Projecting California Light-Duty Vehicle Attributes (2019–2035)

Catherine Ledna, Aaron Brooker, and Dong-Yeon Lee

National Renewable Energy Laboratory

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Abstract

In this report, we estimated a set of future vehicle attribute scenarios for new light-duty vehicles for the California market using the Automotive Deployment Options Projection Tool (ADOPT). ADOPT starts simulations with all existing vehicle makes and models and endogenously creates new vehicle models over time based on assumed technology improvements and market conditions. For this study, we simulated four scenarios with varied technology, policy, and electric vehicle infrastructure assumptions. We aggregated simulation results into up to 30 vehicle classes (covering size and price classifications) for each powertrain, for six powertrains. We simulated model years 2019 to 2035. We present results for four vehicle attributes: vehicle acceleration, fuel economy (including electric and gasoline for plug-in hybrid electric vehicles [PHEVs]), vehicle range, and vehicle purchase price. We also present results showing the estimated number of vehicle models available in each vehicle class over time. In the *Mid* scenario, which contains conditions between our most conservative and most optimistic assumptions for emerging electric and hydrogen technologies, we observe improvements in acceleration, range (for battery-electric vehicles [BEVs]), and vehicle purchase price for electric and hydrogen powertrains. In some cases, we project that consumer preferences lead to trade-offs between vehicle attributes, such as reduced fuel economy in exchange for improved acceleration. Conventional vehicles show modest improvements in fuel economy in these scenarios due to the high numbers of BEV and PHEV sales, which reduce the improvements required in conventional vehicles to meet fleet fuel economy standards. In scenarios with advanced technology assumptions (including reduced battery price and improved energy density), we observe further improvements in BEV range and price relative to the improvements in the *Mid* scenario.

List of Acronyms

ADOPT	Automotive Deployment Options Projection Tool
BEV	battery-electric vehicle
CAFE	Corporate Average Fuel Economy
CEC	California Energy Commission
DCFC	DC fast charging
EVSE	electric vehicle supply equipment
FCEV	hydrogen fuel cell electric vehicle
L2	Level 2
LDV	light-duty vehicle
MPGGE	miles per gasoline gallon equivalent
MSRP	manufacturer's suggested retail price (in constant 2015 U.S. dollars)
MY	vehicle model year
NREL	National Renewable Energy Laboratory
PEV	plug-in electric vehicle; encompasses battery-electric vehicles and plug-in hybrid electric vehicles
PHEV	plug-in hybrid electric vehicle
TZEV	transitional zero-emission vehicle; for this analysis refers to plug-in hybrid electric vehicles
ZEV	zero-emission vehicle; specifically refers to battery-electric vehicles and hydrogen fuel cell electric vehicles

Executive Summary

This report documents one approach to generate scenarios of vehicle attribute projections for new light-duty vehicles (LDVs) sold in the California market. Vehicle attribute projections were developed for use in LDV market forecasts conducted by the California Energy Commission (CEC), and span model years 2019 to 2035. The Automotive Deployment Options Projection Tool (ADOPT) model, a historically validated consumer choice model, was used to develop attribute projections (Brooker, Gonder, Lopp, et al. 2015; NREL 2022a). In contrast to other studies that project future vehicle attributes (e.g., Islam et al. [2020]; Islam et al. [2021]), this study models both technology progress assumptions and consumer preferences for vehicle attributes. In addition, this study incorporates California-specific policies, including state vehicle subsidies and zero-emission vehicle (ZEV) sales requirements (consistent with state regulations through MY2025 [13 CCR § 1962.2] in all scenarios). The policies modeled in this study are consistent with existing legislation as of May 2021, when simulations were performed.

ADOPT starts simulations with all existing vehicle makes and models. During the simulation, it applies exogenous technology improvements to those vehicles (e.g., reductions in battery costs) and endogenously creates new vehicle models based on market conditions and simulated policies. New vehicle models are created using the Future Automotive Systems Technology Simulator (FASTSim) (Brooker, Gonder, Wang, et al. 2015; NREL 2022b), which estimates vehicle technology specifications including fuel economy, acceleration, and range. Those technology specifications are then used by ADOPT in combination with other market elements, such as fuel price, purchase incentives, fuel economy standards, and electric vehicle charging infrastructure availability, to estimate vehicle sales.

We generated aggregate vehicle attributes by computing sales-weighted averages of individual vehicle model attributes simulated in the ADOPT-FASTSim framework. We aggregated attributes into 30 vehicle classes: 15 size classes (e.g., Car-Compact, Car-Midsize, etc.) and two price classes (standard and premium). We modeled six powertrains: conventional gasoline vehicles, conventional diesel vehicles, hybrid gasoline vehicles, plug-in hybrid electric vehicles (PHEVs), battery-electric vehicles (BEVs), and hydrogen fuel cell electric vehicles (FCEVs). For this study we report the following attributes: vehicle acceleration, fuel economy, manufacturer's suggested retail price (MSRP), and vehicle driving range. We also report the number of vehicle models in each vehicle class, which shows the projected additions and retirements of vehicle models from the market. The attribute projections incorporate both future technology evolution and estimated consumer purchasing preferences.

Four scenarios (*Low*, *Mid*, *High*, and *Bookend*) were evaluated for this report. Assumptions spanned a range of technology progress rates, fuel prices, state and federal policies (federal tax credits and state purchase rebates for BEVs, PHEVs, and FCEVs, and Corporate Average Fuel Economy [CAFE] standards), and plug-in electric vehicle (PEV) infrastructure assumptions. One scenario, the *Bookend* scenario, includes a state-level ZEV sales mandate requiring 100% ZEV sales by 2035. Other scenarios hold ZEV sales requirements constant after 2025 in accordance with existing legislation as of 2021 (13 CCR § 1962.2), when simulations were performed. Scenarios range from least favorable to ZEVs (the *Low* scenario) to most favorable to ZEVs (the *High* and *Bookend* scenarios). The resulting vehicle attributes show potential trajectories for the

evolution of the light-duty vehicle market, conditional on our scenario assumptions. However, they should not be considered definitive forecasts.

The vehicle attribute projections presented in this report were used to inform vehicle market forecasts developed by the California Energy Commission (CEC) as part of the Transportation Energy Demand Forecast for the 2021 Integrated Energy Policy Report (IEPR) (CEC 2022). Additional adjustments to attribute projections were made by the CEC for use in the 2021 IEPR. The attributes presented in this report are the values provided by NREL to the CEC but do not necessarily reflect the final values used in the 2021 IEPR.

This report includes the following sections:

- A description of the ADOPT model, including the implementation of mechanisms to enforce a ZEV sales mandate in the California market.
- The postprocessing assumptions used to classify vehicle makes and models into vehicle classes.
- Input assumptions for the California market, including vehicle database inputs, technology evolution for conventional and alternative fuel vehicles (BEVs, PHEVs, and FCEVs), fuel price, CAFE standards, vehicle purchase subsidies, and electric vehicle infrastructure availability.
- Validation of the ADOPT model in historical years in both the U.S. and California markets. ADOPT-modeled outputs were validated on a national level against real-world consumer sales data from IHS Markit (IHS 2020). We compared modeled sales by powertrain, range, class, acceleration, and other aspects. For this study, we additionally validated ADOPT's sales of BEVs, PHEVs, and FCEVs against California historical sales data.
- Resulting vehicle attributes by vehicle class and powertrain, including postprocessing assumptions and comparisons of attributes across scenarios.

Our analysis yields the following key outcomes:

- In all scenarios, the number of ZEV models increases over the course of the simulation period. In these scenarios, the number of PHEV models is projected to increase in early years, while the number of BEV models is projected to expand in later years. By 2035, BEVs account for the greatest number of vehicle models out of all powertrains in all scenarios except for the *Low* scenario. The number of conventional gasoline vehicle models declines in lower price classes but not higher price classes in most scenarios. This suggests that the market for more expensive vehicles may be less sensitive to incentives aimed at phasing out conventional vehicles and promoting additional ZEV sales.
- In all scenarios, fleetwide average fuel economy exceeds CAFE standards due to high BEV and PHEV sales. The fuel economy of conventional powertrains increases in most vehicle classes but still remains lower than CAFE standards for the LDV fleet. This is because increased BEV and PHEV sales allow the fleet to achieve CAFE standards without substantial improvements in conventional vehicle fuel economy.
- In the *Mid* scenario, which includes the assumption of moderate technology progress for ZEVs, a majority of ZEV classes show improvements in range, fuel economy, vehicle purchase price (MSRP), and acceleration. In some cases, trade-offs between attributes are

observed, such as reduced fuel economy in exchange for improved acceleration or increased MSRP in exchange for improved acceleration and range. These trade-offs are a result of consumer preferences for some vehicle attributes over others.

- Aggressive technology improvement assumptions in the *High* and *Bookend* scenarios (particularly battery price reductions for BEVs and PHEVs) result in increased BEV range and lower MSRP in most vehicle classes.

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1 Introduction

Objective

This report documents one approach used to develop scenarios of vehicle attribute projections for personal light-duty vehicles (LDVs) in California for model years (MY) 2019–2035. Vehicle attributes, including price, driving range, fuel economy, and performance, are understood to drive consumer purchasing decisions, and are therefore a foundational aspect of vehicle choice models that aim to explore future market evolution scenarios. Preferences for vehicle attributes may vary across different consumer segments and income levels, with consumers weighing trade-offs between different attributes such as performance and fuel economy (Greene et al. 2018; Kontou, Melaina, and Brooker 2018).

Vehicle attribute projection scenarios for the national light-duty market are produced by a number of sources. The Annual Energy Outlook (EIA 2021) projects attributes such as fuel economy, horsepower, and weight of light-duty vehicles by class and powertrain. The Annual Technology Baseline (NREL 2020) compiles projections of vehicle cost, fuel economy, and cost of driving attributes for light-duty powertrains, based on vehicle simulation studies such as those conducted by Islam et al. (2020). Such studies consider future technological evolution and its impact on vehicle attributes, but do not necessarily consider consumer preferences for these attributes. Our approach is distinct from such studies, as we consider the impact of both technology changes and consumer preferences on the evolution of best-selling vehicle attributes.

In this report, we present vehicle attribute projections for the California market for multiple exploratory scenarios. Our scenario assumptions include state-specific considerations such as fuel prices, consumer income levels, and public infrastructure availability. We also include state-level policies such as vehicle rebates and the California zero-emission vehicle (ZEV) mandate, which requires an increasing percentage of ZEV sales over time. Scenario assumptions range from conservative to optimistic with respect to future ZEV technology progress and adoption incentives. We include one scenario that simulates the impact of a 100% ZEV sales mandate in 2035.

We used the Automotive Deployment Options Projection Tool (ADOPT) (Brooker, Gonder, Lopp, et al. 2015; NREL 2022a), a historically validated consumer choice model, to develop vehicle attribute projections. ADOPT integrates simulations of potential future vehicles with a consumer choice model, allowing us to simulate interactions between technology improvements and consumer purchasing decisions. ADOPT captures the impact of consumer income, federal policies such as Corporate Average Fuel Economy (CAFE) standards and tax credits, state-level incentives, electric vehicle infrastructure, and technology assumptions, setting it apart from models that only consider technology-level trends. ADOPT results were validated by comparing sales projections to historical U.S. vehicle sales data.

The resulting attribute projections were used to inform analysis of future vehicle stock and energy consumption in California as part of the Transportation Energy Demand Forecast for the 2021 Integrated Energy Policy Report (IEPR) conducted by the California Energy Commission (CEC) (CEC 2022). These attribute projections were further adjusted by the CEC for use in the 2021 IEPR. The values presented in this report are not necessarily the final values used in the 2021 IEPR analysis.

A previous iteration of this study (Kontou, Melaina, and Brooker 2018) developed attribute projections for model years 2015–2030, with an emphasis on evaluating fuel economy results with and without a CAFE extension. Our report expands the number of vehicle classes evaluated in the previous study to include standard (lower-priced) and premium (higher-priced) classes. Our analysis focuses on projections of future ZEV attributes.

Report Organization

This report contains three sections. Section 2: Methods documents the ADOPT model, including details of the updates made to the model for this study and input assumptions specific to California. Also in this section are descriptions of input assumptions for each of four exploratory scenarios, a description of the vehicle classification system used to map vehicle models in ADOPT to vehicle classes provided by the CEC, and a description of postprocessing steps. Section 3: Results presents attribute projections for the *Mid* scenario, including vehicle purchase price (manufacturer's suggested retail price [MSRP]), range, fuel economy, and acceleration. It also includes results for the number of vehicle models in each class by year. Selected results are also presented from other scenarios. Additional results can be found in the supplemental data accompanying this study. Finally, Section 4: Conclusions and Future Research highlights key takeaways from this report, as well as areas for future research.

2 Methods

2.1 The ADOPT Model

ADOPT was used to estimate future vehicle attributes (Brooker, Gonder, Lopp, et al. 2015; NREL 2022a). ADOPT is a vehicle choice and stock model created to estimate the impact of vehicle technology improvements on sales, energy, and emissions. ADOPT was developed by the National Renewable Energy Laboratory (NREL) with support from the U.S. Department of Energy's Vehicle Technologies Office, Bioenergy Technologies Office, and Hydrogen and Fuel Cell Technologies Office. ADOPT's sales simulations start with all existing vehicle makes, models, and options available on the market. This provides a realistic representation and accurate starting point for vehicle attributes. A full representation of vehicle makes and models also helps capture the attributes that make up the majority of advanced vehicle sales, specifically high-priced battery-electric vehicles (BEVs). ADOPT steps through time in 1-year increments, modifying vehicles based on technology improvements and estimating sales and sales-weighted attributes. Sales are estimated using a logit model that calculates consumers' perceived value of attributes, which include vehicle price, fuel cost per mile, acceleration, range, and passenger and luggage space. ADOPT captures variations in consumer preferences by income level. Historical vehicle sales data show that higher-income households are less concerned about price and more interested in performance and size, so in ADOPT, the perceived values of these attributes change as a function of income. Sales estimates trigger the creation of a new vehicle model in ADOPT under three different conditions:

- Condition 1: When sales start for a new powertrain, additional new vehicle options are introduced for the next 10 years. The number of options introduced for the new powertrain is consistent with the number introduced for hybrid electric vehicles. This creates a set of initial market offerings for the new powertrain, which may expand if one of the next two conditions are met.
- Condition 2: A vehicle's sales exceed the average sales for other vehicle models of equivalent price. This trigger captures how additional powertrain model options will be introduced when one option does well relative to the rest of the market.
- Condition 3: A third trigger captures the way in which more options for a powertrain are introduced in the case that one becomes the best-selling vehicle model for a consumer income bin. The number of new model options created by this trigger is inversely proportional to the share of powertrain model options currently in the market. For example, if a BEV becomes the best-selling vehicle model and there are not many BEV model options, a significant number of new options are introduced. As BEV model options saturate the market, fewer new options are created in the case of a best-selling BEV.

ADOPT creates each new vehicle model by optimizing powertrain component sizes to maximize estimated sales demand. An optimizer tries different combinations of engine, battery, and fuel tank sizes. These components are put in a vehicle model and run through the Future Automotive Systems Technology Simulator (FASTSim) (Brooker, Gonder, Wang, et al. 2015; NREL, 2022b) to estimate efficiency and performance attributes. Component size scaling information is used to estimate changes in passenger space and trunk space. Component price models are used to estimate the impact of each component on the vehicle price. ADOPT's logit model then estimates the value of those attributes to the consumer, where price attributes are less of a concern to higher income households. The vehicle model with the combination of component sizes that maximizes sales is added to the existing vehicle option list. New options trigger the scrappage of poor selling vehicle options. Only the remaining vehicle models and their sales inform vehicle attributes over time. We note that consumers choose vehicle classes endogenously in ADOPT, weighing vehicle size against other characteristics.

