Cost of Plug-in Electric Vehicle Ownership: The Cost of Transitioning to Five Million Plug-In Vehicles in California

June 2021

A Research Report from the National Center for Sustainable Transportation

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ITS UCDAVIS INSTITUTE OF TRANSPORTATION STUDIES

TECHNICAL REPORT DOCUMENTATION PAGE

1. Report No.	2. Government Accession No.	3. Recipient's Catalog No.
NCST-UCD-RR-21-05	N/A	N/A

4. Title and Subtitle Cost of Plug-in Electric Vehicle Ownership: The Cost of Transitioning to Five Million Plug-In Vehicles in California	**5. Report Date** June 2021 **6. Performing Organization Code** N/A
7. Author(s) Debapriya Chakraborty, PhD, https://orcid.org/0000-0001-9898-4068 Koral Buch, https://orcid.org/0000-0002-6909-6122 Gil Tal, PhD, https://orcid.org/0000-0001-7843-3664	**8. Performing Organization Report No.** UCD-ITS-RR-21-20
9. Performing Organization Name and Address University of California, Davis Institute of Transportation Studies 1605 Tilia Street, Suite 100 Davis, CA 95616	**10. Work Unit No.** N/A **11. Contract or Grant No.** Caltrans 65A0686 Task Order 032 USDOT Grant 69A3551747114
12. Sponsoring Agency Name and Address California Department of Transportation Division of Research, Innovation and System Information, MS-83 1727 30th Street, Sacramento, CA 95816 U.S. Department of Transportation Office of the Assistant Secretary for Research and Technology 1200 New Jersey Avenue, SE, Washington, DC 20590	**13. Type of Report and Period Covered** Final Report (January 2020 – December 2020) **14. Sponsoring Agency Code** USDOT OST-R

15. Supplementary Notes

DOI: https://doi.org/10.7922/G257199D
Dataset DOI: https://doi.org/10.25338/B80D10

16. Abstract

Total cost of ownership (TCO) studies are generally used as a tool to understand how and when plug-in electric vehicle (PEV) technology will reach cost parity with conventional fuel vehicles. Post cost-parity, the PEV market should be able to sustain without government intervention. The researchers present here a detailed analysis of vehicle manufacturing costs and market-level TCO accounting for technology uncertainties, behavioral heterogeneity, and key decision parameters of automakers. Using the estimates of the vehicle manufacturing costs, they estimate the cost of electrification of California's LDV fleet to achieve the state's net-zero emission goal by 2045. The results suggest that PEVs may not be cost competitive even in 2030 without stronger policy support and automakers initiative. Moreover, TCO is not a single number, and the cost of electrification will vary across the population based on the cost of vehicles available in the market, their charging capabilities at home and public, and energy costs. The TCO estimates and the cost of fleet electrification analysis not only has important implications for policymakers but can also offer a foundation for understanding the effect of market dynamics on the cost-competitiveness of the PEV technology.

17. Key Words	18. Distribution Statement
Total cost of ownership, zero emission vehicles, teardown analysis, market segments	No restrictions.

19. Security Classif. (of this report)	20. Security Classif. (of this page)	21. No. of Pages	22. Price
Unclassified	Unclassified	79	N/A

Form DOT F 1700.7 (8-72) Reproduction of completed page authorized

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Acknowledgments

This study was funded, partially or entirely, by a grant from the National Center for Sustainable Transportation (NCST), supported by the U.S. Department of Transportation (USDOT) and the California Department of Transportation (Caltrans) through the University Transportation Centers program. The authors would like to thank the NCST, the USDOT, and Caltrans for their support of university-based research in transportation, and especially for the funding provided in support of this project. We would also like to thank the Karim Hamza from the Toyota Research Group and the participants of the STEPS Plus Fall Symposium (December 2020) for their comments and feedback.

