Title

Vehicle Choice Modeling for Light-, Medium-, and Heavy-Duty Zero-Emission Vehicles in California

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Abstract

Transportation is widely recognized as one of the largest contributors to air pollution and greenhouse gas emissions worldwide. To support the transition to zero-emission vehicles (ZEVs), California has long been investing in a wide range of initiatives, including incentives for ZEV purchases, expanding battery charging and hydrogen refueling infrastructure, and promoting public awareness of the benefits of ZEVs. California has enacted legislation stipulating that the sale of fossil fuel engine powered vehicles will be prohibited post-2035 (for LDVs) and 2036 (for MD/HDVs). Consequently, all vehicles available for sale thereafter must qualify as ZEVs. In this report, the research presents the decision factors used by purchasers of cars and trucks and how these factors would affect purchases of ZEVs. The study uses representations of household consumer and fleet preferences and includes a probability analysis approach to determine market shares for ZEVs for 2020-2040. The new approach is applied to light-duty vehicles and medium-/heavy-duty trucks. Market share results are presented for a number of scenarios for different vehicle and infrastructure development strategies. The results are compared with those using other approaches for analysis and with California Air Resources Board (CARB) targets for ZEV market development. Our findings indicate that battery electric and fuel cell vehicles will likely gain market share over time, but that a diverse range of measures and policies must be implemented to encourage consumers to adopt ZEVs as rapidly and completely (by 2035) as the state targets.

Keywords: zero-emission vehicles; battery electric vehicle; fuel cell vehicle; market share; penetration; consumer preference; light-duty vehicle; medium-duty vehicle; heavy-duty vehicle

1. Introduction

Widespread adoption of electric vehicles in California and in the global automotive market is moving ahead, but several challenges remain to be overcome [1]. Vehicle choice modeling is concerned with projecting and predicting which vehicles new car buyers will purchase when given choices that include zero-emission vehicle (ZEV) technologies and alternative fuels. This project involves battery electric and hydrogen fuel cell vehicles in competition with gasoline and diesel engine vehicles. Both light-duty vehicles and trucks will be considered. California has established regulations stating that by 2035 for light-duty vehicles (LDVs) [2], and by 2036 for medium-duty and heavy-duty vehicles (MD/HDVs) [3], all vehicles sold must be either plug-in or fuel cell vehicles. Consequently, engine-powered vehicles will no longer be available for purchase. This study addresses these questions: what factors will matter in the decisions to purchase ZEVs? How will these combine to affect vehicle technology preferences over time? What will be the market shares of the ZEVs between now and 2040?; and is it likely that the mass market will be able to transition to only ZEVs of all types in the time frames desired?

In this report, a method is developed to model how buyers decide whether they want to purchase a ZEV rather than the engine-powered vehicles they would normally be buying. There are several factors involved for both LDV and MD/HDV buyers in making that decision. For example, all buyers will expect that the ZEV will meet their needs at least as well as the engine-powered vehicle they are currently using. The vehicle choice model will attempt to quantitatively evaluate the decision factors and calculate the probability that buyers will decide to purchase one of the ZEV technologies.

Vehicle choice models have been in use since the 1990s in connection with assessing the marketability of vehicles using alternative fuels to reduce emissions and the use of petroleum. David Greene of Oak Ridge National Laboratory (ORNL) published a paper in 1994 [4] describing in detail a multinomial logit-type model for analyzing the alternative fuels market. ORNL has been involved with vehicle choice modeling ever since and their latest model and software MA3T (Market Acceptance of Advanced Automotive Technologies) are among the best available. That model and other multinomial logit programs like it make it difficult to determine the inputs used in their analysis. One of the objectives of this study was to develop a simpler approach in which the inputs in the model are easier to follow.

The decision factors used in the model discussed in this paper are similar to those used in previous vehicle choice models. Some of the factors are calculated from detailed calculations of vehicle cost and performance at specified years in the future out to 2040. Other factors are more subjective and are estimated based on the literature and the experience of the model user. Most of the factors relate the characteristics and market situations of ZEV and ICEV. Most of the factors apply to both LDVs and trucks of various classes. This report will discuss in detail the model approach and inputs and results obtained using the model to project the ZEV markets in California for 2020-2040.

The structure of this paper includes five sections. Initially, we scrutinize past approaches to vehicle choice modeling for both LDVs and MD/HDVs. This offers a foundation for understanding historical methods in the field and uncovers certain limitations of past models. Next, we introduce a new approach to vehicle choice modeling, designed to overcome the deficiencies of previous methods and to predict vehicular market dynamics more accurately. Following this, we present results obtained using the PPA (Purchase Probability Analysis) model under different scenarios, encompassing varying policy environments and market conditions. This will provide an in-depth understanding of how the model functions in practice and help comprehend its potential impact. In the fifth segment, we compare market share projections between our model and the models developed at the Department of Energy National Laboratories. Through this comparison, we assess the performance of the PPA model and suggest avenues for its improvement in the future. This arrangement allows for a comprehensive investigation into vehicle choice modeling, offering valuable insights for future directions in research.

2. Past approaches to vehicle choice modeling

The dynamic discrete choice (DDC) model is one of the most prominent approaches in economic modeling to represent consumer choice decisions. DDC models typically assume that aggregate agent expectations are rational expectations, which is a widely accepted assumption in economic modeling. Such choice models provide insights into the factors that drive individual decision-making and can be used to predict choice behavior under different scenarios or policy changes. They allow researchers to quantify the influence of different attributes, evaluate the relative importance of alternatives, and analyze market shares or demand for different options. Most of the past approaches to vehicle choice modeling were based on the nested multinomial logit method approach. The nested multinomial logit model is a specific type of discrete choice model that incorporates a nested structure among the alternatives. It extends the standard multinomial logit (MNL) model by allowing for correlation and heterogeneity within groups or nests of alternatives. A comprehensive review of these methods applied to light-duty vehicles is given in [5]. A detailed study of the method applied to MD and HD trucks is given in [6]. In the multinomial logit method, the generalized lifetime costs of various types of vehicles using a wide range of powertrains and energy storage technologies are calculated. The resultant cost differences between the vehicles are used to project the sales fraction of each of the vehicles as the performance and costs of the different technologies matures in future years. The generalized costs include both cost components like initial vehicle cost, maintenance cost, and fuel cost that are normally expressed in monetary ($) terms, but also the estimated monetary values to consumers of subjective purchase factors for which monetary value is not customarily assigned. These subjective factors include range anxiety, limited refilling infrastructure, inconvenient refilling time, and limited availability of vehicle models using the new technologies.

3. A new approach to vehicle choice modeling

3.1. Basis of the new approach

The intricacies of consumer and fleet preferences when selecting vehicles to purchase and operate are pivotal in shaping the course of our modeling efforts. In this analysis, we curate elaborate representations of these preferences within the context of our energy-economy model. Our attention is particularly drawn towards capturing both the financial and non-financial considerations that weigh on the decisions of individuals and fleet operators. In developing this preferential architecture, we employ the PPA model approach. This method allows us to incorporate the intricate layers of decision-making factors that drive vehicle choice, providing a nuanced perspective on the consumer and fleet purchase process. A comprehensive list of these decision factors, which form the backbone of our model, is presented in **Table 1**. For an in-depth discourse on these elements, we direct readers to **Appendix A**.

Table 1. Decision factors for the purchase of vehicles using various technology options.

No.	Attribute
1	Vehicle cost
2	All-electric or hydrogen driving range (mi)
3	Number of models available to purchase
4	Inconvenience to charge or refuel ZEVs in the city compared to ICEV
5	Inconvenience to charge or refuel ZEV on the highway compared to ICEV
6	Battery charging or hydrogen refueling time (minutes)
7	Availability of a second market for ZEVs compared to ICEVs
8	Maintenance cost ($/mi)
9	Energy operating cost ($/mi)
10	Environmental concern compared to ICEVs
11	Safety concern compared to ICEVs
12	Drivability of ZEVs compared to ICEVs
13	Reliability/durability of ZEVs compared to ICEVs
14	Excitement with the ZEV technologies compared to ICEVs
15	TCO (Total Cost of Ownership $/mi)
16	Cost of a terminal ($/vehicle) to provide for charging/hydrogen refueling compared to ICEVs
17	Payload penalty reduction compared to ICEVs

3.2. The formulation of the Purchase probability Analysis approach

This part of the paper will present in detail how the PPA model is formulated and results calculated in EXCEL spreadsheets. The probability (P_r) that a decision factor will favorably influence the vehicle purchase is assumed to be of the form

$$Pr = e^{a(1-1/x)} \quad (1)$$

This form applies to each decision factor for each vehicle and year. “x” is a ratio that indicates the status of that factor relative to the ICEV. “x” can be greater or less than 1. x=1 means that decision factor has no effect on the purchase decision and $P_{rob}=1$. x<1 means the decision factor’s status lowers the vehicle purchase probability. x>1 means the decision factor’s status enhances the purchase probability. “a” is a parameter that indicates the importance of the decision factor. a>1 indicates the factor is important and a<1 indicates it is of minor importance. “a” is normally in the range 0.5>a<3.

In analyzing the market share for each vehicle type, a value of Pr is calculated for each of the decision factors using the input “x” values pertaining to that vehicle. The product $\pi_i^n P_{ri}$ of the probabilities Pr for all the decision factors is calculated and the average decision probability Prav is determined from the nth root of the product

$$\text{Average decision probability Prav} = (\pi_i^n P_{ri})^{i/n} \quad (2)$$

A Prav value is calculated for each ZEV option (j) being analyzed for a particular vehicle type including the reference ICE vehicle. The market shares of each <u>ZEV</u> option is calculated from

$$\text{Sum(Pravj)} = \sum P_{ravj} \text{ for all the } \underline{\text{ZEV}} \text{ options} \quad (3)$$

If sum(Pravj) <1, the market share Ms_j for the <u>ZEV</u> options j are

$$Ms_j = \text{Pravj and } Ms_{ICE} = 1 - \text{sum(Pravj)} \quad (4)$$

If sum(Pravj) >1, the market share Ms_j for the <u>ZEV</u> options j are

$$Ms_j = \text{Pravj/sum(Pravj) and } Ms_{ICE} = 0 \quad (5)$$

The market share analysis is performed using EXCEL spreadsheets. Calculations are made for a number of ZEV options – BEV, FC-HEV, FC-PHEV, PHEV, and for an ICE and various LDV and MD/HDV types. For LDVs, the vehicle types are mid-size car, small SUV, mid-size SUV, and LD pickup. For MD/HD trucks, the vehicle types are city delivery vans class 3, city delivery trucks class 4, 5, 6, 7, and 8, and long-haul class 8. The market share calculations are made for 2020-2040.

The PPA vehicle choice model has been implemented using EXCEL spreadsheets. The decision factors and associated “x” values are given along with the calculated Prob (same as P_r) values for each decision factor. The ‘average product’ (same as Prav) and market share for each ZEV option are also shown. As for all vehicle choice modeling approaches, there are many inputs needed and some are subjective, non-financial in character. However, for the PPA approach, the inputs and outputs are shown on a single spreadsheet that is easy to follow. The results are given for each ZEV option, each vehicle type, and each year of the analysis. Consideration of various aspects of applying the PPA approach to vehicle choice modeling are given in subsequent sections of the paper.

3.3. Considerations of decision factors

In this section, the decision factors and how the inputs for them have been determined will be discussed. The decision factors considered in the PPA model are similar to those used in other vehicle choice models that include ZEVs. Some of the decision factors can be expressed in numerical terms. Those that are financial in character will be given in dollars ($). The status of other decision factors is subjective in character and more difficult to express numerically. Both types of decision factors are considered in this section.

3.3.1. Financial decision factors

The decision whether to purchase a ZEV is influenced by the upfront capital cost and costs of daily and future operating costs for energy and maintenance. These costs have been considered in detail in previous research at UC Davis [7][8]. The results of those studies will be used to determine the ratios of the ZEV to ICE costs in assigning “x” values to decision factors 1, 2, 8, 9, and 15. These factors play a critical role in determining the consumer’s choice of a vehicle, especially for mass adoption of ZEVs. The bases of the cost projections in future years are discussed in the Appendices,

3.3.2. Non-financial decision factors

The vehicle purchase decision becomes more complex when considering the diverse range of non-financial decision factors that consumers and fleets consider. These factors include the number of available models and brands, the driving experience (such as acceleration and response), fascination with new technologies (such as autonomous driving, electric 4-wheel drive, and large computer screens), environmental considerations, battery durability as well as depreciation and the 2nd market. For ZEVs, driving range and the availability of infrastructure for battery charging and hydrogen refueling are crucial decision factors. The convenience of battery charging depends both on the availability of chargers and the ability of the battery to accept a fast, complete charge in 20 minutes or less. Refueling hydrogen fuel cell vehicles can be as fast as ICEVs, but whether it is convenient depends on having an adequate number of hydrogen stations and supply of sufficient hydrogen at a reasonable price. Decision factors 4, 5, and 6 on refueling ZEVs are subjective in character but they have quantitative features that effect the “x” value associated with them. The non-financial decision factors are typically quantified as ‘intangible costs’ in most vehicle choice models and are monetized and then added to the ‘real’ financial costs to determine a lifetime generalized cost of vehicle ownership. Unfortunately, for ZEVs, the intangible costs can be very large and assigning them is critical to the results obtained using the model. It is assumed in the models that customers will purchase the vehicles with the lowest ownership cost and relate the purchase probabilities to the generalized costs. In the PPA model, the average purchase probability is more directly related to the decision factors as shown in **Table 1**.

3.4. Preparation of the input data for various ZEV development scenarios

The key step in applying the PPA model is setting up the base and "x" value tables for each ZEV and ICEV to be considered in the market analysis. The tables must include values for the time period 2020-2040. During this period, the vehicle technologies, the vehicle markets, and the refueling infrastructure will be maturing simultaneously. Hence the tables must reflect the effect of radical changes in all these areas, which will be affected by industrial strategies and public policy resulting in multiple market penetration scenarios. Some of the key "x" values for LDV and MD/HDV modeling are shown in **Appendix A and Appendix B,** respectively.

The four decision factors for which "x" values in Scenario_1 (**Table 2**) are shown in the Fig 1a in the case of LD ZEVs are vehicle cost, model quantity, inconvenience of charging/fueling in the city and inconvenience of charging/fueling on the highway.

Vehicle Cost: During the early-mid 2020s, the costs of ZEVs were significantly higher than comparable ICE vehicles due to the high cost of batteries/fuel cells and their integration into the powertrains of the ZEVs. This resulted in high values for "x". As the technologies matured, the cost differences decreased and the x values decreased approaching x=1. BEV x values approached 1 by 2030 and those for FCV about 5 to 8 years later.

Model Quantity: Throughout the early-mid 2020s, the number of LD ZEV models were much less than the number for ICE vehicles. As a result, the x values were small for both BEVs and FCVs. In 2020-2025, a growing number of automakers began developing BEVs and the number of models for sale began to increase for BEVs and their x values increased reaching near by 2040. The number of models for FCVs are not assumed to increase as fast as those for BEVs because concerns about H2 refueling. x values for LD FCV are only projected to be only x=0.2 by 2040 compared to ICEVs

Inconvenience of Charging/Fueling in the City: In the early 2020s, vehicle range (miles) was an important issue to buyers of BEVs, but by 2023, the key issues concerned the inconvenience of battery charging especially to those without the possibility of home charging. Hence for BEVs improving public battery charging both in the city and along highways became critical to making BEVs attractive to LDV buyers. Projecting how fast battery charging can approach the convenience of gasoline refueling is very difficult. The x values for battery charging are assumed to increase slowly reaching x=0.45 by 2030 and x=0.7 by 2040. Public charging is assumed to be fast charging in 40-60 minutes at the present time to 10-15 minutes in 2040. In the case of FCVs, refueling time is not the issue. For FCVs, the convenient availability of hydrogen stations is the critical issue. At the present time, there are very few hydrogen stations even in large cities like Los Angeles. Hydrogen refueling will improve in the future, but likely more slowly than for battery charging. We have assumed x=0.15 in 2030 and x=0.6 in 2040 for in-city hydrogen refueling.

Inconvenience of Charging/Fueling on the Highway: Throughout the 2020s, the scarcity of charging and hydrogen refueling stations along highways added significant hurdles to long-distance travel with ZEV LDVs. In the case of BEVs, this deficiency is further intensified by the long battery charging time at present even using fast charging. In the future, it is assumed that there will be more convenient charging facilities and fast charging times will decrease to 10-15 minutes. The time for hydrogen refueling will be less than 10 minutes. The x value is measure of the convenience of ZEV refueling compared to ICE vehicles. We have assumed for BEVs that x=0.3 in 2030 and x=0.5 in 2040. For FCVs, x=0.15 in 2030 and 0.3 in 2040. Achieving these x values will require a large investment in infrastructure at highway rest-stops.

The four decision factors for which x values in Scenario_1 (**Table 3**) are shown in Fig. 1b in the case of MD/HDVs are vehicle cost, model quantity, terminal cost, and safety concerns.

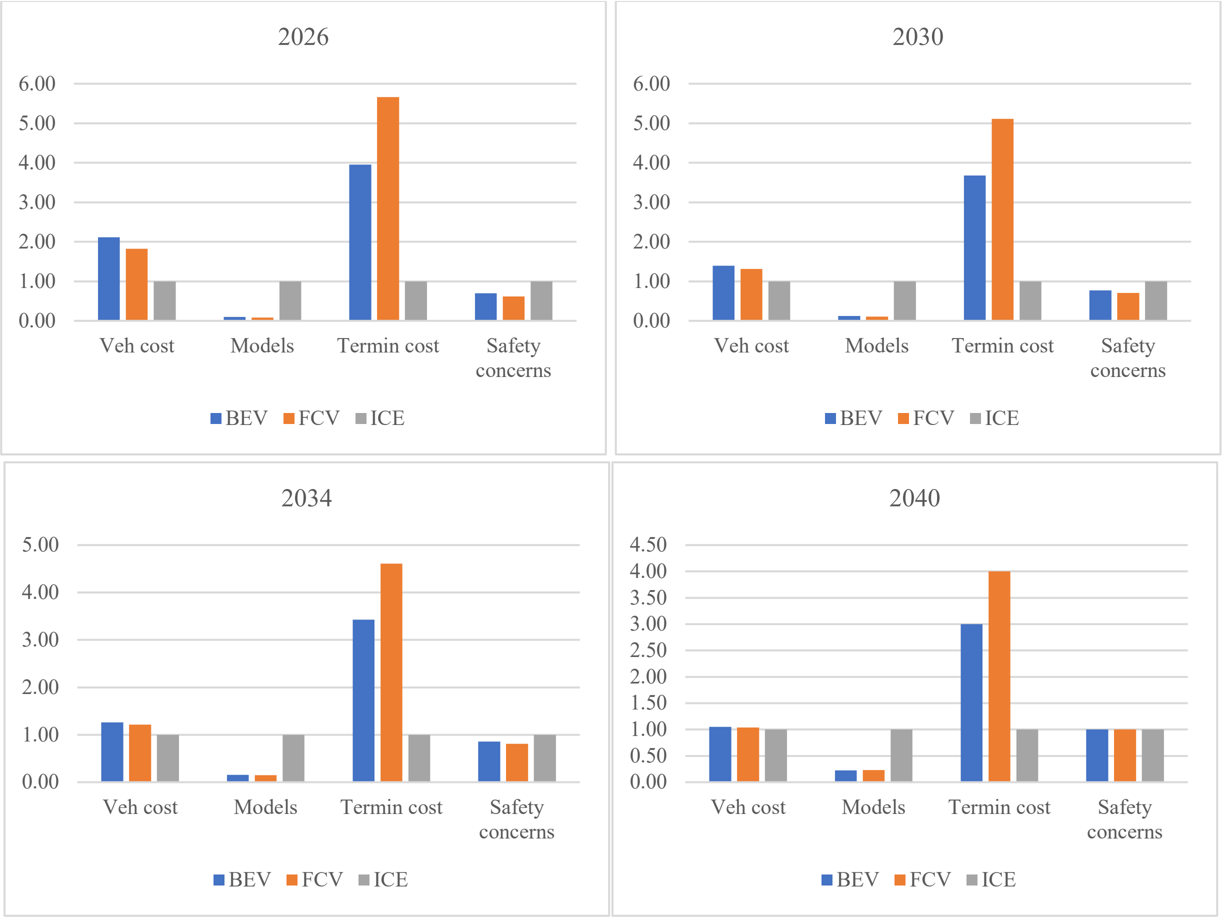
Vehicle Cost: Throughout the early to mid 2020s, the costs of MD/HDVs are expected to be much higher than comparable ICE vehicles due to the high costs of the large batteries needed in the BEVs and high power fuel cell needed in the FCVs. The cost of the battery and fuel cell components will decrease as the technologies mature significantly reducing the cost of the ZEVs. Hence the x values will be relatively high in 2020-2026 and approach x=1 beyond 2035. For BEV trucks, x=1.4 in 2030 and x=1.05 in 2040. For FCV trucks, x=1.32 in 2030 and x=1.04 in 2040. These reductions in the cost of ZEV trucks will high sales ZEV trucks in 2025-2030.

Model Quantity: During the early to mid 2020s, the number of ZEV trucks available for sale will be limited compared to ICE diesel trucks. This will be especially true of FC trucks as most truck manufacturers are concentrating on developing BEV trucks. In the case of long haul FC trucks, they are being developed by start-up truck manufacturers. The x values assumed for BEVs are x= 0.5 in 2030 and x=1 in 2040 and x= 0.1 in 2030 and x=0.35 in 2040 for MD trucks and HD trucks, respectively. The x values assumed for FC trucks are x=0.15 in 2030 and x=0.4 in 2040.

