LDVs reach roughly 80% ZEV market share while most trucks reach 60% ZEV market share. Transit bus ZEVs have the same market share as in the ZEV scenario while long-haul trucks reach 40% ZEV market share.

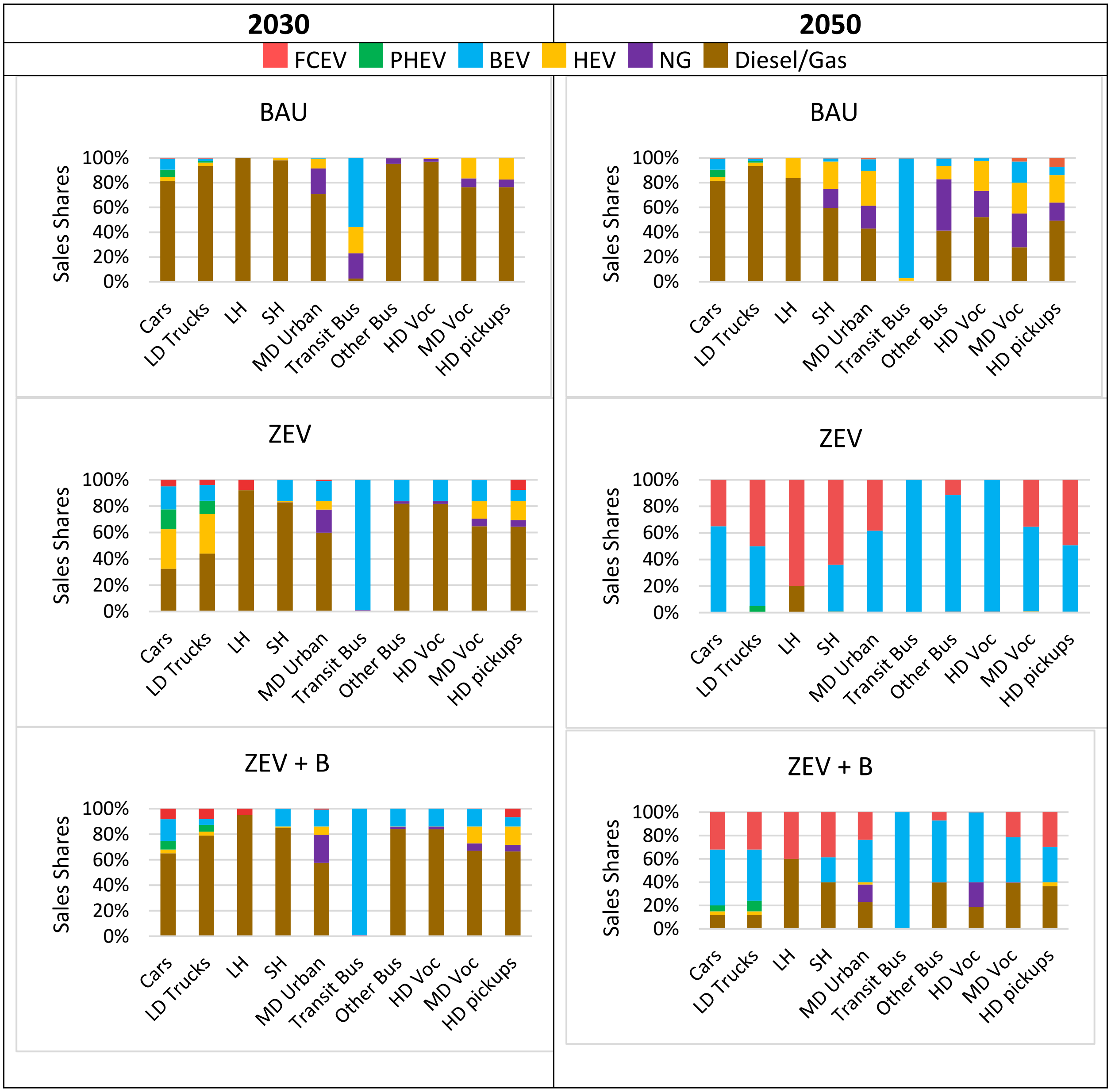


Figure 4-3. Percentage of vehicle sales by technology type and vehicle type for the BAU, ZEV, and ZEV+B scenario in the years 2030 and 2050.

(Abbreviations: LH, long-haul, SH, short-haul; MD, medium duty; HD, heavy duty; Voc, vocational; FCEV, fuel cell electric vehicle; PHEV, plug-in hybrid vehicle; BEV, battery electric vehicle; HEV, hybrid electric vehicle; NG, natural gas; LD, light-duty; LH, long-haul trucks; SH, short-haul trucks; MD, medium-duty; HD, heavy duty; Voc, vocational)

4.2 Result #2: Fleet Stock

The TTM calculates stock turnover for each vehicle type. Figure 4-4 shows the light-duty fleet mix by technology type through 2050 for the BAU, ZEV, and ZEV+B scenarios. The overall increase in vehicle stock for the light-duty category is roughly 20%. The BAU scenario shows a very modest increase of ICEVs through 2050 with the remainder consisting of HEVs, PHEVs, BEVs, and a very small number of FCEVs. The ZEV scenario shows a large decrease in ICEVs starting after 2020 and continuing through 2050. The remaining stock consists of significant percentages of HEVs, PHEVs, BEVs, and FCEVs. The ZEV+B scenario shows a similar but slightly less increase in these vehicle types.

Figure 4-5 shows the increase in fleet stock for long-haul trucks through 2050 for each scenario. The stock of trucks increases by roughly 40-50% from 2010 to 2050 depending on truck type. Figure 4-6 shows the stock mix of each technology in heavy-duty pickups and vans over time for each scenario.

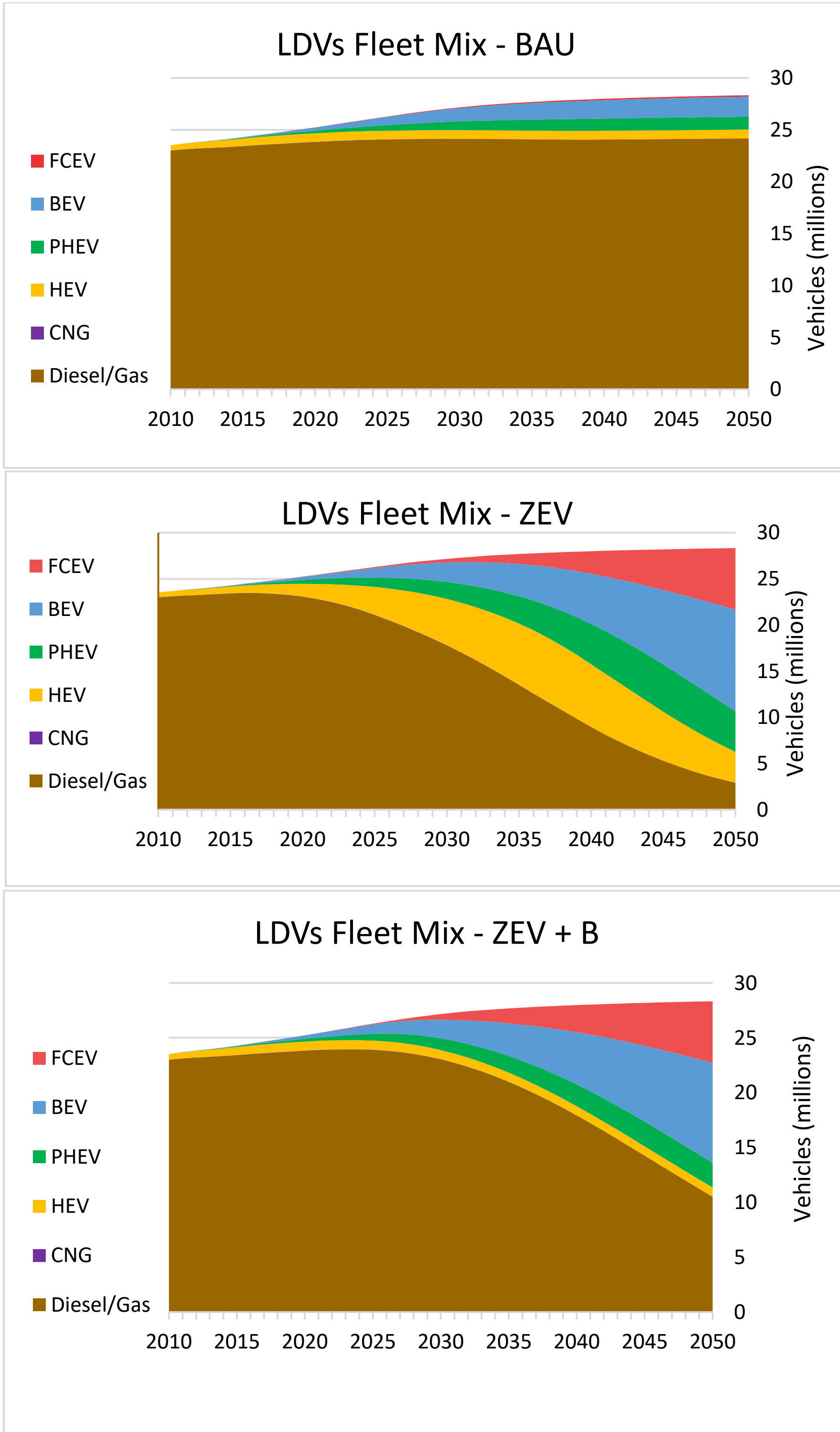


Figure 4-4. Fleet mix of LDVs through 2050 for the BAU, ZEV, and ZEV+B scenarios.
(FCEV, fuel cell electric vehicle; BEV, battery electric vehicle; PHEV, plug-in hybrid electric vehicle; HEV, hybrid electric vehicle; CNG, compressed natural gas[vehicle].)

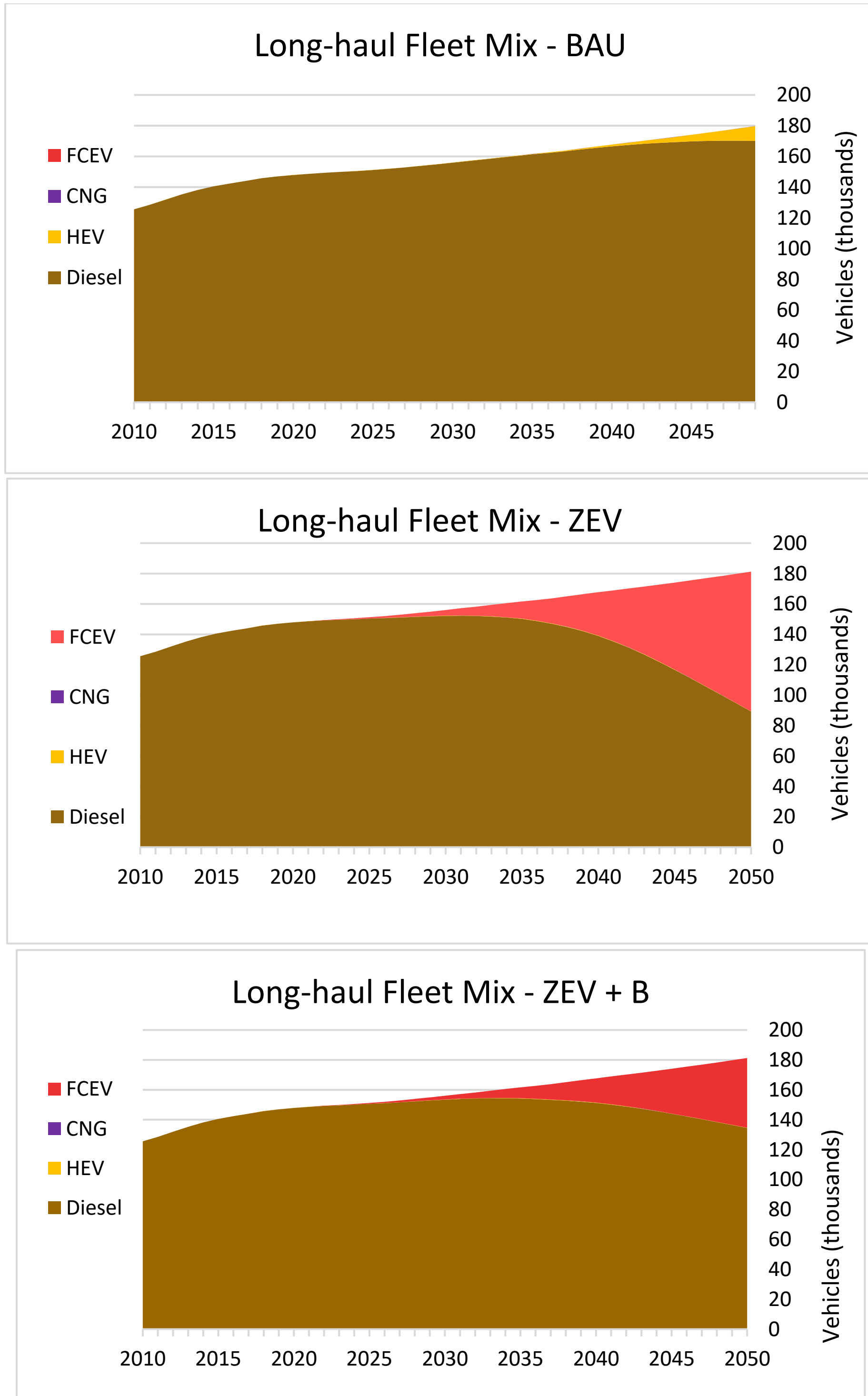


Figure 4-5. Fleet mix of long-haul trucks through 2050 for the BAU, ZEV, and ZEV+B scenarios. (FCEV, fuel cell electric vehicle; CNG, compressed natural gas [vehicle]; HEV, hybrid electric vehicle.)

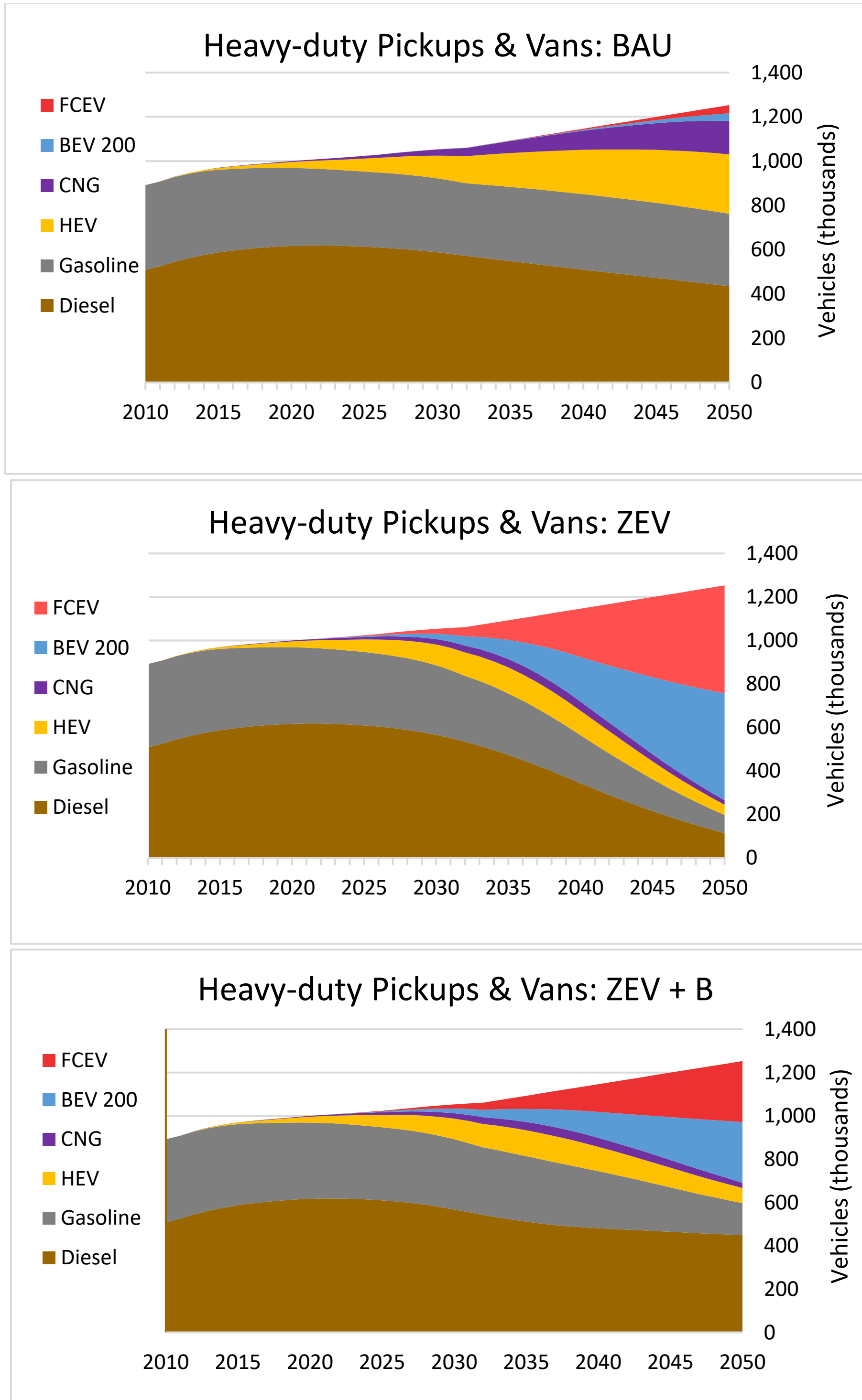


Figure 4-6. Fleet mix of heavy-duty pickups and vans through 2050 for the BAU, ZEV, and ZEV+B scenarios.

(FCEV, fuel cell electric vehicle; BEV200, battery electric vehicle with 200-mile range; CNG, compressed natural gas [vehicle]; HEV, hybrid electric vehicle.)

Figure 4-7 shows the fleet stock of technology types in 2030 and 2050 for all 10 vehicle types in the BAU, ZEV, and ZEV+B scenarios. The BAU fleet stock is dominated by gasoline and diesel vehicles. Only transit buses show a significant contribution of advanced technology vehicles.

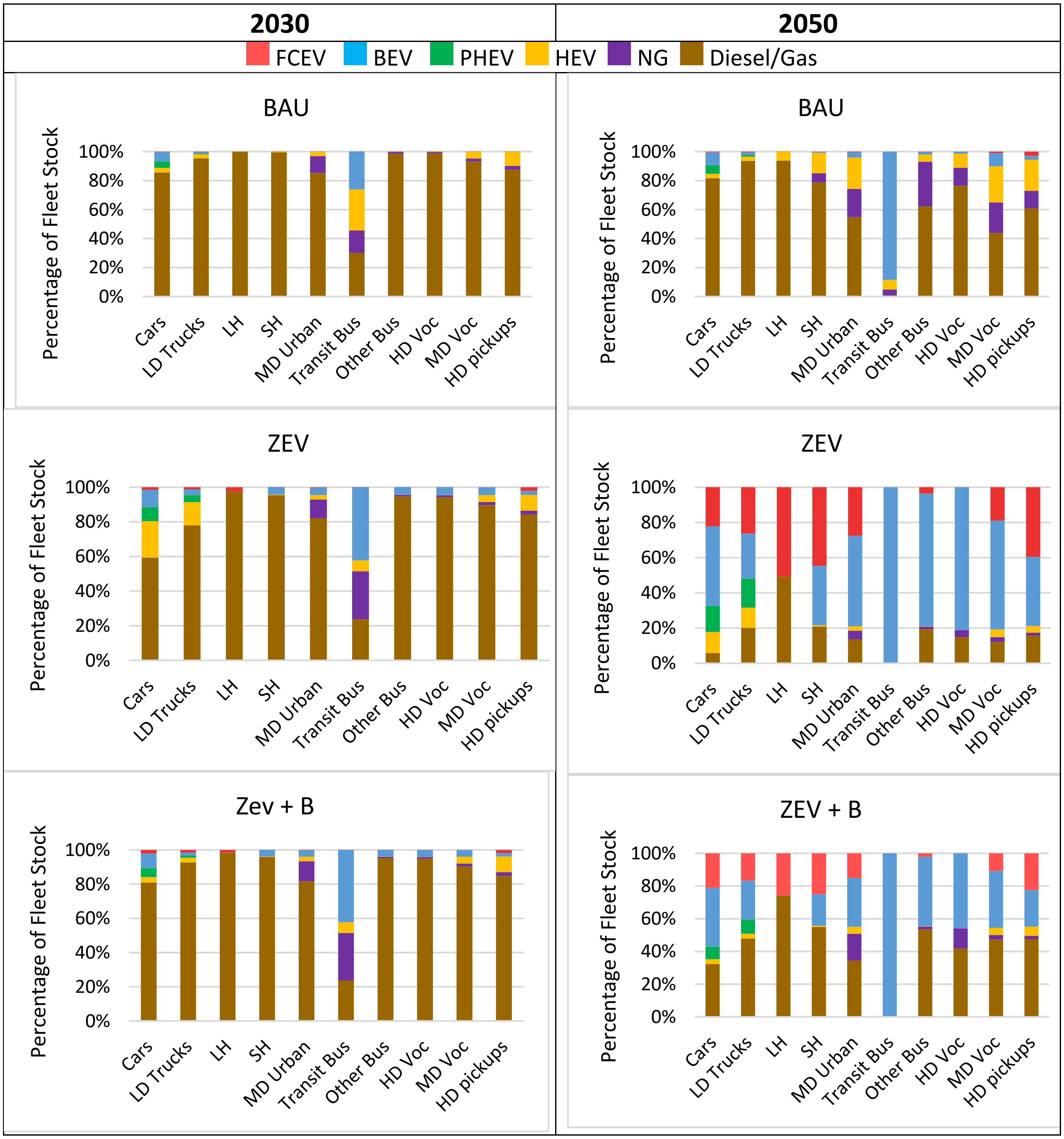


Figure 4-7. Percentage of fleet stock for all 10 vehicle types in the BAU, ZEV and ZEV+B scenario for years 2030 and 2050.