2.2 ADOPT Updates

2.2.1 Vehicle Database Updates

ADOPT's vehicle database contains data by make and model for all MY 2015 light-duty vehicles sold in the United States, as well as a subset of additional electric and fuel cell vehicles introduced between 2015 and 2020. Additional vehicle makes and models are endogenously created in ADOPT, simulating market evolution after the base year of 2015. In some instances in this study, influential real-world vehicles were not represented through ADOPT's vehicle database or endogenously created models, necessitating supplementation of the vehicle database. Additions to ADOPT's vehicle database are described in Appendix A. Vehicle specifications for these additions are based on publicly released information at the time simulations were performed (May 2021).

ADOPT's representation of light trucks and SUVs encompasses vehicles with a gross vehicle weight rating (GVWR) below 8,500 lbs. To improve our representation of light heavy-duty-engine vehicles (Classes 2b–3 in the U.S. Environmental Protection Agency classification system), we added a subset of these models to ADOPT's vehicle database (documented in Appendix A).

2.2.2 Model Updates

We updated ADOPT to incorporate the ability to enforce a binding ZEV sales mandate in California, following Executive Order N-79-20 (CARB 2021a), which calls for 100% ZEV and transitional ZEV (TZEV) sales of new light-duty vehicles by 2035. For the purposes of this analysis, TZEVs refer only to plug-in hybrid electric vehicles (PHEVs). ZEV regulations are defined using a credit system. A manufacturer may earn ZEV credits for selling a ZEV or TZEV, with current regulations giving more credits for ZEVs. The number of ZEV credits needed to meet requirements is based on total sales.

The ZEV sales mandate is enforced in two steps in ADOPT:

1. ADOPT assesses annual ZEV credit compliance at the level of the California LDV market. For this study, we assumed that ZEV credit requirements were based on existing regulations for BEVs, FCEVs, and PHEVs through MY 2025 (13 CCR § 1962.2). For MY 2026 and later, our scenarios considered two cases: one in which credit requirements were held constant, and another in which credit requirements were increased until 100% ZEV sales were reached. Our approach implicitly assumed that ZEV credits would be traded among manufacturers to achieve compliance.
2. If the LDV market in ADOPT complies with the simulated regulations, no action is taken. If the LDV market is not in compliance, ADOPT applies a series of incentives and penalties to ZEV and non-ZEV models. These incentives and penalties have the effect of lowering or increasing vehicle MSRP for consumers, which subsequently alters their purchasing decisions. ZEV models receive incentives proportional to the credits they generate, while non-ZEV models receive a constant penalty. PHEVs may be either incentivized or penalized, depending on how many are sold. If the minimum ZEV credit

percentage requirement is not met and the number of PHEVs sold exceeds the maximum allowable PHEV credit requirement, then they are penalized; otherwise, they are incentivized. ADOPT selects vehicle incentives and penalties within maximum and minimum bounds to optimize enforcement of the ZEV sales mandate. In cases where the ZEV mandate cannot be met in the current year, the regulation is held constant in the following year, simulating a delay or loosening of regulations.

The maximum incentives for ZEV models and maximum penalties for non-ZEV models used by ADOPT were set based on California regulations. The maximum penalty applied to non-ZEV models was set at $20,000 per vehicle model. This penalty was calculated by multiplying the maximum number of credits attainable from selling a ZEV (4 credits based on current regulations) by the current regulatory penalty for failing to attain ZEV mandate requirements ($5,000 per ZEV credit [CA Health & Safety Code § 43211]). This penalty is an estimate of the potential penalty from selling a non-ZEV rather than a ZEV when a manufacturer is not in compliance with the ZEV mandate. The maximum ZEV incentive size was similarly capped at $20,000. Minimum incentives and penalties were set at $0 per vehicle model.

2.3 Scenarios

We developed four scenarios that cover a range of assumptions about the market for future alternative fuel vehicles (a term that encompasses BEVs, PHEVs, and FCEVs). Scenario inputs vary for fuel prices, state and federal incentives and regulations, and technology costs and component-level performance characteristics (Table 1).

The *Low* scenario contains fuel price assumptions that are less favorable for alternative fuel vehicles, have less optimistic technology progress assumptions (for both conventional and alternative fuel vehicles), and have limited state and federal policy interventions (subsidies, tax credits, and CAFE standard stringency) that would incentivize the adoption of alternative fuel vehicles. The availability of public electric vehicle supply equipment (EVSE) is also assumed to grow less rapidly in the *Low* scenario.

The *Mid* scenario contains fuel prices that are moderately favorable to alternative fuel vehicles and have moderate technology progress assumptions for both conventional and alternative fuel vehicles. Public policy assumptions in the *Mid* scenario are a mix of conservative and optimistic inputs. CAFE and greenhouse gas standards are aligned with conservative *Low* scenario assumptions, while vehicle purchase subsidies and tax credits (for alternative fuel vehicles) are aligned with the optimistic *High* scenario assumptions. DC fast charging (DCFC) speed for EVSE increases more rapidly in the *Mid* scenario than the *Low* scenario. However, EVSE availability grows at the same rate as in the *Low* scenario. In the *Low*, *Mid*, and *High* scenarios, the ZEV sales mandate is held constant at MY 2025 levels for MY 2026–2035.

Finally, the *High* and *Bookend* scenarios contain assumptions for fuel prices, technology progress, public policy, and EVSE that are most favorable to alternative fuel vehicles. The *Bookend* scenario differs from the *High* scenario by including more aggressive improvements in electric vehicle battery prices and a more stringent ZEV sales mandate for MY 2026–2035, requiring 100% ZEV and PHEV (TZEV) sales by 2035 (Table 2). The *Bookend* scenario is identical to the *High* scenario for other inputs. Input assumptions are documented in more detail in the following section and in Table 1.

We note that these simulations were performed in May 2021, prior to the approval of the Advanced Clean Cars II rule, which established a path to 100% ZEV sales by 2035 in California (CARB 2022). The *Bookend* scenario simulates a 100% ZEV sales mandate but is not fully aligned with the Advanced Clean Cars II rule. Other scenarios simulate ZEV requirements through MY2025, but do not include the Advanced Clean Cars II rule. Electric vehicle tax credit provisions in the 2022 Inflation Reduction Act were not simulated in this study (H.R. 5376 2022).

Table 1. ADOPT Scenarios and Key Assumptions

Scenario	*Low*	*Mid*	*High*	*Bookend*
ZEV Mandate	ZEV requirements held constant after MY 2025	ZEV requirements held constant after MY 2025	ZEV requirements held constant after MY 2025	ZEV sales requirements linearly increase from MY 2025 to 100% in 2035. TZEVs can supply up to 11% of credits in 2035.
Fuel Prices	National fuel prices from Low Oil Price and High Renewable Cost scenarios (EIA 2021). Hydrogen prices from 2020 Benefits Analysis – Low scenario (Brooker et al. 2021).[a]	Midpoint of *High* and *Low* fuel prices	National fuel prices from High Oil Price and Low Renewable Cost scenarios (EIA 2021). Hydrogen prices are from 2020 Benefits Analysis – High scenario (Brooker et al. 2021).[a]	
Technology Costs	Battery prices reach $108/kWh by 2035 (Pham 2021); other assumptions follow Islam et al. (2020) “Low” scenario	Battery prices reach $88/kWh by 2035 (Pham 2021); other assumptions follow midpoint of Islam et al. (2020) “High” and “Low” scenarios	Battery prices reach $67/kWh by 2035 (Pham 2021); other assumptions follow Islam et al. (2020) “High” scenario	Battery prices reach $47/kWh by 2035 (Pham 2021); other assumptions follow Islam et al. (2020) “High” scenario
CAFE Standards	Restored to midpoint of original (2012) and updated (2020) MY 2021–2025 standards, then increase at 1.5% per year until 2035		Restored to original (2012) MY 2021–2025 standards, then increase linearly until 2035	
State Vehicle Subsidies	Clean Vehicle Rebate Project (CVRP): $2,000/BEV, $1,000/PHEV, $4,500/FCEV to 2025 (amounts based on CARB 2021b); Clean Fuel Reward: $1,500 maximum for BEVs and PHEVs to 2025 (amount based on 17 CCR § 95483)	CVRP: $2,000/BEV, $1,000/PHEV, $4,500/FCEV to 2035 Clean Fuel Reward: $1,500 maximum for BEVs and PHEVs to 2035		
Federal Tax Credit	Federal tax credit limited to 200,000 vehicles sold per manufacturer (IRS 2009). Does not include provisions from the 2022 Inflation Reduction Act (H.R. 5376 2022).	Federal tax credit expanded to 600,000 vehicles per manufacturer. Does not include provisions from the 2022 Inflation Reduction Act (H.R. 5376 2022).		
EVSE	Full availability by 2030; average 150-kW DCFC by 2030	Full availability by 2030; average 150-kW DCFC by 2025	Full availability by 2025; average 150-kW DCFC by 2025	

[a] These results use draft hydrogen fuel prices from the 2020 Benefits Analysis, and therefore differ somewhat from values referenced in Brooker et al. (2021).

Table 2. ZEV Sales Mandate Assumptions, Bookend Scenario

	2018	2020	2025	2030	2035
Minimum ZEV credit percent requirement	2%	6%	16%	52.5%	89%
Maximum TZEV (PHEV) credit percent requirement	2.5%	3.5%	6%	8.5%	11%
Total minimum ZEV percent requirement	4.5%	9.5%	22%	61%	100%
Maximum credits per ZEV	4	4	4	1.1	1
Maximum credits per TZEV	1.1	1.1	1.1	1	1

2.4 Input Assumptions

This section documents the following input assumptions: total vehicle sales, fuel prices, technology component assumptions, CAFE standards, and household income. Assumptions were selected to reflect conditions in two geographical market segments: California and the rest of the U.S.

2.4.1 Total Vehicle Sales

ADOPT takes total LDV sales as an exogenous input. National total LDV sales were taken from the Annual Energy Outlook 2021 for all years (EIA 2021). In California, for historical years (2015–2020), total LDV sales were taken from the CEC's "Zero Emission Vehicle and Infrastructure Statistics" (CEC 2021b). To compute projected total California sales for years 2021–2035, we used sales projections from the Annual Energy Outlook 2021 Pacific region. These projections were downscaled from the Pacific region to California by taking the ratio of California total LDV sales to Pacific total LDV sales for the year 2020 (EIA 2021). Figure 1 shows national and California total LDV sales for 2015–2035. Reductions in total LDV sales due to the COVID-19 pandemic were included in both the California and nationwide historical input data. However, we made no further assumptions about the impact of COVID-19 on future consumer vehicle purchase decisions or travel behavior.

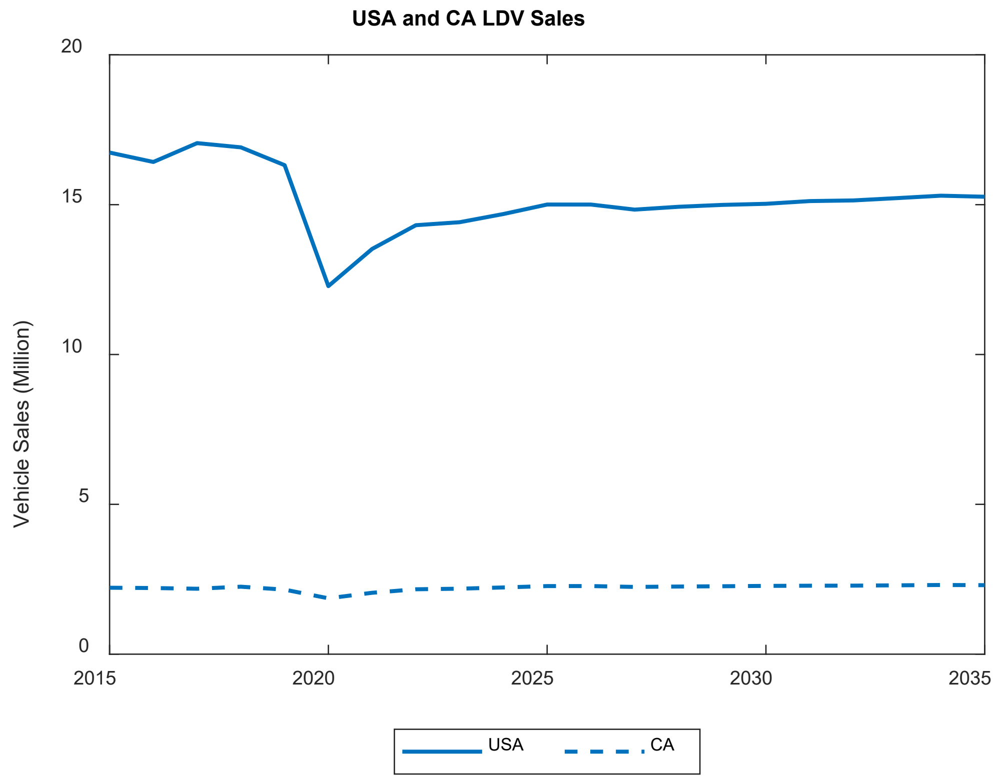

Figure 1. National and California total LDV sales assumptions, 2015–2035

2.4.2 Fuel Prices

Figure 2 shows national and California fuel prices from the sources listed in Table 1. California gasoline price assumptions were assumed to be consistent with national fuel price assumptions, except for the addition of a $0.33/gallon premium. This premium was chosen based on historical average gasoline price differences between California and the rest of the U.S. between 2001 and 2015 (EIA 2022b). We caveat that since 2015, the difference in gasoline prices between California and the rest of the U.S. has increased; however, for this study we assumed that gasoline price differences between California and the rest of the U.S. would match long-term trends. Other California fuel prices such as electricity and hydrogen were assumed to be the same as national prices. Electricity prices range from $0.11/kWh to $0.13/kWh in all scenarios. We caveat that real-world California retail electricity prices are higher than US-wide electricity prices (EIA 2022a). However, we do not expect this to have a substantial impact on results due to the low fuel cost per mile when driving on electricity and the high consumer discount rates assumed for future fuel price savings. *Mid* scenario fuel prices (not shown) were computed as the midpoint of *High* and *Low* prices.

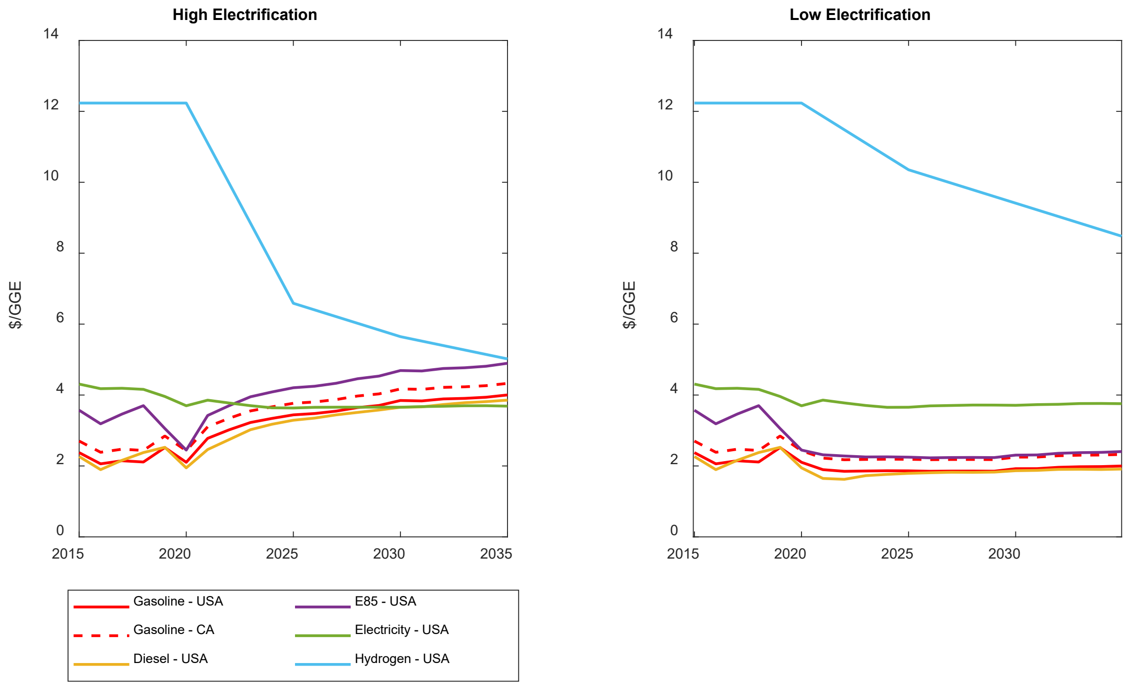

Figure 2. National and California fuel price assumptions, 2015–2035

2.4.3 Technology Component Assumptions

Technology component costs (including battery pack prices) and efficiency assumptions were input to the ADOPT-FASTSim framework. Battery pack prices influence vehicle attributes in two ways in ADOPT. First, lower battery prices reduce the price of existing PEV models over time. In addition, lower battery prices influence component sizing when new vehicle options are created. Lower battery prices tend to lead to larger battery sizes, resulting in vehicles with faster acceleration and improved range. These improvements tend to lead to increased PEV sales, which may result in the creation of additional PEV models. Figures 3 and 4 show technology component cost and efficiency assumptions. Battery pack price assumptions were provided by the CEC (Figure 3) for 2021–2035, resulting from a meta-analysis of an array of sources that estimated future battery price projections (Pham 2021). Historical (2015–2020) battery pack prices were taken from BloombergNEF (2020). Other technology component cost and efficiency projections were taken from Islam et al. (2020) (Figure 4). For the cost and efficiency projections shown in Figure 4, *Mid* scenario projections were assumed to be the midpoint of *High* and *Low* values. All costs are presented in constant 2015 U.S. dollars.

