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Technology and Fuel Transition: Pathways to Low Greenhouse Gas Futures for Cars and Trucks in the United States

Authors

Wang, Qian
Miller, Marshall
Fulton, Lewis

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Technology and Fuel Transition

Pathways to Low Greenhouse Gas Futures for Cars and Trucks in the United States

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Prepared By:

Qian Wang, Marshall Miller, Lewis Fulton

UC DAVIS Institute of Transportation Studies

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Abstract

In this study, we investigate how potential changes in US light-duty and medium/heavy-duty vehicle technology and fuel mix from 2020 to 2050 may affect the transition to a very low-carbon future in the United States. Given US targets to reach 50% or more zero-emission vehicle sales by 2030, we consider new sales trajectories for battery-electric vehicles and hydrogen fuel cell vehicles, and rates of uptake across the country needed to reach these. We also consider biofuels use (ethanol and renewable diesel) in remaining internal combustion engine cars and trucks to minimize GHG emissions from those vehicles. Costs of all vehicles sold, and their fuel and other operating costs, are calculated and projected. To account for characteristics of specific vehicle types (e.g., weight, application, fuel economy, drive cycle), we disaggregate light-duty vehicles and medium/heavy-duty vehicles into ten subcategories. Relative to a business-as-usual case, we develop a series of low-carbon scenarios where three regions of the US adopt zero-emission vehicles at different rates. One is California, where the strongest targets and policies have been set. We also consider "Section 177" states that have agreed to adopt at least some California policies, and the third is the remaining states. Our findings suggest that even slower adoption scenarios can reduce greenhouse gas emissions in 2050 by 90% of 2015 levels. Greater reductions can be attained with rapid adoption cases. However, even a case with all US states adopting California-style policies with a five-year delay—for LDVs, essentially the equivalent of the April 2023 regulatory proposals of the US EPA—may not be quite sufficient to reach the apparent US targets. Despite significant upfront investments required to undertake transitions in the near-term, these scenarios all feature large net savings to consumers after 2030 (or sooner) as fuel and maintenance savings exceed higher costs in purchasing vehicles. Overall net savings from 2020 to 2050 (mostly accrued after 2030) are in the range of $1.7 to $4.8 trillion. However, achieving these full benefits could be challenging due to the need for a rapid rate of zero-emission vehicle adoption and possibly high production volumes of low-carbon biofuels.

Table of Contents

List of Figures

List of Tables

Abbreviations and Acronyms

BAU	Business-as-usual
BBD	Biomass-based diesel
BBE	Biomass-based ethanol
BEV	Battery electric vehicle
CA	California
CARB	California Air Resources Board
CI	Carbon intensity (typically CO_2e grams per megajoule of energy or similar energy unit)
CNG	Compressed natural gas
CO_2e	Carbon dioxide-equivalent emissions (including CH4 and N2O)
EMFAC	EMissions FACtor (California Air Resources Board emissions inventory model)
EPA	Environmental Protection Agency
FCV	Fuel cell (electric) vehicle
GGE	Gasoline gallon equivalent
GHG	Greenhouse gas
H_2	Hydrogen
HD	Heavy-duty
HD voc	Heavy-duty vocational
HEV	Hybrid electric vehicle
ICCT	International Council on Clean Transportation
ICE	Internal combustion engine
LC	Low carbon
NGLDV	Light-duty vehicle

LH	Long-haul
LNG	Liquefied natural gas
MD	Medium duty
MD voc	Medium-duty vocational
MHDV	Medium/heavy-duty vehicle
MOVES	MOtor Vehicle Emission Simulator
mpgge	Miles per gallon gasoline equivalent
OEM	Original equipment manufacturer
O&M	Operation and maintenance
P40	Plug-in hybrid electric vehicle with 40-mile electric driving range
P80	Plug-in hybrid electric vehicle with 80-mile electric driving range
PHEV	Plug-in hybrid electric vehicle
SH	Short haul
TCM	Truck choice model
TTM	Transportation transitions model
VMT	Vehicle miles traveled
ZEV	Zero-emission vehicle

1. Executive Summary

While the United States has not formally adopted long term targets for the sales of zero emission vehicles (ZEVs), including battery electric, plug-in hybrid, and fuel cell vehicles, the Biden administration is targeting a 50% sales share of light-duty ZEVs by 2030 and the US EPA has issued a proposed rule intended to slightly exceed this target (US EPA 2023). California has adopted a regulation for 100% light-duty vehicle (LDV) ZEV sales by 2035 and is expected to adopt a requirement for 100% medium/heavy-duty vehicle (MHDV) ZEV sales by 2036 (CARB 2019; 2022a)[1]. Given that 16 “Section 177” states (CARB 2022b) have committed to adopting at least parts of the CA ZEV program, it is clear the US is accelerating its transition to ZEVs[2]. This report considers such scenarios and continues these trajectories to 2050. It also considers some slightly less ambitious versions, where different regions of the country transition at different rates. In any case, the transition to 100% ZEVs will be challenging and will create a revolution in US vehicle stock by 2050.

Previous research from the University of California, Davis, analyzed a transition to 100% ZEVs in California (Fulton et al., 2019) and these scenarios were included in a major California transition study (Brown et al., 2021). In this study, we extend the analysis to the entire US. We examine the costs and challenges of reducing road transportation GHG emissions to near-zero by 2050, through rapid uptake of ZEV vehicles and low-carbon fuels for remaining internal combustion engine vehicles. We acknowledge that reaching a 100% reduction target may also be helped by changes in travel patterns and personal transportation and goods movement mode choice. However, in this report, we assume that total travel and the modal split of travel in all scenarios are the same as in the “business-as-usual” scenario.

We modeled five market penetration scenarios for new technologies and fuels into LDVs and MHDVs with the following key features:

- **The business-as-usual (BAU) scenario** reflects a continuation of current trends and assumes no significant climate change policies will go into effect to accelerate the market penetration of zero emission vehicles. It results in relatively low CO_2 abatement through 2050 and provides a basis for comparison of the other scenarios.
- **The low carbon California (LC CA) scenario** includes very aggressive ZEV sales growth, assuming the entire US follows the low carbon (LC) pathway planned in California, which reaches 100% ZEV sales by 2035 for all LDVs and trucks. Even though this scenario appears very challenging, it sets a benchmark of CO_2 reductions for the other alternative scenarios.
- **Three other low carbon (LC) scenarios** include less aggressive ZEV sales growth than the LC CA scenario by assuming that different parts of the US have certain years of delay of ZEV penetration compared to the low carbon scenario in the California transportation transition model (CA TTM). These are:
    - LC 0-5, with no delay in Section 177 states and 5 years of delay elsewhere
    - LC 5-10, with 5 and 10 years of delay, respectively

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[1] *See also:* relevant staff reports found on referenced web pages.

[2] In accordance with Clean Air Act § 177, “Section 177” states have indicated they will follow California’s lead, although not all have signed on to the California ZEV program at this time. As of April 2023, states adopting California’s ZEV standards include Colorado, Connecticut, Maine, Maryland, Massachusetts, Minnesota, Nevada, New Jersey, New Mexico, New York, Oregon, Rhode Island, Virginia, Vermont, and Washington.

- LC 10-15, with 10 and 15 years of delay, respectively

The goal of the scenarios is to consider alternative pathways to meet a deep reduction in emissions in road vehicles, not to determine the best or most likely path for decarbonization. One parameter with significant effects on outcomes is which types of vehicles are sold (Figure 1-1). Our analysis assesses resulting rates of change, overall CO_2 emissions reductions, potential costs of each scenario, and the general implications for policy.

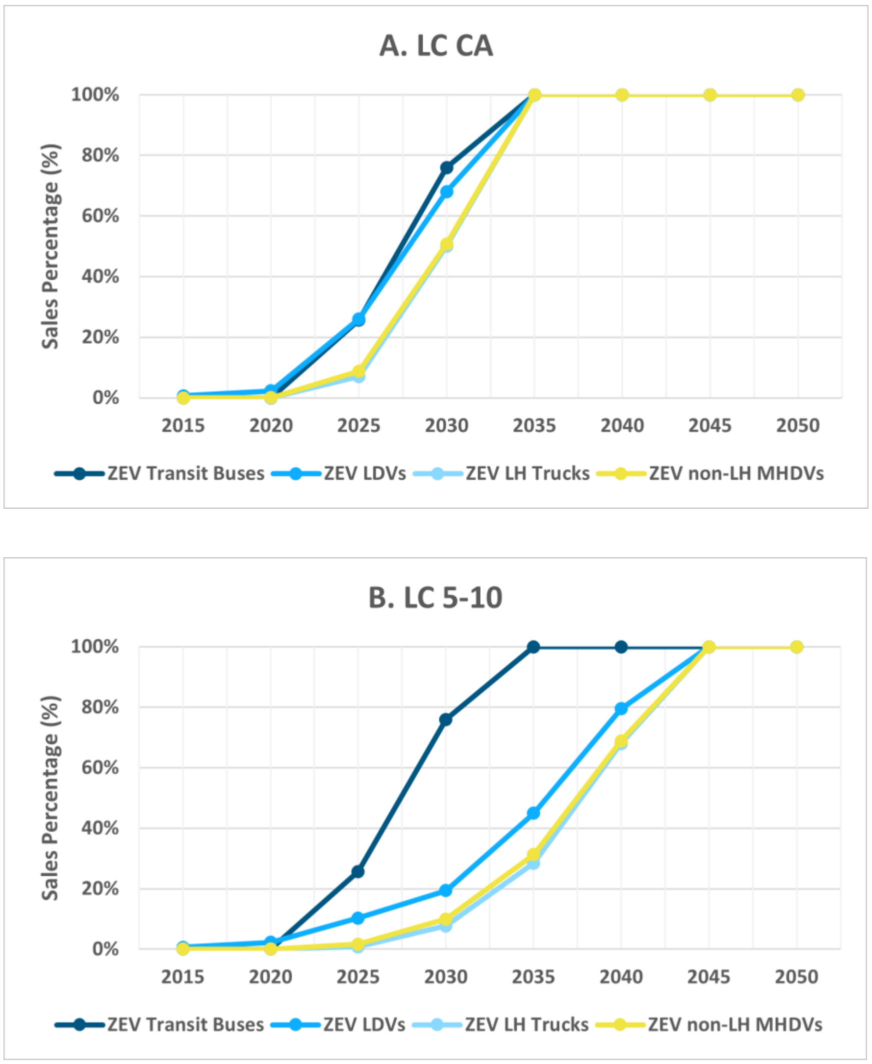

Figure 1-1. Sales fractions of zero emission vehicles (ZEV) among each vehicle type over time. Low carbon scenarios assuming very aggressive (A) and a less aggressive (B) ZEV sales growth shown. LDV=light-duty vehicle, LH=long-haul, MHDV=medium/heavy-duty vehicle.

1.1 Major Findings

Each low-carbon scenario shows significant promise in reducing GHGs and fossil fuel use by 2050. The more aggressive the scenario, the more GHG reductions between 2025 and 2050, and the more challenging it likely will be to implement. Major findings include:

- The LC CA scenario is the most ambitious, reaching 100% ZEV sales nationwide by 2035, and 90% ZEV stock by 2050. It involves achieving 68% and 51% of ZEV sales by 2030 for LDVs and trucks, respectively, which will be challenging over the coming seven years.
- The LC 10-15 scenario (the least ambitious) reaches 100% ZEV sales nationwide by 2050, 54% stock by 2050, and an overall GHG reduction of 90%.
- Achieving deep GHG reductions presented by alternative scenarios requires that energy for these vehicles, namely hydrogen and electricity, must eventually come from very low GHG sources.
- In the LC scenarios, the ZEV sales targets will be easier to achieve than in the LC CA scenario, but the trade-off is a build-up to very high—possibly infeasible or unsustainable—levels of advanced, very low-carbon biofuel use to ensure ongoing GHG reductions of transportation energy. A transition will be needed from today's dominant grain and oil-based biofuels to predominantly cellulosic biomass-based fuels to maximize their GHG benefits.
- Cumulative costs of the alternative scenarios from 2020 to 2050, aggregated across LDVs and trucks, are much lower than the BAU scenario. The faster the transition, the greater the net savings to 2050. This is mainly due to the lower need for maintenance and higher fuel efficiency of ZEVs. As the price of ZEVs comes down over time, savings on vehicle costs of the alternative scenarios also contribute to overall savings. However, for some specific vehicle types, such as long-haul (LH) trucks that are dominated by fuel cell vehicles (FCV) with only a modest increase in fuel economy over diesel trucks, there are no fuel cost savings, so overall costs are higher than the BAU scenario.
- Alternative scenarios can achieve huge cost savings throughout the period studied. To realize these long-term savings, investments would need to be made in the near future, while ZEVs are still very expensive. Investments required until a break-even point is reached would be small compared to savings accrued by 2050, but still represent tens of billions of dollars of initial outlay over the next five to eight years.
- 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 the vehicle and fuel-related costs, of attaining deep GHG emissions reductions from transportation. We did not explore this, but lower vehicle miles traveled (VMT) has clear benefits for both costs and emissions.
- Faster adoption of ZEVs will help meet air quality goals. Estimating these aspects is beyond the scope of this report and could be done in a follow-up study.
- Strong policies, like California's ZEV sales mandates, will be needed to achieve the rapid ZEV uptake included in these scenarios. Incentives to reduce the first cost of vehicles will also help. The additional costs over the next five to eight years shown in these scenarios (Section 4.7.3) provide an indication of what those incentives might need to be.

1.2 Projecting Technology Portfolios in Transportation

To maximize US GHG reduction by 2050, most new LDVs and trucks will eventually need to be ZEVs, either battery electric vehicles (BEVs) or FCVs. Some plug-in hybrid electric vehicles (PHEVs) may also coexist. As shown in Figure 1-2, the shares achieved in the considered scenarios vary both by scenario and across vehicle type though, in 2030, internal combustion engine (ICE) vehicles still dominate sales in most cases. By 2050, most vehicle types are dominated by some combination of electric and hydrogen vehicles in alternative scenarios. Light-duty vehicles are mostly electric and non-long-haul trucks are mixed. Long-haul trucks are dominated by fuel cells due to a strong match between their duty cycles, the projected range limitations of batteries and significant battery recharge times. In 2030, the LC 5-10 scenario has a much lower ZEV penetration than the LC CA scenario, although they both have 100% ZEV sales in 2050.

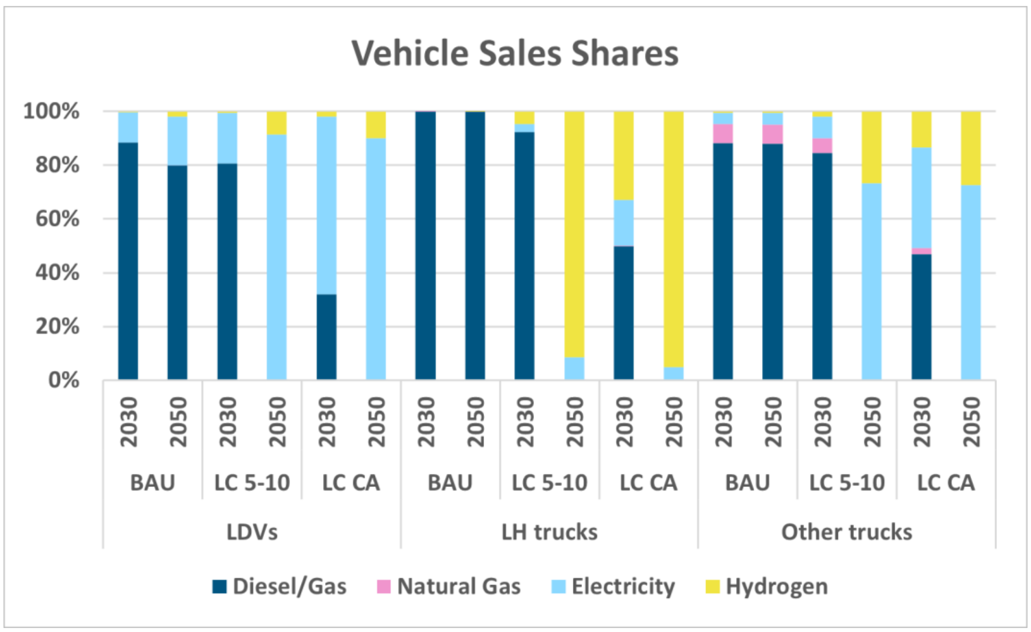

Figure 1-2. Vehicle sales shares across vehicle types, scenarios, technologies, and years. "Natural Gas" includes compressed and liquefied natural gas. LDV=light-duty vehicle, LH=long-haul.

1.3 Impacts on Fuel Consumption and Greenhouse Gas emissions

In the BAU scenario, there is a 13% reduction in fuel use between 2015 and 2050 due mainly to improved vehicle efficiency (Figure 1-3). For alternative scenarios, this reduction ranges from 39% to 58%. In the LC 10-15 scenario, over 65% of energy is still consumed by internal combustion engine (ICE) vehicles in 2050, all coming from biofuels, i.e., advanced renewable diesel and cellulosic ethanol. Very little compressed natural gas (CNG) remains in the mix. In the LC 5-10, LC 0-5, and LC CA scenarios, more than half of the energy consumed in 2050 is from electricity and hydrogen, with electricity accounting for a slightly higher share. The rest of the energy is mainly supplied by biofuels.

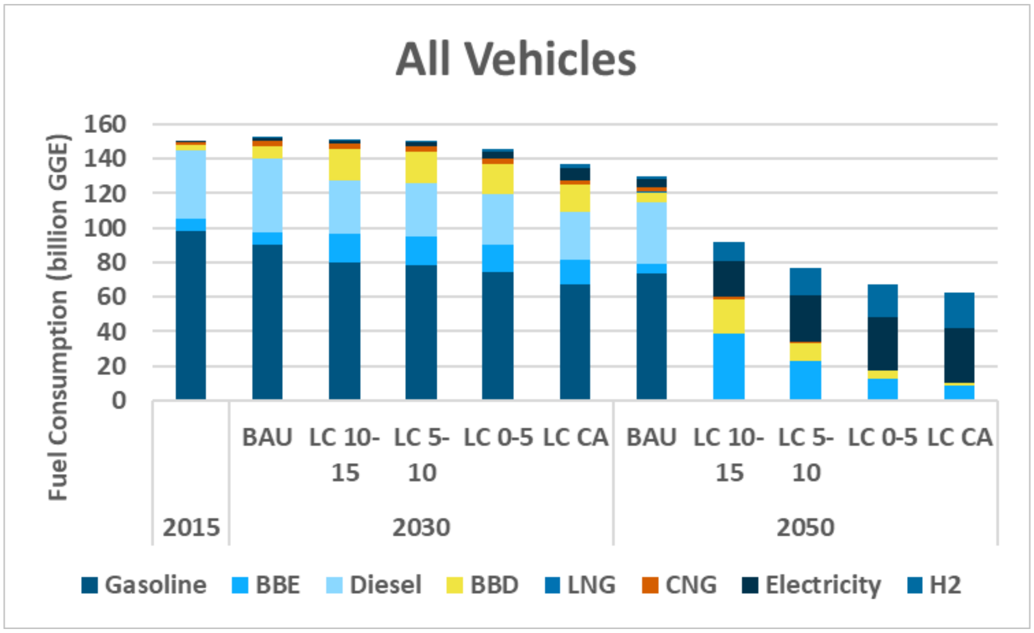

Figure 1-3. Fuel consumption by scenario for all vehicles. BBE=biomass-based ethanol, BBD=biomass-based diesel, LNG=liquid natural gas, CNG=compresed natural gas, H_2=hydrogen.

Total (well-to-wheel) GHG emissions from light-duty vehicles (LDV) and trucks for each scenario are shown in Figure 1-4. In the BAU scenario, LDVs and trucks achieve 22% and 11% reduction in GHGs from 2015 to 2050, respectively, due to improvements in fuel economy and some uptake of ZEVs and biofuels. For all the alternative scenarios, LDVs and trucks combined achieve at least 90% CO_2e reduction in 2050 compared to 2015. As the scenario becomes more aggressive, more reductions in GHGs are achieved. The most aggressive LC CA scenario reduces over 98% CO_2e in 2050 compared to 2015.

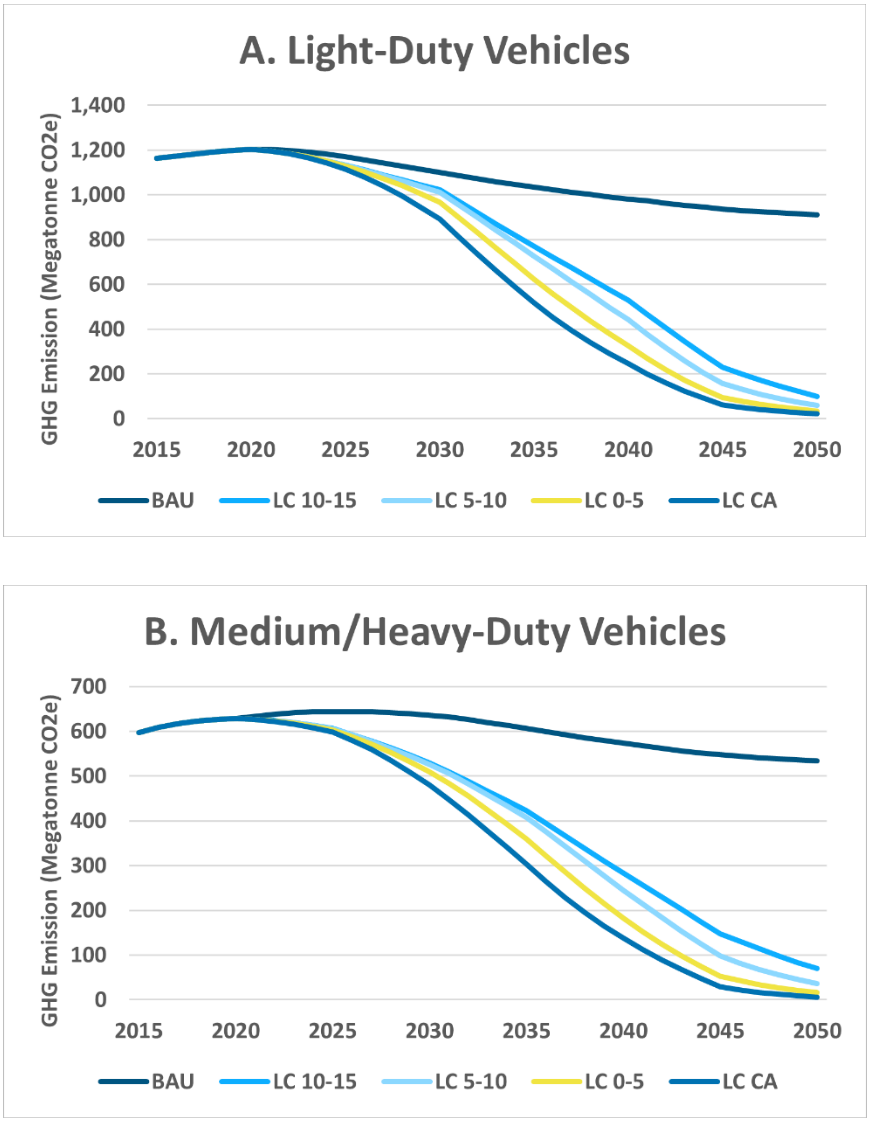

Figure 1-4. Greenhouse gas emissions from light-duty vehicles (A) and medium/heavy-duty vehicles (B) over time for each scenario.

1.4 Impacts on Costs

This study includes cost estimates for vehicle purchasing, fueling, and maintenance. All costs are projected to 2050 by technology and fuel type, with no discounting. This includes capital costs, fuel costs, and maintenance costs, as retail price equivalents. It does not include any subsidies or taxes.

We compare the total nation-wide costs of different low-carbon scenarios in terms of differences from the BAU scenario (Figure 1-5). For all comparisons, the only net cost increases are in vehicle costs of trucks. This is mainly due to the additional costs of battery electric and fuel cell technologies. This does not apply to LDVs because we assume the economy of scale will bring down prices of light-duty ZEVs more quickly than for trucks. The main source of fuel savings is the lower cost-per-mile of electricity compared to gasoline and diesel fuel, in turn due to the increased fuel economy of battery-electric vehicles (BEVs). 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.

Overall, there is a net reduction of $1.5 to $4.2 trillion in the costs of LDVs in the alternative scenarios compared to BAU. For trucks, there is a $0.2 to $0.6 trillion decrease in costs in alternative scenarios compared to BAU. Higher overall savings from LDVs are largely due to the significantly larger vehicle population and vehicle cost savings, compared to trucks.

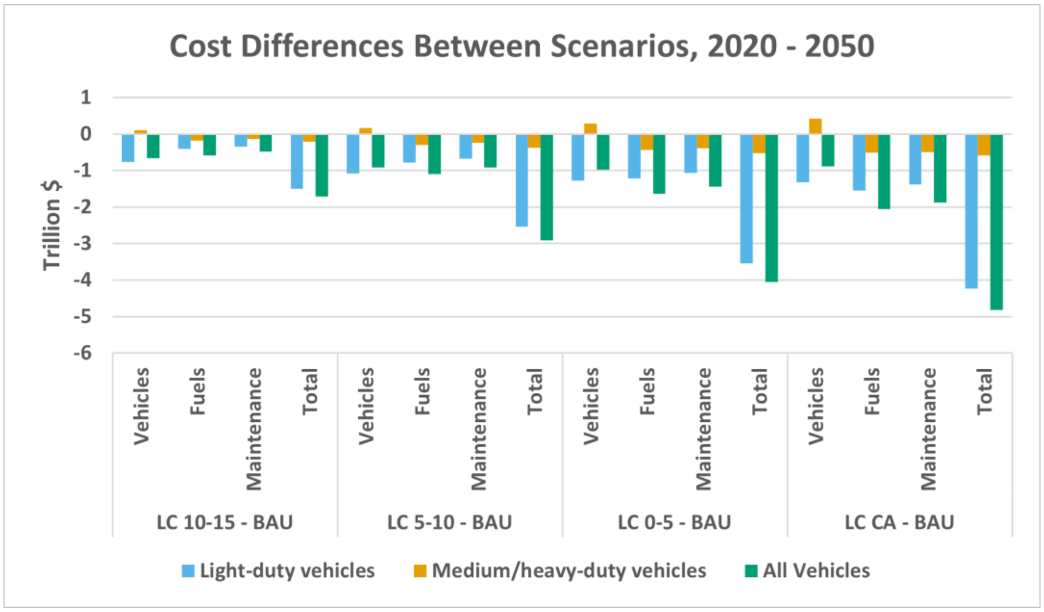

Figure 1-5. Cost differences between scenarios. Cumulative US-wide cost differences for vehicles, fuels, and maintenance relative to BAU from 2020 to 2050.

Next, we compare LC CA and LC 5-10 scenarios to BAU, evaluating costs over time for vehicles, operation and maintenance (O&M) (fuels and maintenance), and total cost difference (Figure 1-6). These scenarios have higher net costs than the BAU scenario until around 2030, and then have lower net costs. The LC CA scenario requires much higher investments from 2020 to 2030 than the LC 5-10 scenario because it involves purchasing more ZEVs while their prices are still very high.