(Abbreviations: FCEV, fuel cell electric vehicle; BEV, battery electric vehicle; PHEV, plug-in hybrid vehicle; HEV, hybrid electric vehicle; NG, natural gas; LD, light-duty; LH, long-haul trucks; SH, short-haul trucks; MD, medium-duty; HD, heavy-duty; Voc, vocational.)

The ZEV scenario results in a significant percentage of ZEVs in every vehicle type by 2050. ZEVs make up more than 80% of the fleet stock for cars and more than 70% for light-duty trucks. Transit buses reach 100% ZEVs by 2050; other truck categories reach roughly 80%. Compared to the ZEV scenario, the ZEV+B scenario shows a smaller percentage of ZEVs and near-ZEVs in every vehicle type except transit buses, but the fleet stock still exceeds 40% for most truck types and 50% for LDVs.

4.3 Result #3: Vehicle Miles Traveled (VMT) by technology

Figure 4-8 shows the percentage of fleet VMT by fuel type for each vehicle type for each scenario in the years 2030 and 2050. This reflects both the stock of each vehicle type and its average travel per vehicle. Long haul trucks travel much farther than other truck types, so they play a more important role in VMT than in stock.

The LDV scenarios have BEVs with ranges of 100 and 200 miles. The truck BEVs have ranges of 200 miles. Given the range restrictions, these vehicles may not drive as far as conventional vehicles during the first several years. We assume that all the BEVs have the same VMT as conventional vehicles throughout their lifetimes. The LDV BEVs with a 100-mile range are phased out fairly early and never reach greater than a 4% market share so their contribution to the outputs of the study are minimal.

In the BAU, by 2050, LDVs and trucks show a very modest contribution from hydrogen and electricity. For the ZEV scenario in 2050, electricity and hydrogen combine to reach roughly 80% for most vehicle types with transit buses using 100% electricity and long-haul trucks using 60% hydrogen.

In the ZEV+B scenario, the ZEV VMT of each car and truck type is significantly less than in the ZEV scenario except for transit buses which use 100% electricity. The percentage of VMT for ethanol is 21% in both 2030 and 2050. The percentage of VMT for diesel biofuels is 33% and 30% in 2030 and 2050 respectively.

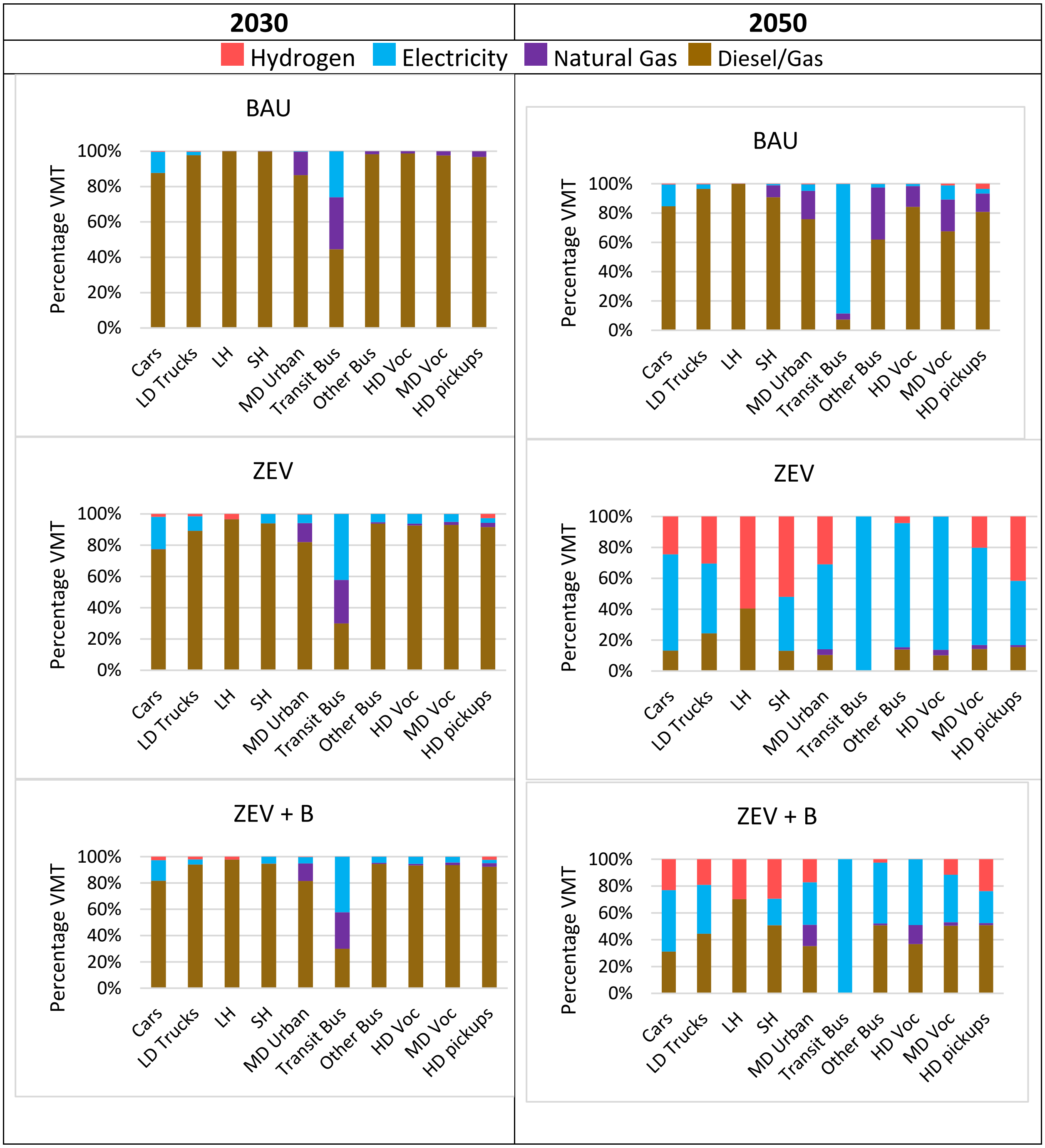


Figure 4-8. Percentage of fleet VMT by fuel type and vehicle type for the BAU, ZEV and ZEV+B scenario for years 2030 and 2050.

(Abbreviations: LD, light duty; LH, long-haul, SH, short-haul; MD, medium duty; HD, heavy duty; Voc, vocational.)

4.4 Result #4: Fuel Consumption by Fuel Type

Figure 4-9 shows the 2030 and 2050 fuel consumption for each fuel type by scenario; each panel represents a different grouping of vehicles: all vehicles together (LDVs, medium- and heavy-duty trucks), LDVs, and all trucks. The scenarios are also compared to past consumption in 2010 and 2015.

In the analysis of all vehicle types together, overall fuel consumption drops significantly in the BAU scenario due to efficiency gains but remains primarily gasoline and diesel fuel. In the ZEV scenario, overall fuel use drops by about half in 2050 compared to 2010, with about half coming from electricity and hydrogen. Fuel use drops less in the ZEV+B scenario, with less electricity and hydrogen but more ethanol and biodiesel.

The separate LDV and truck figures reflect deeper fuel use cuts and shifts for LDVs than for trucks. Trucks show a modest decrease in overall fuel use in the BAU to 2050 because increases in fuel economy are mostly offset by increases in VMT. The ZEV scenarios reflect a roughly equal use of electricity and hydrogen in LDVs, but greater use of hydrogen in trucks. In the ZEV+B scenario, trucks use almost the same amount of energy in 2050 as they do in the BAU, though diesel use is cut in half.

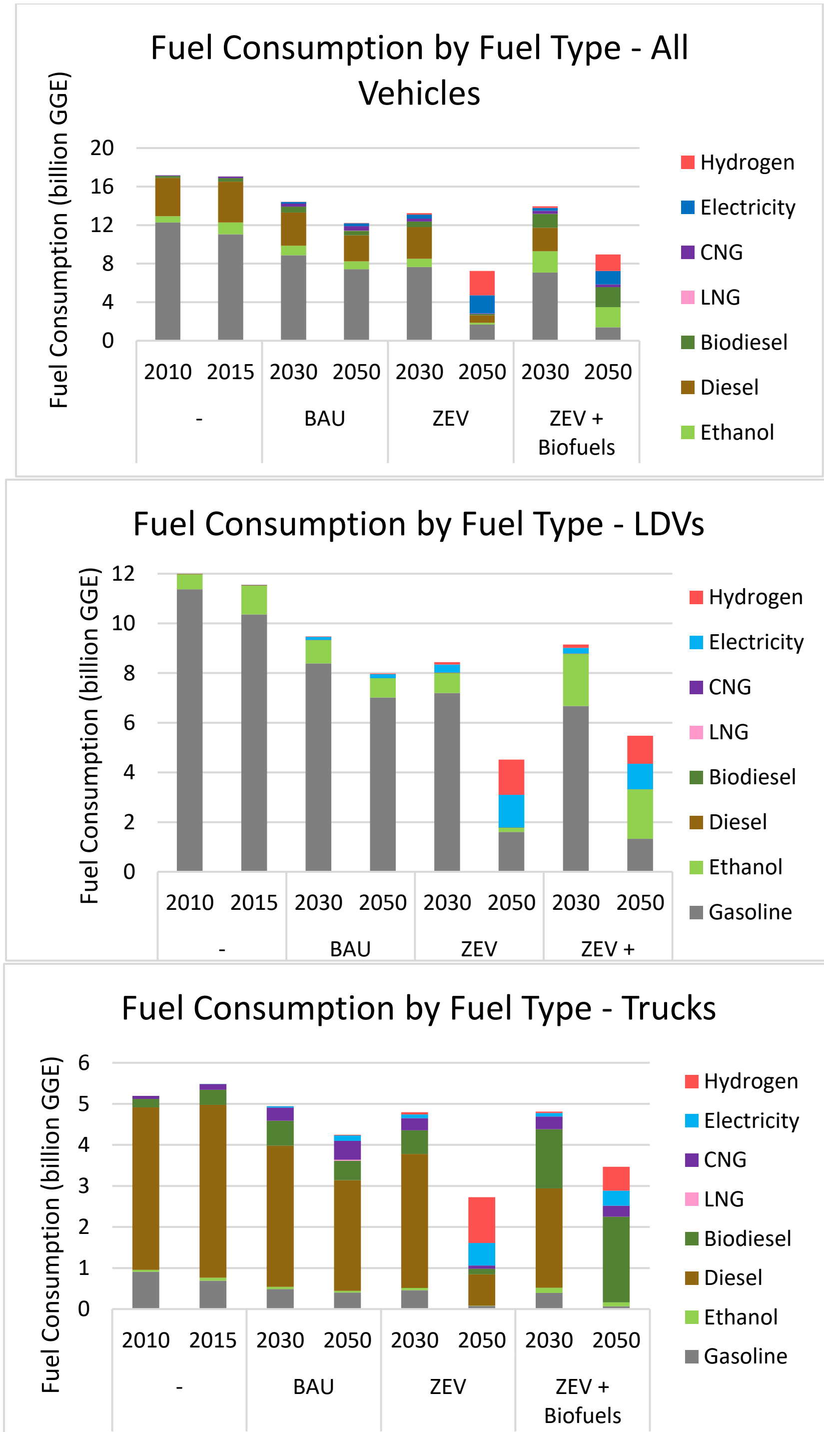


Figure 4-9. Fuel consumption by fuel type in the past (2010, 2015) and in 2030 and 2050 in each scenario (BAU, ZEV, and ZEV + Biofuels).

Analysis performed for: all vehicle categories (LDVs + trucks) together and separately.

Biofuels play a fairly steady role through 2030 in the BAU and ZEV scenarios, with significant growth in the ZEV+B scenario. By 2050, compared to 2030, in ZEV, biofuel use has been scaled down substantially in the ZEV scenario but scaled-up in the ZEV+B scenario. Across all scenarios, LDVs account for nearly all ethanol demand and trucks for nearly all biodiesel and RNG demand.

As shown in Figure 4-10, in the ZEV+B scenario, advanced (cellulosic) ethanol and biomass-based biodiesel use grows dramatically after 2030. By 2050, they grow close to 1.4 and 1.0 billion gallons gasoline equivalent respectively. This is complemented by some remaining conventional biofuels (corn ethanol and oil-based biodiesel) which would be fully phased out after 2050. The transition to cellulosic biofuels reflects their low carbon intensities and thus strong CO_2 reduction characteristics.

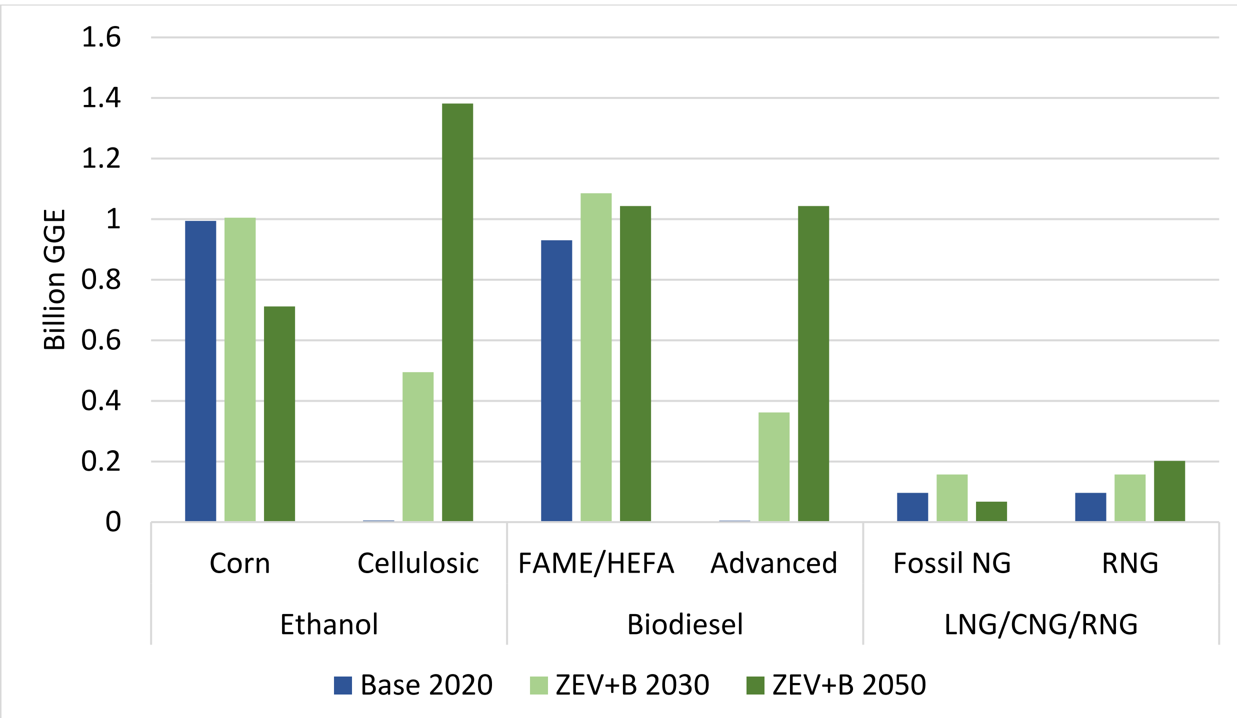


Figure 4-10. Biofuel consumption in the ZEV and ZEV+B scenario for both LDVs and trucks. (FAME, fatty acid methyl esters; HEFA, hydroprocessed esters and fatty acids; LNG, liquefied natural gas; CNG, compressed natural gas; RNG, renewable natural gas)

The California Council on Science and Technology (CCST) found that the fuel production potential for in-state California biomass is 3.3. billion GGE in their baseline scenario and 9.8 billion GGE in their optimistic scenario (CCST 2013). The Billion-Ton report from the US Department of Energy estimates that the US potential for biomass production is 1.2 billion dry tons or roughly 10 times the CCST optimistic value for California (DOE 2016). Both reports indicate that biofuels resources likely will be sufficient for our ZEV+B scenarios.

4.5 Result #5: Reduction of GHGs

As they enter the market, new technologies and fuels have the potential to reduce GHG emissions. The magnitude of GHG reductions depends on the increase in VMT, the decrease in fuel use as vehicle efficiency rises, and the decrease in fuel carbon intensity (CI). The VMT increase is constant for all scenarios while the vehicle efficiency and fuel CI vary significantly from scenario to scenario.

Table 9 shows the GHG emissions reductions from 2010 values in 2050. The reductions from the ZEV and ZEV + Biofuels scenarios are very similar.

Table 9. GHG reductions in 2050 from 2010 values for the LDV and truck scenarios.

Scenario	GHG Reduction in 2050 from 2010 (%)
LDV BAU	-39
LDV ZEV	-86
LDV ZEV+B	-83
Truck BAU	-34
Truck ZEV	-82
Truck ZEV+B	-84
Combined LDV and truck BAU	-38
Combined LDV truck ZEV	-85
Combined LDV and truck ZEV+B	-83

The ZEV scenarios can produce large GHG reductions through the higher vehicle efficiency of EVs and FCEVs coupled with the much lower fuel CIs of electricity and hydrogen compared with gasoline and diesel fuel (Figure 4-11). These lower CIs are particularly low because electricity and hydrogen come from renewable feedstocks.

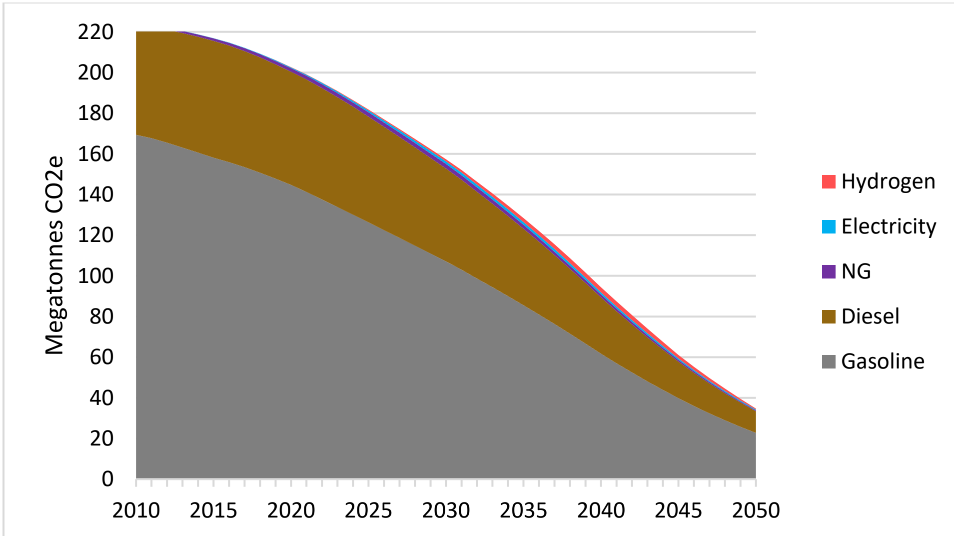


Figure 4-11. Total (LDVs and trucks) GHG emissions in ZEV scenario through 2050.
(NG, natural gas)

Figure 4-12 displays the reduction in GHG emissions for the LDV fleet showing the contribution by fuel type. The BAU scenario manages to decrease GHG emissions 39% from 2010 levels by 2050, due to significant fuel economy increases. The ZEV and ZEV+B scenarios reduce GHG emissions by over 80% by 2050.