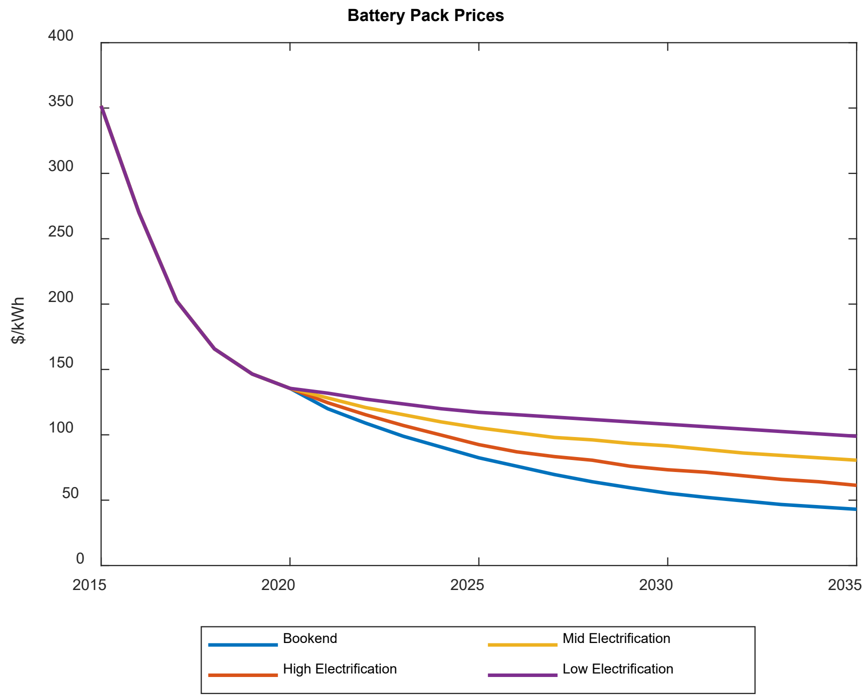

Figure 3. Electric vehicle battery pack price assumptions (2015 U.S. dollars).

Pack prices are benchmarked to a vehicle with 160-kW battery power and 60-kWh battery energy

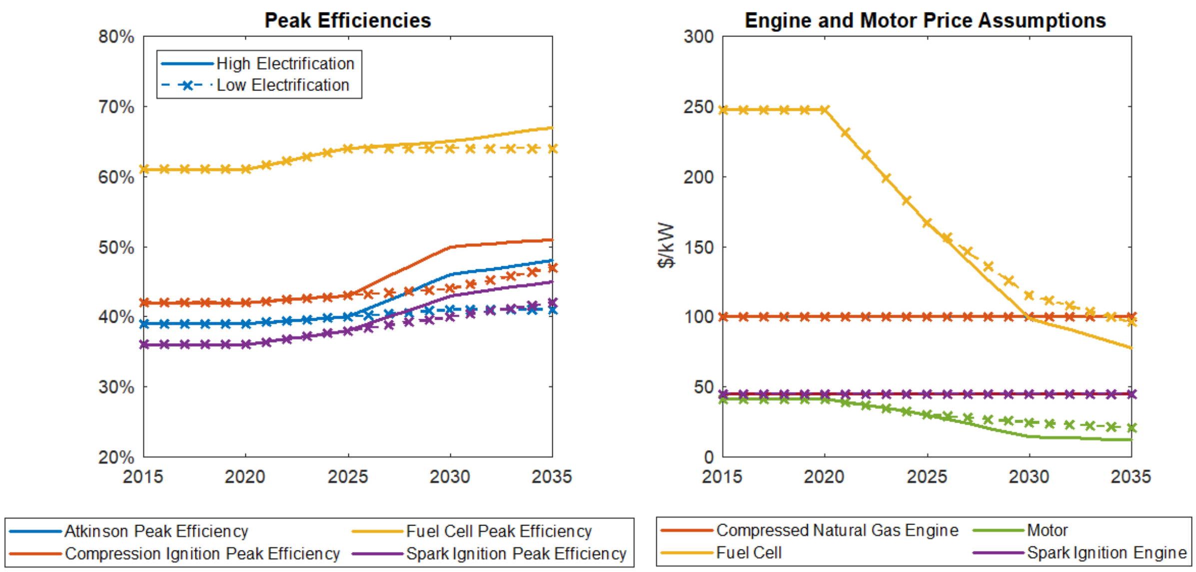

Figure 4. ADOPT technology assumptions, conventional and alternative fuel vehicles

2.4.4 CAFE Standards

Figure 5 presents the CAFE standards input into ADOPT for this analysis. In the *Low* and *Mid* scenarios, CAFE standards for MY 2021–2025 were set as the average of the values specified in the 2012 (77 Fed. Reg. 62,624) and 2020 rulemakings (85 Fed. Reg. 24,174) for MY 2021–2025. After 2025, the fuel economy requirements were assumed to increase at a rate of 1.5% per year. In the *High* scenario, CAFE standards were set to the 2012 rulemaking for MY 2021–2025 and linearly extended to 2035. While ADOPT's vehicle optimization attempts to comply with fuel economy standards, the model pauses and delays CAFE standards if they are deemed too expensive to enforce, which may result in differences between the CAFE standards input and those required in the results.

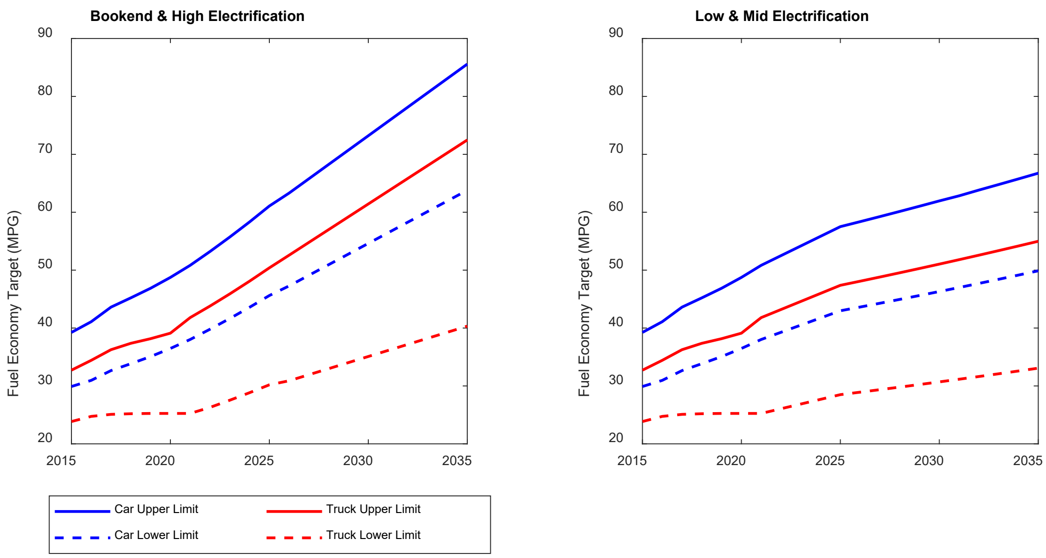

Figure 5. CAFE standards in miles per gallon, MY 2015–2035

2.4.5 Household Income

Figure 6 shows U.S. and California household counts by income bin. We updated California-specific consumer income distributions for this study based on data from the most recent American Community Survey from 2015 to 2019 (U.S. Census Bureau 2021). The number of households in each bin in California was assumed to grow at the same rate as the number of households in the rest of the United States after 2019.

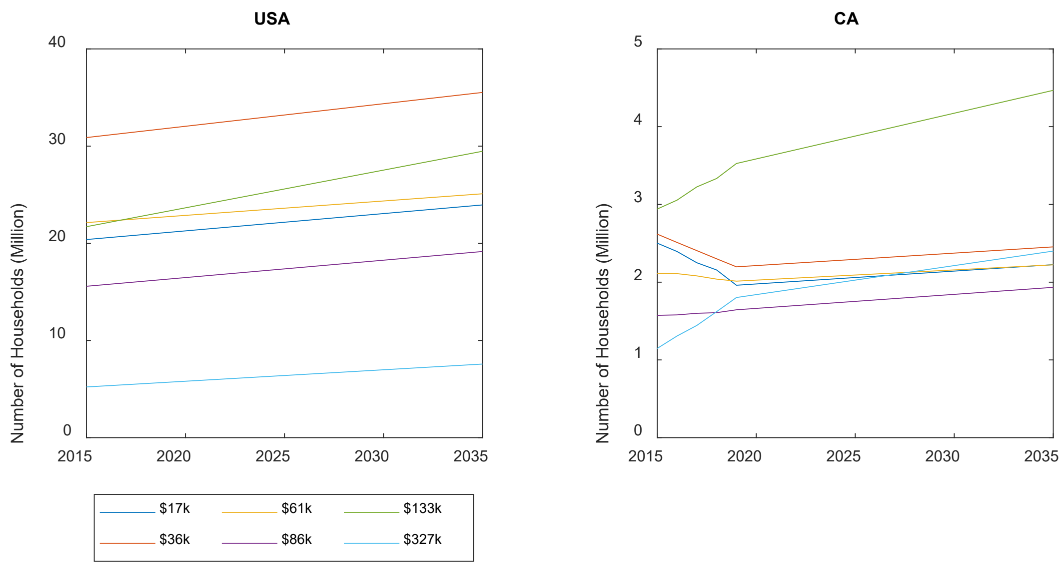

Figure 6. Number of households by income bin, United States and California

2.5 Public Charging Infrastructure

Public electric vehicle charging infrastructure, also referred to as EVSE, is one of the factors that ADOPT considers when estimating vehicle sales by powertrain. The calculations for the value of public EVSE for each vehicle in ADOPT factor in available charging speed, vehicle range, charging availability, and charging type (including Level 2 [L2] and DCFC). Interregional charging, defined as charging located along rural highway corridors, and intraregional charging, defined as charging located within urban areas, are computed separately. ADOPT assumes that PHEVs rely solely on L2 charging and that BEVs use a mix of L2 and DCFC. Assumptions regarding the split between L2 and DCFC BEV charging use were derived from observed charging behavior data from Tal et al. (2020) for this study.

Equations developed by Greene et al. (2020) were used to calculate the value of EVSE coverage to consumers for BEVs and PHEVs. These equations were implemented in ADOPT using the methods described in Ledna et al. (2022). For PHEVs, the value of public EVSE coverage was calculated in ADOPT as the value of fuel cost savings from additional L2 infrastructure. For BEVs, the value of public EVSE coverage was calculated in ADOPT as the value of enabled miles of travel from L2 and DCFC infrastructure minus the following costs: travel limitations due to insufficient infrastructure availability, time spent charging, and time spent accessing charging (time to station). We assumed that BEVs with smaller batteries (under 40-kWh battery pack) were limited to 50-kW DCFC, in line with the limitations for existing models such as the 2018 Nissan Leaf (Tomaszewska et al. 2019; Figenbaum 2020).

Table 3 presents charging availability assumptions for California from 2020 to 2025 in the *Low* and *Mid* scenarios. Charging availability was computed by dividing observed chargers by required public chargers. Required public chargers is an estimate of the number of chargers needed to support the plug-in electric vehicle (PEV) fleet. As PEV fleet size is an ADOPT output rather than an input, we used fleet sizes from Crisostomo et al. (2021) to estimate charging requirements. Required intraregional public chargers were estimated from EVI-Pro Lite (AFDC

2020). These estimates suggested that existing intraregional L2 and DCFC public charging infrastructure was adequate to support PEVs in 2020. However, Crisostomo et al. (2021) projected that additional public charging would be needed to achieve California's goal of 250,000 chargers in 2025. Required public chargers for DCFC interregional chargers were estimated by scaling estimates from Lee and Wood (2020) to match fleet size assumptions.

In the *Low* and *Mid* scenarios, we assumed that additional required chargers would be added between 2025 and 2030 to achieve 100% charging availability by 2030. In the *High* and *Bookend* scenarios, we assumed that 100% charging availability would be achieved by 2025. In the *High* and *Bookend* scenarios, we also assumed that chargers would be added to keep pace with subsequent PEV fleet growth after 2025. In all scenarios, we assumed that charging availability would remain constant at 100% after 2030. Table 4 presents charging speed and time to station (an estimate of the time required to reach an available charging station, based on station coverage) from 2020 to 2035 for the *Low* and *Mid* scenarios.

Table 3. 2020–2025 California Charging Availability Estimates, *Low* and *Mid* Scenarios

	Year	Observed or Estimated Public Chargers [a]	Required Public Chargers	Charging Availability
Level 2 chargers	2020	22,531	20,816	100%
	2025	65,525	87,954	74%
DCFCs – intraregional	2020	4,818	2,022	100%
	2025	9,459	10,000	95%
DCFCs – interregional	2020	500	2,736	18%
	2025	1,870	3,400	55%

[a] Observed 2020 and estimated 2025 L2 and intraregional public charger counts were taken from Crisostomo et al. (2021). L2 counts were adjusted to exclude shared private L2 chargers. The number of DCFC interregional chargers in 2020 was inferred from historical counts presented in Ledna et al. (2022) using the average of 2015–2019 historical growth rates.

Table 4. ADOPT L2 and DCFC Assumptions

Scenario	Parameter	2020	2025	2030	2035
Low	L2 charging speed (kW)	5	10	15	15
	L2 time to station	Same as gasoline by 2030			
	DCFC charging speed (kW)	125	137.5	150	150
	DCFC time to station	Same as gasoline by 2030			
Mid	L2 charging speed (kW)	5	15	15	15
	L2 time to station	Same as gasoline by 2030			
	DCFC charging speed (kW)	125	150	150	150
	DCFC time to station	Same as gasoline by 2030			
High & Bookend	L2 charging speed (kW)	5	15	15	15
	L2 time to station	Same as gasoline by 2025			
	DCFC charging speed (kW)	125	150	150	150
	DCFC time to station	Same as gasoline by 2025			

2.6 Vehicle Classification and Attribute Processing

Vehicles were assigned classifications based on their type (car, truck, SUV, and van) and size (subcompact, compact, midsize, large, and heavy) using a classification system provided by the CEC. Although factors such as vehicle size may evolve for a vehicle model over time, vehicle models were not reclassified for this study based on changes in size. This decision was made to reflect market perceptions of the marquee vehicle. For example, the Toyota Corolla was classified as a compact car throughout the analysis, even though its wheelbase has increased 18% since its introduction in 1966.

