Spatial Scenarios for Market Penetration of Plug-in Battery Electric Trucks in the U.S.

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16. Abstract

Carbon emissions targets require large reductions in greenhouse gases (GHGs) in the near- to mid-term, and the transportation sector is a major emitter of GHGs. To understand potential pathways to GHG reductions, this project developed the U.S. Transportation Transitions Model (US TTM) to study various scenarios of zero-emission vehicle (ZEV) market penetration in the U.S. The model includes vehicle fuel economy, vehicle stock and sales, fuel carbon intensities, and costs for vehicles and fuels all projected through 2050. Market penetration scenarios through 2050 are input as percentages of sales for all vehicle types and technologies. Three scenarios were developed for the U.S.: a business as usual (BAU), low carbon (LC), and High ZEV scenario. The LC and High ZEV include rapid penetration of ZEVs into the vehicle market. The introduction of ZEVs requires fueling infrastructure to support the vehicles. Initial deployments of ZEVs are expected to be dominated by battery electric vehicles. To estimate the number and cost of charging stations for battery electric trucks in the mid-term, outputs were used from a California Energy Commission (CEC) study projecting the need for chargers in California. The study used the HEVI-Pro model to estimate electrical energy needs and number of chargers for the truck stock in several California cities. The CEC study outputs were used along with the TTM model outputs from this study to estimate charger needs and costs for six U.S. cities outside California. The LC and High ZEV scenarios reduced carbon emissions by 92% and 94% in the U.S. by 2050, respectively. Due to slow stock turnover, the LC and High ZEV scenarios contain significant numbers of ICE trucks. The biomass-based liquid volume reaches 70 (High ZEV) to 80 (LC) billion GGE by 2045. For the cities in this study, the charger cost ranges from $5 million to $2.6 billion in 2030 and from roughly $1 billion to almost $30 billion in 2040.

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TABLE OF CONTENTS

List of Tables

List of Figures

Spatial Scenarios for Market Penetration of Plug-in Battery Electric Trucks in the U.S.

EXECUTIVE SUMMARY

To meet carbon emissions targets that will keep the effects of climate change manageable, significant market penetration of zero emission vehicles must occur in the near- to mid-term. We developed a U.S. national-level vehicle stock turnover model to evaluate various ZEV market penetration scenarios. The model is based on our previously developed CA Transportation Transitions model (CA TTM) which includes on-road vehicles in California. The CA TTM was extended to create the US TTM that covers the entire U.S. and includes California as a region.

The US TTM is calibrated to vehicle stock projections from the U.S. MOVES3 model. The model includes two LDV types and 8 medium- and heavy-duty truck and bus applications. Inputs include vehicle fuel economy, VMT, cost, scrappage rates, fuel cost and fuel carbon intensities. The model produces outputs through 2050 for vehicle stock, fuel use, greenhouse gas emissions, and vehicle and fuel costs all as a function of vehicle and technology type.

Several scenarios were developed for the CA TTM including a business-as-usual (BAU) scenario with relatively little ZEV market penetration, a Low Carbon (LC) scenario where ZEVs reach 100% sales shares by 2040 for both LDVs and trucks, and a High ZEV scenario where ZEVs reach 100% sales shares by 2035. These scenarios were modified for the US TTM based on expected ZEV policies in different regions of the country.

The U.S. was divided into three regions: California, Section 177 states that have adopted CA ZEV standards, and other states. Compared to our projection of ZEV sales in CA, the ZEV market penetration was delayed by 5 years in Section 177 states and by 10 years in the remaining states to create new LC and High ZEV scenarios. These scenarios were used to estimate U.S. fuel use, vehicle stock by technology type, and carbon emissions. The LC and High ZEV scenarios reduced carbon emissions by 92% and 94% by 2050 respectively.

The study further estimated the number of medium- and heavy-duty ZEVs that would be sold in six U.S. cities, consistent with our national scenarios, to project the number of charging stations needed to support those ZEV vehicles. This city-level analysis provides case studies for what types of infrastructure growth and investment may be needed around the country. We rely on a recent study by the California Energy Commission (CEC) that estimated the required number of chargers in California for a given number of medium- and heavy-duty ZEVs, using a detailed model that included ZEV stock projections, vehicle trip data, and vehicle spatial information. Using the CEC results, we selected Houston, Newark/New York, Dallas, Philadelphia, Kansas City, and Portland, Oregon and scaled results from California cities to estimate the number of 50 kW and 350 kW chargers needed in each city to support the ZEV vehicles in 2030 and 2040, given our scenarios. Using estimates of charging station costs, we then estimated the cost of the chargers including installation costs in those cities.

Table ES-1 shows results for the analysis of chargers in the six U.S. cities. Three of these cities reside in Section 177 states (with more rapid ZEV sales) while the other three do not. The table shows the number of chargers and the cost of those chargers in each city for the years 2030 and 2040.

Table ES-1. Number of projected chargers and their cost, including installation, in six states for the years 2030 and 2040.

	2030				2040			
U.S. Cities	**50 kW units**	**350 kW units**	**Cost of 50 kW chargers ($million)**	**Cost of 350 kW chargers ($million)**	**50 kW units**	**350 kW units**	**Cost of 50 kW chargers ($million)**	**Cost of 350 kW chargers ($million)**
Houston	106	12	15	4	18770	2130	2639	645
New York	14971	1699	2105	514	163101	18508	22932	5602
Dallas	46	5	6	2	8068	915	1134	277
Philadelphia	2041	232	287	70	22240	2524	3127	764
Kansas City	29	3	4	1	5133	582	722	176
Portland	1458	165	205	50	15885	1803	2233	546

The differences in infrastructure need reflect both population and type of state. The differences can be large, especially in 2030. For example, in that year NY/Newark requires on the order of 300 times more 50 kW and 350 kW units than does Dallas. Even Philadelphia requires nearly 50 times more. By 2050 all the cities require a large number of stations, though differences across city remain substantial. Those cities in Section 177 states will need to move particularly fast and organize for large, multibillion dollar investments to be made. As market size of chargers grow, the possibility that unit costs come down should help the slower moving cities, though we do not assume such cost savings in this study.

Conclusions from the study include:

- High carbon reductions in the transportation sector require aggressive ZEV market penetration plus very low fuel carbon intensity.
- Due to slow stock turnover, the LC and High ZEV scenarios contain significant numbers of ICE trucks. The biomass based liquid volume reaches 70 (High ZEV) to 80 (LC) billion GGE by 2045.
- Electricity usage in 2045 increases from 5 billion GGE in the BAU scenario to 20 billion GGE in the High ZEV scenario.
- Cities within non-Section 177 states require a relatively low number of chargers by 2030. The cost for these chargers in non-port cities could be lower than $10 million.

- Cities within the Section 177 states require significantly greater number of chargers and would incur a much higher cost in 2030 compared to cities outside the 177 states.
- For the cities in this study, the charger cost ranges from $5 million to $2.6 billion in 2030 and from roughly $1 billion to almost $30 billion in 2040.

Introduction

A recent Intergovernmental Panel on Climate Change report on the impacts of global warming concludes that a 1.5^{o} C warming above pre-industrial levels could be achieved if global carbon emissions decrease substantially by 2030 and reach net zero global anthropogenic CO_2 emissions by 2050 [1]. These emissions levels would result in manageable changes to the environment. Multiple studies demonstrate that in the transportation sector fuel economy improvements alone will not be sufficient to reduce carbon emissions to the required levels by 2050 and that a transition from fossil fuel-based vehicles to zero emission vehicles (ZEVs), such as battery electric or fuel cell vehicles, will be necessary [2-3].

In the U.S., California has led the effort to reduce carbon emissions. Initial regulations targeted light-duty vehicles (LDVs) through a ZEV mandate [4], but more recently programs and regulations have targeted medium- and heavy-duty vehicles [5-6]. In 2019 the California Air Resources Board approved the Advanced Clean Trucks regulation that sets a manufacturer's ZEV sales requirement for medium- and heavy-duty trucks through 2035 [7]. At the U.S. level several states have adopted California's Zero-Emissions Vehicle regulation under section 177 of the Clean Air Act [8]. These so called 177 states may follow the Advanced Clean Trucks regulation as well.

Both battery electric and fuel cell vehicles emit zero emissions from their tailpipes, but the economics of battery electric trucks are likely to be more favorable than fuel cell trucks in the next 5-10 years [9]. The total cost of ownership (TCO) based on the capital and operating costs is projected to be lower; therefore, the market penetration of battery electric trucks may lead fuel cell trucks by several years. While regulation mandating ZEV medium- and heavy-duty trucks exists in California and may soon exist for the 177 states, fueling infrastructure must be in place in order to support the rollout of ZEV vehicles. Fleets will not purchase ZEV vehicles without the ability to charge or refuel them.

This study focuses on battery electric trucks and the infrastructure necessary to charge those vehicles. A model, the U.S. Transportation Transitions Model (US TTM), was developed to project stocks of advanced vehicles in the U.S. through 2050. The US TTM estimates the number of trucks in various truck classes and the volume of fuel necessary to operate the trucks year-by-year through 2050 throughout the U.S. The study selected six representative cities in the U.S. and estimated the number of charging stations within those cities necessary to charge the truck population serving those cities in the year 2030.

In order to meet the emissions reductions target, significant progress must occur by 2030. The ZEV market share must increase considerably by then to pave the way for reaching 100% ZEV sales in time to ensure the turnover of the truck stock such that internal combustion engine vehicles constitute a very small portion of the overall fleet by 2050. Charging infrastructure must increase by 2030 to support the growth of the battery electric fleet and understanding these charging requirements at that time is critical for meeting the aggressive goal of net zero carbon emissions in 2050.

The Methodology chapter describes the US TTM model, the input and outputs, and the process involved in developing the model. That chapter also describes the methods used to estimate the number of trucks in the selected U.S. cities in 2030, the number of charging stations necessary to support that fleet, and the cost of those chargers.

The Results chapter describes a variety of outputs from the US TTM model including number of trucks in different applications, fuel usage for the fleet, carbon emissions for the fleet, and vehicle and operating costs. The chapter then describes the outputs for the city charging station analysis including the city truck stock, number of chargers to support the city fleet, and the cost of the chargers.

The Summary chapter describes the most important results from the US TTM outputs and the city charging station analysis.

Methodology

This chapter discusses the development of the US TTM model and the process used to estimate the number and cost of chargers necessary to support the battery electric truck fleet in three representative U.S. cities in the year 2030.

U.S. Transportation Transitions Model (US TTM)

The TTM is a spreadsheet-based model that projects into the future both vehicle sales/stocks and fuel/feedstock pathways. This model allows exploration of a broad range of scenarios and input assumptions and estimates outputs such as vehicle stock by vehicle type and technology, fuel use, carbon emissions, and costs. The US TTM was modified from an earlier model developed for California, the CA TTM [10].

The CA TTM model is based on the Argonne VISION model modified by the California Air Resources Board and includes relevant economic costs associated with these vehicles based on a detailed component level analysis for key technologies, such as fuel storage, batteries, fuel cells, and electric drivetrains. The model is disaggregated into different vehicle types.

The model is a stock turnover model the projects fuel usage, carbon emissions, vehicle stock, vehicle and operating costs year by year through 2050. The model inputs vehicle stock by technology type (e.g., diesel, natural gas, battery electric, fuel cell, etc.) starting in the base year of 2010. Other inputs include vehicle fuel economy, vehicle cost, fuel carbon intensity, fuel cost, vehicle miles traveled per year (VMT), and vehicle scrappage rates.

In the TTM, the light-duty sector is segmented into cars and light duty-trucks. These two categories are representative of the average vehicle across the numerous car and light-truck classes (e.g., subcompact, compact, midsize, full-size cars, and small and full-sized SUVs, pickups and vans). The medium- and heavy-duty (MDV/HDV) sectors are segmented into 8 categories to capture the diversity of truck characteristics (application, size, fuel economy, drive cycle, refueling time). Table 1 shows the vehicle types for both LDVs and medium- and heavy-duty vehicles.