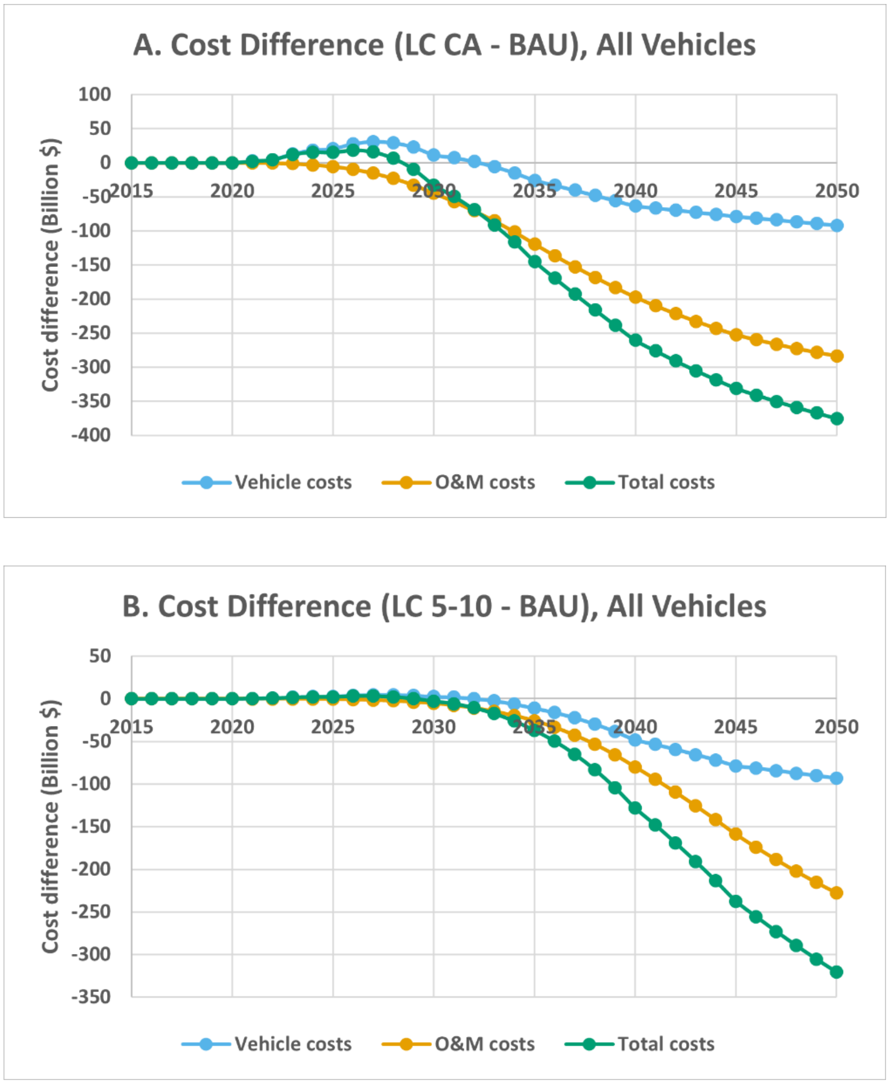

Figure 1-6. Total vehicle and operation and maintenance (O&M) cost differences from 2015 to 2050 for light-duty vehicles and trucks combined. Scenarios LC CA vs. BAU (A) and LC 5-10 vs. BAU (B).

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:

- While California's strategy is not assured to succeed, it provides an example for the rest of the US to follow. Some states have already made it clear they intend to do so. If all Section 177 states adopt California policies on LDV and MHDV ZEVs, this would represent around 40% of the US market. At some point it may be easier for other states or the federal government to follow with similar targets and policies, or perhaps a tipping point will be reached where the transition happens rapidly even without such alignment.
- In any case, there is an ongoing need for policy support to address the vehicle cost gap between ZEVs and conventional vehicles. This may be more critical for trucks than LDVs, as fleet managers appear more likely to want to minimize the purchase cost (and total cost of ownership) of vehicles than are households. This cost challenge is commonly expected to decline over time.
- These incentive policies will be more easily phased out once vehicle purchase costs decline sufficiently to fully establish the market. It is difficult to predict when that will be, and this will vary by vehicle type and market class.
- The role of FCVs is uncertain. Many now consider these to be most important for long-haul trucking, though they may still matter for other truck types and even LDVs, depending on the market success of BEVs. If battery technologies advance sufficiently to allow penetration into all market segments, including longer-range truck applications, that could fundamentally change the expected vehicle portfolio and obviate the need for FCVs. This question should be resolved within the next few years, allowing researchers to focus on the ultimate strategy and direction. In the meantime, pursuing FCV adoption makes sense as a complement to a BEV strategy.
- Even with the ZEV technology uptake rates in the fastest scenario, achieving GHG emissions reductions targets (such as near-zero net GHG by 2050) may require strong uptake of biofuels, as a full ZEV transition may take longer. This, in turn, may be challenging due to limited sustainable feedstock supply and could result in higher fuel costs.

Continuing research is needed to understand how costs may change over time and what level of policy support may be needed, depending on how the future unfolds. The net societal costs of various types of policies and/or regulatory strategies are also important, though often difficult to estimate. Our research over the coming one to two 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 and Background

This study explores the transition to a low-carbon future using advanced vehicle technology in the on-road car and truck sector. We assess the potential for technologies such as battery electric vehicles (BEV), fuel cell vehicles (FCV), plug-in hybrid electric vehicle (PHEV), and liquid biofuels for internal combustion engine vehicles. Using a variety of “what-if” vehicle scenarios for market penetration, we estimate the resulting reduction in greenhouse gases (GHGs) along with the fuel use and costs for each scenario through 2050.

We base much of this study on prior studies focusing on California (Brown et al. 2021, Fulton et al. 2019). Those studies developed vehicle market penetration scenarios for both light-duty vehicles (LDV) and trucks and utilized a stock turnover model known as the California Transportation Transition Model (CA TTM) to project vehicle stocks, fuel use, vehicle miles traveled, costs, and GHG reductions. Our TTM disaggregated vehicles into 10 types including two LDV and eight medium/heavy-duty vehicles (MHDV).

In this study we expand the focus from California to the entire US. The basic model is similar to the CA TTM, with the major difference being a modification of the CA TTM scenarios. California has regulations in place or in progress mandating the sale and purchase of zero emission vehicles (ZEV) (CARB 2021, CARB 2022a). Section 177 states plan to adopt similar regulations to California, but the remainder of states have not made any plans for regulating ZEVs. To create the scenarios for the US Transportation Transition Model (US TTM), we assume California will proceed on-schedule with its regulations while Section 177 states and the remainder of the US may have delayed adoption.

3. Scope and Methodology

3.1. General Approach

In this project, both LDVs and MHDVs are studied. To account for the characteristics (e.g., weight, application, fuel economy, drive cycle, etc.) of specific vehicle types, we disaggregate LDVs and MHDVs into several categories (Table 3-1). This approach allows separate analyses of the emission impact of different vehicle types. The LDVS include cars and light-duty trucks, and the MHDVs include eight vehicle types from class 2b through class 8 including buses. For simplicity, we often refer to these eight vehicle types simply as "trucks."

We developed five scenarios that can be compared in terms of their costs, emissions reductions, and fuel use. These scenarios, described below, specify various sales shares for each vehicle type and technology through 2050.

- **Business-as-usual (BAU):** Projects sales with the assumption that no significant climate change policies that would accelerate the market penetration of zero emission vehicles will go into effect.
- **Low Carbon California (LC CA):** very similar to a scenario developed in our California TTM which projects very aggressive ZEV market penetration.
- **Low Carbon (LC):** Three related scenarios assume significant climate change policies push aggressive market penetration for ZEVs. Variations of this scenario were developed to investigate delays for ZEV market penetration between California and the rest of the US.

3.2. Modeling Approach

To obtain vehicle stocks and miles traveled by vehicle type and technology, we use a TTM with vehicle sales assumptions as inputs. To develop the sales shares assumptions, we modified the CA TTM scenarios. For LDVs, the CA TTM uses an approach similar to Yang et al. (2016), which is based on the California TIMES optimization model. For MHDVs, we use a truck choice model (TCM) (Miller et al. 2017). LDVs have two subcategories, namely, cars and light-duty trucks, which represent most of the passenger vehicles (e.g., subcompact/compact/midsize/full-size cars and SUVs, light-duty pickups, minivans). Medium- and heavy-duty sectors are segmented into eight categories (Table 3-1).

Table 3-1. Vehicle categories and their definitions.

	Vehicle Categories	Definition
LDV	Cars	Passenger cars
	Light-duty trucks	Vehicles with a gross vehicle weight < 8500 lbs., used primarily for transporting property
MHDV	Long-haul trucks	Heavy-duty trucks that generally travel > 250 mile/day and do not return to base every night
	Short-haul trucks	Heavy-duty trucks that generally travel < 250 mile/day and return to base every night
	Heavy-duty vocational trucks	Heavy-duty trucks that carry equipment or materials rather than cargo (e.g., refuse or mixers)
	Medium duty vocational trucks	Medium-duty trucks that do not transport cargo (e.g., utility truck)
	Medium-duty urban trucks	Medium-duty trucks operating on urban drive cycles that generally transport cargo (e.g., delivery box truck)
	Urban buses	Transit buses operating primarily on urban drive cycles
	Other buses	Coaches operating primarily on highway drive cycles
	Heavy-duty pickups and vans	Pickup trucks or vans with gross vehicle weight > 8500 lbs. and < 14,000 lbs.

3.3. Development of Scenarios

In the US TTM study, five scenarios are developed to investigate economic costs and GHG reductions resulting from different management choices. In each scenario, year-by-year vehicle sales percentages by vehicle type and technology are specified from 2020 to 2050. These scenarios should be considered “what if” analyses of the effects of future technology deployments.

The US TTM model uses the same inputs as the CA TTM but varies the scenarios by taking possible trends and regulations of the entire US into account. While California has regulations that mandate the sales of LDV and truck ZEVs, the remainder of the US presently has fewer or no such regulations. The US TTM scenarios are created from the CA TTM scenarios and assume that market penetration of ZEVs will be delayed in states other than California.

In a recent study analyzing pathways to net zero carbon emissions in California by 2045, several scenarios were developed for the CA TTM model that show pathways to reaching this emissions goal (Brown et al. 2021). Two of these scenarios were modified and included in the US TTM model. These scenarios are BAU and LC. These CA TTM scenarios are described below.

The BAU scenario reflects existing trends and considers how these trends will be affected by existing California transportation- and CO_2-related policies. Market penetration of LDV ZEVs grows modestly from present sales shares. Sales shares of MHDV ZEVs remain below 2% through 2050 except for transit buses, which reach 100% ZEV sales shares by 2035. Although California has enacted the Advanced Clean Cars and Advanced Clean Trucks regulations, we assume the BAU scenario is unaffected by them.

The LC scenario is designed to achieve 100% ZEV market shares by 2035 for all vehicles, which is compliant with California Advanced Clean Cars (CARB 2019) and Advanced Clean Trucks regulations (CARB 2022a). It also includes a ramp-up to exclusive use of non-petroleum, low-carbon energy for these ZEVs, and low-carbon fuels for the remaining ICE vehicles. The LC scenario matches current LDV sales shares and uses regulation targets to guide sales shares.

To create the alternative scenarios, we started with the CA scenarios and modified them based on ZEV market penetration expectations for three sections of the US: California, 177 states, and the remaining states. Throughout the alternative scenarios, we assumed that California would follow the LC scenario in the CA TTM. In the most aggressive LC CA scenario, 177 states, and the remaining states would follow the LC scenario in the CA TTM as well.

We also have a series of less aggressive LC scenarios. Given that the 177 states might adopt ZEV requirements similar to California's, we assumed these states would have similar sales shares but with the ZEV market penetration delayed by X years; the remaining states would have similar sales shares but with the ZEV market penetration delayed by X+5 years.

ZEV sales shares ultimately reach 100% for each of the three US sections for each scenario, but the year when this benchmark is achieved varies (Table 3-2).US

Table 3-2. Year that zero-emission vehicle sales shares reach 100%. Scenarios for three US regions are included here.

Scenario	California	177 states	Other states
LC CA	2035	2035	2035
LC 0-5	2035	2035	2040
LC 5-10	2035	2040	2045
LC 10-15	2035	2045	2050

We created the LC scenarios for each section of the US using the process described above. We then created the overall US LC scenarios by using a weighted average of the sales shares for each vehicle and technology type. Weights are based on the population of each region, i.e., California 12%, 177 states 24%, remaining states 64%. Note that we made slight adjustments where necessary to ensure a smooth progression of market shares. Figure 3-1Figure 3-1 shows the ZEV sales shares for transit buses, LDVs, and trucks for the CA LC and the US LC scenarios.

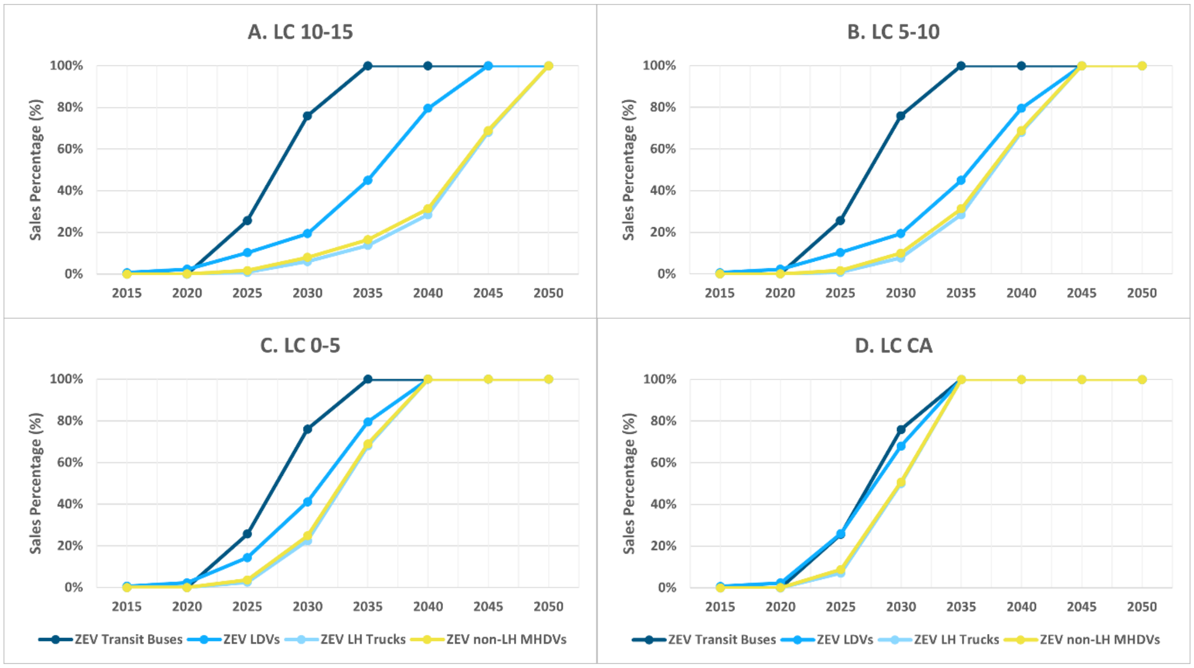

Figure 3-1. Zero emission vehicle (ZEV) sales shares for LC 10-15 (A), LC 5-10 (B), LC 0-5 (C), and LC CA (D) scenarios from 2015 to 2050. LDV=light-duty vehicle, LH=long-haul, MHDV=medium/heavy-duty vehicle.

3.4. Costs of Owning and Operating the Vehicle

According to our assumptions of the capital cost of vehicles and new vehicle sales, the total capital costs of each year's new vehicles can be computed. Similarly, each year's total cost of fuels can be calculated based on our assumptions of VMT, fuel price, and fuel efficiency.

Our approach includes several caveats. First, we decided not to discount future costs, partially due to the difficulty of properly discounting fuel costs that are distributed among future years. Second, fuel and maintenance costs incurred after 2050 are not incorporated in our framework as they are beyond our planning horizon. Lastly, we assume all capital costs of vehicles take place in the year when they enter the market for simplicity. This is not accurate as vehicle owners often spread out their vehicle capital costs into future payments (e.g., loans). These caveats are ameliorated by the nature of our analysis, which is based on comparisons between the BAU scenario and other alternative scenarios.

3.5. Key Model Inputs

In this section, we present important technology assumptions and projections that enter our models. Higher-level factors discussed below include technology and market share, vehicle survival, fuel economy, vehicle costs, biofuel blends, fuel costs, carbon of fuels, vehicle stock, and VMT. A list of key inputs and outputs of the models can be found in Table 3-3. The key model inputs are detailed subsequently in this section.

Table 3-3. Summary of key inputs and outputs of the models.

Model	Module	Inputs	Outputs
Truck Choice Model *(TCM)*		Capital cost Operating cost Fuel economy Non-monetary factors Subsidies Carbon tax Vehicle miles travelled *(VMT)*	Market shares of vehicle technologies for medium/heavy-duty vehicles (MHDVs) *(Inputs 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) *(Inputs to vehicle module)*
	Vehicle module	Vehicle cost Vehicle fuel economy Vehicle survival rate Initial stock numbers Vehicle market shares	Fuel demand Number of vehicles *(Inputs to fuel module)* Total mileage by technology and vehicle type Total emissions *(Carbon footprint)* Total fuel consumption Vehicle and fuel cost

3.5.1. Technology Market Share

Technology market share, also known as the percentage of sales by technology, represents the fraction of new sales of a particular technology type in a vehicle type. The US TTM uses technology market share and new sales volume to determine the number of new vehicles entering the fleet by technology and vehicle type. A detailed discussion of technology market share can be found in Section 3.5.1.

Technology market shares of all vehicle types and scenarios are listed in Appendix A.

3.5.2. Vehicle Survival

Vehicle survival assumptions are essential for calculating fleet stock with US TTM. The survival rate is defined as the fraction of new vehicles that remain in the fleet one year later. We assume a vector of survival rates by vehicle age (up to 20+ years old) for each vehicle type. For simplicity, we keep survival rates the same across different technology types within the same vehicle type.

For example, we assume long-haul (LH) diesel trucks have the same survival rates as LH fuel cell trucks. Our survival assumptions for MHDVs and LDVs are based on the California Air Resources Board's Vision 2.0 (CARB 2015) and US Environmental Protection Agency (US EPA 2016), respectively.

Vehicle survival assumptions for LH trucks and cars, as examples, are shown in Table 3-4. Note that these are survival rates for vehicles of given ages instead of cumulative survival rates.

Table 3-4. Vehicle survival assumptions for long-haul (LH) trucks and cars.

Age	LH trucks	Cars
1	1.00	1.00
2	1.00	1.00
3	1.00	1.00
4	1.00	0.99
5	0.99	0.99
6	0.97	0.99
7	0.97	0.98
8	0.96	0.98
9	0.96	0.97
10	0.96	0.97
11	0.95	0.96
12	0.95	0.95
13	0.93	0.91
14	0.93	0.85
15	0.93	0.83
16	0.92	0.81
17	0.92	0.80
18	0.90	0.79
19	0.90	0.78
20	0.89	0.77
20+	0.87	0.75

3.5.3. Fuel Economy

Vehicle fuel economy assumptions and projections by vehicle type and technology are crucial inputs to the TTM as they determine the fuel consumptions and GHG emissions. Our LDV fuel economy estimates come from the Autonomie vehicle simulation model of Argonne National Laboratory (ANL 2019). Fuel economy information is embedded within the MA3T model from Oak Ridge National Laboratory (Lin and Greene 2011). Corresponding numbers for cars and light trucks are extracted. In these projections, improvements in engine efficiency and road load are assumed and applied. Therefore, fuel consumption by vehicles, even traditional ICE vehicles, decreases through 2050. For MHDVs, the fuel economy of traditional ICE vehicles is estimated from CARB's 2014 EMission FACtor model (EMFAC 2017). Fuel economy of FCVs, BEVs, and hybrid vehicles are obtained with the Advisor vehicle simulation program and by relating to the present EMFAC values of diesel vehicles (Burke and Zhao 2015).

For detailed fuel economy assumptions and projections, see Appendix C.

3.5.4. Vehicle Costs

We calculate vehicle costs by adding up the costs of different vehicle components. We consider:

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

The cost of components depends on their size (e.g., batteries, motors, fuel cells, and hydrogen storage), so we introduce a size multiplier to adjust cost (e.g., $/kWh of battery, $/kW of fuel cell system). In the case of LDVs, we refer to the National Research Council study median scenario (NRC 2013) for component sizes, which are kept constant over time. Costs of components, however, decrease over time thanks to technological and manufacturing advancements. For MHDVs, the Advisor dynamic vehicle model (Burke and Zhao 2015) is used to determine component sizes. We use existing literature to decide the costs for engine, engine after treatment system, and transmission.

The costs of batteries and fuel cells have experienced large declines over time and this trend is likely to continue. Some sources that predict the future price of batteries are Bloomberg New Energy Finance, with very aggressive projections through 2030 (BNEF 2018; 2019), and the International Council on Clean Transportation, with less aggressive projections (ICCT 2014; Moultak et al. 2017). We determine costs for LDVs by extrapolating Bloomberg's forecasts through 2050. For MHDVs, we use the values that are roughly midway between the Bloomberg and ICCT predictions and then extrapolate them out to 2050. Note that these numbers represent costs of producing batteries for the original equipment manufacturers (OEMs). Therefore, multipliers reflecting integration costs were applied to calculate actual component costs.

Our assumptions for battery costs ($/kWh) to the manufacturer and costs with integration costs are shown in Table 3-5. For a graphical presentation of the same information, see Figure 3-2. More detailed truck cost information is provided in Appendix B.

Table 3-5. Battery costs ($/kWh). Values for LDVs and MHDVs with and without integration costs over time are shown.

Year	LDV	LDV + Integration	MHDV	MHDV + Integration
2015	368	479	400	600
2020	160	192	225	338
2025	125	144	175	263
2030	85	94	100	150
2035	75	79	85	128
2040	60	63	70	98
2045	55	58	70	98
2050	55	58	70	98

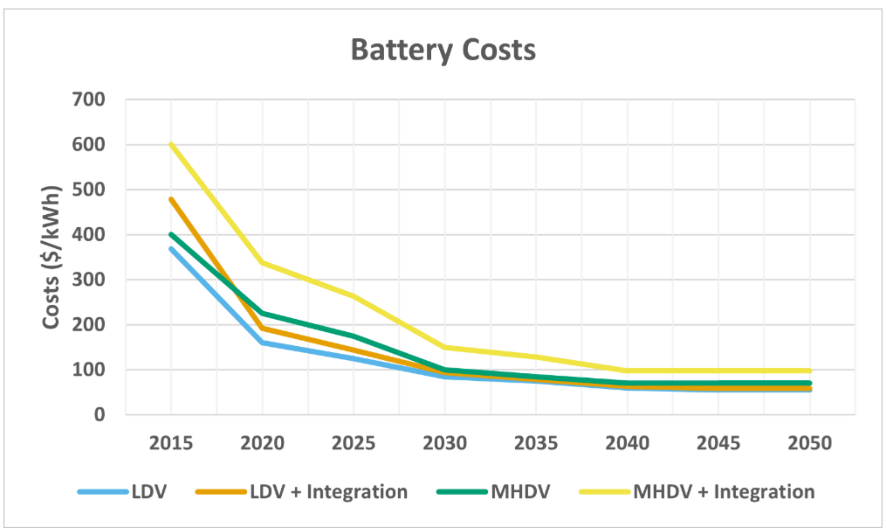

Figure 3-2. Battery costs. Values for light-duty vehicles (LDV) and medium/heavy-duty vehicles (MHDV), and for the same vehicles with and without integration costs over time are shown.

Our fuel cell costs are extracted from an analysis by Strategic Analysis (2016). The estimated cost is a function of sales volume. We determine the year-by-year costs by using annual expected sales of the ZEV scenario. For MHDVs, the volume sales are up to 1,000 units/yr. LDVs have higher volume sales and their costs are thus determined by extrapolation. Note that these numbers incorporate internal markups but fail to include final OEM integration costs. Therefore, multipliers reflecting the integration costs were applied again.

Fuel cell costs ($/kW) for both LDVs and MHDVs with and without integration costs are demonstrated in Table 3-6.

Table 3-6. Fuel cell costs ($/kW) for LDVs and MHDVs with and without integration costs over time.

Year	LDV	LDV + Integration	MHDV	MHDV + Integration
2015	300	390	1000	1500
2020	225	270	525	788
2025	100	115	193	290
2030	70	77	118	177
2035	50	53	95	143
2040	45	47	78	109
2045	43	45	78	109
2050	43	45	78	109

Total vehicle costs decrease rapidly until around 2030 and then level off. Total vehicle costs for LDVs (cars and light trucks), LH trucks, and HD pickups and vans over time are illustrated in Figure 3-3.

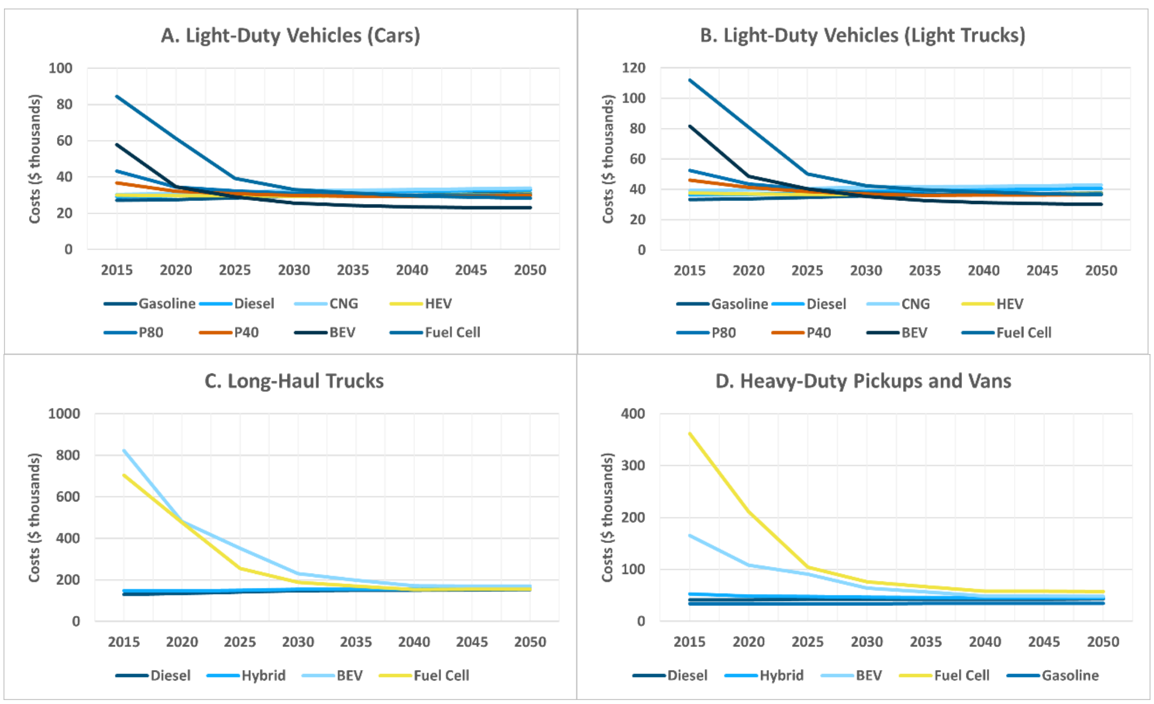

Figure 3-3. Vehicle costs over time for light-duty cars (A) and trucks (B), long-haul trucks (C), and heavy-duty pickups and vans (D), by fuel source.

3.5.5. Biofuel Blends

Alternative scenarios in the US TTM have aggressive ZEV market penetrations. However, due to long stock turnover times, there still exist a significant number of legacy ICE vehicles in later years. In order to reduce the GHG emissions for those ICE vehicles, we assume a ramp-up to exclusive use of non-petroleum low-carbon liquid fuels (biomass-based diesel and gasoline) for the remaining internal combustion engine vehicles by 2045. The progression of blend percentages of biofuels in gasoline and diesel for BAU and alternative scenarios are demonstrated in Table 3-7.

Table 3-7. Biofuel blend percentages in gasoline and diesel over time.