Terminal Cost: In early to mid 2020s, the costs to the create the battery charging and the hydrogen refueling facilities at terminal for over-night terminal are expected to be a significant barrier for fleet operators considering the transition to ZEV MD/HDVs. However, by 2040, these terminal costs are projected to substantially decrease. This decrease will be facilitated by the maturing of the infrastructure technologies being built for ZEV LDVs. The terminal cost in 2030 for Class 7 BEVs is projected to be 3.75 times the cost for diesel refueling and for hydrogen refueling the cost ratio is 5.0. The corresponding x values are 0.26 and 0.2. In 2040, the cost ratio is 3.0 for BEVs and 4.0 for FC trucks. The corresponding x values are 0.33 and 0.25. It is expected that the cost of refueling BEV and FC trucks will always be more expensive than refueling diesel trucks.

Safety Concerns: During the early to mid 2020s, there has been some concern regarding the safety of handling, use, and storage of very large-kWh batteries for BEVs and the storage and use of large quantities (>20 kg) of hydrogen in FC trucks. In the case of large battery packs in buses and trucks, extensive battery management systems/units have been developed and demonstrated in the field. The present experience with large kWh batteries in buses and trucks been largely uneventful. In the case of the use of large quantities of hydrogen in buses and trucks, there has been less field experience than with large kWh batteries. However, there has been safe experience using hydrogen for fuel cells in LDVs and in many industrial and oil refining situations. It has been assumed in this study that the use of very large batteries and hydrogen in MD/HD vehicles will cause modest safety concerns to buyers in 2026 (x=0.6 for BEVs and x=0.5 for FCVs) and gradually become less in later years (x=0.8 and 0.7 in 2030 and x=0.9 and 0.8 in 2034) and x=1 for both BEVs and FCV in 2040. risks. Furthermore, the implementation of stringent safety regulations and standards will provide additional assurance of safety. The decision factors and how the "x" values are determined are discussed in detail in **Appendices A and B.**

(a) Inputs for LDV modeling (midsize SUV as an example)



(b) Inputs for MD/HDV modeling (Class 7 as an example)

Figure 1. Some x values for vehicle choice modeling. (a) one example for LDV, (b) one example for MD/HDV.

In this study, eight scenarios are defined to evaluate the impact of various decision factors on the market share of ZEVs. The principal differences between the scenarios are the rates at which the battery charging and hydrogen refueling infrastructures are expanded and the degree that the costs of the batteries and fuel cells are reduced by the manufacturers. It will be assumed that the present rapid development of batteries and fuel cells will continue resulting in the significant decrease in their cost. Calculations of the projected market penetration of ZEVs will also be made with and without incentives to reduce their purchase cost. The expansion of the infrastructures and vehicle cost incentives will depend on both federal and California government policies.

The various scenario cases for LDVs, Sxyz, are defined in **Table 2** where x (1-3) designates the infrastructure expansion condition for the scenario, y (1-3) designates the cost (high, base, and low) of the battery and fuel cell components, and z designates the value of incentives (1 or 2). This same code is used to mark the curves in the presentation of results in all the figures in this report.

Scenario 1 (S1) is the base scenario and considered the most likely unless strong government policies are in place to encourage sales of ZEVs. It includes four different cases, including S_{111}, S_{121}, S_{131} and S_{122}. The first three is used to investigate the effect of vehicle costs on the market share of ZEVs, including high, base, and low costs of energy storage and power production devices (i.e., batteries and fuel cells) under different technology improvements. Although the costs of BEVs are currently much higher than those of comparable ICE vehicles, the price difference is expected to decrease by 2030 due to the marked decrease in the cost ($/kWh) of batteries over the past decade. Fuel cells are presently costly ($/kW), and whether their cost will decrease markedly as batteries have depends on how rapidly the market for them develops. The projected cost of batteries and fuel cells are discussed in **Appendix B**. The last one, S_{122} is used to investigate the effect of financial incentives on the market share of ZEVs for the base costs of batteries and fuel cells.

Scenario 2 (S2) is constructed to explore the trajectory of a business-as-usual model, wherein BEVs enjoy dominance, buoyed by government-backed enhancements in battery charging infrastructure. In this scenario, we postulate significant upgrades to BEV charging facilities in both urban and highway settings, boosting the convenience factor for owners to recharge their electric vehicles using DC fast chargers.

Scenario 3 (S3) is conceived to portray a landscape of rapid proliferation of hydrogen infrastructure, coupled with a steady response from vehicle manufacturers to avail fuel cell vehicles in the marketplace. Within this context, an augmented hydrogen refueling network for FCVs is presumed, extending to both cityscapes and highways. This amplification in infrastructure significantly improves the convenience for vehicle owners seeking to refuel their FCVs.

Scenario 4 (S4) is bifurcated into two sub-scenarios – one considering incentives in place until 2032, and the other extending till 2040. Both are set against a backdrop of declining costs for batteries and fuel cells, along with the assurance of ample charging and hydrogen refueling infrastructure by 2040. These conditions aim to match, if not surpass, the convenience level currently offered by ICE vehicles, with refueling times being 20 minutes or less. The multifaceted aspects of devising an infrastructure conducive for ZEVs are explored in greater detail in **Appendix A**.4 and 5.

Overall, these scenarios aim to provide insight into the effects of various factors on the market share of ZEVs in California, including vehicle costs, financial incentives, battery charging and hydrogen refueling infrastructure as well model availability.

Table 3 shows the inputs for modeling MD/HDVs, which are similar to the scenarios for LDVs. The only difference is that for classes 3 to 7, we assume they use terminal charging infrastructure instead of charging or refueling using public stations. However, for class 8 long-haul trucks, they use the public charging and hydrogen stations as LDVs do on a daily basis.

Table 2. Vehicle penetration scenarios under different assumptions for LDVs.

Model	Code	Battery cost	H_2 System Volume	Chargers+/inconvenience	H2 stations+/inconvenience	Incentives
S1	S_{111}	High	High	Base Charger availability	Base H2 availability	With[1]
	S_{121}	Base	Base	Base Charger availability	Base H2 availability	With[1]
	S_{131}	Low	Low	Base Charger availability	Base H2 availability	With[1]
	S_{122}	Base	Base	Base Charger availability	Base Chargers availability	With[2]
S2	S_{221}	Base	Base	Expanding Charger availability	Base H2 availability	With[1]
S3	S_{321}	Base	Base	Base Charger availability	Expanding the H2 availability	With[1]
S4	S_{431}	Low	Low	Expanding Charger availability	Expanding the H2 availability	With[1]
	S_{432}	Low	Low	Expanding Charger availability	Expanding the H2 availability	With[2]

1. Incentives and rebates including Clean Vehicle Tax Credits (CVTC) [9] between 2020 and 2032 and the Clean Vehicle Rebate Project (CVRP) [10] between 2020 and 2022.

2. Both CVTC and CVRP are available between 2020 and 2040, but with linear decrease year by year since 2032.

Table 3. Vehicle penetration scenarios under different assumptions for MD/HDVs.

Model	Code	Battery cost	H2 System Volume	Chargers+/inconvenience	H2 stations+/inconvenience	Incentives
S1	S_{111}	High	High	Base terminal cost for class 3 to class 7, base charger availability for class 8yes	Base terminal cost for class 3 to class 7, base H2 availability for class 8	With[1]
	S_{121}	Base	Base	Base terminal cost for class 3 to class 7, base charger availability for class 8	Base terminal cost for class 3 to class 7, base H2 availability for class 8	With[1]
	S_{131}	Low	Low	Base terminal cost for class 3 to class 7, base charger availability for class 8	Base terminal cost for class 3 to class 7, base H2 availability for class 8	With[1]
	S_{122}	Base	Base	Base terminal cost for class 3 to class 7, base charger availability for class 8	Base terminal cost for class 3 to class 7, base H2 availability for class 8	With[2]
S2	S_{221}	Base	Base	Reduced terminal cost for class 3 to class 7, improved charger availability for class 8	Base terminal cost for class 3 to class 7, base H2 availability for class 8	With[1]
S3	S_{321}	Base	Base	Base terminal cost for class 3 to class 7, base charger availability for class 8	Reduced terminal cost for class 3 to class 7, improved H2 availability for class 8	With[1]
S4	S_{431}	Low	Low	Reduced terminal cost for class 3 to class 7, improved charger availability for class 8	Reduced terminal cost for class 3 to class 7, improved H2 availability for class 8	With[1]
	S_{432}	Low	Low	Reduced terminal cost for class 3 to class 7, improved charger availability for class 8	Reduced terminal cost for class 3 to class 7, improved H2 availability for class 8	With[2]

1. Incentives and rebates including California's Hybrid and Zero-Emission Truck and Bus Voucher Incentive Project (HVIP) [11] and Clean Vehicle Tax Credit (CVTC) [9] between 2020 and 2030, but with a steady decrease rate since 2024.

2. Both HVIP and CVTC are available between 2020 and 2036, but with a steady decrease rate since 2024.

3.5. Calibration of the Model

Model calibration represents a methodical process of fine-tuning a statistical model's outcomes to align closely with the true probabilities of the predicted results. Simply put, a well-calibrated model yields prediction probabilities that faithfully represent the actual occurrence likelihood of the forecasted events. Calibration carries immense importance as it provides compelling evidence that the model's inputs can be adeptly adjusted to yield outputs congruent with the actual market data for Battery Electric Vehicles (BEVs) sold in 2020 and 2022. In the framework of this study, model calibration encompasses several strategic steps. Initially, we assemble probability tables for BEVs and Fuel Cell Hybrid Electric Vehicles (FC-HEVs) specific to the years 2020 and 2022. This is followed by a comprehensive calculation of the market share, whose results are then juxtaposed against the authentic market data. The comparative analysis between the outcomes of the PPA model and the real-world market data for Light-Duty Vehicles (LDVs) underscores the efficacy of the PPA model. This conclusively attests its ability to generate reliable, rational, and defensible forecasts of market shares.

4. Results obtained using the PPA model for different scenarios

4.1. Light-duty vehicle markets

Vehicle electrification and grid decarbonization are considered the primary means of achieving significant reductions in greenhouse gas (GHG) emissions in the US LDV market. To achieve the net-zero GHG emissions goal by 2040, ZEVs must completely dominate the on-road vehicle stock. This requires the annual sales of ZEVs to dominate the market well before 2040. Therefore, the growth in sales share of ZEVs over the next two decades is crucial for transitioning to cleaner transportation energy sources, provided that grid decarbonization is happening concurrently. **Figure 2** illustrates the market dynamics of eight scenarios (defined in **Table 2**), depicting the decline of ICE. Moreover, **Figure 3** shows the market penetration of EV (BEV & PHEV) and FCV (FCHEV & FCPHEV), respectively. The findings reveal a rapid expansion of ZEV sales across some scenarios. In this study, internal combustion engine vehicles (ICEVs) include both gasoline-powered and non-plugin hybrid vehicles. This section will focus on each scenario and provide analysis of the results.

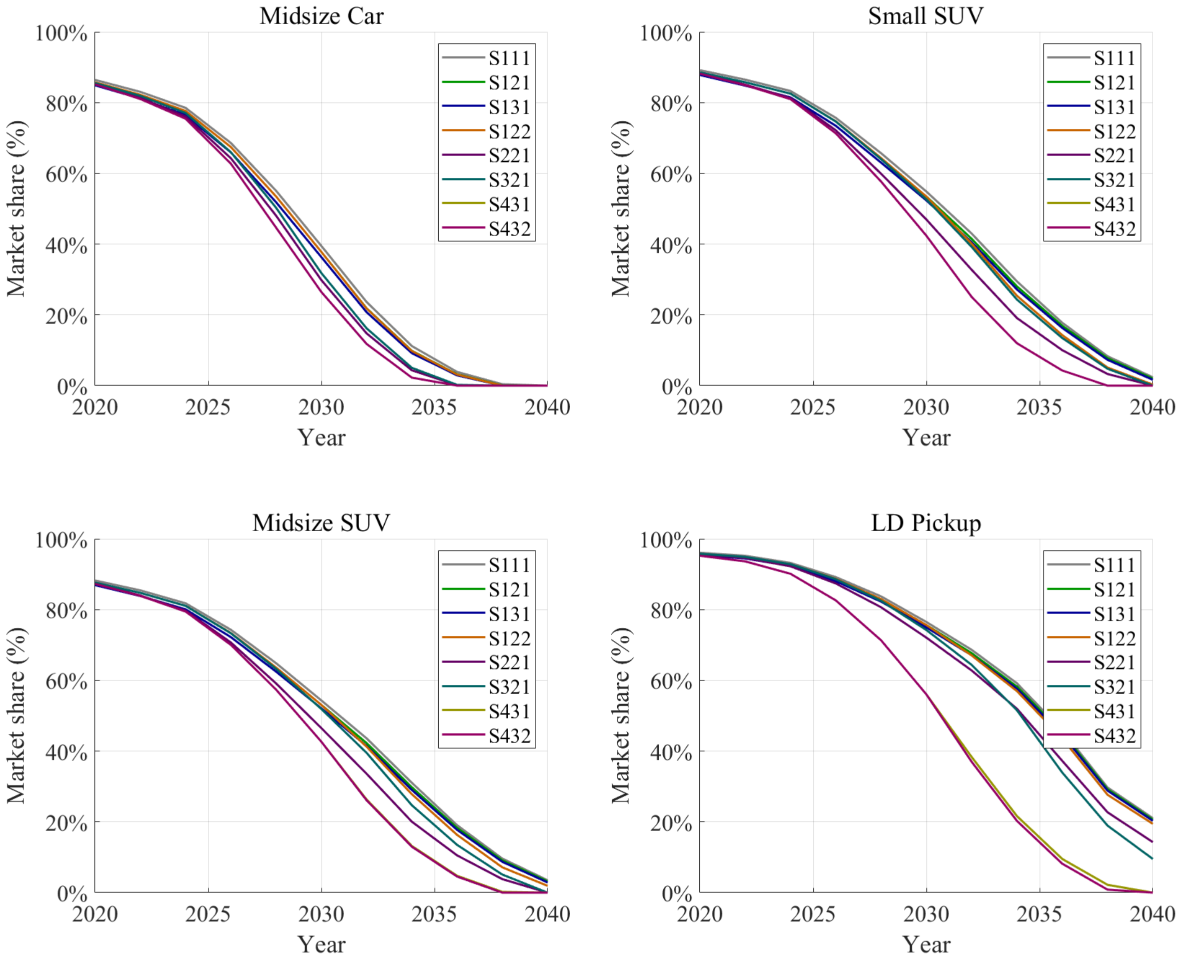
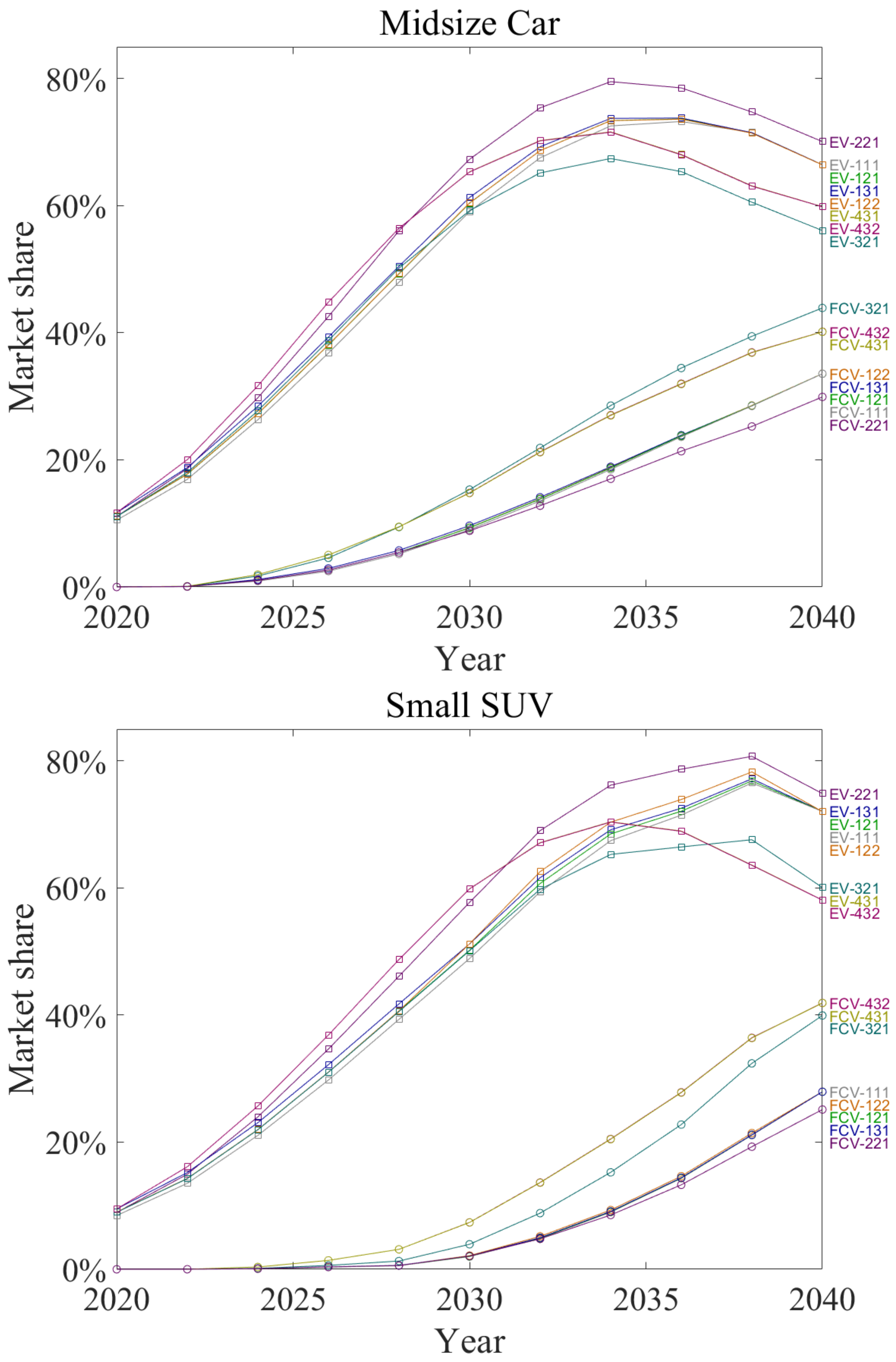


Figure 2. Projected market shares of light-duty ICEVs in the California for all the scenarios.


Midsize Car
Market share
80%
60%
40%
20%
0%
2020
2025
2030
2035
2040
Year
EV-221
EV-111
EV-121
EV-131
EV-122
EV-431
EV-432
EV-321
FCV-321
FCV-432
FCV-431
FCV-122
FCV-131
FCV-121
FCV-111
FCV-221
Small SUV
Market share
80%
60%
40%
20%
0%
2020
2025
2030
2035
2040
Year
EV-221
EV-131
EV-121
EV-111
EV-122
EV-321
EV-431
EV-432
FCV-432
FCV-431
FCV-321
FCV-111
FCV-122
FCV-121
FCV-131
FCV-221

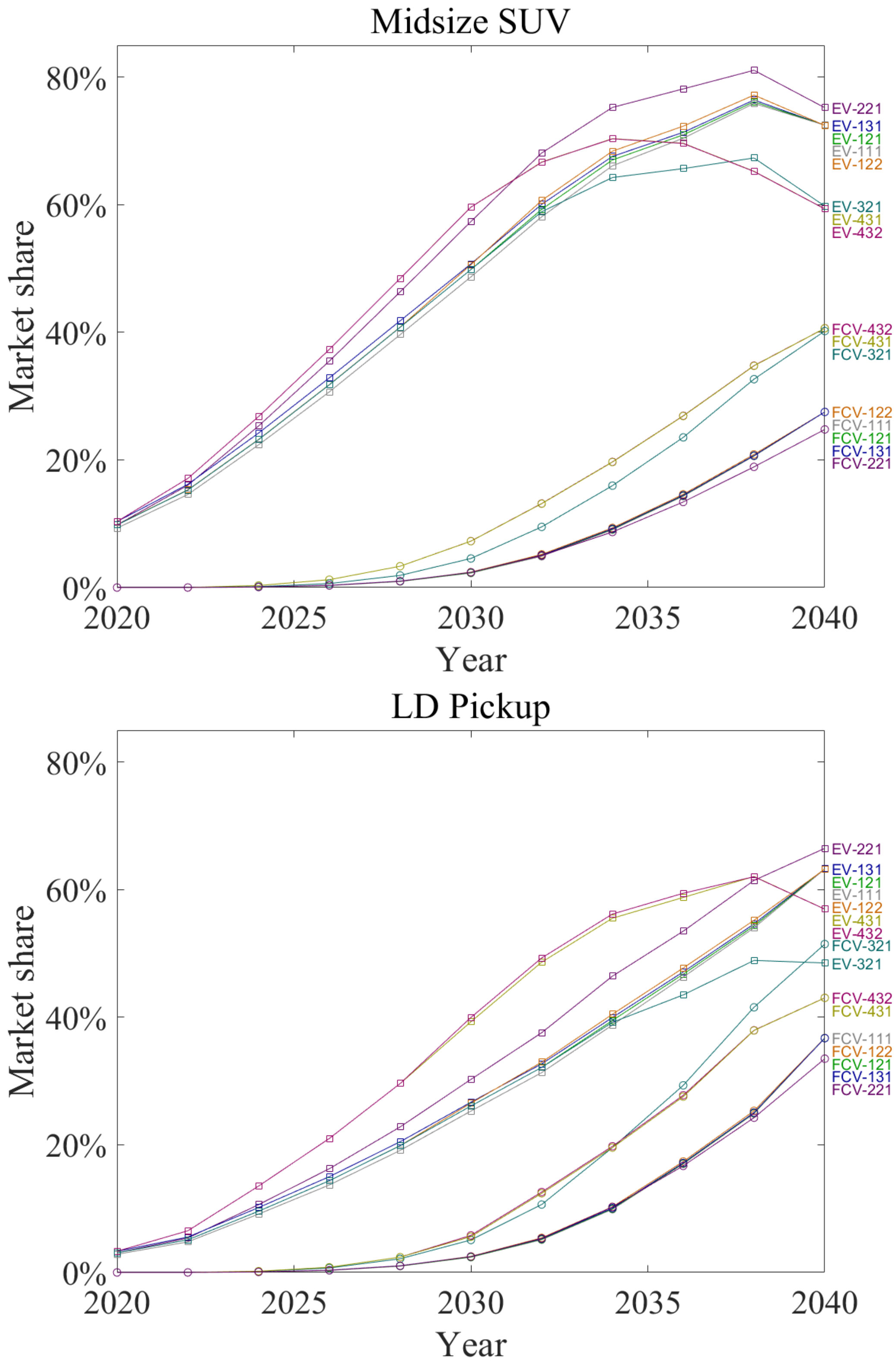


Figure 3. Projected market shares of light-duty EVs (BEVs & PHEVs) and FCVs (FC-HEVs & FC-PHEVs) in the California for all the scenarios.