Vehicle models were first classified as either standard or premium (described in Section 2.6.1) and then further categorized into the following 15 different classes: Car–Subcompact, Car–Compact, Car–Midsize, Car–Large, Car–Sports, SUV–Subcompact, SUV–Compact, SUV–Midsize, SUV–Large, Van–Compact, Van–Large, Van-Heavy, Pickup–Compact, Pickup–Standard, or Pickup-Heavy. The Car–Sports class contains vehicles that are classified as a car but have a 0–60-mph acceleration of 6 seconds or less.

2.6.1 Standard vs. Premium

Vehicles were designated as standard or premium based on their manufacturer (vehicle make) and the MSRP. Table 5 lists vehicle manufacturers that were designated as premium. Among premium vehicle makes, cars with an MSRP lower than $40,000 and light trucks with an MSRP lower than $42,000 were reclassified as standard vehicles. All other vehicles that did not belong to the list of premium makes, regardless of their MSRP, were designated as standard. This MSRP threshold was chosen based on data on existing vehicle MSRP distributions in the United States (Vehicle Technologies Office 2017).

Table 5. Vehicle Manufacturers Classified as Premium in ADOPT

Manufacturer Name		
Acura	Hummer	Porsche
Aston	Infiniti	Rolls-Royce
Audi	Jaguar	Saab
Bentley	Land Rover	Tesla
BMW	Lexus	Volvo
Cadillac	Lincoln	
Genesis	Mercedes-Benz	

2.6.2 Calculation of Vehicle Attribute Values

After ADOPT simulations were completed, all vehicle models in ADOPT were classified into vehicle classes for each model year. We then developed aggregated vehicle attribute values for each class and model year based on sales-weighted averages of all the models within a class. Equation 1 describes this process:

$$V_{a,c,y} = \frac{\sum_{j=1}^{N} u_{a,j,y} \times s_{j,y}}{\sum_{j=1}^{N} s_{j,y}} \quad (1)$$

The variable $V_{a,c,y}$ is the value of vehicle attribute a for vehicle class c for model year y. The variable a refers to the vehicle attribute in question: vehicle range (miles), MSRP (dollars), acceleration (seconds, 0–60 mph), or fuel economy (miles per gallon gasoline equivalent [MPGGE]). The variable c refers to the vehicle class (one of 30 classes: 15 size classes and either standard or premium). The variable $u_{a,j,y}$ denotes the model-specific attribute value for vehicle model j. This value is weighted by the sales $s_{j,y}$ of that model. The variable N refers to the number of models in each class. This approach means that for each class, better-selling vehicles have more influence on the class-wide vehicle attributes.

2.6.3 Postprocessing of Attributes Data

ADOPT creates and discontinues vehicle models in response to market demand. In some cases, discontinuous behavior occurred in the results as vehicle classes entered and exited the market abruptly in response to sales. This was observed particularly for classes that are composed of only a few models. To ensure continuous behavior, postprocessing was applied in some cases:

- Based on input from the CEC, we excluded conventional vehicle classes created by ADOPT that were not present in 2021 vehicle class data provided by the CEC (CEC 2021a). This reflects the assumption that no new conventional vehicle classes will be created. For ZEVs, we included attributes for all vehicle classes that existed in 2020. We assumed that these vehicles would persist in the market even if sales ended in the ADOPT results. For these ZEV classes, we held attribute values constant at the levels of the last year in which sales occurred in ADOPT.
- For models that existed in 2020, in cases where discontinuities occurred (classes exiting the market one year and re-entering the market in subsequent years), we interpolated attributes for gap years.

- Finally, for ZEV classes introduced after 2020, we interpolated sales for any gap years if the class existed for 5 or more years in ADOPT. Classes that were introduced after 2020 and existed for less than 5 years in ADOPT were dropped from our attributes results.

Table 6 documents the ZEV classes for which attributes were interpolated or extended in one or more years.

Table 6. ZEV Classes Extended in Postprocessing

	BEV	PHEV	FCEV
Standard	Subcompact Car	Compact car Midsize Car	N/A
Premium	N/A	Midsize Car Large Car	N/A

In the *Bookend* scenario, some conventional and hybrid vehicle models continued to sell in ADOPT in 2035 despite the ZEV sales mandate. These models were primarily premium models with high MSRPs. To simulate the effect of a fully binding ZEV sales mandate, the sales and number of model options for these classes were linearly interpolated between ADOPT's 2033 sales numbers and an assumed value of zero in 2035. Additional model development is needed to ensure that these vehicles are retired endogenously within ADOPT under a ZEV sales mandate.

3 Results

We present vehicle attribute projections for up to 30 vehicle classes and six powertrains. Vehicle classes are composed of constituent vehicle models, and attributes are weighted by the sales of each model. Vehicle attribute projections may be influenced by the following factors:

1. **Technological change**: ADOPT updates existing vehicle models' attributes in response to changes in technological inputs (e.g., reduced battery prices and improved battery energy density will lead to lower MSRPs and longer electric ranges for future versions of an existing PEV). Vehicle class attributes are influenced by the changes in attributes of the constituent vehicle models in each class due to changes in technological inputs.
2. **Changes in sales of vehicle models within a class**: Because vehicle attributes are sales-weighted averages, changes in the relative proportion of sales of each model may change attributes.
3. **Model entry and exit**: New vehicle models are created in ADOPT when powertrain sales exceed key sales thresholds, representing the projected expansion of the vehicle market. Models are retired from the vehicle market offering due to low projected sales. Vehicle classes with relatively few models, or that have rapid expansion or reduction in the number of models in their class, may display more sudden changes in vehicle attributes due to model entries and exits.

As noted in previous sections, these vehicle attribute projections were provided by NREL to the CEC for use in the 2021 IEPR analysis. Further adjustments and post-processing were done by the CEC, and the results presented in this section are not necessarily the same as the final attribute values used in the 2021 IEPR.

This section is organized as follows. Section 3.1 presents results showing the ADOPT model's validation to historical U.S. and California sales trends. Section 3.2 then presents results from the *Mid* scenario, which is emphasized because it is a midpoint between our most conservative and optimistic input assumptions for alternative fuel vehicles. Finally, Section 3.3 presents additional results from the *Low*, *Mid*, *High*, and *Bookend* scenarios in order to show the impact of alternative technology and policy assumptions on vehicle attributes and to show trends that persist across scenarios.

3.1 Model Validation

We first validate ADOPT's simulation outputs by comparing them to historical data. Figure 7 presents a comparison of 2015 ADOPT-modeled U.S. sales versus actual 2015 U.S. sales data from IHS Markit (IHS 2020). ADOPT's sales results match closely on overall sales by class, as well as on attributes such as fuel economy, acceleration, price, and power. ADOPT's results also match well on BEV and PHEV sales by range. The model results somewhat overestimate the average household income of BEV purchasers and underestimate the average household income of PHEV purchasers, but capture the income difference between these two groups; the average income of BEV purchasers is higher than that of PHEV purchasers.

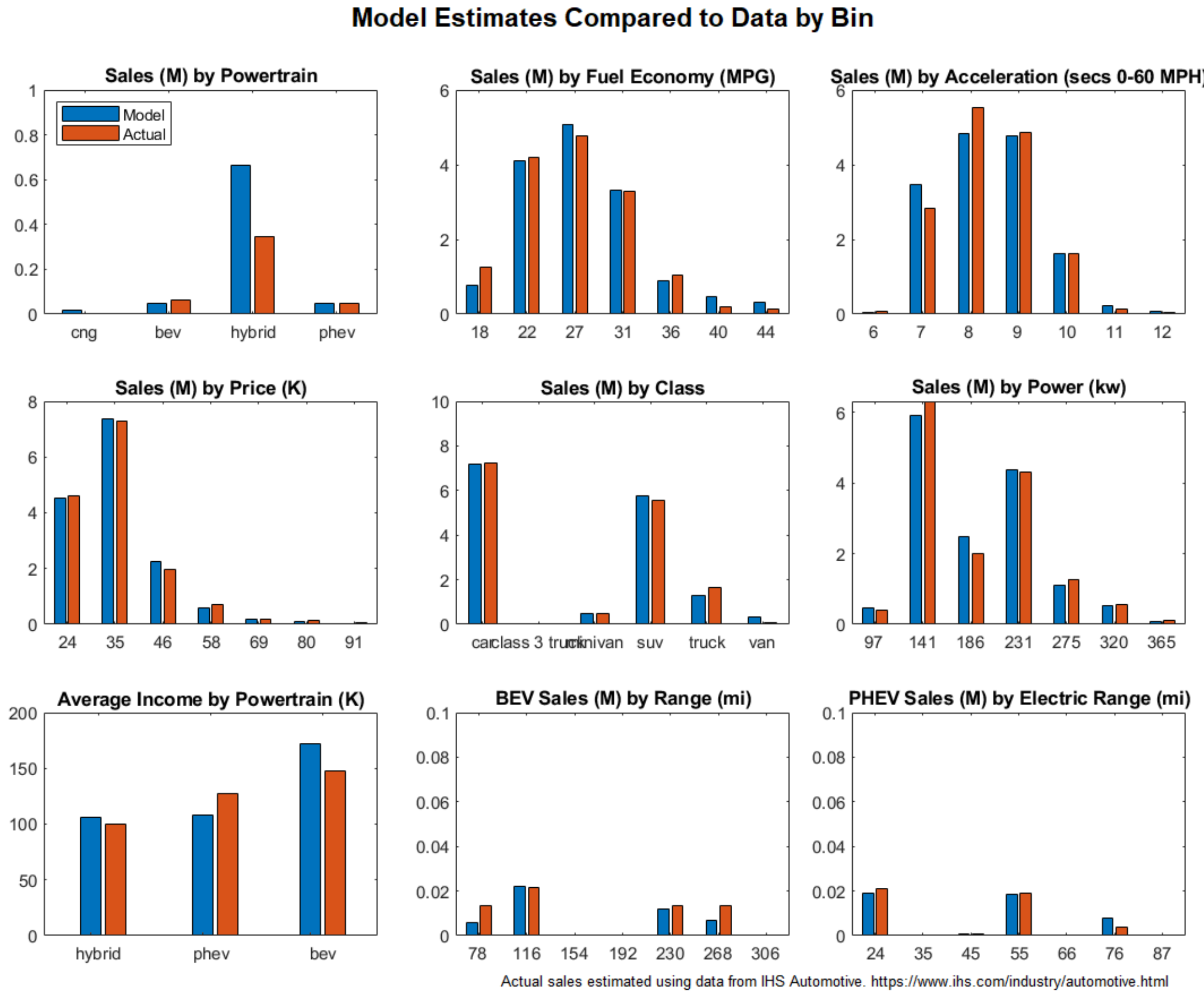

Figure 7. Comparison of ADOPT and U.S. sales data, 2015

Figures 8 and 9 present comparisons of ZEV and PHEV sales by powertrain and BEV sales by range in California, respectively, for historical years (2015–2020). California historical data are from the CEC (CEC 2021b). ADOPT's sales results are similar to the general trends in California: BEV sales are higher than PHEV sales, BEV sales grow over time, and FCEV sales remain limited. After 2018, BEV sales modeled in ADOPT show the same trends as actual sales data: sales of longer-range BEVs (200+ miles) increase and sales of shorter-range BEVs (below 200 miles) decline.

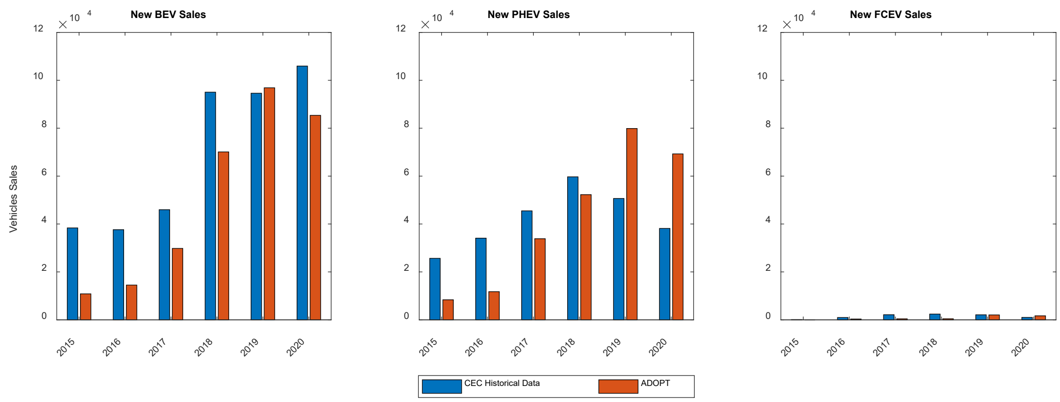

Figure 8. ADOPT and California ZEV and TZEV sales by powertrain, 2015–2020

Figure 9. Share of ADOPT and California BEV sales by range, 2015–2020

Figure 10 compares actual sales-weighted average LDV acceleration for historical years (1978–2020) to ADOPT's estimates for simulated years in the *Mid* scenario (2015–2035). The U.S. light-duty fleet's average 0–60-mph acceleration time has generally decreased over time, with the exception of increases in the late 1970s through the early 1980s when CAFE standards were introduced (EPA 2021). For years in which there is overlap (2015–2020), ADOPT shows good alignment with historical trends. ADOPT's estimate for acceleration time deviates from the historical trend by a maximum of 8% in any year and by 5% or less in most years of the overlap. In the *Mid* scenario, ADOPT projects continued decreases in sales-weighted average acceleration time at a rate of 1.6% per year between 2020 and 2035. This is due to expanded PEV sales, particularly sales of BEVs, which tend to have faster acceleration than conventional vehicles.

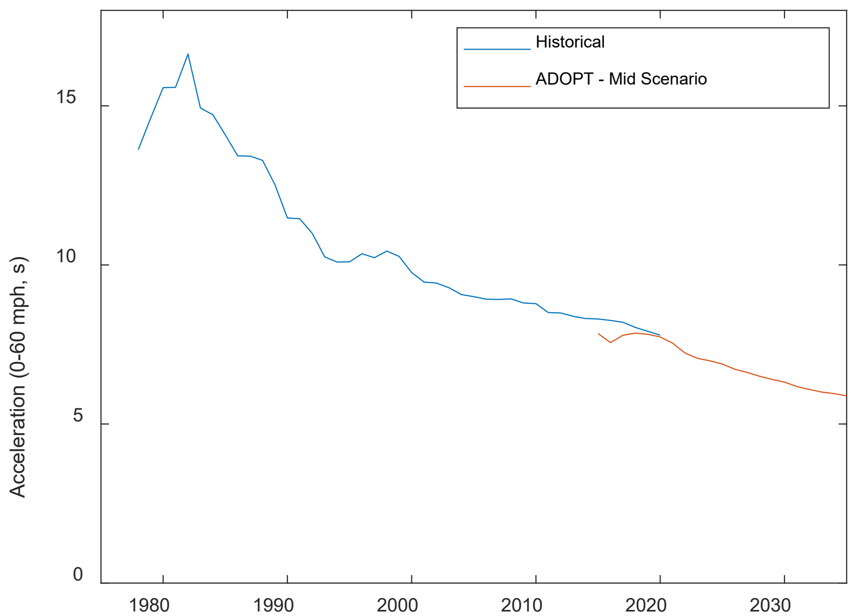

Figure 10. Historical and simulated acceleration trends, U.S. LDVs, sales-weighted average.

Historical data from *The 2021 EPA Automotive Trends Report* (EPA 2021)

3.2 The *Mid* Scenario

The *Mid* scenario was designed as a midpoint between conservative and optimistic technology and policy assumptions for alternative fuel vehicles. We present vehicle attribute projections from this scenario to establish a central set of attribute projections. Our results include projections of four vehicle attributes: acceleration, fuel economy, vehicle range, and MSRP. A fifth result, the number of vehicle models, is discussed in Section 3.3. Results are presented for model years 2019 to 2025.