Year	Gasoline (BAU)	Gasoline (alternative)	Diesel (BAU)	Diesel (alternative)
2020	7%	15%	7%	15%
2025	7%	15%	11%	23%
2030	7%	15%	17%	37%
2035	7%	15%	39%	50%
2040	7%	15%	60%	71%
2045	7%	15%	90%	90%
2050	7%	15%	100%	100%

3.5.6. Fuel Costs

Our fuel price assumptions and projections for gasoline and diesel are based on the US Energy Information Administration's Annual Energy Outlook 2021 (EIA 2021). For all other fuels, the prices are based on literature. The progression of fuel costs (without tax) over time are demonstrated in Figure 3-4. The top panel reflects the fuel costs for liquid fuels, namely, gasoline, ethanol, diesel blend, diesel, and renewable diesel. The bottom panel shows the fuel costs for CNG, electricity, and hydrogen. The costs of hydrogen feature a sharp decline, mainly due to the economy of scale.

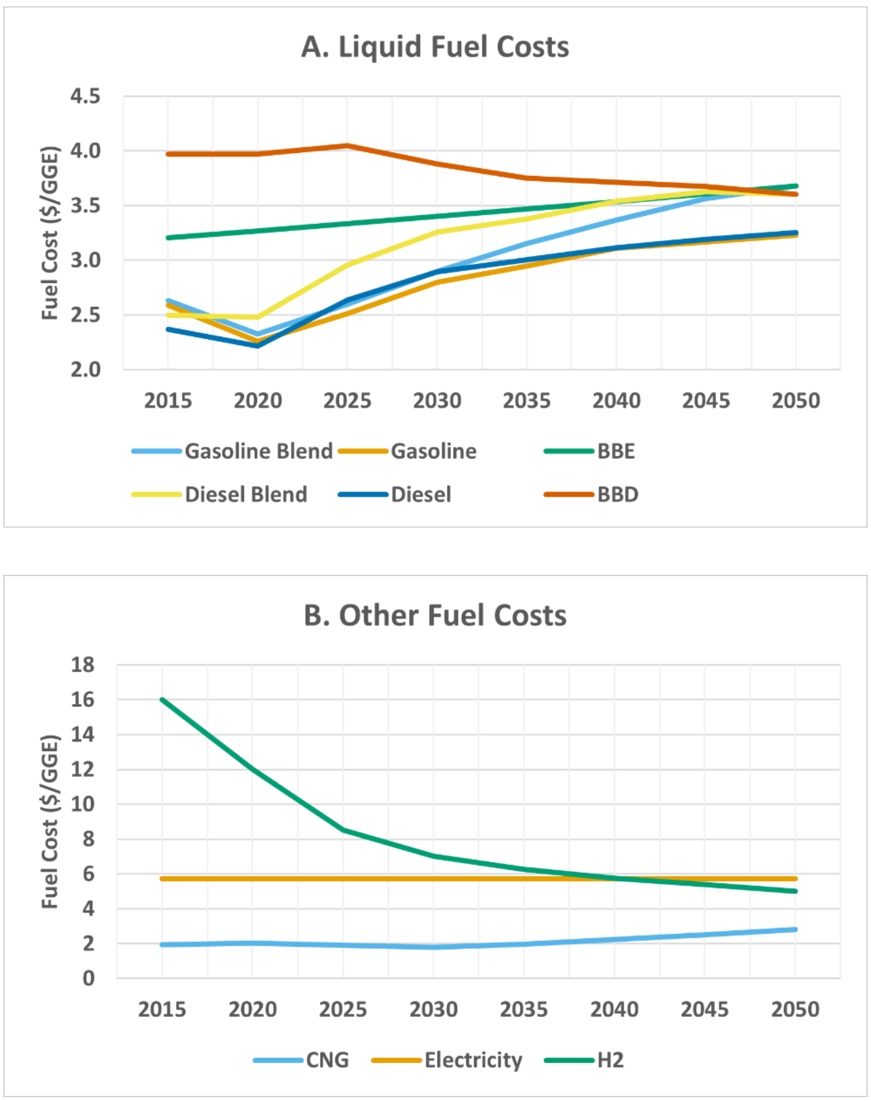

Figure 3-4. Fuel costs from 2015 to 2050 for liquid fuels (A) and other fuels (B). BBE= biomass-based ethanol, BBD= biomass-based diesel,CNG=compressed natural gas, H_2=hydrogen.

3.5.7. Carbon Intensity of Fuels

According to CARB (2017), the carbon intensities (CI) of pure gasoline and diesel are 13,300 gCO_2e/GGE and 13,200 gCO_2e/GGE, respectively. However, gasoline and diesel fuel also include blends of ethanol and biodiesel, respectively. Therefore, the true carbon intensities of gasoline and diesel fuels also depend on the biofuel CI and the fraction of blends, which both vary with time. For all other fuels, the prices are based on literature. Figure 3-5 shows the progression of carbon intensities for various fuels over time in the LC scenarios. The top and bottom panels represent liquid fuels and other fuels, respectively. Note that this figure reflects the carbon intensities in the low CI scenario. With these CI projections, TTM then computes GHG emissions for each year, with vehicle stock, fuel economy, and VMT assumptions.

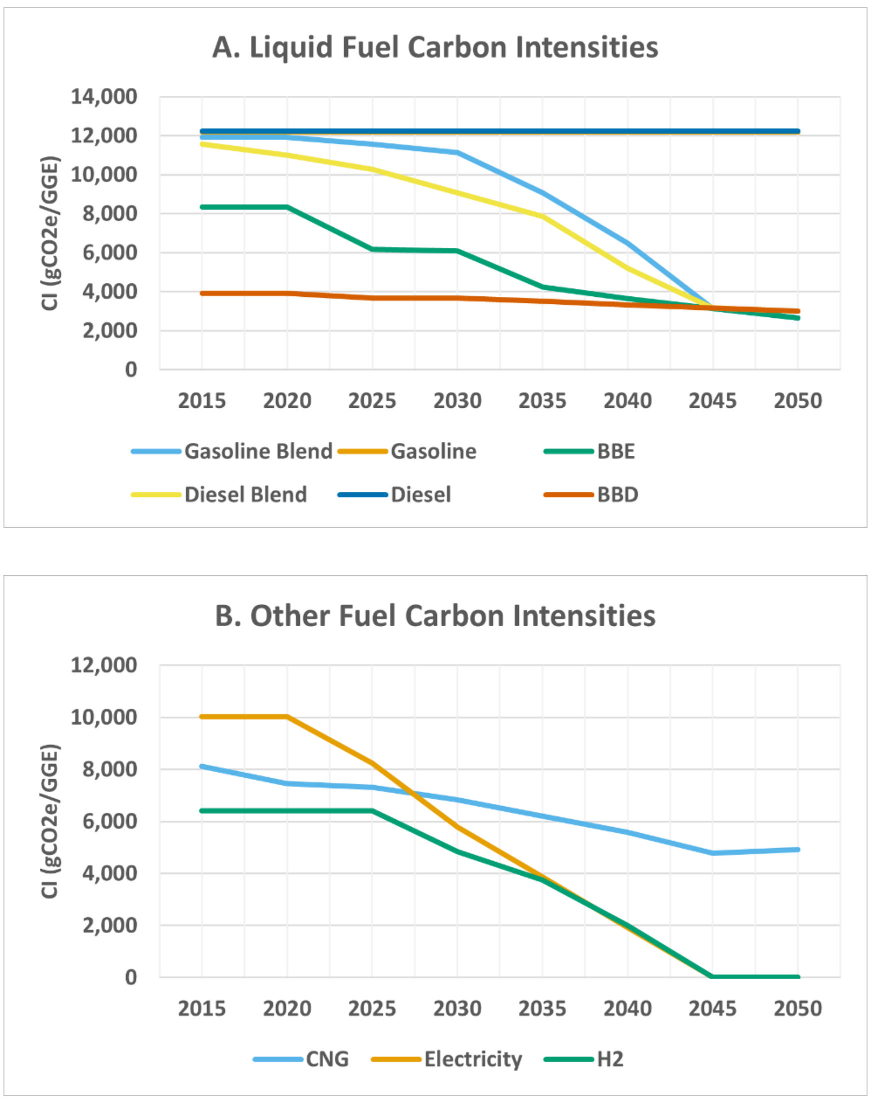

Figure 3-5. Fuel carbon intensities of the Low Carbon scenarios from 2015 to 2050 for liquid fuels (A) and other fuels (B). BBE= biomass-based ethanol, BBD= biomass-based diesel,CNG=compressed natural gas, H_2=hydrogen.

3.5.8. Vehicle Stock

Our vehicle stock projections are based on the United States Environmental Protection Agency's Motor Vehicle Emission Simulator (MOVES) and CARB's EMFAC (EMFAC 2017). The comparison of stock numbers is based on a predetermined approach which maps the MOVES source types and regulatory classes into the TTM vehicle categories. In the first step, we pin down vehicle stock projections for 2020 and 2050. The 2010 and 2020 stock numbers from MOVES are taken as given. However, we think the projected 2050 stock numbers of MOVES are problematic. For example, from 2020 to 2050, the population of LH trucks only increases by approximately 3% while the heavy-duty vocational category more than doubles its population. Therefore, we decided to make our predictions for each vehicle category. For simplicity, we assume a linear vehicle population growth from 2020 to 2050. We believe the population growth of certain vehicle categories should be somewhat parallel to economic growth (i.e., LH, short-haul (SH), and medium-duty urban) while others should follow the human population growth more closely. We then fine-tuned the growth ratios of 2050 to 2020 using MOVES and EMFAC numbers as references. The stock number assumptions are shown in Table 3-8.

Table 3-8. Vehicle stock number assumptions by vehicle type for 2020 and 2050.

Vehicle Type	2020 population	2050 population	2050 to 2020 ratio
LH	1,814,888	2,849,374	1.57
SH	1,182,235	1,915,221	1.62
HD voc	1,443,754	1,920,193	1.33
MD voc	1,826,991	2,375,088	1.30
MD urban	2,798,297	4,589,207	1.64
Urban bus	598,121	795,501	1.33
Other bus	342,981	456,165	1.33
HD pickup	12,632,510	15,790,638	1.25
Car	114,183,874	151,864,552	1.33
Light truck	132,355,157	172,061,704	1.30

However, these stock numbers are not the direct inputs – the TTM computes vehicle population based on a starting stock number (in the year 2010), new sales for each year, and vehicle scrappage assumptions. Therefore, the 2010 vehicle population (with age distribution) of MOVES are extracted, which enter the TTM as the starting stock numbers. The 2020 and 2050 stock numbers in Table 3-8 serve as the standards of calibration. Next, the MOVES population of age-zero vehicles in 2010 and 2050 are treated as the new vehicle sales numbers of corresponding years. These numbers are used as starting points for the adjustment of TTM sales numbers. The sales numbers between 2010 and 2050 are determined by interpolation. Lastly, the sales numbers of 2010 and 2050 are adjusted until the University of California, Davis, (UC Davis) stock numbers of 2020 and 2050 converge to the standards. Convergence is achieved when the difference of corresponding UC Davis numbers and standards is within 2,000 vehicles.

3.5.9. Vehicle Miles Traveled

Our annual average VMT per-vehicle by vehicle type assumptions for MHDVs and LDVs are based on CARB's Vision 2.0 (CARB 2015) and US EPA (2016), respectively (Table 3-9). As vehicles age, VMT decreases. We assume BEVs and FCVs have the same VMT as conventional vehicles.

Table 3-9. Vehicle miles traveled (VMT) per vehicle assumptions for new vehicles by vehicle type.

Vehicle Type	VMT (1,000 mi/year)
LH	81.0
SH	44.8
HD voc	17.5
MD voc	5.9
MD urban	25.5
Urban bus	18.7
Other bus	23.8
HD pickup	16.8
Car	20.2
Light truck	20.8

4. Results

4.1. Market Share of Zero Emission Vehicles

We first present a comparison of ZEV penetration between different scenarios (Figure 4-1). The ZEV percentages in the BAU scenario are low even in 2050. All four alternative scenarios feature much deeper ZEV penetrations. The LC 0-5 scenario experiences a steady increase of ZEV percentages after 2025, reaching 100% ZEV by 2040. The LC CA scenario has an even steeper rise of ZEVs after 2025, achieving 100% ZEV by 2035.

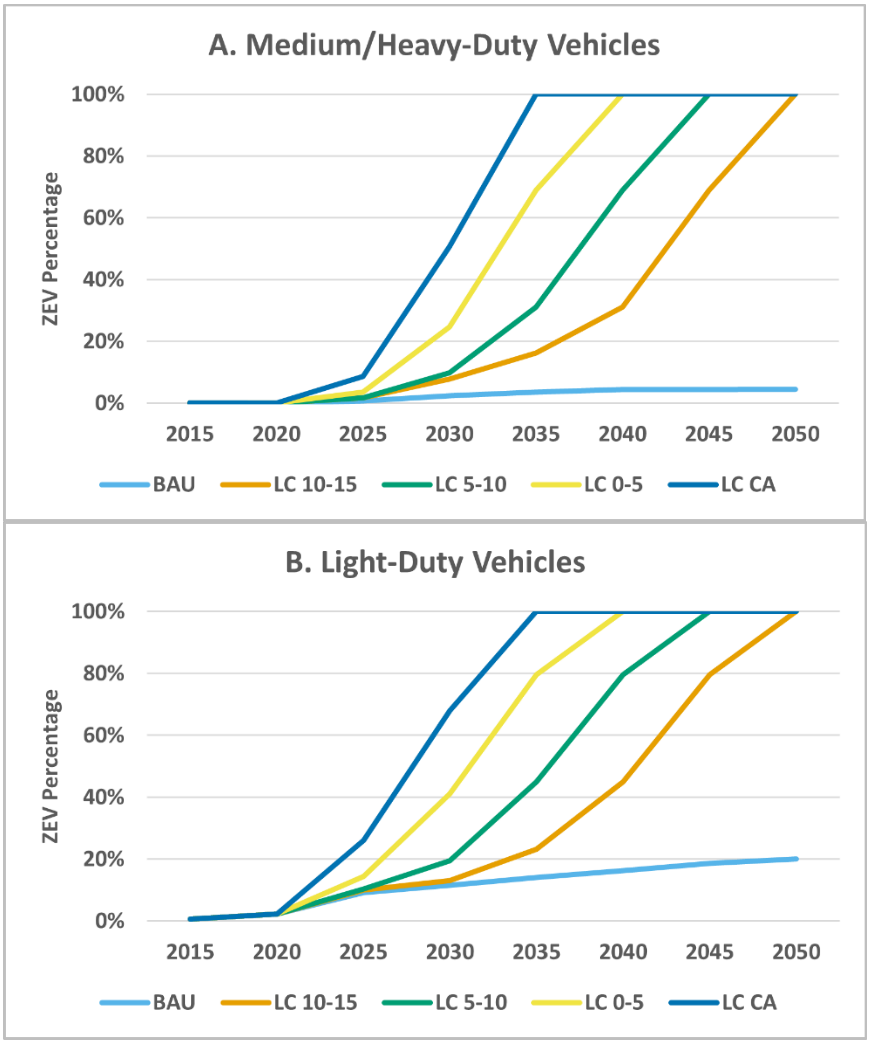

Figure 4-1. Sales-weighted zero emission vehicle percentages of all scenarios for medium/heavy-duty vehicles (A) and light-duty vehicles (B) from 2015 to 2050.

In the BAU scenario, gasoline vehicles dominate the market throughout the time horizon, with a market share of 68% even in 2050. ZEV technologies only account for 20% of total sales in 2050. We start to observe much more ZEV penetrations from the LC 10-15 scenario. The sales of gasoline vehicles decline gradually, down to 0% by 2050. ZEVs experience a significant expansion during the same period, reaching 100% by 2050. The other alternative scenarios have very similar trends to the LC 10-15 scenario but with accelerated ZEV penetrations. It is noted that none of these scenarios include a significant amount of FCVs (no more than 10%) (Figure 4-2).

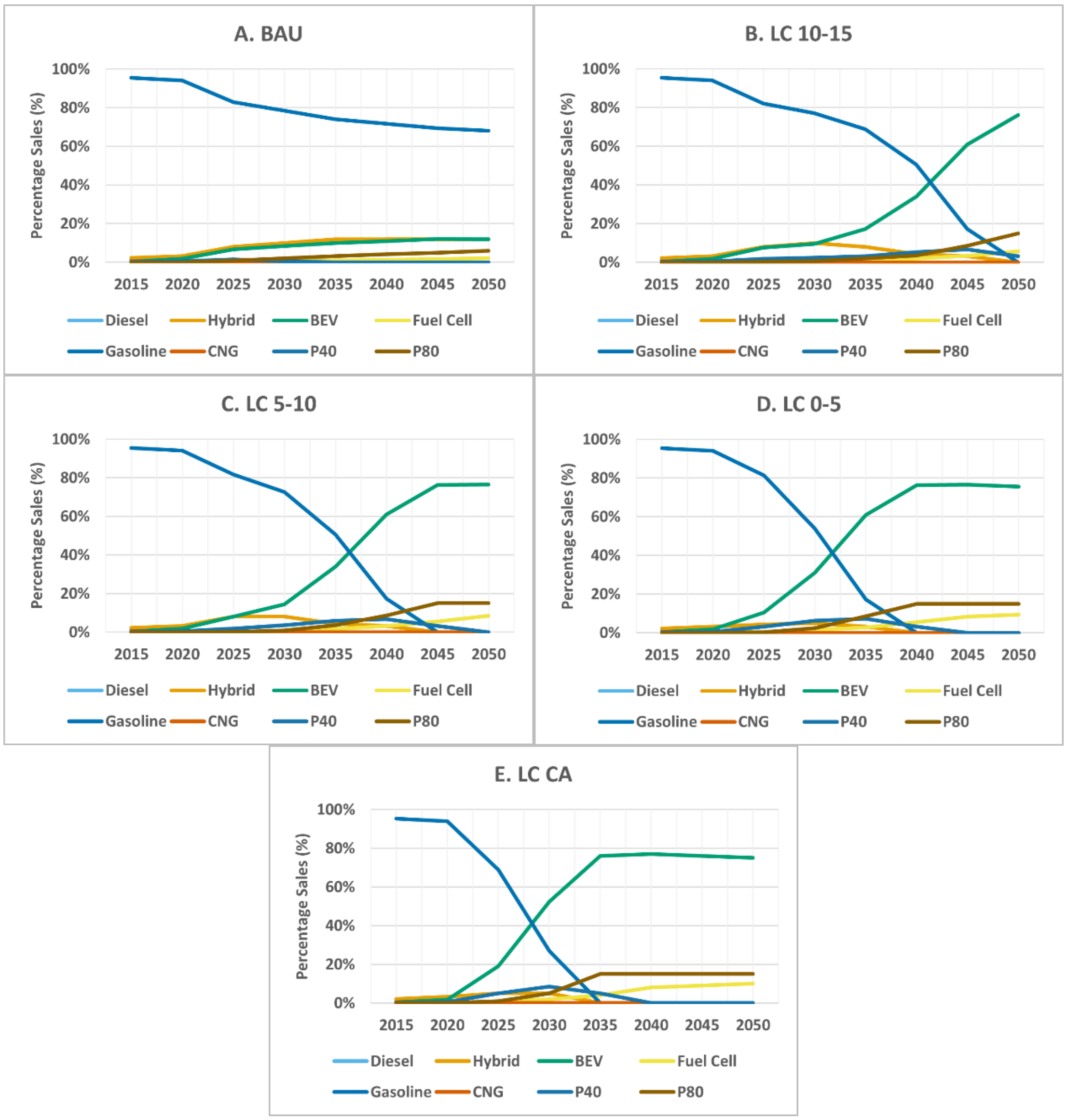

Figure 4-2. Sales shares of light-duty vehicles for each scenario from 2015 to 2050.

Three important truck categories are LH trucks, MD urban trucks, and HD pickups. In the BAU scenario, no ZEV vehicles are sold by 2050. The sales share of hybrid vehicles rises to approximately 16% in 2050. In the LC 10-15 scenario, the growth of ZEV sales is still slow before 2030. However, significant ZEV penetration happens after 2030, reaching 68% in 2045 and 100% by 2050. In the LC 5-10 scenario, ZEV sales take off around 2030, achieving 100% in 2045. The LC 0-5 scenario has a similar trend while achieving 100% ZEV sales by 2040. The LC CA scenario has an even more aggressive ZEV penetration, starting around 2025 and reaching 100% by 2035. All ZEV sales of LH trucks feature a major bias towards FCVs due to the limited range of BEVs for this application (Figure 4-3).

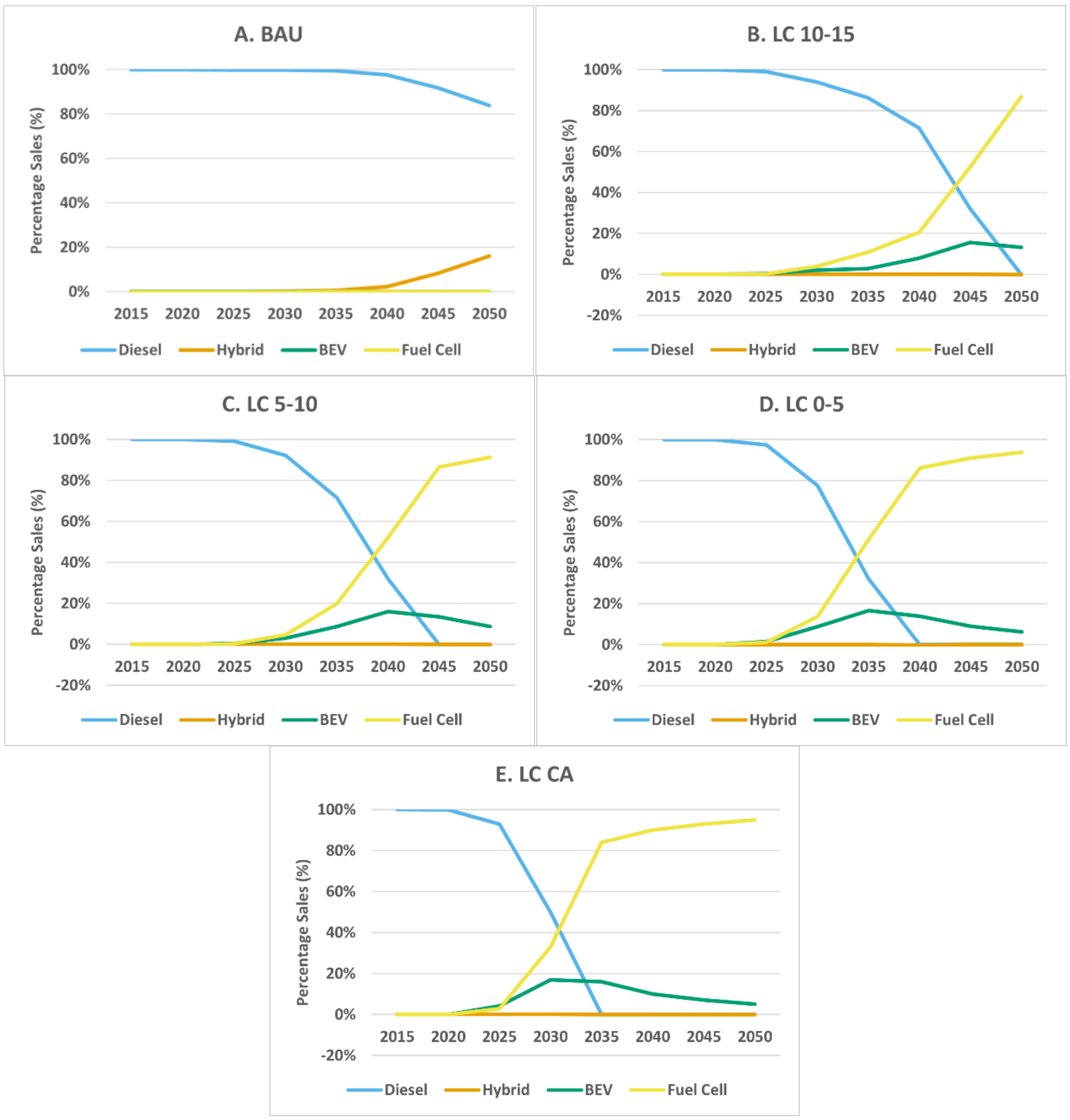

Figure 4-3. Sales shares of long-haul trucks for each scenario from 2015 to 2050.

Next, we assess the progression of sales shares for MD urban trucks for all scenarios. Contrary to LH trucks, the sales of MD urban trucks are much more heterogeneous in technology types. In the BAU scenario, almost no ZEV penetration happens even in 2050. The market is dominated by ICE vehicles which represent over 70% of sales for the entire time frame. There is a slow but steady rise in hybrid sales, reaching 28% in 2050. LC 10-15 and LC 5-10 scenarios start to have significant ZEV penetrations after 2030, reaching 100% in 2050 and 2045, respectively. Market shares of ICE vehicles drop as ZEV sales begin to grow. The replacement of ICE vehicles by ZEVs happens even earlier in LC 0-5 and LC CA scenarios. They reach 100% ZEV sales by 2040 and 2035, respectively. In all alternative scenarios, BEVs are much more popular than FCVs (Figure 4-4).

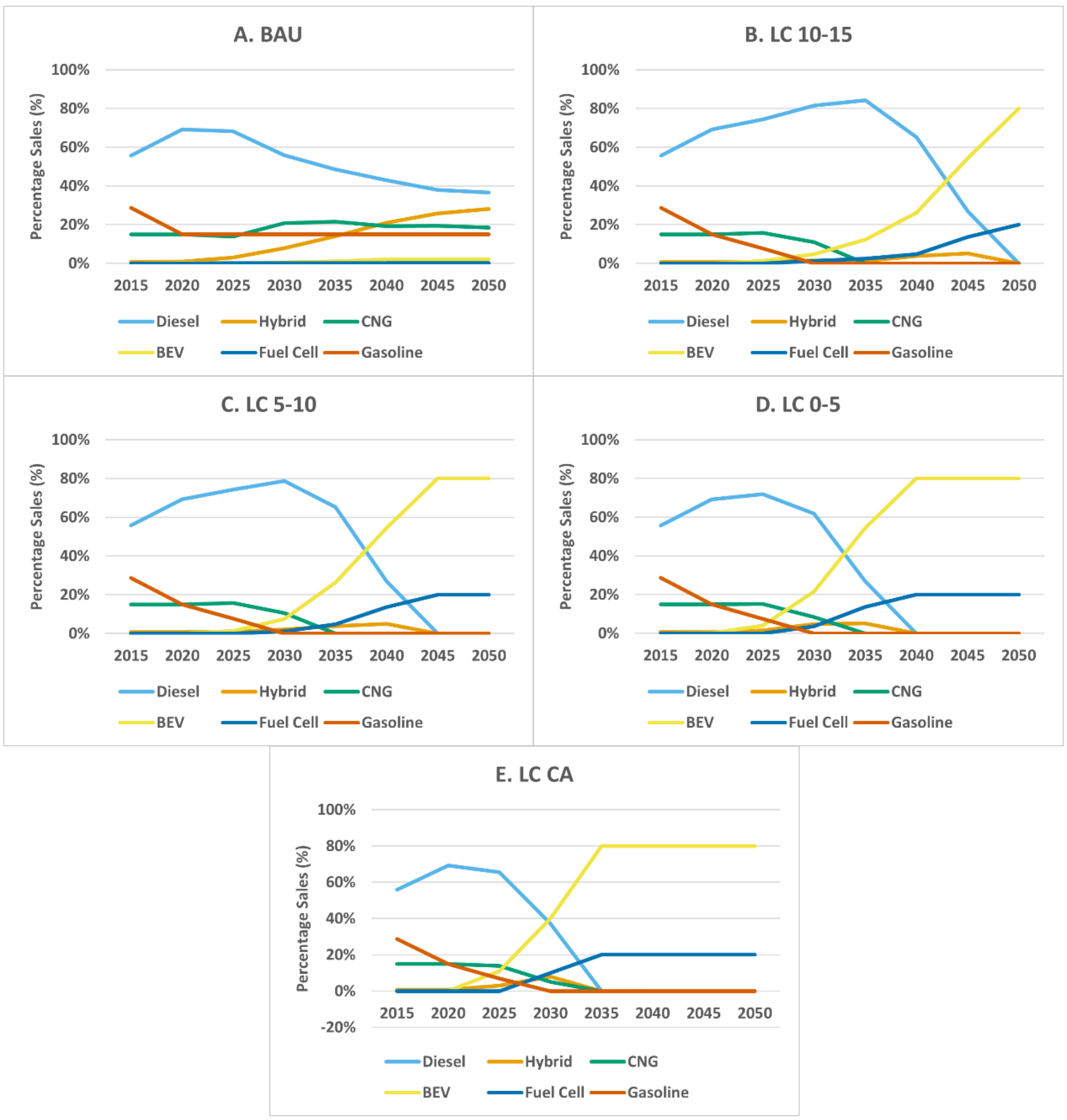

Figure 4-4. Sales shares of medium duty urban trucks for each scenario from 2015 to 2050.