Table 1. LDV and truck categories in the TTM.

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

The truck and bus categories are defined as follows:

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

This level of disaggregation enables the determination of which vehicle and fuel technologies may be appropriate for specific vehicle types (e.g., battery electric vehicles may be less suitable for long-haul trucks, but possible for short-haul trucks).

The technologies considered for the vehicle types are:

- Gasoline
- Diesel
- Natural gas
- Hybrid
- Plug-in hybrid
- Battery electric
- Fuel cell

Not every vehicle type includes each technology; for example, the trucks do not include plug-in hybrids.

The fuels considered in the TTM are

- Gasoline
- Ethanol (more generally biomass-based gasoline substitutes)
- Diesel
- Diesel biofuels (more generally biomass-based diesel substitutes)
- Natural Gas
- Electricity
- Hydrogen

The model develops transitions in a "what-if" style, with multiple scenarios that can be compared in terms of their transition pathway and cost implications. The scenarios are defined by the sales shares for each vehicle and technology type year by year through 2050. These scenarios vary based on the aggressiveness of the market penetration of ZEVs.

The US TTM model uses the same inputs as the CA TTM but varies the scenarios. While California has regulations that mandate the sales of LDV and truck ZEVs, the remainder of the country has fewer or no such regulations. The US TTM scenarios are created from the CA TTM scenarios but assume the 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 [11]. Three of these scenarios were modified and included in the US TTM model. These scenarios are business as usual (BAU), low carbon (LC), and high ZEV (HZ). The scenarios are described below.

The BAU scenario reflects existing trends and considers how these trends will be affected by a number of existing California transportation and CO_2 related policies. Market penetration of LDV ZEVs grow modestly from the present sales shares. Medium- and heavy-duty truck and bus ZEV sales shares remain below 2% through 2050 except for transit buses that reach 100% ZEV sales shares by 2030. Although California has enacted the Advanced Clean Trucks regulation, the BAU does not assume this regulation affects trucks.

The LC scenario is designed to achieve a near-net-zero CO_2 emissions transportation system by 2045, with a rapid ramp-up in ZEV sales for light-duty vehicles and trucks, reaching 100% ZEV market shares by 2040. 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 internal combustion engine vehicles (ICEVs) by 2045. Finally, it includes a 15% reduction in per-capita LDV VMT in 2045 compared to the BAU case.

The LC scenario matches current LDV sales shares and uses near-term vehicle stock targets to guide sales shares in the mid-term. The early sales shares for medium- and heavy-duty trucks are guided by the Advanced Clean Trucks regulation. Table 2 shows the required sales shares for ZEVs in three market classes.

Table 2. Advanced Clean Trucks regulation manufacturer required market share for three truck classes.

Year	Class 2b-3	Class 4-8	Tractor
2025	7%	11%	7%
2030	30%	50%	30%
2035	55%	75%	40%

In order to reach 100% sales shares by 2040, the sales shares in 2035 were increased for class 2b-3 and class 7-8 tractors.

The high ZEV scenario is similar to the LC scenario, but ZEV market penetration is accelerated such that ZEV sales shares reach 100% five years earlier in 2035. In 2020, California Governor Gavin Newsom signed an executive order setting a goal that the state will mandate 100% ZEV sales for passenger vehicles by 2035 and medium- and heavy-duty trucks by 2045 [13]. The high ZEV scenario is more aggressive requiring truck ZEV sales shares to reach 100% by 2035.

To create the US TTM scenarios, we started with the CA scenarios and modified them based on ZEV market penetration expectations for three sections of the country: California, 177 states, and the remaining states. We assumed that California would meet each scenario sales shares projections. Given that the 177 states might adopt similar ZEV requirements to California, we assumed these states would have similar sales shares but with the ZEV market penetration delayed by 5 years. We assumed the remaining states would have similar sales shares but with the ZEV market penetration delayed by 10 years. Table 3 shows the year ZEV sales shares reach 100% for each of the three U.S. sections for each scenario. The table also shows the percentage of the U.S. population contained in those sections.

Table 3. Year LDV and MDV/HDV ZEV sales shares reach 100% for the LC and High ZEV scenarios for the three U.S. sections.

Year ZEV Sales reach 100%			
Region	**Population Percentage**	**LC Scenario**	**High ZEV Scenario**
California	12	2040	2035
177 States	24	2045	2040
Remainder U.S.	64	2050	2045

We created the LC and high ZEV scenarios for each section of the country using the process described above. We then created the overall U.S. LC and high ZEV scenarios by using a weighted average of the sales shares for each vehicle and technology type. The U.S. LC and High ZEV scenarios do not include a reduction in VMT from the BAU. Figure 1 shows the ZEV sales shares for transit buses, LDVs, and trucks for the CA BAU and the U.S. BAU scenarios. Figure 2 shows the ZEV sales shares for transit buses, LDVs, and trucks for the CA LC and the U.S. LC scenarios. The Appendix gives detailed vehicle sales shares for the BAU, LC, and High ZEV scenarios for all eight truck types for years from 2015 through 2050.

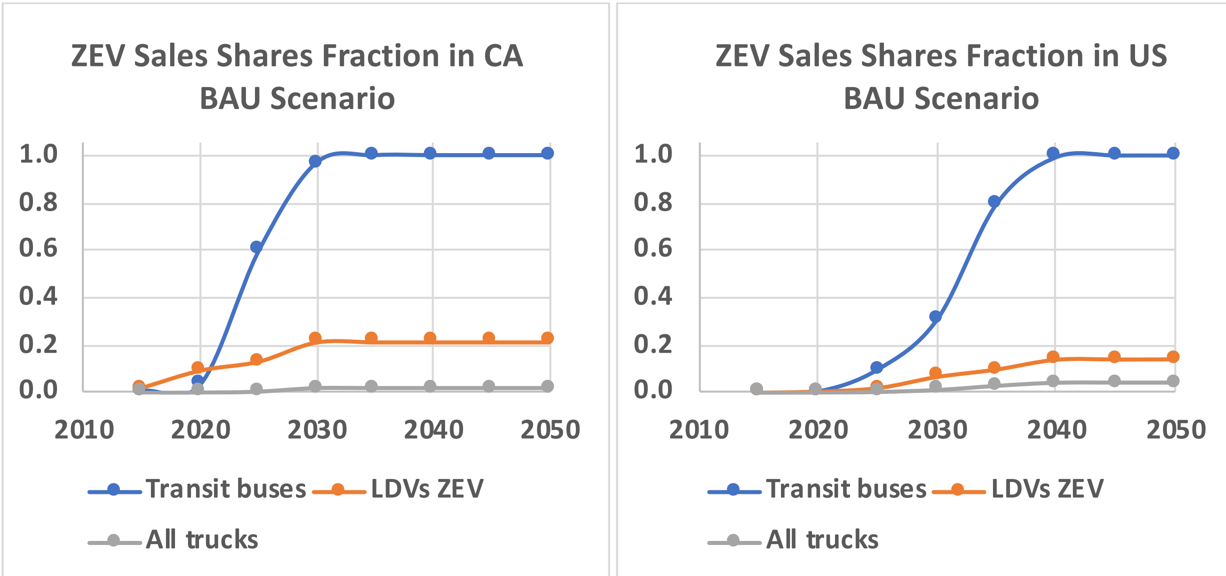

Figure 1. ZEV sales shares for transit buses, LDVs, and trucks in the CA BAU (left) and U.S. BAU (right).

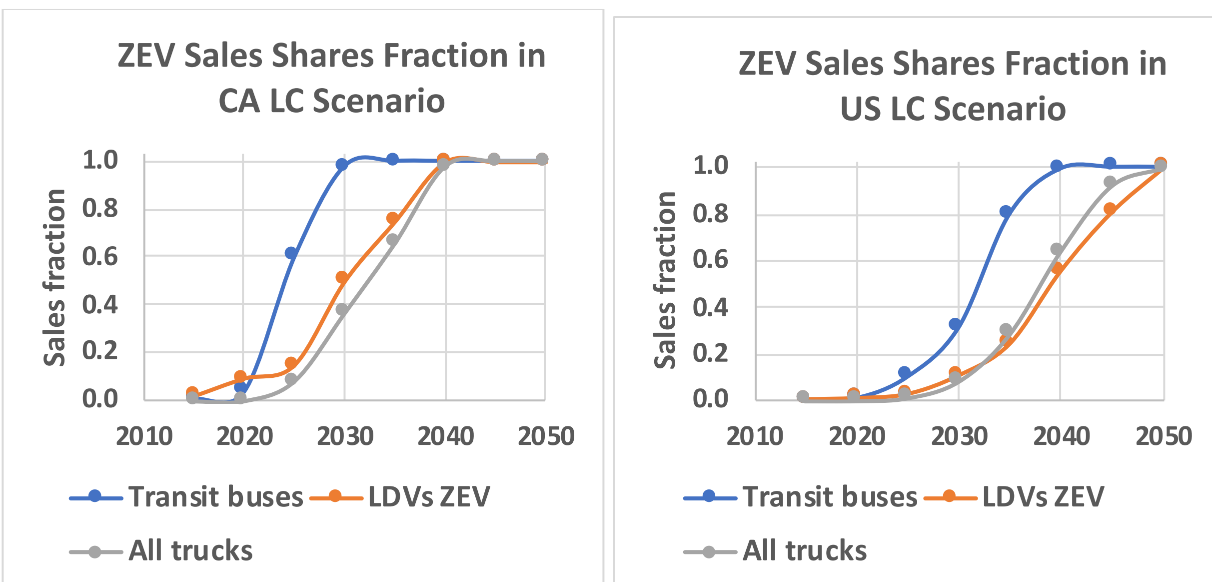

Figure 2. ZEV sales shares for transit buses, LDVs, and trucks in the CA LC scenario (left) and U.S. LC scenario (right).

The U.S. scenarios exhibit a delayed ZEV market penetration compared to the CA scenarios.

Figure 3 shows a comparison of ZEV sales shares in 2040 in the CA TTM and the US TTM for the LC and High ZEV scenarios by vehicle type. By 2040 the California scenarios reach 100% ZEV sales shares for all vehicle types, but the U.S. scenarios vary from roughly 40–75% based on vehicle type.

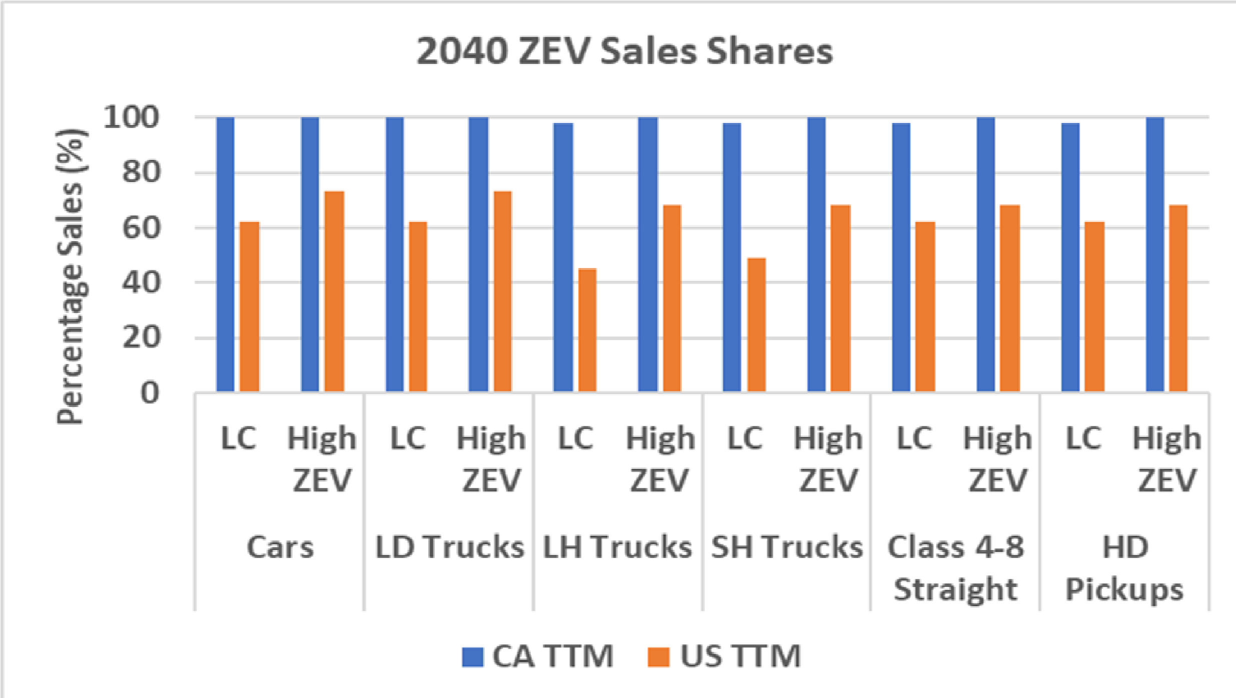

Figure 3. Comparison of ZEV sales shares in 2040 in the CA TTM and the US TTM for the LC and High ZEV scenarios by vehicle type. LD Trucks = light-duty trucks, LH Trucks = long-haul trucks, SH Trucks = short-haul trucks, Class 4-8 Straight includes medium-duty urban, medium-duty vocational, and HD vocational.