4.1.1. Scenario 1

This is the base case for the 3 levels (high, base, and low) of battery and fuel cell costs between 2020 and 2040. For BEVs, the charging availability – the convenience in the city and on the highway – is assumed to be 0.33 – 0.66 (city) and 0.2 – 0.5 (HW), respectively, between 2020 and 2040. For PHEVs, we assume that the owners only consider the inconvenience of charging on the highway, which is set to be equal to the case of BEVs. For FC-HEVs, the hydrogen station availability – the convenience in the city and on the highway – is assumed to be 0.005 – 0.16 between 2020 and 2040. For FC-PHEVs, the vehicle owners will charge their vehicles primarily in the city, which is assumed to be equal to the case of BEVs and PHEVs, while they will refuel primarily with hydrogen on the highway, which is assumed to be equal to the case of FC-HEVs. **Figure 4** presents a comparison of market shares for battery and fuel cell vehicles under different cost scenarios for energy storage device technologies in the context of S1 infrastructures. The model results suggest that the market share of ZEVs will not be significantly impacted by variations in battery and fuel cell costs within the range considered in this study. This is primarily because our study does not assume an unrealistic decrease in vehicle costs for ZEVs. It is notable that under scenarios with lower costs of energy storage devices, the decrease is more rapid than in higher cost scenarios during the early years. However, by 2040, the differences between the various cost scenarios become negligible.

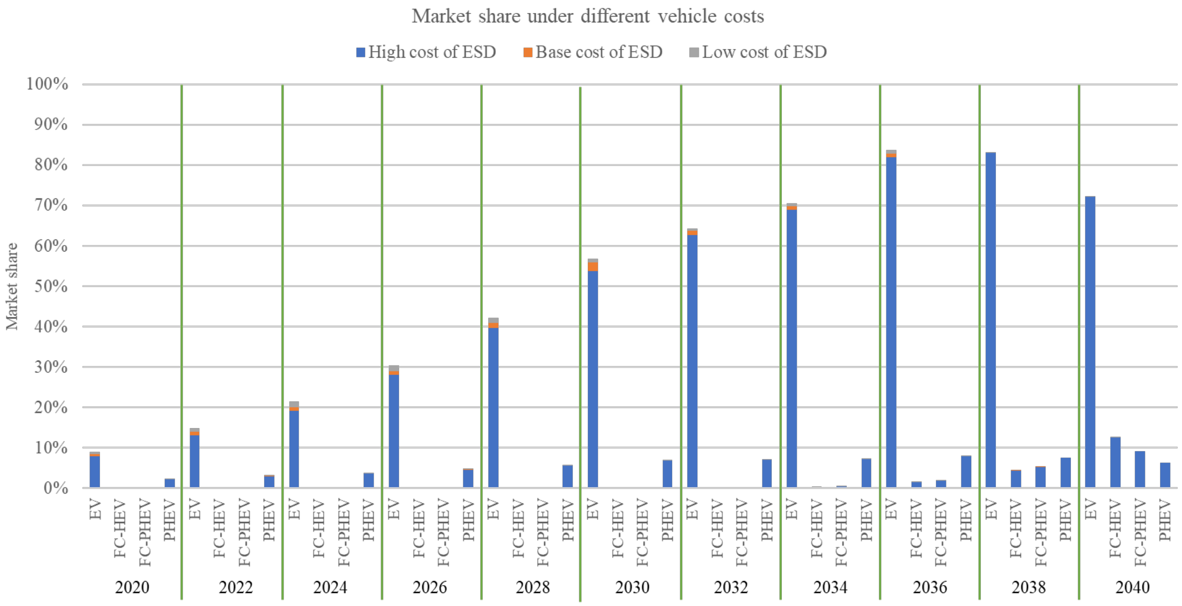


Figure 4. Market shares of battery-electric and fuel cell vehicles for different levels of the ESCD technologies for the S1 infrastructures (S_{111}, S_{121} and S_{131}).

The effect of financial incentives (**Appendix B**.5) on the market share of ZEVs is shown in **Figure 5**. This study explores the impact of financial incentives based on current policies in California, such as Federal Tax Credits and the Clean Vehicle Rebate Project for LDVs, with a particular focus on their continued influence between 2034 and 2040. The findings suggest that even if financial incentives for purchasing

ZEVs are discontinued, the market share of Internal Combustion Engine (ICE) vehicles would see only a minor decline.

In the midsize car market, various financial incentives explored in this study did not substantially affect ICE sales. This outcome appears to be due to the prices of these vehicles, which are nearing equivalence with ICE counterparts. Consequently, the absence of financial incentives post-2036 for midsize vehicles is unlikely to have a significant impact.

Interestingly, the market share of FCVs, including FC-HEVs and FC-PHEVs, does not show sensitivity to financial incentives. This could be attributed to the limited availability of vehicle models and the inadequacy of hydrogen refueling infrastructure. Thus, implementing financial incentives solely for FCVs is unlikely to have a major influence on sales until the availability of more models increases and the hydrogen infrastructure undergoes significant improvement. However, it is worth noting that if both Federal Tax Credits and Clean Vehicle Rebate Project incentives are sustained until 2034 for midsize cars, near 100% market penetration for BEVs appears achievable by 2034.

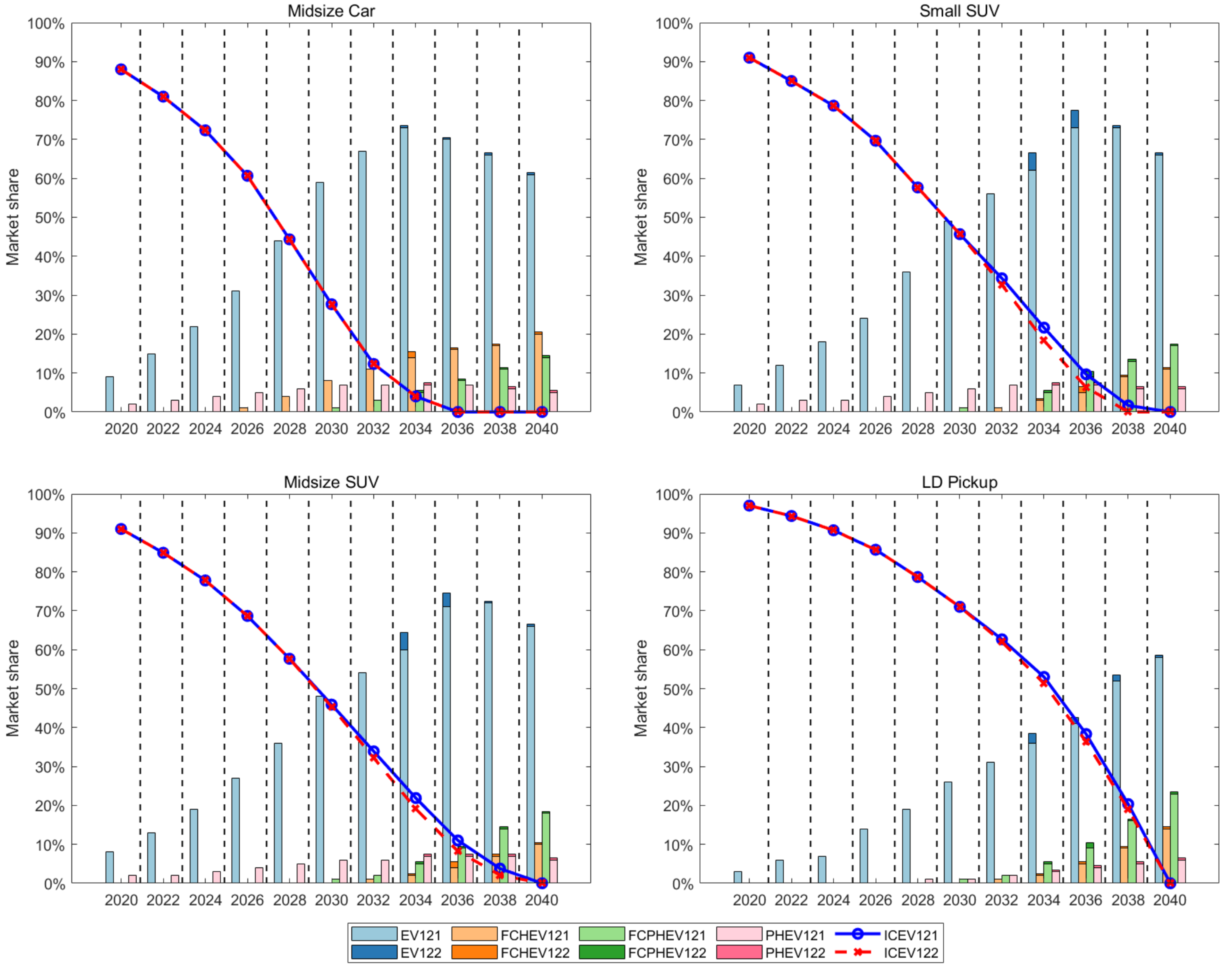
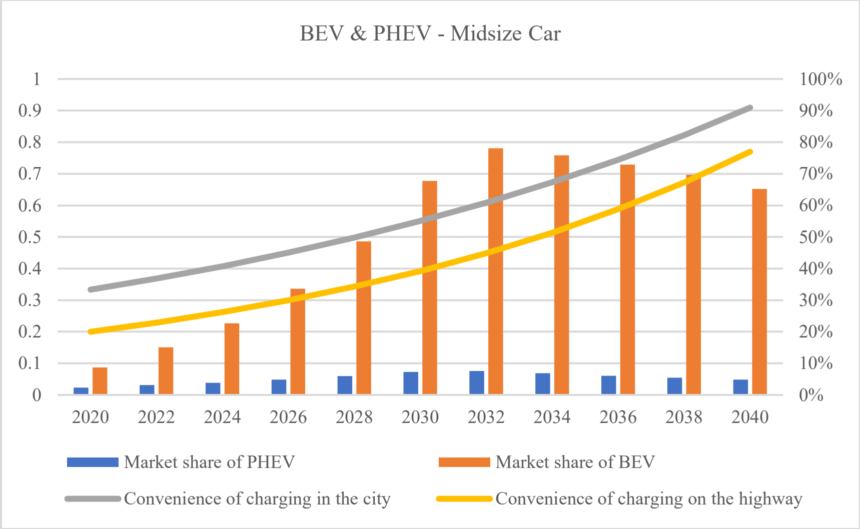
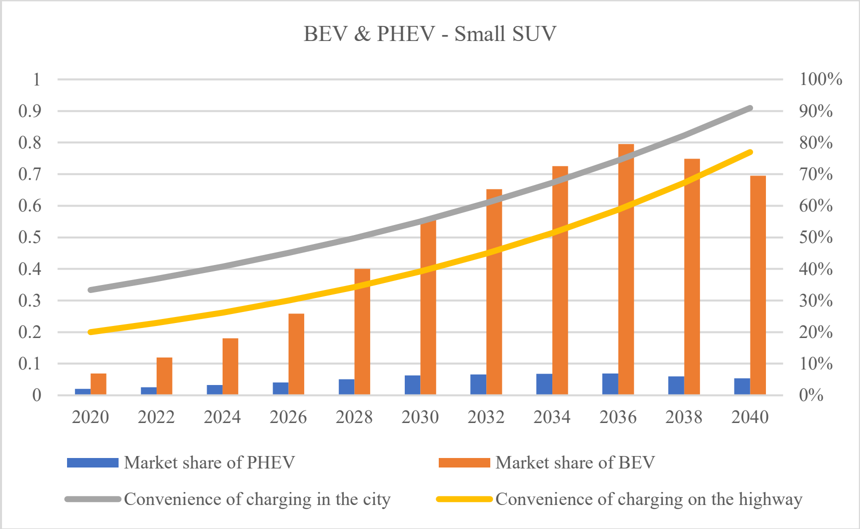


Figure 5. The market share of ZEVs under different financial incentive plans for the S1 infrastructure cases (S_{121} and S_{122}).

4.1.2. Scenario 2

This scenario is based on the base case for the cost of battery-electric and fuel cell components and an improved battery charging infrastructure. The scenario assumes DC fast chargers both in the city and along highways will be as convenient as gasoline ICE refueling in 2040 with charging times of 20 minutes or less. The battery charging infrastructure will improve gradually between 2020 and 2040. In this scenario, it is assumed the infrastructure for fuel cell vehicles is changed little from S1. **Figure 6** presents results for the market penetration of BEVs and PHEVs for each vehicle size/type. In this scenario, BEVs of all types have high market penetration, but the penetration is lower for the large LDVs.


BEV & PHEV - Midsize Car
1
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
100%
90%
80%
70%
60%
50%
40%
30%
20%
10%
0%
2020
2022
2024
2026
2028
2030
2032
2034
2036
2038
2040
Market share of PHEV
Market share of BEV
Convenience of charging in the city
Convenience of charging on the highway


BEV & PHEV - Small SUV
1
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
100%
90%
80%
70%
60%
50%
40%
30%
20%
10%
0%
2020
2022
2024
2026
2028
2030
2032
2034
2036
2038
2040
Market share of PHEV
Market share of BEV
Convenience of charging in the city
Convenience of charging on the highway

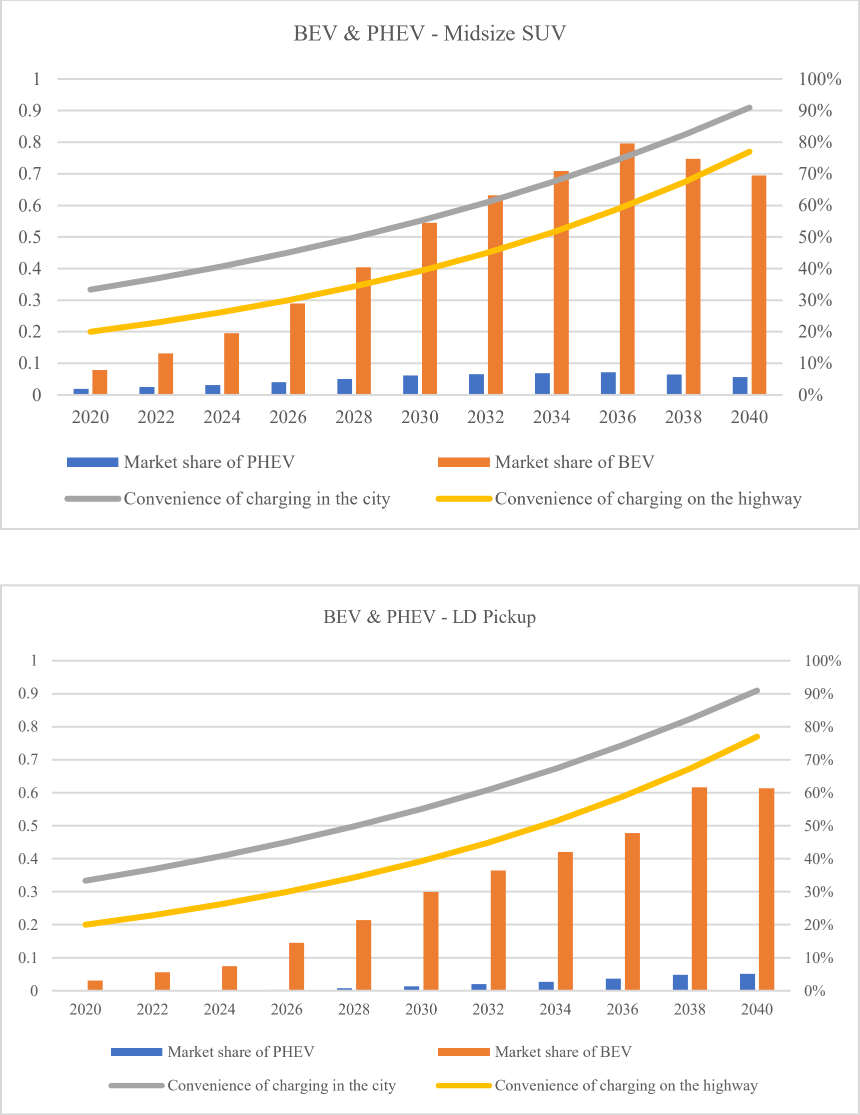


Figure 6. Market shares of BEV and PHEV under different charging infrastructure for S2 (S_{221}).

The results shown in **Figure 7** show that better charging availability can potentially increase the market share of BEVs by over 20% in certain vehicle categories. It also indicates the market share of PHEVs likely may decrease with better battery charging infrastructure. This decrease is because vehicle buyers seem to prefer pure BEVs over PHEVs when better charging availability is provided for EVs.