Figure 4-5 demonstrates the progression of sales shares for HD pickups and vans for all scenarios. Like MD urban trucks, the sales of HD pickups and vans are more heterogeneous in technology types than LH trucks. In the BAU scenario, traditional diesel and gasoline vehicles still dominate the market, with a combined sales share of over 90% throughout the time frame. ZEV sales only account for 2% in 2050. In the LC 10-15 scenario, the combined sales of traditional diesel and gasoline vehicles fluctuate but drop to 26% in 2045 and are out of the market by 2050. The sales of ZEV vehicles enjoy a gradual but steady growth to 68% in 2045 and 100% in 2050. The trend of the LC 5-10 scenario is almost identical to the LC 10 scenario, with ZEV sales reaching 100% by 2045. LC 0-5 and LC CA scenarios have even faster ZEV penetrations, achieving 100% ZEV sales by 2040 and 2035, respectively.

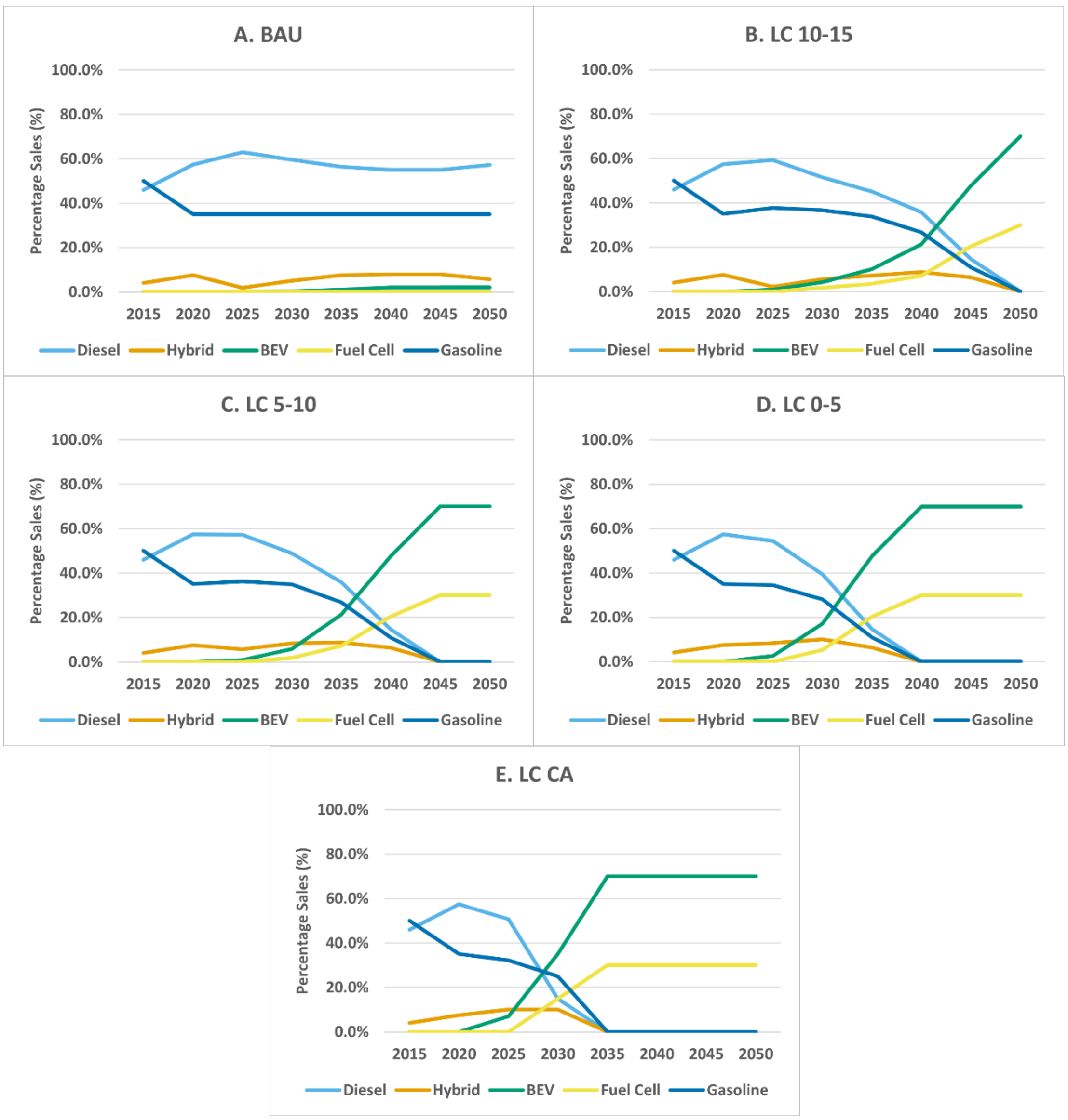

Figure 4-5. Sales shares of heavy-duty pickups and vans for each scenario from 2015 to 2050.

Figure 4-6 illustrates sales shares by technology type, in 2030 and 2050, for all vehicle types and scenarios. In the BAU scenario, ZEV penetration is low even in 2050, except for transit buses due to heavy subsidies. All alternative scenarios have much deeper ZEV penetration, reaching 100% ZEV sales by 2050. Among ZEVs, BEVs dominate the ZEV sales except for LH trucks.

Figure 4-6. Sales shares by technology type for all vehicle types and scenarios in 2030 and 2050.

4.2. Fleet Stock

According to sales and vehicle survival assumptions, TTM computes fleet stock for each year. Figure 4-7 shows the fleet mix by technology type for all scenarios over time for LDVs. From 2020 to 2050, the total vehicle stock increases by over 30%. In the BAU scenario, ICE vehicles still dominate the fleet through 2050. In 2050, HEVs and PHEVs account for approximately 15% of the stock. ZEVs represent 12% of the total stock, with few FCVs. The LC 10-15, LC 5-10, and LC 0-5 scenarios are very similar to each other. They all feature an upsurge of ZEV stock after 2030. The ZEV percentages in 2050 are 44%, 59%, and 70%, respectively, most of which are BEVs. Traditional ICE vehicle percentages drop to 41%, 25%, and 15% in 2050, respectively. The rest of the stock is filled by HEVs and PHEVs. The LC CA scenario has an even deeper penetration of ZEVs after 2030 with the ZEV share surpassing 75% in 2050. HEVs and PHEVs take up 1% and 15%, respectively. Less than 10% of ICE vehicles remain in use.

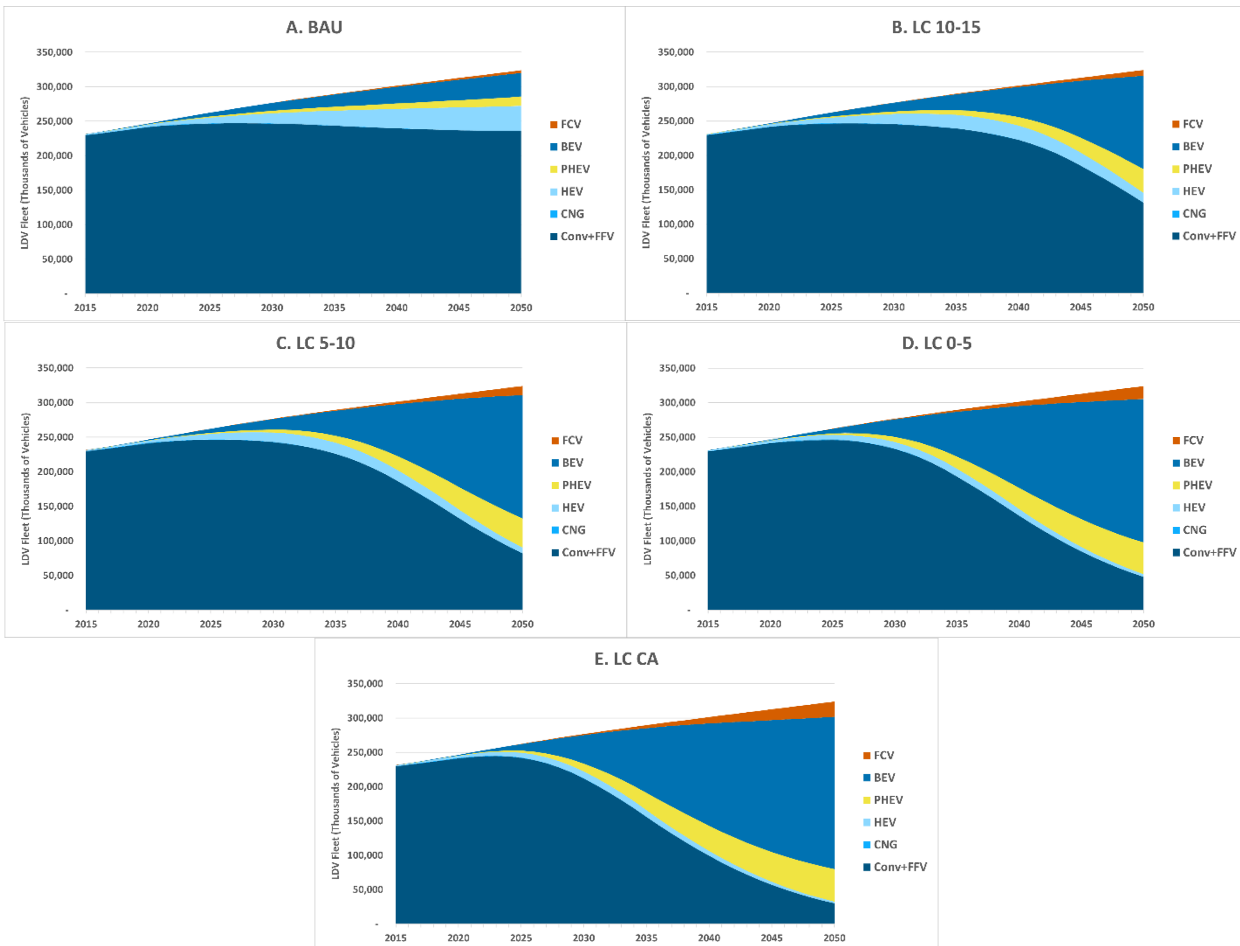

Figure 4-7. Fleet mix of light-duty vehicles for all scenarios from 2015 to 2050.

Figure 4-8 shows the fleet mix by technology type for all scenarios over time for LH trucks. From 2020 to 2050, the total vehicle stock increases by 57%. In the BAU scenario, diesel vehicles dominate the fleet through 2050. The only other significant technology type is HEV, accounting for roughly 6% in 2050. The alternative scenarios share a very similar trend, with different degrees of ZEV penetrations. Most ZEVs are FCVs due to the limited range of BEVs for this application.

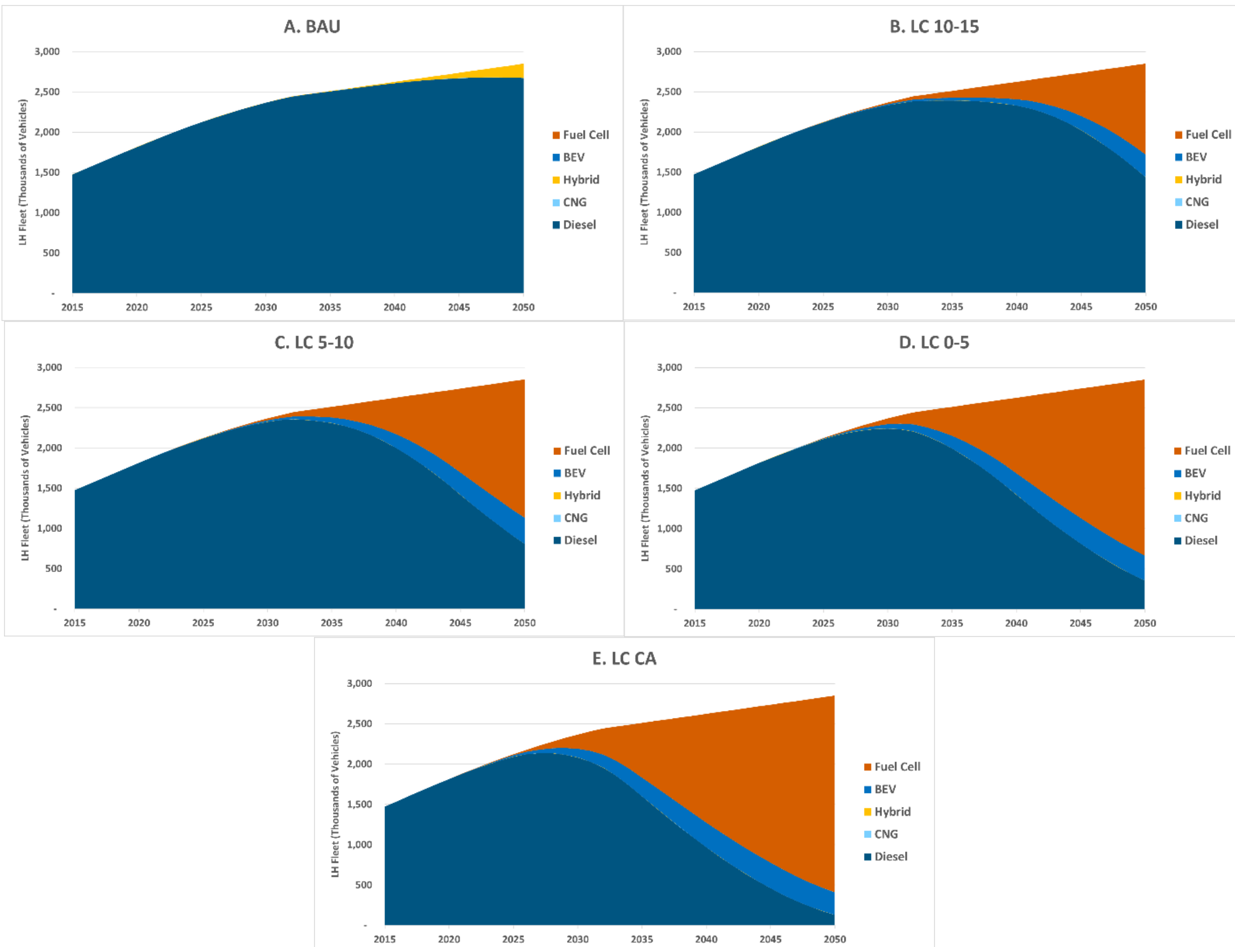

Figure 4-8. Fleet mix of long-haul trucks for all scenarios from 2015 to 2050.

Figure 4-9 shows the fleet mix by technology type for all scenarios over time for MD urban trucks. From 2020 to 2050, the total vehicle stock increases by 64%. In the BAU scenario, ICE vehicles dominate the fleet throughout the entire time frame, although with a declining trend due to the rise of HEVs. In 2050, HEVs account for 21% of the fleet stock. In all the alternative scenarios, ZEVs begin to grow in the fleet after 2030, crowding out ICE vehicles and HEVs. In 2050, ZEVs represent 48% to 94% of the total fleet stock. As opposed to LH trucks, most ZEVs are BEVs in this vehicle category.

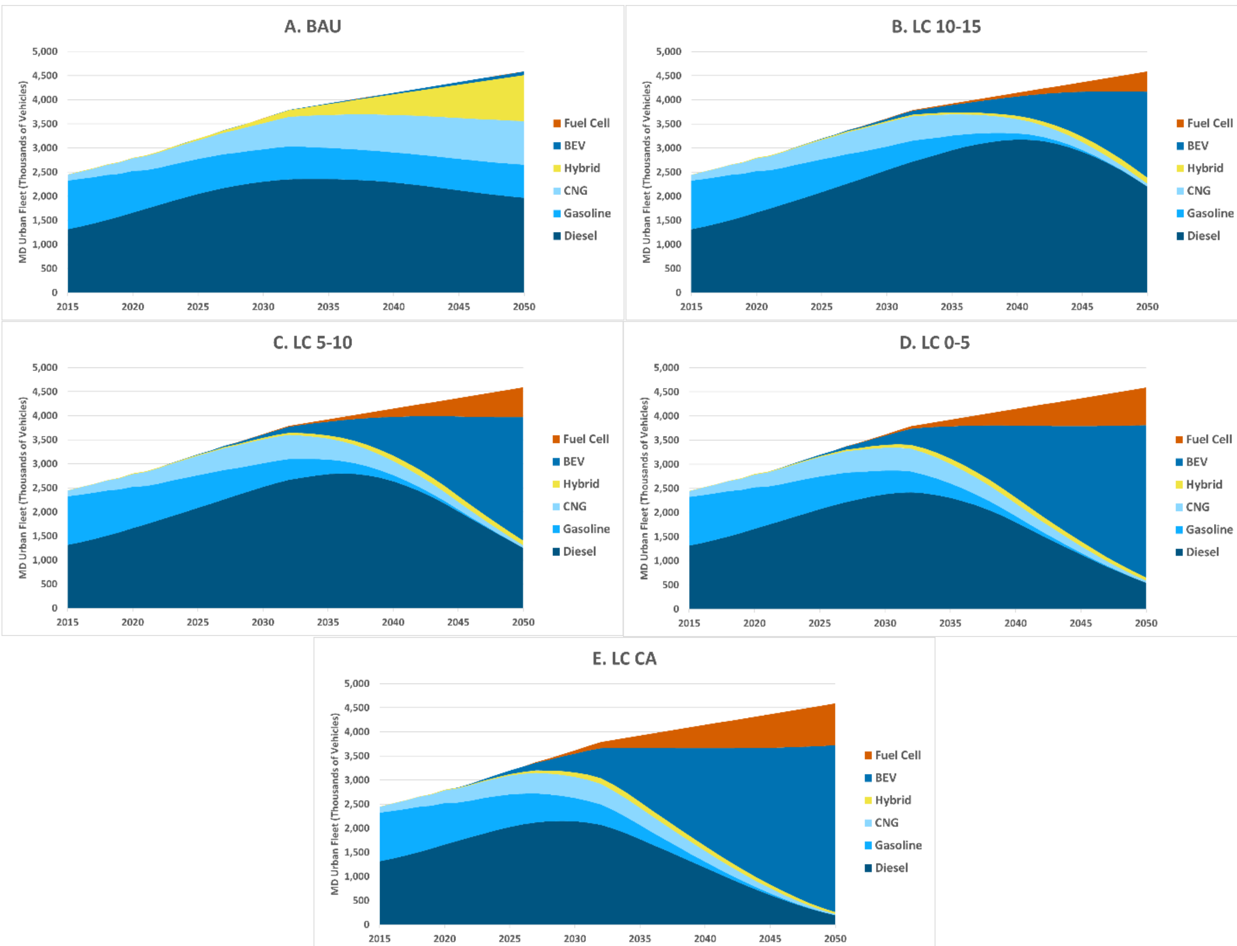

Figure 4-9. Fleet mix of medium-duty urban trucks for all scenarios from 2015 to 2050.

[Figure 4-10](#) shows the fleet mix by technology type for all scenarios over time for HD pickups and vans. From 2020 to 2050, total vehicle stock increases by 25%. In the BAU scenario, traditional diesel and gasoline vehicles still dominate the fleet through 2050, with a combined percentage of 91% in 2050. In 2050, HEVs account for 7% of vehicles and less than 2% are BEVs. The alternative scenarios again share a very similar trend, with different degrees of ZEV penetration. For the LC 0-5 and LC CA scenarios, ICE vehicles only represent 11% and 4% of total stock in 2050, respectively.

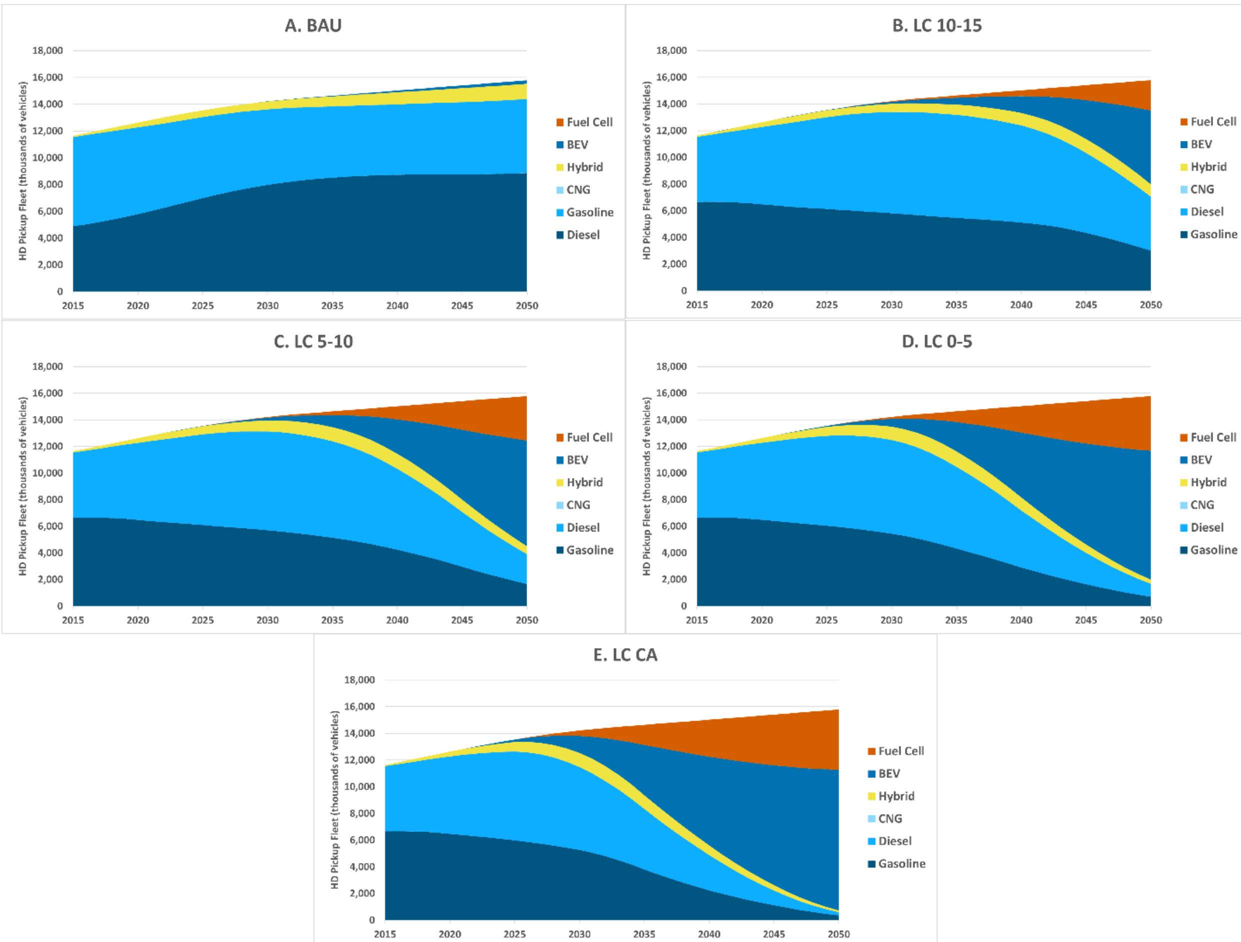

Figure 4-10. Fleet mix of heavy-duty pickups and vans for all scenarios from 2015 to 2050.

[Figure 4-11](#) illustrates the shares of fleet stock by technology type, in 2030 and 2050, for all vehicle types and scenarios. In the BAU scenario, traditional ICE vehicles still dominate except for transit buses. Over 97% of transit buses are BEVs in 2050. The LC scenarios feature much more aggressive ZEV penetrations. For the LC 5-10 and LC 0-5 scenarios, all vehicle categories achieve over 69% and 82% ZEV stock in 2050, respectively. The LC CA scenario is dominated by ZEVs in 2050, with more than 90% ZEVs for almost all vehicle categories.

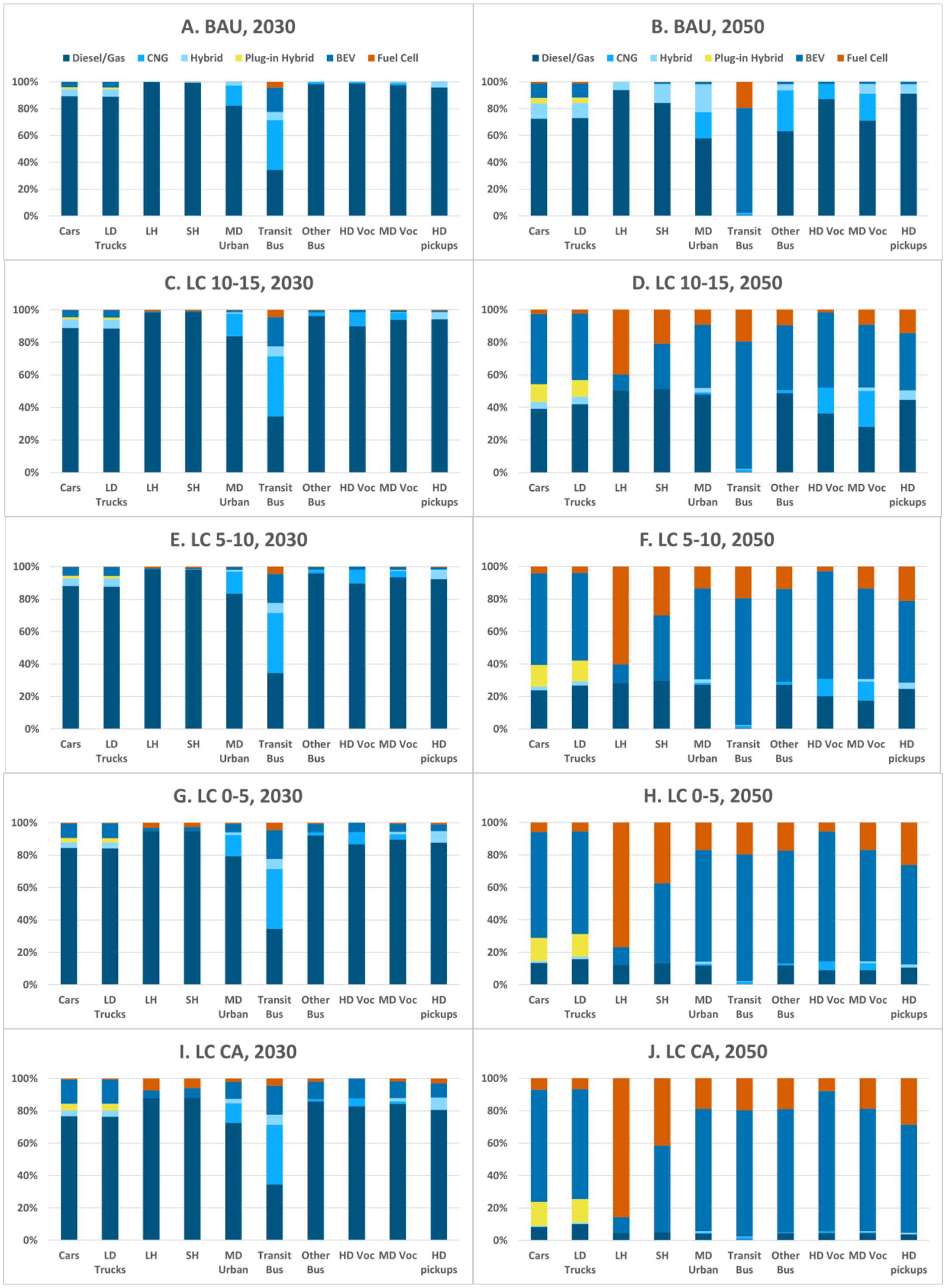

Figure 4-11. Percentage of fleet stock by technology type for all vehicle types and scenarios in 2030 and 2050.