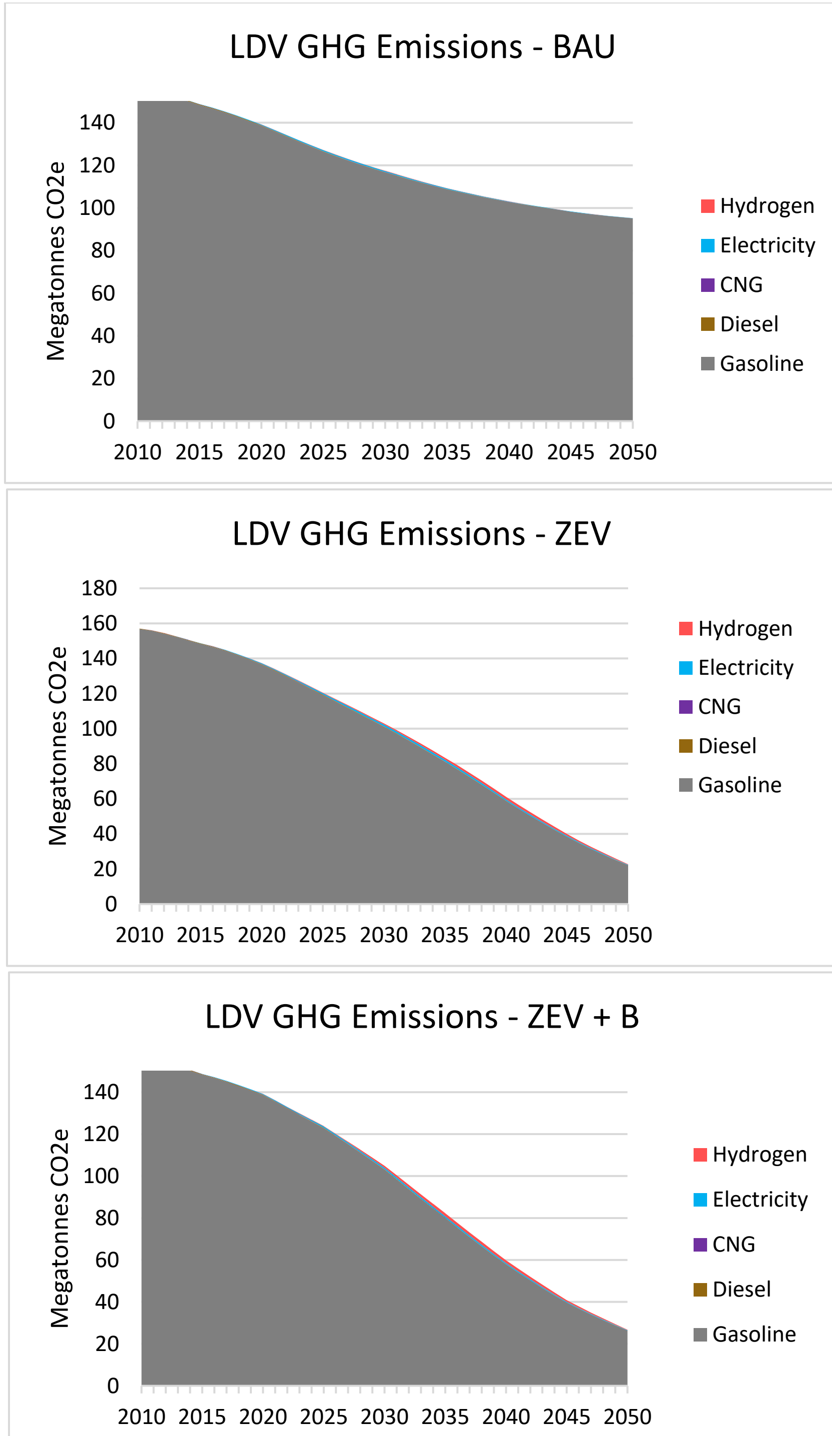


Figure 4-12. LDV GHG emissions by fuel type for the BAU, ZEV, and ZEV+B scenarios.

Figure 4-13 shows the GHG emissions as a function of fuel for each of the three truck scenarios through 2050. The BAU scenario reduces GHGs by 34% from 2010. Both the ZEV and ZEV + Biofuels scenarios show reductions of greater than 80% by 2050.

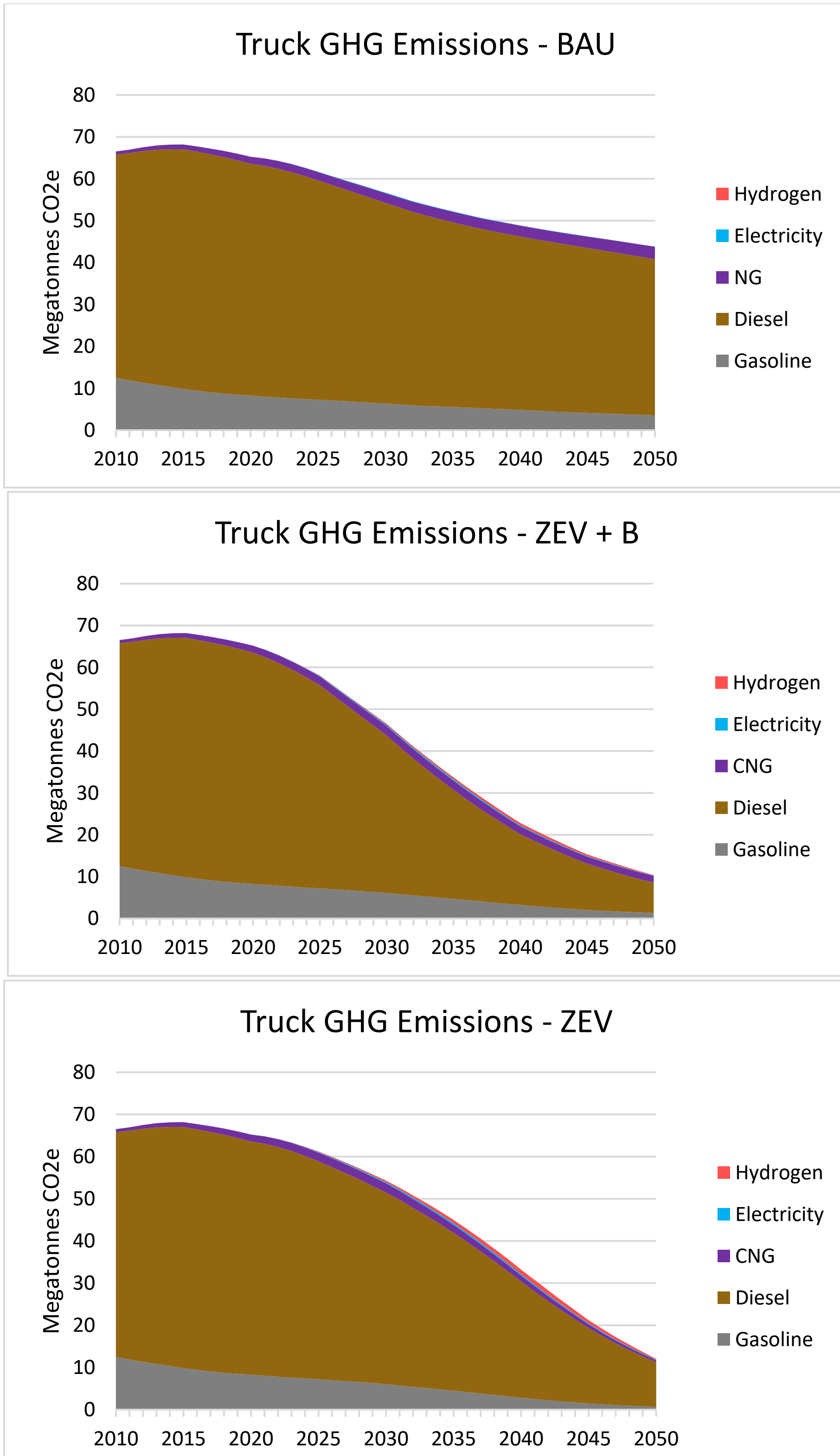


Figure 4-13. Truck GHG emissions by fuel type for the BAU, ZEV, and ZEV+B scenarios.

4.6 Result #6: Costs

This study includes estimates of the costs of purchasing and fueling LDVs and trucks with all costs projected to 2050 by technology and fuel type. In this cost accounting, we track total costs in each year out to 2050, so do not fully account for the operating costs of vehicles purchased by 2050 that operate beyond that year. Further, no discounting of future costs is undertaken. In addition, costs are reported in real 2018 dollars, but in an undiscounted fashion; even a 3% discount rate would cause the estimates after 2030 to be relatively unimportant compared to those before 2030.

4.6.1 Costs in the Baseline Fuel Price Case

Figure 4-14 shows cost results as totals across the 2015–2050 time frame, for LDVs and trucks, breaking out vehicle and fuel costs. It also shows differences across the scenarios for the entire time frame and separated by the period through 2030 and the period 2030-2050.

As shown in Figure 4-14A, the total costs of purchasing and fueling LDVs and trucks in California over the full time frame is estimated at about $4 trillion. About 60% of this cost is for LDVs and 40% for trucks; the LDV costs are dominated by vehicle costs whereas the truck costs are dominated by fuel costs. This reflects the more energy intensive nature and longer driving distances typical of trucks.

Figure 4-14A also shows that the total costs across the three scenarios appear similar. While accurate in the big picture, this masks important differences for specific vehicle types at specific points in time. The overall differences between scenarios are shown in Figure 4-14B. While these differences can be significant—in the billions of dollars over the time frame—they are small compared to the total costs shown in Figure 4-14A, i.e., typically under 1% of total cost. The relatively small size of the differences in total cost between scenarios is partially due to offsetting effects: the truck purchase costs are higher in the ZEV and ZEV+B scenarios, whereas energy costs are lower—except in the ZEV+B scenario for trucks. The main reason that vehicle costs are higher in these scenarios is the additional costs of battery electric and fuel cell technologies; the main reason for fuel savings is the lower cost per mile of electricity compared to diesel fuel. Biofuels costs, particularly advanced renewable diesel fuel, are expensive and take away fuel savings in the ZEV+B scenario.

As shown in Figure 4-14B, there is a net reduction of about $10 billion in the cost of all vehicles and fuels in the ZEV scenario compared to the BAU, and an increase in cost of about $40 billion in the ZEV+B vs. BAU. However, these costs should be kept in context; the total cost of all vehicle and fuel purchases and operations over this time frame in the BAU in California is projected in our study to be about $4 trillion. Thus $10 billion reduction in the ZEV scenario is about a 0.25% savings off this BAU; the $40 billion increase in ZEV+B is about a 1% increase. These percent differences vary by year and can reach several percent in certain years. Our per-vehicle cost estimates for ZEVs can be higher still.

These costs can be quite different in the pre-2030 vs post-2030 period, with a marked contrast between LDVs and trucks. For the total vehicle and fuel cost of LDVs, before 2030 there is a net increase close to $20 billion whereas after 2030 there is a net decrease close to $40 billion, with this result holding for both ZEV and ZEV+B. For trucks there is an increase in costs both before and after 2030, with this increase about $6 billion before and $4 billion after in the ZEV scenario but about $20 billion before and $40 billion after in the ZEV + B scenario. These higher costs are due mainly to the cost of advanced diesel biofuels.

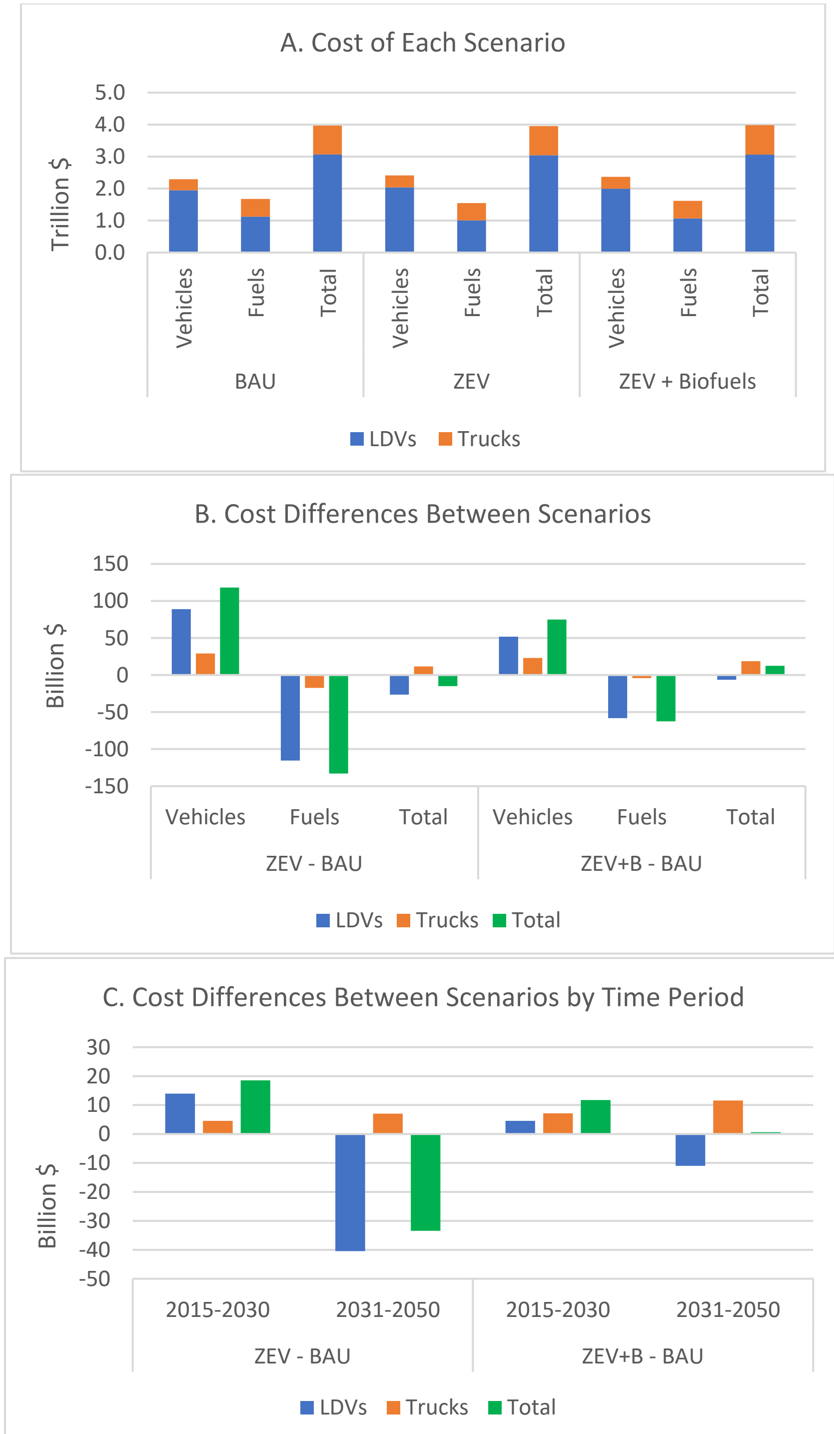


Figure 4-14. (A) Total costs by scenario, vehicles and fuels, LDVs and trucks, 2015-2050; (B) Cost differences in ZEV and ZEV+B scenarios vs BAU, and (C) Cost breakdowns for LDVs and trucks by time period (2015-2030 and 2031-2050).

The following figures break these results down into more detail in terms of time slices. Each figure compares the ZEV or ZEV+B scenario costs to those of the BAU scenario.

Figure 4-15 shows a comparison of costs under the BAU and ZEV scenarios. The plot values represent the ZEV scenario costs minus the BAU costs, so that negative values indicate savings in the ZEV scenario. The blue and orange curves show the vehicle and fuel cost differences respectively, and the green curves show the total cost difference for vehicles and fuel. Vehicle costs represent the total cost for all new vehicles purchased that year (i.e., the full cost of a vehicle purchased in 2030 is assigned to 2030). Fuel costs include the total cost of all fuel used by the fleet in a given year. Note that any fuel savings or increased expenditures for vehicles purchased before 2050 which accrue after 2050 are not included.

4.6.2 ZEV – BAU Costs

Figure 4-15 (top panel) shows the cost difference for LDVs. The initial rise of the blue curve (vehicle cost) indicates that advanced vehicles cost more than the vehicles they replace. The vehicle cost difference rises quickly since costs for advanced technologies (especially ZEVs) are significantly higher than for ICEVs and a greater number of advanced vehicles enter the fleet each year. As advanced vehicle costs fall, the cost difference flattens out and begins to decrease. By 2050, BEVs with a 200-mile range have a comparable cost to ICEVs.

As advanced vehicles with higher fuel economies initially enter the fleet, the fuel cost for the ZEV scenario is lower than the BAU scenario. This cost difference increases (i.e., the ZEV scenario saves more money) as the stock of advanced vehicles increases. In later years, the ZEV scenario requires very low CI fuels. This includes hydrogen made from renewable sources such as electrolysis of water, and this process is significantly more expensive than hydrogen made from natural gas. As more hydrogen is produced from electrolysis and more fuel cell vehicles enter the fleet, both hydrogen fuel consumption and the fuel cost per fuel cell vehicle increases. Around 2040, this combination causes the fuel cost difference to begin to flatten. The overall cost difference between light-duty vehicle ZEV and BAU scenarios increases to 2025 due to rising ZEV sales, but then declines and becomes net negative around 2030 due to fuel cost savings.

The truck cost curves (Figure 4-15 [middle]) look similar on the fuel side with the increased hydrogen costs causing the fuel difference to turn over and decrease. Even though ZEV vehicle costs decrease, the vehicle cost difference always remains positive. The fuel cost difference starts off negative but eventually begins to climb as renewable hydrogen dominates. The fuel savings are not large enough to overcome the increased vehicle costs, and the total cost is always higher for the ZEV scenario than the BAU scenario.

Figure 4-15 (bottom) shows the combined (LDV and truck) cost difference for the vehicle cost, fuel cost, and total cost in the baseline fuel-price case. This plot is similar to the LDV plot since LDVs dominate the overall costs. The total cost difference falls below zero (ZEV case less expensive), but instead of continuing to fall as in the LDV case, it starts to flatten after 2045.

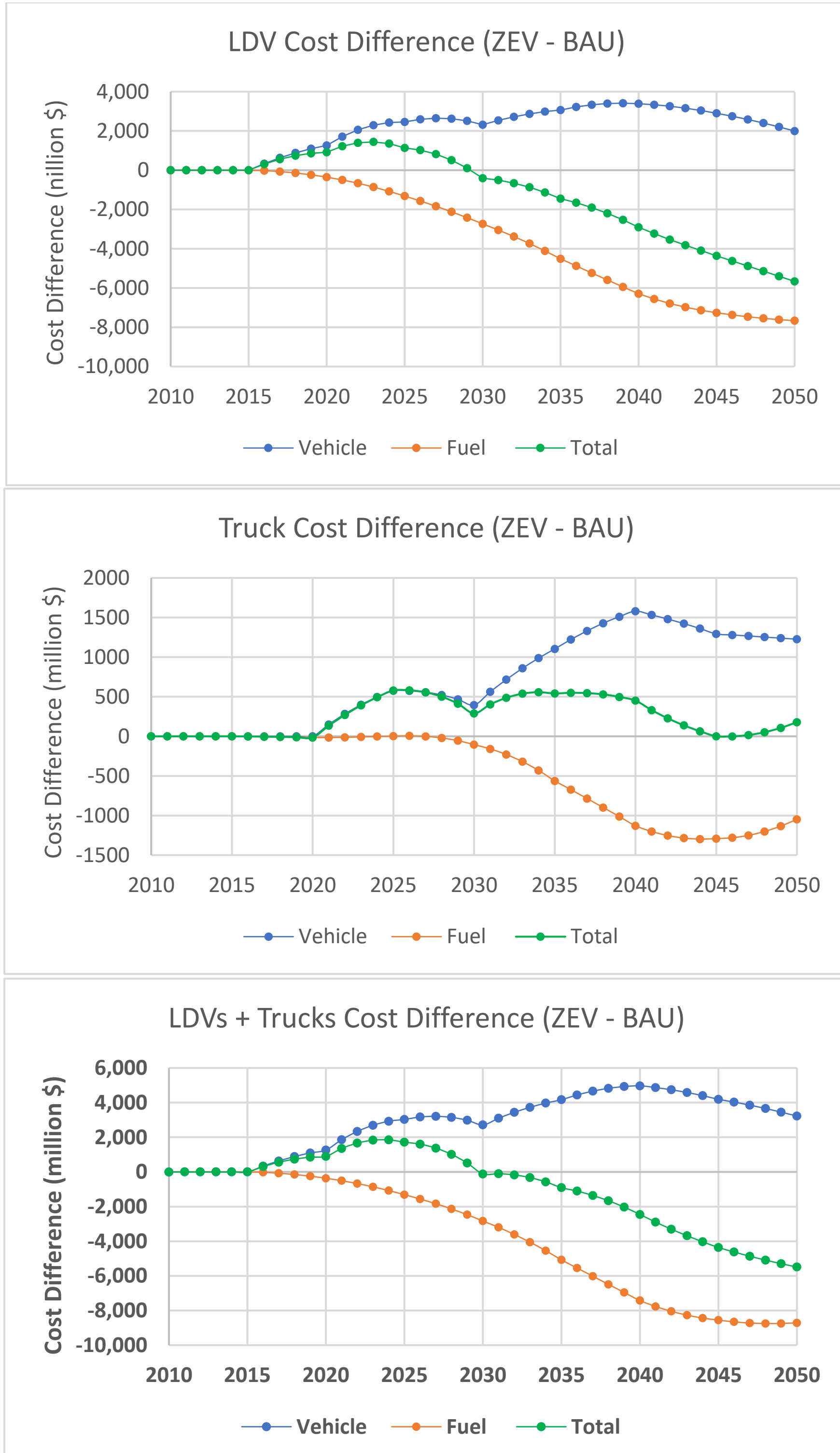


Figure 4-15. Cost differences between the ZEV and BAU scenario (ZEV – BAU) for LDVs, trucks, and both for the baseline fuel-price case.