3.2.1 Acceleration and Fuel Economy

Improvements in vehicle acceleration and fuel economy may trade off against one another, particularly in response to fuel economy standards (Knittel 2011; Kontou, Melaina, and Brooker 2018; Whitefoot, Fowlie, and Skerlos 2017). The *Mid* scenario includes CAFE standards that require a 42% improvement in fleet average fuel economy for cars (a fleet average between 50 and 67 MPGGE in 2035 [40–54 MPGGE using real-world estimates[1]]) and 31%–44% improvement in fleet average fuel economy for light trucks between 2019 and 2035 (a fleet average between 33 and 55 MPGGE in 2035 [26–44 MPGGE using real-world estimates]). We find that vehicle attribute projections for alternative fuel vehicles meet or exceed these averages, while vehicle attribute projections for conventional gasoline and diesel vehicles do not, as sales of alternative fuel vehicles lessen the fuel economy improvements required for conventional vehicles to comply with fleetwide fuel economy standards. Both acceleration and fuel economy improve for a majority of vehicle classes and powertrains. In some cases, trade-offs are observed, particularly for PEVs.

[1] Real-world fuel economy is lower than CAFE fuel economy by 20%, reflecting real-world drive cycles. Reported fuel economy attribute projections use real-world estimates.

Figures 11 and 12 plot vehicle attribute projections for acceleration and real-world fuel economy for conventional and hybrid electric powertrains. Acceleration (time in seconds from 0 to 60 mph) improves for most conventional and hybrid electric vehicle classes and powertrains from the beginning to the end of the simulation period (Figure 11). Sales-weighted average acceleration declines from 7.8 to 6.5 seconds between 2019 and 2035 for conventional and hybrid powertrains across all classes (an average improvement of 1% per year). This rate is in line with historical rates of improvement in acceleration (an average improvement of 1% per year from 1990 to 2020 across all powertrains [EPA 2021]). Improvements in projected acceleration are explained by improvements in underlying technology assumptions, particularly gains in engine efficiency (Figure 4).

Fuel economy also improves for a majority of conventional and hybrid electric vehicle classes (Figure 12), though at a lower rate than what has been historically observed. Sales-weighted average fuel economy improves from 26 MPGGE to 28 MPGGE from 2019 to 2035 for conventional and hybrid powertrains across all classes (an average increase of 0.3% per year). Historically, fuel economy has improved at a rate of 0.7% per year on average for all powertrains from 1990 to 2020 (EPA 2021). For cars, fuel economy ranges between 26 and 49 MPGGE in 2035, with a sales-weighted average of 30 MPGGE. For pickups, SUVs, and vans, fuel economy ranges between 21 and 40 MPGGE in 2035, with a sales-weighted average of 26 MPGGE. These averages are substantially lower than the fleet average fuel economy required to meet CAFE standards in 2035.

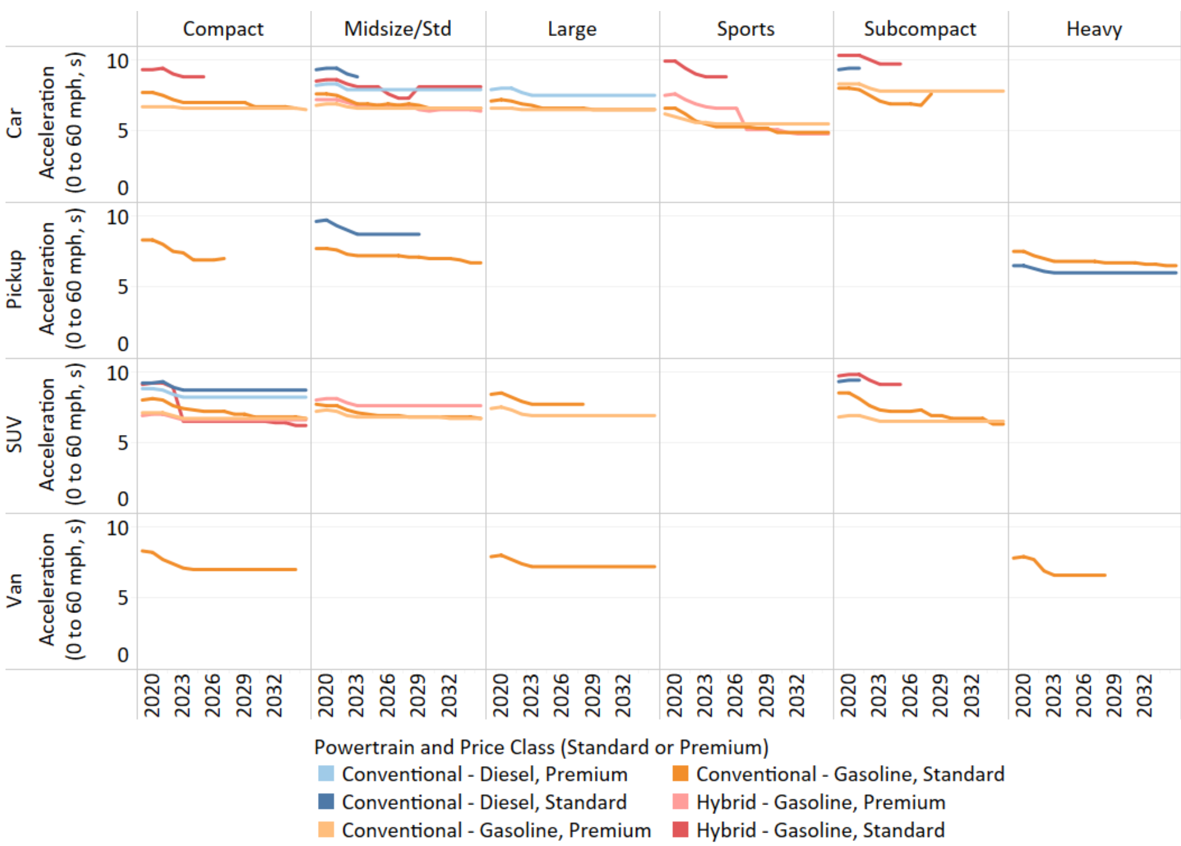

Figure 11. *Mid* scenario: acceleration by model year, conventional powertrains – standard and premium classes

Data for this figure can be found in Appendix B.

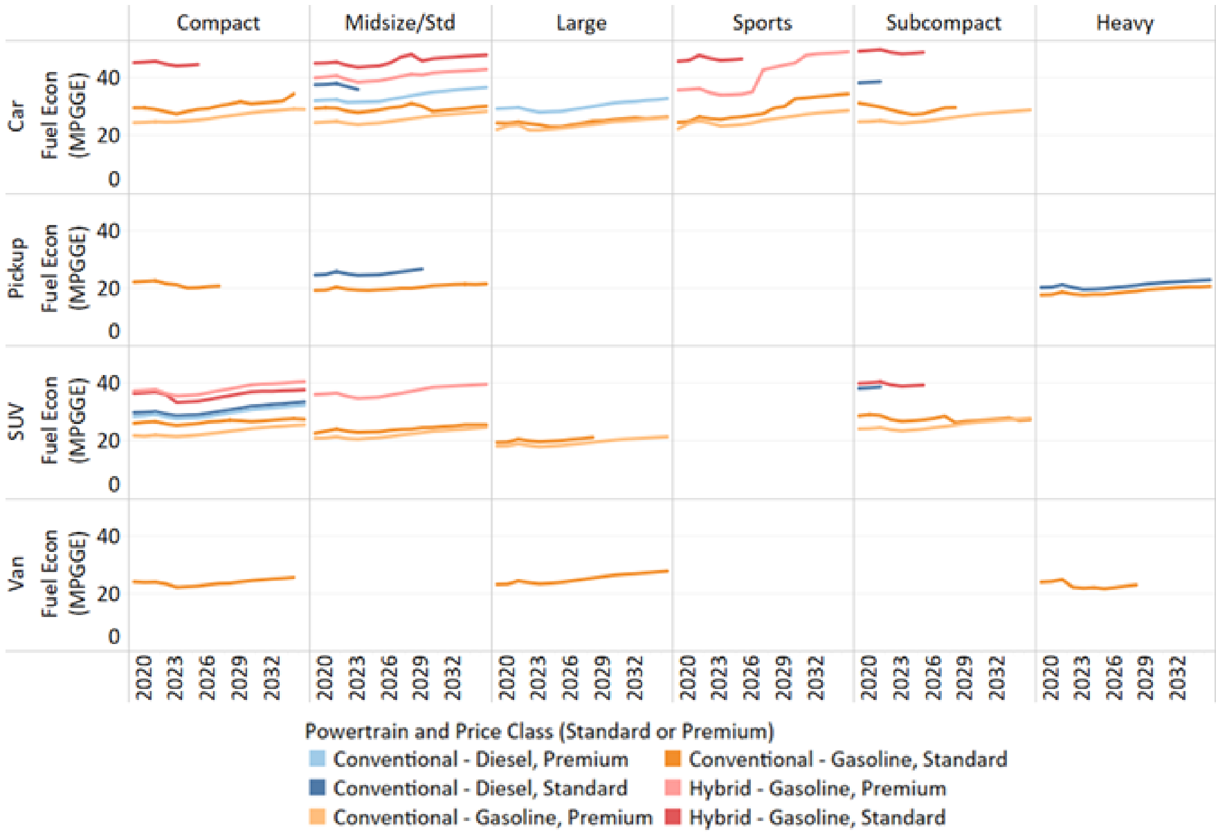

Figure 12. *Mid* scenario: fuel economy by model year, conventional powertrains – standard and premium classes

Data for this figure can be found in Appendix B.

Figures 13–15 plot projected acceleration and real-world fuel economy for alternative fuel vehicles. Acceleration (Figure 13) improves for a majority of alternative fuel vehicle classes over the simulation period (for 33 out of 48 classes in total). Variation is observed within powertrains. For BEVs, 13 out of 23 classes show improved acceleration, compared to 15 out of 19 PHEV classes and 5 out of 6 FCEV classes. Sales-weighted average acceleration across all BEV classes increases from 5.3 to 5.5 seconds, despite improvements within classes. This may be due to increased sales of some vehicle models with slower acceleration over the course of the simulation period. Sales-weighted average acceleration improves from 6.9 to 6.4 seconds across all PHEV classes (0.4% per year) and from 10.2 to 8.4 seconds across all FCEV classes (1% per year).

Similarly, a majority (33 out of 48) of alternative fuel vehicle classes show improved fuel economy over the simulation period (Figures 14–15). For BEVs, 11 out of 23 classes show improved fuel economy, compared to 16 out of 19 PHEV classes (considering electric and/or gasoline fuel economy improvements) and all FCEV classes. BEV fuel economy improvements tend to occur in larger vehicles (pickups and some SUV classes), while smaller vehicle classes are less likely to improve. On average across all classes, fuel economy declines for BEVs from 95 MPGGE (0.35 kWh per mile) to 81 MPGGE (0.41 kWh per mile) from 2019 to 2035. This is due to expanded sales of lower fuel-economy vehicles (pickups and SUVs) during the simulation period. Combined PHEV fuel economy improves from 94 to 95 MPGGE (0.1% per year), while

FCEV fuel economy improves from 73 to 74 MPGGE (0.1% per year). PHEV combined fuel economy is high due to high electric ranges (discussed in the following section). In 2035, fleet average fuel economy for all alternative fuel car classes ranges between 79 and 142 MPGGE, with a sales-weighted average of 105 MPGGE. Fleet average fuel economy for alternative fuel pickups, trucks, and SUVs ranges between 55 and 89 MPGGE, with a sales-weighted average of 76 MPGGE. These values are within or above those required by CAFE standards in 2035.

In some cases, fuel economy and acceleration trade off against one another for alternative fuel vehicles. This is further discussed in Section 3.2.4 in the context of trade-offs among other projected attributes.

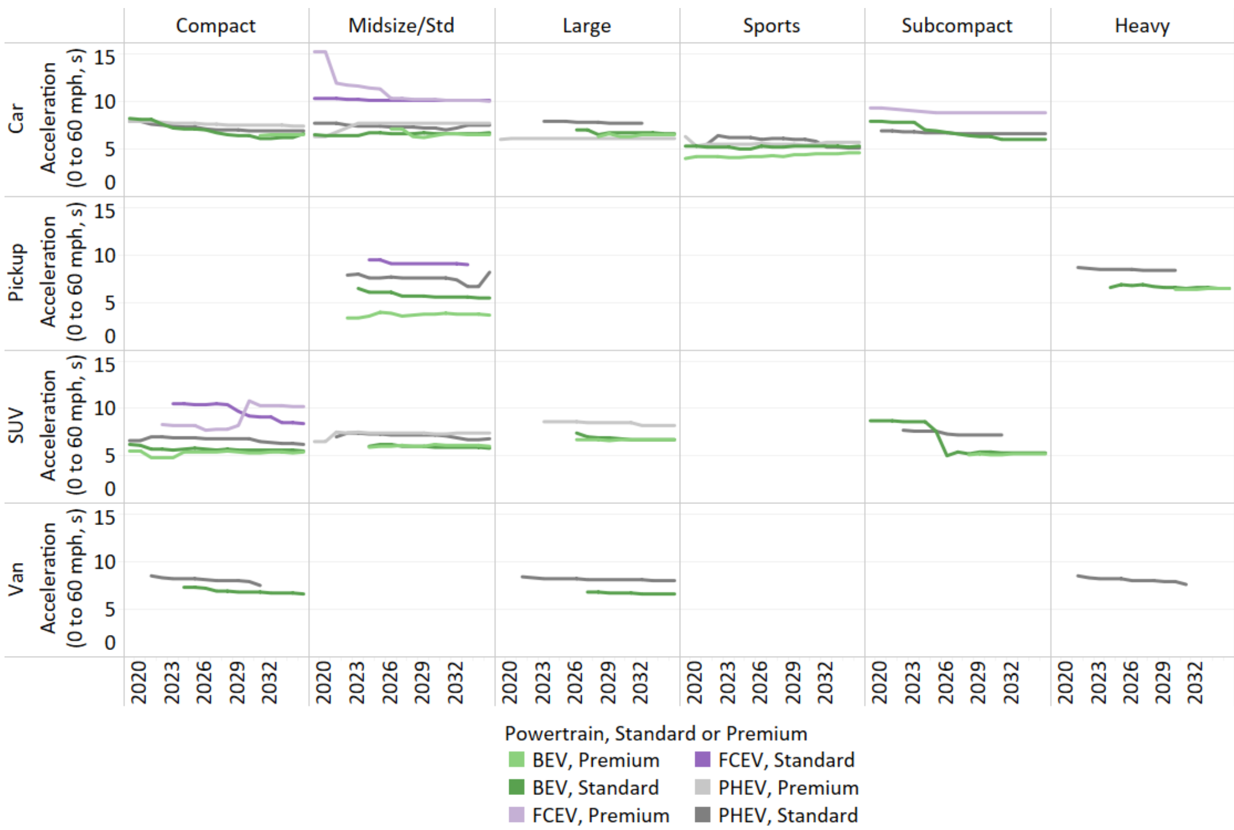

Figure 13. *Mid* scenario: acceleration by model year, BEV, PHEV, and FCEV powertrains – standard and premium classes

Data for this figure can be found in Appendix B.

Figure 14. *Mid* scenario: electric efficiency – BEV and PHEV (charge-depleting mode) powertrains by model year – standard and premium classes

Data for this figure can be found in Appendix B.

Figure 15. *Mid* scenario: gasoline-equivalent fuel economy, PHEVs (charge-sustaining mode) and FCEVs by model year – standard and premium classes

Data for this figure can be found in Appendix B.

3.2.2 Vehicle Range

We next present results for projected vehicle range (including total and electric-only for PHEVs) for all powertrains. Vehicle range is a particularly relevant attribute for BEVs, which may have shorter ranges than other powertrains due to high battery costs. In ADOPT, the value of BEV range to consumers is considered together with public EVSE availability. Widely available public EVSE may compensate for vehicles with lower ranges by reducing travel limitations. The value of additional range in ADOPT has diminishing returns after vehicles exceed ranges of 200–300 miles. There is less incentive in ADOPT to create vehicles with ranges above this threshold, as consumers may have stronger preferences for other attributes.