4.3. Vehicle Miles Traveled by Technology

We assume the same VMT schedule for ZEVs as conventional vehicles. In the BAU scenario, only the transit bus category shows a large ZEV contribution, with over 98% by 2050. The VMT of other vehicle types is primarily contributed by ICE vehicles. The LC scenarios are, again, very similar. For the LC 5-10 and LC 0-5 scenarios, the contribution from ZEVs surpasses 70% and 86% in 2050, for all vehicle types, respectively. The ZEV contribution in the LC CA scenario is even higher, with all vehicle types exceeding 93% in 2050. The percentage of VMT by technology type, in 2030 and 2050, for all vehicle types and scenarios, is demonstrated in Figure 4-12.

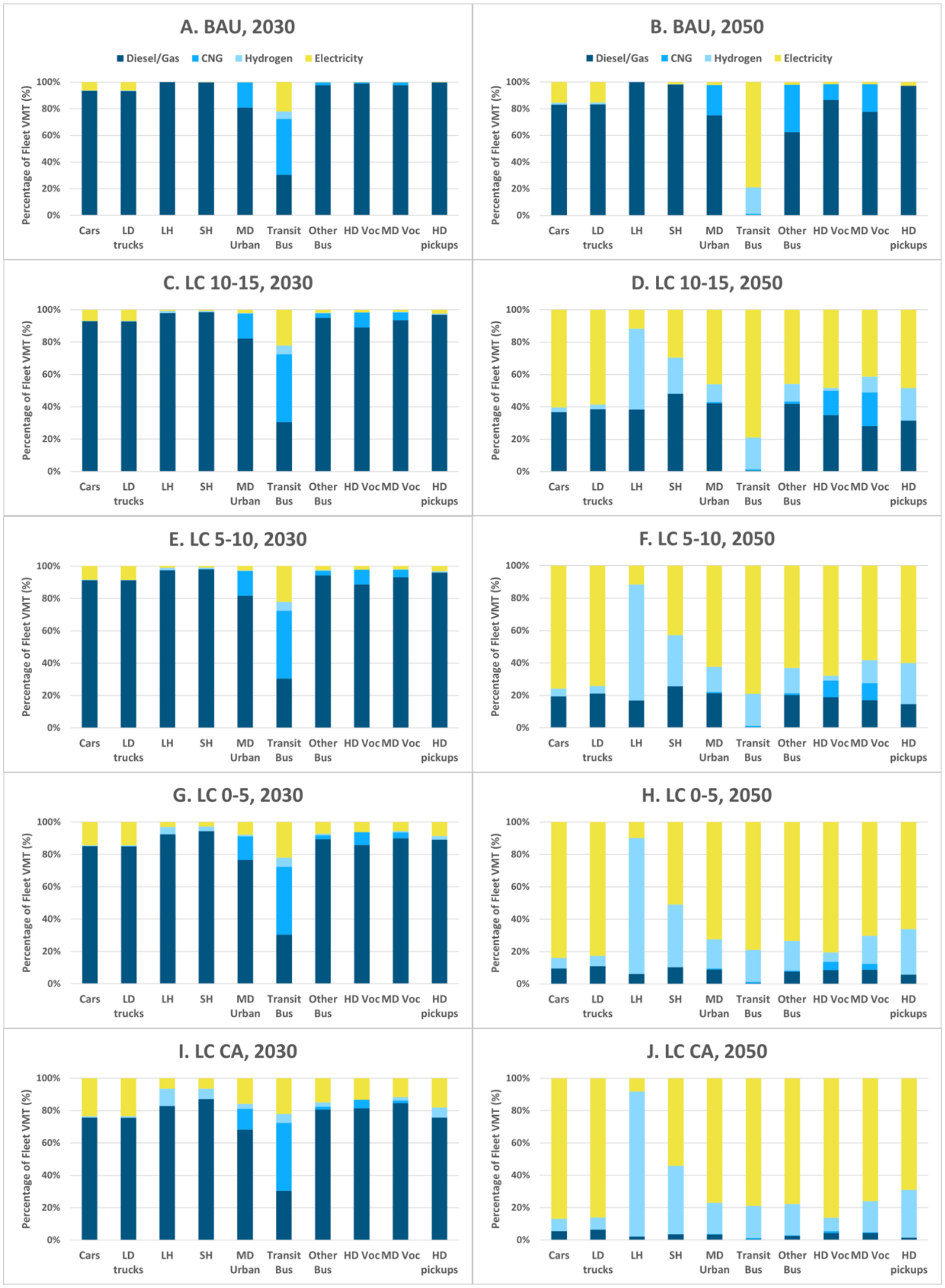

Figure 4-12. Percentage of vehicle miles traveled by technology type for all vehicle types and scenarios in 2030 and 2050.

4.4. Fuel Consumption by Fuel Type

Figure 4-13 shows fuel consumption by fuel type for each scenario of 2030 and 2050 and presents the actual historical fuel consumption in 2015. Panel A reflects the fuel consumption of all vehicles. From BAU to LC CA scenario, a greater reduction is achieved by 2050. In the BAU scenario, although diesel and gasoline remain the primary fuel in 2050, the total fuel consumption drops approximately 13% compared to 2015, mainly due to fuel efficiency gains. The other scenarios have a 39% to 58% reduction in 2050, compared to 2015, with alternative fuels dominating the consumption.

Panels B and C represent the fuel consumptions for LDVs and MHDVs, respectively. The general trend is similar to panel A. For LDVs, the BAU scenario features a drop of 19%, from 2015 to 2050, as fuel efficiency gains more than offset increases in VMT. It is also clear that LDVs favor gasoline/BBE over diesel/BBD in the BAU scenario, and electricity (BEVs) over hydrogen (FCVs) in alternative scenarios. MHDVs generally have less reduction than LDVs. As opposed to LDVs, MHDVs favor diesel/BBD over gasoline/BBE in the BAU scenario. There is more hydrogen usage than electricity in MHDVs in alternative scenarios because FCVs dominate LH trucking.

In all vehicle categories, biofuel plays an important role in the transition to cleaner fuels and ultimately reaches 100% of liquid fuels by 2050.

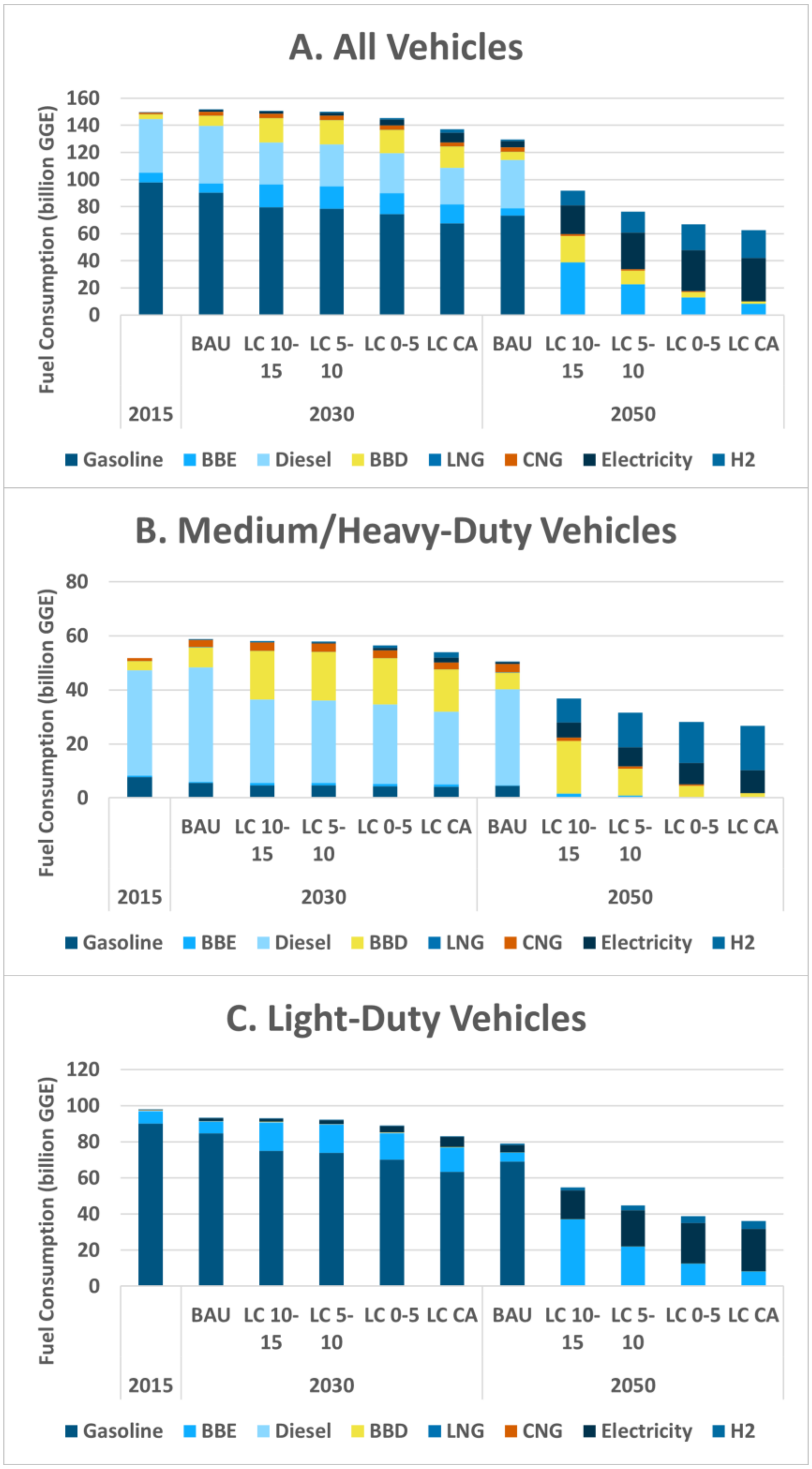

Figure 4-13. Fuel consumption by fuel type for all scenarios in 2030 and 2050. Historical fuel consumption by fuel type for 2015 shown.

4.5. Reduction of Greenhouse Gases

The introduction of new technologies and fuels can reduce GHG reductions due to their improved fuel efficiency and lower CI. However, GHG emissions are also affected by increases in VMT. In our models, we assume the same VMT schedule for all scenarios. Table 4-1. Percentage greenhouse gas reductions in 2050 from 2015 by scenario for light-duty vehicles (LDV) and medium/heavy-duty vehicles (MHDV) demonstrates the percentage GHG reductions in 2050, from 2015, by scenario, for LDVs and MHDVs.

Table 4-1. Percentage greenhouse gas reductions in 2050 from 2015 by scenario for light-duty vehicles (LDV) and medium/heavy-duty vehicles (MHDV).

Scenario	Percentage GHG Reduction in 2050 from 2015
LDV BAU	21.6%
LDV LC 10-15	91.5%
LDV LC 5-10	95.0%
LDV LC 0-5	97.1%
LDV LC CA	98.1%
MHDV BAU	10.7%
MHDV LC 10-15	88.4%
MHDV LC 5-10	93.9%
MHDV LC 0-5	97.4%
MHDV LC CA	99.0%
Combined LDV and MHDV BAU	17.9%
Combined LDV and MHDV LC 10-15	90.4%
Combined LDV and MHDV LC 5-10	94.6%
Combined LDV and MHDV LC 0-5	97.2%
Combined LDV and MHDV LC CA	98.4%

Figure 4-14 shows graphic comparisons of GHG emissions between different scenarios for MHDVs and LDVs.

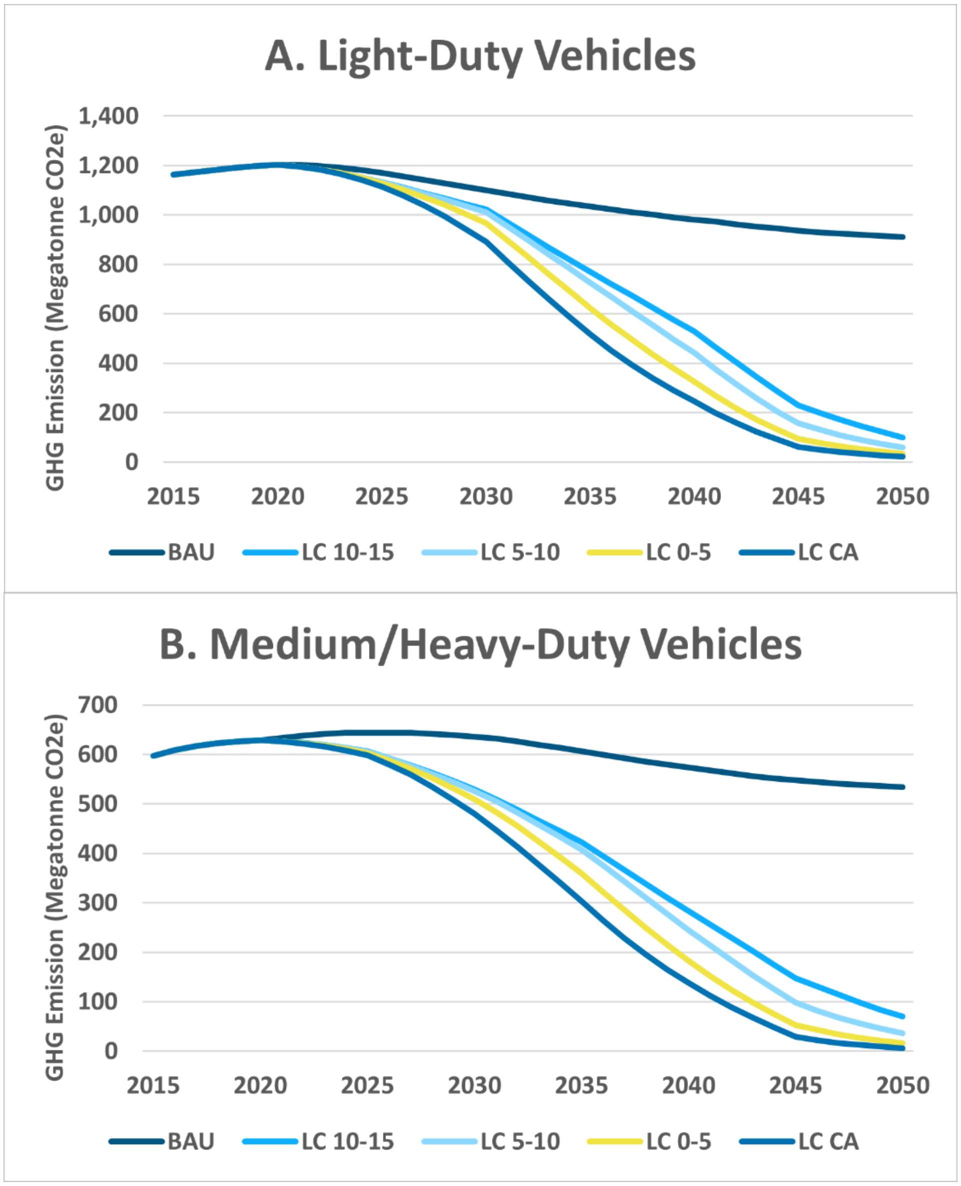

Figure 4-14. Comparisons of greenhouse gas emissions between different scenarios for light-duty vehicles (LDV) and medium/heavy-duty vehicles (MHDV), from 2015 to 2050.

The LC CA scenario achieves the largest GHG reductions of all scenarios (Table 4-1) due to improved efficiency of ZEVs and reduced CI of electricity and hydrogen compared to traditional vehicles and fuels, as illustrated in Figure 4-15. Electricity and hydrogen produced by renewable feedstocks contribute significantly to the lowered CI.

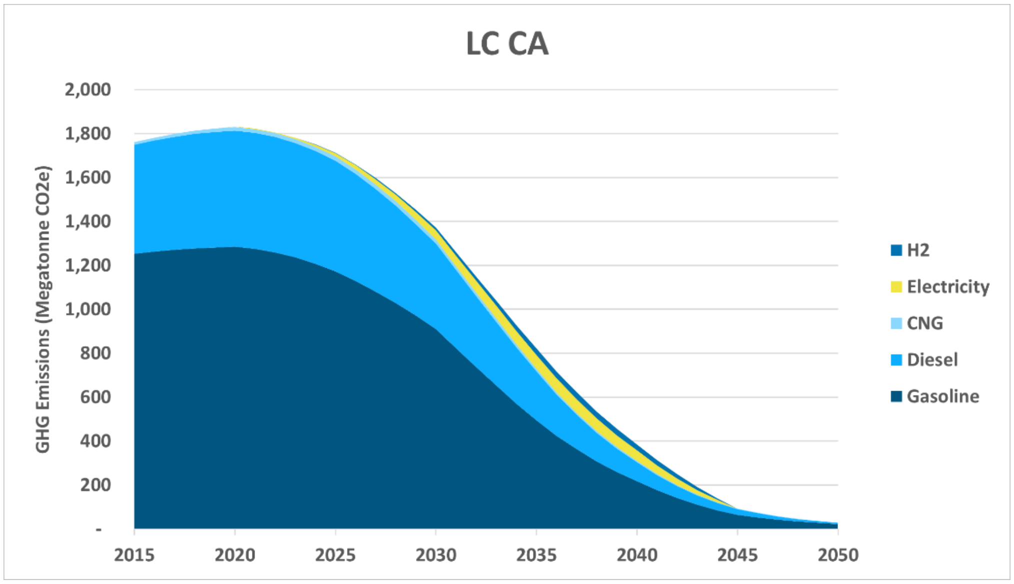

Figure 4-15. Greenhouse gas emission of the LC CA scenario, by fuel type, from 2015 to 2050, for all vehicles.

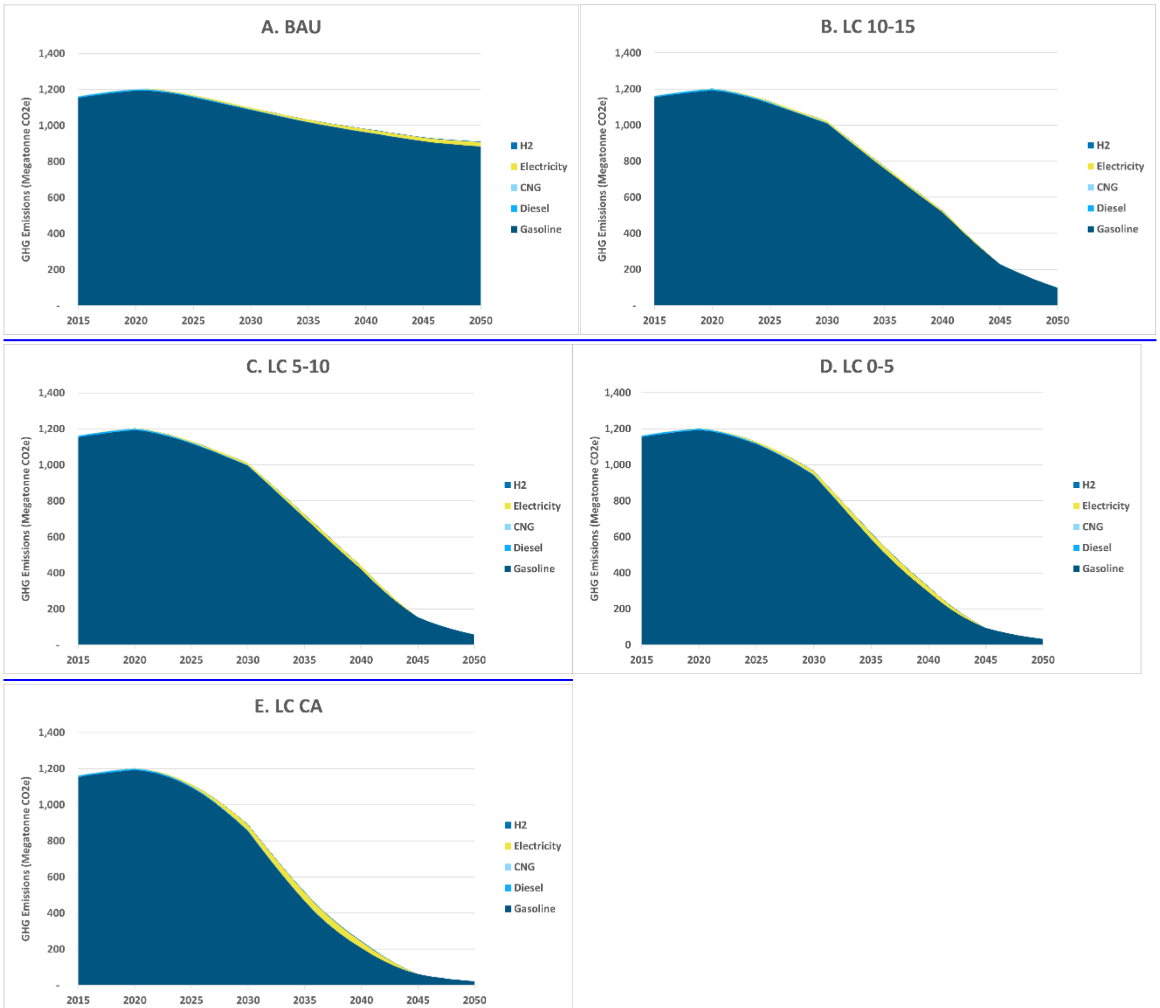

Figure 4-16 shows the GHG emission of all scenarios by fuel type, from 2015 to 2050, for LDVs. The BAU scenario has a total GHG reduction of 22% in 2050, compared to 2015. GHG reduction of alternative scenarios is at least 91% in 2050, compared to 2015.

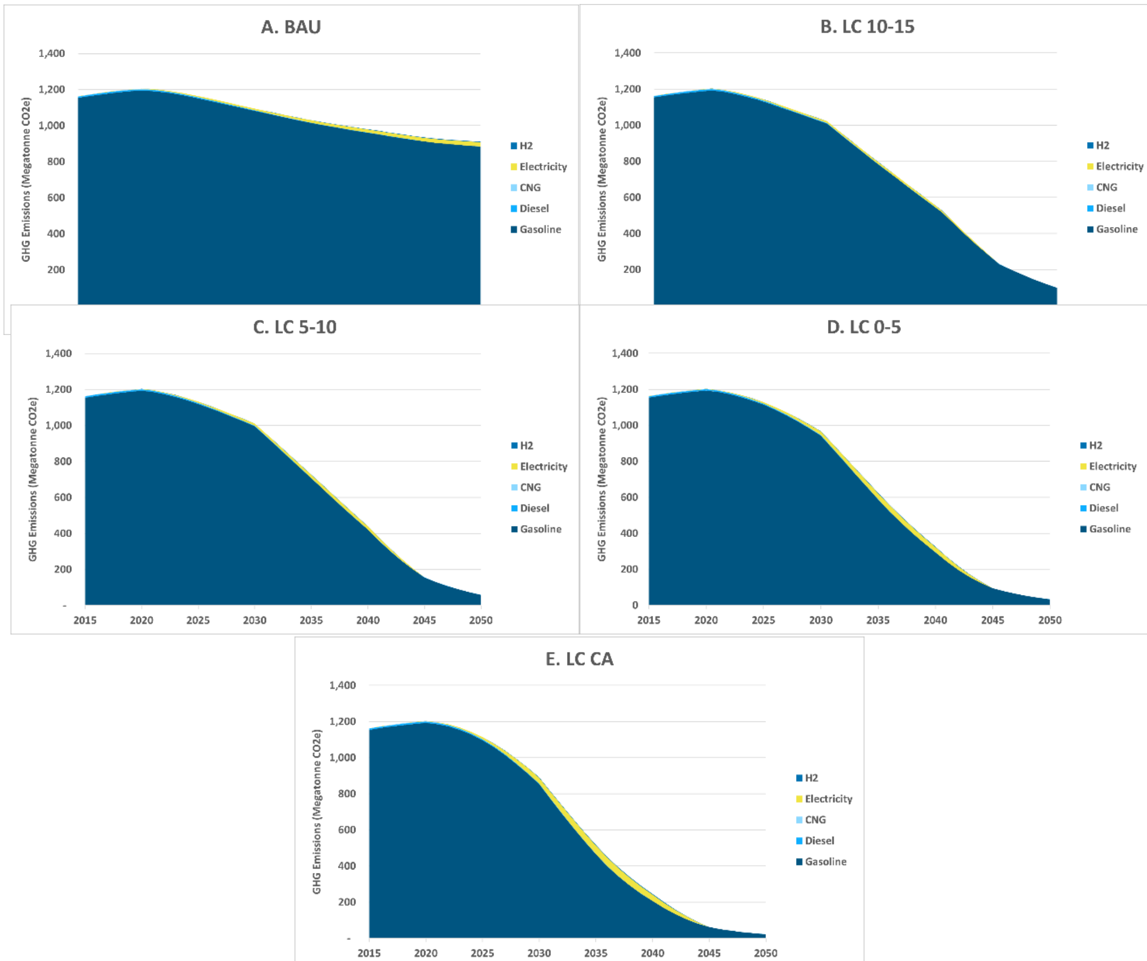

Figure 4-16. Light-duty vehicle greenhouse gas emission for all scenarios by fuel type, from 2015 to 2050.

[Figure 4-17](#) shows the GHG emission of all scenarios by fuel type, from 2015 to 2050, for MHDVs. The BAU scenario has a slight total GHG reduction of 11% in 2050, compared to 2015. GHG reduction of alternative scenarios is at least 88% in 2050, compared to 2015.

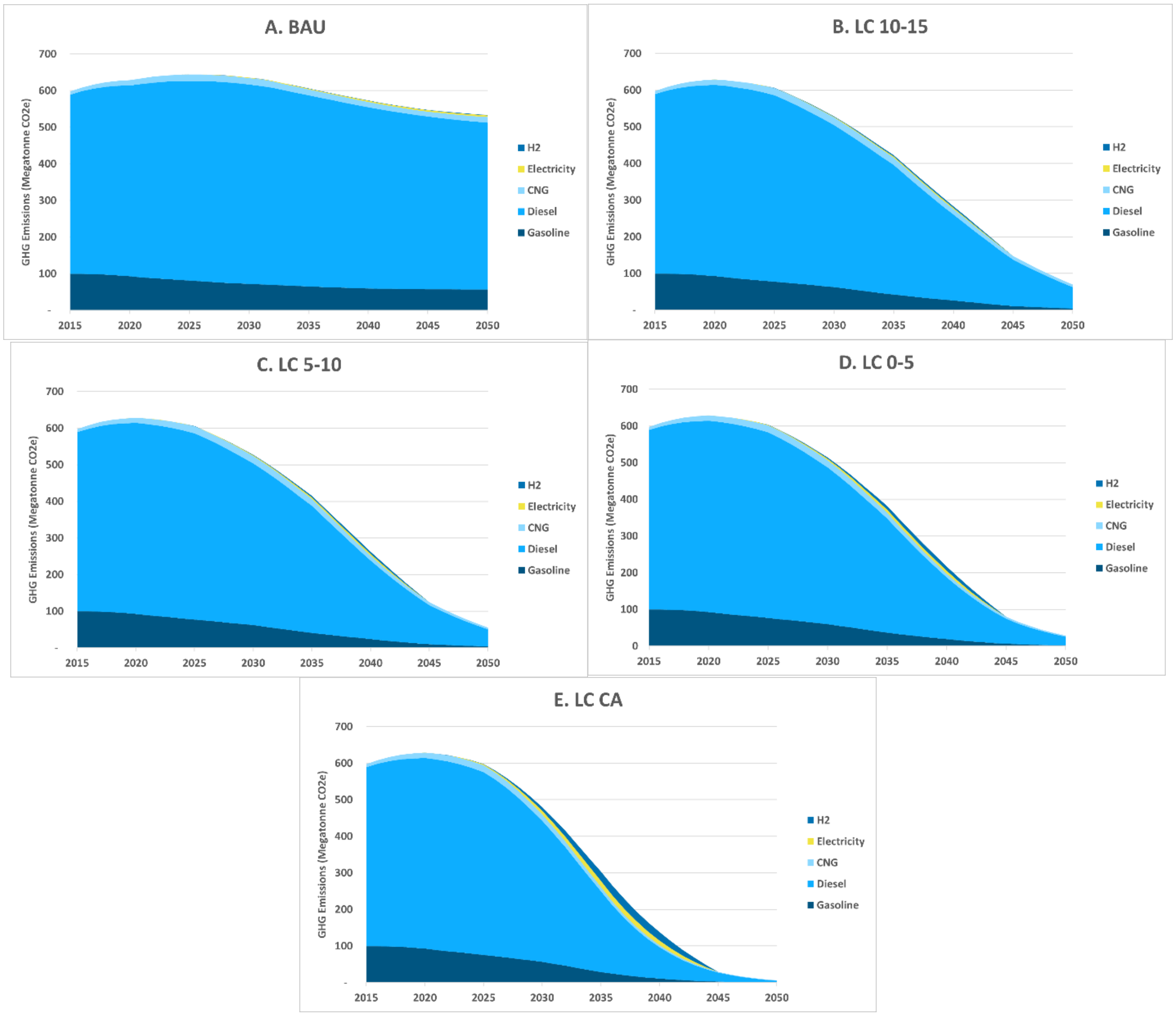

Figure 4-17. Medium/heavy-duty vehicle greenhouse gas emissions for all scenarios by fuel type, from 2015 to 2050.