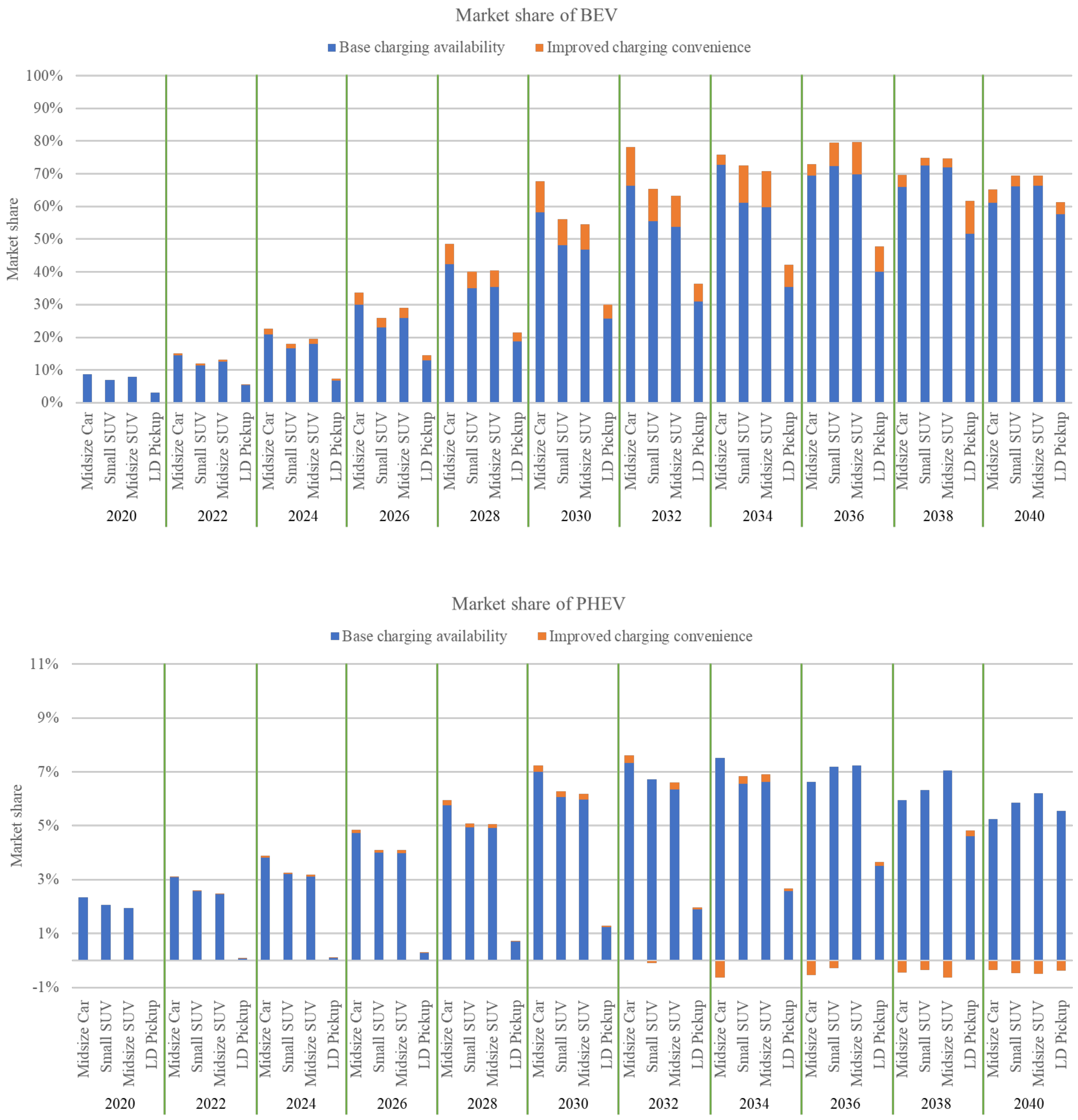
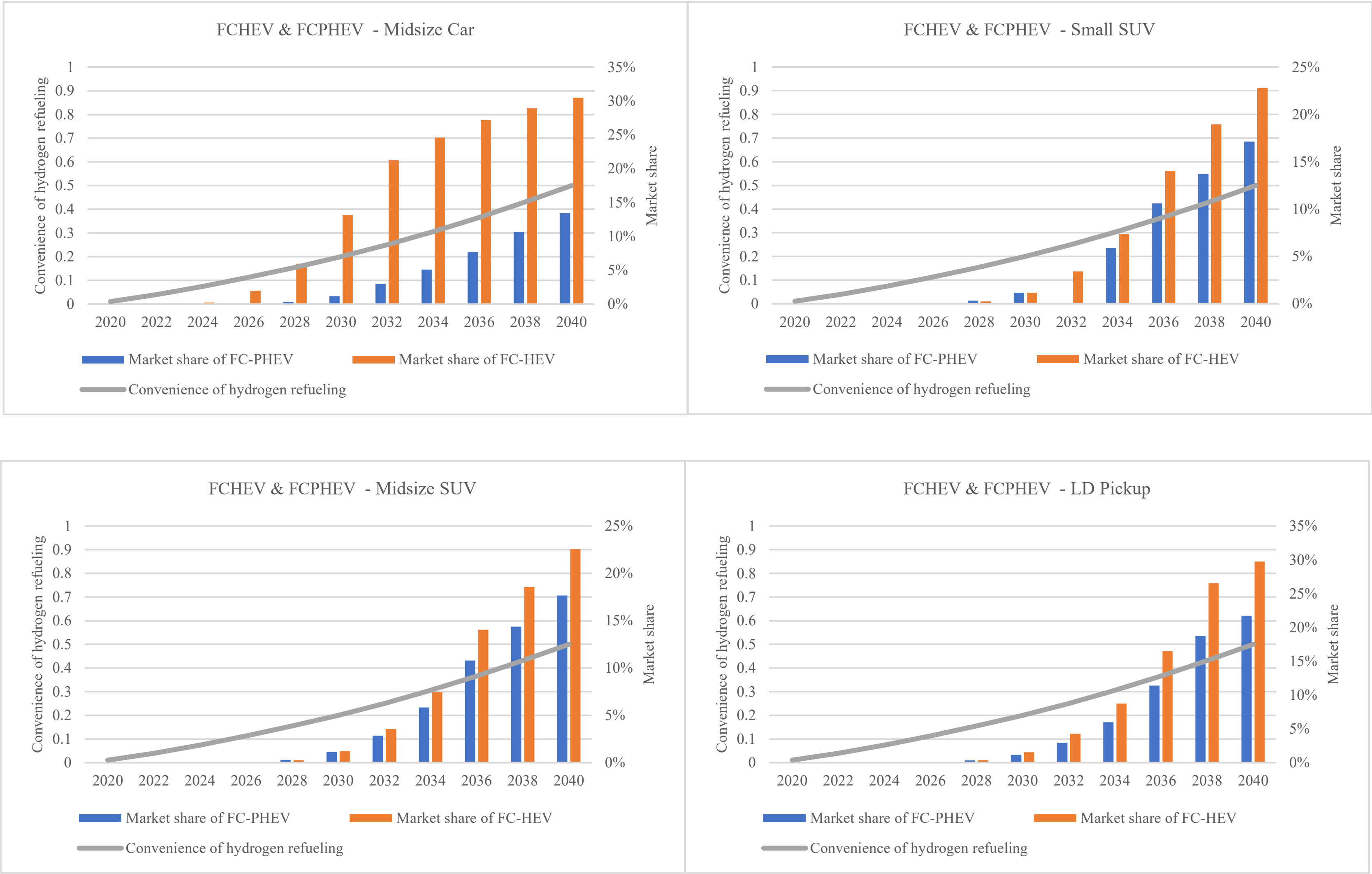


Figure 7. Comparison of the market shares of BEV and PHEV under different charging availability (S_{121} and S_{221}).

4.1.3. Scenario 3

In S3, it is assumed that the hydrogen refueling infrastructure will be improved to the same convenience of refueling as gasoline ICE vehicles at both highway and city stations by 2040. Availability rates for the intervening years will be linearly interpolated. The base cost of fuel cells is used in this scenario and it is assumed that more FCV models are available for purchase with improved hydrogen infrastructure. The market penetration in this case is presented in **Figure 8**. The market share of FCVs is projected to be about 30% for all the vehicle types.



FCHEV & FCPHEV - Midsize Car

FCHEV & FCPHEV - Small SUV

FCHEV & FCPHEV - Midsize SUV

FCHEV & FCPHEV - LD Pickup

Figure 8. Projected market shares of FC-HEV and FC-PHEV under improved hydrogen refueling infrastructure (S_{321}).

Figure 9 compares the base case with a scenario featuring improved hydrogen availability. The figure suggests that an increase in hydrogen refueling station availability has a significant impact on the market share of FCVs, including FC-HEVs and FC-PHEVs, by 2040.

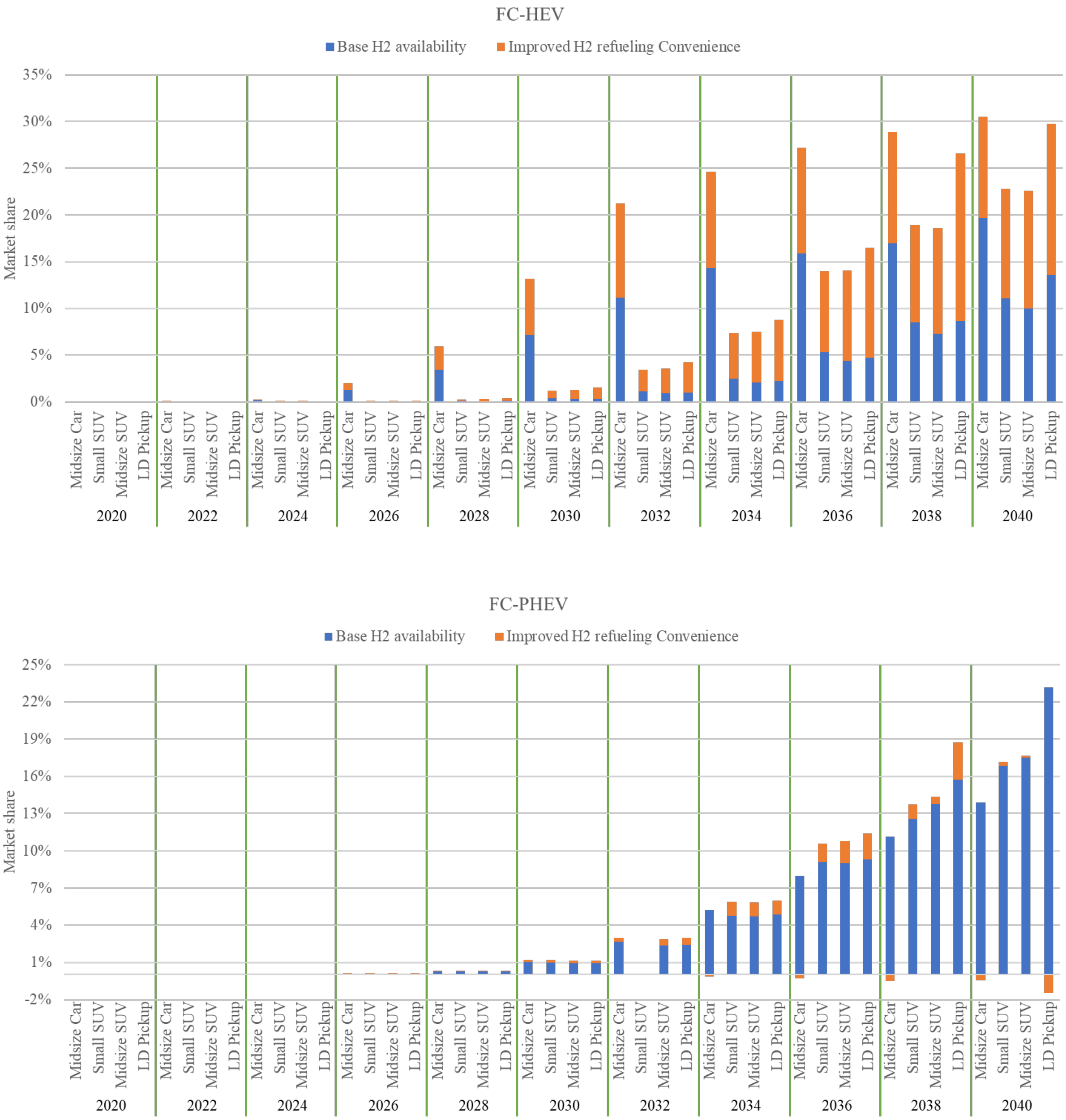


Figure 9. Comparison of the market shares of FCV (FC-HEV + FC-PHEV) under different H2 availability (base and improved case (S_{121} and S_{321}).

4.1.4. Scenario 4

This scenario explores market conditions needed to achieve the CARB targets for the sale of ZEVs — that is, 2025: 10% of new passenger car sales to be ZEV, 2030: 55% of new passenger car sales to be ZEVs, 2035: 100% of new passenger car sales to be ZEVs. The PPA model results for the S431 scenarios are shown in **Figure 10**, California can achieve 100% ZEV sales by 2035. LD pickup is the toughest case to achieve the CARB target in the early years.

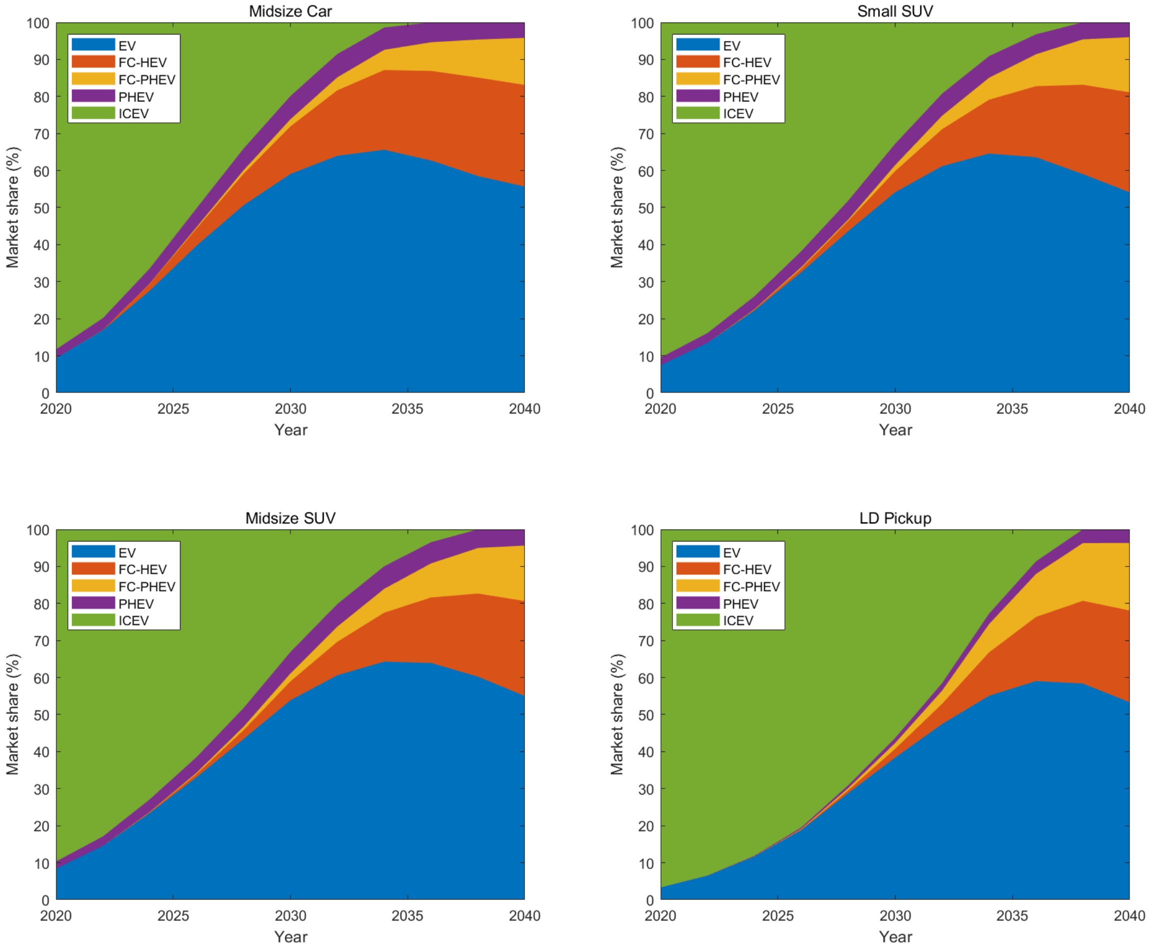


Figure 10. Market shares of ZEVs in California for the S4 scenario.

In order to meet 100% ZEV sales by 2036, financial incentives seem to be needed. The output of S_{431} shows that the 100% ZEV target can be achieved before 2036 if the federal tax credits are available until 2032. In addition, the low costs of batteries and fuel cells are needed as well as the aggressive construction of charging and hydrogen refueling infrastructure over the next two decades.

4.2. Medium and heavy-duty truck markets

Decarbonizing the transportation sector in the United States is a critical task. One of the key steps towards achieving this goal is the electrification of MD/HDVs. The process of electrifying MD/HDVs, which were responsible for over 20% of the total energy consumption in the U.S. transportation sector in 2019 [12], is a crucial measure in the pursuit of decarbonizing the country's transportation infrastructure.

As a result, BEVs and FCVs are becoming an increasingly attractive options for electrification of trucks. Due to their lower energy and maintenance costs, reduced downtime as the new technologies mature, and less stressful driving, the electrified trucks can be an appealing choice for commercial trucking operations. Hence, electrifying their trucks can significantly reduce operating costs and improve the bottom line for trucking companies, while also contributing to the decarbonization of the transportation sector.

Figure 11 and **Figure 12** shows the modeling results for class 3 to class 8 trucks in the case of ICEVs and ZEVs (BEVs & FCEVs). The scenarios are described in **Table 3** using the same code as used for LDVs. The model results for the base case project that the ZEV trucks can be 100% of sales for Class 3 and 4 and 90% of truck sales for class 5 and 6 in 2040. Sales of ZEV trucks in classes 7 and 8 in the base case would be 60-80% in 2040. The results for other scenario (S2, S3, and S4) show 100% ZEV sales before 2040 for class 3-6 trucks and 100% ZEV sales for class 7-8 by 2040. The results for all the scenarios will be discussed in detail later in this section of the report.

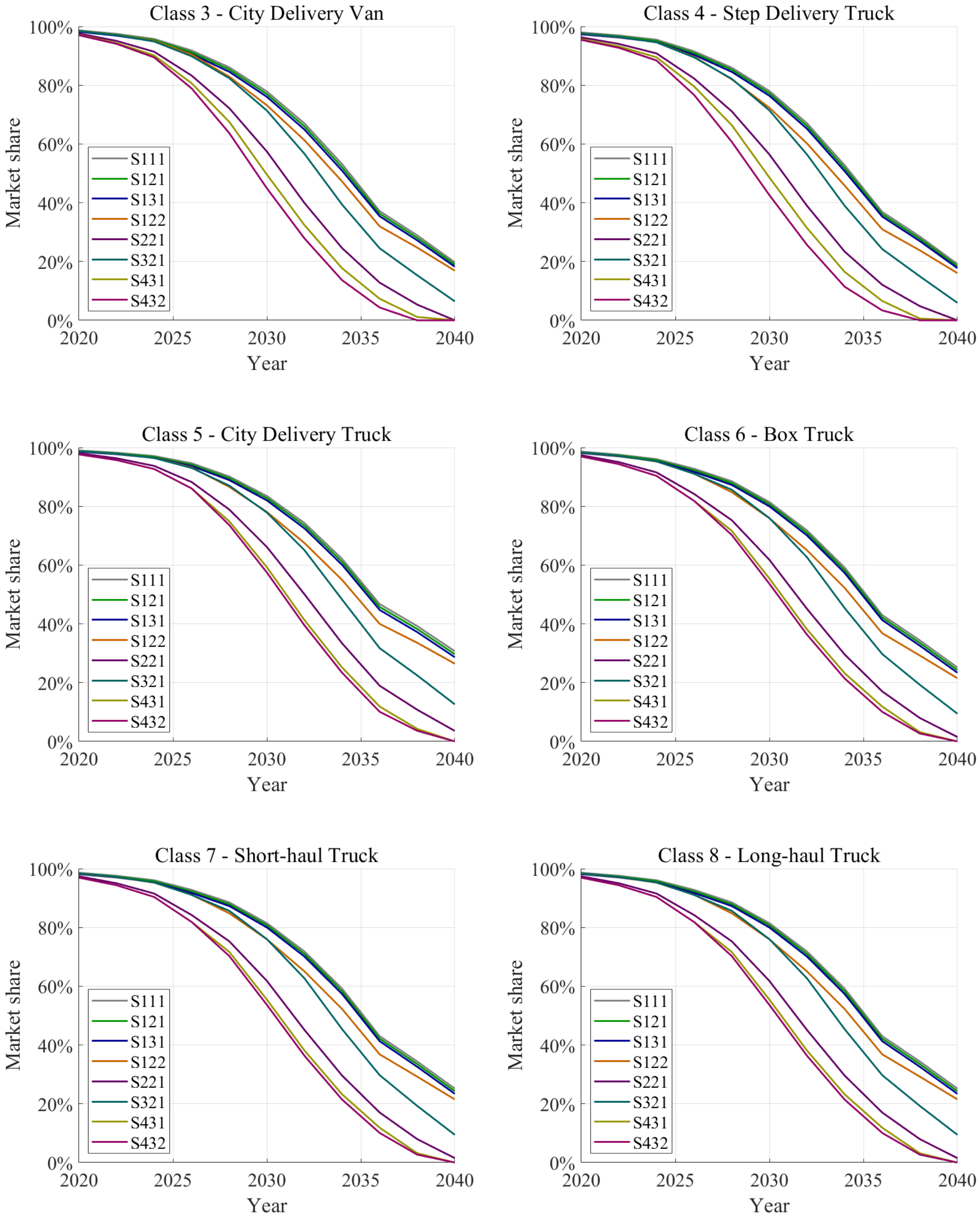


Figure 11. Projected market shares of medium and heavy-duty ICEVs for all the scenarios in this study.