4.6.3 ZEV+B – BAU Costs

Figure 4-16 shows the cost difference for the ZEV+B and BAU scenarios for LDVs, trucks, and all vehicles. The top panel shows the LDVs case. For LDVs, the ZEV+B scenario is very similar to the ZEV scenario. This is because: (a) the price of the gasoline blend with increased ethanol is relatively close to the price of gasoline with only a 10% ethanol blend; and (b) the market penetration of advanced vehicles in the ZEV+B scenario only differs somewhat from the ZEV scenario in later years. The major difference is lower fuel savings, given the lower share of high fuel economy vehicles. The vehicle cost of the ZEV+B scenario is not as high as the ZEV scenario due to lower ZEV sales shares.

Figure 4-16 (middle) shows the truck ZEV+B – BAU cost differences. The major difference between the truck ZEV and ZEV+B scenarios is the ZEV+B fuel cost due to the high price of diesel biofuels. The fuel cost difference rises as the percentage of biofuels in the diesel blend increases and the cost difference between the diesel blend and diesel increases. This cost difference peaks before 2030 and then decreases as biofuel costs decrease. Eventually the higher cost of renewable hydrogen causes the cost difference to level off toward 2050. From 2025 through 2050 diesel blends in the ZEV+B scenario cost slightly higher than in the ZEV scenario peaking at $0.15 higher in 2030. The ZEV+B scenario also uses much more diesel fuel since the ZEV market share is less than the ZEV scenario market share. The total cost difference for trucks in the ZEV − BAU case never gets below zero, so the ZEV+B scenario is always more expensive than the BAU scenario.

Figure 4-16 (bottom) shows the combined LDV and truck case. The LDVs dominate and the curves for LDVs + trucks resemble the LDV curves. The crossover point where the ZEV+B scenario costs less than the BAU is closer to 2040 rather than 2030.

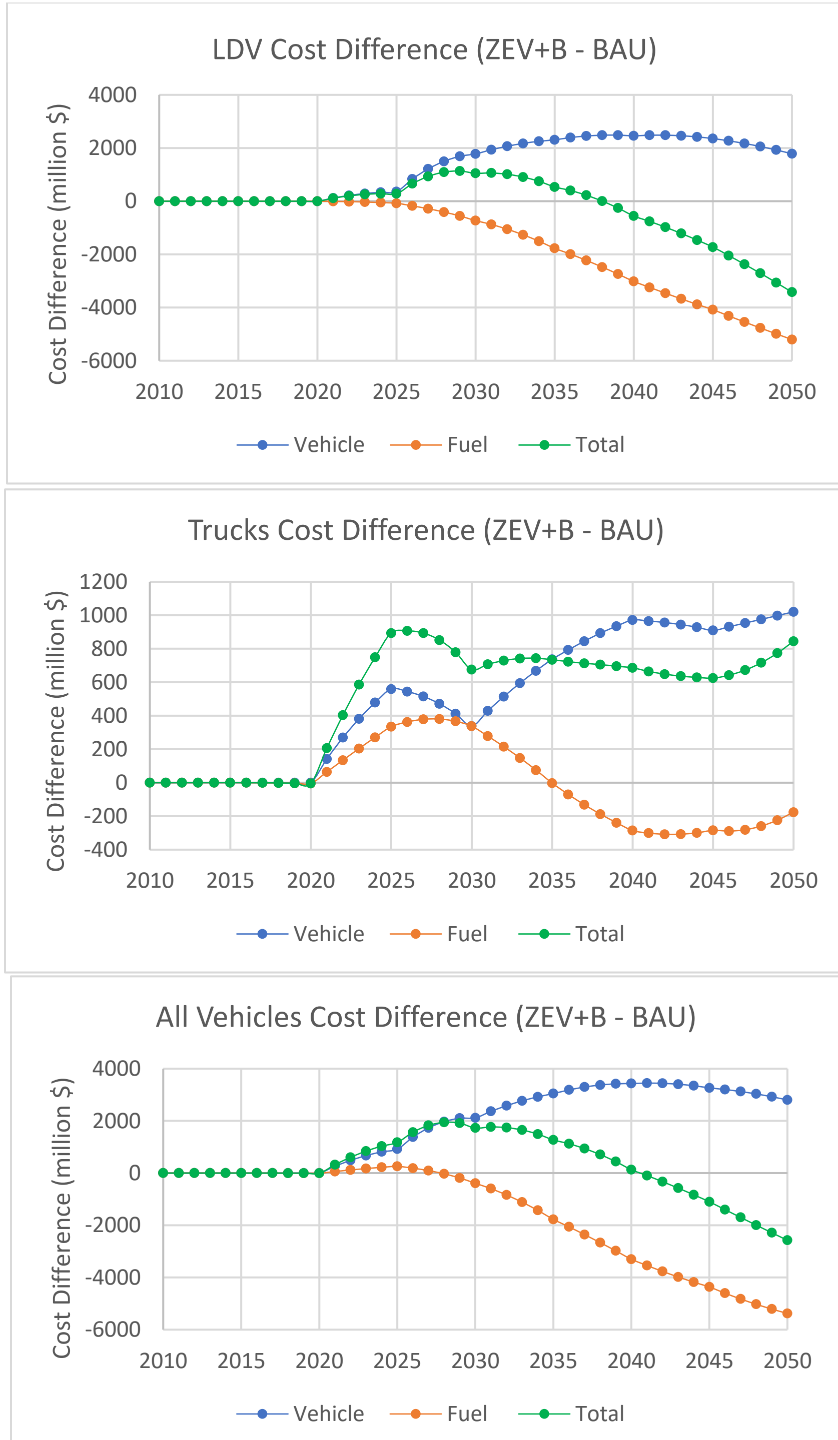
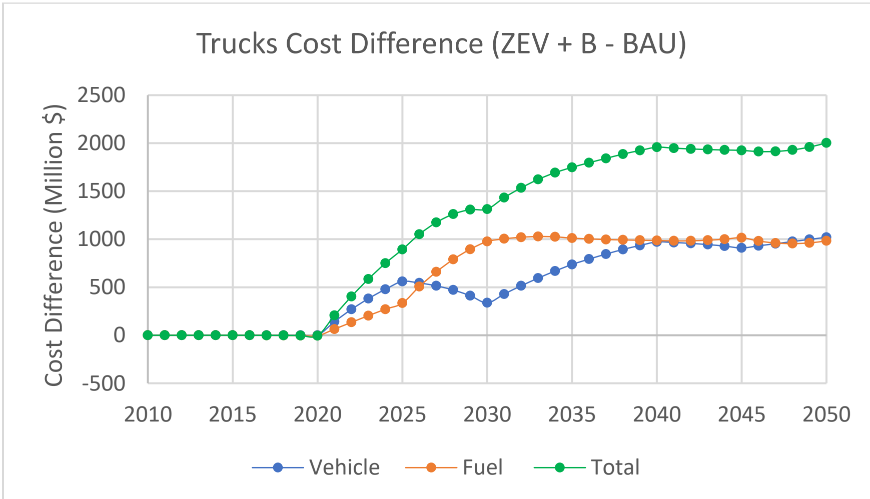


Figure 4-16. Cost differences between the ZEV+B and BAU scenarios (ZEV+B – BAU) for LDVs and trucks for the baseline fuel-price case.

Figure 4-17 (top) shows the cost difference between the ZEV+B and the BAU scenarios for trucks where biofuels are 20% more expensive than in the baseline fuel-price case. The fuel cost difference is never negative due to the increased cost of biofuels. Figure 4-17 (middle) shows the high biofuels cost case for the LDVs and trucks combined. The cost difference becomes negative slightly later here than in the baseline biofuel-price case (Figure 4-16 [bottom]).



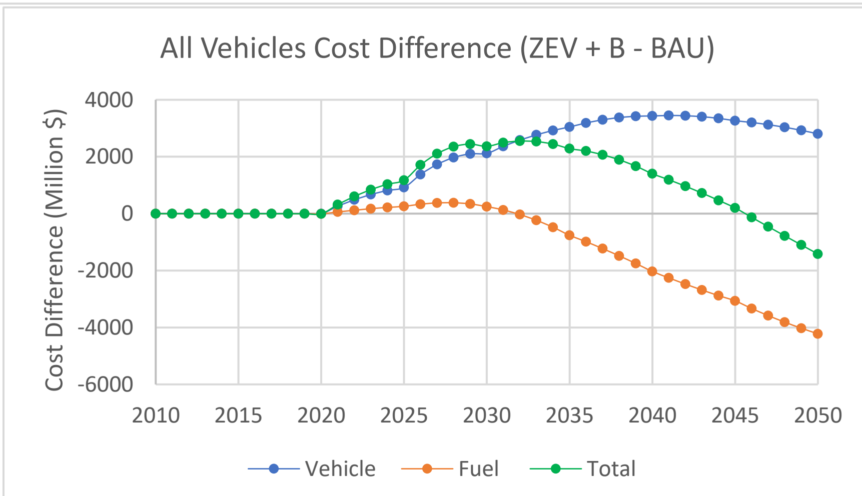


Figure 4-17. Cost differences between the ZEV+B and BAU scenarios (ZEV+B – BAU) in the high-price biofuels cases: for (A) trucks and (B) trucks + LDVs.

4.6.3.1 Costs in the Low-Price Fossil Fuel Case

The low-price fossil fuel case reduces gasoline and diesel fuel costs by 20% from the baseline-price case. The ZEV scenario shifts fuel use from petroleum products to natural gas, electricity, and hydrogen; therefore, when gasoline and diesel prices are lowered, the ZEV scenario fuel costs rise with respect to the BAU scenario. Figure 4-18 shows the LDV, truck, and combined vehicle, fuel, and total costs under the low fuel price case.

The shape of the fuel cost difference curve is roughly the same for each corresponding graph in Figure 4-15, but now the curve rises much higher in later years. In the case of LDVs the total cost difference reaches near zero by 2040, and in the combined case, the total cost difference reaches zero between 2040 and 2045 and flattens out after 2045.

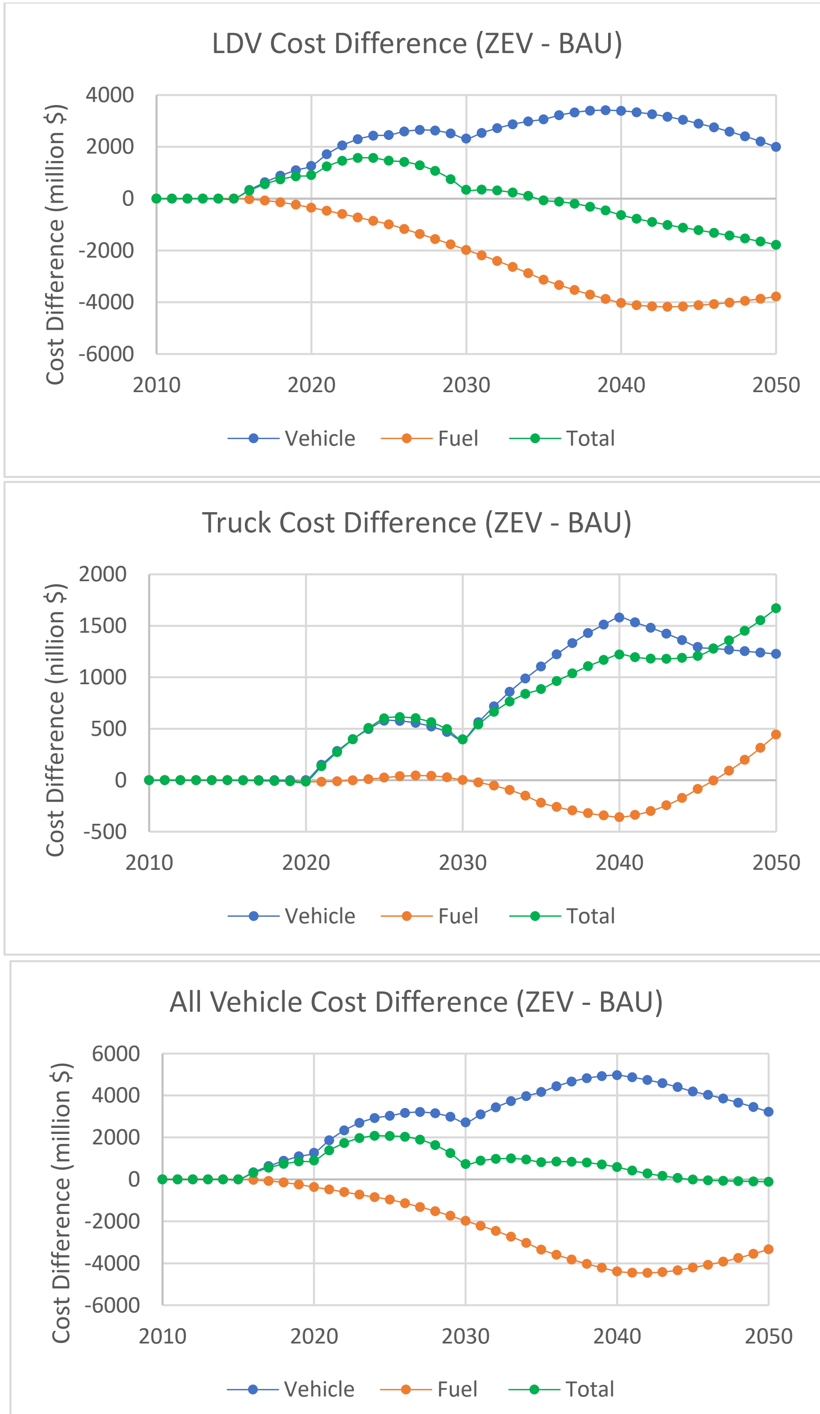


Figure 4-18. Cost differences between the ZEV and BAU scenarios (ZEV – BAU) for LDVs and trucks for the low-price fossil fuel case.

4.6.3.2 Costs in the Low Fuel Price and Low Hydrogen Price Case

As mentioned earlier, the cost of hydrogen for the ZEV scenario rises significantly after 2035 due to shifting production from relatively less expensive natural gas reformation to more expensive renewable production. By 2050, the costs reach $5.95/GGE (roughly the same as a kg of hydrogen). It is possible that new technologies or production processes could help reduce the cost of renewable hydrogen without sacrificing low carbon emissions. Figure 4-19 shows the results of the low-price fossil fuel case coupled with lower hydrogen fuel prices. In this case the price of hydrogen falls to $5.00/GGE by 2050.

With these lower hydrogen fuel prices, the fuel cost difference of ZEV−BAU for LDVs and trucks combined flattens out rather than turning upward. As the vehicle cost difference falls, the total cost difference does become negative between 2040 and 2045 and continues to become more negative (in other words, the ZEV scenario cost decreases).

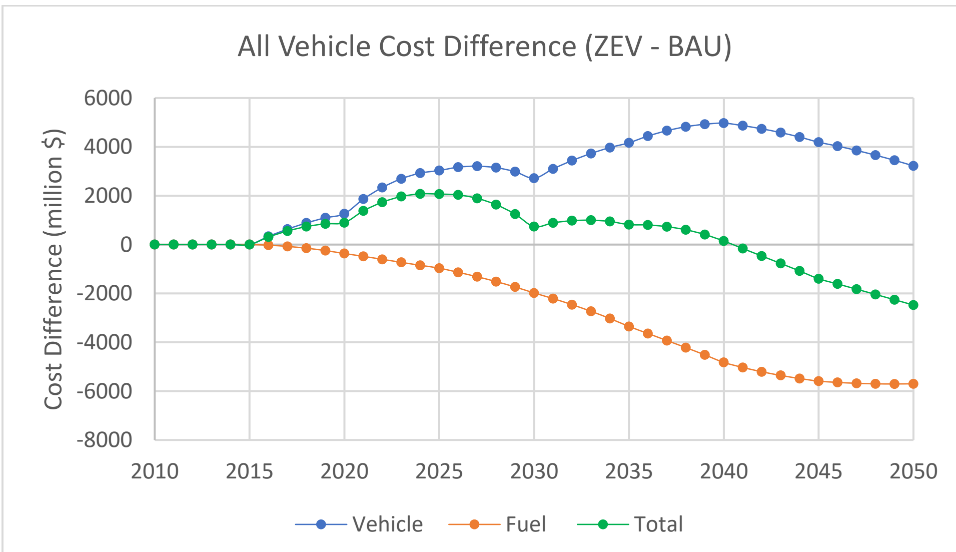


Figure 4-19. Cost differences between the ZEV and BAU scenarios (ZEV – BAU) for LDVs and trucks together in the low-price fossil fuel and low-price hydrogen case.

4.6.3.3 Costs in the High-Price Fossil Fuel Case

The high-price fossil fuel case increases gasoline and diesel fuel costs by 20% from the baseline case. When gasoline and diesel prices are increased, the BAU scenario fuel costs rise with respect to the ZEV scenario. Figure 4-20 shows the vehicle, fuel, and total costs for all vehicles under the high-price fossil fuel case.

In the baseline case the fuel cost difference initially fell but flattened near 2045 (Figure 4-15[bottom]). With 20% higher gasoline and diesel prices, the fuel cost difference between ZEV and BAU falls significantly further and does not rise toward 2050 (Figure 4-20). The fuel costs dominate the total cost difference, which becomes negative (less expensive ZEV scenario) near 2030 and continues to fall through 2050.

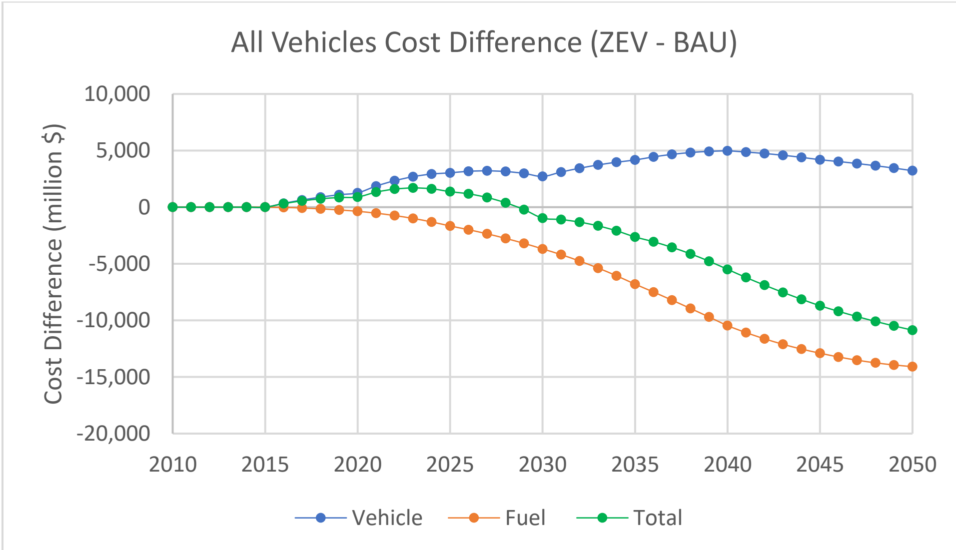


Figure 4-20. Cost difference between the ZEV and BAU scenarios (ZEV – BAU) for trucks in the high-price fossil fuel case.

In sum, the cost difference between the ZEV and BAU scenarios depends strongly on fuel prices. In all cases the vehicle, fuel, and total costs start off higher for the ZEV scenario than for the BAU scenario, but the relative value of gasoline and diesel fuel compared to new technology fuels (especially hydrogen) can produce large variances in the total cost difference curves. In some cases, the total cost of the ZEV scenario just barely falls below the cost of the BAU scenario around 2045; whereas, in other cases, the ZEV scenario total cost can fall below the BAU total cost near 2030 and continue to become significantly less expensive.

4.6.3.4 Costs in the high battery cost scenario

The high-cost battery case increases battery costs by 25%. All vehicles that use batteries (HEVs, BEVs, and FCEVs) will see an increase in cost. Figure 4-21 shows the cost for both LDVs and trucks in this case. The fuel cost difference does not change from the baseline ZEV–BAU case, since the fuel costs and the fuel economies remain the same. The difference in the vehicle cost peaks at almost $6 billion compared to the baseline case where the peak is below $5 billion.