Figures 16 and 17 present projected total vehicle range for conventional and alternative fuel vehicles. In general, conventional and hybrid electric vehicle ranges tend to increase over time as fuel economy improves. Sales-weighted average conventional and hybrid vehicle range increases by 0.9% per year (from 442 miles to 507 miles from 2019 to 2035). However, this is not uniformly true for all vehicle classes. In some cases, such as premium hybrid sports cars and standard hybrid midsize cars, range may change abruptly. These changes are tied to the projected exit and entry of vehicle models within these classes. The low number of vehicle models in each class makes these classes highly sensitive to the entry or exit of additional models and to changes in the relative sales of each model.

For BEVs, projected vehicle range generally increases over the course of the simulation but remains lower than other powertrains in most vehicle classes (Figure 17). Sales-weighted average BEV range increases by 0.6% per year across all classes (from 219 to 240 miles from 2019 to 2035). By 2035, all BEV classes have ranges over 150 miles, with the majority over 200 miles. This is a result of decreasing battery costs, efficiency improvements, and ADOPT consumer preferences for vehicles over 200 miles of range. However, because the *Mid* scenario (and all scenarios) include fully available public EVSE by 2035, the value of additional range may be lower than the value of improvements in other attributes.

PHEVs and FCEVs have longer ranges than BEVs in general—over 250 miles for all classes except subcompact PHEV cars in 2035. In most but not all cases, total range increases for these classes as a result of fuel economy improvements. Sales-weighted average total PHEV range declines from 321 to 318 miles from 2019 to 2035, while FCEV range increases by 0.2% per year (326 to 336 miles) in the same period. For some premium PHEV classes (Car–Sports, Car–Large, Car–Midsize, and SUV–Midsize), total range abruptly declines between 2019 and 2023. These classes begin the simulation composed of only one or two vehicle models. The addition of new vehicle models between 2019 and 2023 strongly affects class-level attributes for total range and electric-only range (Figure 18).

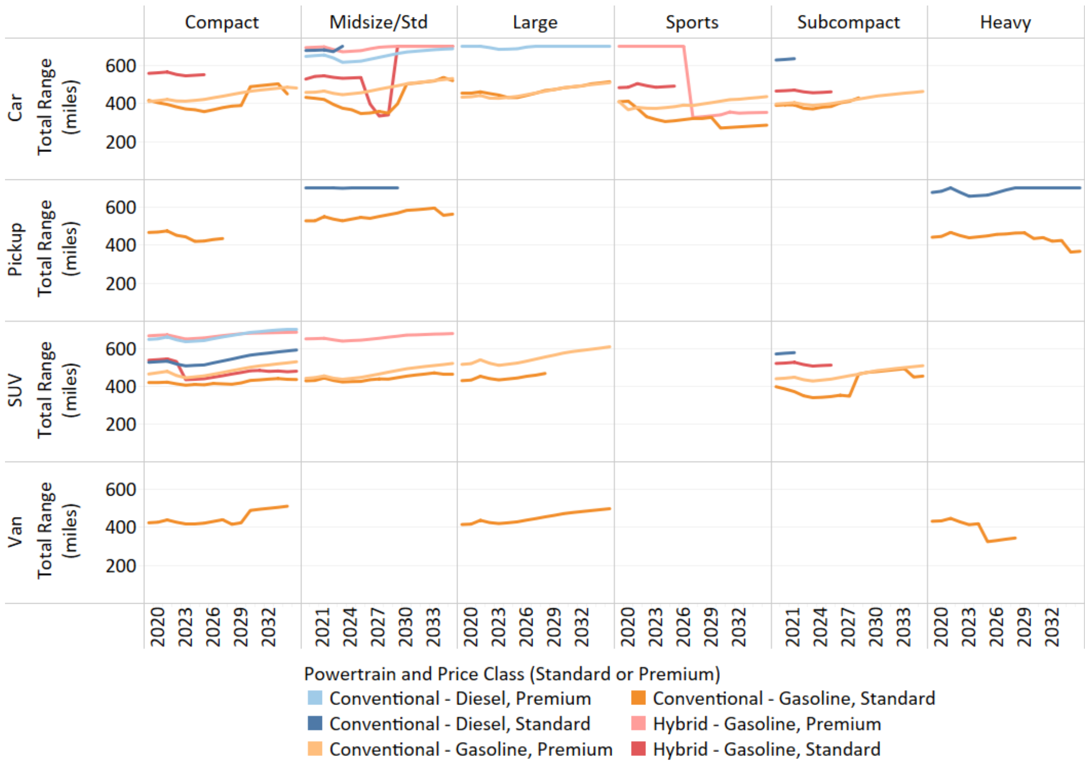

Figure 16. *Mid* scenario: vehicle range, conventional powertrains – standard and premium classes

Data for this figure can be found in Appendix B.

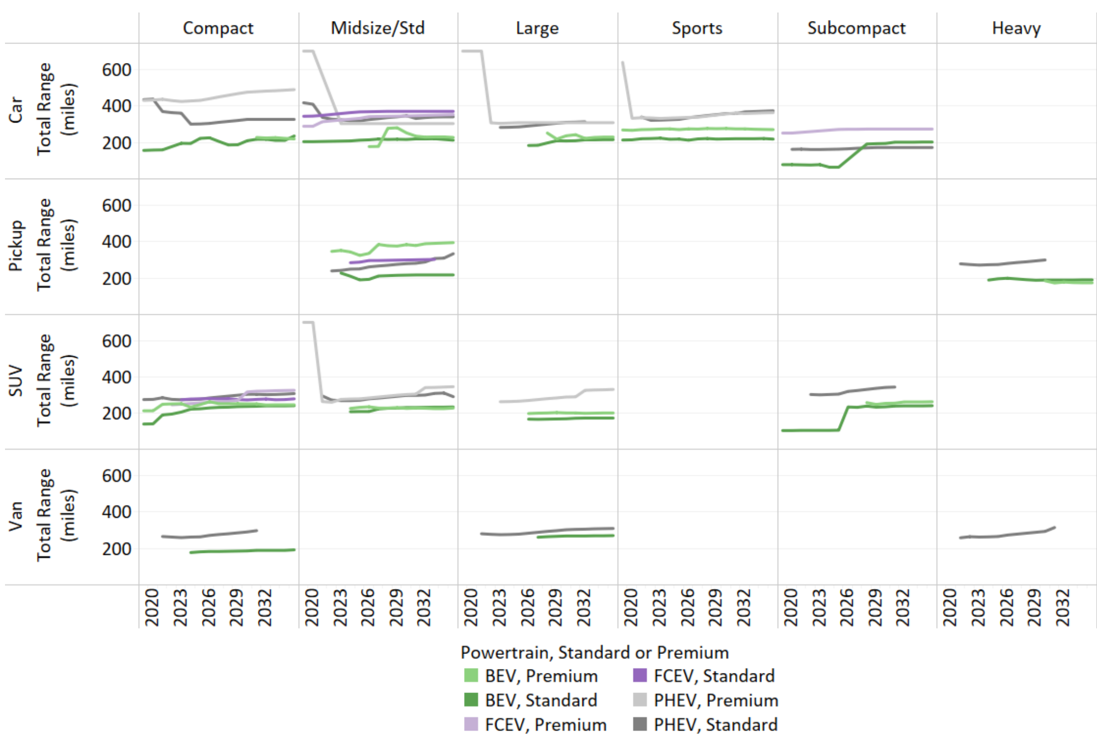

Figure 17. *Mid* scenario: total vehicle range, BEV, PHEV, and FCEV powertrains – standard and premium classes

Data for this figure can be found in Appendix B.

Finally, Figure 18 shows PHEV electric range. In general, ADOPT models consumer preferences for high PHEV ranges (between 50 and 100 miles), which increase with improvements in electric efficiency. PHEV sports cars have the greatest electric range, at over 100 miles in 2035. This may occur because additional battery size and power enables both faster acceleration and longer range. Electric range increases between the year of introduction and 2035 for almost all PHEV classes.

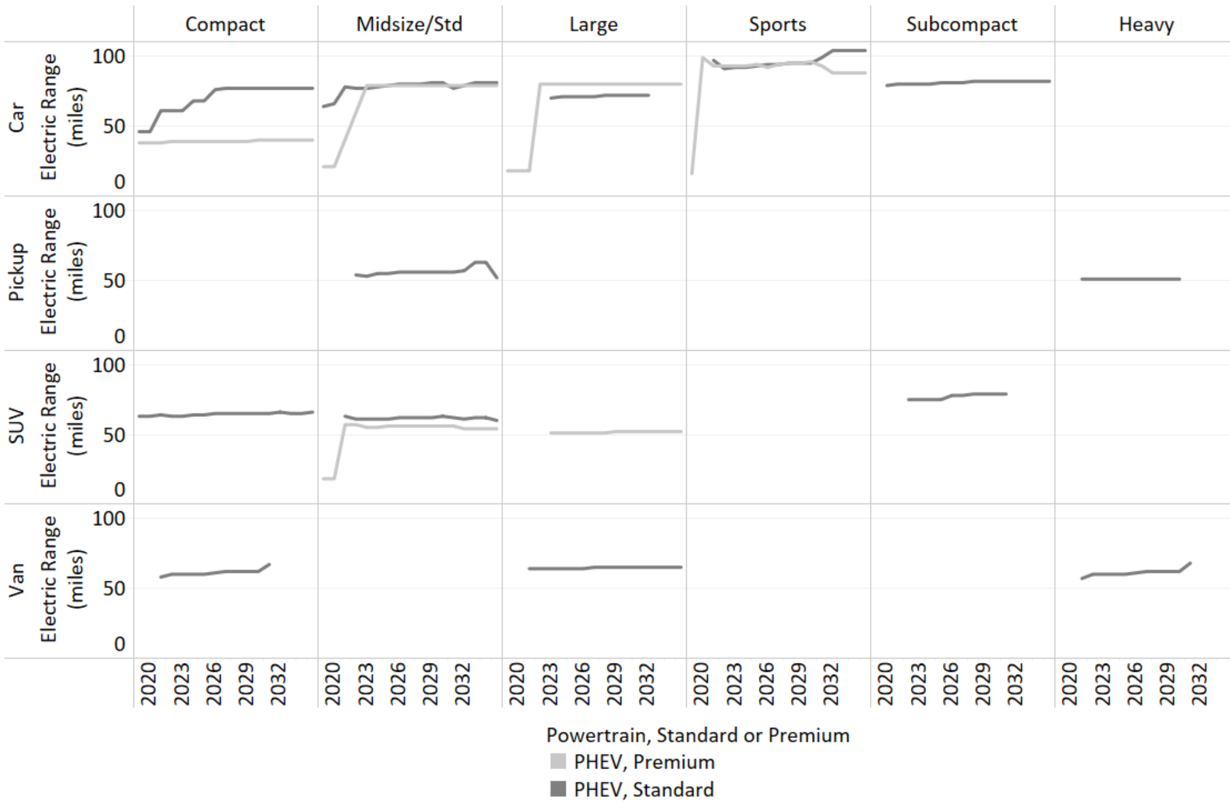

Figure 18. ***Mid*** **scenario: PHEV electric range – standard and premium classes**

Data for this figure can be found in Appendix B.

3.2.3 *MSRP*

Figures 19 and 20 present projected MSRP for conventional and ZEV powertrains. MSRP is influenced by trends in technology progress, trade-offs between MSRP and other vehicle attributes, and the projected exit and entry of vehicle models.

MSRP for conventional and hybrid powertrains remains relatively constant but may increase for some vehicle classes as a result of improving acceleration and vehicle light-weighting. Some classes show abrupt changes in MSRP due to changes in the number of vehicle models in each class. Sales-weighted average MSRP increases from $31,000 to $46,000 (in 2015 USD) from 2019 to 2035 (3% per year). However, this change is largely due to the projected exit of standard (lower-priced) vehicle models from the market due to competition with alternative fuel vehicles, rather than increases in vehicle cost among existing vehicles.

As battery and fuel cell prices decline, MSRP tends to decline for alternative fuel vehicles, with some exceptions. For BEVs, MSRP declines in 14 out of 23 classes, and sales-weighted average MSRP decreases from $47,400 in 2019 to $39,100 in 2035 (a 1% decrease per year). For PHEVs, MSRP declines in most (16 out of 19) classes. However, the sales-weighted average does not substantially change, increasing slightly from $32,100 to $32,700 due to changes in relative sales of different vehicle models. For FCEVs, MSRP declines in all vehicle classes, and sales-weighted average MSRP decreases from $40,000 to $39,000 from 2019 to 2035. For most vehicle classes, BEV and PHEV MSRPs are near or lower than MSRPs of corresponding conventional gasoline vehicles by 2035. PHEVs tend to be less expensive than BEVs. FCEV MSRP is near or lower than conventional gasoline MSRP in all classes by 2035.

Figure 19. *Mid* scenario: vehicle MSRP by model year, conventional powertrains – standard and premium classes

Data behind these figures can be found in Appendix B.

Figure 20. *Mid* scenario: vehicle MSRP by model year, BEV, PHEV, and FCEV powertrains – standard and premium classes

Data behind these figures can be found in Appendix B.

3.2.4 *Trade-offs Between Attributes for Alternative Fuel Vehicles*

Tables 7-9 summarize improvements in all projected attributes for alternative fuel vehicle classes and identify classes where trade-offs may occur. Trade-offs are largely the result of the projected entry of new vehicle models into each vehicle class, offering more choices to consumers in the simulation and different mixes of vehicle attributes. Trade-offs are most frequently observed between projected acceleration and fuel economy improvements. Nine classes (primarily BEVs) show improved acceleration but reduced fuel economy. Because BEVs and PHEVs are generally well above CAFE requirements, they are able to reduce efficiency and improve performance without incurring regulatory penalties. Conversely, nine classes show improved fuel economy but reduced acceleration (primarily premium BEV truck and SUV classes). Fuel economy improvements may be more valuable to consumers for vehicles with lower starting fuel economy.

Interactions between MSRP and other attributes are also observed. MSRP increases tend to be traded off against improvements in acceleration, range, or both attributes, particularly for BEVs. This is due to increases in battery sizes, which can lead to improvements in these attributes and increases in MSRP.

We note that two BEV classes do not have improvements in any of the attributes reported in this study. These classes may be affected by other factors, such as the creation of more expensive vehicle models with other luxury features (reflected in more expensive glider prices) that are not considered in the reported attribute projections.

Table 7. Summary of *Mid* Scenario Improvements in BEV Attributes, All Vehicle Classes

An 'X' notes improvement in the projected attribute from the year of introduction to the end of the simulation (or the point at which the class is discontinued).

Price Class	Size Class	Acceleration	Fuel Economy	Total Range	MSRP
Standard	Car-Compact	X		X	
	Car-Large	X		X	
	Car-Midsize		X	X	
	Car-Sports			X	X
	Car-Subcompact	X		X	
	Pickup-Heavy	X	X	X	X
	Pickup-Std	X	X		X
	SUV-Compact	X		X	X
	SUV-Large	X	X	X	X
	SUV-Midsize	X	X	X	X
	SUV-Subcompact	X		X	
	Van-Compact	X		X	X
	Van-Large	X	X	X	X
Premium	Car-Compact				
	Car-Large				
	Car-Midsize	X		X	
	Car-Sports			X	X
	Pickup-Heavy		X		X
	Pickup-Std		X	X	X
	SUV-Compact	X		X	
	SUV-Large		X	X	X
	SUV-Midsize		X	X	X
	SUV-Subcompact		X	X	X

Table 8. Summary of *Mid* Scenario Improvements in PHEV Attributes, All Vehicle Classes

An 'X' notes improvement in the projected attribute from the year of introduction to the end of the simulation (or the point at which the class is discontinued).

Price Class	Size Class	Acceleration	Fuel Economy	Total Range	MSRP
Standard	Car-Compact	X			X
	Car-Large	X	X	X	X
	Car-Midsize	X	X		
	Car-Sports	X	X	X	
	Car-Subcompact	X	X	X	X
	Pickup-Heavy	X	X	X	X
	Pickup-Std		X	X	
	SUV-Compact	X	X	X	X
	SUV-Midsize	X	X		X
	SUV-Subcompact	X	X	X	X
	Van-Compact	X	X	X	X
	Van-Heavy	X	X	X	X
	Van-Large	X	X	X	X
Premium	Car-Compact	X	X	X	X
	Car-Large		X		X
	Car-Midsize				X
	Car-Sports	X	X		X
	SUV-Large	X	X	X	X
	SUV-Midsize				X

Table 9. Summary of *Mid* Scenario Improvements in FCEV Attributes, All Vehicle Classes

An 'X' notes improvement in the projected attribute from the year of introduction to the end of the simulation (or the point at which the class is discontinued).