4.6. Biofuel Consumption

All alternative scenarios have a similar trend: biofuel consumption increases until reaching a peak, and then drops quickly. The initial rise is a result of increasing blend percentages of BBD/BBE in the diesel/gasoline blend. As more ZEVs enter the fleet, consumption of diesel/gasoline blend decreases and eventually offsets the increasing biofuel content, leading to the decline of biofuel consumption. As scenarios feature a more aggressive ZEV penetration, the peak comes earlier and is lower (Figure 4-18).

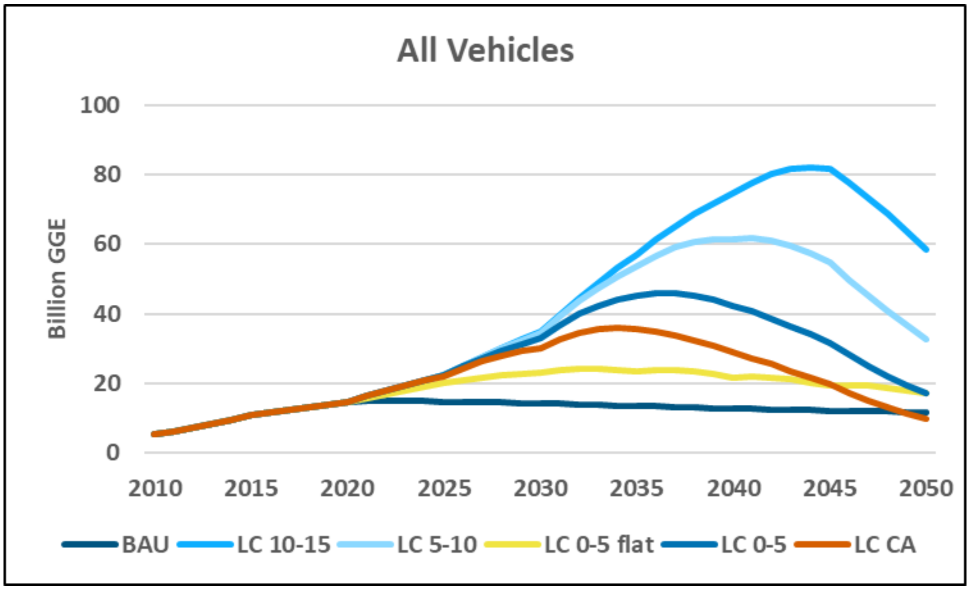

Figure 4-18. Biofuel consumption of all scenarios by fuel type for all vehicles from 2015 to 2050.

This biofuel consumption pattern raises several important questions:

- What is the maximum US production capacity for biofuels?
- What are the feedstocks for those biofuels?
- If US consumption falls well below supply 5 to 10 years after the peak, what can we do with the excess production?

These questions are yet to be studied in-depth. Here we partially address these concerns by introducing an "LC 0-5 flat" scenario. It is the same as the LC 0-5 scenario except for the biofuel percentages of diesel/gasoline blend. We lower the biofuel content in the diesel/gasoline blend so that the "LC 0-5 flat" scenario has a gradual increase of biofuel consumption. This achieves the same GHG reduction as the LC 0-5 scenario in 2050, when biofuels reach 100% of liquid fuel use. The cumulative GHG emissions of the LC 0-5 and "LC 0-5 flat" scenarios, from 2020 to 2050, are 29.9 and 32.7 Gt CO_2e, respectively. Therefore, the "LC 0-5 flat" scenario can avoid the peak demand problem while only having 9% more cumulative GHG emissions than the LC 0-5 scenario. These results suggest that there is no urgent need to ramp up the biofuel production too quickly, as in the LC 0-5 scenario.

4.7. Costs

The US TTM predicts the vehicle, fuel, and maintenance costs for LDVs and MHDVs across the 2020-to-2050-time frame. As mentioned in Section 3.4, we do not account for the costs that will incur beyond 2050, and future costs are not discounted. The model also compares cost differences between scenarios for the entire time frame, and separately for two time periods, 2020 to 2030, and 2031 to 2050 (Figure 4-19).

The total costs of purchasing, operating, and maintaining vehicles over the entire time frame range approximately from $53 to $58 trillion (Figure 4-19-A). Roughly 30% and 70% of the total costs are represented by MHDVs and LDVs, respectively. The LDV costs are dominated by vehicle costs while for MHDVs both fuel and maintenance costs are higher than vehicle costs. This reflects the lower fuel economy and longer driving distances typical of MHDVs.

Total costs decrease as a scenario has a more aggressive ZEV penetration (Figure 4-19-A). With more ZEVs, the huge savings in fuel and maintenance dominate cost comparisons (Figure 4-19-B). The main reason for fuel savings is the higher energy efficiency of ZEVs, while the main reason for maintenance savings is the lower expected need for maintenance of ZEVs.

Cost comparisons between scenarios look very different if we break down the entire time frame into two time periods, 2020 to 2030, and 2031 to 2050 (Figure 4-19-C). From 2020 to 2030, adopting alternative scenarios generally means slightly more total costs. In these years ZEVs are much more expensive than traditional ICE vehicles because they are still relatively new technologies produced in lower quantities, which more than offsets the savings in fuel and maintenance. However, as costs of purchasing ZEVs decrease over time due to learning-by-doing and the economy of scale. From 2031 to 2050 the overall costs of alternative scenarios are significantly lower than BAU.

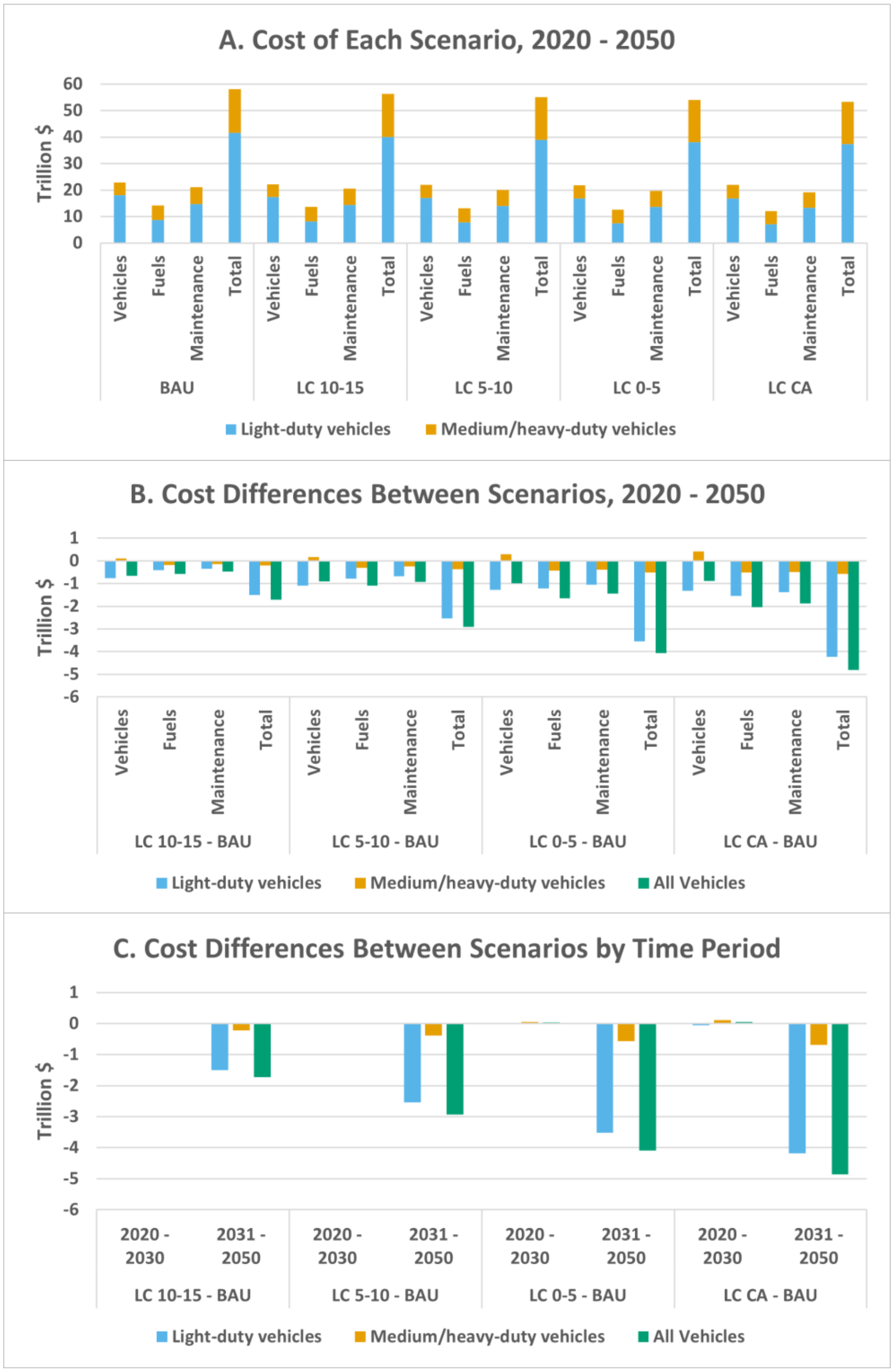

Figure 4-19. Summary of differences between scenarios. (A) Vehicle, fuel, and maintenance costs by scenario from 2020 to 2050; (B) Vehicle, fuel, maintenance, total cost differences between scenarios from 2020 to 2050; (C) Total cost differences between scenarios for two periods from 2020 to 2030 and 2031 to 2050.

4.7.1. LC 5-10 – Business as Usual Costs

Here, we present year-by-year cost comparisons between two low-carbon scenarios and the BAU scenario. Figure 4-20 illustrates the cost differentials between the LC 5-10 and BAU scenarios, i.e., the costs of the LC 5-10 scenario minus the costs of the BAU scenario, from 2015 to 2050. Figure 4-21 is a zoomed-in version of Figure 4-20, highlighting the period from 2020 to 2030. Negative values correspond to savings in the LC 5-10 scenario. The blue and orange curves represent the cost differences in purchasing new vehicles and operating and maintaining vehicles, respectively. The green curves are the addition of the blue and orange curves, thus reflecting differences in total costs.

Comparing LDVs shows that the difference in vehicle costs is slightly positive by 2029 because advanced clean vehicles are more expensive than ICE vehicles in the early years (Figure 4-20-A and Figure 4-21-A). As the costs of purchasing advanced vehicles fall, the blue curve crosses zero and becomes negative in 2030. The cost of ICE vehicles exceeds BEVs and FCVs by 2030 and 2040, respectively. The operation and maintenance (O&M) cost differential is negative throughout, mainly due to the lower maintenance required for ZEVs, relative to ICE vehicles. The LC 5-10 scenario also achieves fuel savings compared to the BAU scenario. Although alternative fuels are more expensive than fossil fuels, the much higher fuel efficiency of advanced vehicles more than offsets the price difference, thus leading to overall savings in fuel. As a result, the total cost difference curve has a declining trend similar to the other two curves.

When comparing MHDVs, vehicle cost difference remains positive for the entire time frame because most advanced MHDVs are more expensive than diesel vehicles, even in 2050 (Figure 4-20-A). Although the price difference between advanced vehicles and diesel vehicles decreases as time moves forward, the vehicle cost difference is almost uniformly increasing because a growing number of advanced vehicles are purchased year-by-year to meet the ZEV targets. The comparison of O&M costs is similar to LDVs. The difference in total costs fluctuates in the early years, then eventually declines and becomes negative after 2033, when the savings of O&M costs become dominant.

The comparison of LDVs and MHDVs combined is shown in the bottom panel (Figure 4-20-A and Figure 4-21-A). The trend is almost identical to LDVs as they dominate the overall costs.

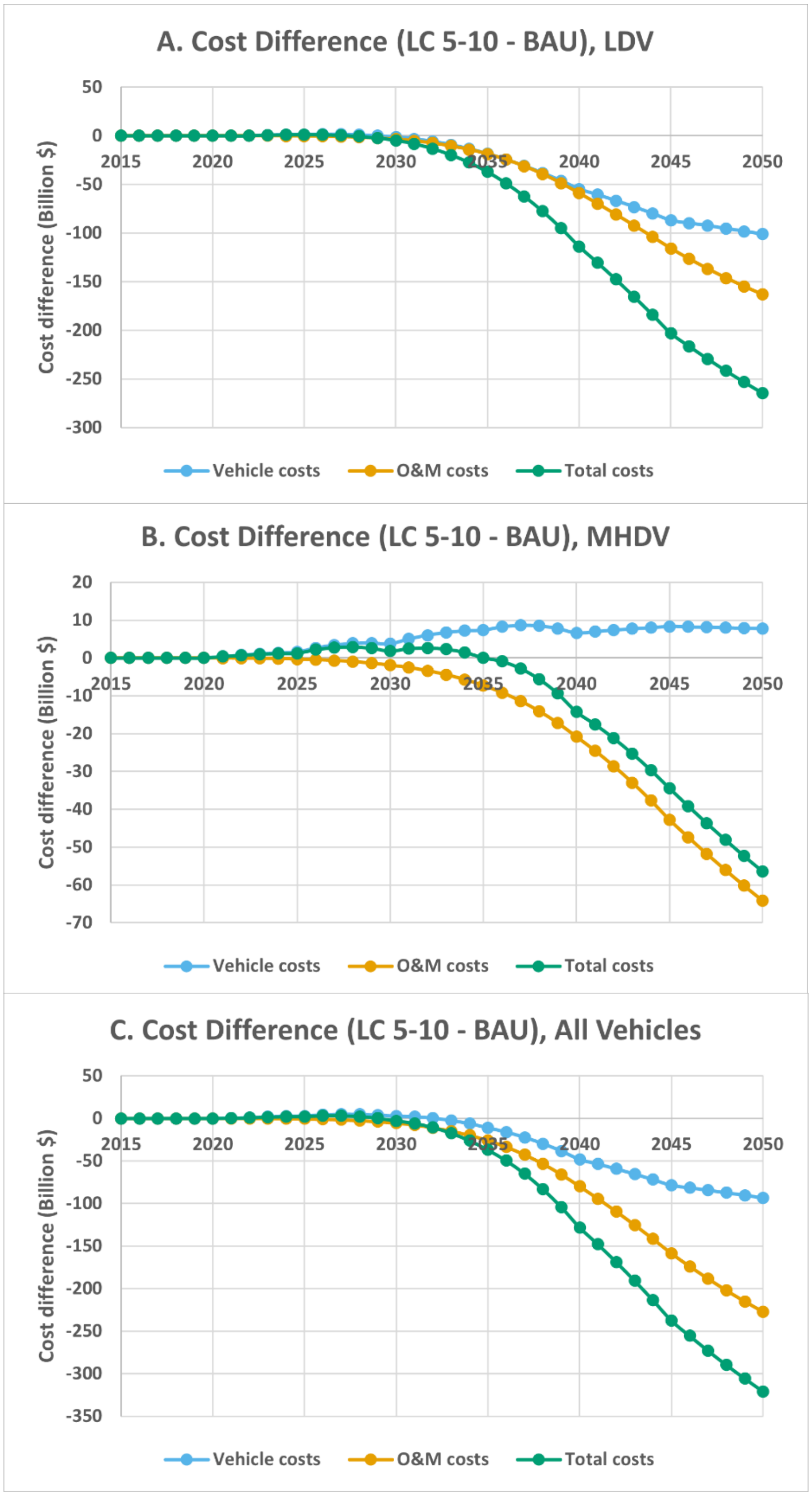

Figure 4-20. Cost comparisons between LC 5-10 and BAU scenarios from 2015 to 2050 for light-duty vehicles (LDV) (A), medium/heavy-duty vehicles (MHDV) (B), and all vehicles (C).

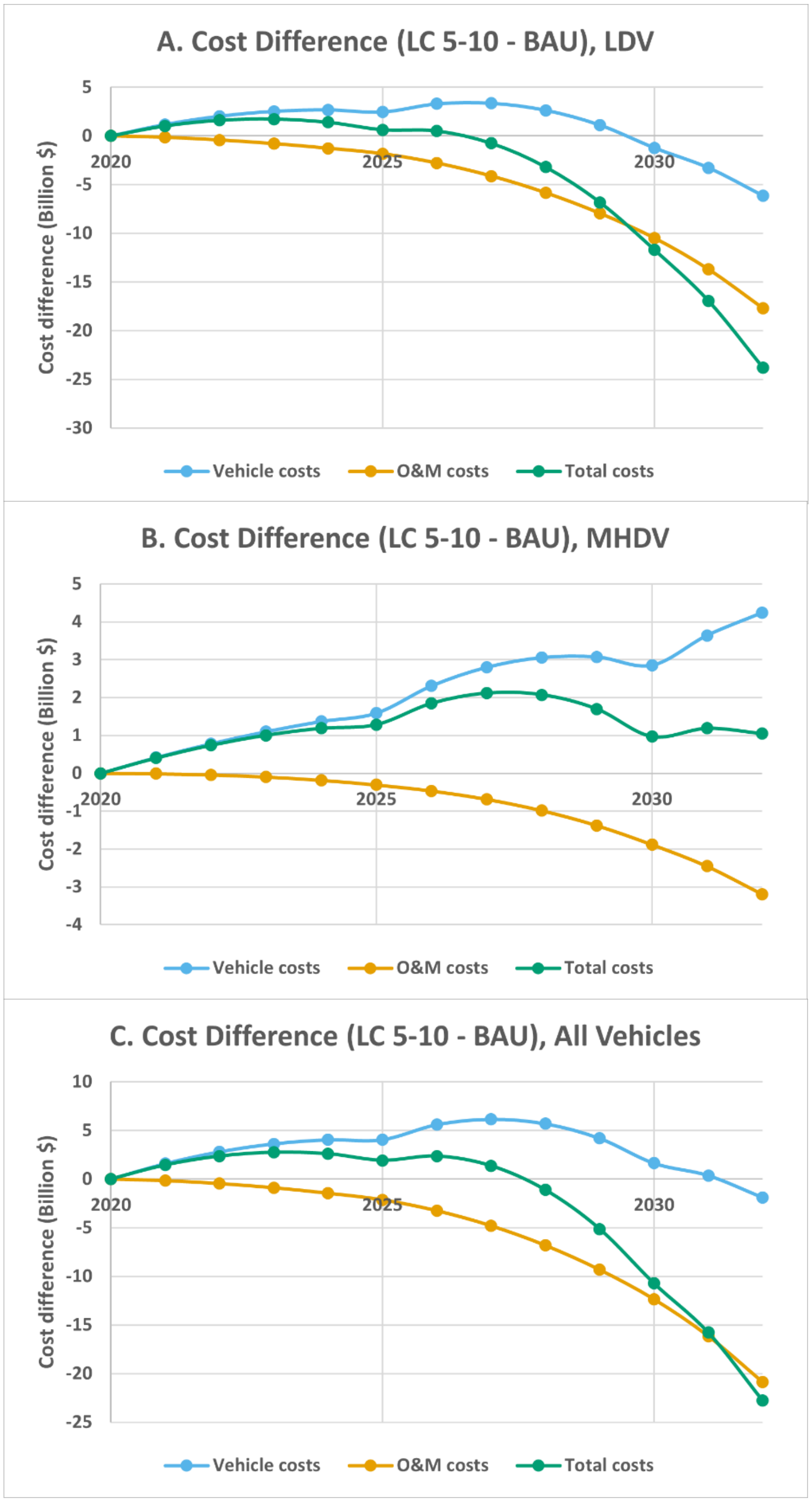

Figure 4-21. Cost comparisons between the LC 5-10 and BAU scenarios from 2020 to 2030 for light-duty vehicles (LDV) (A), medium/heavy-duty vehicles (MHDV) (B), and all vehicles (C).

4.7.2. LC CA – Business as Usual Costs

Figure 4-22 illustrates the cost differentials between the LC CA and BAU scenarios, i.e., LC CA scenario costs minus BAU scenario costs.

When comparing LDVs, the trend is similar to comparisons between the LC 5-10 and BAU scenarios (Figure 4-22-A), although the initial positive vehicle cost differential is more pronounced, reflecting faster ZEV penetration of LC CA relative to LC 5-10. The difference in O&M cost is strictly negative and decreasing, due to higher fuel efficiency and lower maintenance requirements of advanced vehicles. The total cost difference curve has a slight rise initially and then plunges to negative.

The comparison of MHDVs is more complicated than LDVs (Figure 4-22-B). The initial rise of the blue curve is smooth until 2025, when the slope increases rapidly. This can be explained by accelerated ZEV penetration from 2025 to 2035 in the LC CA scenario. The blue curve starts to drop around 2035 as the price of advanced vehicles falls close to diesel vehicles. The blue curve levels off from 2040 to 2050, remaining positive because most advanced MHDVs continue to be more expensive than diesel vehicles in this period. The difference in O&M cost is again strictly negative and decreasing. The shape of the total cost difference curve is similar to the vehicle cost difference curve, dropping moderately due to the O&M cost difference curve.

The comparisons of LDVs and MHDVs combined are shown in the bottom panel (Figure 4-22-C). This comparison shares the same trend as LDVs because they dominate the cost comparisons.

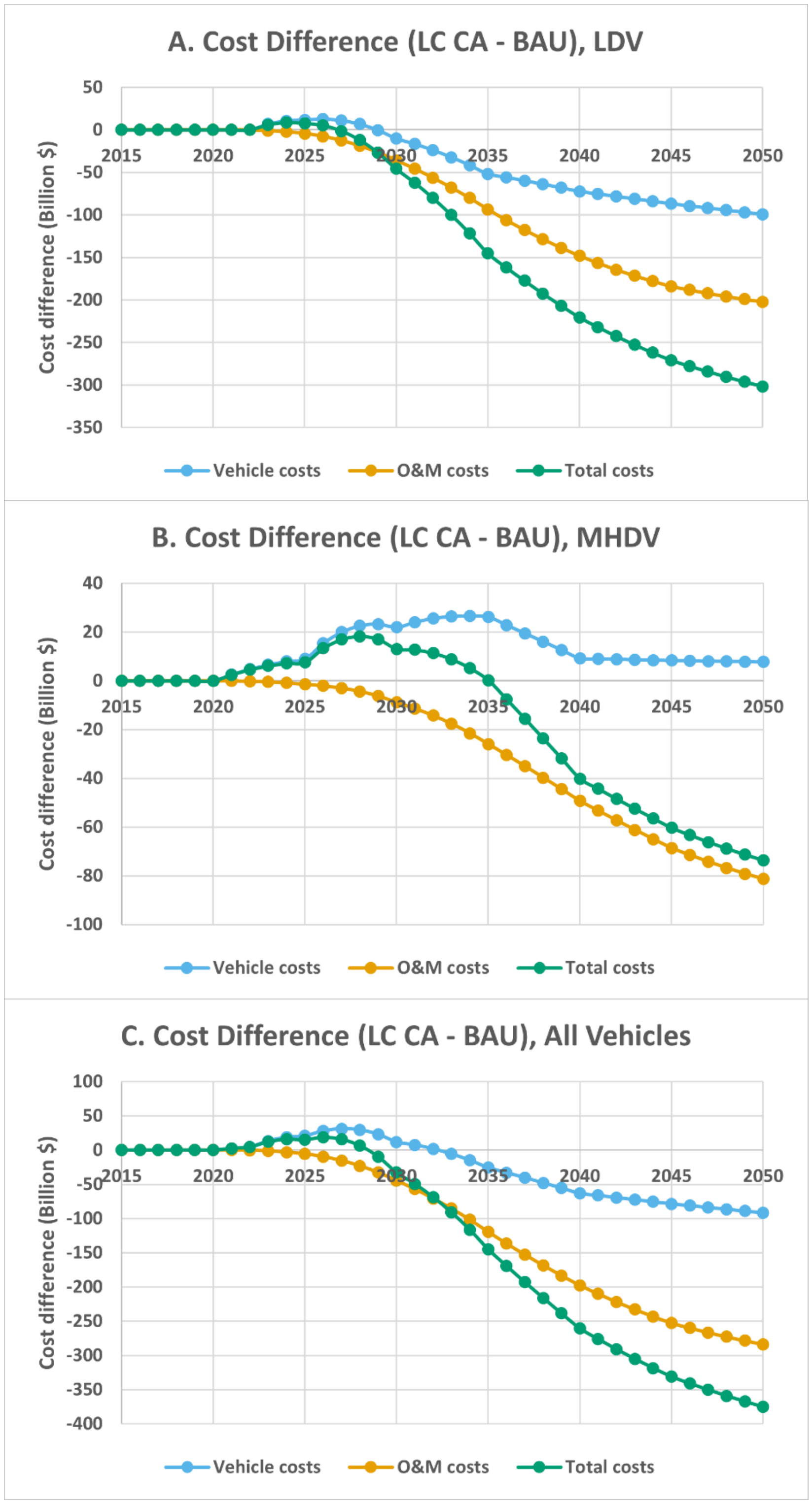

Figure 4-22. Cost comparisons between the LC CA and BAU scenarios from 2015 to 2050 for light-duty vehicles (LDV) (A), medium/heavy duty vehicles (MHDV) (B), and all vehicles (C).

4.7.3. Summary of Cost Comparisons

In this section, we have shown that adopting alternative scenarios returns huge overall cost savings by 2050, and extra spending relative to the BAU scenario is necessary for the near future. Table 4-2 below summarizes the additional investments and savings of alternative scenarios relative to the BAU scenario.

Table 4-2. Additional investments and savings of alternative scenarios relative to the business as usual (BAU) scenario. Relevant time periods shown in parenthesis.

Comparison	Investments	Savings ($B)
LC 10-15 - BAU	14.5 (2020-2030)	1,727.0 (2031-2050)
LC 5-10 - BAU	16.8 (2020-2029)	2,932.4 (2030-2050)
LC 0-5 - BAU	44.7 (2020-2028)	4,100.3 (2029-2050)
LC CA - BAU	91.0 (2020-2028)	4,903.7 (2029-2050)

As can be seen from Table 4-2, initial investments are trivial relative to savings in all comparisons. Initial investments and savings both increase as alternative scenarios become more aggressive, and so do net savings. Note that, in Section 4.5, we have demonstrated that even the least aggressive LC 10-15 scenario is able to achieve over 90% of GHG reductions in 2050 compared to 2015. There appears to be no urgent need to adopt a very aggressive alternative scenario, however, we should keep in mind that net savings increase with aggressiveness.