The CA TTM uses California historical stock data and projected stock from the California EMFAC (EMission FACtor) model that provides California's emissions inventories of on-road and off-road mobile sources [14]. EMFAC contains stock numbers for on-road vehicle types and projects stock increases through 2050. The US TTM uses stock numbers from EPA's Motor Vehicle Emission Simulator (MOVES3) [15]. MOVES is a bottom-up model estimating emissions from separate physical emission processes depending on the source, while accounting for the phase-in of federal vehicle emission standards. MOVES covers on-road vehicles such as cars, trucks, and buses, as well as nonroad equipment such as bulldozers and lawnmowers.

In order to use historical data for vehicle stock and project stock out to 2050, we ran the MOVES3 model at the national scale and then extracted the default national activity data including the vehicle population and VMT for a number of years such as 2010, 2020, 2021, and 2050. The national scale contains a total of 53 jurisdictions: 50 states, DC, Puerto Rico, and Virgin Islands. The vehicle population and VMT data contain details such as emission source type (aka vehicle class), vehicle regulatory class, fuel type, and vehicle model year. A MOVES snapshot of the national fleet in a year is composed of 31 model years, spanning ages from 0 through 30. We used this data to calibrate vehicle stock for the US TTM model.

Both EMFAC and MOVES3 disaggregate vehicles into more vehicle classes than the TTM does. We mapped EMFAC and MOVES3 vehicle classes onto our 10 LDV and truck classes based on vehicle characteristics such as regulatory class and VMT. For each model, we then used the 2010 stock data as a starting point and adjusted vehicle sales by vehicle type to match the projected stock for that vehicle type through 2050.

While there may be differences in fuel costs, fuel carbon intensities, percentage of biomass-based liquids in diesel and gasoline, and other inputs to the TTM model for different regions of the U.S., we assumed that all these inputs would be the same for both the CA TTM and the US TTM.

U.S. City Charging Station Analysis

To keep the effects of global climate change manageable, the on-road vehicle contribution to carbon emissions must be reduced significantly by 2030 and further reduced close to zero by 2050. To reduce carbon emissions, the U.S. must create policies to enable significant market penetration of medium- and heavy-duty ZEVs. A large percentage of these ZEVs will likely be battery electric vehicles due to lower TCO. In order to support the operation of these battery electric vehicles, electric charging infrastructure must be greatly expanded.

In California there is progress on installing chargers for both LDVs and trucks, but throughout the U.S. such infrastructure is minimal. To prepare for the rollout of medium- and heavy-duty ZEVs cities must estimate the number of chargers necessary to support the expected fleets. Additionally, the cost for these chargers must be paid by private and public funds. Knowing the estimated cost will be useful in procuring the required funding.

The task of estimating the number of electric chargers to support a fleet of medium- and heavy-duty ZEVs requires the use of detailed models. The models must project the number and type of battery electric medium- and heavy-duty ZEVs, the charging profiles (kWh used and time of recharging) for these vehicles, and the vehicle routes and locations. Few cities have the ability to model these vehicle characteristics.

The California Energy Commission (CEC) was tasked to develop such a model and project battery electric ZEV stock, charging profiles, and routes. In 2018, California Assembly Bill (AB) 2127 codified ZEV stock targets for 2030 and tasked the CEC with preparing biennial assessments of the charging infrastructure needed to meet these goals [16]. The CEC developed several models to estimate charging infrastructure needs. The model used for medium- and heavy-duty vehicles is HEVI-Pro. Using this model, the CEC projected ZEV truck and bus stock for 2030 and estimated the electrical energy needs to charge the overall fleet. From that energy estimate, the CEC projected the number of chargers needed to support the ZEVs in California [17].

To estimate the numbers of chargers needed in various cities in the U.S. in 2030, this study used results from the CEC infrastructure analysis for specific California cities and extrapolated those results to U.S. cities outside California. A brief description of the CEC analysis and the methodology used to extrapolate California results to other cities is given below.

The HEVI-Pro model, developed at LBNL, uses a top-down approach to estimate infrastructure needs. The model projects battery electric medium- and heavy-duty vehicle stock from a variety of sources, inputs vehicle powertrain characteristics and battery parameters, and allocates energy consumption to individual vehicle trips. The model estimates the charging probabilities based on trip activity and makes an infrastructure assessment using charger configurations of 50 kW and 350 kW and fleet locations [18].

The CEC analysis considers three battery electric vehicle market penetration scenarios. The Medium Charging Demand and High Charging Demand projections came from the 2020 Integrated Energy Policy report [19] with modifications to exclude catenary trucks. The Mobile Source Strategy scenario serves as an upper bound [20]. Table 4 shows the projected battery electric medium- and heavy-duty ZEV stock in 2030 from these scenarios.

Table 4. Projected battery electric medium- and heavy-duty ZEV stock in 2030.

Scenario	Medium Charging Demand	High Charging Demand	Mobile Source Strategy
BEV stock	75,000	81,000	180,000

The Medium Charging Demand scenario projects lower BEV stock and uses an optimistic rate of improvement in battery technology and typical loading characteristics. The High Charging Demand and the Draft Mobile Source Strategy scenarios project higher BEV stock and assume heavily loaded operations and conservative improvements in battery technology. The stock projections were independent of the rate of battery technology improvements. The CA TTM model projects a BEV stock of roughly 167,000 in 2030 for the LC scenario. This stock projection fits squarely in the middle of the Medium Charging Demand and Mobile Source Strategy scenarios.

The CEC analysis provides two charging options: charging overnight using a 50 kW charger or charging during the day using a 350 kW charger. The high BEV stock from the Mobile Source Strategy requires roughly 141,000 50 kW chargers and 16,000 350 kW chargers to complete the required trips.

This analysis relied on data from the HEVI-Pro analysis that included details of the 2030 projected vehicle stock for the California cities: Los Angeles, Sacramento, and San Diego. We assume that the number of chargers required for each city is roughly proportional to the number of medium- and heavy-duty ZEVs in each city. Using this assumption, we can associate a number of 50 kW and 350 kW chargers for cities with particular characteristics and a given population.

To estimate the number of chargers needed for medium- and heavy-duty ZEVs in cities outside of California we must take into account the fact that states other than California do not have aggressive ZEV mandates, and therefore, cities in those states will likely have lower ZEV stock in 2030 or other years. To estimate the number of medium- and heavy-duty ZEVs in other cities, we use the CA TTM model but with a delayed LC scenario to project the number of ZEVs expected from less aggressive policies.

The CA TTM LC scenario yields 167,000 medium- and heavy-duty ZEVs in California in 2030. The delayed (5 or 10 years) LC scenarios will result in fewer ZEVs in 2030. We can use the lower numbers to scale expectations for ZEV stock, and therefore, chargers in other cities.

As an example, consider a city in one of the 177 states but similar to Los Angeles in population and port container volume. We start by determining the number of chargers in Los Angeles based on the fraction of Los Angeles ZEVs to California ZEVs in 2030. We then can run the CA TTM with the LC scenario with ZEV market penetration delayed by 5 years to estimate the number of medium- and heavy-duty ZEVs in California in 2030 for that scenario. Using the ratio of the number of ZEVs from the delayed LC scenario to the number from the normal LC scenario and the ratio of the 177 state city population to Los Angeles's population, we can estimate the number of chargers in the 177 state city by scaling the number of Los Angeles charger by those ratios.

We use that process to estimate the number of chargers required for projected medium- and heavy-duty ZEVs in 2030 for 4 cities outside California—2 from 177 states and 2 from non 177 states. We select each city based on a rough match in population and city characteristics.

After estimating the number of chargers needed to support the fleet of medium- and heavy-duty ZEVs in a given city, we then estimate the cost for those chargers. Charger costs vary considerably based on the charger power, number of chargers per pedestal, installation costs, and other charger specifications.

Charger cost estimates give costs for the charger and for installation. We used an ICCT paper [21], a Harvard Kennedy School working paper [22], and an EVgo paper [23] to estimate the charger costs. Table 5 shows the costs from these three sources for a 50 kW charger and a 350 kW charger.

Table 5. Estimated per charger costs for 50 kW and 350 kW chargers including both the charger cost and installation costs.

Source	Charger power (kW)	Charger Cost ($)	Installation Cost ($)
ICCT	50	28,400	27,000–45,500
Harvard	50	35,000	85,000
EVgo	50	20,000–35,800	35,000–53,000
ICCT	350	140,000	39,000–66,000
Harvard	350	100,000	92,500
EVgo	350	128,000–150,000	66,000–173,000

To estimate the cost of charger with installation we use the mid value where a range exists and then sum the charger and installation costs. We then average the three estimates for both the 50 kW and 350 kW chargers. The final costs used are given in Table 6.

Table 6. Total per charger total costs and the average of the three sources.

Source	Charger power (kW)	Charger + Installation Cost ($)
ICCT	50	100,900
Harvard	50	205,000
EVgo	50	115,900
Average	50	140,600
ICCT	350	245,000
Harvard	350	285,000
EVgo	350	378,000
Average	350	302,667

Analysis Results

This chapter shows results for both the US TTM model and the U.S. city charging analyses. For each of the figures the abbreviations are:

- LH – long-haul
- SH – short-haul
- MD – medium-duty
- Voc – vocational
- NG – natural gas
- RNG – renewable natural gas
- BEV – battery electric vehicle
- H2 – hydrogen
- BBD – biomass-based diesel
- BBG – biomass-based gasoline

U.S. Transportation Transitions Model Results

Figure 4 shows the percentage of vehicle sales by technology type for each of the 10 vehicle types, for the BAU, LC and High ZEV scenarios, in the years 2030 and 2045. Typically, the 2045 shares of ZEVs in the BAU are very low, with the major exception being transit buses. This reflects an expectation that BEV transit buses will be highly competitive by 2030 or well before. The transit bus sales shares are identical for each of the three scenarios. Natural gas vehicle sales in 2045 are significant for medium-duty urban, other bus, medium- and heavy-duty vocational trucks. In 2045 there is a large share of diesel and gasoline vehicle sales.

In the LC scenario, the share of ZEVs in 2030 remains low with small percentages appearing in most vehicle types. By 2045 the vast majority of sales are ZEVs or plug-in hybrids with diesel/gasoline vehicles making up less than 20% in all vehicle types except long-haul trucks. There's a small percentage of natural gas truck sales in the medium- and heavy-duty vocational trucks.