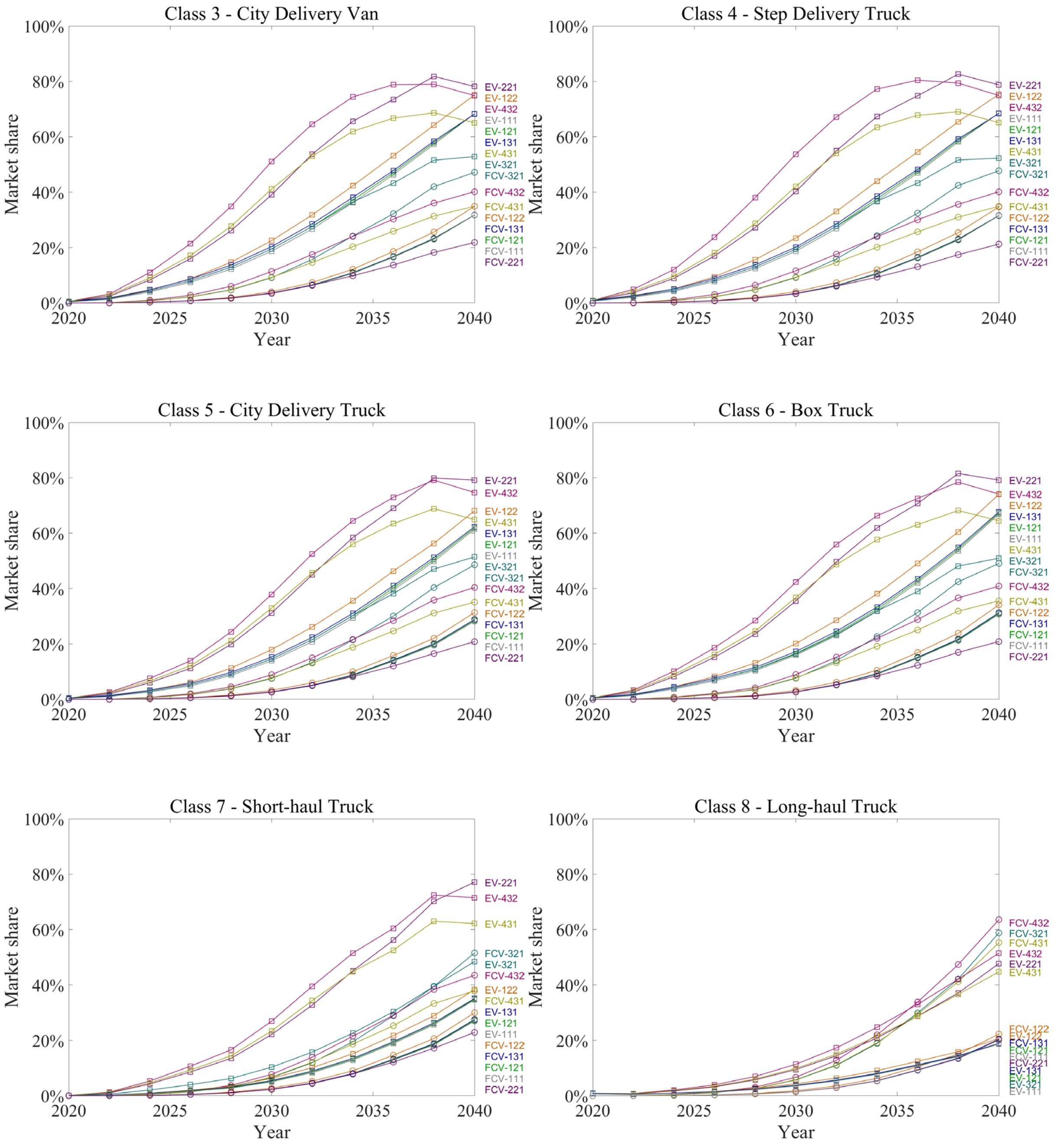
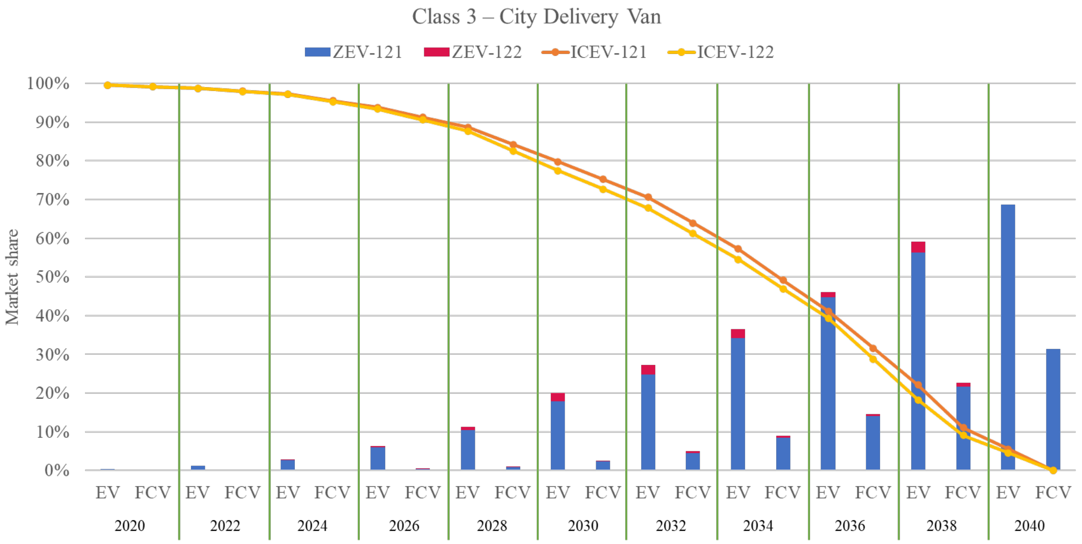
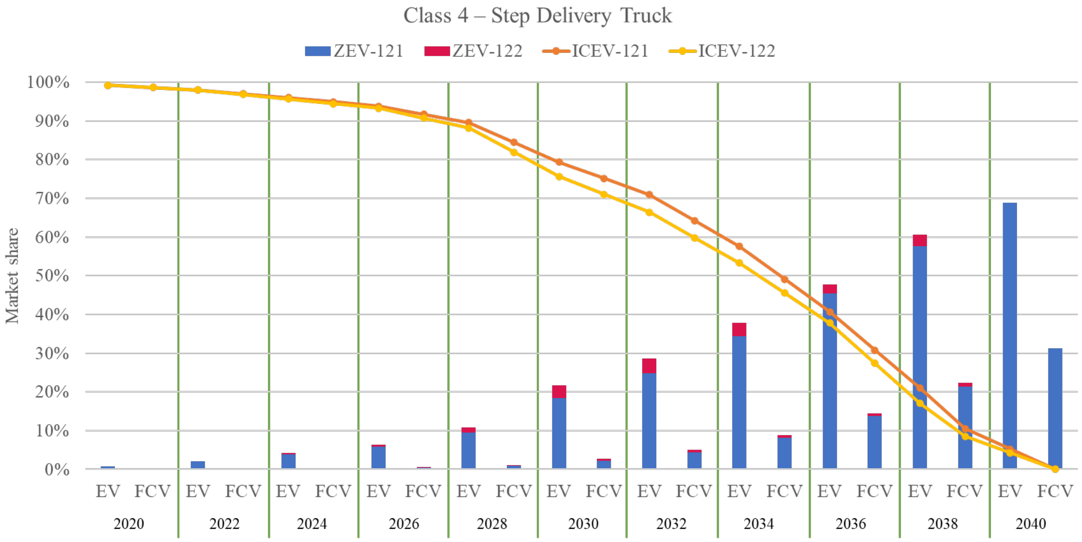


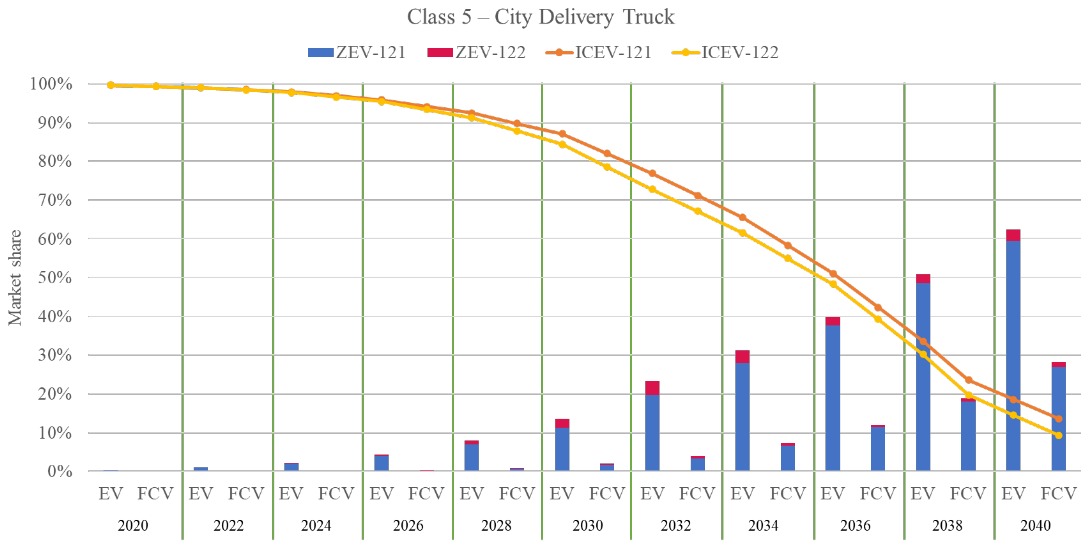
Figure 12. Projected market shares of medium and heavy-duty BEVs and FCVs for all the scenarios in this study.

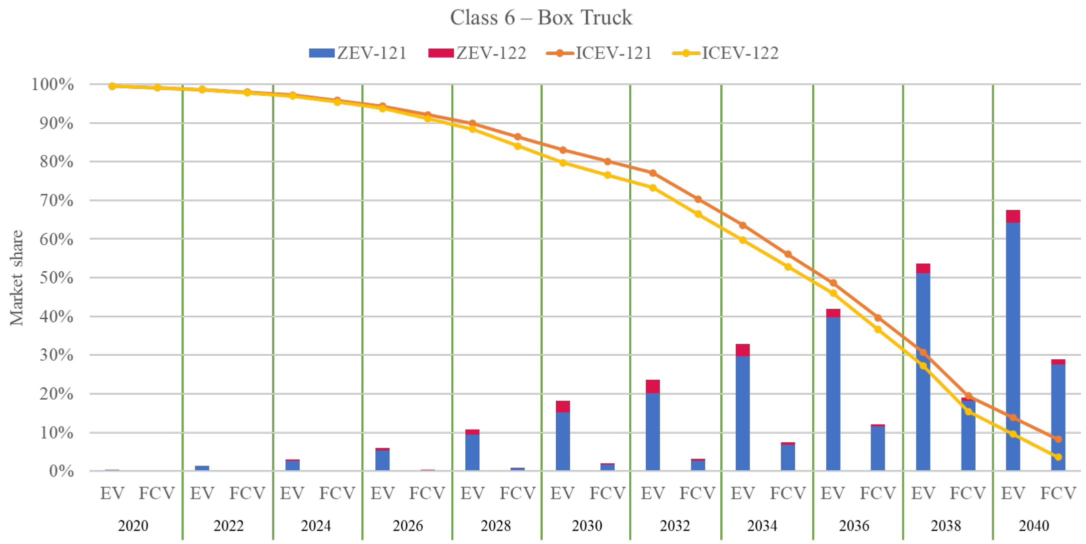
4.2.1. Scenario 1

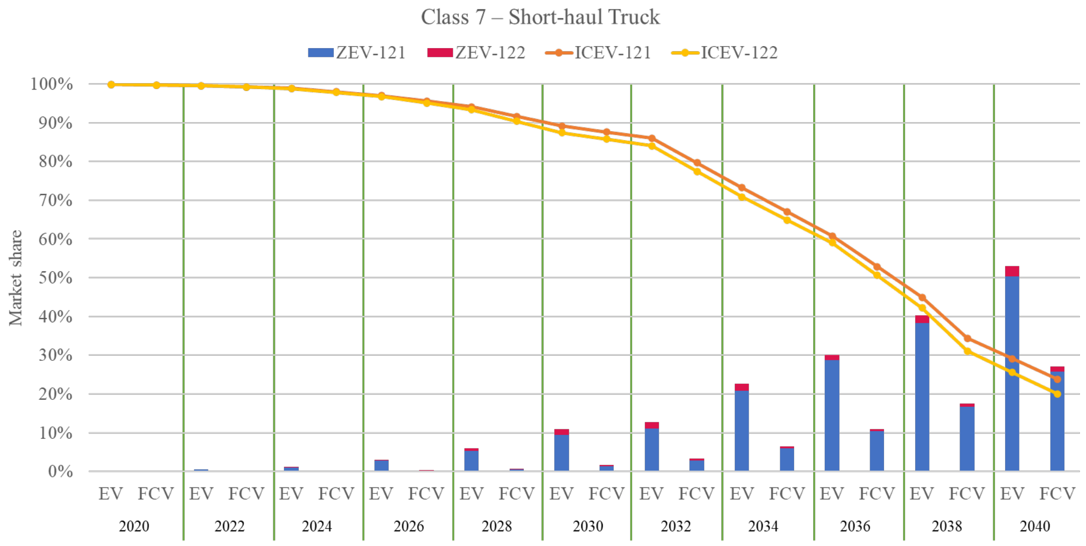
This is the base scenario. The market share results are shown for the three different battery costs (high_1: base_2: and low_3), which are given in **Appendix B.1.** The results show that the different costs of the batteries do not significantly affect the market share of BEVs for the 6 truck types, because the impact of other decision factors is greater than the ZEV truck cost. The influence of financial incentives (detailed in **Appendix B**.5) on ZEV market share have been evaluated as depicted in **Figure 14**. These results indicate that the market share of both BEVs and FCVs are not sensitive to the financial incentives even when the ZEV truck prices are similar to the ICE trucks after the incentives are applied. This insensitivity is primarily due to the larger impact of restricted number of truck models available, long charging time on the highway and the cost of providing fleet charging facilities.






Class 5 – City Delivery Truck
ZEV-121
ZEV-122
ICEV-121
ICEV-122
Market share
100%
90%
80%
70%
60%
50%
40%
30%
20%
10%
0%
EV FCV EV FCV EV FCV EV FCV EV FCV EV FCV EV FCV EV FCV EV FCV EV FCV EV FCV
2020 2022 2024 2026 2028 2030 2032 2034 2036 2038 2040


Class 6 – Box Truck
ZEV-121
ZEV-122
ICEV-121
ICEV-122
Market share
100%
90%
80%
70%
60%
50%
40%
30%
20%
10%
0%
EV FCV EV FCV EV FCV EV FCV EV FCV EV FCV EV FCV EV FCV EV FCV EV FCV EV FCV
2020 2022 2024 2026 2028 2030 2032 2034 2036 2038 2040



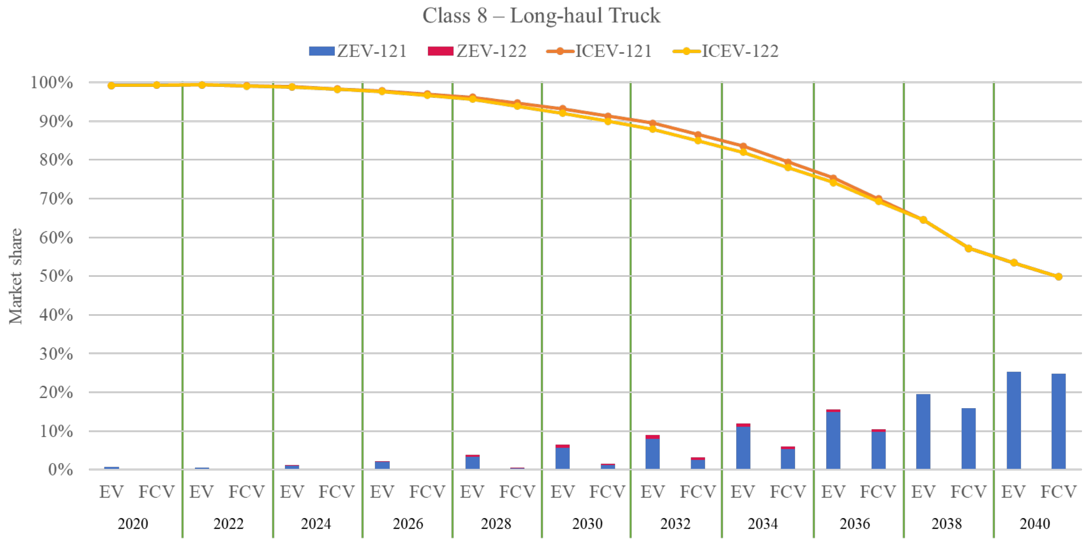


Figure 13. Projected market shares of different ZEVs with incentives by 2030 or by 2036 (S_{121} and S_{122}).

4.2.2. Scenario 2

This scenario builds upon the base case. It incorporates reduced terminal costs for charging the battery-powered electric trucks. It assumes that the terminal cost for BEVs will be 50% higher than that for refueling diesel engine trucks in 2040 and that terminal charging costs are reduced linearly between 2020 and 2040. In this scenario, the battery costs remain at the base cost. **Figure 15** shows the market penetration of BEVs in the various truck classes with lower battery charging facility cost and reduced inconvenience in charging. **Figure 16** shows the differences in BEV market share for the various truck classes due to the improved terminal charging facilities in scenarios S1 and S2. In all cases, the effect on market shares is significant indicating that battery charging infrastructure is a key decision factor for battery-electric trucks.

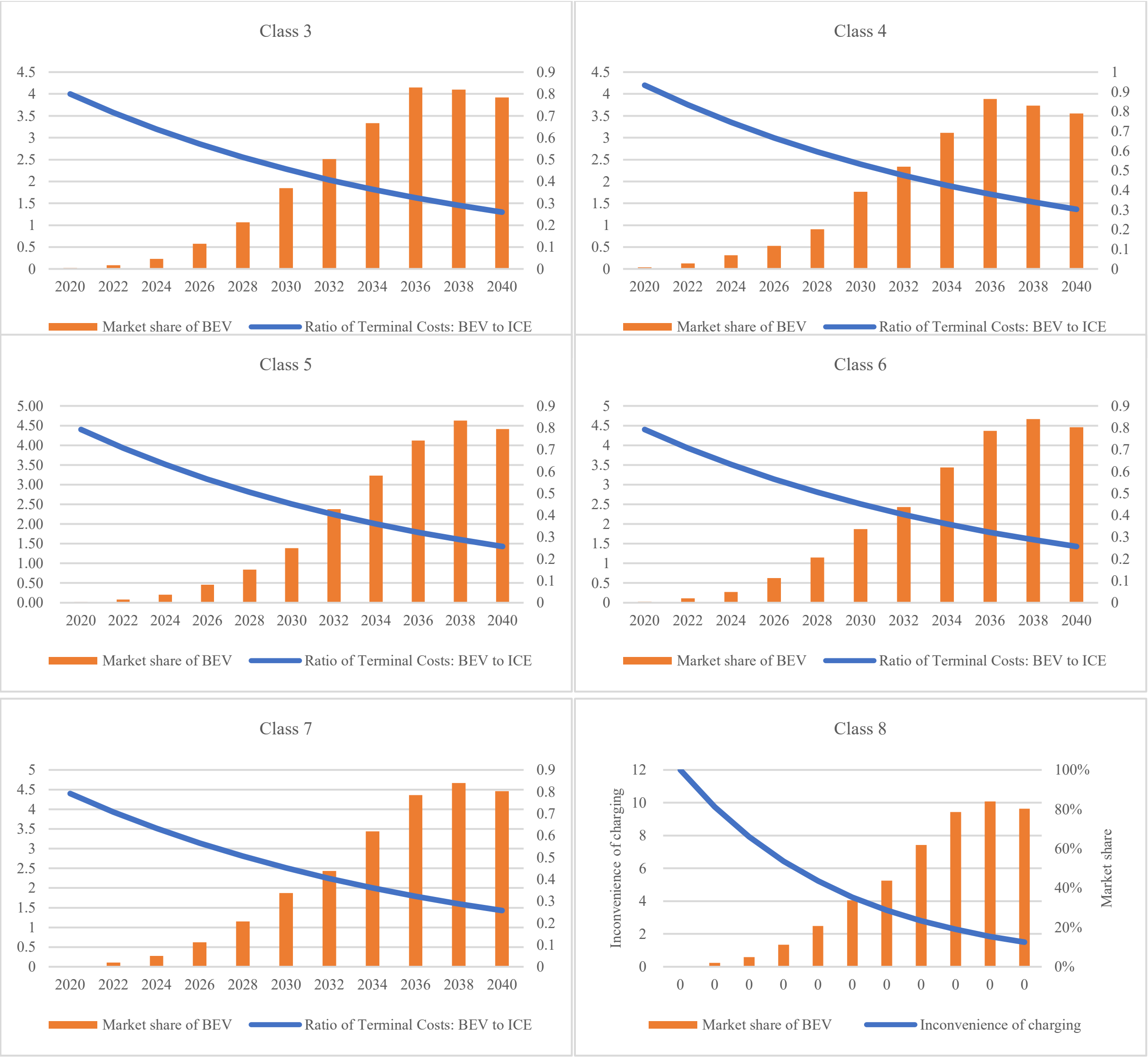


Figure 14. Market shares of BEV under reduced terminal costs and charging infrastructure availability (S_{221}).

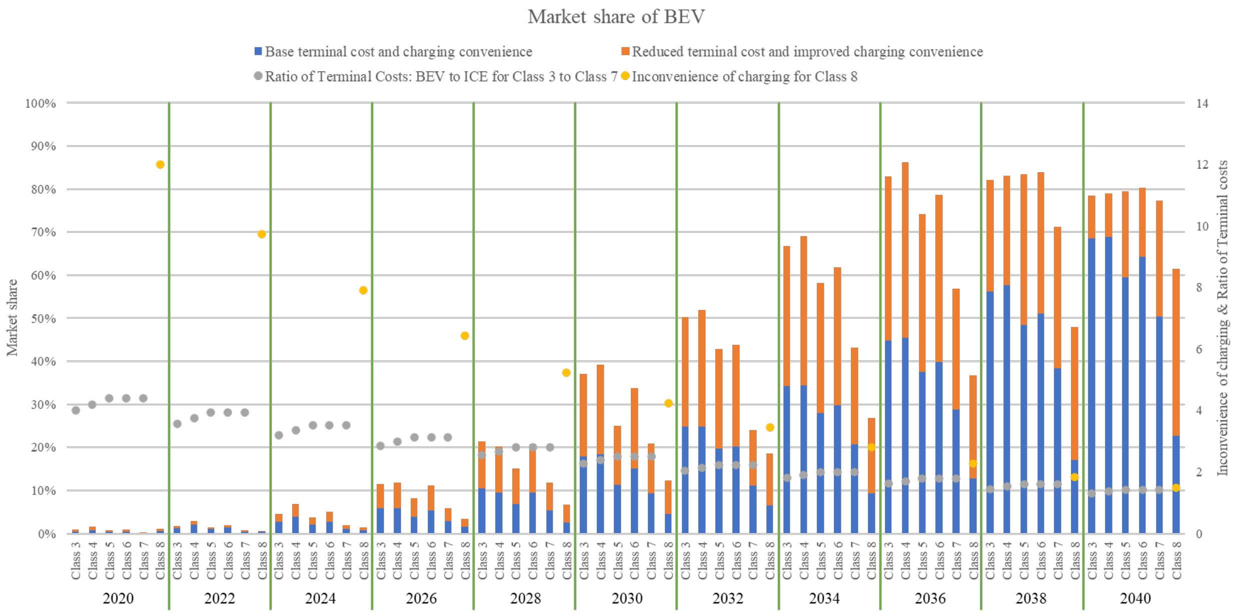


Figure 15. Comparison of the market shares of BEVs under reduced terminal costs and improved charging infrastructure availability in Scenario S2 (S_{121} and S_{221}).