5. Appendices

Appendix A – Market Share

The following tables demonstrate the percentage sales for LDVs for all scenarios.

Table 5-1. Cars BAU scenario.

	2010	2015	2020	2025	2030	2035	2040	2045	2050
ICE	97.3%	95.4%	94.0%	82.9%	78.5%	74.0%	71.7%	69.4%	68.0%
DSL	1.2%	1.2%	0.5%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
CNG	0.5%	0.5%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
HEV	1.0%	2.2%	3.2%	8.0%	10.0%	12.0%	12.0%	12.0%	12.0%
P80	0.0%	0.0%	0.0%	1.0%	2.1%	3.2%	4.1%	5.0%	6.0%
P40	0.0%	0.3%	0.5%	1.4%	0.5%	0.0%	0.0%	0.0%	0.0%
EV	0.0%	0.4%	1.8%	6.7%	8.5%	10.0%	11.0%	12.0%	12.0%
FC	0.0%	0.0%	0.0%	0.0%	0.4%	0.8%	1.2%	1.6%	2.0%

Table 5-2. Light-duty trucks BAU scenario.

	2010	2015	2020	2025	2030	2035	2040	2045	2050
ICE	97.3%	95.4%	94.0%	82.9%	78.5%	74.0%	71.7%	69.4%	68.0%
DSL	1.2%	1.2%	0.5%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
CNG	0.5%	0.5%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
HEV	1.0%	2.2%	3.2%	8.0%	10.0%	12.0%	12.0%	12.0%	12.0%
P80	0.0%	0.0%	0.0%	1.0%	2.1%	3.2%	4.1%	5.0%	6.0%
P40	0.0%	0.3%	0.5%	1.4%	0.5%	0.0%	0.0%	0.0%	0.0%
EV	0.0%	0.4%	1.8%	6.7%	8.5%	10.0%	11.0%	12.0%	12.0%
FC	0.0%	0.0%	0.0%	0.0%	0.4%	0.8%	1.2%	1.6%	2.0%

Table 5-3. Cars LC 10-15 scenario.

	2010	2015	2020	2025	2030	2035	2040	2045	2050
ICE	97.3%	95.4%	94.0%	82.0%	77.0%	68.8%	50.6%	17.3%	0.0%
DSL	1.2%	1.2%	0.5%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
CNG	0.5%	0.5%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
HEV	1.0%	2.2%	3.2%	8.0%	10.0%	8.0%	4.4%	3.2%	0.0%
P80	0.0%	0.0%	0.0%	0.2%	0.7%	2.0%	3.6%	8.6%	15.0%
P40	0.0%	0.3%	0.5%	1.9%	2.5%	3.1%	5.3%	6.7%	3.2%
EV	0.0%	0.4%	1.8%	7.6%	9.6%	17.3%	34.0%	60.9%	76.1%
FC	0.0%	0.0%	0.0%	0.3%	0.3%	0.8%	2.1%	3.3%	5.7%

Table 5-4. Light-duty trucks LC 10-15 scenario.

	2010	2015	2020	2025	2030	2035	2040	2045	2050
ICE	97.3%	95.4%	94.0%	82.0%	77.0%	68.8%	50.6%	17.3%	0.0%
DSL	1.2%	1.2%	0.5%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
CNG	0.5%	0.5%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
HEV	1.0%	2.2%	3.2%	8.0%	10.0%	8.0%	4.4%	3.2%	0.0%
P80	0.0%	0.0%	0.0%	0.2%	0.7%	2.0%	3.6%	8.6%	15.0%
P40	0.0%	0.3%	0.5%	1.9%	2.5%	3.1%	5.3%	6.7%	3.2%
EV	0.0%	0.4%	1.8%	7.6%	9.6%	17.3%	34.0%	60.9%	76.1%
FC	0.0%	0.0%	0.0%	0.3%	0.3%	0.8%	2.1%	3.3%	5.7%

Table 5-5. Cars LC 5-10 scenario.

	2010	2015	2020	2025	2030	2035	2040	2045	2050
ICE	97.3%	95.4%	94.0%	81.7%	72.6%	50.6%	17.3%	0.0%	0.0%
DSL	1.2%	1.2%	0.5%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
CNG	0.5%	0.5%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
HEV	1.0%	2.2%	3.2%	8.0%	8.0%	4.4%	3.2%	0.0%	0.0%
P80	0.0%	0.0%	0.0%	0.1%	0.8%	3.6%	8.6%	15.0%	15.0%
P40	0.0%	0.3%	0.5%	1.8%	3.5%	5.9%	6.7%	3.2%	0.0%
EV	0.0%	0.4%	1.8%	8.0%	14.5%	33.9%	61.0%	76.2%	76.5%
FC	0.0%	0.0%	0.0%	0.3%	0.5%	1.6%	3.2%	5.6%	8.5%

Table 5-6. Light-duty trucks LC 5-10 scenario.

	2010	2015	2020	2025	2030	2035	2040	2045	2050
ICE	97.3%	95.4%	94.0%	81.7%	72.6%	50.6%	17.3%	0.0%	0.0%
DSL	1.2%	1.2%	0.5%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
CNG	0.5%	0.5%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
HEV	1.0%	2.2%	3.2%	8.0%	8.0%	4.4%	3.2%	0.0%	0.0%
P80	0.0%	0.0%	0.0%	0.1%	0.8%	3.6%	8.6%	15.0%	15.0%
P40	0.0%	0.3%	0.5%	1.8%	3.5%	5.9%	6.7%	3.2%	0.0%
EV	0.0%	0.4%	1.8%	8.0%	14.5%	33.9%	61.0%	76.2%	76.5%
FC	0.0%	0.0%	0.0%	0.3%	0.5%	1.6%	3.2%	5.6%	8.5%

Table 5-7. Cars LC 0-5 scenario.

	2010	2015	2020	2025	2030	2035	2040	2045	2050
ICE	97.3%	95.4%	94.0%	81.3%	53.9%	17.3%	0.0%	0.0%	0.0%
DSL	1.2%	1.2%	0.5%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
CNG	0.5%	0.5%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
HEV	1.0%	2.2%	3.2%	4.4%	5.0%	3.2%	0.0%	0.0%	0.0%
P80	0.0%	0.0%	0.0%	0.4%	2.4%	8.6%	15.0%	15.0%	15.0%
P40	0.0%	0.3%	0.5%	3.1%	6.3%	7.3%	3.2%	0.0%	0.0%
EV	0.0%	0.4%	1.8%	10.5%	31.0%	60.9%	76.4%	76.6%	75.6%
FC	0.0%	0.0%	0.0%	0.4%	1.4%	2.7%	5.4%	8.4%	9.4%

Table 5-8. Light-duty trucks LC 0-5 scenario.

	2010	2015	2020	2025	2030	2035	2040	2045	2050
ICE	97.3%	95.4%	94.0%	81.3%	53.9%	17.3%	0.0%	0.0%	0.0%
DSL	1.2%	1.2%	0.5%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
CNG	0.5%	0.5%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
HEV	1.0%	2.2%	3.2%	4.4%	5.0%	3.2%	0.0%	0.0%	0.0%
P80	0.0%	0.0%	0.0%	0.4%	2.4%	8.6%	15.0%	15.0%	15.0%
P40	0.0%	0.3%	0.5%	3.1%	6.3%	7.3%	3.2%	0.0%	0.0%
EV	0.0%	0.4%	1.8%	10.5%	31.0%	60.9%	76.4%	76.6%	75.6%
FC	0.0%	0.0%	0.0%	0.4%	1.4%	2.7%	5.4%	8.4%	9.4%

Table 5-9. Cars LC CA scenario.

	2010	2015	2020	2025	2030	2035	2040	2045	2050
ICE	97.3%	95.4%	94.0%	69.0%	27.0%	0.0%	0.0%	0.0%	0.0%
DSL	1.2%	1.2%	0.5%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
CNG	0.5%	0.5%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
HEV	1.0%	2.2%	3.2%	5.0%	5.0%	0.0%	0.0%	0.0%	0.0%
P80	0.0%	0.0%	0.0%	1.0%	5.0%	15.0%	15.0%	15.0%	15.0%
P40	0.0%	0.3%	0.5%	5.0%	8.6%	5.0%	0.0%	0.0%	0.0%
EV	0.0%	0.4%	1.8%	19.0%	52.4%	76.0%	77.0%	76.0%	75.0%
FC	0.0%	0.0%	0.0%	1.0%	2.0%	4.0%	8.0%	9.0%	10.0%

Table 5-10. Light-duty trucks LC CA scenario.

	2010	2015	2020	2025	2030	2035	2040	2045	2050
ICE	97.3%	95.4%	94.0%	69.0%	27.0%	0.0%	0.0%	0.0%	0.0%
DSL	1.2%	1.2%	0.5%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
CNG	0.5%	0.5%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
HEV	1.0%	2.2%	3.2%	5.0%	5.0%	0.0%	0.0%	0.0%	0.0%
P80	0.0%	0.0%	0.0%	1.0%	5.0%	15.0%	15.0%	15.0%	15.0%
P40	0.0%	0.3%	0.5%	5.0%	8.6%	5.0%	0.0%	0.0%	0.0%
EV	0.0%	0.4%	1.8%	19.0%	52.4%	76.0%	77.0%	76.0%	75.0%
FC	0.0%	0.0%	0.0%	1.0%	2.0%	4.0%	8.0%	9.0%	10.0%

The following tables demonstrate the percentage sales for MHDVs for all scenarios.

Table 5-11. Long-haul trucks BAU scenario.

	2010	2015	2020	2025	2030	2035	2040	2045	2050
Diesel	100%	100%	99.9%	99.9%	99.9%	99.5%	97.7%	91.7%	83.9%
Hybrid	0.0%	0.0%	0.1%	0.1%	0.1%	0.5%	2.3%	8.2%	16.0%
CNG	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
LNG	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%
Fuel Cell	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
Gasoline	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%

Table 5-12. Short-haul trucks BAU scenario.

	2010	2015	2020	2025	2030	2035	2040	2045	2050
Diesel	100%	100%	99.9%	99.6%	97.7%	92.1%	85.1%	79.8%	75.8%
Hybrid	0.0%	0.0%	0.1%	0.3%	1.8%	6.8%	12.9%	18.2%	22.2%
CNG	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
LNG	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%	0.1%	0.4%	1.0%	1.8%	1.8%	1.8%
Fuel Cell	0.0%	0.0%	0.0%	0.0%	0.0%	0.1%	0.2%	0.2%	0.2%
Gasoline	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%

Table 5-13. Medium-duty urban trucks BAU scenario.

	2010	2015	2020	2025	2030	2035	2040	2045	2050
Diesel	59.5%	55.8%	69.2%	68.2%	55.9%	48.4%	42.9%	37.9%	36.5%
Hybrid	0.5%	0.6%	0.8%	2.9%	7.9%	14.0%	20.9%	25.7%	28.1%
CNG	10.0%	15.0%	15.0%	13.8%	20.7%	21.5%	19.2%	19.3%	18.3%
LNG	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%	0.1%	0.4%	1.0%	2.0%	2.0%	2.0%
Fuel Cell	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
Gasoline	30.0%	28.6%	15.0%	15.0%	15.0%	15.0%	15.0%	15.0%	15.0%

Table 5-14. Urban buses BAU scenario.

	2010	2015	2020	2025	2030	2035	2040	2045	2050
Diesel	22.2%	25.7%	22.9%	20.5%	6.1%	0.0%	0.0%	0.0%	0.0%
Hybrid	2.8%	3.0%	5.4%	11.7%	3.2%	0.0%	0.0%	0.0%	0.0%
CNG	45.0%	46.3%	45.3%	42.2%	14.7%	0.0%	0.0%	0.0%	0.0%
LNG	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%	20.5%	60.8%	80.0%	80.0%	80.0%	80.0%
Fuel Cell	0.0%	0.0%	0.0%	5.1%	15.2%	20.0%	20.0%	20.0%	20.0%
Gasoline	30.0%	25.0%	26.4%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%

Table 5-15. Other buses BAU scenario.

	2010	2015	2020	2025	2030	2035	2040	2045	2050
Diesel	64.6%	69.4%	79.3%	83.8%	79.9%	76.9%	63.2%	52.7%	45.9%
Hybrid	0.0%	0.0%	0.1%	0.2%	0.3%	0.9%	2.6%	6.3%	10.7%
CNG	0.4%	0.5%	0.6%	0.9%	4.4%	16.2%	32.2%	39.1%	41.4%
LNG	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%	0.1%	0.4%	1.0%	2.0%	2.0%	2.0%
Fuel Cell	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
Gasoline	35%	30%	20%	15.0%	15.0%	5.0%	0.0%	0.0%	0.0%

Table 5-16. Heavy-duty vocational trucks BAU scenario.

	2010	2015	2020	2025	2030	2035	2040	2045	2050
Diesel	99.5%	99.6%	99.2%	98.8%	97.3%	96.1%	89.3%	81.7%	76.8%
Hybrid	0.0%	0.0%	0.1%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
CNG	0.5%	0.3%	0.7%	1.1%	2.2%	2.8%	8.7%	16.2%	21.2%
LNG	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%	0.1%	0.4%	1.0%	2.0%	2.0%	2.0%
Fuel Cell	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
Gasoline	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%

Table 5-17. Medium-duty vocational trucks BAU scenario.

	2010	2015	2020	2025	2030	2035	2040	2045	2050
Diesel	99.8%	99.7%	99.1%	97.9%	90.6%	81.1%	72.4%	61.4%	61.7%
Hybrid	0.0%	0.1%	0.6%	0.4%	1.9%	2.7%	5.7%	12.6%	9.1%
CNG	0.2%	0.2%	0.3%	1.6%	7.1%	15.2%	19.9%	24.0%	27.2%
LNG	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%	0.1%	0.4%	1.0%	2.0%	2.0%	2.0%
Fuel Cell	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
Gasoline	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%

Table 5-18. Heavy-duty pickup trucks BAU scenario.

	2010	2015	2020	2025	2030	2035	2040	2045	2050
Diesel	40.0%	45.9%	57.4%	63.0%	59.5%	56.4%	55.1%	55.1%	57.2%
Hybrid	0.0%	4.1%	7.6%	2.0%	5.1%	7.6%	7.9%	7.9%	5.8%
CNG	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
LNG	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%	0.1%	0.4%	1.0%	2.0%	2.0%	2.0%
Fuel Cell	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
Gasoline	60.0%	50.0%	35.0%	35.0%	35.0%	35.0%	35.0%	35.0%	35.0%

Table 5-19. Long-haul trucks LC 10-15 scenario.

	2010	2015	2020	2025	2030	2035	2040	2045	2050
Diesel	100%	100%	99.9%	99.1%	94.0%	86.3%	71.5%	32.0%	0.0%
Hybrid	0.0%	0.0%	0.1%	0.0%	0.0%	0.1%	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%
LNG	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%	0.5%	2.0%	2.9%	7.9%	15.6%	13.2%
Fuel Cell	0.0%	0.0%	0.0%	0.3%	4.0%	10.8%	20.6%	52.4%	86.8%
Gasoline	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%

Table 5-20. Short-haul trucks LC 10-15 scenario.

	2010	2015	2020	2025	2030	2035	2040	2045	2050
Diesel	100%	100%	99.9%	99.2%	94.0%	86.3%	71.5%	32.0%	0.0%
Hybrid	0.0%	0.0%	0.1%	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%
LNG	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%	0.4%	3.0%	8.4%	15.0%	37.7%	60.2%
Fuel Cell	0.0%	0.0%	0.0%	0.4%	3.0%	5.3%	13.5%	30.3%	39.8%
Gasoline	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%

Table 5-21. Medium-duty urban trucks LC 10-15 scenario.

	2010	2015	2020	2025	2030	2035	2040	2045	2050
Diesel	59.5%	55.8%	69.2%	74.4%	81.5%	84.2%	65.2%	26.9%	0.0%
Hybrid	0.5%	0.6%	0.8%	0.8%	1.5%	1.2%	3.8%	5.1%	0.0%
CNG	10.0%	15.0%	15.0%	15.7%	11.0%	0.0%	0.0%	0.0%	0.0%
LNG	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%	1.3%	4.8%	12.2%	26.2%	54.4%	80.0%
Fuel Cell	0.0%	0.0%	0.0%	0.0%	1.2%	2.4%	4.8%	13.6%	20.0%
Gasoline	30.0%	28.6%	15.0%	7.7%	0.0%	0.0%	0.0%	0.0%	0.0%

Table 5-22. Urban buses LC 10-15 scenario.

	2010	2015	2020	2025	2030	2035	2040	2045	2050
Diesel	22.2%	25.7%	22.9%	20.5%	6.1%	0.0%	0.0%	0.0%	0.0%
Hybrid	2.8%	3.0%	5.4%	11.7%	3.2%	0.0%	0.0%	0.0%	0.0%
CNG	45.0%	46.3%	45.3%	42.2%	14.7%	0.0%	0.0%	0.0%	0.0%
LNG	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%	20.5%	60.8%	80.0%	80.0%	80.0%	80.0%
Fuel Cell	0.0%	0.0%	0.0%	5.1%	15.2%	20.0%	20.0%	20.0%	20.0%
Gasoline	30.0%	25.0%	26.4%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%

Table 5-23. Other buses LC 10-15 scenario.

	2010	2015	2020	2025	2030	2035	2040	2045	2050
Diesel	64.6%	69.4%	79.3%	97.7%	85.7%	78.5%	68.9%	32.0%	0.0%
Hybrid	0.0%	0.0%	0.1%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
CNG	0.4%	0.5%	0.6%	1.0%	8.2%	6.8%	0.0%	0.0%	0.0%
LNG	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%	1.3%	4.8%	12.2%	26.2%	54.4%	80.0%
Fuel Cell	0.0%	0.0%	0.0%	0.0%	1.2%	2.4%	4.8%	13.6%	20.0%
Gasoline	35%	30%	20%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%

Table 5-24. Heavy-duty vocational trucks LC 10-15 scenario.

	2010	2015	2020	2025	2030	2035	2040	2045	2050
Diesel	99.5%	99.6%	99.2%	87.6%	65.7%	44.3%	55.1%	25.6%	0.0%
Hybrid	0.0%	0.0%	0.1%	0.0%	0.0%	0.1%	0.0%	0.0%	0.0%
CNG	0.5%	0.3%	0.7%	11.1%	28.2%	41.0%	13.8%	6.4%	0.0%
LNG	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%	1.3%	6.0%	14.5%	30%	66%	96%
Fuel Cell	0.0%	0.0%	0.0%	0.0%	0.0%	0.2%	0.6%	2.0%	4.3%
Gasoline	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%

Table 5-25. Medium-duty vocational trucks LC 10-15 scenario.

	2010	2015	2020	2025	2030	2035	2040	2045	2050
Diesel	99.8%	99.7%	99.1%	96.4%	73.6%	42.1%	32.8%	14.4%	0.0%
Hybrid	0.0%	0.1%	0.6%	0.4%	0.8%	1.2%	3%	3%	0%
CNG	0.2%	0.2%	0.3%	1.8%	19.6%	42.1%	33%	14%	0%
LNG	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%	1.3%	4.8%	12.2%	26.2%	54.4%	80.0%
Fuel Cell	0.0%	0.0%	0.0%	0.0%	1.2%	2.4%	4.8%	13.6%	20.0%
Gasoline	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%

Table 5-26. Heavy-duty pickup trucks LC 10-15 scenario.

	2010	2015	2020	2025	2030	2035	2040	2045	2050
Diesel	40.0%	45.9%	57.4%	59.3%	51.5%	45.2%	35.8%	14.6%	0.0%
Hybrid	0.0%	4.1%	7.6%	2.2%	5.6%	7.2%	8.8%	6.4%	0.0%
CNG	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
LNG	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%	0.8%	4.2%	10.1%	21%	48%	70%
Fuel Cell	0.0%	0.0%	0.0%	0.0%	1.8%	3.6%	7.2%	20.4%	30.0%
Gasoline	60.0%	50.0%	35.0%	37.7%	36.8%	33.9%	26.9%	11.0%	0.0%

Table 5-27. Long-haul trucks LC 5-10 scenario.

	2010	2015	2020	2025	2030	2035	2040	2045	2050
Diesel	100%	100%	99.9%	99.1%	92.3%	71.5%	32.0%	0.0%	0.0%
Hybrid	0.0%	0.0%	0.1%	0.0%	0.1%	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%
LNG	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%	0.5%	3.0%	8.6%	15.9%	13.5%	8.7%
Fuel Cell	0.0%	0.0%	0.0%	0.3%	4.7%	19.9%	52.1%	86.5%	91.3%
Gasoline	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%

Table 5-28. Short-haul trucks LC 5-10 scenario.

	2010	2015	2020	2025	2030	2035	2040	2045	2050
Diesel	100%	100%	99.9%	99.1%	92.3%	71.5%	32.0%	0.0%	0.0%
Hybrid	0.0%	0.0%	0.1%	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%
LNG	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%	0.4%	3.8%	15.8%	38%	60%	56%
Fuel Cell	0.0%	0.0%	0.0%	0.4%	3.8%	12.7%	30.2%	39.6%	44.5%
Gasoline	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%

Table 5-29. Medium-duty urban trucks LC 5-10 scenario.

	2010	2015	2020	2025	2030	2035	2040	2045	2050
Diesel	59.5%	55.8%	69.2%	74.3%	78.6%	65.2%	26.9%	0.0%	0.0%
Hybrid	0.5%	0.6%	0.8%	0.9%	2.1%	3.8%	5.1%	0.0%	0.0%
CNG	10.0%	15.0%	15.0%	15.7%	10.6%	0.0%	0.0%	0.0%	0.0%
LNG	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%	1.3%	7.4%	26.2%	54.4%	80.0%	80.0%
Fuel Cell	0.0%	0.0%	0.0%	0.0%	1.2%	4.8%	13.6%	20.0%	20.0%
Gasoline	30.0%	28.6%	15.0%	7.7%	0.0%	0.0%	0.0%	0.0%	0.0%

Table 5-30. Urban buses LC 5-10 scenario.

	2010	2015	2020	2025	2030	2035	2040	2045	2050
Diesel	22.2%	25.7%	22.9%	20.5%	6.1%	0.0%	0.0%	0.0%	0.0%
Hybrid	2.8%	3.0%	5.4%	11.7%	3.2%	0.0%	0.0%	0.0%	0.0%
CNG	45.0%	46.3%	45.3%	42.2%	14.7%	0.0%	0.0%	0.0%	0.0%
LNG	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%	20.5%	60.8%	80.0%	80.0%	80.0%	80.0%
Fuel Cell	0.0%	0.0%	0.0%	5.1%	15.2%	20.0%	20.0%	20.0%	20.0%
Gasoline	30.0%	25.0%	26.4%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%

Table 5-31. Other buses LC 5-10 scenario.

	2010	2015	2020	2025	2030	2035	2040	2045	2050
Diesel	64.6%	69.4%	79.3%	97.7%	83.3%	63.4%	32.0%	0.0%	0.0%
Hybrid	0.0%	0.0%	0.1%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
CNG	0.4%	0.5%	0.6%	1.0%	8.0%	5.5%	0.0%	0.0%	0.0%
LNG	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%	1.3%	7.4%	26.2%	54.4%	80.0%	80.0%
Fuel Cell	0.0%	0.0%	0.0%	0.0%	1.2%	4.8%	13.6%	20.0%	20.0%
Gasoline	35%	30%	20%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%

Table 5-32. Heavy-duty vocational trucks LC 5-10 scenario.

	2010	2015	2020	2025	2030	2035	2040	2045	2050
Diesel	99.5%	99.6%	99.2%	87.5%	63.8%	35.8%	25.6%	0.0%	0.0%
Hybrid	0.0%	0.0%	0.1%	0.0%	0.1%	0.0%	0.0%	0.0%	0.0%
CNG	0.5%	0.3%	0.7%	11.1%	27.4%	33.1%	6.4%	0.0%	0.0%
LNG	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%	1.3%	8.7%	30.8%	66.9%	96.0%	91.9%
Fuel Cell	0.0%	0.0%	0.0%	0.0%	0.0%	0.2%	1.1%	4.0%	8.1%
Gasoline	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%

Table 5-33. Medium-duty vocational trucks LC 5-10 scenario.

	2010	2015	2020	2025	2030	2035	2040	2045	2050
Diesel	99.8%	99.7%	99.1%	96.2%	70.7%	32.8%	14.4%	0.0%	0.0%
Hybrid	0.0%	0.1%	0.6%	0.6%	1.8%	3.4%	3.2%	0.0%	0.0%
CNG	0.2%	0.2%	0.3%	1.8%	18.8%	32.8%	14.4%	0.0%	0.0%
LNG	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%	1.3%	7.4%	26.2%	54.4%	80.0%	80.0%
Fuel Cell	0.0%	0.0%	0.0%	0.0%	1.2%	4.8%	13.6%	20.0%	20.0%
Gasoline	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%

Table 5-34. Heavy-duty pickup trucks LC 5-10 scenario.

	2010	2015	2020	2025	2030	2035	2040	2045	2050
Diesel	40.0%	45.9%	57.4%	57.2%	48.9%	35.8%	14.6%	0.0%	0.0%
Hybrid	0.0%	4.1%	7.6%	5.6%	8.4%	8.8%	6.4%	0.0%	0.0%
CNG	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
LNG	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%	0.9%	5.9%	21.3%	48%	70%	70%
Fuel Cell	0.0%	0.0%	0.0%	0.0%	1.8%	7.2%	20.4%	30.0%	30.0%
Gasoline	60.0%	50.0%	35.0%	36.3%	34.9%	26.9%	11.0%	0.0%	0.0%

Table 5-35. Long-haul trucks LC 0-5 scenario.

	2010	2015	2020	2025	2030	2035	2040	2045	2050
Diesel	100%	100%	99.9%	97.4%	77.5%	32.0%	0.0%	0.0%	0.0%
Hybrid	0.0%	0.0%	0.1%	0.1%	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%
LNG	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%	1.5%	8.7%	16.6%	13.8%	8.9%	6.3%
Fuel Cell	0.0%	0.0%	0.0%	1.0%	13.7%	51.4%	86.2%	91.1%	93.7%
Gasoline	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%

Table 5-36. Short-haul trucks LC 0-5 scenario.

	2010	2015	2020	2025	2030	2035	2040	2045	2050
Diesel	100%	100%	99.9%	97.4%	77.5%	32.0%	0.0%	0.0%	0.0%
Hybrid	0.0%	0.0%	0.1%	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%
LNG	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%	1.3%	11.2%	38.7%	60.5%	55.6%	54.6%
Fuel Cell	0.0%	0.0%	0.0%	1.3%	11.2%	29.3%	39.5%	44.4%	45.4%
Gasoline	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%

Table 5-37. Medium-duty urban trucks LC 0-5 scenario.

	2010	2015	2020	2025	2030	2035	2040	2045	2050
Diesel	59.5%	55.8%	69.2%	71.9%	61.9%	26.9%	0.0%	0.0%	0.0%
Hybrid	0.5%	0.6%	0.8%	1.5%	4.7%	5.1%	0.0%	0.0%	0.0%
CNG	10.0%	15.0%	15.0%	15.2%	8.3%	0.0%	0.0%	0.0%	0.0%
LNG	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%	4.0%	21.4%	54.4%	80.0%	80.0%	80.0%
Fuel Cell	0.0%	0.0%	0.0%	0.0%	3.6%	13.6%	20.0%	20.0%	20.0%
Gasoline	30.0%	28.6%	15.0%	7.5%	0.0%	0.0%	0.0%	0.0%	0.0%

Table 5-38. Urban buses LC 0-5 scenario.