In the High ZEV scenario, diesel and gasoline vehicle dominate sales in 2030 with the exception of transit buses. By 2045 all vehicle sales are ZEV or plug-in hybrid. In the CA TTM High ZEV scenario vehicle sales reach 100% by 2035, so even with the 10-year delay in ZEV sales shares for states outside California and the 177 states, ZEV sales reach 100% by 2045.

LDVs and trucks may remain in the fleet for 15 or 20 years or longer; therefore, older diesel and gasoline vehicles can continue in use past the period when all sales are ZEVs. Figure 5 shows the fleet mix by vehicle and technology type for the years 2030 and 2045 for each of the three scenarios.

The BAU scenario stocks are dominated by diesel and gasoline vehicle except for transit buses that reach almost 80% ZEVs by 2045. Natural gas vehicles constitute a modest portion of the vehicle stock for 5 of the vehicle types. Almost 20% of LDVs are ZEVs or plug-in hybrids, but there are almost no ZEVs in the entire truck fleet.

In the LC scenario, the stock of ZEVs is little different from the BAU scenario with only transit buses showing even modest numbers. By 2045 all vehicle types contain large numbers of ZEVs in their fleet stock. Most vehicle types have roughly 40% ZEVs in the stock. The High ZEV scenario also shows little evidence of ZEVs in the fleet stock by 2030; however, by 2045 the percentage of ZEVs in all vehicle type stock is roughly 50%.

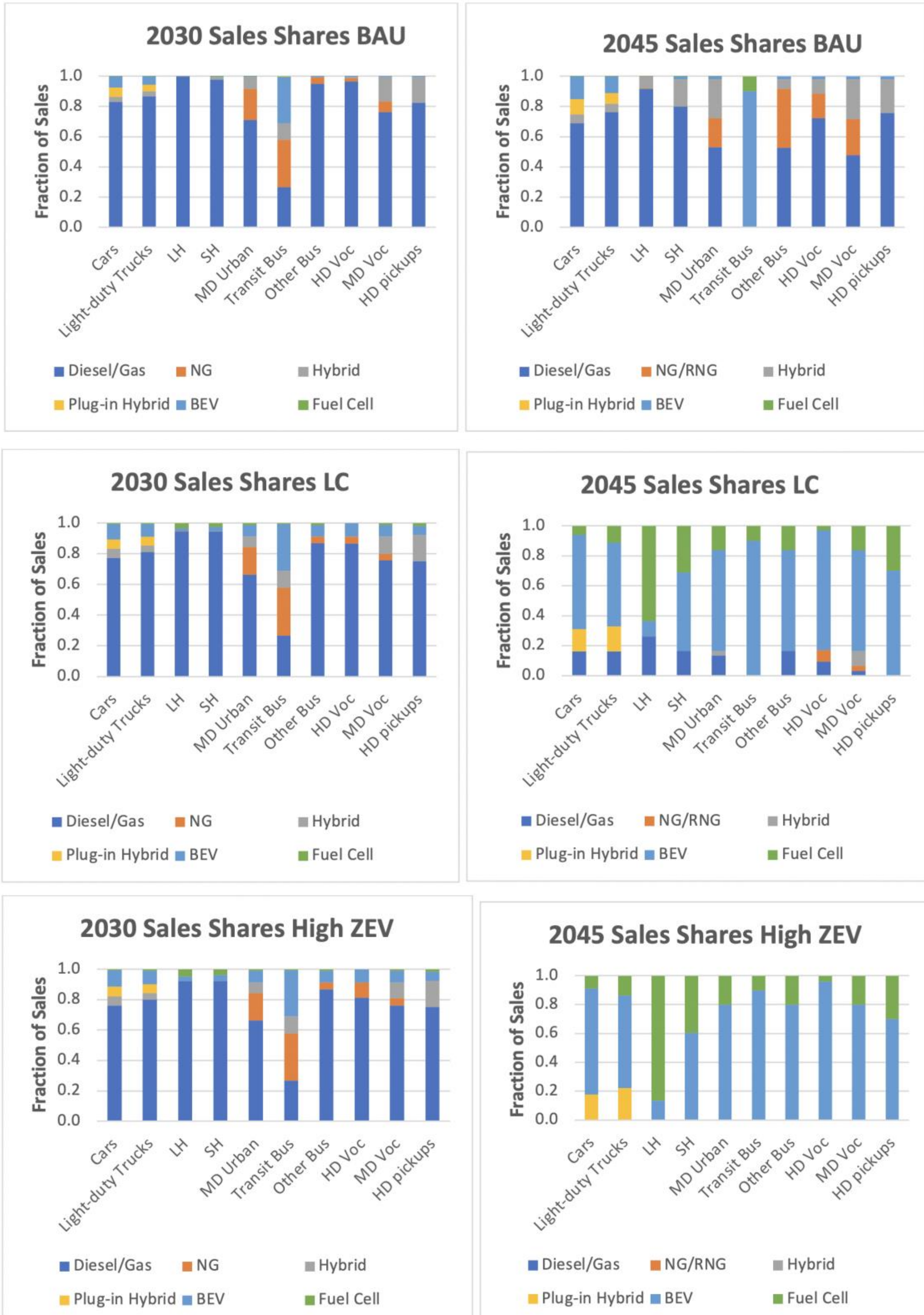

Figure 4. Percentage of vehicle sales by technology type and vehicle type for the BAU, LC, and High ZEV scenarios in the years 2030 and 2045.

For both the LC and High ZEV scenarios, battery electric vehicles dominate the sales and fleet stock. Studies of vehicle TCO show that battery electric vehicles are cost competitive with gasoline or diesel vehicles in the 2025–2030 timeframe. Fuel cell vehicles generally do not become cost competitive until somewhat later. Due to this initial cost advantage, the TTM models increase battery electric sales shares above fuel cell vehicle sales shares.

One exception to the battery electric dominance is long-haul trucks. While both fuel cell and battery electric vehicles encounter significant barriers in this application, battery electric trucks require a very large battery pack to meet the range requirements. The extra weight would potentially decrease payload and cut into margins. Additionally, charging the large battery pack would require long charge times or enormous power chargers. One possibility for battery electric long-haul trucks is to reduce the range requirement to 300 miles or less and have the trucks charge more frequently. Even a 300-mile long-haul battery electric truck would require a large pack that could reduce income due to payload restrictions, and fleets tend to view ranges shorter than 500 miles as not a viable option.

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

The TTM models includes significant fuel economy increases for all vehicle types. The models also have substantial increases in vehicle stock from 2020 through 2050 so overall VMT rises significantly. The combination results in somewhat lower greenhouse gas emissions for the BAU scenario, but without a transition to vehicles with markedly high fuel economies using fuels with vastly lower carbon intensities, the reduction in emissions is modest.

Both battery electric and fuel cell vehicles have much higher fuel economies than diesel and gasoline vehicles. The reduction in fuel use is, therefore, quite large. This fuel reduction would be useful but not enable the on-road fleet to approach net zero emissions without the additional reduction in fuel carbon intensity. The TTM models assume that both hydrogen and electricity can reach a zero carbon fuel intensity by 2045. In addition, the model assumes that the percentage of biomass based liquid fuels in diesel and gasoline increases to reach 100% by 2045. These biomass-based fuels have carbon intensities less than 25% of diesel or gasoline.

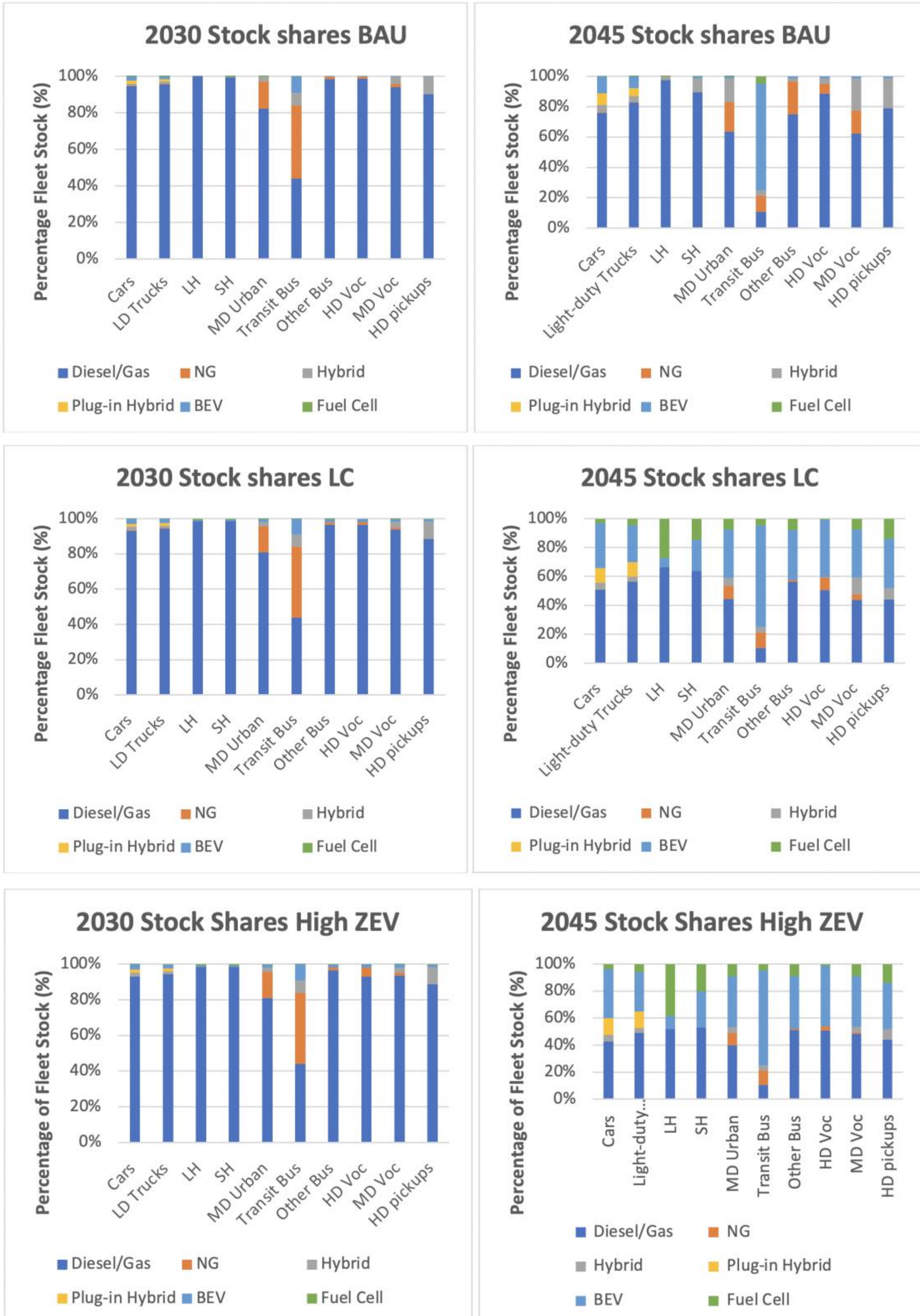

Figure 5. Percentage of vehicle stock by technology and vehicle type for the BAU, LC, and High ZEV scenarios in the years 2030 and 2045.

In order to reduce the carbon intensity of transportation fuels, California enacted the Low Carbon Fuel Standard (LCFS). The LCFS is designed to decrease the carbon intensity of California's transportation fuel pool and provide an increasing range of low-carbon and renewable alternatives, which reduce petroleum dependency, achieve air quality benefits, and reduce carbon emissions [24].

In the LC and High ZEV scenarios, the LCFS program targets were increased to reach a 25% CI reduction in 2030. This target approximately matches the “Accelerated Progress” scenario in the *California’s Clean Fuel Future* report [25]. After 2030, the LCFS target accelerates rapidly, going from 25% to 80% by 2040. The carbon intensity of electricity and hydrogen reach 0 by 2045.