Price Class	Size Class	Acceleration	Fuel Economy	Total Range	MSRP
Standard	Car-Midsize	X	X	X	X
	Pickup-Std	X	X	X	X
	SUV-Compact	X	X	X	X
Premium	Car-Midsize	X	X	X	X
	Car-Subcompact	X	X	X	X
	SUV-Compact		X	X	X

3.3 Comparisons Across Scenarios

Finally, we compare the *Mid* scenario to results from other scenarios (*Low*, *High*, and *Bookend*). These scenarios differ across fuel prices, technology cost and performance specifications (particularly battery prices), CAFE standards, vehicle purchase subsidies, state and federal tax credits, and public PEV infrastructure assumptions. The *Low* scenario is least favorable to alternative fuel vehicles, while the *High* and *Bookend* scenarios are most favorable to alternative fuel vehicles. The *Bookend* scenario also includes a 100% ZEV sales mandate by 2035 in California, implemented in the form of incentives for ZEVs and penalties for conventional and hybrid electric gasoline and diesel vehicles. All non-ZEV powertrains sold in California are phased out by 2035 in the *Bookend* scenario. However, we note that under real-world conditions, retirement may occur earlier due to forward-looking behavior by manufacturers.

3.3.1 *Number of Vehicle Models*

In ADOPT, the number of vehicle models offered for a powertrain is correlated to vehicle sales. As sales of a vehicle powertrain expand, the number of vehicle models increases, providing more options for consumers. Conversely, low-selling vehicle models are retired from the market. Vehicle attribute projections for classes with a small number of models may be substantially influenced by the expansion or contraction of the number of vehicle models in a class.

Figure 21 plots the number of projected vehicle models by scenario, price class (standard or premium), and powertrain for BEVs, PHEVs, FCEVs, and conventional and hybrid vehicles (combining conventional gasoline, conventional diesel, and hybrid electric vehicles). Across all scenarios, some similarities are observed. First, all scenarios display a pattern of early market growth for PHEVs (between 2021 and 2025) and late market decline (between 2030 and 2035). The number of BEV models increases as the number of PHEV models decreases, reflecting competition between powertrains. For standard vehicles, BEVs have the greatest number of vehicle models by 2035. However, for premium vehicles, conventional and hybrid vehicles have the greatest number of vehicle models in all scenarios except the *Bookend* scenario. FCEVs have fewer than 15 models in all years and scenarios.

We also observe some differences across scenarios. In the *Low* and *Mid* scenarios, higher battery price assumptions result in the creation of more expensive BEVs in ADOPT. As a result, the number of premium BEV models is greater than the number of standard models. This pattern reverses in the *High* and *Bookend* scenarios, consistent with the expansion of BEVs into higher-sales, lower-cost market segments. Overall, the *High* and *Bookend* scenarios have the greatest number of BEV models in 2035, followed by *Mid* and *Low* scenarios. The *Low* scenario has fewer PHEV models and more conventional and hybrid models than other scenarios, especially in the early market (2022–2024). This is a result of more conservative technology and policy assumptions, which produce lower PHEV sales and induce the creation of fewer vehicle models. The *Low* scenario also has more standard conventional and hybrid models than other scenarios in all years as a result of these assumptions.

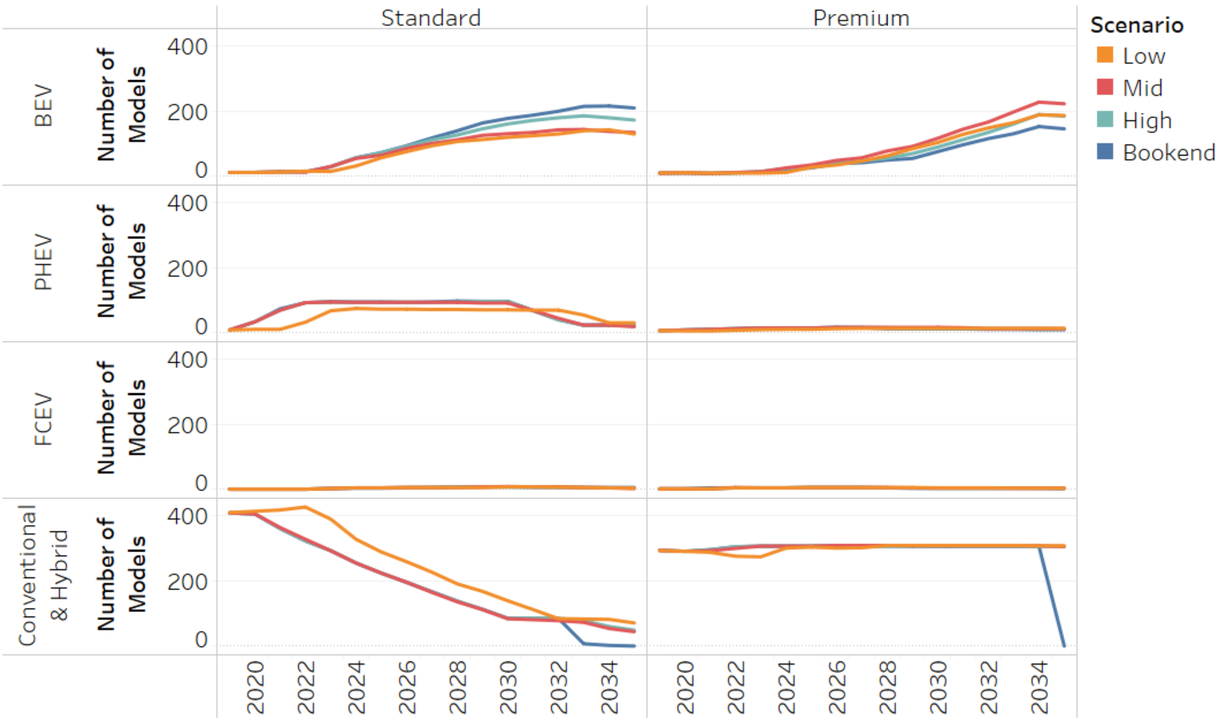

Figure 21. Number of vehicle models by model year, powertrain, and scenario.

Data behind these figures can be found in Appendix B.

3.3.2 Conventional Fuel Economy and CAFE Standards

Projected conventional fuel economy is driven by both technology improvement assumptions and CAFE standards. Across scenarios, differences in the market share of alternative-fuel vehicles affect projected fuel economy for conventional vehicles as a result of CAFE standards. The *Low* scenario has the lowest rate of technology improvement for both conventional and alternative-fuel powertrains and the lowest CAFE standards (along with the *Mid* scenario). However, Figure 22 shows that in early years (2022 to 2024), the *Low* scenario has the highest projected conventional gasoline fuel economy of all scenarios for the vehicle classes shown. Similar patterns are seen in the vehicle classes that are not plotted. This result is due to low PHEV sales in early years in the *Low* scenario, which increase the level of fuel economy improvements required for conventional and hybrid electric vehicles to meet CAFE. After 2024, BEV sales increase in all scenarios, lessening the requirements for conventional and hybrid electric vehicles to improve to meet CAFE standards. Subsequently, fuel economy improvements for conventional vehicles are more influenced by technology improvement assumptions, resulting in the *High* and *Bookend* scenarios having the highest projected fuel economy in 2035. As shown in the *Mid* scenario, conventional fuel economy in all scenarios is well below the fleet averages required by CAFE standards. Sales-weighted average projected conventional and hybrid electric fuel economy in 2035 ranges from 26 MPGGE (*Low* scenario) to 30 MPGGE (*High* scenario). The *Bookend* scenario has no sales of conventional or hybrid electric vehicles in 2035 in California but is similar to the *High* scenario in other years.

Figure 23 plots sales-weighted average projected real-world fuel economy for conventional and hybrid powertrains and for all powertrains for the U.S. market, compared against CAFE standards. Because the market considered includes the entire United States, this figure differs somewhat from Figure 22, which includes only California sales. In all scenarios except the *Low* scenario, CAFE standards are met in all years. In all scenarios, average fuel economy for conventional and hybrid powertrains is substantially below CAFE fuel economy requirements for the entire U.S. fleet. The *Low* scenario has the highest conventional and hybrid average fuel economy between 2019 and 2029, as more fuel-efficient conventional vehicles must be sold to comply with CAFE. After 2030, increased BEV sales lessen fuel economy requirements for conventional vehicles.

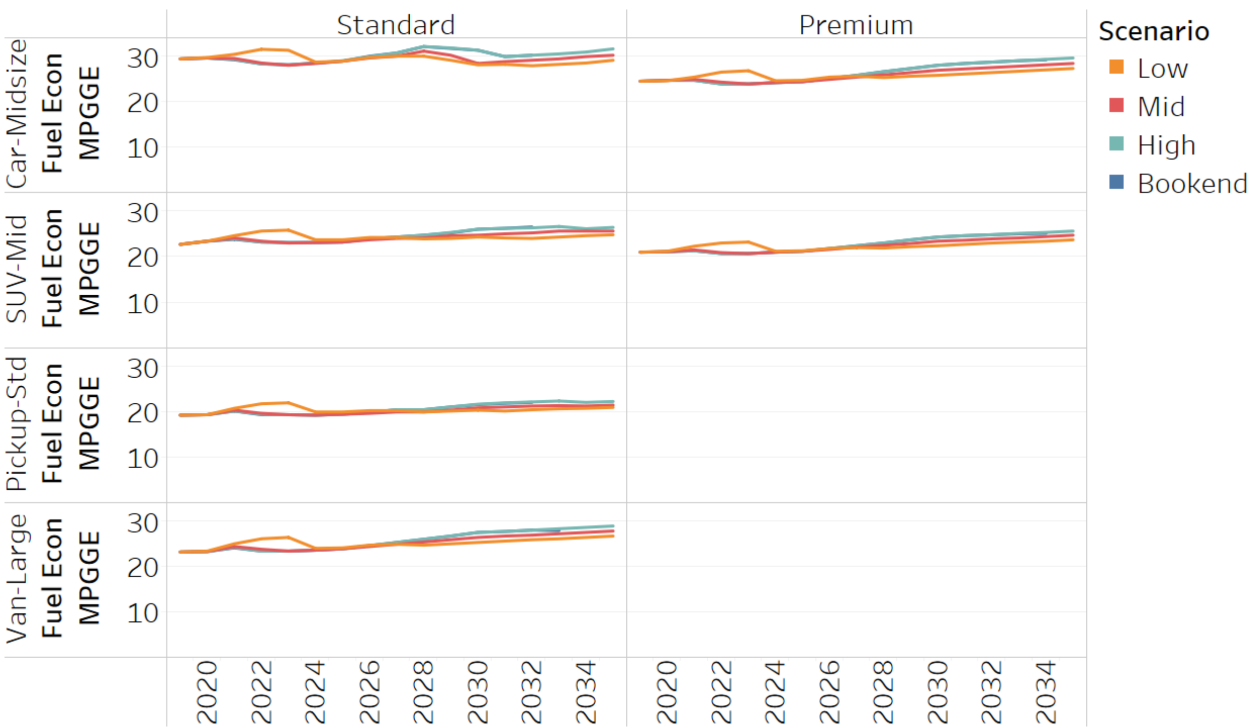

Figure 22. Fuel economy, conventional gasoline-powered vehicles, selected vehicle classes – all scenarios, California market

Data behind these figures can be found in Appendix B.

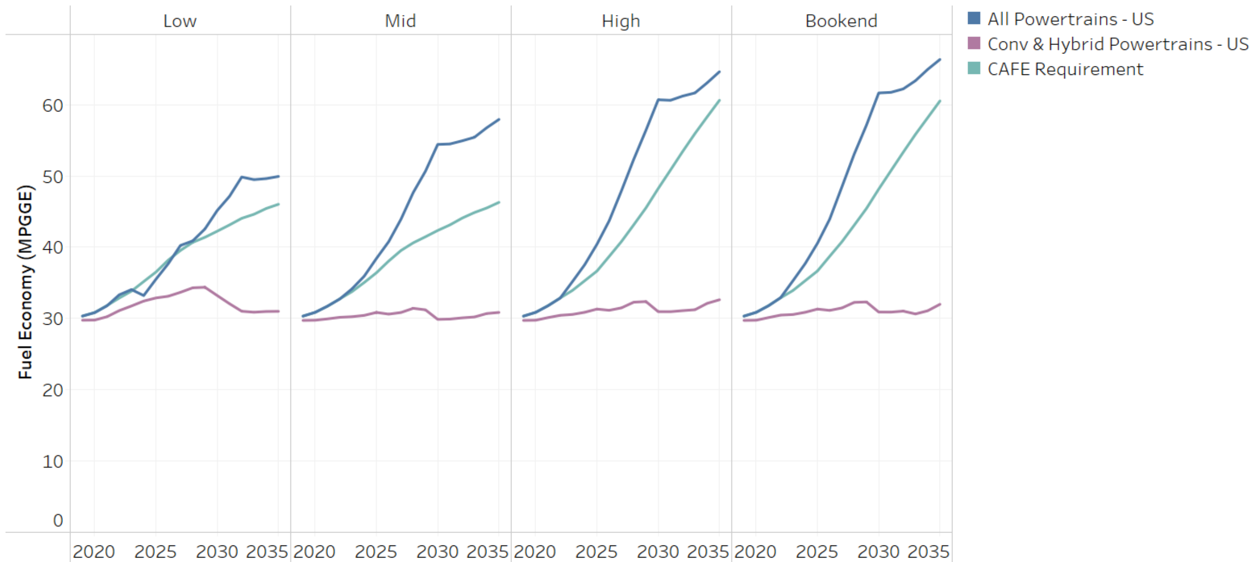

Figure 23. U.S. average fuel economy versus CAFE standards, conventional and hybrid powertrains, and all powertrains, all scenarios.

CAFE standards in this figure differ from CAFE standards shown in Figure 5 because real-world MPGGE is plotted. Conventional fuel economy is shown for the *Bookend* scenario in 2035 because values include vehicles sold in the entire U.S. market.

3.3.3 BEV Attributes

Due to differences in technology and policy assumptions, the largest differences between scenarios are observed for BEVs. Figures 24 and 25 plot trends in projected BEV MSRP and range, respectively, for selected vehicle classes. Due to differences in technology assumptions, particularly the price of batteries, the *High* and *Bookend* scenarios tend to have the lowest MSRP, while the *Low* scenario tends to have the highest MSRP. Projected BEV MSRP tends to decline over time in most scenarios and vehicle classes, but this does not always occur due to trade-offs between MSRP and improvements in other attributes or changes in the number of models in a class.

Most scenarios project constant or increasing range after 2030 in a majority of vehicle classes, when vehicle classes stabilize and are less sensitive to the entry and exit of vehicle models. In the *Low* scenario, electric range slightly declines for some classes as vehicles with lower MSRP and smaller batteries are more competitive. In the *Bookend* scenario, the premium Pickup–Standard class declines in range in MY 2034 due to the exit of an influential vehicle model (reclassified as standard due to its price falling below the $42,000 MSRP threshold). By 2035, a majority of BEV classes have ranges over 200 miles in all scenarios, and most vehicle classes have ranges between 200 and 300 miles.