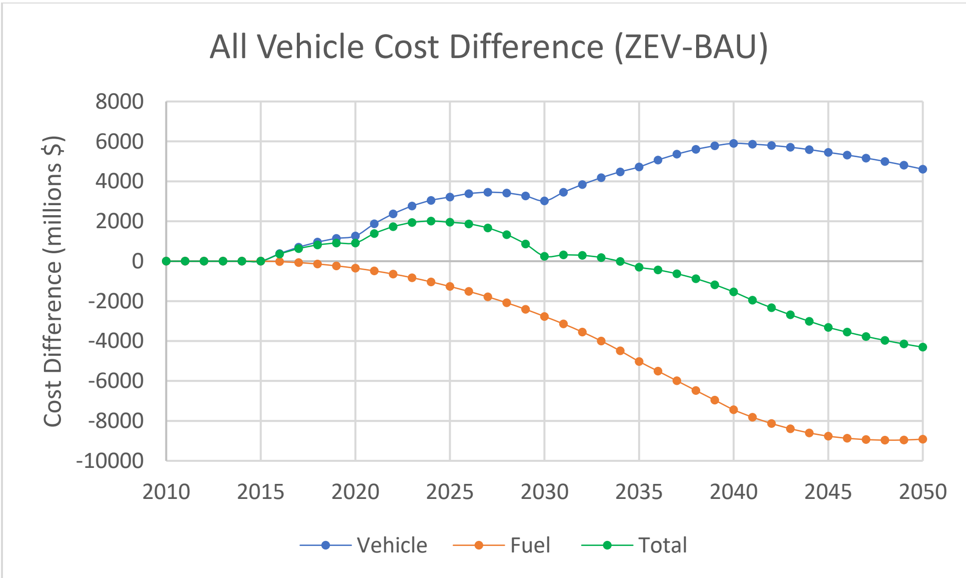


Figure 4-21. Cost difference between ZEV and BAU scenarios (ZEV − BAU) for all vehicles (LDVs and trucks) in the high-cost battery case.

4.6.3.5 Sensitivity of costs to fuel prices

The sensitivity analysis shows that, under various conditions, cost results can vary significantly. General conclusions for the scenarios are the following:

- All vehicle cost differences (ZEV − BAU) rise to a peak and then decrease in later years as the vehicle costs of advanced vehicle technologies decrease.
- Fuel cost differences (ZEV − BAU) initially fall below zero (ZEV less expensive) due to increased fuel economies for vehicles in the ZEV scenario. This cost difference generally continues to become more negative until the higher cost of renewable hydrogen diminishes the difference.
- The total cost difference is initially higher for ZEV scenarios but generally decreases such that the ZEV scenarios may be less expensive. For the case of baseline fuel prices with LDVs and trucks together, this cost difference becomes negative near 2030.

The truck ZEV+B scenario differs from the ZEV scenario primarily in fuel cost. The combined LDV and truck cost difference falls below zero roughly a decade later than for the ZEV scenario. The high-price diesel biofuel case increases the truck fuel cost difference (ZEV+B − BAU), and consequently, the total combined LDV and truck cost difference falls below zero a few years later, slightly after 2045.

In the low fossil fuel price case for the ZEV scenario, the truck total cost difference remains above zero (ZEV more expensive) through 2050 with the combined truck and LDV cost difference reaching zero near 2045 but remaining essentially flat through 2050.

In the low-price fossil fuel and low-price hydrogen case, the fuel cost difference does not increase as much as in the low-price fossil fuel case. The combined total cost difference falls below zero near 2040 and continues to fall through 2050.

In the high-price fossil fuel case, the combined total cost difference falls below zero roughly at the same time as in the baseline cost case (near 2030), but the total cost difference falls more rapidly, so cost savings for the ZEV scenario are significantly higher.

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6 Appendices

6.1 Appendix A – Market Share

The following tables show the percentage sales for cars and light-duty trucks for both the BAU, ZEV, and ZEV+B scenarios.

Table 10. Cars BAU scenario.

	2010	2015	2020	2025	2030	2035	2040	2045	2050
ICE	95.5%	91.8%	87.4%	81.5%	81.5%	81.5%	81.5%	81.5%	81.5%
DSL	0.3%	0.3%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
CNG	0.2%	0.2%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
HEV	4.0%	4.0%	3.0%	3.0%	3.0%	3.0%	3.0%	3.0%	3.0%
P10	0.0%	1.0%	1.8%	3.0%	3.0%	3.0%	3.0%	3.0%	3.0%
P40	0.0%	1.0%	1.8%	3.0%	3.0%	3.0%	3.0%	3.0%	3.0%
EV100	0.0%	1.2%	2.2%	4.0%	4.0%	4.0%	4.0%	4.0%	4.0%
EV200	0.0%	0.5%	3.7%	5.0%	5.0%	5.0%	5.0%	5.0%	5.0%
FC	0.0%	0.0%	0.1%	0.5%	0.5%	0.5%	0.5%	0.5%	0.5%

Table 11. Light-duty trucks BAU scenario.

	2010	2015	2020	2025	2030	2035	2040	2045	2050
ICE	96.5%	94.8%	95.3%	93.3%	93.3%	93.3%	93.3%	93.3%	93.3%
DSL	0.5%	0.5%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
CNG	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
HEV	3.0%	4.0%	3.0%	3.0%	3.0%	3.0%	3.0%	3.0%	3.0%
P10	0.0%	0.2%	0.4%	0.8%	0.8%	0.8%	0.8%	0.8%	0.8%
P40	0.0%	0.1%	0.2%	0.4%	0.4%	0.4%	0.4%	0.4%	0.4%
EV100	0.0%	0.0%	0.5%	1.0%	1.0%	1.0%	1.0%	1.0%	1.0%
EV200	0.0%	0.2%	0.5%	1.0%	1.0%	1.0%	1.0%	1.0%	1.0%
FC	0.0%	0.3%	0.1%	0.5%	0.5%	0.5%	0.5%	0.5%	0.5%

Table 12. Cars ZEV scenario.

	2010	2015	2020	2025	2030	2035	2040	2045	2050
ICE	95.5%	91.8%	70.0%	45.6%	32.5%	11.0%	0.0%	0.0%	0.0%
DSL	0.3%	0.3%	0.3%	0.1%	0.0%	0.0%	0.0%	0.0%	0.0%
CNG	0.2%	0.2%	0.2%	0.1%	0.0%	0.0%	0.0%	0.0%	0.0%
HEV	4.0%	4.0%	16.0%	30.0%	30.0%	33.0%	15.0%	3.0%	0.0%
P10	0.0%	1.0%	3.0%	2.0%	0.0%	0.0%	0.0%	0.0%	0.0%
P40	0.0%	1.0%	4.0%	7.0%	15.0%	20.0%	25.0%	15.0%	0.0%
EV100	0.0%	1.2%	2.0%	2.0%	0.0%	0.0%	0.0%	0.0%	0.0%
EV200	0.0%	0.5%	4.0%	12.2%	17.5%	25.5%	40.0%	55.0%	65.0%
FC	0.0%	0.0%	0.5%	1.0%	5.0%	10.5%	20.0%	27.0%	35.0%

Table 13. Light-duty trucks ZEV scenario.

	2010	2015	2020	2025	2030	2035	2040	2045	2050
ICE	96.5%	94.8%	83.5%	60.8%	44.0%	21.0%	4.0%	2.0%	0.0%
DSL	0.5%	0.5%	0.5%	0.2%	0.0%	0.0%	0.0%	0.0%	0.0%
CNG	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
HEV	3.0%	4.0%	10.0%	25.0%	30.0%	28.0%	12.0%	1.0%	0.0%
P10	0.0%	0.2%	3.0%	2.0%	0.0%	0.0%	0.0%	0.0%	0.0%
P40	0.0%	0.1%	1.0%	5.0%	10.0%	20.0%	30.0%	20.0%	5.0%
EV100	0.0%	0.0%	0.5%	2.0%	0.0%	0.0%	0.0%	0.0%	0.0%
EV200	0.0%	0.2%	1.0%	3.0%	12.0%	18.0%	27.0%	35.0%	45.0%
FC	0.0%	0.3%	0.5%	2.0%	4.0%	13.0%	27.0%	42.0%	50.0%

Table 14. Cars ZEV+B scenario.

	2010	2015	2020	2025	2030	2035	2040	2045	2050
ICE	95.5%	91.8%	87.4%	77.8%	65.0%	51.0%	35.0%	22.1%	12.0%
DSL	0.3%	0.3%	0.0%	0.1%	0.0%	0.0%	0.0%	0.0%	0.0%
CNG	0.2%	0.2%	0.0%	0.1%	0.0%	0.0%	0.0%	0.0%	0.0%
HEV	4.0%	4.0%	3.0%	3.0%	3.0%	3.0%	3.0%	3.0%	3.0%
P10	0.0%	1.0%	1.8%	4.0%	0.0%	0.0%	0.0%	0.0%	0.0%
P40	0.0%	1.0%	1.8%	4.0%	6.7%	9.0%	10.0%	7.0%	5.0%
EV100	0.0%	1.2%	2.2%	4.0%	0.0%	0.0%	0.0%	0.0%	0.0%
EV200	0.0%	0.5%	3.7%	6.0%	17.0%	25.0%	34.1%	42.0%	48.0%
FC	0.0%	0.0%	0.1%	1.0%	8.3%	12.0%	17.9%	25.9%	32.0%

Table 15. Light-duty trucks ZEV+B scenario.

	2010	2015	2020	2025	2030	2035	2040	2045	2050
ICE	96.5%	94.8%	95.3%	90.7%	79.0%	63.0%	45.0%	25.2%	12.0%
DSL	0.5%	0.5%	0.0%	0.2%	0.0%	0.0%	0.0%	0.0%	0.0%
CNG	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
HEV	3.0%	4.0%	3.0%	3.0%	3.0%	3.0%	3.0%	3.0%	3.0%
P10	0.0%	0.2%	0.4%	0.8%	0.0%	0.0%	0.0%	0.0%	0.0%
P40	0.0%	0.1%	0.2%	1.5%	5.3%	8.5%	11.0%	12.0%	9.0%
EV100	0.0%	0.0%	0.5%	1.0%	0.0%	0.0%	0.0%	0.0%	0.0%
EV200	0.0%	0.2%	0.5%	1.7%	4.5%	14.0%	25.0%	36.0%	44.0%
FC	0.0%	0.3%	0.1%	1.0%	8.2%	11.5%	16.0%	23.8%	32.0%

ICE – Internal combustion engine; DSL - Diesel; CNG – Compressed natural gas vehicle; HEV - Hybrid; P10 - Plug-in 10 mile range; P40 - Plug-in 40 mile range; EV100 - Battery electric 100 mile range; EV200 - Battery electric 200 mile range; FC - Fuel Cell; FCP10 - Fuel Cell plug-in hybrid 10 mile range; FCP40 - Fuel Cell plug-in hybrid 40 mile range

The following tables show the percentage sales for all truck types for the three scenarios – BAU, ZEV, and ZEV plus biofuels.

Table 16. Long Haul BAU scenario.

	2000	2010	2015	2020	2025	2030	2035	2040	2045	2050
Diesel	100.0%	100.0%	100.0%	99.9%	99.9%	99.9%	99.5%	97.7%	91.7%	83.8%
Hybrid	0.0%	0.0%	0.0%	0.1%	0.1%	0.1%	0.5%	2.3%	8.2%	16.0%
LNG CI	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
LNG SI	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
CNG SI	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.1%
Fuel Cell	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
BEV	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%

Table 17. Short Haul BAU scenario.

	2000	2010	2015	2020	2025	2030	2035	2040	2045	2050
Diesel	100.0%	100.0%	100.0%	99.9%	99.6%	97.9%	92.2%	83.6%	73.1%	59.6%
Hybrid	0.0%	0.0%	0.0%	0.1%	0.3%	1.8%	6.8%	12.9%	18.2%	22.2%
LNG CI	0.0%	0.0%	0.0%	0.0%	0.1%	0.2%	0.8%	3.3%	8.2%	15.4%
LNG SI	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
CNG SI	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
Fuel Cell	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.1%	0.1%	0.4%
BEV	0.0%	0.0%	0.0%	0.0%	0.0%	0.1%	0.1%	0.2%	0.4%	2.5%

Table 18. Heavy-duty vocational BAU scenario.

	2000	2010	2015	2020	2025	2030	2035	2040	2045	2050
Diesel	99.5%	99.5%	99.6%	99.2%	98.7%	96.9%	94.8%	85.7%	72.4%	52.2%
Hybrid	0.0%	0.0%	0.0%	0.1%	0.3%	0.8%	2.1%	4.4%	9.6%	24.3%
CNG SI	0.5%	0.5%	0.3%	0.7%	1.1%	2.2%	2.8%	8.7%	16.2%	21.2%
Fuel Cell	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.1%	0.2%	0.3%
BEV	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.2%	1.1%	1.6%	2.0%

Table 19. Medium-duty vocational BAU scenario.

	2000	2010	2015	2020	2025	2030	2035	2040	2045	2050
Diesel	100.0%	99.8%	99.7%	99.1%	94.9%	76.4%	60.4%	47.7%	35.8%	27.9%
Hybrid	0.0%	0.0%	0.1%	0.6%	3.5%	16.3%	23.4%	27.0%	26.4%	25.0%
CNG SI	0.0%	0.2%	0.2%	0.3%	1.6%	7.1%	15.2%	19.9%	24.0%	27.2%
Fuel Cell	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.1%	0.4%	1.1%	3.0%
BEV	0.0%	0.0%	0.0%	0.0%	0.0%	0.2%	0.9%	5.0%	12.8%	17.0%

Table 20. Medium-duty urban BAU scenario.

	2000	2010	2015	2020	2025	2030	2035	2040	2045	2050
Diesel	86.2%	86.4%	81.4%	69.9%	61.1%	48.7%	41.3%	36.7%	31.4%	26.0%
Gasoline	12.8%	9.9%	14.5%	20.4%	21.9%	22.1%	21.9%	21.4%	19.5%	17.0%
Hybrid	0.0%	0.5%	0.6%	0.8%	2.9%	7.9%	14.0%	20.9%	25.7%	28.1%
CNG	1.0%	3.2%	3.4%	8.9%	13.8%	20.7%	21.5%	19.2%	19.3%	18.3%
Fuel Cell	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.1%	0.1%	0.3%	1.1%
BEV	0.0%	0.0%	0.0%	0.0%	0.3%	0.5%	1.2%	1.7%	3.7%	9.4%

Table 21. Urban Buses BAU scenario.

	2000	2010	2015	2020	2025	2030	2035	2040	2045	2050
Diesel	65.3%	65.3%	45.2%	35.6%	7.1%	2.6%	1.2%	0.4%	0.2%	0.2%
Hybrid	2.8%	2.8%	7.5%	15.4%	31.5%	21.5%	13.0%	5.5%	2.6%	2.1%
CNG SI	32.0%	32.0%	46.3%	45.0%	16.5%	20.3%	8.6%	1.9%	0.9%	0.7%
Fuel Cell	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.1%	0.4%
BEV	0.0%	0.0%	1.0%	4.0%	44.9%	55.6%	77.2%	92.1%	96.1%	96.6%

Table 22. Other Buses BAU scenario.

	2000	2010	2015	2020	2025	2030	2035	2040	2045	2050
Diesel	100.0%	99.6%	99.4%	99.3%	98.9%	95.3%	82.8%	64.7%	52.8%	41.4%
Hybrid	0.0%	0.0%	0.0%	0.1%	0.2%	0.3%	0.9%	2.6%	6.3%	10.7%
CNG SI	0.0%	0.4%	0.5%	0.6%	0.9%	4.4%	16.2%	32.2%	39.1%	41.4%
Fuel Cell	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.1%	0.2%	0.4%
BEV	0.0%	0.0%	0.0%	0.0%	0.1%	0.1%	0.1%	0.5%	1.8%	6.2%

Table 23. HD Pick-Ups and Vans BAU scenario.

	2000	2010	2015	2020	2025	2030	2035	2040	2045	2050
Diesel	70.7%	70.7%	66.1%	59.8%	52.0%	45.7%	40.6%	36.3%	32.1%	27.4%
Gasoline	29.3%	29.3%	29.3%	31.3%	32.3%	30.7%	29.1%	27.3%	25.0%	22.0%
Hybrid	0.0%	0.0%	4.1%	7.6%	12.5%	17.2%	20.0%	21.9%	22.5%	22.2%
CNG	0.0%	0.0%	0.5%	1.4%	3.1%	6.2%	9.6%	11.9%	13.8%	14.4%
Fuel Cell	0.0%	0.0%	0.0%	0.0%	0.1%	0.1%	0.4%	1.3%	3.4%	7.3%
BEV	0.0%	0.0%	0.0%	0.0%	0.1%	0.1%	0.4%	1.2%	3.2%	6.6%

Table 24. Long Haul ZEV scenario.

	2000	2010	2015	2020	2025	2030	2035	2040	2045	2050
Diesel	100.0%	100.0%	100.0%	99.9%	97.0%	92.0%	79.3%	56.0%	32.4%	20.0%
Hybrid	0.0%	0.0%	0.0%	0.1%	0.1%	0.1%	0.2%	0.0%	0.0%	0.0%
LNG CI	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
LNG SI	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
CNG SI	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
Fuel Cell	0.0%	0.0%	0.0%	0.0%	2.9%	7.9%	20.4%	44.0%	67.6%	80.0%
BEV	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%

Table 25. Short Haul ZEV scenario.

	2000	2010	2015	2020	2025	2030	2035	2040	2045	2050
Diesel	100.0%	100.0%	100.0%	99.9%	96.2%	82.8%	48.6%	15.0%	3.0%	0.5%
Hybrid	0.0%	0.0%	0.0%	0.1%	0.3%	1.0%	1.3%	1.1%	0.5%	0.2%
LNG CI	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
LNG SI	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
CNG SI	0.0%	0.0%	0.0%	0.0%	0.0%	0.1%	0.0%	0.0%	0.1%	0.0%
Fuel Cell	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	15.4%	47.5%	60.9%	64.0%
BEV	0.0%	0.0%	0.0%	0.0%	3.5%	16.1%	34.7%	36.4%	35.5%	35.2%

Table 26. Heavy-duty vocational ZEV scenario.

	2000	2010	2015	2020	2025	2030	2035	2040	2045	2050
Diesel	99.5%	99.5%	99.6%	99.2%	95.3%	81.7%	47.0%	7.4%	0.0%	0.0%
Hybrid	0.0%	0.0%	0.0%	0.1%	0.1%	0.1%	0.1%	0.1%	0.0%	0.0%
CNG SI	0.5%	0.5%	0.3%	0.7%	1.1%	2.2%	2.8%	8.7%	3.5%	0.7%
Fuel Cell	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.1%	0.1%
BEV	0.0%	0.0%	0.0%	0.0%	3.5%	16.0%	50.0%	83.8%	96.4%	99.2%

Table 27. Medium-duty vocational ZEV scenario.

	2000	2010	2015	2020	2025	2030	2035	2040	2045	2050
Diesel	100.0%	99.8%	99.7%	99.1%	91.6%	64.7%	30.6%	8.1%	1.5%	0.4%
Hybrid	0.0%	0.0%	0.1%	0.6%	3.3%	13.4%	11.9%	4.6%	1.1%	0.3%
CNG SI	0.0%	0.2%	0.2%	0.3%	1.5%	5.7%	7.5%	3.4%	1.0%	0.4%
Fuel Cell	0.0%	0.0%	0.0%	0.0%	0.1%	0.2%	2.3%	15.9%	23.3%	35.4%
BEV	0.0%	0.0%	0.0%	0.0%	3.6%	16.0%	47.7%	68.0%	73.1%	63.6%

Table 28. Medium-duty urban ZEV scenario.

	2000	2010	2015	2020	2025	2030	2035	2040	2045	2050
Diesel	86.2%	86.4%	81.4%	69.9%	59.1%	41.1%	24.0%	6.0%	1.0%	0.0%
Gasoline	12.8%	9.9%	14.5%	20.4%	21.1%	18.7%	10.0%	4.0%	0.0%	0.0%
Hybrid	0.0%	0.5%	0.6%	0.8%	2.8%	6.5%	6.0%	2.0%	1.5%	0.0%
CNG	1.0%	3.2%	3.4%	8.9%	13.4%	17.5%	10.0%	5.0%	1.6%	0.7%
Fuel Cell	0.0%	0.0%	0.0%	0.0%	0.1%	0.9%	10.0%	29.0%	36.0%	38.3%
BEV	0.0%	0.0%	0.0%	0.0%	3.5%	15.2%	40.0%	54.0%	59.9%	61.0%

Table 29. Urban Buses ZEV scenario.

	2000	2010	2015	2020	2025	2030	2035	2040	2045	2050
Diesel	65.3%	65.3%	45.2%	35.6%	2.0%	0.0%	0.0%	0.0%	0.0%	0.0%
Hybrid	2.8%	2.8%	7.5%	15.4%	5.0%	0.0%	0.0%	0.0%	0.0%	0.0%
CNG SI	32.0%	32.0%	46.3%	45.0%	24.0%	1.0%	0.0%	0.0%	0.0%	0.0%
Fuel Cell	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
BEV	0.0%	0.0%	1.0%	4.0%	69.0%	99.0%	100.0%	100.0%	100.0%	100.0%

Table 30. Other Buses ZEV scenario.

	2000	2010	2015	2020	2025	2030	2035	2040	2045	2050
Diesel	100.0%	99.6%	99.4%	99.3%	95.8%	81.8%	45.7%	13.4%	2.7%	0.5%
Hybrid	0.0%	0.0%	0.0%	0.1%	0.2%	0.2%	0.4%	0.3%	0.1%	0.0%
CNG SI	0.0%	0.4%	0.5%	0.6%	0.5%	1.9%	3.9%	2.4%	0.8%	0.2%
Fuel Cell	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.2%	0.9%	3.4%	11.5%
BEV	0.0%	0.0%	0.0%	0.0%	3.5%	16.0%	49.7%	83.0%	93.1%	87.7%

Table 31. HD Pick-Ups and Vans ZEV scenario.