Figure 6 displays the greenhouse gas emissions reductions for both LDVs and MDVs/HDVs for the BAU, LC, and High ZEV (HZ) scenarios through 2050 as a function of fuel type. The BAU scenario results in a 17% emissions reduction in 2050 from 2015. The LC scenario achieves a 92% reduction, and the High ZEV scenario reaches a 94% reduction.

The effect of hydrogen in fuel cell vehicles and electricity in battery electric vehicles cannot be easily seen because the emissions contributions are so small. The increase in battery electric and fuel cell vehicle fuel economy coupled with the carbon intensity reductions for hydrogen and electricity eventually reaching zero in 2045 combine to reduce emissions to zero in that timeframe.

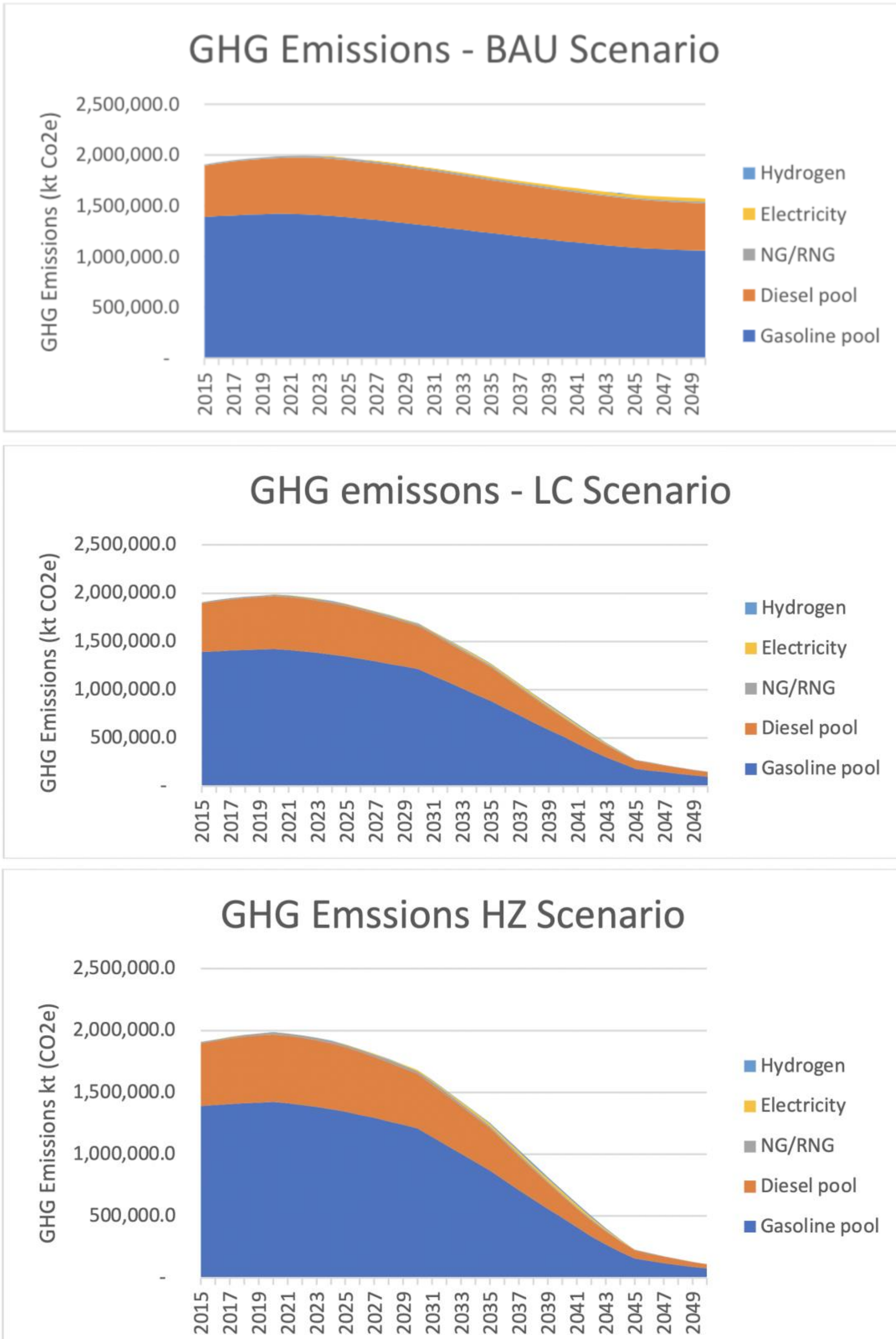

Figure 6. Total greenhouse gas emissions in CO2e for LDVs and trucks as a function of fuel type.

All three scenarios reduce fuel consumption due to increases in vehicle fuel economy. Figure 7 shows fuel consumption by fuel type for the BAU scenario. The fuel mix in the BAU scenario shifts only modestly towards lower carbon fuels (H2, hydrogen; electricity; CNG/RNG, compressed natural gas/renewable natural gas; BBD, bio-based diesel; BBG, bio-based gasoline), and the overall reduction is modest. The BAU scenario keeps the percentage of biomass based liquid fuels in diesel and gasoline constant at today's levels so there are only small contributions from biomass-based diesel (BBD) and biomass-based gasoline (BBC).

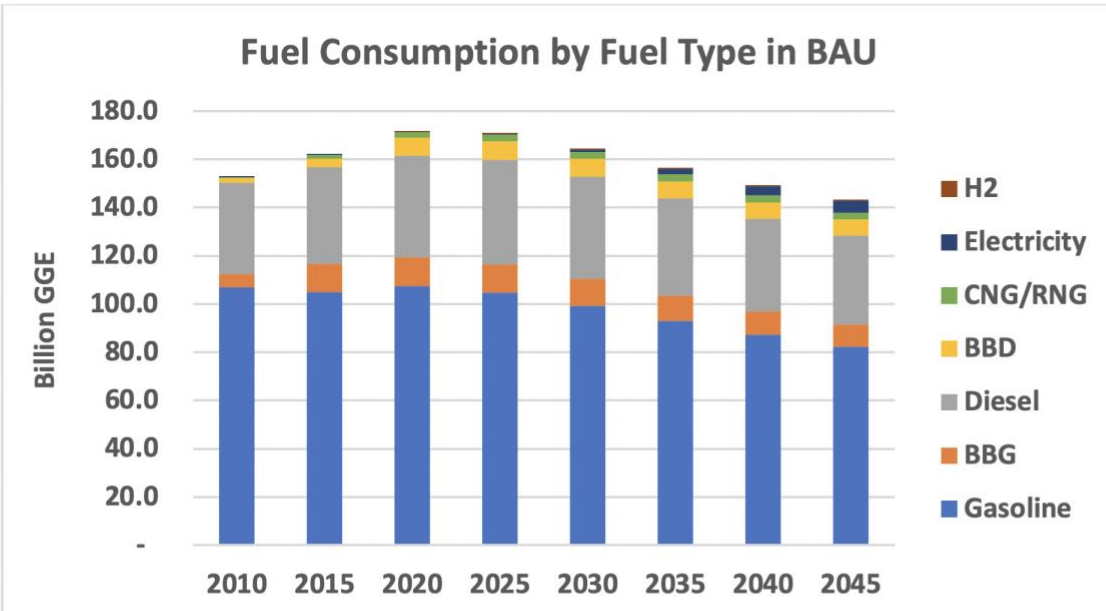

Figure 7. Fuel consumption by fuel type in the BAU scenario for LDVs and MDVs/HDVs.

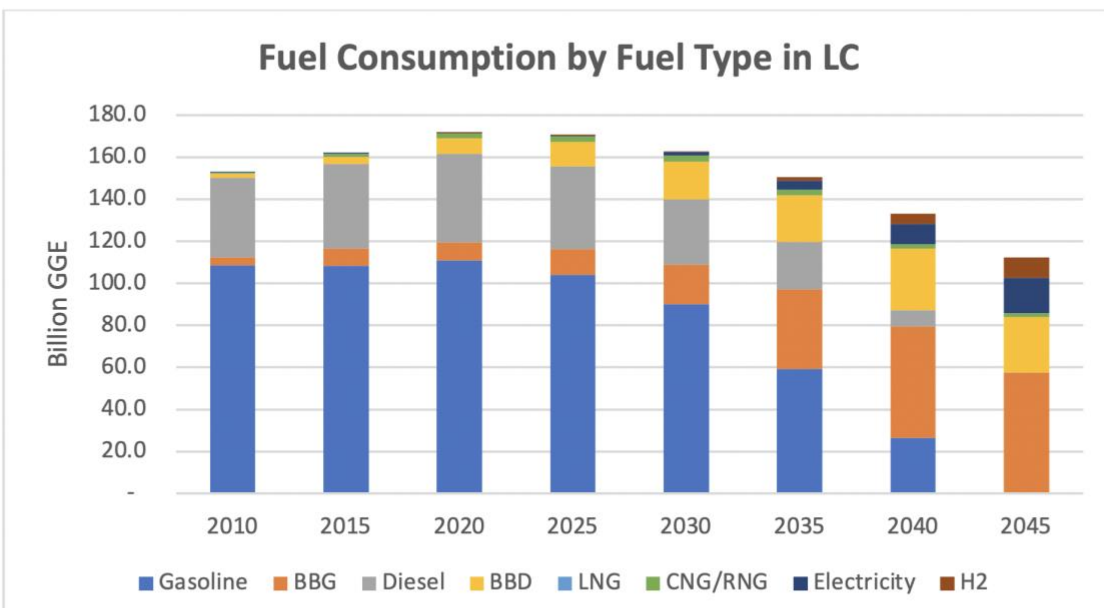

Figure 8. Fuel consumption by fuel type in the LC scenario for LDVs and MDVs/HDVs.

Figure 8 shows fuel consumption by fuel type for the LC scenario. The reduction in overall fuel use is significantly greater than for the BAU scenario, and the fuel mix shifts almost completely from gasoline and diesel to the low carbon fuels, electricity, hydrogen, BBD, and BBG. Even though ZEVs make up roughly 50% of the vehicle fleet, biomass-based liquids equal 75% of the fuel usage.

Figure 9 shows fuel consumption by fuel type for the High ZEV scenario. The reductions in overall fuel use are slightly greater than for the LC scenario, and the fuel mix shifts to the low carbon fuels, electricity, hydrogen, BBD, and BBG. Biomass based liquid fuels are reduced by 16% from the LC scenario.

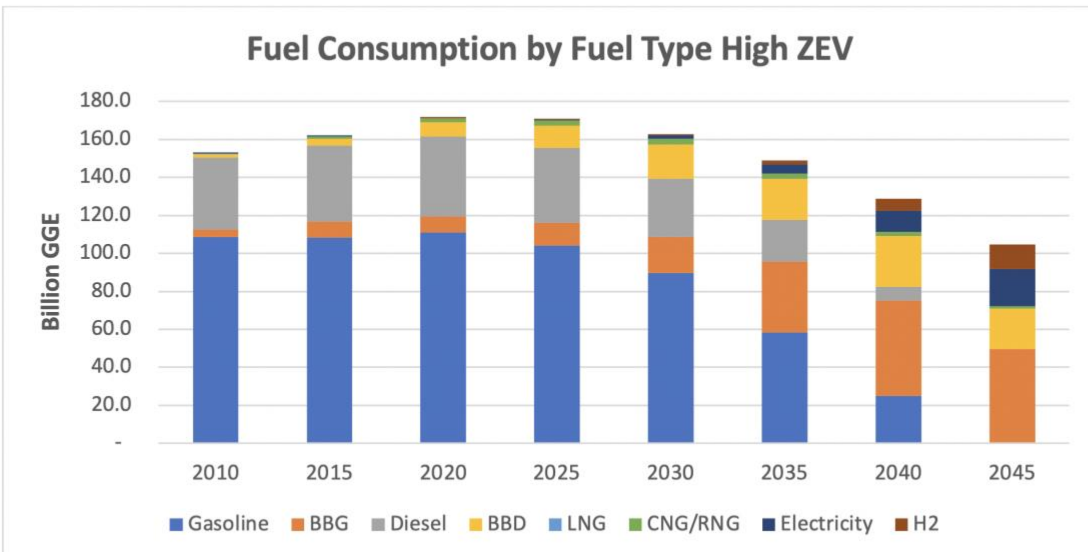

Figure 9. Fuel consumption by fuel type in the High ZEV scenario for LDVs and MDVs/HDVs.