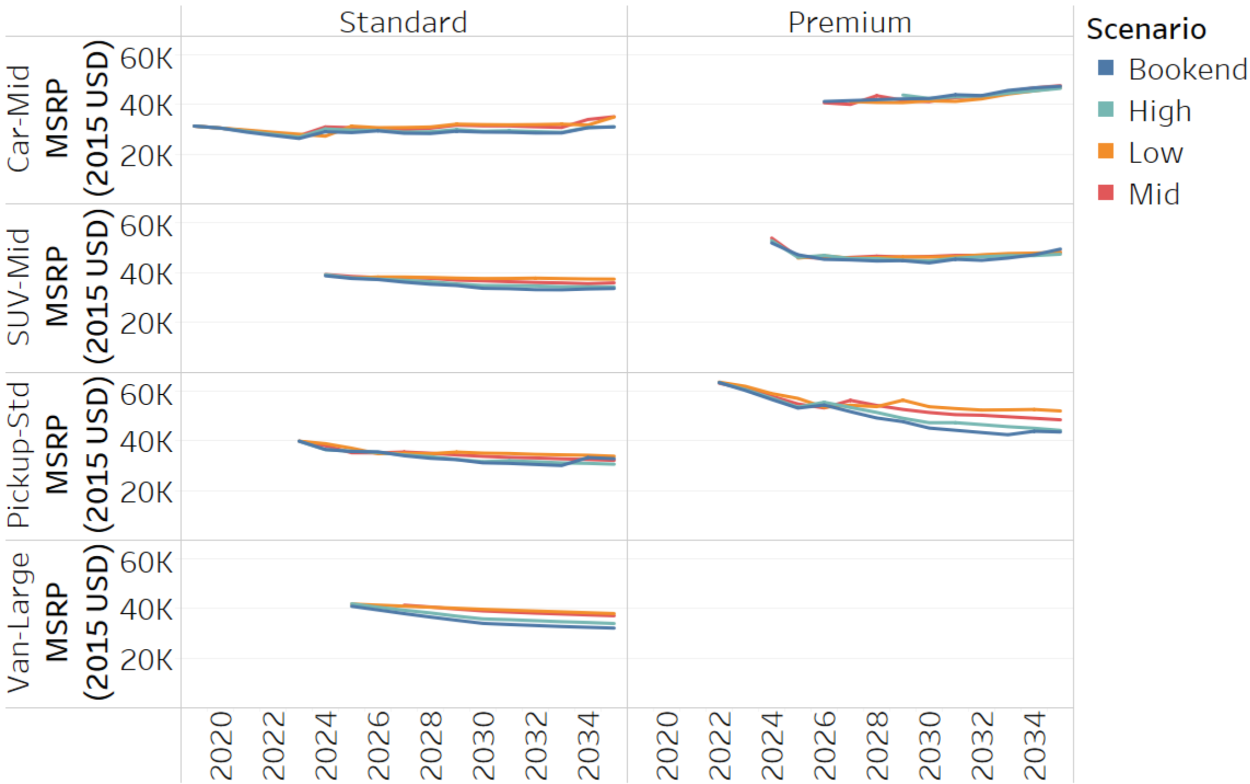

Figure 24. BEV MSRP by scenario for selected vehicle classes.

Data behind these figures can be found in Appendix B.

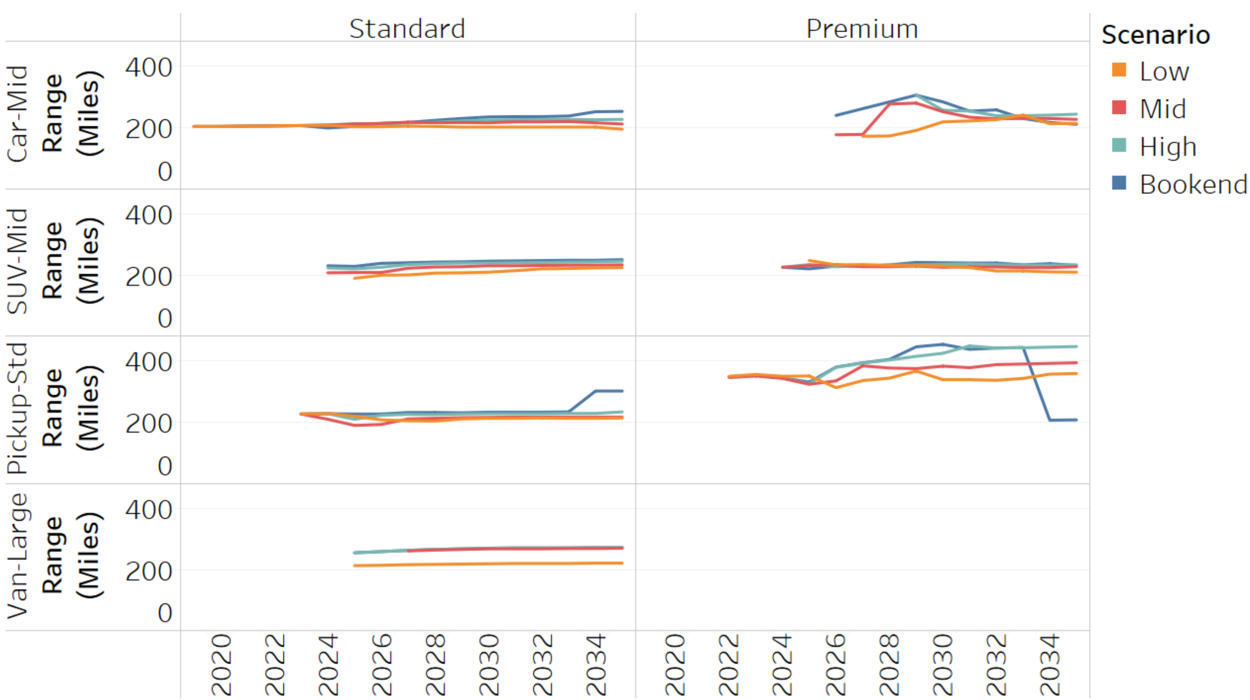

Figure 25. BEV electric range by scenario, selected vehicle classes.

Data behind these figures can be found in Appendix B.

Tables 10 and 11 summarize BEV attribute values in 2035 relative to conventional gasoline attributes in all scenarios except the *Bookend* scenario. Table 10 shows the number of vehicle classes in which a BEV class has more favorable projected attribute values than a conventional vehicle for classes in which both powertrains are represented. By 2035, BEV powertrains are represented in more vehicle size classes than conventional gasoline powertrains for all standard classes and for almost all premium classes. In the *Low* scenario, BEV MSRP is lower than conventional gasoline MSRP in 5 out of 11 standard vehicle size classes in which both powertrains are represented. In the *High* scenario, this share increases to 9 out of 10 standard vehicle size classes. Similar trends are observed for projected MSRP for premium vehicle size classes and for acceleration for standard and premium vehicle size classes. BEVs have higher fuel economy and lower range than conventional gasoline vehicles in all vehicle classes in all scenarios.

Table 11 summarizes the sales-weighted average BEV and conventional gasoline attribute values that result from different scenario assumptions. These values are not meant to be representative of vehicle size classes or individual vehicle models. From the *Low* to *Bookend* scenarios, the number of standard BEV models increases, BEV MSRP declines on average (except in the *Bookend* scenario), and BEV range and acceleration improve on average. BEV fuel economy does not improve on average from the *Low* to *Bookend* scenarios, reflecting a tendency for improvements in performance to be preferred over improvements in efficiency. For premium vehicles, these trends are somewhat different. The number of premium BEV models declines in *High* and *Bookend* scenarios, as BEVs are cheaper on average and more likely to be classified as standard vehicles. BEV MSRP declines on average from the *Low* to *High* scenarios. The *Bookend* scenario has lower average BEV range, higher average BEV MSRP, and slower BEV average acceleration than other scenarios. This is primarily due to more vehicles being classified as standard in this scenario that would be considered premium in other scenarios. This leaves fewer premium models in the *Bookend* scenario and shifts the composition of attributes.

By 2035, BEVs have lower average MSRP than corresponding conventional gasoline vehicles in all scenarios except the *Low* scenario (for standard vehicles). BEVs also have faster average acceleration and higher fuel economy in all scenarios (82 to 85 MPGGE on average, versus 26 to 30 MPGGE for conventional vehicles). BEV range remains lower on average than conventional vehicles due to diminishing returns to additional range modeled in ADOPT and trade-offs between range and other attributes such as price. We caveat this result by noting that individual vehicle classes and models may vary when comparing powertrains; these results reflect sales-weighted average trends across the entire LDV market.

Table 10. Comparison of BEV and Conventional Gasoline Vehicle Attributes, All Vehicle Classes, 2035

Price Class	Scenario	Number of Classes with BEV	Number of Classes with Conventional Gas	Number of Classes with Both BEV and Conventional Gas	Number of BEV Classes with Lower MSRP	Number of BEV Classes with Greater Range	Number of BEV Classes with Faster Acceleration	Number of BEV Classes with Higher Fuel Economy
Standard	*Low*	14	11	11	5 (45%)	0	8 (73%)	11 (100%)
	Mid	13	9	9	6 (66%)	0	5 (55%)	9 (100%)
	High	13	10	10	9 (90%)	0	10 (100%)	10 (100%)
	Bookend	13	0	0	-	-	-	-
Premium	*Low*	9	9	7	6 (86%)	0	5 (71%)	7 (100%)
	Mid	10	9	8	7 (88%)	0	8 (100%)	8 (100%)
	High	10	9	8	7 (88%)	0	8 (100%)	8 (100%)
	Bookend	9	0	0	-	-	-	-

Table 11. Sales-Weighted Average Attributes by Scenario, Standard and Premium BEVs and Conventional Gasoline Vehicles (Parentheses), 2035.

Attributes are aggregated over all vehicle size classes. The *Bookend* scenario does not sell conventional gasoline vehicles in 2035.

Price Class	Scenario	Average Acceleration (0–60 mph, s)	Average Fuel Economy (MPGGE)	Average Range (miles)	Average MSRP (2015 U.S. dollars)	Number of Models
Standard	Low	5.9 (6.8)	82 (26)	219 (446)	$35,224 ($33,707)	130 (67)
	Mid	5.7 (6.6)	82 (27)	229 (445)	$33,721 ($34,526)	135 (40)
	High	5.6 (6.6)	83 (30)	241 (474)	$32,072 ($36,280)	173 (43)
	Bookend	5.4 (-)	82 (-)	258 (-)	$32,115 (-)	210 (-)
Premium	Low	5.4 (6.4)	85 (26)	242 (488)	$49,096 ($53,190)	187 (277)
	Mid	5.3 (6.4)	84 (28)	258 (513)	$48,020 ($54,071)	223 (275)
	High	5.0 (6.4)	84 (29)	276 (538)	$46,714 ($55,202)	183 (276)
	Bookend	5.7 (-)	84 (-)	240 (-)	-	146 (-)

4 Conclusions and Future Research

In this study, we used the ADOPT model to develop a set of vehicle attribute projection scenarios for the California LDV market for 30 vehicle classes and six powertrains. We developed four scenarios with different technological, economic, and policy assumptions with varying levels of favorability for PEV and FCEV adoption. The resulting attribute projections are influenced by both technology assumptions and consumer preferences for vehicle attributes. These attribute projections are scenario-dependent and subject to substantial uncertainty stemming from input assumptions and model design. They do not reflect a "definitive" set of attribute projections, but instead may be viewed as potential trajectories that the future vehicle market may evolve toward. Our results suggest the following:

- Across all scenarios, we observe substantial expansion in the number of BEV models, which is consistent with an expansion in sales. PHEV expansion is more limited, with the number of PHEV models growing earlier in the simulation period and declining later in the simulation period due to competition with BEVs. Little expansion in FCEVs is observed. Decreases in the number of conventional vehicle models are concentrated in less expensive (standard) vehicle classes, while the number of conventional models in premium vehicle classes remains relatively constant. Only the *Bookend* scenario eliminates all conventional vehicle classes due to its 100% ZEV sales mandate in 2035.
- We observe constant or increasing fuel economy for the majority of conventional vehicle classes across scenarios. Electric efficiency for BEVs and PHEVs in electric-only mode improves for most vehicle classes but trades off with improved acceleration for some vehicle classes. All scenarios exceed CAFE standards in almost every year due to the high number of BEV and PHEV sales. However, fuel economy for conventional vehicle classes is lower than CAFE fleetwide requirements due to increased ZEV sales.
- BEV range increases in the majority of vehicle classes in all scenarios from the start to end of the simulation period. The *Low* scenario has lower range in most vehicle classes as a result of higher battery prices and trade-offs between range and MSRP. BEV range is between 200 and 300 miles for most vehicle classes in all scenarios.
- BEV MSRP remains constant or declines in most scenarios and classes as a result of decreases in battery cost. BEV MSRP is lowest on average in the *Bookend* and *High* scenarios, which have the most aggressive battery cost reductions. BEV MSRP increases some vehicle classes as a result of trade-offs between MSRP and other attributes.
- Results in some vehicle classes are highly sensitive to the projected entry and exit of vehicle models, which may produce abrupt changes in classes made up of fewer vehicle models. BEV results contain more variability in earlier simulation years (prior to 2025), when vehicle classes are smaller, and stabilize in later years as the number of model options in each class grows. This is a reflection of the approach, which relies on sales-weighted average attributes and a high number of vehicle classes (30 in total).

Future research might include the following:

- Our results suggest that further study of trade-offs between zero-emission vehicle sales mandates and the fuel economy of conventional vehicles may be warranted. While we observe constant or increasing fuel economy for conventional vehicles in most scenarios, conventional fuel economy is lower than CAFE standards for fleet average fuel economy due to increases in ZEV sales. It is possible that future scenarios with a combination of high ZEV sales and low CAFE standards may produce outcomes in which conventional vehicle fuel economy decreases due to lower regulatory pressures.

- We might investigate the finding that the number of more expensive (premium) conventional vehicle models is less likely to decrease in response to an expanded BEV market. This research might include enhancing our understanding of preferences for premium vehicles among high-income consumers and the elasticity of demand for these vehicles in response to incentives.
- We might further refine our representation of charging infrastructure for BEVs and PHEVs. Our current representation assumes that all PEVs have access to reliable overnight charging, with public charging providing additional value to consumers when available. An expanded modeling framework that includes representation of heterogeneity in overnight charging access, as well as a better understanding of the role of public charging in incentivizing electric vehicle purchases across consumer segments, would allow us to more fully model the market for BEVs, particularly as they become more widespread within multiple consumer segments.

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Appendix A: ADOPT Vehicle Database Updates

To better represent existing and future BEV models in ADOPT, we added the following vehicles to the ADOPT vehicle database:

- Tesla Model 3, introduced beginning in 2018.
- Tesla Cybertruck, with a planned introduction in 2022.

Details of the Tesla Cybertruck are described in Table A1 and are based on publicly available data as of May 2021, at the time that simulations were performed. We additionally added a subset of Class 2b and 3 vehicles to the ADOPT vehicle database, as described in Table A2.

Table A1. Tesla Cybertruck Specifications in the ADOPT Model

Model	Cybertruck Single-Motor Rear-Wheel Drive	Cybertruck Dual-Motor All-Wheel Drive	Cybertruck Tri-Motor All-Wheel Drive
ADOPT introduction year	2023	2022	2022
MSRP [a]	$39,900	$49,900	$69,900
Curb weight (kg) [b]	2,180	2,710	4,003
EPA range (miles) [a]	250	300	500
Acceleration 0–60 mph (s) [a]	6.5	4.5	2.9
Battery size (kWh) [b]	100	120	260
Motor power (kW) [c]	285	500	597

[a] As announced by Tesla (2021)

[b] Estimated using ADOPT technology assumptions from Islam et al. (2020) (weight) and FASTSim simulation (battery size)

[c] We assume that the single-motor rear-wheel drive uses the Tesla Model S rear-wheel drive motor, while the dual- and tri-motor models use the forthcoming Raven and Plaid motors, respectively (Car and Driver 2021; Seabaugh 2019).

Table A2. Class 2b and 3 Vehicles Added to the ADOPT Vehicle Database

Class 2b	Class 3
Ford F-250	Ford F-350
GMC Sierra 2500	GMC Sierra 3500 HD
Chevrolet Silverado 2500HD	Chevrolet Silverado 3500HD
Dodge Ram 2500	Dodge Ram 3500

Appendix B: Supplemental Data

Supplemental data, including tables for all attributes, scenarios, classes, and powertrains explored in this report, can be found in the Excel spreadsheets that accompany this report. These spreadsheets can be found at https://data.nrel.gov/submissions/195.