4.2.3. Scenario 3

This scenario investigates the impact of enhancements in hydrogen refueling amenities at terminals. It is projected that by 2040, the cost associated with hydrogen refueling infrastructure will be trimmed down to a level that is merely 65% higher than the expenditure for diesel truck refueling. In the context of this scenario, the hydrogen station cost in 2026 is predicted to be about quadruple the cost of a diesel refueling station, with costs linearly adjusting over the years in between. The fuel cell costs in this scenario are based on the base cost details provided in **Appendix B**.1. **Figure 17** visually represents the market penetration for various classes of fuel cell vehicles for the S3 scenario, contrasted with the base S1 scenario. A noteworthy increase in the market share of fuel cell vehicles starts to surface from 2030, accelerating to reach between 40-50% by 2040, owing to the enhanced hydrogen refueling infrastructure. Interestingly, it is observed that improvements in hydrogen refueling facilities at terminals have a more substantial influence on the market share for Fuel Cell Vehicles (FCVs) than the enhancements in battery charging amenities.

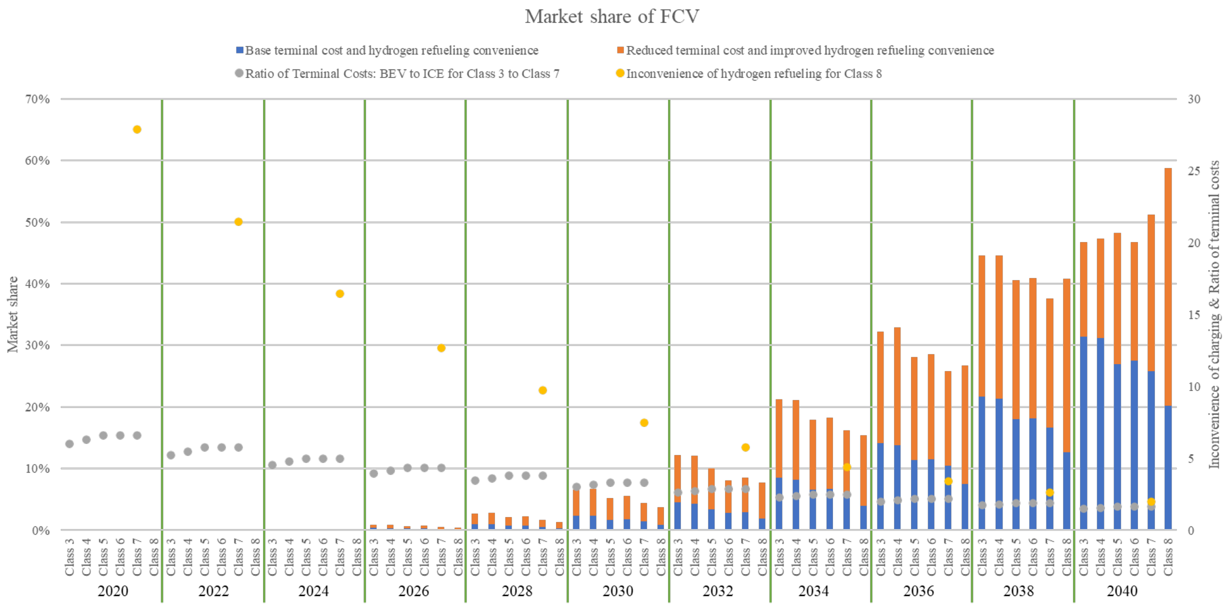


Figure 16. Comparison of the market shares of FCVs under different terminal costs and improved charging infrastructure availability (S_{121} and S_{321}).

4.2.4. Scenario 4

S4 includes low-cost battery and fuel cells, enhanced terminal facilities for charging batteries and refueling hydrogen vehicles, and incentives to 2030 (S431) and 2036 (S432). **Figure 18** shows the S432 model results for various classes of trucks. The results indicate that the S4 scenario can lead to meeting the CARB goals (**Table 4**) by 2040 even for Class7 and 8 trucks. A more detailed discussion of the model results and CARB goals/mandates for ZEVs will be given later in the report.

Table 4. ZEV CARB fleet milestones by milestone group and year [3].

Percentage of vehicles that must be zero-emission	**10%**	**25%**	**50%**	**75%**	**100%**
Milestone Group 1: Box trucks, vans, buses with two axles, yard tractors, light-duty package delivery vehicles	2025	2028	2031	2033	2035 and beyond
Milestone Group 2: Work trucks, day cab tractors, buses with three axles	2027	2030	2033	2036	2039 and beyond
Milestone Group 3: Sleeper cab tractors and specialty vehicles	2030	2033	2036	2039	2042 and beyond

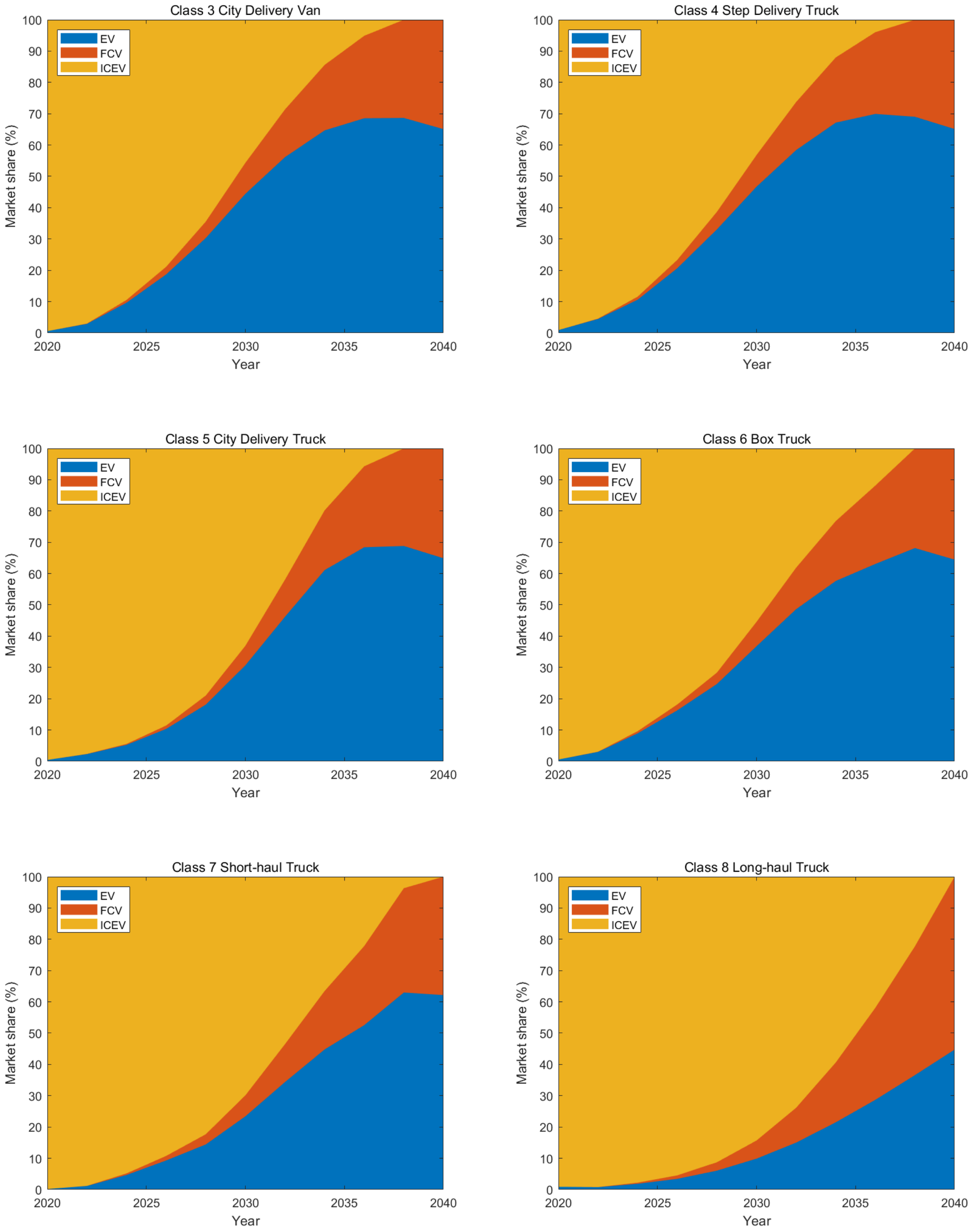


Figure 17. Projected market share results for trucks for Scenario_431.

5. Comparison of market share projections between the UC Davis PPA model and models developed at the DOE National Laboratories

The DOE National Laboratories have been developing for a number of years methods/models to project ZEV market shares during 2020-2050. It is of interest to compare the ITS-UCD results with the DOE projections from their papers. DOE Oak Ridge/Argonne Labs have made projections for light-duty vehicles [13] and NREL has dealt with MD/HD trucks [14]. We obtained the MA3T program from Oak Ridge Lab and have run the program to obtain results for California to compare with results using the PPA model. The results from NREL model (TEMPO/MDHD) are taken from the NREL paper [14]. All the models utilize essentially the same decision factors, but each model accounts for changes in the conditions influencing the decision factors in a different way. The MA3T and TEMPO models calculate the lifetime ownership costs of each vehicle option by summing the financial contributions of each decision factor. In the case of non-financial decision factors, relationships are developed to calculate a financial ($) value for that factor. The market shares are determined from the relative ownership costs of the vehicles. The lower the ownership cost for an option, the higher the market penetration.

As discussed in Section 3, the UC Davis approach deals directly with the purchase probabilities associated with each of the decision factors and calculates an average probability for each vehicle option. A market share for the vehicle options is determined from the average probabilities. All the vehicle choice models must cope with non-financial factors which require subjective judgements to include in the model. In addition, many of the inputs to the models are expected to change as the ZEV technologies mature over the next 20+ years. How these technologies and the associated vehicle infrastructure develop is very uncertain and the subject of much speculation. As a result, all the groups doing vehicle choice modeling construct different scenarios on which their market share results depend. In making our comparisons of results from the different models, we will indicate key factors and differences in the scenarios for which the results apply. The comparisons will made separately for LDVs and MD/HDVs.

5.1. Comparisons of vehicle choice model results for LDVs

The LDV comparisons will be made using results from the MA3T program from Oak Ridge/Argonne Labs. We will be using recent results from [13] and a run made with the program at UC Davis. Other MA3T results are given in [15]-[17]. The most recent MA3T results do not show any market for fuel cell powered LDVs. The results shown in **Table 5** include only BEV and PHEV plug-in vehicle options. The three scenarios are the following: S1- base battery costs and base (limited) battery charging infrastructure, S2- lowest cost batteries and small improvement in battery charging, S4 — lowest battery costs and optimum battery charging. The results in **Table 5** indicate that improvements in battery cost and infrastructure increase the market share of the plug-in vehicles, but in the later years, the PHEVs show the largest increases. These projections indicate a market resistance to purchasing BEVs when their sales share reaches about 40%. The MA3T results in **Table 5** are assumed to apply to the United States as a whole.

Table 5. MA3T LDV results for the United States for various battery scenarios [3].

Year	BEV-S1 Base battery cost Base battery charging facility	PHEV-S1 Base battery cost Base battery charging facility	BEV- S2 Base battery cost Expanding Charger availability	PHEV-S2 Base battery cost Expanding Charger availability	BEV-S4 Optimized battery cost Expanding Charger availability	PHEV-S4 Optimized battery cost Expanding Charger availability
2025	8	3	8	3	8	3
2030	12	8	25	5	32	7
2035	22	6	34	12	42	16
2040	26	12	34	18	42	28
2045	28	14	33	26	41	39
2050	30	20	32	36	41	49

The MA3T program was run at UC Davis using the inputs as received from Oak Ridge Lab. The results shown in **Table 6** are for California. This version of the MA3T inputs resulted in significant sales of fuel cell powered vehicles, but nearly all those vehicles were FC-PHEVs. The results in **Table 6** indicate a very rapid increase in market share for BEVs up to 2030 and a slower decrease in BEV market share as the PHEV and FC-PHEV market shares increase in later years beyond 2030. This trend is consistent with the results shown in **Table 5**.

Table 6. MA3T LDV results for California.

Year	Total sales (k)	% BEV	%FC-PHEV	%PHEV	Total % ZEV
2020	784	5	0	2	7
2025	472	45	1	2	48
2030	970	70	5.5	8	83
2035	1292	62	11	17	90
2040	1481	50	17	27	94
2045	1662	41	20	34	95
2050	1937	39	20	38	97

The UC Davis PPA model was run for the scenarios described in **Table 2**. The PPA results are assumed to apply to California with the LDV incentives available in 2022 in effect until 2032. Market share results were obtained for a series of vehicle types from compact cars to mid-size SUVs. Those results have been discussed in Section 4 of the report. In this section, average market shares for LDVs were calculated for comparison with the MA3T results. The PPA results for the base case are shown in **Table 7** for 2020-2040. The base case uses the base costs for the batteries and fuel cells and infrastructure for both battery charging and hydrogen refueling that is likely to exist without intense California and federal intervention. The results shown in **Table 7** indicate that the market shares of battery-electric plug-in vehicles are projected to increase steadily in future years reaching 82 % in 2040. In the base case, the development of the market for fuel cell vehicles does not occur until late in the 2030s. This is consistent with the projections obtained with MA3T. The base case results for California (**Table 7**) indicate a faster growth of market share for plug-in vehicles than projected by Oak Ridge Lab in **Table 5** for the United States. This is not surprising when one considers the focus on BEVs in California compared to most other states.

The MA3T results (**Table 5**) for California indicate a rapid growth of BEV market share similar to the PPA results in **Table 7**. The MA3T results consistently show a higher market share for PHEVs than in the PPA results. The reason for this difference should be investigated.

Table 7. LDV Base Scenario S_{121} with incentives to 2032.

Year	%BEV	%FC-HEV	%FCPHEV	%PHEV	%total ZEV
2020	7.6	0	0	2.0	9.6
2024	17.9	0	0	3.3	21.2
2028	38.4	0	0	5.1	43.5

2032	56.5	0	0	6.6	63.1
2036	73.6	0	0.4	7.4	81
2040	75.5	7.3	10.4	6.8	82.3

Table 8-**Table 10** show results from the PPA model for Scenarios S2, S3, and S4. In these scenarios, the infrastructure for battery charging and hydrogen refueling are expanded to be closer to that available for refueling gasoline ICE vehicles than in the base model (S1). In scenario S2, the battery charging infrastructure is improved and in scenario S3, the hydrogen infrastructure is improved. In scenario S4, both infrastructures are reasonably close to that for gasoline fueled vehicles. The model results indicate that large increases in market share for fuel cell vehicles will not occur until the late 2030s even with improved hydrogen infrastructure. The primary reason for this is that the development of the technologies and markets for BEVs is about 10 years ahead of that for hydrogen fuel cell vehicles. In the long term, the model results indicate that the market share for FCVs will be significant for LDVs.

Table 8. LDV Scenario S2 with incentives to 2032.

Year	%BEV	%FC-HEV	%FCPHEV	%PHEV	%total ZEV
2020	7.6	0	0	2.1	9.7
2024	19.4	0	0	5.0	24.4
2028	41.6	0	0	5.3	46.9
2032	66.6	0	0	6.8	73.4
2036	84.6	0.7	1.8	7.4	94.5
2040	78.2	6.4	9.3	6.1	100

Table 9. LDV Scenario S3 with incentives to 2032.

Year	%BEV	%FC-HEV	%FCPHEV	%PHEV	%total ZEV
2020	7.6	0	0	2.1	9.7
2024	18.0	0	0	3.3	21.3
2028	36.6	0	0	5.3	41.9
2032	56.9	.7	0.5	6.5	64.6
2036	69.6	10.1	6.7	7.0	93.3

2040	53.7	25.4	16.0	4.8	100

Table 10. LDV Scenario S4 with incentives to 2032.

Year	% BEV	%FC-HEV	%FCPHEV	%PHEV	% total ZEV
2020	8.1	0	0	2.1	10.3
2024	21.3	0	0	3.4	24.7
2028	44.1	0	0	5.3	49.4
2032	69	0.9	0.4	6.8	77.1
2036	75.5	11.8	6.3	6.3	100
2040	54.7	26.9	14.2	4.2	100

The CARB proposed annual requirements for sales of LDVs are shown in **Figure 19**. The PPA projections for scenario S4 is close to the CARB requirements.

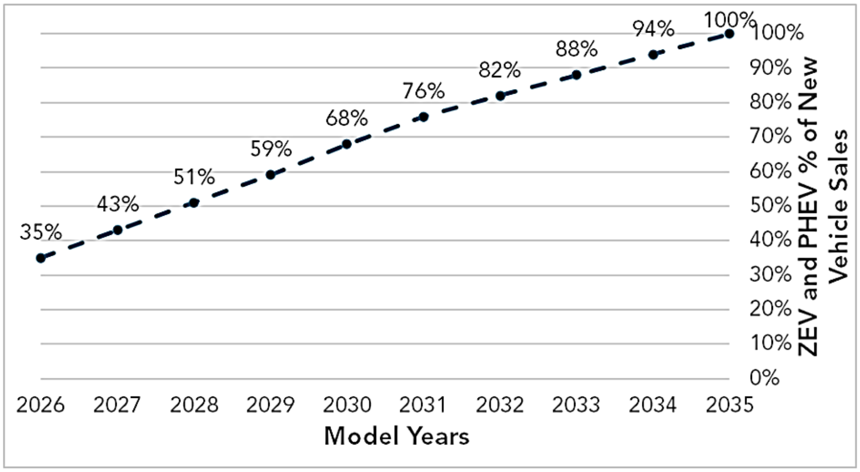


Figure 18. CARB proposed annual ZEV requirements for LDVs [18].

5.2. Comparisons of vehicle choice model results for MD/HDVs

The UC Davis PPA results for medium and heavy-duty trucks will be compared with those obtained at NREL using the TEMPO program [14]. The NREL study scrutinizes an array of vehicle classes, coupled with their respective applications and driving ranges, with a spotlight on three unique categories. They assume that these vehicles often employ central refueling strategies, thereby mitigating potential infrastructural challenges.

Comparison of the NREL and UC Davis results for the ZEV trucks is more difficult than the previous comparisons for LDVs because the refueling considerations for trucks are more complicated. NREL assumes the refueling (battery charging and H2 refilling) will be done at public infrastructure with assumed cost of ownership penalties for the time to refuel. In the UC Davis study, it was assumed that fleets would have refueling capability at private terminals except for long haul trucks that would refuel at truck stops along the highways. The cost of the terminal facilities would be covered by the fleets. For both NREL and UCD, the ultimate goal for the infrastructure for the ZEV trucks is a convenience approaching that of refueling diesel trucks. Convenient, cost effective refueling is key to the development of ZEV truck markets. For trucks, refueling is done daily and it affects directly the economics of truck operation. NREL discusses in detail cost parity between the ZEV trucks and comparable diesel trucks and finds that in most cases parity is reached by 2030-2035 or even sooner for light-medium trucks. This assumes that adequate ZEV models for sale will appear on the market and that the proper infrastructure for both battery-electric and fuel cell trucks will be established by 2030. In the UC Davis vehicle choice modeling, we attempt to assess the probabilities for the various decision factors for truck purchasing that include TCO and infrastructure considerations.

In their papers, NREL gives average market shares for trucks in general for 2030, 2040, and 2050. As indicated in Section 4 of this report, UCD shows market share results for different truck types from Class 2b-8. Hence the truck comparisons will be made on an average truck basis and for the later years -2030 and beyond.

The key issues are how soon will the truck manufacturers produce enough ZEV models at prices close to diesel equivalents including incentives available in California and when can the high-power electrical connections required to charge truck batteries be installed at truck fleet terminals by electric utilities. It seems likely that fuel cell powered trucks at reasonable cost and hydrogen refueling stations dispensing H2 at $5-6/kgH2 will not be available until after 2030.

The NREL results for ZEV heavy trucks are summarized in **Table 11** and **Figure 20**. The higher market shares in the central case are due to the lower costs and higher fuel economy assumed for the advanced vehicles. The assumed increase in the fuel economies of the ZEVs in the NREL study for 2020-2050 were significantly larger than assumed in the UCD study. The conservative costs of the battery-electric truck were higher than assumed in our study.

Table 11. Summary of NREL vehicle choice results for ZEV MD/HD trucks [14].

	Central (base)		Conservative	
Year	**BEV %**	**FC %**	**BEV %**	**FC %**
2030	40	2	7	0
2040	77	21	35	10
2050	83	17	49	22

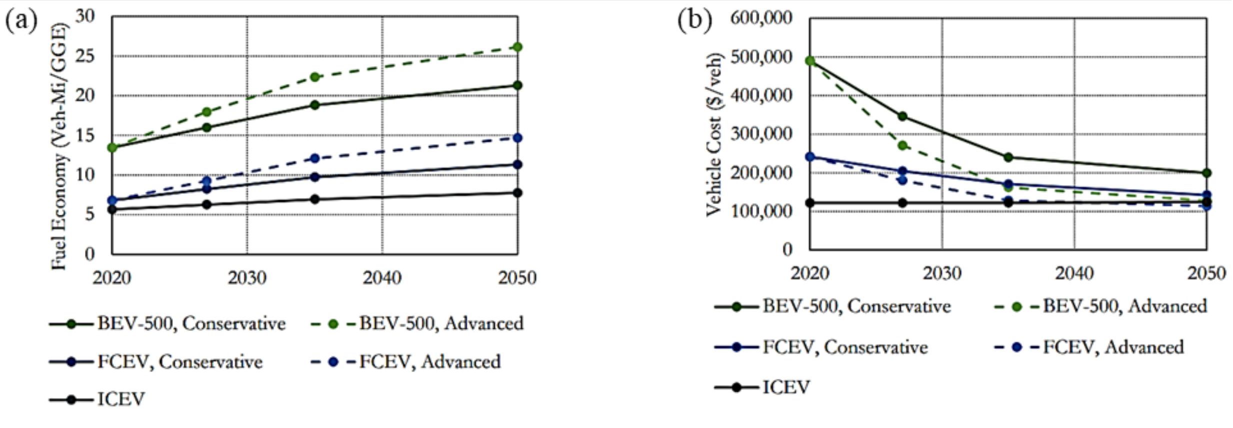


Figure 19. Summary of vehicle inputs for NREL heavy truck vehicle choice analysis [14]. (a) Vehicle fuel economy (miles/gasoline gallon equivalent). (b) Vehicle cost ($/vehicle).