Figure 10 shows fuel consumption by fuel type for the three scenarios in the years 2030 and 2045. In the year 2030 there is little difference between the scenarios except for the increase in BBD and BBG. The total fuel use is roughly the same because the increase in ZEV sales has not yet created a significant difference in the fleet stock. By 2045 the large fuel reductions in the LC and High ZEV scenarios contrast favorably with the modest reduction seen in the BAU.

The shift in fuel mix to hydrogen, electricity, and biomass based liquid fuels for the LC and High ZEV scenarios create the large reductions in carbon emissions due to the vastly lower or zero carbon intensity of these fuels.

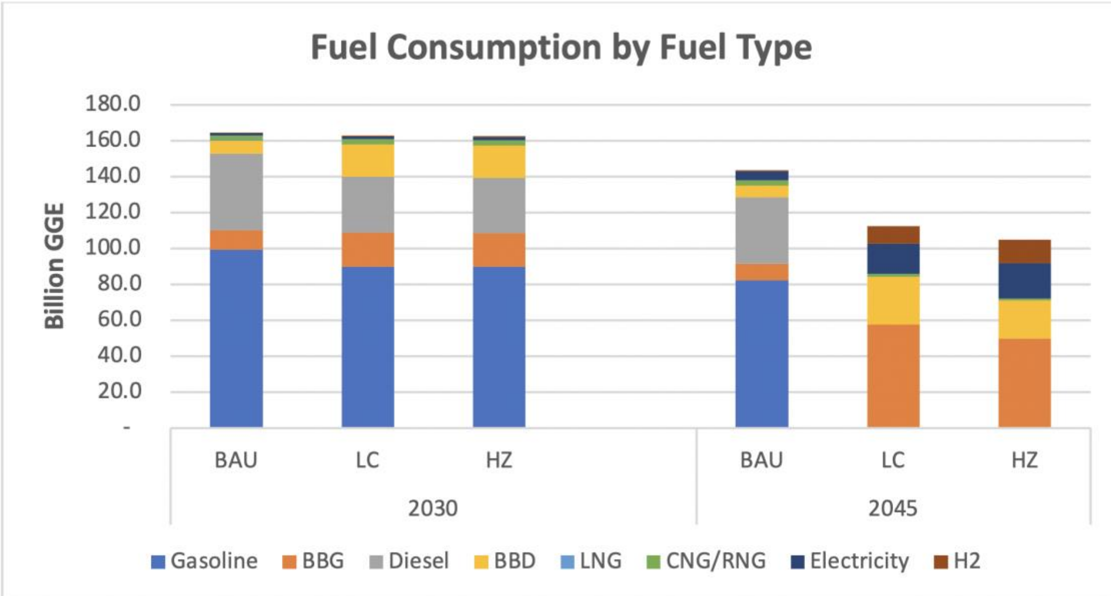

Figure 10. Fuel consumption by fuel type for LDVs and MDVs/HDVs in the three scenarios for the years 2030 and 2045.

Figure 11 shows the electricity consumption for the U.S. for each of the three scenarios. The electricity consumption in the BAU is dominated by LDVs because there are few ZEVs in the trucking sector for that scenario. The consumption in the High ZEV scenario is roughly 70% from the LDVs. Trucks would contribute much more to the electricity fuel usage, but long-haul trucks are predominately fuel cell rather than battery electric. Only 13% of long-haul ZEV fuel usage comes from electricity.

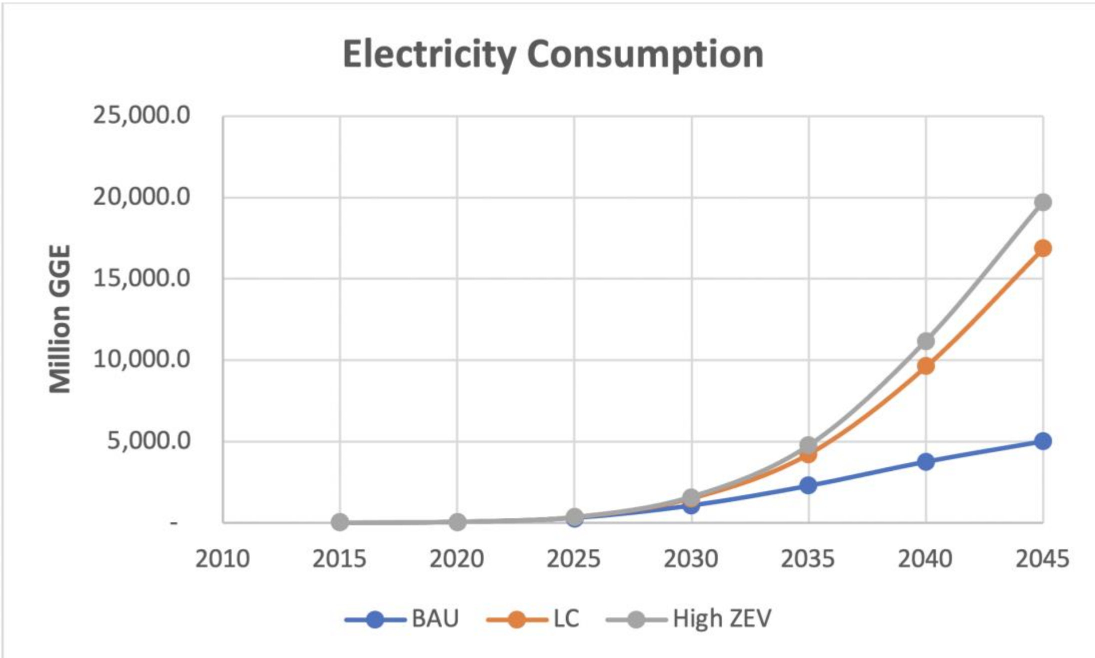

Figure 11. Electricity consumption for the BAU, LC, and High ZEV scenarios for battery electric LDVs and MDVs/HDVs.

U.S. City Charging Station Analysis Results

The analysis of city charging stations makes several assumptions that increase the uncertainty in the results. The numbers from the CEC charger analysis for California used a detailed model that included vehicle stock, trip information, and locations. The extrapolations for other cities in this study do not rely on such detailed information. Instead, the calculations assume that the projected truck stock, trips, and locations for California cities are similar to those of the other cities. We attempted to choose cities for this study that were similar to the California cities described in the CEC charging analysis.

Each city may have a somewhat different mix of truck types. For example, port cities will have many drayage trucks while other cities will not. Depending on commerce in a given city, there may be more or fewer delivery trucks. Long-haul trucks vary their routes, and some cities may have fewer long-haul trips through the city or fewer truck stops within the city. Different truck types will use varying kWhs of electricity each day, and the requirements for charging will vary accordingly.

This analysis uses population as a proxy for the stock of trucks. This assumption may be reasonable for delivery trucks but possibly inaccurate for other truck types. The populations used in this report are all from the 2020 census (July 1, 2019). Cities may grow at differing rates such that in 10 to 20 years the population ratios may vary from the 2020 values.

Truck routes within cities may vary in length and congestion leading to varying fuel usage and a differing need for chargers. The number of stops along a route and the congestion of the roads could cause large variations in fuel use in diesel vehicles. Battery electric vehicles use relatively little energy during stops because the battery does not idle so this issue may be relatively modest.

The largest uncertainty in this analysis comes from the scenario assumptions. California has clear regulations and ZEV targets for medium- and heavy-duty trucks in the state. The 177 states may soon have similar regulations and policies, but it's unclear when these will take effect. The assumption of a 5-year delay may be too long or too short depending on legislative actions. The remaining U.S. states have no regulations or plans for such regulations as of now. They could delay for a longer time than the 10-year assumption in this analysis. On the other hand, global warming effects could spur actions to put them more in line with the 177 states. The number of ZEVs expected in the 2030 or 2040 timeframe can vary by large factors.

While regulation seems likely to have the strongest effect on ZEV market penetration, other factors could substitute for such policies. As battery prices drop and ZEV technologies mature, the TCO of battery electric trucks drops closer to that of diesel trucks. Battery electric buses are considered a good option for transit buses in the near future, and bus manufacturers may begin transitioning to ZEVs with little or no regulation. If other truck applications saw similar transitions, U.S. states not part of the 177 states could see ZEV market penetration faster than the scenarios assumed for this study.

This study considers only charging stations for electric infrastructure. A major concern for utilities in supplying appropriate power for battery electric ZEVs is upgrading the make-ready infrastructure. CEC modeling indicates that the make-ready infrastructure needed to support charging stations requires special attention and investment. The costs that make up this investment include transformers, meters, breakers, wires, conduit, and associated civil engineering work. These costs are highly variable and difficult to predict.

When fleets purchase battery electric trucks to operate out of a particular depot, those trucks may require large power during charging. The location of the depot will determine if modest or large upgrade to the make-ready infrastructure in that region are necessary. Some fleets may not require any modifications, and others may require modest upgrades. Some may need substations to support the necessary power or significant trenching for long conduits to bring power from the grid to the chargers.

The need for major make-ready upgrades, in general, must wait for site-by-site analysis, so until fleets purchase ZEVs and work with utilities to install chargers to support their fleet, the actual hardware upgrades and cost will not be known. Because of the uncertainty in the need and cost for make-ready infrastructure, the cost is outside the scope of this study.

Table 7 shows projected ZEV and charger information in 2030 for three cities in California: Los Angeles, San Diego, and Sacramento. The HEVI-Pro model projected the number of medium- and heavy-duty ZEVs in Los Angeles, San Diego, and Sacramento. The number of ZEVs in each city is shown as a percentage of the total ZEVs in the state. The number of 50 kW and 350 kW chargers are calculated based on the percentage of ZEVs and the total number of chargers projected in the state. The table also shows the population from the 2020 U.S. census as of July 1, 2019 [26].

Table 7. Projected MDV/HDV ZEV stock and estimated number of chargers in 2030 for three California cities.

City	ZEVs	% CA total ZEVs	Number of 50 kW chargers	Number of 350 kW chargers	Population
Los Angeles	42202	0.23	32902	3734	3,980,000
Sacramento	6985	0.04	5446	618	514,000
San Diego	11203	0.06	8734	991	1,424,000
Total	60390	0.33	47081	5343	

Six U.S. cities were selected for this study to be representative of large U.S. cities from various regions of the country. The intent was to select two cities similar to each of the three California cities in Table 7 based on population size and ports. One of those cities would be in a 177 state while the other would not. The 177 states are:

- California
- New York
- Massachusetts
- Vermont
- Maine
- Pennsylvania
- Connecticut
- Rhode Island
- Washington
- Oregon
- New Jersey
- Maryland
- Delaware
- Colorado

There are 13 states aside from California in the 177 states.

Table 8 shows the six selected cities and shows their population from the 2020 census and displays whether they are a 177 state or not. The two cities, Houston and Newark/New York were selected as similar to Los Angeles. All three of those cities rank in the top 5 of U.S. ports based on number of TEUs (twenty-foot equivalent units or containers), and their populations are over 2 million. Dallas and Philadelphia have similar populations to San Diego and small or no ports. Similarly, Kansas City and Portland, OR have similar populations to Sacramento and are inland cities.

Table 8. The six selected cities outside of California. The table shows whether they are a 177 state and gives their population.