	2000	2010	2015	2020	2025	2030	2035	2040	2045	2050
Diesel	70.7%	70.7%	66.1%	59.8%	50.2%	38.5%	20.5%	6.2%	2.6%	0.0%
Gasoline	29.3%	29.3%	29.3%	31.3%	31.2%	25.8%	14.7%	4.7%	2.0%	0.7%
Hybrid	0.0%	0.0%	4.1%	7.6%	12.0%	14.5%	10.1%	3.8%	0.0%	0.0%
CNG	0.0%	0.0%	0.5%	1.4%	3.0%	5.1%	4.6%	1.9%	0.0%	0.0%
Fuel Cell	0.0%	0.0%	0.0%	0.0%	1.7%	7.7%	26.1%	43.9%	46.4%	49.3%
BEV	0.0%	0.0%	0.0%	0.0%	1.9%	8.4%	23.9%	39.4%	49.0%	50.0%

Table 32. Long Haul ZEV+B scenario.

	2000	2010	2015	2020	2025	2030	2035	2040	2045	2050
Diesel	100.0%	100.0%	100.0%	99.9%	97.9%	94.9%	86.7%	78.0%	67.0%	60.0%
Hybrid	0.0%	0.0%	0.0%	0.1%	0.1%	0.1%	0.2%	0.0%	0.0%	0.0%
LNG CI	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
LNG SI	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
CNG SI	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
Fuel Cell	0.0%	0.0%	0.0%	0.0%	2.0%	5.0%	13.0%	22.0%	33.0%	40.0%
BEV	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%

Table 33. Short Haul ZEV+B scenario.

	2000	2010	2015	2020	2025	2030	2035	2040	2045	2050
Diesel	100.0%	100.0%	100.0%	99.9%	96.4%	85.0%	70.2%	55.8%	45.7%	39.8%
Hybrid	0.0%	0.0%	0.0%	0.1%	0.3%	1.0%	1.3%	1.1%	0.5%	0.2%
LNG CI	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
LNG SI	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
CNG SI	0.0%	0.0%	0.0%	0.0%	0.0%	0.1%	0.0%	0.0%	0.1%	0.0%
Fuel Cell	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	8.8%	24.4%	33.9%	38.7%
BEV	0.0%	0.0%	0.0%	0.0%	3.3%	13.9%	19.7%	18.7%	19.8%	21.3%

Table 34. Heavy-duty vocational ZEV+B scenario.

	2000	2010	2015	2020	2025	2030	2035	2040	2045	2050
Diesel	99.5%	99.5%	99.6%	99.2%	95.6%	83.8%	68.5%	48.1%	30.0%	18.8%
Hybrid	0.0%	0.0%	0.0%	0.1%	0.0%	0.1%	0.1%	0.1%	0.0%	0.0%
CNG SI	0.5%	0.5%	0.3%	0.7%	1.1%	2.2%	2.8%	8.7%	16.2%	21.2%
Fuel Cell	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.1%
BEV	0.0%	0.0%	0.0%	0.0%	3.3%	13.9%	28.5%	43.1%	53.7%	59.9%

Table 35. Medium-duty vocational ZEV+B scenario.

	2000	2010	2015	2020	2025	2030	2035	2040	2045	2050
Diesel	100.0%	99.8%	99.7%	99.1%	91.9%	67.1%	52.1%	48.9%	44.2%	39.3%
Hybrid	0.0%	0.0%	0.1%	0.6%	3.3%	13.3%	11.9%	4.6%	1.1%	0.3%
CNG SI	0.0%	0.2%	0.2%	0.3%	1.5%	5.7%	7.5%	3.4%	1.0%	0.4%
Fuel Cell	0.0%	0.0%	0.0%	0.0%	0.0%	0.2%	1.3%	8.2%	13.0%	21.4%
BEV	0.0%	0.0%	0.0%	0.0%	3.3%	13.7%	27.2%	34.9%	40.7%	38.6%

Table 36. Medium-duty urban ZEV+B scenario.

	2000	2010	2015	2020	2025	2030	2035	2040	2045	2050
Diesel	86.2%	86.4%	81.4%	69.9%	59.4%	38.9%	33.0%	30.2%	24.7%	19.0%
Gasoline	12.8%	9.9%	14.5%	20.4%	21.1%	18.7%	10.1%	6.3%	4.4%	4.0%
Hybrid	0.0%	0.5%	0.6%	0.8%	2.8%	6.5%	8.4%	5.4%	2.2%	2.0%
CNG	1.0%	3.2%	3.4%	8.9%	13.4%	22.0%	20.0%	15.0%	15.0%	15.0%
Fuel Cell	0.0%	0.0%	0.0%	0.0%	0.1%	0.8%	5.7%	13.6%	19.5%	23.6%
BEV	0.0%	0.0%	0.0%	0.0%	3.2%	13.1%	22.8%	29.5%	34.2%	36.4%

Table 37. Urban Buses ZEV+B scenario.

	2000	2010	2015	2020	2025	2030	2035	2040	2045	2050
Diesel	65.3%	65.3%	45.2%	35.6%	2.0%	0.0%	0.0%	0.0%	0.0%	0.0%
Hybrid	2.8%	2.8%	7.5%	15.4%	5.0%	0.0%	0.0%	0.0%	0.0%	0.0%
CNG SI	32.0%	32.0%	46.3%	45.0%	24.0%	1.0%	0.0%	0.0%	0.0%	0.0%
Fuel Cell	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
BEV	0.0%	0.0%	1.0%	4.0%	69.0%	99.0%	100.0%	100.0%	100.0%	100.0%

Table 38. Other Buses ZEV+B scenario.

	2000	2010	2015	2020	2025	2030	2035	2040	2045	2050
Diesel	100.0%	99.6%	99.4%	99.3%	96.0%	84.0%	67.2%	54.2%	45.4%	39.7%
Hybrid	0.0%	0.0%	0.0%	0.1%	0.2%	0.2%	0.4%	0.3%	0.1%	0.0%
CNG SI	0.0%	0.4%	0.5%	0.6%	0.5%	1.9%	3.9%	2.4%	0.8%	0.2%
Fuel Cell	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.1%	0.4%	1.9%	7.0%
BEV	0.0%	0.0%	0.0%	0.0%	3.3%	13.9%	28.4%	42.7%	51.8%	53.0%

Table 39. HD Pick-Ups and Vans ZEV+B scenario.

	2000	2010	2015	2020	2025	2030	2035	2040	2045	2050
Diesel	70.7%	70.7%	66.1%	59.8%	50.5%	38.6%	36.7%	39.2%	34.8%	31.7%
Gasoline	29.3%	29.3%	29.3%	31.3%	31.2%	28.0%	20.0%	12.0%	7.0%	5.0%
Hybrid	0.0%	0.0%	4.1%	7.6%	12.0%	14.5%	10.1%	3.8%	3.5%	3.4%
CNG	0.0%	0.0%	0.5%	1.4%	3.0%	5.1%	4.6%	1.9%	1.0%	0.0%
Fuel Cell	0.0%	0.0%	0.0%	0.0%	1.6%	6.6%	14.9%	22.7%	26.1%	29.8%
BEV	0.0%	0.0%	0.0%	0.0%	1.7%	7.3%	13.6%	20.4%	27.6%	30.2%

6.2 Appendix B – Truck Cost

The following figures show the capital cost of trucks for each truck type and technology through 2050.

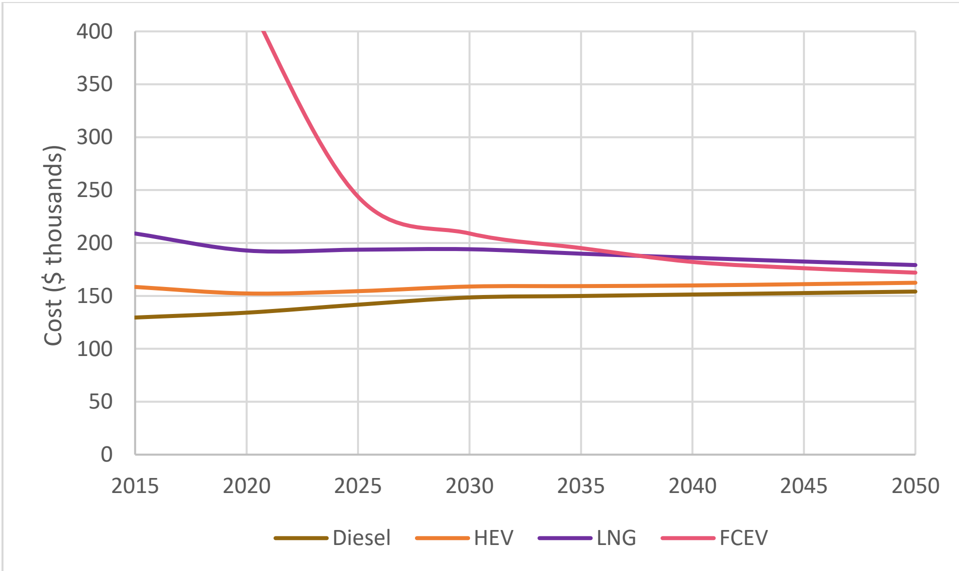

Figure 6-1. Long-haul vehicle cost as a function of technology through 2050.

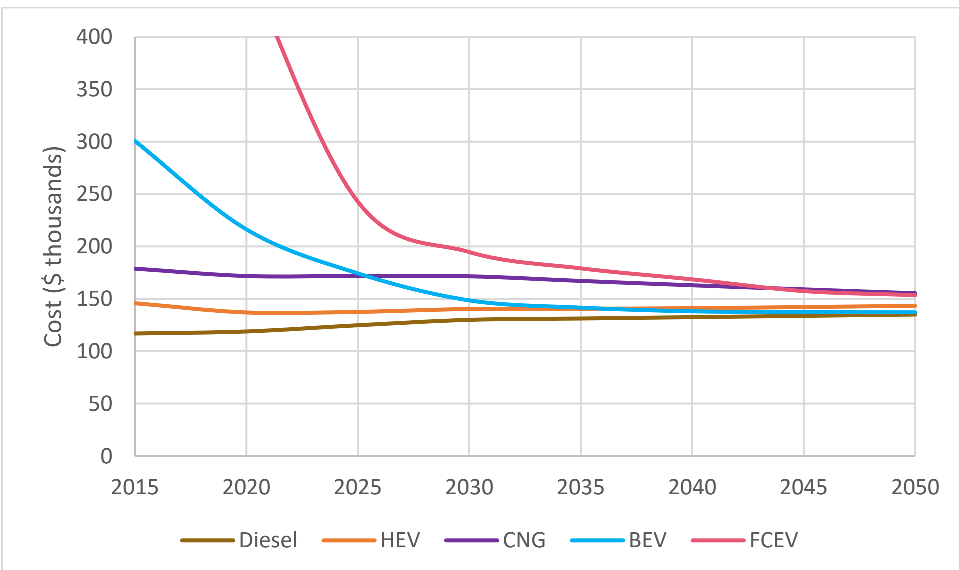

Figure 6-2. Short-haul vehicle cost as a function of technology through 2050.

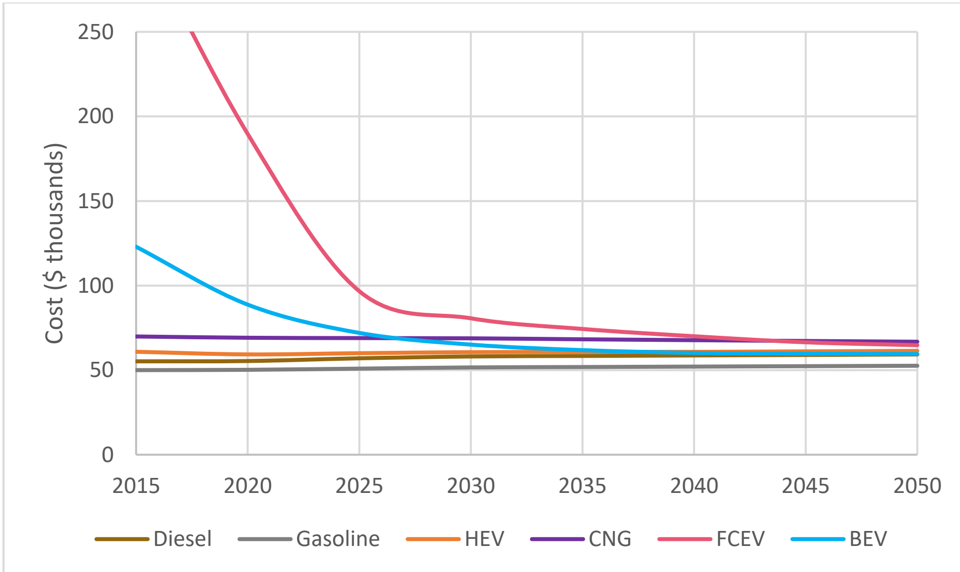

Figure 6-3. Medium-duty urban vehicle Cost as a function of technology through 2050.

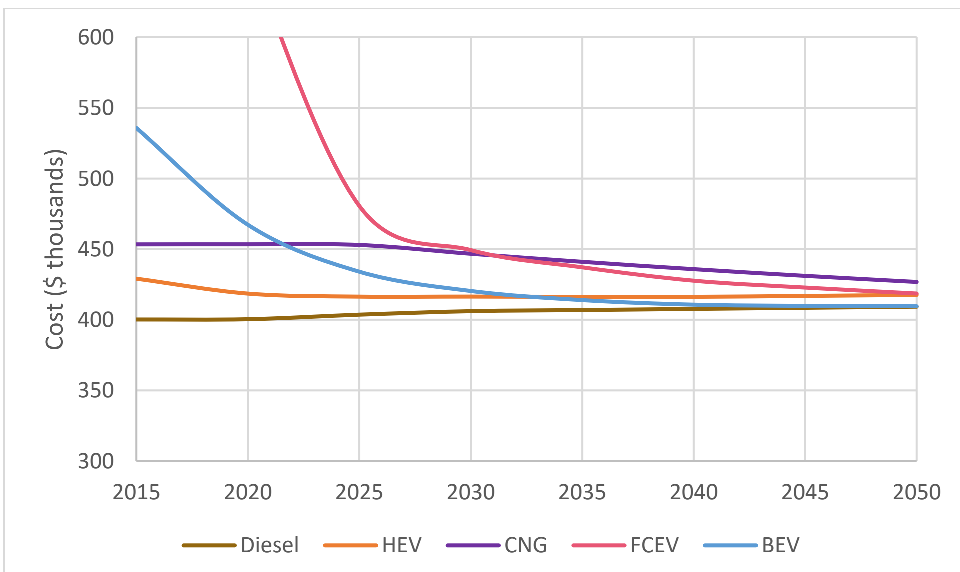

Figure 6-4. Urban bus cost as a function of technology through 2050.

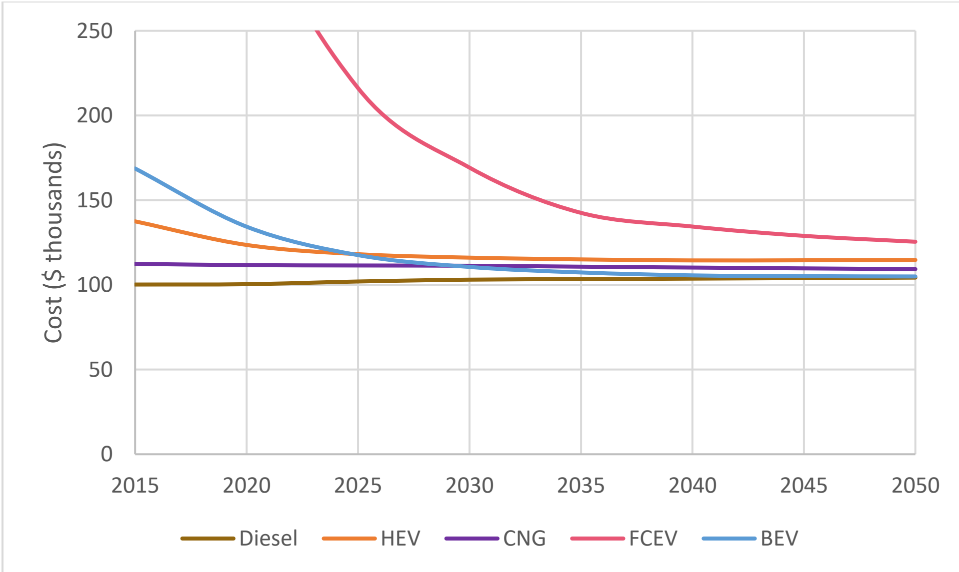

Figure 6-5. Other bus cost as a function of technology through 2050.

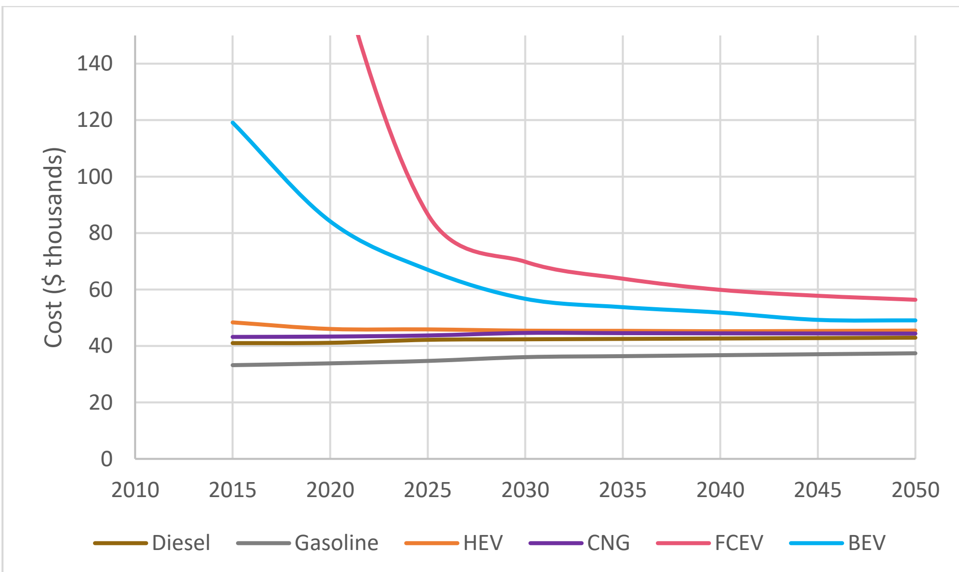

Figure 6-6. Heavy-duty pickup and van cost as a function of technology through 2050.

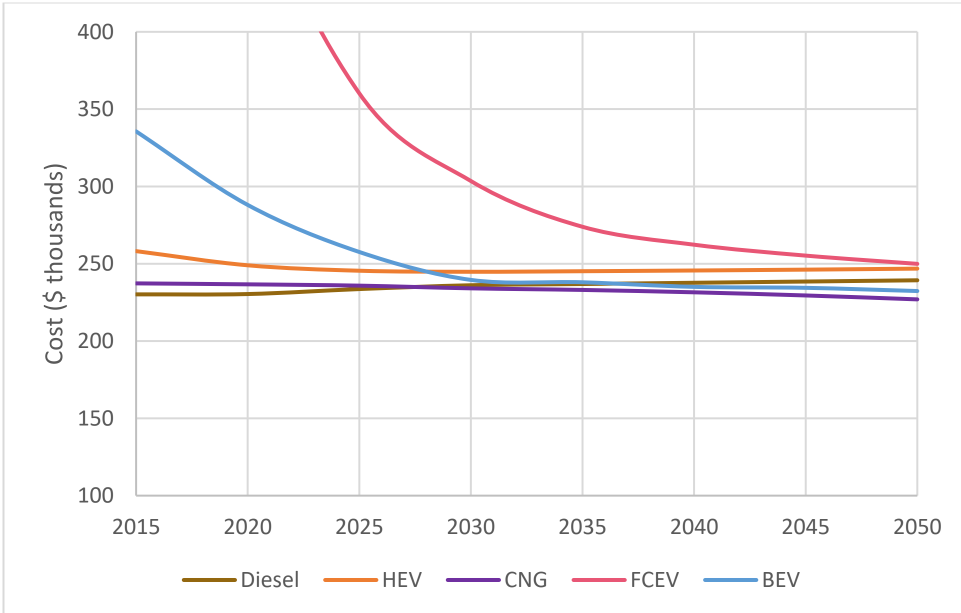

Figure 6-7. Heavy-duty vocational cost as a function of technology through 2050.