UCD/PPA results for several scenarios are shown in **Table 12**-**Table 15**. The base scenario for MD/HD trucks is S_{121} shown in **Table 12**. It uses the base costs of batteries and fuel cells and relatively expensive terminal facilities for charging batteries and refueling fuel cell vehicles. This scenario does not show significant ZEV sales until after 2030. The results for scenario S_{221} are shown in **Table 13**. This scenario also uses the base battery and fuel costs, but it includes lower cost and more developed terminal facilities for charging batteries than in the base scenario S_{121}. This results in higher market shares for the ZEVs than in the base scenario S_{121}.

Table 12. PPA base Scenario S_{121} for MD/HDVs.

Year	%BEV	%FC-HEV	%ICE
2020	0.4	0	100
2024	2.1	0	97.9
2028	7.8	0.7	91.5
2032	19.4	3.5	77.1
2036	38.5	12.1	49.4
2040	62.0	28.2	9.8

Table 13. PPA scenario S_{221} with enhanced battery charging.

Year	%BEV	%FC-HEV	%ICE
2020	0.43	0	100
2024	4.4	0	95.6
2028	17.8	0.8	81.4
2032	42.5	3.6	53.9
2036	75.7	12.2	12.1
2040	78.9	21.1	0

The PPA results for scenario S4 are shown in **Table 14** and **Table 15**. This scenario uses low-cost batteries and fuel cells and enhanced terminal facilities for both battery charging and hydrogen refueling of the ZEV trucks. As shown in **Figure 21**. the results for the market shares for BEVs and FCVs are close to the CARB fleet milestones [3].

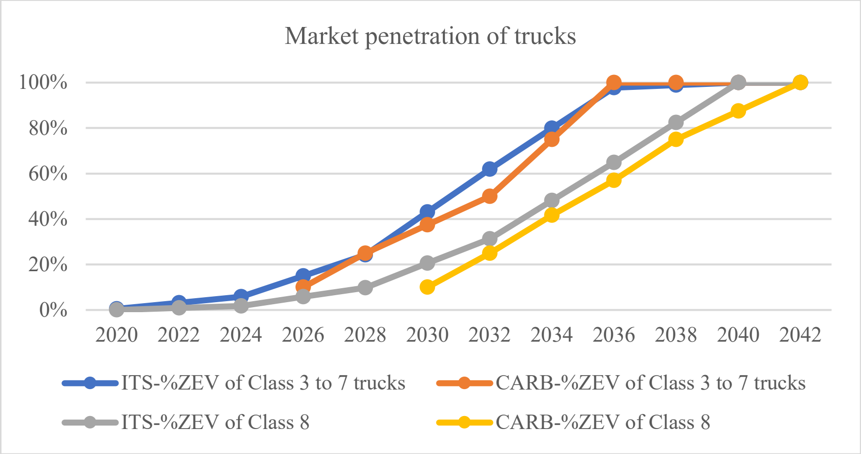


Figure 20. Comparison of PPA projected ZEV market shares with the CARB milestones for ZEV trucks of various classes.

Table 14. PPA scenario S_{432} results for Class 3-7 trucks with enhanced terminal facilities for both battery charging and hydrogen refueling.

Year	**%BEV**	**%FC-HEV**	**%ICE**
2020	0.5	0	100
2024	5.6	0.2	94.2
2028	21.5	2.7	75.8
2032	50.2	11.7	38.1
2036	70.5	27.3	2.2
2040	64.7	35.3	0

Table 15. PPA S_{432} results for Class 8 trucks.

Year	%BEV	%FC-HEV	%ICE
2020	0.6	0	100
2024	1.8	0	98.2
2028	7.9	1.9	90.2
2032	21.8	9.3	68.9
2036	39.3	25.6	35.1
2040	54.9	45.1	0

The UCD PPA results for 2030 and 2040 are in reasonable agreement with the central case of the NREL results. The conservative NREL results show lower market shares than even the UCD base case S_{121} (**Table 12**). Both the NREL and UCD studies indicate that after 2030, both battery-electric and fuel cell can have relatively high market shares.

6. Summary and conclusions

To support the transition to ZEVs, California has long been investing in a wide range of initiatives, including incentives for ZEV purchases, expanding battery charging and hydrogen refueling infrastructure, and promoting public awareness of the benefits of ZEVs. California has mandated that fossil fueled, engine powered vehicles cannot be sold in the state after 2036 and all vehicles available for sale at that time must be ZEVs. The research discussed in this report considers the decision factors used by purchasers of cars and trucks and how they apply to purchases of ZEVs. A new vehicle choice method of analysis-PPA was developed to project the market shares of ZEVs as the vehicle and infrastructure technologies mature in 2020-2040. The new approach was applied to light-duty vehicles and medium/heavy duty trucks. Market share results are presented for a number of scenarios for different vehicle and infrastructure development strategies. The results are compared with those using other approaches for vehicle choice analysis and with CARB targets for ZEV market development.

The PPA results presented in this report apply to California and not the United States as a whole. The assumptions made regarding infrastructure development and state policy apply to California. The assumptions regarding ZEV vehicle development and costs are global in scope. For both LDV and MD/HDVs, the PPA results indicate relatively high market shares for battery-electric plug-in vehicles of various sizes and classes by 2030. Significant market shares for hydrogen fuel cell vehicles are not projected until the mid-2030s. In general, the PPA results indicate that with aggressive efforts to establish infrastructure for battery charging and hydrogen refueling, the CARB ZEV mandates/requirements for both LDVs and MD/HDVs can be met in some scenarios analyzed.

Comparisons of the PPA projections with those from DOE Labs (Oak Ridge, Argonne, and NREL) indicate reasonable agreement for comparable scenarios. In the case of light-duty vehicles, UC Davis is more optimistic concerning the development of markets for hydrogen fuel cell vehicles, even in California, than Oak Ridge Lab as indicated by their MA3T results. Fuel cell development in trucks is expected earlier than in LDV by both UC Davis and the DOE National Labs.

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Appendices

8. Appendix A: Definition and importance of decision factors

General comments

The purchase probabilities are analyzed in terms of sixteen decision factors. The influence of each decision factor is described in terms of a base value (bv), an input value (inpv), and an importance value (a). These quantities are used to calculate the P_r for each decision factor

$$\mathrm{Pr} = e^{a(1-1/x)} \tag{1}$$

x= inpv/bv is the measure of the status of the vehicle being analyzed compared to the comparable ICE vehicle. The ratio is selected such that x<1 for the early years and might increase to >1 in later years as inpv changes. x and P_r are calculated from the input values of bv, inpv, and "a" by the EXCEL spreadsheet program for each decision factor as discussed in the following sections.

8.1. Vehicle cost

The purchase cost of each vehicle included in the analysis has been calculated in [7][8].

$$\text{Vehicle\_cost} = \text{Glider cost} + \text{cost of the powertrain and energy storage components} \tag{2}$$

The glider cost was determined by subtracting the ICE cost from the cost of the ICE vehicle. The powertrain and energy storage and conversion components were sized to achieve the desired acceleration and range for each vehicle type and ZEV option -BEV, FCV, and PHEV. The cost of each component was calculated based on its size and unit cost. For example, battery cost = (kWh)x($/kWh), fuel cell cost = (kW)x($/kW), electric motor cost = (kW)x($/kW), hydrogen storage unit cost= (kgH2)x($/kgH2). The unit costs of the electric drive, batteries, and fuel cells were reduced systematically from 2020-2040 to reflect maturing of the technologies. The cost of integrating the various components into the driveline was done by multiplying the cost of the component by a factor (1+Δ). Δ was decreased as the technologies matured. The details of all these vehicle cost calculations are given in [7][8] and in Appendix **B** for the costs of batteries and fuel cells.

For the vehicle cost decision factor,

$$x = \text{veh cost ICE/veh cost ZEV} \tag{3}$$

The base vehicle cost bv is in all cases the cost of the comparable ICE vehicle. Selecting an appropriate" a" value for the vehicle cost factor is important especially in the early years before 2030 when the cost of ZEVs can be relatively high. "a" between 1-3 seems like a reasonable choice.

Costs of ZEV LDVs

The UCD projected costs of BEVs and FCVs for 2020-2040 [7][8] are compared with the corresponding costs published by Oak Ridge National Laboratory (ORNL) [13],[15] and DOE Argonne National Laboratory (ANL) [26] and ICCT [27] in **Table A1(a-e)**. Vehicle costs are shown for various powertrain types, including BEV-300, FC-HEV, and PHEV-40. In the case of BEV and PHEV, the projected UCD costs are somewhat lower than those of both ANL and ORL for the next two decades (2020 to 2040). However, for FC-HEV, our costs are higher than both ANL and ORL values in the 2020s, but they converge and become similar as we approach 2040. The UCD projections exhibit a larger, steady decrease in ZEV costs up to 2030 and beyond. The ANL approach [26] to estimating future costs involves calculating the manufacturing cost of the ZEV and then applying an assumed markup factor to determine the purchase price of the vehicle. On the other hand, in the UCD analysis of ZEV cost analysis, it was assumed that all component costs (batteries, fuel cell, and electric driveline) were retail costs with no markup applied. As shown in **Table A1a-e**, these different approaches result in similar but somewhat different cost values.

Table A1a. Comparison of ORNL [15] and UCD [8] cost inputs for mid-size cars for 2025-2040.

Powertrain technology	Source	2025	2030	2040	Markup
Conventional	ORNL	$26,068	$26,320	$26,403	1.6
	UCD	$26,500	$26,500	$26,500	
EV-200 miles	ORNL	$37,169	$32,443	$30,181	1.7-1.64
	UCD	$28,647	$25,046	$23,250	
EV-300 miles	ORNL	$44,248	$36,934	$33,214	1.7-1.68
	UCD	$31,700	$26,800	$24,300	
FC-400 miles	ORNL	$34,860	$33,800	$31,660	1.42-1.53
	UCD	$53,700	$42,500	$36,200	
PHEV-40 miles	ORNL	$39,238	$33,898	$33,214	1.6
	UCD	$32,300	$30,000	$28,500	

Table A1b. Summary of ZEV cost projections from UCD, ANL [26], and ICCT [27] for mid-size passenger car.

Mid-size passenger car (k$)	EV - 300 mi.			PHEV - 40 mi.		
Year	UCD	ANL	ICCT	UCD	ANL	ICCT
2022	34	47	39	34	42	39
2025	32	42	35	32	40	36
2030	27	35	28	30	34	34
2035	25	33	26	29	33	34

Table A1c. Summary of ZEV cost projections from UCD, ANL [26], and ICCT [27] for small SUV.

Crossover LDV/small SUV (k$)	**EV - 300 mi.**			**PHEV - 40 mi.**		
Year	UCD	ANL	ICCT	UCD	ANL	ICCT
2022	38	47	42	38	43	38
2025	35	42	36	35	39	34
2030	29	35	31	29	34	32
2035	27	34	28	27	33	31

Table A1d. Summary of ZEV cost projections from UCD, ANL [26], and ICCT [27] for mid-SUV.

Sport Utility/mid-SUV (k$)	EV - 300 mi.			PHEV - 40 mi.		
Year	UCD	ANL	ICCT	UCD	ANL	ICCT
2022	47	58	60	44	45	58
2025	43	49	52	43	42	56
2030	37	41	41	41	36	54
2035	35	40	40	40	35	52

Table A1e. Summary of ZEV cost projections from UCD, ANL [26], and ICCT [27] for LD pickup truck.

LD pickup truck (k$)	EV - 300 mi.			PHEV - 40 mi.		
Year	UCD	ANL	ICCT	UCD	ANL	ICCT
2022	49	68	58	45	50	54
2025	45	58	52	44	46	52
2030	38	47	44	40	39	50
2035	36	46	42	39	37	48

All-electric or hydrogen range (mi)

The range of a battery-electric vehicle is determined primarily by the size (kWh) of the battery in the vehicle. Range was a key factor in the cost of EVs when batteries cost $200-300/kwh and higher, but now that battery costs are much lower the effect of range on EV cost is of less concern. Electric LDV vehicles with ranges of 300-400 miles are on the market. For this study, 300 miles has been selected as the base range for the BEVs. This is significantly less than that of ICE vehicles and the battery charging time is relatively long even at fast chargers, but EV sales indicate that 300 miles seems to be acceptable to many buyers. Our EV cost studies indicate that 300 miles permits cost equity with ICE vehicles by 2030.

The range of a fuel cell vehicle depends primarily on the kgH2 stored onboard the vehicle. Hydrogen storage limits are set by the volume available for the H2 storage tanks. Hydrogen storage is expensive, but not nearly as expensive as for electricity in batteries. Fuel cell passenger cars on the market currently have ranges of 300-400 miles. The hydrogen refilling time for fuel cell vehicles is comparable to that of ICE vehicles. 400 miles has been selected for the base range of the light-duty fuel cell vehicles in this study. That range should result in near equity in fuel cell vehicle costs with ICE vehicles in 2030 and beyond as fuel cell technology matures.

For the range decision factor, x =range ZEV/range ICE, where Range ICE = 500 miles, Range BEV = 300 miles, range FC = 400 miles. An "a" value of 1-2 seems appropriate as the ZEV ranges are not an important issue for class 3-7 at the present time. Range is a key issue for long haul trucks that need ranges over 300 miles.

8.2. Number of ZEV models available to purchase

In the early years, the small number of ZEV models available to purchase is an important issue. At the present time, there seems no doubt that auto industry will rapidly provide many new models of BEVs. However, there are only a few FCV models on the market and the present prospects for many more in the near future are not promising. Setting the input values for the model decision factor is difficult. The approach taken in this study was to set an arbitrary number like 50 or 100 for the base number for ICE vehicles and then to think in terms of the fraction of the base value for the input value for the ZEV vehicle options. In the case of BEVs, the model number is getting relatively large, approaching the base, while for FCVs the model number is a small fraction of the base number. For the model number decision factor, x = number of ZEV models/base number of modeled needed.

8.3. Inconvenience to charge or refuel ZEVs in the city compared to ICEV

This decision factor is concerned with refueling ZEVs for short trips in the city and its influence on the purchase decision. Refueling with electricity is basically different than with hydrogen so battery-electric and hydrogen fuel cell vehicles will be considered separately.

8.3.1. Battery-electric vehicles

BEVs used by people living in single-family homes can be charged conveniently over-night at home. Hence, a significant fraction (50-75%) of the early EV users have home charging. People without home charging will have to depend on public charging facilities. For these people, they will need chargers relatively close to their homes for convenient charging of their BEV. The question of proper city infrastructure for BEVs deals with how many public fast chargers are needed so those without home charging can conveniently charge their vehicles. The question is further complicated because it is expected that those with home charging will occasionally need to use public chargers.

All the chargers are 300 kW with 2-plugs capable of charging the vehicles in 20 minutes or less. The goal of the battery charging infrastructure is to make battery charging as convenient as possible compared to refilling a vehicle with gasoline. There are about 8000 gasoline stations with an average of 8 pumps in California to refill about 25 million vehicles. Hence, it is assumed that the number of chargers needed is

$$\text{Number chargers} = 8 \text{ x } 8 \text{ x } 8.3\text{x}.5\ 10^3 / 25 \text{ million BEVs} \qquad (4)$$

to match gasoline refilling convenience. The ‘8.3 factor” is to account for the time it takes to charge the battery and the more times the battery is charged compared to refueling the ICE vehicle. The number of chargers needed for 1 and 5 million BEVs are shown below.

$$1 \text{ million BEVs No. of chargers}=8 \text{ x}8\text{x}8.3 \text{ x } 0.5\text{x } 1/25 \text{ x } 10^3 = 10624 \qquad (5)$$

$$5 \text{ million BEVs No. of chargers}=8 \text{ x}8\text{x}8.3 \text{ x } 0.5\text{x } 5/25 \text{ x } 10^3 = 53120 \qquad (6)$$

We need to account for home charging in the formula for “x”.

$$x = x_{home} + \text{number chgr/base chgr}, \quad x_{home} = 0.4 \qquad (7)$$

It also seems reasonable to pre-build about 10 % of the total chargers needed by 2022. The change in number of chargers available in 2020-2040 depends on the strategy in building the charger infrastructure. The base value depends on the number of BEVs expected to be on the road in 2040.

8.3.2. Hydrogen stations for FCVs

Hydrogen stations are needed to refuel all the FC vehicles on the road. The typical mid-size FCV will use about 168 kgH2/yr. so the H2 demand at the stations will be 168 million kgH2/yr./million vehicles. If the average H2 station dispenses 1000 kg/day with a utilization factor of 0.5, the number of H2 stations needed for 1 million FC vehicles will be the following.

$$\text{Number of 1000 kgH2/da sta.} = 168 \text{ x } 10^6 / (365\text{x}1000 \text{ x } 0.5) = 920 \qquad (8)$$

We could have fewer stations if they are larger, or we assume a higher utilization factor say 0.7. The California Partnership is projecting 1000 H2 stations and 1 million FC vehicles for 2030 [19].

Assuming each refilling is 5 kg, that is 34 refilling per year. The base values for H2 stations is then

$$\text{1 million FCVs 920 sta. 2-3 dispensers} \tag{9}$$

$$\text{5 million FCVs 4600 sta. 2-3 dispensers} \tag{10}$$

For the H2 stations,

$$x = \text{number of H2 stations/ base value for stations} \tag{11}$$

We need to pre-build 10% of the total stations needed in 2030.

8.4. Inconvenience to charge or refuel ZEV on the highway compared to ICEV

All BEV owners will need public chargers for long trip travel beyond the range of their vehicle. This will require the availability of fast chargers at which they can get a significant charge (at least 65% of battery kWh capacity in 20 minutes or less). The FCV owners will need hydrogen stations located along highways much like present gasoline stations as the hydrogen refueling times are comparable. The charger and H2 station projections made in the previous section for decision factor 4 include satisfying refuel needs for long trips. The “x” values will be determined using the same formula as for short trips.

8.5. Battery charging or hydrogen refueling time (minutes) compared to the ICEV

As noted previously, the charging times of BEVs at public chargers will be much longer than for refueling hydrogen fuel cell vehicles at public H2 stations. This difference will be included in the calculation of “x” and P_r for the BEV and FCVs. At the present time (2022), the minimum time for fast charging batteries is 30-40 minutes with the charge (kWh) added being 65% or less of the battery kWh capacity. In the future with improvements in battery technology, it seems likely that the minimum fast charging time will be reduced to 15 minutes or less. Hence the base value for fast charging BEVs is set at 15 minutes and the input value will be decreased from 40 to 15 minutes from 2020-2040. Hence

$$x = \text{input min cgh time/15 for BEVs} \tag{12}$$

In the case of FCVs, it is assumed the refill time with H2 will be essentially the same as with gasoline in ICEV2. Hence, x=1 for all FCV using hydrogen.

8.6. Availability of a second market for ZEVs compared to ICEVs

The availability of a second market for ZEVs is critical to the development of the mass market for them. There seems little doubt that a second market similar to that available for ICE vehicles will develop as their market fraction and number of ZEVs on the road increases in the future. It will take time for the second market to develop. This is included in the probability calculations by gradually increasing the x value of decision factor 7 over the time period 2020-2040.

8.7. Maintenance cost ($/mi) of ZEVs compared to ICEVs

The maintenance cost was included in the economic analysis of the ZEVs in [7][8]. The maintenance values are based on and given as $/mi. For each type of vehicle, the maintenance value is calculated by dividing the annual maintenance cost by the annual mileage. The base value is the maintenance cost of the ICE vehicle [20]-[22]. The x values of maintenance of the ZEVs are assumed to decrease in future years as the technologies mature. Hence,

$$x = (\$/\mathrm{mi})_{\mathrm{ZEV}} / (\$/\mathrm{mi})_{\mathrm{ICEV}} \qquad (13)$$

for both BEVs and FCVs.

8.8. Energy operating cost ($/mi) of ZEVs compared to ICEVs

The energy operating cost was calculated in the economic analysis of the ZEVs in [7][8]. The energy cost values ($/mi) are based on the energy used per mi (kWh/mi or kgH2/mi) and the cost of energy ($/kWh or $/kgH2). The energy cost values decrease in future years for all the vehicles as the technologies mature (energy/mi decreases) and the price of energy, especially hydrogen, is reduced.

The base value is the energy cost ($/mi) of the ICE vehicle The value of x for energy use is given by

$$x = (\$/\mathrm{mi})_{\mathrm{ICE}} / (\$/\mathrm{mi})_{\mathrm{ZEV}} \qquad (14)$$

for both BEVs and FCVs. x in the early years is less than 1, but later years x can be significantly greater than 1. In this case, the value P_r is also greater than 1 and decision factor 9 can have a big effect on the average purchase probability of the vehicle.

8.9. Environmental concern of ZEV buyers compared to ICEV buyers

The regulated and GHG emissions of ZEVs are very low, essentially zero. To some potential vehicle purchasers, the reduced environmental/climate change impact of ZEVs is very important. In that case, the value of x for ZEVs and the resultant probability would be greater than 1. It is assumed that x>1 for all ZEVs and years and that it increases from 2020-2040 as the general public gains a greater understanding of climate change and the need to reduce GHG emissions. The base value is 1 for all vehicles. x <1 for any vehicle with an ICE even PHEVs. x is defined as

$$x = (\text{envir concern})_{\mathrm{ZEV}} / (\text{envir concern})_{\text{ICE base}} \qquad (15)$$

Setting values for this decision factor is subjective, but important nevertheless.