U.S. Cities	Region	Population
Houston	Other	2,320,000
Newark/NY	177	8,619,000
Dallas	Other	1,344,000
Philadelphia	177	1,584,000
Kansas City	Other	495,000
Portland	177	655,000

To estimate the number of chargers necessary to support the projected medium- and heavy-duty ZEVs in the years 2030 and 2040 for those six cities, we scale the California city numbers by the ratio of city populations and the ratio of projected California ZEVs from the CA TTM scenarios to the number of California ZEVs assumed in the HEVI-Pro analysis for 2030 (180,000). The California scenarios are the standard LC scenario, the LC scenario with ZEV market penetration delayed by 5 years, and the LC scenario with ZEV market penetration delayed by 10 years. Table 9 shows the number of ZEVs for the three scenarios for the years 2030 and 2040.

Table 9. Number of projected MDV/HDV ZEVs in California for the years 2030 and 2040 for the standard LC scenario and two scenarios with ZEV market penetration delays.

Scenario	ZEV market delay (years)	2030 ZEVs	2040 ZEVs
Standard LC	0	167,000	746,000
177 state LC	5	38,000	414,000
Other state LC	10	1,000	177,000

Table 10 shows the number of projected chargers and the cost, including installation, when scaling the six cities for population and number of projected ZEVs.

Table 10. Number of projected chargers for MDVs/HDVs and their cost, including installation, in six U.S. cities for the years 2030 and 2040.

	2030				2040			
U.S. Cities	**50 kW units**	**350 kW units**	**Cost of 50 kW chargers ($million)**	**Cost of 350 kW chargers ($million)**	**50 kW units**	**350 kW units**	**Cost of 50 kW chargers ($million)**	**Cost of 350 kW chargers ($million)**
Houston	106	12	15	4	18,770	2,130	2,639	645
Newark/NY	14,971	1,699	2,105	514	163,101	18,508	22,932	5,602
Dallas	46	5	6	2	8,068	915	1,134	277
Philadelphia	2,041	232	287	70	22,240	2,524	3,127	764
Kansas City	29	3	4	1	5,133	582	722	176
Portland	1,458	165	205	50	15,885	1,803	2,233	546

The number and total cost of chargers in Section 177 states grow significantly by 2030. Large cities in these states may want to increase investments in the near- to mid-term to provide the necessary number of public chargers before the vehicles arrive that need them. Large cities in the non-Section 177 states may have a longer timeline to provide chargers but eventually will require large investments as well.

Summary and Conclusions

The US TTM model uses “what if” scenarios of vehicle technology market penetration to estimate various outputs such as fuel use and carbon emissions in the on-road transportation sector. The three scenarios can be expanded to explore other possibilities. The LC scenario aggressively increases ZEV sales shares to reach 100% in California in 2040, in 177 states in 2045, and in the remaining U.S. states by 2050. The High ZEV scenario is even more aggressive and reaches 100% Zev sales shares 5 years earlier in each region. Other scenarios could include a High Liquid Fuels scenario where the rate of ZEV market penetration is reduced, and more biomass-based liquid fuels are necessary to reduce carbon emissions. In the LC and High ZEV scenarios battery electric vehicles dominate over fuel cells for most vehicle types. A high fuel cell scenario could be created to explore the effects of significantly higher fuel cell vehicle stock.

Although the LC and High ZEV scenarios include aggressive ZEV market penetration, the stock of diesel and gasoline vehicles remaining in the fleet in 2050 results in liquid fuels comprising over 70% of the fuel use by energy. In order to reach net zero carbon emissions, the stock of diesel and gasoline vehicles must be further reduced in some manner. Vehicles can remain in the fleet for 15–20 years so it’s unlikely that ZEV market penetration can be increased to the point where turnover removes all diesel and gasoline vehicles. Policies will have to be developed to reduce these remaining vehicles in the 2050 timeframe.

In the LC scenario biomass based liquid fuels reach a volume of roughly 80 billion GGE by 2045. It is not clear whether that volume can be produced with very low carbon intensities and at competitive costs. Either significant progress must occur in this field or internal combustion engine vehicles must be removed from the fleet through policies that either exclude internal combustion engines from on-road travel or incentivize their removal.

The results from the city charger analysis show that cities outside the 177 states likely will need relatively few chargers to support the fleet of medium- and heavy-duty ZEVs in 2030. The number of vehicles and chargers is small due to the delayed market penetration of ZEVs. Even in a large port city such as Houston, the cost for chargers is under $20 million in that timeframe. By 2040 cities in non 177 states will see large numbers of medium- and heavy-duty ZEVs and chargers necessary to support the ZEV fleet. The cost of the chargers by 2040 would reach roughly $1 billion even for smaller non-port cities.

Large port cities in the 177 states could require over $1 billion to fund the purchase and installation of the chargers necessary to charge the fleet of ZEVs in 2030. Smaller cities could require well over $100 million for their chargers. By 2040 costs for most medium sized cities in the 177 states will exceed several billion dollars. These cities will need to find enough public and private funding to cover these costs.

Cities in 177 states that might see significant ZEV market penetration in the 2030 or somewhat later timeframe may need to develop the modeling capability necessary to estimate their need for charging stations for both LDVs and fleets. The models require detailed data on projected fleet stock, vehicle trips, and spatial information. Without such models, knowing the number of chargers, their optimal locations, and the costs will be difficult.

The issue of make-ready infrastructure is potentially problematic. The actual costs are unknown and difficult to estimate. In California there is modest public funding available. Most of the funding will come from utility programs that use rate payers to fund necessary upgrades. In the next few years fleets will begin to purchase battery electric ZEVs and work with utilities to ensure the necessary make-ready infrastructure is present. The true costs will begin to become apparent at that time. Other states may be able to look to California to better estimate their make-ready costs before the upgrades begin.

Conclusions from this study

Though the U.S. overall will likely see a slower market penetration of ZEVs than California, the greenhouse gas reductions can still be considerable. The LC scenario achieves 92% carbon reductions in 2050 from 2015 values, and the High ZEV scenario achieves 94% carbon reductions.

To achieve very high carbon reductions, not only must there be very aggressive ZEV market penetration but also the carbon intensity of fuels must be minimized. The LC and High ZEV scenarios reduce the carbon intensity of electricity and hydrogen to zero in 2045 and replace all diesel and gasoline with biomass based liquid fuels.

Due to slow stock turnover, even rapid ZEV market penetration scenarios, such as the LC or High ZEV scenarios, will still contain significant numbers of internal combustion engine vehicles in their stock by 2050. The biomass based liquid fuel volume reaches 70 (High ZEV) to 80 (LC) billion GGE by 2045.

Electricity usage in 2045 increases from 5 billion GGE in the BAU scenario to 20 billion GGE in the High ZEV scenario.

Expected delays in ZEV market penetration for states other than California vastly decrease the number of ZEVs and the required number of chargers, particularly in 2030. For non-port cities not part of the Section 177 states, the number of necessary chargers in 2030 could remain below 50 and the cost for these chargers could be lower than $10 million. However, cities may want to push market growth faster with advance investments, to increase the number of public chargers before the vehicles arrive that really need them.

Cities within the 177 states require significantly greater number of chargers and would incur a much higher cost in 2030 compared to cities outside the 177 states.

The range of charger costs for cities varies enormously depending on factors such as population, inclusion in the 177 states, and the existence of a port. For the cities in this study, the charger cost ranges from $5 million to $2.6 billion in 2030 and from roughly $1 billion to almost $30 billion in 2040.

Although non-port cities outside 177 states see very few chargers and would incur a small charger cost in 2030, these cities would see rapid increase in chargers, and by 2040 approach or exceed the projected numbers in California in 2030.

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Data Summary

Products of Research

We collected data on the number of trucks projected for California in 2030 disaggregated into trucking vehicle type for all California and for the cities of Los Angeles, Sacramento, and San Diego. We collected data on the number of battery electric trucks projected for California in 2030 disaggregated into trucking vehicle type for all California and for the cities of Los Angeles, Sacramento, and San Diego.

We also collected data on charger cost, city population, and the California TTM model projected number of ZEV trucks in the California for 2030 and 2040.

Data Format and Content

All the data are in Excel files.

Battery Vehicle Forecasting: the number of battery electric trucks projected for California in 2030 disaggregated into trucking vehicle type for all California and for the cities of Los Angeles, Sacramento, and San Diego.

All Vehicle Forecasting: the number of battery electric trucks projected for California in 2030 disaggregated into trucking vehicle type for all California and for the cities of Los Angeles, Sacramento, and San Diego.

Data Access and Sharing

The data, as Excel files, are available to the public at https://doi.org/10.25338/B8Q34J. The following citation should be used:

> Miller, Marshall (2022), Spatial Scenarios for Market Penetration of Plug-in Battery Electric Trucks in the U.S. Dryad, Dataset, https://doi.org/10.25338/B8Q34J

Reuse and Redistribution

There are no restrictions on the use of the data.

Spatial Scenarios Charger Calcs:

Fulton, L., Miller. M., Burke, A., Wang, Q., Yang, C., Technology and Fuel Transition Scenarios to Low Greenhouse gas Futures for Cars and Trucks in California, Institute of Transportation Studies, University of California, Davis, Research Report UCD-ITS-RR-19-35, 2019. https://escholarship.org/uc/item/8wn8920p

Battery Vehicle Forecasting and *All Vehicle Forecasting*:

Wang, Bin, Doug Black, Fan Tong, and Cong Zhang (Lawrence Berkeley National Laboratory). 2020. "Presentation — Medium- and Heavy-Duty Electric Vehicle Infrastructure Projections (HEVI-Pro)." Integrated Energy Policy Report August 6th workshop. https://efiling.energy.ca.gov/getdocument.aspx?tn=234209

Appendix

The appendix shows the sales shares for each truck type and technology for the BAU, LC, and High ZEV scenarios. The truck type abbreviations are:

- MD – medium-duty
- HD – heavy-duty
- Voc – vocational

BAU Scenario

Table 11. Sales shares for each truck type and technology for the BAU scenario.

		2015	2020	2025	2030	2035	2040	2045	2050
Long Haul	Diesel	100.0%	99.9%	99.9%	99.9%	99.5%	97.7%	91.7%	83.9%
	Hybrid	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%
	LNG	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%
	Fuel Cell	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
		2015	2020	2025	2030	2035	2040	2045	2050
Short Haul	Diesel	100.0%	99.9%	99.6%	97.7%	92.1%	85.1%	79.8%	75.8%
	Hybrid	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%
	BEV	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%	0.1%	0.2%	0.2%	0.2%
	Gasoline	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
		2015	2020	2025	2030	2035	2040	2045	2050
MD Urban	Diesel	55.8%	69.2%	68.2%	55.9%	48.4%	42.9%	37.9%	36.5%
	Hybrid	0.6%	0.8%	2.9%	7.9%	14.0%	20.9%	25.7%	28.1%
	CNG	15.0%	15.0%	13.8%	20.7%	21.5%	19.2%	19.3%	18.3%
	BEV	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%
	Gasoline	28.6%	15.0%	15.0%	15.0%	15.0%	15.0%	15.0%	15.0%
		2015	2020	2025	2030	2035	2040	2045	2050
Urban Bus	Diesel	25.5%	22.1%	21.0%	20.2%	10.2%	0.0%	0.0%	0.0%
	Hybrid	3.0%	5.4%	9.1%	11.2%	3.4%	0.6%	0.0%	0.0%
	CNG	46.3%	45.3%	41.6%	31.2%	6.4%	0.0%	0.0%	0.0%
	BEV	0.2%	0.7%	9.7%	30.2%	77.1%	93.2%	90.0%	90.0%
	Fuel Cell	0.0%	0.0%	0.1%	0.8%	2.8%	6.2%	10.0%	10.0%
	Gasoline	25.0%	26.4%	18.4%	6.4%	0.0%	0.0%	0.0%	0.0%
		2015	2020	2025	2030	2035	2040	2045	2050
Other Bus	Diesel	69.4%	79.3%	83.8%	79.9%	76.9%	63.2%	52.7%	45.9%
	Hybrid	0.0%	0.1%	0.2%	0.3%	0.9%	2.6%	6.3%	10.7%
	CNG	0.5%	0.6%	0.9%	4.4%	16.2%	32.2%	39.1%	41.4%
	BEV	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%
	Gasoline	30%	20%	15.0%	15.0%	5.0%	0.0%	0.0%	0.0%
		2015	2020	2025	2030	2035	2040	2045	2050
HD voc	Diesel	99.6%	99.2%	98.6%	96.5%	94.0%	84.9%	72.1%	52.5%
	Hybrid	0.0%	0.1%	0.3%	0.8%	2.1%	4.4%	9.6%	24.3%
	CNG	0.3%	0.7%	1.1%	2.2%	2.8%	8.7%	16.2%	21.2%
	BEV	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%
	Gasoline	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
		2015	2020	2025	2030	2035	2040	2045	2050
MD voc	Diesel	99.7%	99.1%	94.8%	76.2%	60.4%	51.1%	47.7%	45.8%
	Hybrid	0.1%	0.6%	3.5%	16.3%	23.4%	27.0%	26.4%	25.0%
	CNG	0.2%	0.3%	1.6%	7.1%	15.2%	19.9%	24.0%	27.2%
	BEV	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%
	Gasoline	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
		2015	2020	2025	2030	2035	2040	2045	2050
HD pickup	Diesel	45.9%	57.4%	52.4%	47.4%	43.9%	41.1%	40.5%	40.8%
	Hybrid	4.1%	7.6%	12.5%	17.2%	20.0%	21.9%	22.5%	22.2%
	CNG	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
	BEV	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%
	Gasoline	50.0%	35.0%	35.0%	35.0%	35.0%	35.0%	35.0%	35.0%

LC Scenario

Table 12. Sales shares for each truck type and technology for the LC scenario.