NCST

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EXECUTIVE SUMMARY

Starting with Assembly Bill 32 (AB 32) in 2006 that set the greenhouse gas (GHG) reduction targets for the state of California, numerous legislations have been passed to support the mission. In the realm of transportation, the state government has a target of 5 million zero-emission vehicles (ZEVs) on California roads by 2030 and net-zero carbon emission from the sector by 2045. Over the past decade, there has been a slew of policy initiatives to support the adoption of ZEVs, primarily battery electric vehicles (BEV), plug-in hybrid vehicles (PHEV), and fuel cell electric vehicles (FCEVs). Among other regulations, policymakers have implemented rebate and tax credit programs to reduce the purchase cost and encourage adoption. Though these initiatives have helped the ZEV market so far, there is increasing concern about the overall cost efficiency of these technologies, particularly in absence of the incentives. The cost effectiveness of ZEVs compared to internal combustion engine vehicles (ICEVs) and conventional hybrid electric vehicles (HEVs) are subject to not just improvements in vehicle manufacturing technology in the ZEV market (primarily, battery technology and cost of battery) but also changes in gasoline price, electricity price, travel behavior of vehicle buyers, and government policies like the Corporate Average Fuel Economy (CAFE) standards that mandate vehicle manufacturers to improve the fuel economy of their ICEV fleet. Focusing primarily on BEVs and PHEVs (referred to as plug-in electric vehicles (PEVs)), in this project, we first estimate their average total cost of ownership (TCO) for the period 2020-2030, their cost-competitiveness with ICEVs, and consequently the cost of electrification of California's LDV fleet of ~5 million vehicles by 2030 (referred to as Part 1 of the study). Since a number of sociodemographic, economic, and behavioral factors influence the TCO of a vehicle, to estimate the cost of electrification of the LDV fleet, we consider the TCO of six market segments defined based on household income and housing type: single family + high-, mid-, and low- income; apartment + high-, mid-, and low-income). For the cost of electrification analysis (referred to as Part 2 of the study), we broaden the scope and include FCEVs as part of the fleet required for net-zero carbon emissions.

The main findings from the TCO analysis (market average) for the 2020-2030 period are (Part 1):

- Initial purchase price (not accounting for any incentive) of an ICEV is lower than a PEV, for all vehicle segments (passenger car vs passenger truck and short-, mid-, long-electric range) during the study period (2020-2030).
- Purchase price of ICEVs in the passenger car segment remains lower than PEVs in the study period, even when CAFE standards are stricter.
- High mileage drivers are more likely to benefit from PEV adoption, particularly for the passenger truck segment.

The main findings from the analysis of cost of electrification of the LDV fleet (by market segment) for the 2020-2030 period are (Part 2):

- TCO is not a single number. TCO varies across market segments due to heterogeneity in annual miles traveled, differences in access to home charging, the cost of electricity, and vehicle preference based on household fleet composition.
- Though the average upfront annualized capital cost of ZEVs remains higher than comparable ICEVs for all the household categories, the difference in upfront cost reduces on average by 58% from the year 2020 to 2030 in response to the fall in the cost of the ZEV technologies and economies of scale.
- In terms of operating costs, ZEVs have a lower cost of operation than gasoline vehicles though the difference reduces across the years as gasoline vehicles become more fuel-efficient
- Cost parity is achieved between the years 2025 and 2030 by all six household categories.

The results of the project can help policymakers investigate the trade-off vehicle purchasers face between high purchase cost and long-term cost savings when considering a PEV and how it differs across consumers and over time. Here we identify the conditions under which the cost of owning and operating an ICEV can surpass that of a PEV and vice-versa. This should guide future policies promoting PEV adoption and allow policymakers to evaluate the welfare impact of their strategy to electrify the light-duty vehicle fleet of California.

Introduction

Globally, multiple countries have set ambitious plug-in electric vehicle (PEV) penetration goals to reduce greenhouse gas (GHG) emissions from the transportation sector. In California, the state government aims to achieve 100% ZEV sales by 2035 (new vehicle sales) and a net-zero carbon transportation system by 2045. As a result, the state government has implemented numerous policies and programs to push the electrification of the transportation sector. The light-duty vehicle (LDV) sector accounting for 54% of the total registered on-road vehicles in California[1] is bound to play a major role in achieving the target. Programs like the Clean Car 4 All (originally called the Enhanced Fleet Modernization Program), the state rebate program for PEV purchase, or policies like the ZEV Mandate and the banning of new ICEV sales after 2035 should encourage the transition to PEVs in the LDV sector.