8.10. Safety concerns for ZEVs compared to ICEVs

There are safety concerns about both batteries [23] and hydrogen [24]. In the case of batteries, there are concerns about battery fires and explosions resulting from thermal runway of one or more cells in the battery pack. Such occurrences have been relatively rare, but they can be a concern for some vehicle buyers. In the case of fuel cell vehicles, the use of hydrogen as the fuel brings to mind the Hindenburg airship accident in 1937 [25]. There is no doubt that H2 must be handled with much care to prevent fires and explosions, but over the years, hydrogen has been handled safely in many industrial applications. These applications include considerable safe experience with fuel cell vehicles in both the past and present. Gasoline is a flammable fuel and fires in **gasoline** fueled vehicles occur with relative rarity. Safety is a critical factor in the development of both battery and fuel cell systems. It seems clear we can assume both the ZEVs will be safe now and increasingly safe in the future. Hence x_{11} will be close to 1 in all cases.

8.11. Drivability of ZEVs compared to ICEVs

One of the key advantages of ZEVs compared to engine/transmission powered ICE vehicles is their excellent performance and drivability. ZEVs have fast, smooth acceleration and very quiet operation. The electric driveline has very fast response and high efficiency. After a demonstration drive in a BEV, people express how impressed they are with its drivability. They always rate the drivability of the BEV much superior to the ICEV they customarily drive. The "x" value for this decision factor is defined as

$$x_{12} = (\text{drivability})_{ZEV} / (\text{drivability})_{ICEV} \qquad (16)$$

"x" will be >1 in all cases for ZEVs. In later years, "x" for the ICEV will be <1 as people's drivability expectations become closer to that of BEVs.

8.12. Reliability/durability of ZEVs compared to ICEVs

Purchasers of ZEVs will be concerned about the reliability/durability of their vehicles using new technologies. They will want their ZEVs to have reliability/durability comparable to the ICEVs. That is not likely to be the case in the early years, but as the technologies mature, it will be true in later years. The "x" values used in the probability tables for the ZEVs will reflect their improved durability in future years. x will be <1 in the early years and should approach 1 in the later years. This certainly the case for first car buyers, but the long-term durability for both batteries and fuel cells is still uncertain. The x for durability is defined as

$$x_{13} = (\text{Veh dur})_{Zev} / (\text{veh dur})_{ICEV} \qquad (17)$$

8.13. Excitement with new technology

In the early years, excitement with the new technology of electric drive and fuel cells can be an important consideration in the decision to purchase a ZEV. This factor will not be important to all potential vehicle buyers, but to some it could be very important. ICEVs are an old technology, and the public seems ready for a new one. The "x" value is defined as

$$x_{14} = (\text{excitement})_{ZEV} / (\text{excitement})_{ICEV} \qquad (18)$$

"x" is >1 in all cases for ZEVs. "x" for ICEVs will be <1 in later years.

8.14.TCO (Total Cost of Ownership $/mi) of ZEVs compared to ICEVs

This decision factor is used only for the trucks. Some truck fleets use TCO as an important decision factor in purchasing trucks. TCO was calculated in the UCD study of the economics of ZEV trucks [7]. TCO is expressed in terms of $/mi over a stated number of years. TCO was calculated for 5 and 15 years. In this study, the time period is 5 years. The results for TCO for 15 years is slightly lower values than for 5 years, but the trends for ZEVs compared to ICEVs will be the same.

The TCO depends on the vehicle depreciation, maintenance, and energy use costs and the annual mileage of the vehicle. The battery and fuel cell costs assumed in that study to calculate vehicle costs are given in Appendix B. For LDVs. it was assumed the BEVs had 50% the maintenance of the ICEVs and fuel cell trucks had 75%. In the case of trucks, the maintenance savings are less than for LDVs being 30% for battery-electric and 25% for fuel cell trucks. The energy costs depend on the kWh/mi and kgH2/mi and the cost of electricity and hydrogen. The TCO of fuel cell vehicles is highly dependent on the price ($/kgH2) of hydrogen. Hydrogen prices of $5-6/kg are needed to make fuel cell vehicles competitive with ICEVs in $/mi. For all vehicle types, the value of “x” is defined as

$$x = (TCO)_{ICEV} / (TCO)_{ZEV} \qquad (19)$$

“x” is < 1 in the early years and becomes >1 in the later years. The BEVs have a larger advantage (lower) in TCO in later years than the fuel cell vehicles relative to ICEVs. The same is true for vehicle maintenance. As a result, the x value and P_r for the TCO decision factor is higher for the battery- electric trucks is higher than for the fuel cell trucks.

8.15.Cost of a terminal ($/vehicle) to provide for refueling ZEVs trucks compared to ICEVs

Unlike LDVs that are fueled at home or at public stations, most ZEV trucks will be fueled over-night at private terminals built and maintained by fleets. The battery-electric trucks will utilize battery chargers that can charge the batteries in 2-3 hours. Battery charging at the terminals will not be fast charging as the fleets want to achieve a complete charge of the batteries to maximize useable range of their BEVs. Hydrogen refueling of fuel cell trucks will be done at stations similar to the public H2 refueling stations except that they will likely to be designed to refill the trucks in 30 to 60 minutes rather the fast refill in 5-10 minutes at the public hydrogen. The slow over-night refilling of H2 permits the cost of the private station on a $/kgH2 basis to be significantly lower than the fast fill public H2 stations.

An issue of concern to fleets is how the refueling station costs will be different for battery-electric and fuel cell trucks and how those costs will vary with the number of trucks in the fleet. The cost of the terminal can be given as $k/vehicle it can refuel. The results of the UCD study indicate that the cost of terminals to charge batteries is straight-forward and depends on the kWh of the battery pack and the cost of the chargers. To charge a 142 kWh battery from a Class 3 truck in 2 hours is $18k/vehicle and for a 378-kWh battery in a Class 8 truck, the cost is about $45k/vehicle for terminals of 8 trucks and larger. The cost is nearly linear ($120/veh/ kWh) for a kWh battery.

Determining the cost of hydrogen refilling terminals is not so straight-forward. For stations larger than 5 trucks, the H2 station cost decreases steadily with station capacity. In the case of the Class 3 fuel cell truck the cost is $73k/vehicle for 5 vehicles and $8k/vehicle for a 62-truck terminal. For the Class 8 truck, the cost is $102k/vehicle for 5 trucks and $11k/vehicle for 62 trucks. The cost per truck is about the same for battery charging and hydrogen refilling for 20 truck terminals for the Class 3 truck ($18k/vehicle) and 15 trucks for the Class 8 truck ($36k/vehicle). As expected, the terminal cost for large fleets will be lower for fuel cell trucks than for battery-electric trucks.

It is difficult to define "x" for the terminal cost as they depend on battery kWh, truck kgH2, and the terminal capacity. The cost of the battery charging facility depends primarily on charger installed cost ($/kW) and that of the H2 station on the installed cost of H2 refilling components ($/kgH2/da) for a refill time of 30-45 minutes. The terminal costs for the ZEV stations will be normalized by the cost of a corresponding station to refuel diesel trucks. x is defined as

$$x = \text{cost of diesel sta./ cost of the ZEV sta.} = \text{base/input} \tag{20}$$

$$\text{base} = 1,\ \text{input} = \text{cost of ZEV sta,/cost of diesel sta.} \tag{21}$$

In selecting the input values, it is recognized that the truck capacities of the terminals will increase in years 2020-2040 and the ZEV station costs per vehicle will decrease resulting in steadily decreasing input values for both BEVs and FCV. The cost of the ZEV stations at the terminals will be higher than the diesel refueling facilities in all cases, but the differences will become relatively small by 2040.

8.16.Penalty reduction

Penalty reduction is used as a special decision factor aimed at Class 8 long-haul trucks. In the short term, the payload ability of heavy-duty trucks may be relatively lower due to limitations in battery technology. In the long term, as technology progresses and the market matures, BEV trucks are poised to match or approach diesel trucks in terms of payload ability. Improvements in battery technology will enhance energy density and range, enabling BEV trucks to carry more goods and exhibit better performance and cost-effectiveness in long-haul transportation. The payload penalty reduction factor can be expressed by:

$$\text{weight penalty fraction} = (\text{battery weight-drlkgdif})/\text{payload} \tag{22}$$

$$\text{drlkgdif} = \text{engine} + \text{transmission driveline heavier than electric driveline} \tag{23}$$

9. Appendix B: Key input costs assumed in the ZEV cost calculations.

Some of the decision factors (especially the financial factors) are numerical in character and are based on economic evaluations of ZEVs [7],[8]. The results obtained from these evaluations are highly dependent on the inputs used in the economic analyzes of the vehicles. In this appendix, some of the most critical inputs are presented. These inputs include battery and fuel cell costs, hydrogen costs, and maintenance costs.

9.1. Battery and fuel cell costs

The cost of the BEVs is strongly affected by the cost ($/kWh) of the batteries. The costs ($/kWh) of the batteries assumed in the vehicle cost calculations for LDVs are given in **Table B1**. Three cost levels are given for each year-high, base, and low. The battery costs are assumed to decrease between 2020 and 2040 as the battery technology matures. The battery in each vehicle analyzed was sized based on its kWh/mi and design range. Hence the effect of battery cost on vehicle cost was greater for long range vehicles. An additional battery cost was included to account for integrating the battery into the vehicle's powertrain. As shown in **Table B2**, higher battery costs were assumed for trucks than LDVs.

Table B1: Battery pack costs for LDV in 2020-2040 (costs to OEMs).

Battery cost ($/kWh)	**2020**	**2025**	**2030**	**2035**	**2040**
- Hi cost case	180	140	110	90	70
- Base cost case	160	125	85	75	60
- Low cost case	140	100	75	60	50
Battery integration factor	1.2	1.15	1.11	1.05	1.05

Table B2: Battery pack costs for trucks in 2020-2040 (costs to OEMs).

Battery cost ($/kWh)	**2020**	**2025**	**2030**	**2035**	**2040**
- Hi cost case	250	200	125	100	75
- Base cost case	225	175	100	85	70
- Low cost case	200	150	75	70	65
Battery integration factor	1.6	1.5	1.4	1.35	1.3

The cost of the fuel cell vehicles is strongly affected by the cost ($/kW) of the fuel cells and hydrogen storage ($/kgH2) unit. The costs ($/kW) of the fuel cell system assumed in the vehicle cost calculations for LDVs are given in **Table B3**. Three cost levels are given for each year-high, base, and low. The fuel cell costs are assumed to decrease between 2020 and 2040 as the fuel cell technology matures. The cost of fuel cell vehicle can be strongly affected by the size kW of the fuel cell in high performance vehicles. The assumed costs ($/kgH2) of the energy storage unit are given in **Table B4**. The energy storage unit is sized (kgH2) by the kgH2/mi of the vehicle and its design range. The vehicle cost increases with the range of the fuel cell vehicle, but the effect is smaller than for batteries in BEVs. As for batteries, an additional cost was included to account for integrating the fuel cell system components into the vehicle's powertrain. As shown in **Table B5**, higher fuel cell costs were assumed for trucks than LDVs.

Table B3: Fuel cell costs for LDVs in 2020-2040.

HD $/kW	2020	2025	2030	2035	2040
High cost case	300	135	85	60	50
Base case	225	100	70	50	45
Low cost case	175	60	50	45	40
Fuel cell system integration factor	1.2	1.15	1.1	1.1	1.05

Table B4: Costs for hydrogen storage on the vehicle in 2020-2040.

Year	$/kgH2
2020	1400
2025	800
2030	400
2035	350
2040	300

Table B5: Fuel cell costs for trucks in 2020-2040.

HD $/kW	2020	2025	2030	2035	2040
High cost case	700	240	145	115	90
Base case	525	193	118	95	78
Low cost case	350	145	90	75	65
Fuel cell system integration factor	1.6	1.5	1.4	1.35	1.3

9.2. Vehicle maintenance

Calculation of the TCO values for the vehicles required inputs for their maintenance ($/mi). Information on maintenance especially for the ZEVs is difficult to find. The maintenance values used in this study are shown in **Table B6**.

Table B6: Maintenance cost inputs for LDVs and trucks.

LD Vehicle Types	EV $/mile	FCV $/mile	ICEV $/mi
Compact car	0.031	0.05	0.062
Mid-size car	0.031	0.05	0.062
Small SUV	0.031	0.05	0.062
Mid-size SUV	0.04	0.06	0.07
Large SUV	0.04	0.06	0.07
LD pickup	0.04	0.06	0.07
Trucks of various classes			
Class 3	0.16	0.19	0.2 to 0.33
Class 4	0.16	0.15	0.2 to 0.33
Class 5	0.16	0.15	0.2 to 0.33
Class 6	0.1	0.15	0.2 to 0.33
Class 7	0.1	0.15	0.2 to 0.33
Class 8	0.1	0.15	0.2 to 0.33

9.3. Cost of hydrogen

The energy cost ($/mi) to operate fuel cell vehicles depends on the cost of hydrogen ($/kgH2). The cost of H2 is presently very high, but it is expected to become much lower in the future. Projected hydrogen cost is given in **Table B7**. In the present study the base value of H2 was to calculate the TCO of the fuel cell vehicles.

Table B7: Hydrogen costs ($/kg) for fuel cell trucks produced from electrolysis.

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

9.4. Cost of refueling terminals for ZEV trucks

The battery-electric and fuel cell trucks are assumed to be refueled at their private terminals by the fleets. The cost of these terminals is a decision factor for the fleets as they decide whether to purchase BEVs or FCVs. The cost of the terminals can be given in terms of $/vehicle to be refueled. Results for refueling terminal cost are given in **Table B8** based on our recent analysis. These costs are used to estimate the terminal costs used in this study.

Table B8. Comparison of the costs of battery charging and H2 refueling for fleets of trucks.

Vehicle type	Number of vehicles	Battery charging (142 kWh)	Station cost (k$)	k$/vehicle
City delivery	4	2hr	102	25.5
	8	2hr	140	18
	16	2hr	280	17.5
	40	2hr	700	17.5
		H2 refueling (8 kg H2)		
	5	60 minutes	366	73
	10	60 minutes	366	37
	20	45 minutes	484	17
	30	30 minutes	421	13
	62	30 minutes	487	8
Short haul Class 8	5	2hr	190	38
	10	2 hr	381	38
	15	2hr	571	38
	30	2hr	1142	38
	62	2hr	2475	40
		H2 refueling (18.8 kgH2)		
	5	60 minutes	511	102
	10	60 minutes	511	51
	20	45 minutes	555	28
	30	30 minutes	640	21
	62	30 minutes	707	11

9.5. Financial incentives

9.5.1. Financial incentives for LDVs

The financial incentives from 2020 to 2032 will be based on the current policy, which includes CVCP and CVRP. The incentives for Plan 1 and 2 are shown in **Figure B1**. For Plan 2, from 2032 until 2040, the incentives will gradually decrease at a constant rate each year.

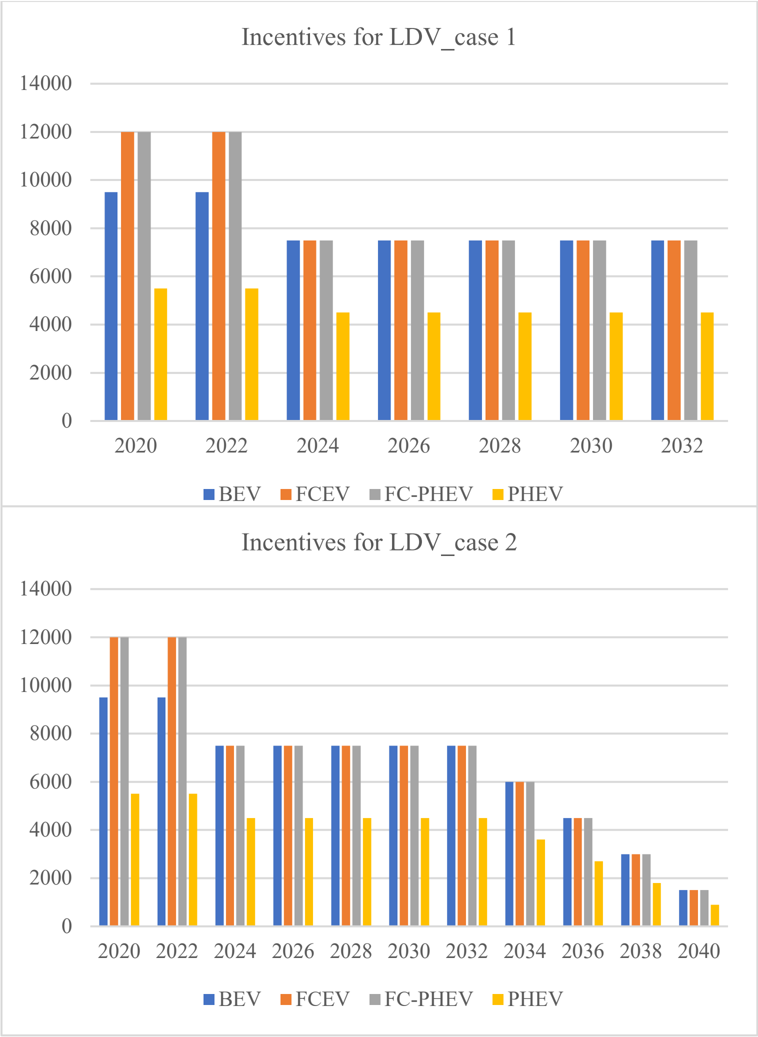
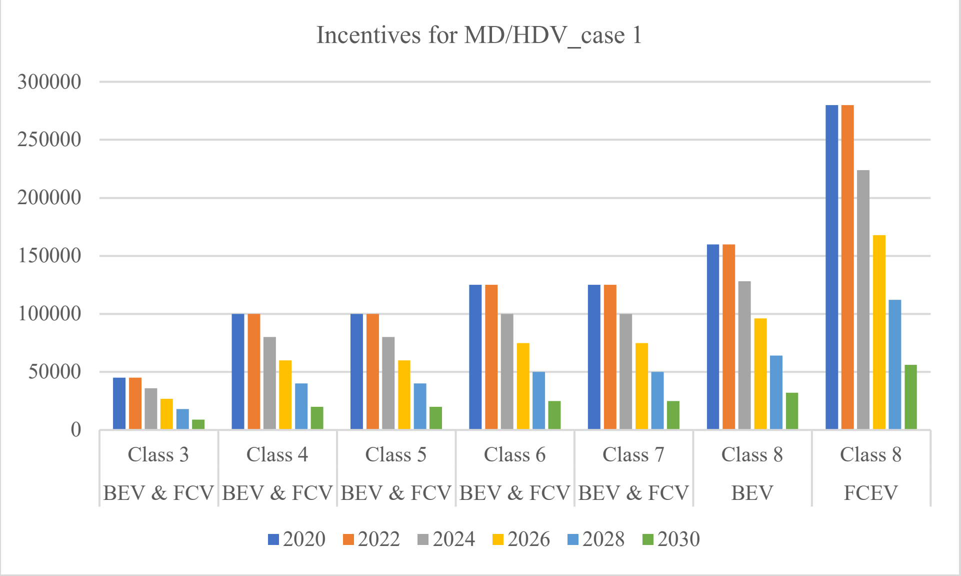


Figure B1: The two incentive strategies for LDVs are used in this study.

9.5.2. Financial incentives for MD/HDVs

The financial incentives from 2020 to 2024 will be based on the current policy, which includes HVIP and CVCP. After 2024, the incentives will gradually decrease at a constant rate each year. The incentives for Plan 1 and 2 in MD/HDV cases are shown in **Figure B2**.



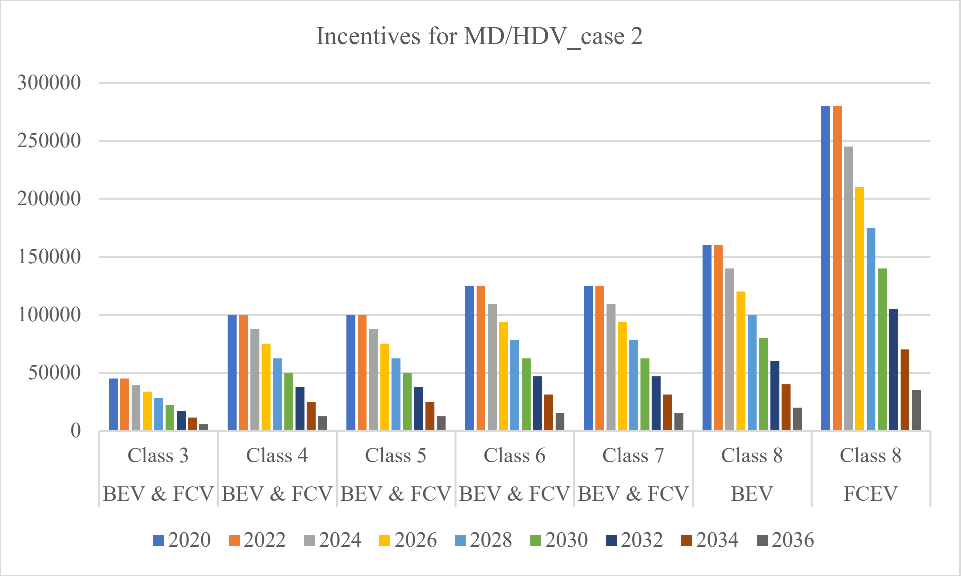


Figure B2: The two incentive strategies for MD/HDVs are used in this study.