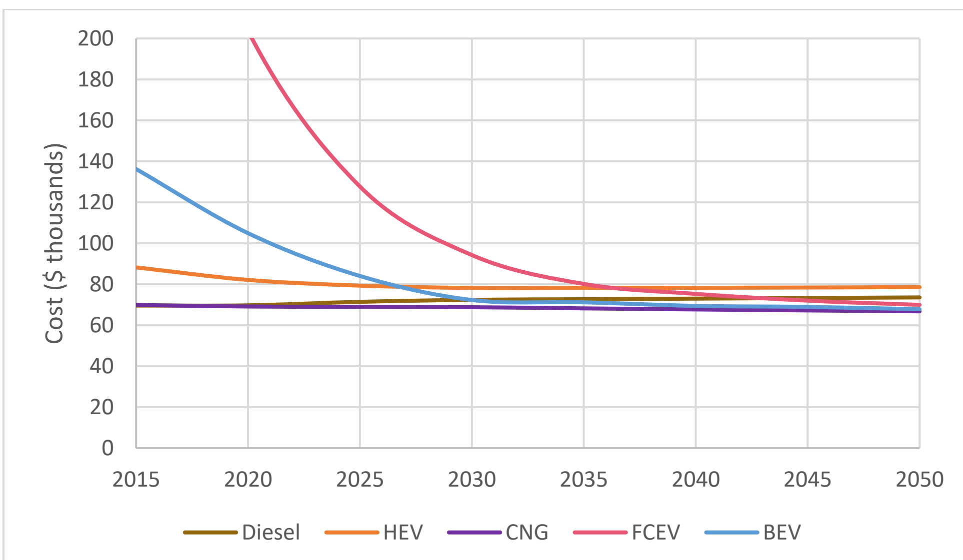

Figure 6-8. Medium-duty vocational cost as a function of technology through 2050.

6.3 Appendix C. Fuel Economy Tables

The following tables show the vehicle fuel economy in mpgge for each LDV and truck type and technology through 2050.

Table 40. Car Fuel Economy Inputs (mpgge).

	2000	2010	2015	2020	2025	2030	2035	2040	2045	2050
ICE	28.5	28.5	33.0	37.6	39.7	42.2	44.1	46.3	48.6	48.6
DSL	34.8	34.8	39.6	43.9	45.7	47.7	49.7	52.0	54.4	54.4
CNG	28.5	28.5	33.0	37.6	39.7	42.2	44.1	46.3	48.6	48.6
HEV	43.4	43.4	47.5	53.4	55.7	58.1	60.2	62.5	64.9	64.9
P10-gas	42.3	42.3	47.0	52.4	54.6	56.9	58.9	61.0	63.3	63.3
P10-elec	153.6	153.6	155.6	161.7	163.8	166.0	166.8	167.7	168.6	168.6
P40-gas	40.1	40.1	44.7	48.6	48.7	48.7	49.9	51.2	52.5	52.5
P40-elec	152.3	152.3	161.2	163.0	166.3	169.7	169.6	169.6	169.6	169.6
EV100	117.7	117.7	137.9	144.5	150.1	156.1	157.2	158.4	159.5	159.5
EV200	116.0	116.0	128.9	137.0	144.2	152.3	153.5	154.7	155.9	155.9
FC	57.5	57.5	61.5	67.6	71.3	75.4	76.6	77.9	79.3	79.3

Source: Lin and Greene 2011

Table 41. Light Trucks Fuel Economy Inputs (mmpge).

	2000	2010	2015	2020	2025	2030	2035	2040	2045	2050
ICE	24.4	24.4	26.9	29.7	30.7	31.7	32.8	34.0	35.3	35.3
DSL	29.8	29.8	32.3	34.7	35.3	35.9	37.0	38.2	39.6	39.6
CNG	24.4	24.4	26.9	29.7	30.7	31.7	32.8	34.0	35.3	35.3
HEV	34.4	34.4	36.7	41.2	40.9	40.7	42.0	43.5	45.0	45.0
P10-gas	33.5	33.5	36.6	40.7	40.5	40.3	41.6	43.0	44.5	44.5
P10-elec	118.4	118.4	122.5	139.0	140.0	141.0	141.3	141.5	141.7	141.7
P40-gas	30.4	30.4	33.9	37.4	35.4	33.6	34.3	35.1	35.9	35.9
P40-elec	100.4	100.4	108.0	113.3	108.5	104.1	104.7	105.2	105.8	105.8
EV100	88.4	88.4	103.3	110.5	107.8	105.1	105.7	106.2	106.7	106.7
EV200	88.5	88.5	96.6	104.6	103.6	102.6	103.2	103.7	104.3	104.3
FC	42.9	42.9	45.4	50.7	50.5	50.3	51.1	51.8	52.6	52.6

Source: Lin and Greene 2011

Table 42. Long Haul Fuel Economy Inputs [MPGGE]

	2000	2010	2015	2020	2025	2030	2035	2040	2045	2050
Diesel		4.79	5.32	5.96	7.36	7.88	8.21	8.58	8.98	9.42
Hybrid		5.04	5.60	6.27	7.74	8.27	8.62	9.01	9.43	9.90
LNG CI		4.69	5.22	5.84	7.21	7.72	8.05	8.41	8.81	9.24
LNG SI		4.26	4.73	5.30	6.69	7.16	7.47	7.81	8.17	8.57
CNG SI		4.26	4.73	5.30	6.69	7.16	7.47	7.81	8.17	8.57
Fuel Cell		5.75	6.38	7.15	8.83	9.45	9.86	10.30	10.78	11.31

Table 43. Short Haul Fuel Economy Inputs [MPGGE]

	2000	2010	2015	2020	2025	2030	2035	2040	2045	2050
Diesel		4.63	4.89	5.20	6.25	6.53	6.77	7.02	7.30	7.60
Hybrid		4.88	5.15	5.47	6.87	7.83	8.12	8.43	8.76	9.13
LNG CI		4.54	4.80	5.10	6.12	6.41	6.64	6.89	7.16	7.45
LNG SI		4.12	4.35	4.62	5.68	5.94	6.15	6.39	6.64	6.91
CNG SI		4.12	4.35	4.62	5.68	5.94	6.15	6.39	6.64	6.91
Fuel Cell		9.72	10.28	10.92	13.12	13.71	14.21	14.75	15.34	15.96
BEV 100		14.81	15.66	16.64	19.99	20.89	21.66	22.48	23.37	24.33
BEV 200		14.81	15.66	16.64	19.99	20.89	21.66	22.48	23.37	24.33

Table 44. Heavy-Duty Vocational Fuel Economy [MPGGE]

	2000	2010	2015	2020	2025	2030	2035	2040	2045	2050
Diesel		3.80	3.80	3.85	4.03	4.72	4.92	5.09	5.26	5.45
Hybrid		5.07	5.07	5.12	5.38	6.29	6.54	6.77	7.00	7.24
CNG SI		3.38	3.38	3.41	3.58	4.20	4.37	4.52	4.68	4.85
Fuel Cell		8.36	8.36	8.46	8.87	10.38	10.82	11.19	11.58	11.99
BEV		12.16	12.16	12.30	12.90	15.09	15.74	16.28	16.84	17.43

Table 45. Medium-Duty Vocational Fuel Economy [MPGGE]

	2000	2010	2015	2020	2025	2030	2035	2040	2045	2050
Diesel		6.99	7.33	7.61	9.33	9.80	10.16	10.54	10.96	11.40
Hybrid		10.75	11.27	11.71	14.35	15.68	16.24	16.87	17.53	18.23
CNG SI		6.21	6.51	6.77	8.29	8.71	9.03	9.37	9.73	10.13
Fuel Cell		14.67	15.39	15.99	19.59	20.58	21.32	22.14	23.01	23.94
BEV		26.55	27.85	28.93	35.45	37.25	38.59	40.06	41.63	43.30

Table 46. Medium Duty Delivery Fuel Economy [MPGGE]

	2000	2010	2015	2020	2025	2030	2035	2040	2045	2050
Diesel		7.24	7.57	7.89	9.32	9.66	9.99	10.35	10.74	11.14
Gasoline		6.54	6.79	7.13	7.99	8.25	8.53	8.81	9.12	9.45
Hybrid (Diesel)		9.65	10.09	10.52	13.97	15.46	15.98	16.56	17.18	17.83
CNG		6.54	6.79	7.13	7.99	8.25	8.53	8.81	9.12	9.45
Fuel Cell		15.21	15.89	16.58	19.57	20.29	20.98	21.74	22.55	23.40
BEV 100		27.52	28.76	30.00	35.41	36.71	37.95	39.33	40.80	42.34
BEV 200		27.52	28.76	30.00	35.41	36.71	37.95	39.33	40.80	42.34

Table 47. Urban Bus Fuel Economy [MPGGE]

	2000	2010	2015	2020	2025	2030	2035	2040	2045	2050
Diesel		3.96	3.96	4.03	4.20	4.91	5.13	5.30	5.48	5.68
Hybrid Diesel		4.75	4.75	4.95	5.17	5.91	6.17	6.38	6.60	6.84
CNG SI		3.52	3.52	3.58	3.73	4.47	4.66	4.81	4.98	5.17
Fuel Cell		8.71	8.71	8.87	9.23	10.81	11.29	11.65	12.06	12.49
BEV		12.67	12.67	12.90	13.43	15.72	16.42	16.95	17.55	18.16

Table 48. Other Bus Fuel Economy [MPGGE]

	2000	2010	2015	2020	2025	2030	2035	2040	2045	2050
Diesel		6.08	6.08	6.31	6.63	7.82	8.11	8.39	8.69	9.01
Hybrid Diesel		6.40	6.40	6.64	6.98	11.74	12.98	13.42	13.90	14.41
CNG SI		6.99	6.99	7.22	7.62	8.54	8.82	9.11	9.42	9.74
Fuel Cell		13.38	13.38	13.88	14.58	17.21	17.85	18.45	19.10	19.83
BEV		19.46	19.46	20.19	21.21	25.04	25.96	26.84	27.79	28.84

Table 49. Heavy-Duty Pick-Up Trucks and Vans Fuel Economy [MPGGE]

	2000	2010	2015	2020	2025	2030	2035	2040	2045	2050
Diesel		15.07	15.71	17.93	20.01	22.85	23.75	24.72	25.78	26.93
Gasoline		13.72	14.29	16.32	18.21	20.80	21.61	22.49	23.46	24.50
Hybrid Diesel		22.61	23.56	26.90	30.02	34.28	35.63	37.08	38.68	40.39
CNG		13.72	14.29	16.32	18.21	20.80	21.61	22.49	23.46	24.50
Fuel Cell		33.16	34.56	39.46	44.02	50.28	52.25	54.38	56.72	59.24
BEV 100		57.28	59.69	68.15	76.04	86.84	90.25	93.93	97.98	102.33
BEV 200		57.28	59.69	68.15	76.04	86.84	90.25	93.93	97.98	102.33

6.4 Appendix D. Individual Truck Types

The paper has discussed medium- and heavy-duty trucks collectively to this point. This section identifies features of individual truck types. The section focuses exclusively on the ZEV scenario for each truck type.

6.4.1 Long Haul

Long haul trucks differ significantly from other trucks in their driving patterns. Their VMT is much higher than other vehicles with yearly travel often well in excess of 100,000 miles. In addition they travel primarily on the highways at high speeds. The high speed travel allows diesel engines to operate at high efficiencies and does not offer large benefits for battery electric, hybrid, or fuel cell drivelines. The large VMT would tend to discourage battery electric configurations due to the large battery pack cost and weight. Our model only considers three technologies—diesel, CNG, and fuel cell.

Figure 6-9 shows the long haul truck fuel consumption for the ZEV scenario. The relatively small benefit in fuel economy for long-haul fuel cell trucks coupled with no battery electric trucks in our ZEV scenario lead to significant hydrogen fuel usage. While the total truck hydrogen fuel consumption for trucks besides long-haul is roughly 28% of the total fuel consumption in 2050, the percentage of hydrogen in long-haul trucks is 54% of the long-haul fuel consumption.

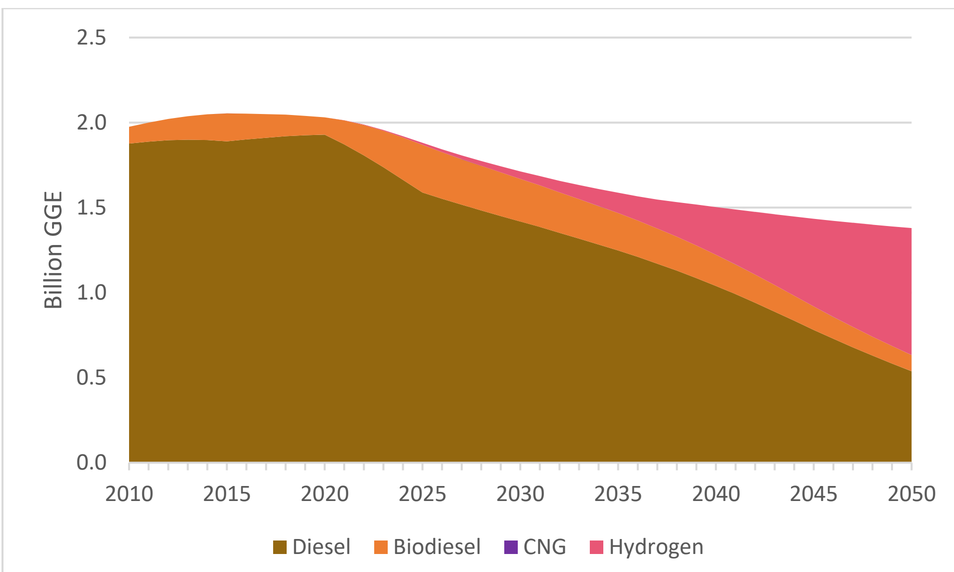

Figure 6-9. Long-haul truck fuel consumption by fuel type in the ZEV scenario.

Figure 6-10 shows the GHG emissions for long haul trucks for the ZEV scenario. Long-haul trucks dominate GHG emissions in trucking making up 57% of trucking GHG emissions in 2050.

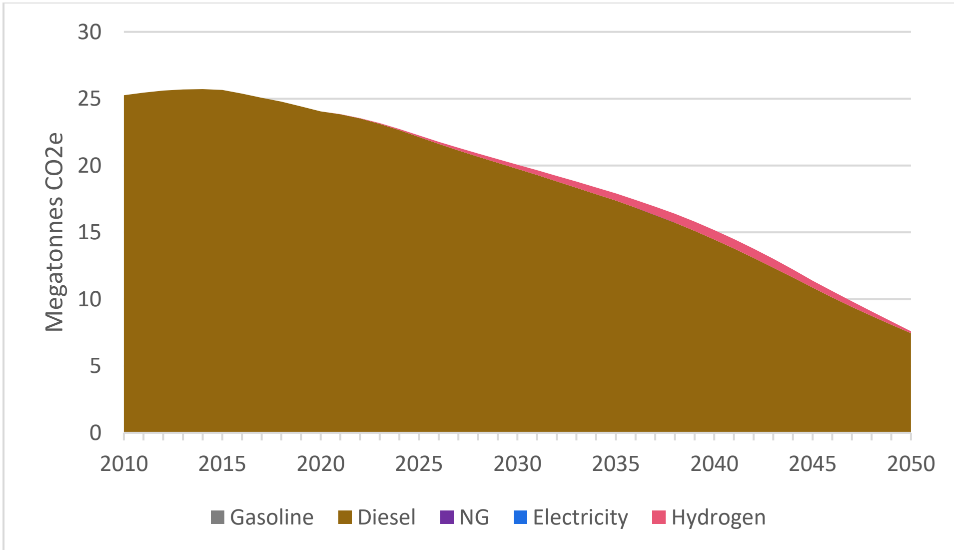

Figure 6-10. Long-haul truck GHG emissions by fuel type for the ZEV scenario.

Reducing GHG emissions from long-haul trucks presents a unique problem. Battery electric and fuel cell vehicles present problems with cost and weight. Biofuels could work but they have large uncertainties in cost, carbon intensity, and volume production. Catenary power for electric long-haul trucks is a potential option although the initial infrastructure cost is very high.

Long-haul battery electric trucks have been studied by Burke and Fulton (Burke and Fulton 2019). A 500 mile range truck would require roughly 6000 kgs of batteries and significantly reduce the available payload, therefore, reducing the revenue. In addition the batteries would be rather expensive and require a long payback period.

Long-haul trucks operate on drive cycles dominated by highway driving. Diesel engines can be quite efficient at highway torque and speed; consequently, fuel cells only increase the fuel economy by 20-30%. On other truck drive cycles, the fuel economy increase is over a factor of two. Hydrogen is expected to cost enough more than diesel fuel such that the modest increase in fuel economy will not make up for the increased fuel price. Unlike other trucks types, long-haul trucks do not get fuel savings to counter the increase in capital cost, Figure 6-11 shows the cost difference between the ZEV and BAU scenarios for long-haul trucks. Both the vehicle and fuel cost difference are positive (higher for the ZEV scenario). As fuel cell long-haul trucks are added to the fleet, the cost becomes more and more expensive compared to diesel trucks.

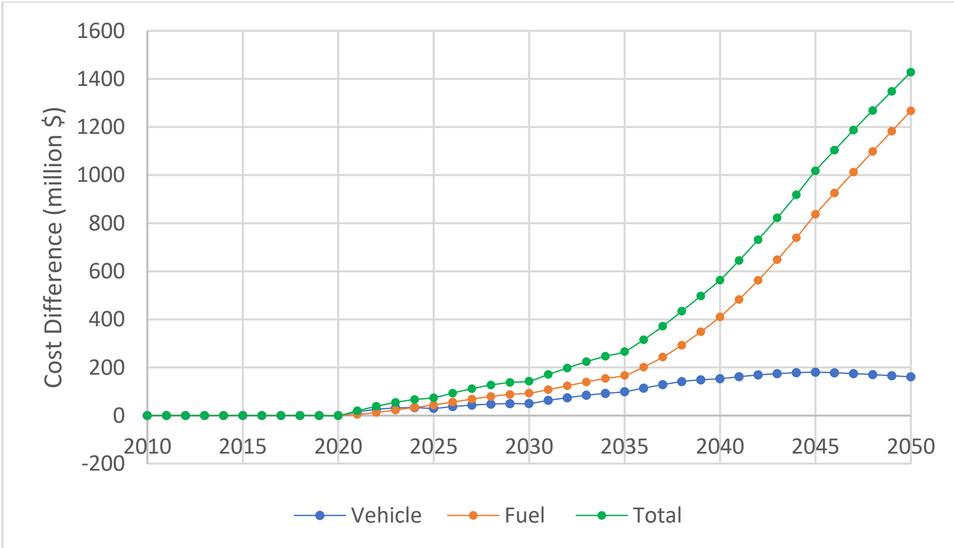

Figure 6-11. Long-haul cost difference between the ZEV and BAU scenarios.

Diesel biofuels could potentially reduce GHG emissions to low values. As mentioned above, diesel biofuels have uncertain costs, carbon intensities, and volume production potential. In addition, biofuels do not reduce criteria pollutants to the value necessary to meet California's future air quality standards.

One possible solution to reducing long-haul GHG emissions is using catenary charging in a hybrid configuration. Catenaries could be constructed on highways such that they would charge the batteries during a portion of driving and then the batteries would power the truck for sections between the catenaries (Zhao 2018). The battery packs could be much smaller, weigh less, and be less expensive than ones that deliver a 500 mile range. The catenary system would have to be widespread enough to allow charging of long-haul trucks throughout their driving patterns. Trucks would need to be able to drive away from main highways far enough to reach their destinations. In order to ensure that trucks could be properly charged, the catenary infrastructure would likely need to be rather extensive during the early rollout. The cost for this early installation could be prohibitive.

6.4.2 Heavy-Duty Pickups and Vans

Heavy-duty pickups and vans have more in common with LDVs than other truck types. The vehicles refuel at public fueling stations, their VMT is relatively small, and vehicle designs are similar to light-duty trucks. This truck type includes a wider variety of technologies than most truck types—diesel, gasoline, hybrid, natural gas, battery electric, and fuel cell. Figure 6-12 shows the market share for these technologies in the ZEV scenario.

Due to the very large stock of vehicles, heavy-duty pickups and vans contribute the second largest contribution to GHG emissions after long haul trucks. The percentage is 21% in 2010 and 19% in 2050. Figure 6-13 shows the reduction in GHG for heavy-duty pickups and vans.

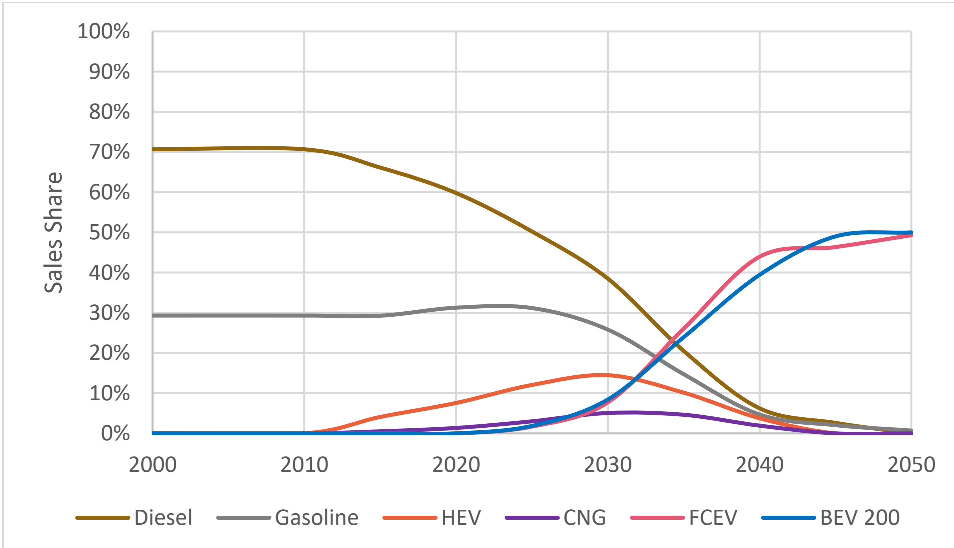

Figure 6-12. Heavy-duty pickups and vans sales shares for the ZEV scenario.