The uptake of PEVs has been rising over the past decade with PEVs comprising about 7.8% of new vehicle sales in California (as of 2019).[2] Nevertheless, there is still apprehension about the possibility of reaching the required sales to meet the net-zero carbon goal within the timeline. A major concern associated with the achievement of a zero-carbon transportation system by 2045 or 5 million PEVs on California roads by 2030 is the cost of transitioning from an ICEV-dominated fleet to one where most vehicles are PEVs. Comparative analysis of the Total Cost of Ownership (TCO) of PEVs and ICEVs for potential vehicle buyers is one way to analyze the cost of transition for the market. TCO accounts for the purchase price, operating costs for the ownership period, and the vehicle resale value.[3] Many past studies on PEV adoption have reported that in addition to range anxiety and availability of refueling infrastructure, the higher purchase price of these vehicles is a major adoption barrier (*1*, *2*). However, proponents of PEVs argue that the higher upfront purchase cost will be compensated by lower operating and maintenance costs, making the TCO of PEVs favorable compared to ICEVs over the vehicle ownership period. While in some cases the above argument can hold, in general, as the operating and maintenance costs are dependent on household characteristics and their vehicle use patterns, TCO benefits can vary(*3*, *4*). First, heterogeneity in travel behavior, vehicle holding, and differences in access to vehicle charging opportunities can make PEVs cheaper than ICEVs for some households and more expensive for others. Second, the cost of PEV adoption compared to ICEV ownership can depend on whether the vehicle is bought new or used, electricity and gasoline price, the period of vehicle ownership (5 years, 10 years, or 15 years), and consequently the price and the residual battery life of the used PEV. Finally, in addition to the uncertainties related to vehicle use at the household level, there are uncertainties associated with the battery cost for PEVs and cost of manufacturing ICEVs due to the CAFE standards. Uncertainty in terms of vehicle production costs and fuel efficiency

[1] Source: California Energy Commission. https://www.energy.ca.gov/data-reports/energy-almanac/transportation-energy/summary-california-vehicle-and-transportation. Accessed December 2020.
[2] Source: Plug-in electric vehicles in California, Wikipedia. https://en.wikipedia.org/wiki/Plug-in_electric_vehicles_in_California. Accessed December 2020.
[3] The TCO estimated in this is consumer-oriented. Social TCO accounts for the environmental cost of driving a PEV or an ICEV in addition to all the components of consumer-oriented TCO.

improvement affects the tradeoff households will face in the future between ICEVs and PEVs regarding the purchase and operating costs.

TCO studies are important for policymakers to design programs to reach the adoption goals. However, it is critical to keep in mind that the TCO of a vehicle is not a single number for the entire market. Due to the sources of heterogeneity among vehicle owners and given the PEV models currently available in the market, PEV adoption at present can offer a positive TCO to some vehicle buyers, while others are better off buying an ICEV (gasoline or a conventional hybrid vehicle). The timeline when a segment of the market facing a negative TCO for a PEV will break-even would depend on how infrastructure improves, how the cost of gasoline and electricity evolve, changes in the technology costs, and how the market for used PEVs mature. Considering California's vehicle market, in this study, we first analyze how the TCO of PEVs and comparable ICEVs change over the next decade (2020-2030) for the overall market (Part 1). The focus in Part 1 is on the impact of change in the vehicle manufacturing costs and fuel efficiency regulations on the tipping point of PEVs. Second, for a better understanding of the heterogeneity in the cost of electrification of the private LDV fleet of California, we analyze the TCO of ZEVs for different consumer segments (Part 2). Consumer segmentation is done based on socio-demographic characteristics and travel behavior.