	2010	2015	2020	2025	2030	2035	2040	2045	2050
Diesel	22.2%	25.7%	22.9%	20.5%	6.1%	0.0%	0.0%	0.0%	0.0%
Hybrid	2.8%	3.0%	5.4%	11.7%	3.2%	0.0%	0.0%	0.0%	0.0%
CNG	45.0%	46.3%	45.3%	42.2%	14.7%	0.0%	0.0%	0.0%	0.0%
LNG	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%	20.5%	60.8%	80.0%	80.0%	80.0%	80.0%
Fuel Cell	0.0%	0.0%	0.0%	5.1%	15.2%	20.0%	20.0%	20.0%	20.0%
Gasoline	30.0%	25.0%	26.4%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%

Table 5-39. Other buses LC 0-5 scenario.

	2010	2015	2020	2025	2030	2035	2040	2045	2050
Diesel	64.6%	69.4%	79.3%	95.0%	68.4%	29.4%	0.0%	0.0%	0.0%
Hybrid	0.0%	0.0%	0.1%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
CNG	0.4%	0.5%	0.6%	1.0%	6.6%	2.6%	0.0%	0.0%	0.0%
LNG	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%	4.0%	21.4%	54.4%	80.0%	80.0%	80.0%
Fuel Cell	0.0%	0.0%	0.0%	0.0%	3.6%	13.6%	20.0%	20.0%	20.0%
Gasoline	35%	30%	20%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%

Table 5-40. Heavy-duty vocational trucks LC 0-5 scenario.

	2010	2015	2020	2025	2030	2035	2040	2045	2050
Diesel	99.5%	99.6%	99.2%	85.1%	52.4%	16.6%	0.0%	0.0%	0.0%
Hybrid	0.0%	0.0%	0.1%	0.1%	0.0%	0.0%	0.0%	0.0%	0.0%
CNG	0.5%	0.3%	0.7%	10.8%	22.5%	15.4%	0.0%	0.0%	0.0%
LNG	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%	4.0%	25.0%	67.3%	97%	92%	86%
Fuel Cell	0.0%	0.0%	0.0%	0.0%	0.0%	0.7%	3.1%	7.9%	13.7%
Gasoline	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%

Table 5-41. Medium-duty vocational trucks LC 0-5 scenario.

	2010	2015	2020	2025	2030	2035	2040	2045	2050
Diesel	99.8%	99.7%	99.1%	92.6%	56.0%	14.4%	0.0%	0.0%	0.0%
Hybrid	0.0%	0.1%	0.6%	1.6%	4.0%	3.2%	0.0%	0.0%	0.0%
CNG	0.2%	0.2%	0.3%	1.8%	14.9%	14.4%	0.0%	0.0%	0.0%
LNG	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%	4.0%	21.4%	54.4%	80.0%	80.0%	80.0%
Fuel Cell	0.0%	0.0%	0.0%	0.0%	3.6%	13.6%	20.0%	20.0%	20.0%
Gasoline	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%

Table 5-42. Heavy-duty pickup trucks LC 0-5 scenario.

	2010	2015	2020	2025	2030	2035	2040	2045	2050
Diesel	40.0%	45.9%	57.4%	54.4%	39.4%	14.6%	0.0%	0.0%	0.0%
Hybrid	0.0%	4.1%	7.6%	8.4%	10.0%	6.4%	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%
LNG	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%	2.6%	17.1%	47.6%	70.0%	70.0%	70.0%
Fuel Cell	0.0%	0.0%	0.0%	0.0%	5.4%	20.4%	30.0%	30.0%	30.0%
Gasoline	60.0%	50.0%	35.0%	34.6%	28.1%	11.0%	0.0%	0.0%	0.0%

Table 5-43. Long-haul trucks LC CA scenario.

	2010	2015	2020	2025	2030	2035	2040	2045	2050
Diesel	100%	100%	99.9%	93.0%	49.9%	0.0%	0.0%	0.0%	0.0%
Hybrid	0.0%	0.0%	0.1%	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%
LNG	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%	4.1%	17.0%	16.0%	10.0%	7.0%	5.0%
Fuel Cell	0.0%	0.0%	0.0%	2.9%	33.0%	84.0%	90.0%	93.0%	95.0%
Gasoline	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%

Table 5-44. Short-haul trucks LC CA scenario.

	2010	2015	2020	2025	2030	2035	2040	2045	2050
Diesel	100%	100%	99.9%	93.0%	50.0%	0.0%	0.0%	0.0%	0.0%
Hybrid	0.0%	0.0%	0.1%	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%
LNG	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%	3.5%	25.0%	63.0%	56.0%	55.0%	54.0%
Fuel Cell	0.0%	0.0%	0.0%	3.5%	25.0%	37.0%	44.0%	45.0%	46.0%
Gasoline	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%

Table 5-45. Medium-duty urban trucks LC CA scenario.

	2010	2015	2020	2025	2030	2035	2040	2045	2050
Diesel	59.5%	55.8%	69.2%	65.5%	37.1%	0.0%	0.0%	0.0%	0.0%
Hybrid	0.5%	0.6%	0.8%	2.9%	7.9%	0.0%	0.0%	0.0%	0.0%
CNG	10.0%	15.0%	15.0%	13.8%	5.0%	0.0%	0.0%	0.0%	0.0%
LNG	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%	11.0%	40.0%	80.0%	80.0%	80.0%	80.0%
Fuel Cell	0.0%	0.0%	0.0%	0.0%	10.0%	20.0%	20.0%	20.0%	20.0%
Gasoline	30.0%	28.6%	15.0%	6.8%	0.0%	0.0%	0.0%	0.0%	0.0%

Table 5-46. Urban buses LC CA scenario.

	2010	2015	2020	2025	2030	2035	2040	2045	2050
Diesel	22.2%	25.7%	22.9%	20.5%	6.1%	0.0%	0.0%	0.0%	0.0%
Hybrid	2.8%	3.0%	5.4%	11.7%	3.2%	0.0%	0.0%	0.0%	0.0%
CNG	45.0%	46.3%	45.3%	42.2%	14.7%	0.0%	0.0%	0.0%	0.0%
LNG	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%	20.5%	60.8%	80.0%	80.0%	80.0%	80.0%
Fuel Cell	0.0%	0.0%	0.0%	5.1%	15.2%	20.0%	20.0%	20.0%	20.0%
Gasoline	30.0%	25.0%	26.4%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%

Table 5-47. Other buses LC CA scenario.

	2010	2015	2020	2025	2030	2035	2040	2045	2050
Diesel	64.6%	69.4%	79.3%	88.1%	45.6%	0.0%	0.0%	0.0%	0.0%
Hybrid	0.0%	0.0%	0.1%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
CNG	0.4%	0.5%	0.6%	0.9%	4.4%	0.0%	0.0%	0.0%	0.0%
LNG	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%	11.0%	40.0%	80.0%	80.0%	80.0%	80.0%
Fuel Cell	0.0%	0.0%	0.0%	0.0%	10.0%	20.0%	20.0%	20.0%	20.0%
Gasoline	35%	30%	20%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%

Table 5-48. Heavy-duty vocational trucks LC CA scenario.

	2010	2015	2020	2025	2030	2035	2040	2045	2050
Diesel	99.5%	99.6%	99.2%	79.0%	40.0%	0.0%	0.0%	0.0%	0.0%
Hybrid	0.0%	0.0%	0.1%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
CNG	0.5%	0.3%	0.7%	10.0%	10.0%	0.0%	0.0%	0.0%	0.0%
LNG	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%	11.0%	50.0%	98.0%	95.0%	87.0%	85.0%
Fuel Cell	0.0%	0.0%	0.0%	0.0%	0.0%	2.0%	5.0%	13.0%	15.0%
Gasoline	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%

Table 5-49. Medium-duty vocational trucks LC CA scenario.

	2010	2015	2020	2025	2030	2035	2040	2045	2050
Diesel	99.8%	99.7%	99.1%	83.9%	40.0%	0.0%	0.0%	0.0%	0.0%
Hybrid	0.0%	0.1%	0.6%	3.5%	5.0%	0.0%	0.0%	0.0%	0.0%
CNG	0.2%	0.2%	0.3%	1.6%	5.0%	0.0%	0.0%	0.0%	0.0%
LNG	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%	11.0%	40.0%	80.0%	80.0%	80.0%	80.0%
Fuel Cell	0.0%	0.0%	0.0%	0.0%	10.0%	20.0%	20.0%	20.0%	20.0%
Gasoline	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%

Table 5-50. Heavy-duty pickup trucks LC CA scenario.

	2010	2015	2020	2025	2030	2035	2040	2045	2050
Diesel	40.0%	45.9%	57.4%	50.7%	15.0%	0.0%	0.0%	0.0%	0.0%
Hybrid	0.0%	4.1%	7.6%	10.0%	10.0%	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%
LNG	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%	7.0%	35.0%	70.0%	70.0%	70.0%	70.0%
Fuel Cell	0.0%	0.0%	0.0%	0.0%	15.0%	30.0%	30.0%	30.0%	30.0%
Gasoline	60.0%	50.0%	35.0%	32.3%	25.0%	0.0%	0.0%	0.0%	0.0%

Appendix B – Truck Cost

The following graphs illustrate the capital cost of MHDVs for each vehicle and technology type through 2050.

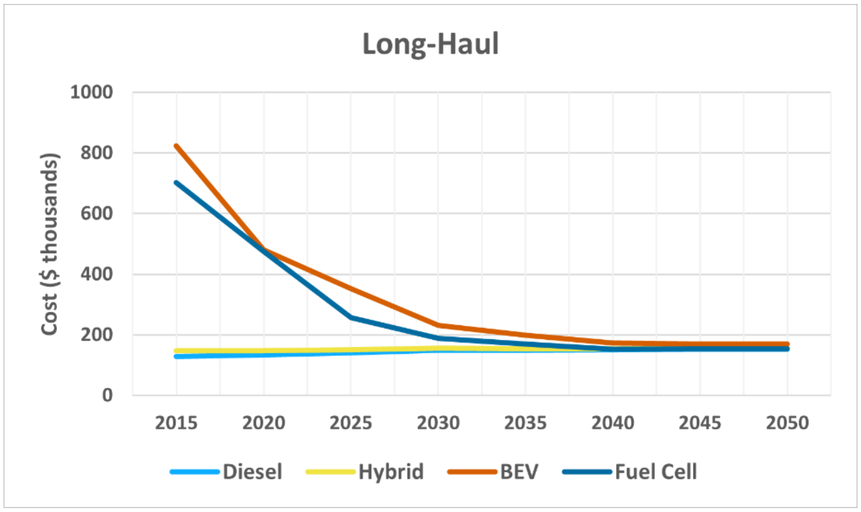

Figure 5-1. Capital cost of long-haul trucks through 2050.

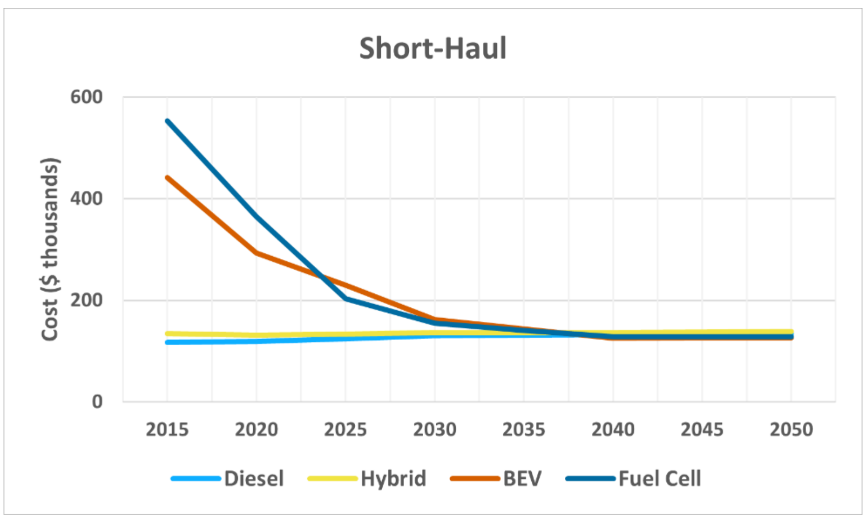

Figure 5-2. Capital cost of shout-haul trucks through 2050.

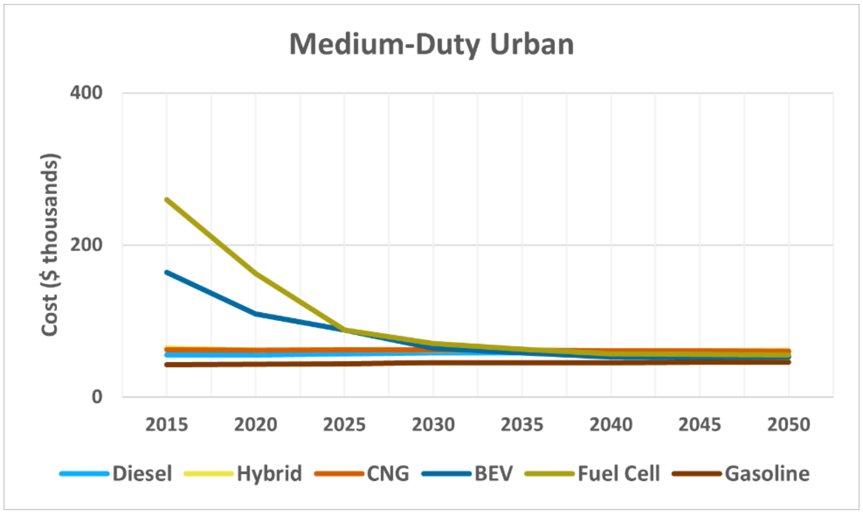

Figure 5-3. Capital cost of medium-duty urban trucks through 2050.

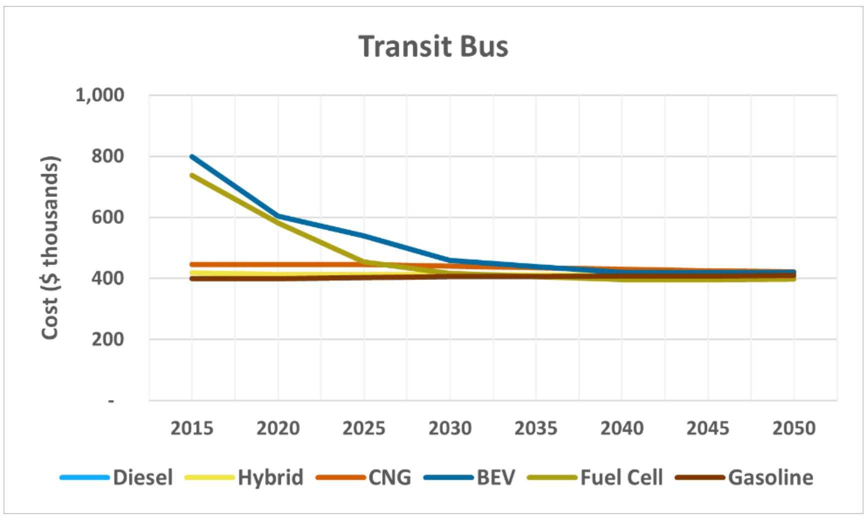

Figure 5-4. Capital cost of transit buses through 2050.

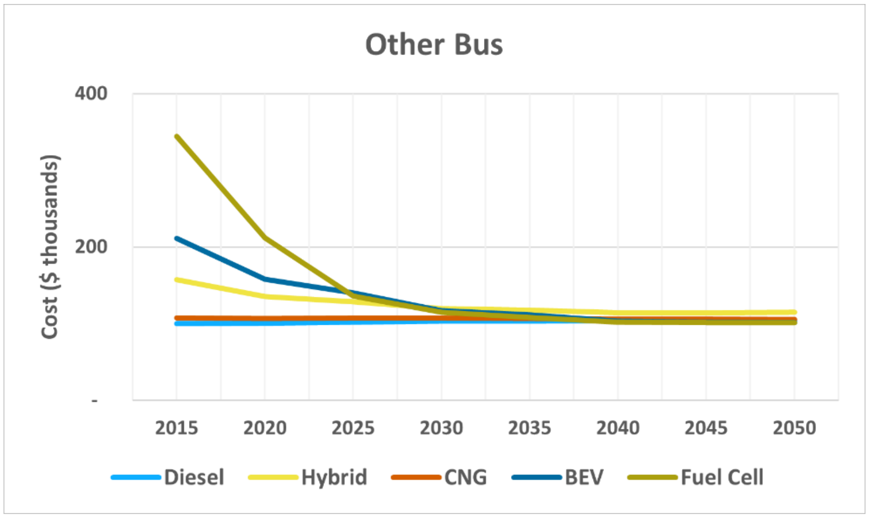

Figure 5-5. Capital cost of other buses through 2050.

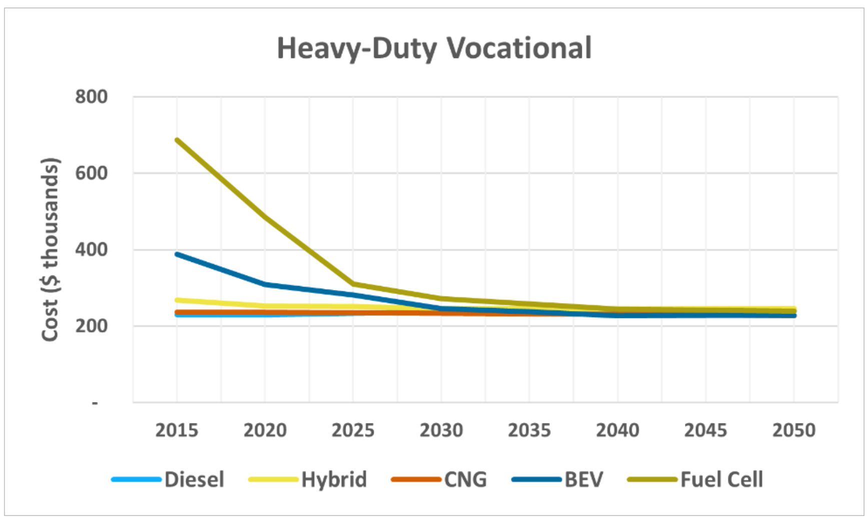

Figure 5-6. Capital cost of heavy-duty vocational trucks through 2050.

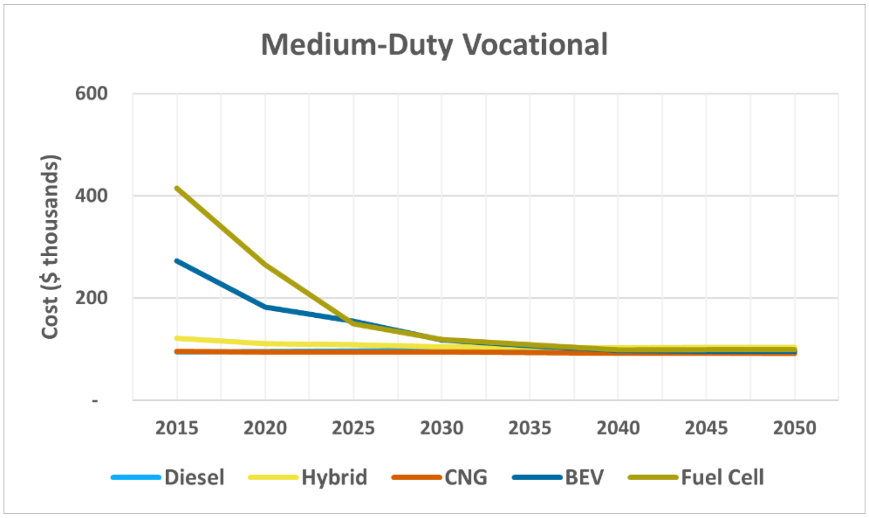

Figure 5-7. Capital cost of medium-duty vocational trucks through 2050.

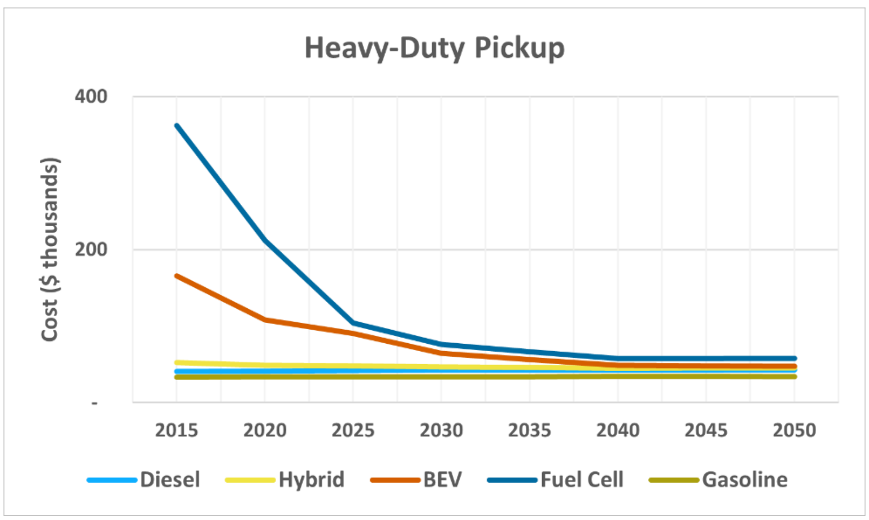

Figure 5-8. Capital cost of heavy-duty pickup trucks through 2050.

Appendix C – Fuel Economy Tables

The following tables demonstrate the fuel economy (in mpgge) of LDVs and MHDVs through 2050.

Table 5-51. Car fuel economy inputs (mpgge).

	2015	2020	2025	2030	2035	2040	2045	2050
ICE	31.0	33.0	39.7	42.2	44.1	46.3	48.6	48.6
DSL	39.6	43.9	45.7	47.7	49.7	52.0	54.4	54.4
CNG	33.0	37.6	39.7	42.2	44.1	46.3	48.6	48.6
HEV	47.5	53.4	55.7	58.1	60.2	62.5	64.9	64.9
P10-gas	47.0	52.4	54.6	56.9	58.9	61.0	63.3	63.3
P10-elec	155.6	161.7	163.8	166.0	166.8	167.7	168.6	168.6
P40-gas	44.7	48.6	48.7	48.7	49.9	51.2	52.5	52.5
P40-elec	161.2	163.0	166.3	169.7	169.6	169.6	169.6	169.6
EV	128.9	137.0	144.2	152.3	153.5	154.7	155.9	155.9
FC	61.5	67.6	71.3	75.4	76.6	77.9	79.3	79.3

Table 5-52. Light-duty trucks fuel economy inputs (mpgge).

	2015	2020	2025	2030	2035	2040	2045	2050
ICE	26.0	27.0	30.7	31.7	32.8	34.0	35.3	35.3
DSL	32.3	34.7	35.3	35.9	37.0	38.2	39.6	39.6
CNG	26.9	29.7	30.7	31.7	32.8	34.0	35.3	35.3
HEV	36.7	41.2	40.9	40.7	42.0	43.5	45.0	45.0
P10-gas	36.6	40.7	40.5	40.3	41.6	43.0	44.5	44.5
P10-elec	122.5	139.0	140.0	141.0	141.3	141.5	141.7	141.7
P40-gas	33.9	37.4	35.4	33.6	34.3	35.1	35.9	35.9
P40-elec	108.0	113.3	108.5	104.1	104.7	105.2	105.8	105.8
EV	96.6	104.6	103.6	102.6	103.2	103.7	104.3	104.3
FC	45.4	47.1	48.7	50.3	51.1	51.8	52.6	52.6

Table 5-53. Long-haul trucks fuel economy inputs (mpgge).

	2015	2020	2025	2030	2035	2040	2045	2050
Diesel	5.7	6.4	7.0	7.6	8.3	8.9	9.3	9.8
Hybrid	6.0	6.7	7.3	7.9	8.7	9.3	9.8	10.2
BEV	13.8	14.3	15.7	17.0	17.9	18.4	18.9	19.4
Fuel Cell	7.3	8.1	9.2	10.4	11.1	11.9	12.5	13.1

Table 5-54. Short-haul trucks fuel economy inputs (mpgge).

	2015	2020	2025	2030	2035	2040	2045	2050
Diesel	5.8	6.2	6.6	7.2	7.9	8.4	8.8	9.1
Hybrid	6.9	7.4	7.9	8.7	9.4	10.1	10.5	11.0
BEV	12.9	13.7	14.3	15.3	16.1	17.9	18.6	19.4
Fuel Cell	8.5	9.1	10.0	10.5	11.1	11.8	12.2	12.7

Table 5-55. Medium-duty urban trucks fuel economy inputs (mpgge).

	2015	2020	2025	2030	2035	2040	2045	2050
Diesel	9.4	9.9	10.6	11.2	11.7	12.3	12.7	13.1
Hybrid	12.6	13.2	15.8	17.9	18.7	19.7	20.3	20.9
CNG	6.8	7.1	8.0	8.3	8.5	8.8	9.1	9.5
BEV	36.9	38.9	40.8	42.8	43.7	45.9	47.3	48.7
Fuel Cell	23.6	24.8	25.5	27.2	27.9	30.8	31.7	32.7
Gasoline	6.8	7.1	8.0	8.3	8.5	8.8	9.1	9.5

Table 5-56. Urban buses fuel economy inputs (mpgge).

	2015	2020	2025	2030	2035	2040	2045	2050
Diesel	3.8	4.0	4.4	4.8	5.3	5.7	5.9	6.1
Hybrid	4.6	4.9	5.4	6.0	6.5	7.0	7.2	7.5
CNG	3.6	3.7	4.5	4.7	4.8	5.0	5.2	5.4
BEV	14.6	15.4	16.1	17.7	18.1	18.4	19.0	19.6
Fuel Cell	9.5	10.0	11.1	12.0	12.7	13.3	13.7	14.1
Gasoline	3.8	4.0	4.4	4.8	5.3	5.7	5.9	6.1

Table 5-57. Other buses fuel economy inputs (mpgge).

	2015	2020	2025	2030	2035	2040	2045	2050
Diesel	5.4	5.7	6.6	7.0	7.9	8.4	8.6	8.9
Hybrid	5.7	6.0	9.9	11.3	12.7	13.4	13.8	14.2
CNG	7.2	7.6	8.5	8.8	9.1	9.4	9.7	10.1
BEV	19.2	20.2	21.5	22.7	24.4	26.9	27.7	28.5
Fuel Cell	11.6	12.2	13.3	14.3	15.4	16.7	17.2	17.7
Gasoline	5.4	5.7	6.6	7.0	7.9	8.4	8.6	8.9

Table 5-58. Heavy-duty vocational trucks fuel economy inputs (mpgge).

	2015	2020	2025	2030	2035	2040	2045	2050
Diesel	3.8	4.0	4.7	4.9	5.1	5.3	5.4	5.6
Hybrid	5.1	5.4	6.3	6.5	6.8	7.0	7.2	7.5
CNG	3.4	3.6	4.2	4.4	4.5	4.7	4.8	5.0
BEV	12.3	12.9	15.1	15.7	16.3	16.8	17.4	18.1
Fuel Cell	8.5	8.9	10.4	10.8	11.2	11.6	12.0	12.4

Table 5-59. Medium-duty vocational trucks fuel economy inputs (mpgge).

	2015	2020	2025	2030	2035	2040	2045	2050
Diesel	6.1	6.4	6.8	7.2	7.7	8.0	8.2	8.5
Hybrid	9.2	9.6	10.2	11.5	12.2	12.8	13.2	13.6
CNG	6.5	6.8	8.3	8.7	9.0	9.4	9.7	10.1
BEV	23.9	25.2	26.2	27.3	28.3	29.1	29.9	30.8
Fuel Cell	15.9	16.7	17.5	18.8	19.8	21.2	21.8	22.5

Table 5-60. Heavy-duty pickup trucks fuel economy inputs (mpgge).

	2015	2020	2025	2030	2035	2040	2045	2050
Diesel	12.5	13.2	15.0	16.4	17.6	19.4	19.9	20.5
Hybrid	18.8	19.8	22.4	26.2	28.2	31.0	31.9	32.9
BEV	66.6	70.1	75.0	82.7	92.2	100.8	103.8	106.9
Fuel Cell	31.7	33.3	34.5	37.0	38.5	40.0	41.2	42.4
Gasoline	11.9	12.5	14.2	15.5	16.7	18.4	18.9	19.5

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