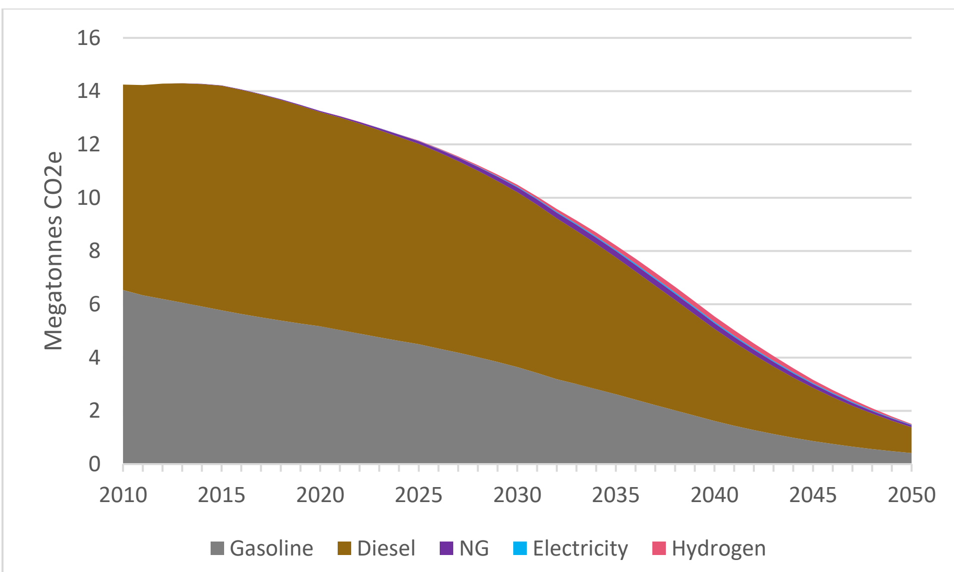

Figure 6-13. Heavy-duty pickups and vans GHG emissions for the ZEV scenario.

6.4.3 Transit Buses

Due to falling battery costs, government subsidies (up to 80% of purchase price), and significant maintenance savings for battery electric buses, the market share for transit buses is expected to be dominated by ZEVs. In our analysis battery electric buses dominate the market due mostly to the dominance in the present market throughout the world. The market share is identical in the ZEV and ZEV+B scenarios with CNG buses reaching almost 50% of sales in the near- to mid-term while battery electric bus sales grow to 100% in 2035. Figure 6-14 shows the transit bus market shares and Figure 6-15 shows the fuel consumption.

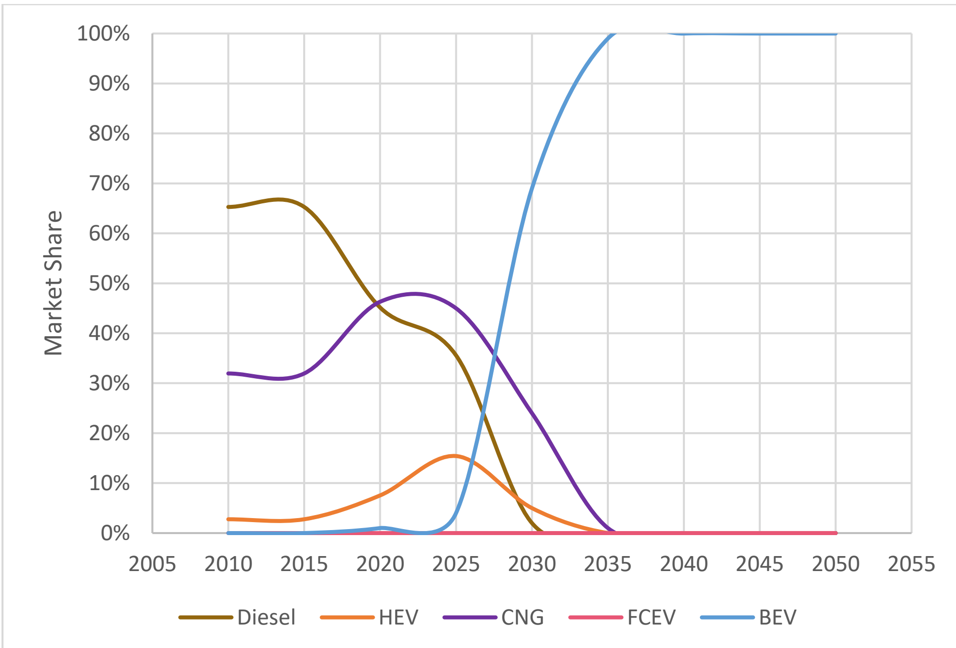

Figure 6-14. Transit bus market share by technology type for the ZEV scenario.

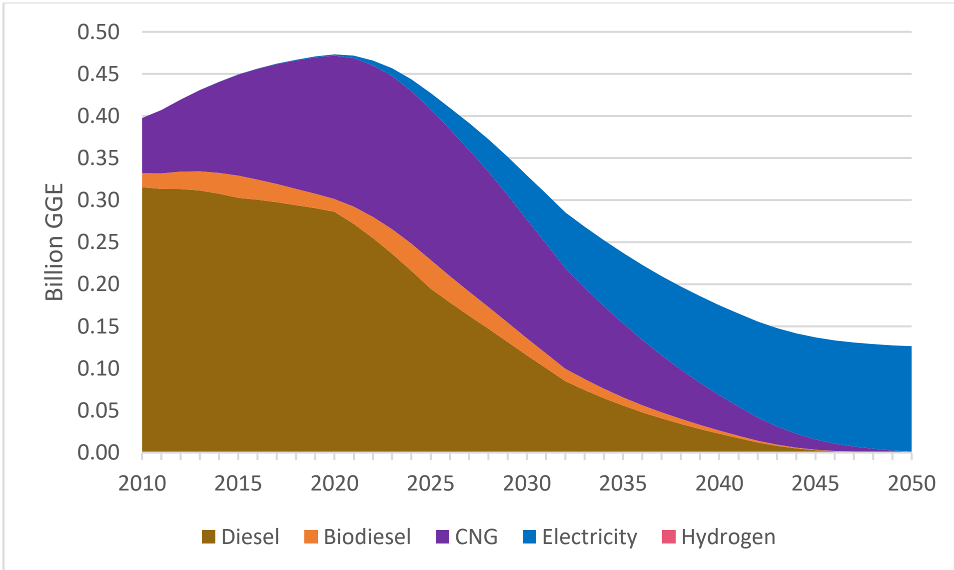

Figure 6-15. Transit bus fuel consumption for the ZEV scenario.

6.4.4 Heavy-Duty Vocational

Heavy-duty vocational trucks use almost 10% natural gas in the ZEV scenario by 2050 (see Figure 6-16). These vehicles are often closely associated with city fleets and could potentially use RNG produced from waste water treatment or municipal solid waste plants effectively.

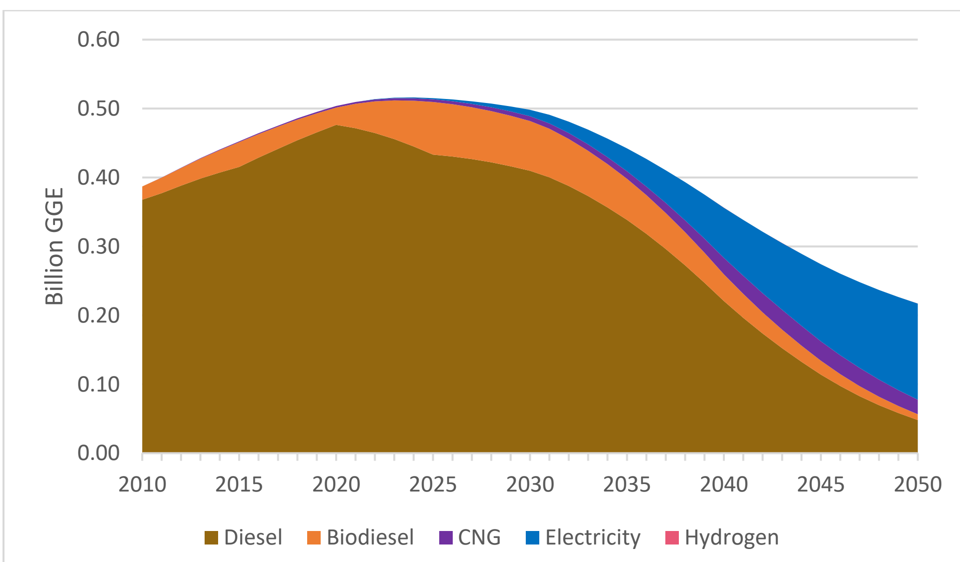

Figure 6-16. HD vocational fuel consumption for the ZEV scenario.

6.4.5 Medium-Duty Urban

The medium-duty urban truck type contains the most diverse technology mix in the ZEV scenario. By 2050 there is a significant contribution to the fleet stock for diesel, gasoline, hybrid, CNG, fuel cell, and battery electric vehicles (see Figure 6-17).

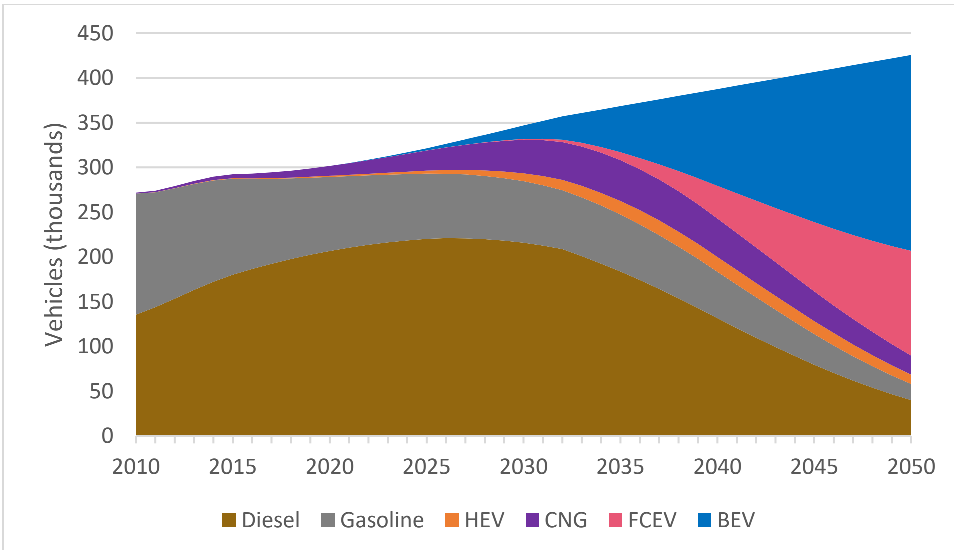

Figure 6-17. Medium-duty delivery fleet mix for the ZEV scenario.

6.4.6 Other Buses

The fleet stock for other buses includes a high percentage of diesel trucks (almost 20%) in the ZEV scenario by 2050 (see Figure 6-18). Reductions in GHG emissions for the ZEV scenario are shown in Figure 6-19).

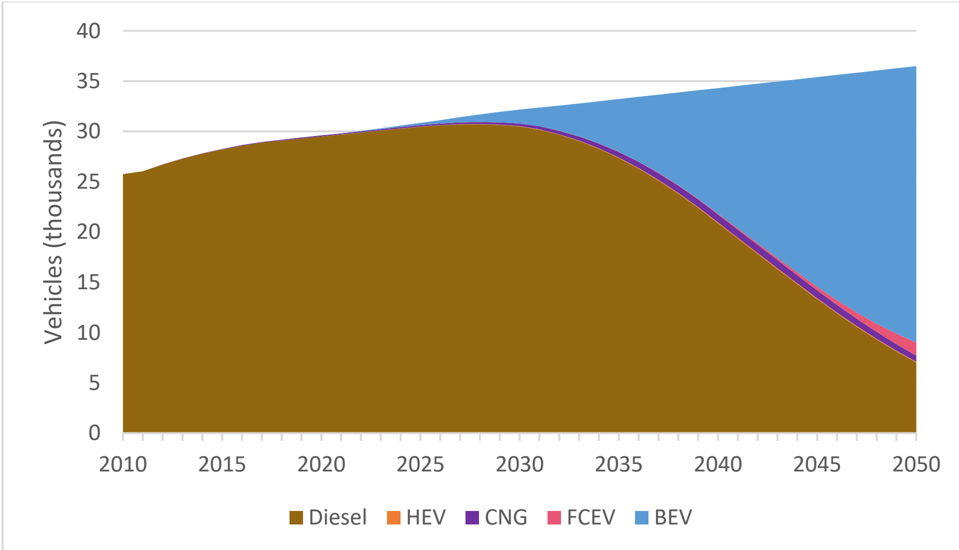

Figure 6-18. Other bus fleet mix for the ZEV scenario.

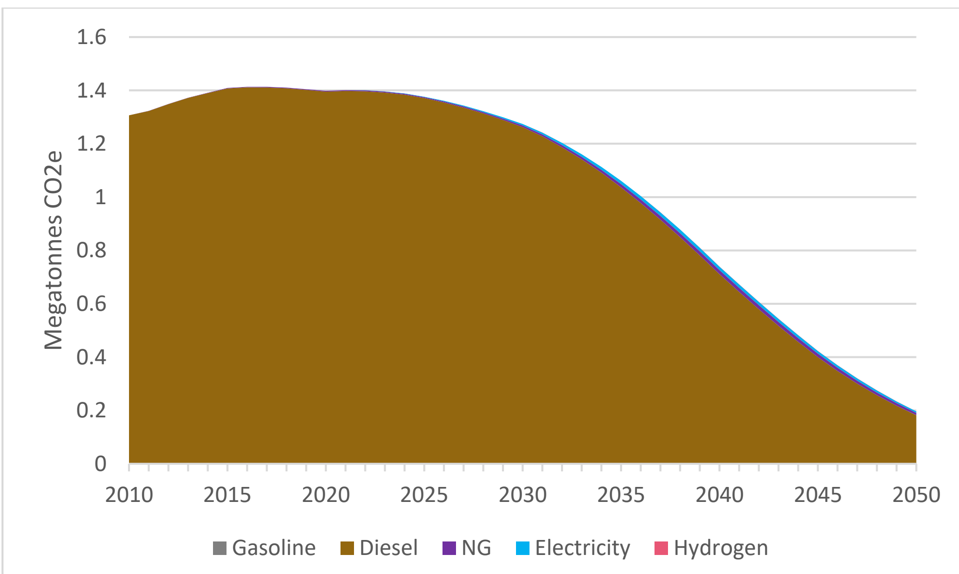

Figure 6-19. Other bus GHG emissions for the ZEV scenario.

6.4.7 Short-haul Trucks

The ZEV scenario fleet stock in 2050 for short-haul trucks contains roughly equal contributions of battery electric and fuel cell trucks with fuel cells slightly higher (see Figure 6-20). The GHG emissions for the ZEV scenario are reduced over 87% from 2010 values shown in Figure 6-21.

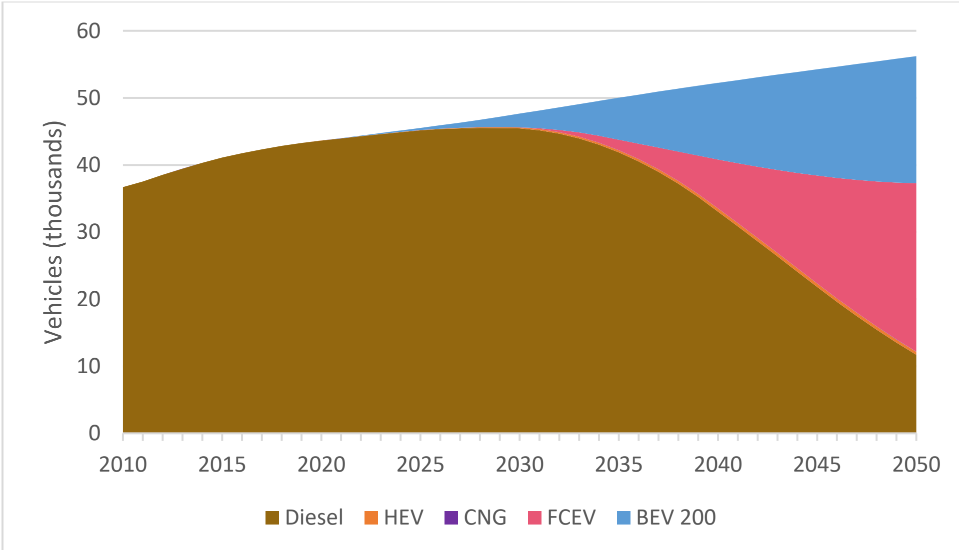

Figure 6-20. Short-haul fleet mix for the ZEV scenario.

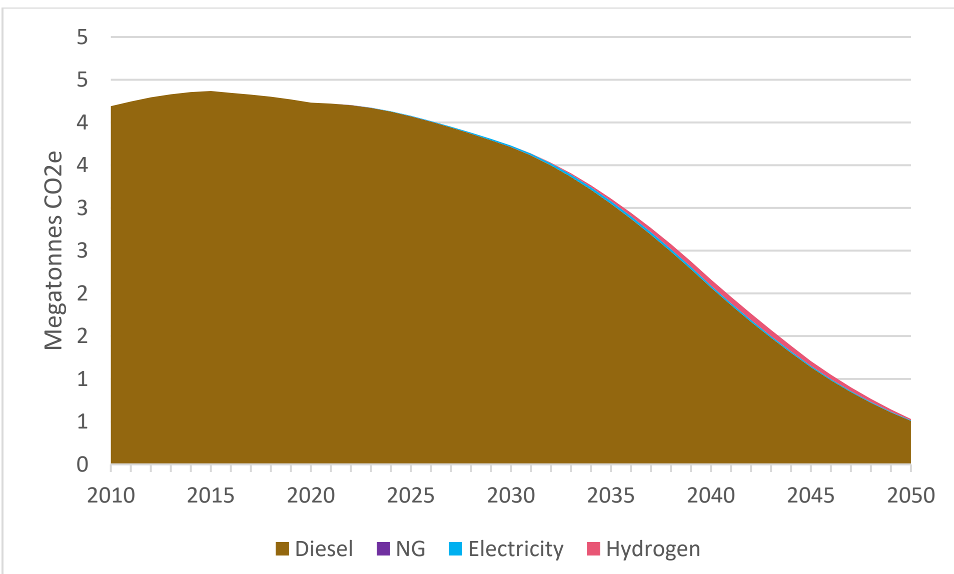

Figure 6-21. Short-haul GHG emissions for the ZEV scenario.

6.4.8 Medium-duty Vocational

The medium-duty vocational ZEV scenario reaches roughly an 80% market share for ZEVs by 2050. Hybrids, gasoline, CNG, and diesel vehicles contribute between 2 and 10% of the market in 2050. Figure 6-22 shows the fleet stock.

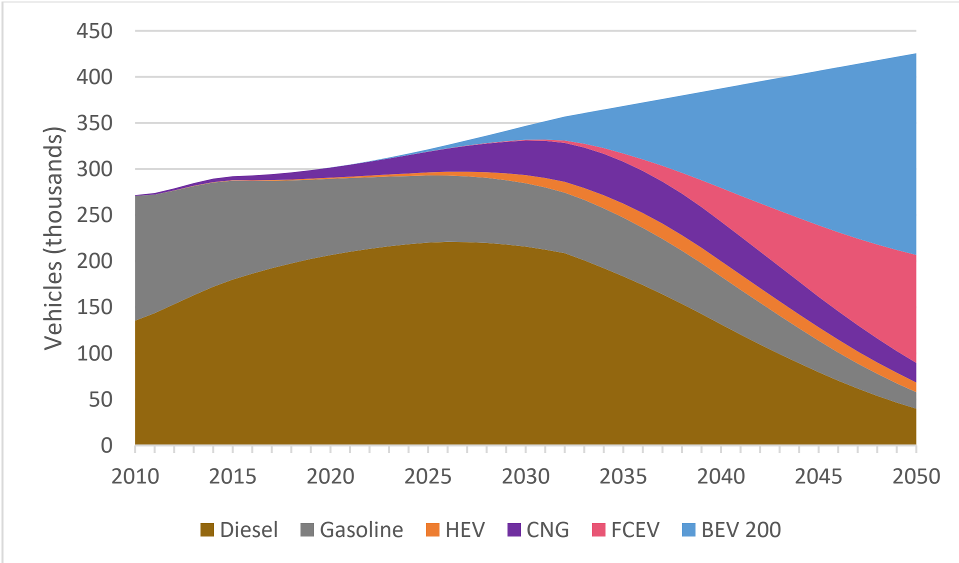

Figure 6-22. MD vocation fleet mix for the ZEV scenario.