		2015	2020	2025	2030	2035	2040	2045	2050
Long Haul	Diesel	100.0%	99.9%	99.1%	94.6%	80.6%	54.6%	26.1%	1.3%
	Hybrid	0.0%	0.1%	0.1%	0.1%	0.5%	0.0%	0.0%	0.0%
	CNG	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
	BEV	0.0%	0.0%	0.5%	1.9%	5.7%	8.8%	10.2%	10.0%
	Fuel Cell	0.0%	0.0%	0.3%	3.3%	13.1%	36.5%	63.7%	88.7%
	Gasoline	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
		2015	**2020**	**2025**	**2030**	**2035**	**2040**	**2045**	**2050**
Short Haul	Diesel	100.0%	99.9%	99.0%	94.5%	78.8%	51.0%	16.5%	1.3%
	Hybrid	0.0%	0.1%	0.1%	0.1%	0.5%	0.0%	0.0%	0.0%
	CNG	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
	BEV	0.0%	0.0%	0.4%	2.7%	12.0%	29%	52%	55%
	Fuel Cell	0.0%	0.0%	0.4%	2.6%	8.7%	20.4%	31.1%	43.4%
	Gasoline	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
		2015	**2020**	**2025**	**2030**	**2035**	**2040**	**2045**	**2050**
MD Urban	Diesel	55.8%	69.2%	66.8%	55.1%	48.1%	28.8%	13.3%	1.3%
	Hybrid	0.6%	0.8%	2.0%	7.0%	6.5%	6.3%	3.2%	0.0%
	CNG	15.0%	15.0%	14.9%	18.0%	13.0%	3.2%	0.0%	0.0%
	BEV	0.0%	0.0%	1.3%	7.5%	23.8%	49.6%	67.2%	80.0%
	Fuel Cell	0.0%	0.0%	0.0%	1.2%	4.2%	12.2%	16.3%	18.7%
	Gasoline	28.6%	15.0%	15.0%	11.2%	4.4%	0.0%	0.0%	0.0%
		2015	**2020**	**2025**	**2030**	**2035**	**2040**	**2045**	**2050**
Urban Bus	Diesel	25.5%	22.1%	21.0%	20.2%	10.2%	0.0%	0.0%	0.0%
	Hybrid	3.0%	5.4%	9.1%	11.2%	3.4%	0.6%	0.0%	0.0%
	CNG	46.3%	45.3%	41.6%	31.2%	6.4%	0.0%	0.0%	0.0%
	BEV	0.2%	0.7%	9.7%	30.2%	77.1%	93.2%	90.0%	90.0%
	Fuel Cell	0.0%	0.0%	0.1%	0.8%	2.8%	6.2%	10.0%	10.0%
	Gasoline	25.0%	26.4%	18.4%	6.4%	0.0%	0.0%	0.0%	0.0%
		2015	**2020**	**2025**	**2030**	**2035**	**2040**	**2045**	**2050**
Other Bus	Diesel	69.4%	79.3%	82.8%	74.1%	69.9%	38.2%	16.5%	1.3%
	Hybrid	0.0%	0.1%	0.0%	0.0%	0.0%	0%	0%	0%
	CNG	0.5%	0.6%	0.9%	4.4%	2.0%	0%	0%	0%
	BEV	0.0%	0.0%	1.3%	7.5%	23.8%	49.6%	67.2%	80.0%
	Fuel Cell	0.0%	0.0%	0.0%	1.2%	4.2%	12.2%	16.3%	18.7%
	Gasoline	30%	20%	15.0%	12.8%	0.0%	0%	0%	0%
		2015	**2020**	**2025**	**2030**	**2035**	**2040**	**2045**	**2050**
HD voc	Diesel	99.6%	99.2%	97.0%	86.6%	60.5%	26.0%	9.3%	2.6%
	Hybrid	0.0%	0.1%	0.0%	0.1%	0.0%	0%	0%	0%
	CNG	0.3%	0.7%	1.6%	4.6%	11.4%	13%	8%	1%
	BEV	0.0%	0.0%	1.3%	8.7%	28.0%	61%	80%	89%
	Fuel Cell	0.0%	0.0%	0.0%	0.0%	0.0%	0.6%	2.8%	8.1%
	Gasoline	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
		2015	**2020**	**2025**	**2030**	**2035**	**2040**	**2045**	**2050**
MD voc	Diesel	99.7%	99.1%	94.7%	75.8%	55.6%	18.2%	3.2%	0.0%
	Hybrid	0.1%	0.6%	3.5%	11.5%	13.0%	14%	10%	1%
	CNG	0.2%	0.3%	0.4%	4.0%	3.3%	6%	3%	0%
	BEV	0.0%	0.0%	1.3%	7.5%	23.8%	49.6%	67.2%	80.0%
	Fuel Cell	0.0%	0.0%	0.0%	1.2%	4.2%	12.2%	16.3%	18.7%
	Gasoline	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
		2015	**2020**	**2025**	**2030**	**2035**	**2040**	**2045**	**2050**
HD pickup	Diesel	45.9%	57.4%	51.6%	45.1%	43.5%	30.0%	0.0%	0.0%
	Hybrid	4.1%	7.6%	12.5%	17.2%	13.0%	2.0%	0.0%	0.0%
	CNG	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
	BEV	0.0%	0.0%	0.9%	5.9%	21.3%	47.6%	70.0%	70.0%
	Fuel Cell	0.0%	0.0%	0.0%	1.8%	7.2%	20.4%	30.0%	30.0%
	Gasoline	50.0%	35.0%	35.0%	30.0%	15.0%	0.0%	0.0%	0.0%

High ZEV Scenario

Table 13. Sales shares for each truck type and technology for the High ZEV scenario.

		2015	2020	2025	2030	2035	2040	2045	2050
Long Haul	Diesel	100.0%	99.9%	99.1%	92.3%	71.5%	32.0%	0.0%	0.0%
	Hybrid	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%
	BEV	0.0%	0.0%	0.5%	3.0%	8.6%	15.9%	13.5%	8.7%
	Fuel Cell	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%
		2015	2020	2025	2030	2035	2040	2045	2050
Short Haul	Diesel	100.0%	99.9%	99.1%	92.2%	71.5%	32.0%	0.0%	0.0%
	Hybrid	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%
	BEV	0.0%	0.0%	0.4%	3.9%	15.8%	38%	60%	56%
	Fuel Cell	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%
		2015	2020	2025	2030	2035	2040	2045	2050
MD Urban	Diesel	55.8%	69.2%	66.8%	55.1%	45.1%	23.7%	0.0%	0.0%
	Hybrid	0.6%	0.8%	2.0%	7.0%	6.5%	5.1%	0.0%	0.0%
	CNG	15.0%	15.0%	14.9%	18.0%	13.0%	3.2%	0.0%	0.0%
	BEV	0.0%	0.0%	1.3%	7.5%	26.2%	54.4%	80.0%	80.0%
	Fuel Cell	0.0%	0.0%	0.0%	1.2%	4.8%	13.6%	20.0%	20.0%
	Gasoline	28.6%	15.0%	15.0%	11.2%	4.4%	0.0%	0.0%	0.0%
		2015	2020	2025	2030	2035	2040	2045	2050
Urban Bus	Diesel	25.5%	22.1%	21.0%	20.2%	10.2%	0.0%	0.0%	0.0%
	Hybrid	3.0%	5.4%	9.1%	11.2%	3.4%	0.6%	0.0%	0.0%
	CNG	46.3%	45.3%	41.6%	31.2%	6.4%	0.0%	0.0%	0.0%
	BEV	0.2%	0.7%	9.7%	30.2%	77.1%	93.2%	90.0%	90.0%
	Fuel Cell	0.0%	0.0%	0.1%	0.8%	2.8%	6.2%	10.0%	10.0%
	Gasoline	25.0%	26.4%	18.4%	6.4%	0.0%	0.0%	0.0%	0.0%
		2015	2020	2025	2030	2035	2040	2045	2050
Other Bus	Diesel	69.4%	79.3%	82.8%	74.1%	68.9%	32.0%	0.0%	0.0%
	Hybrid	0.0%	0.1%	0.0%	0.0%	0.0%	0%	0%	0%
	CNG	0.5%	0.6%	0.9%	4.4%	0.0%	0%	0%	0%
	BEV	0.0%	0.0%	1.3%	7.5%	26.2%	54.4%	80.0%	80.0%
	Fuel Cell	0.0%	0.0%	0.0%	1.2%	4.8%	13.6%	20.0%	20.0%
	Gasoline	30%	20%	15.0%	12.8%	0.0%	0%	0%	0%
		2015	2020	2025	2030	2035	2040	2045	2050
HD voc	Diesel	99.6%	99.2%	88.6%	81.3%	68.9%	32.0%	0.0%	0.0%
	Hybrid	0.0%	0.1%	0.0%	0.0%	0.0%	0%	0%	0%
	CNG	0.3%	0.7%	10.0%	10.0%	0.0%	0%	0%	0%
	BEV	0.0%	0.0%	1.3%	8.7%	30.8%	67%	96%	92%
	Fuel Cell	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%
		2015	2020	2025	2030	2035	2040	2045	2050
MD voc	Diesel	99.7%	99.1%	93.6%	76.1%	60.0%	32.0%	0.0%	0.0%
	Hybrid	0.1%	0.6%	3.5%	10.2%	9.0%	0%	0%	0%
	CNG	0.2%	0.3%	1.6%	5.0%	0.0%	0%	0%	0%
	BEV	0.0%	0.0%	1.3%	7.5%	26.2%	54.4%	80.0%	80.0%
	Fuel Cell	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%
		2015	2020	2025	2030	2035	2040	2045	2050
HD pickup	Diesel	45.9%	57.4%	44.9%	49.1%	44.9%	16.0%	0.0%	0.0%
	Hybrid	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%
	BEV	0.0%	0.0%	0.9%	5.9%	21.3%	47.6%	70.0%	70.0%
	Fuel Cell	0.0%	0.0%	0.0%	1.8%	7.2%	20.4%	30.0%	30.0%
	Gasoline	50.0%	35.0%	44.3%	33.1%	26.6%	16.0%	0.0%	0.0%