Consumer-oriented TCO studies on PEVs often try to answer the question of "when" and "how" the market will reach the point where the cost of a PEV is equal to or lower than the ICEV. These studies help identify factors that can drive the market to reach this desired break-even point (*5*–*8*). Generally, TCO studies comparing PEVs and ICEVs focus on a single aspect: average travel behavior or how the technology and battery costs will affect the TCO of the two types of PEVs. In this study, we aim to combine these two aspects to analyze the cost of moving from an ICEV dominant LDV fleet to a ZEV fleet. We calculate the vehicle purchase cost for the average TCO analysis using a teardown approach accounting for uncertainties in technology costs (like battery costs), auto manufacturer's decisions about research and development (R&D) expenses, and the probability of earning profit from a new vehicle technology. In Part 2 of the study, the analysis of the cost of electrification of California's LDV fleet accounts for heterogeneity in household characteristics, travel behavior, and vehicle charging behavior.

Understanding the factors influencing the TCO of PEVs compared to ICEVs is important for policymakers, consumers, and OEMs. Past research on the importance of incentives in the PEV diffusion process has shown that subsidies are essential for PEV adoption among "followers" whose purchasing capabilities and vehicle usage may differ from the early adopters (*9*, *10*). However, with the financial cost burden of rebate programs rising, policymakers would like to understand the timeline when PEVs can be cost-competitive. From a consumer perspective, since purchase cost and fuel savings can have a major influence on vehicle purchase decision, labeling schemes and online platforms offering TCO-related information can stimulate PEV adoption (*11*, *12*). Lastly, OEMs can benefit from TCO analysis, using it for manufacturing decisions and improvements in marketing strategies (*13*, *14*).

The report is structured as follows. In the next section, we review the literature on total cost of ownership of vehicles and vehicle manufacturing costs. The section titled *TCO Framework* provides an overview of the TCO model used for Part 1 of the study focusing on average TCO of PEVs and ICEVs in the 2020-2030 period. The *Data and Methodology* section describes in detail the data and the method used for the teardown analysis of vehicle manufacturing costs and average TCO of PEVs and ICEVs. Next, we present the results of the comparative analysis of average TCO of PEVs and ICEVs (Part 1 of the study) in t

Literature Review

Research on the TCO of alternative fuel vehicles has been growing over the past few years. Considering the decline in the cost of battery technology, most of the studies generally conclude that even though battery electric vehicles (BEVs) and plug-in hybrid electric vehicles (PHEVs) need to be subsidized in the near future, the tipping point can be attained by 2030 (*7*, *14*–*16*). Fuel cell vehicles (FCVs) would need a longer timeline to achieve cost parity with ICEVs or even PEVs (*17*). While these TCO-based studies vary in terms of the study region, powertrains considered, and the type of model (predictive versus explanatory), their methodology can be broadly classified as bottom-up/teardown analysis or a top-down/aggregate data-based analysis of TCO. Table 1 provides a comprehensive overview of the TCO literature reviewed for this study. The TCO studies using aggregated data for vehicle purchase cost and operating cost usually focus on a few representative vehicle models for the different powertrains and the manufacturer suggested retail price (MSRP) of the basic trim of these models (*6*, *14*–*16*, *18*). The top-down analysis primarily focuses on identifying the factors that drive the difference in TCO of PEVs and ICEVs, offering a snapshot analysis of TCO (*6*, *15*). There are also TCO studies that focus on predicting the future cost of PEVs and ICEVs using aggregated data, estimating the future cost as a percentage or fixed cost reduction from current MSRP based on simplified assumptions (*14*, *16*, *18*). These TCO models based on aggregated data or those using representative vehicle models are informative but restrictive. First, the constrained set of vehicle models is usually unrepresentative of the complete set of vehicle choices available to a consumer. The representative vehicle is often the highest-selling model among the PEVs and ICEVs (often an economy vehicle like Toyota Corolla) available in the market (*15*). The restrictive set of comparative vehicles, particularly ICEVs, can bias the TCO results against PEVs. Second, unlike bottom-up models, models based on aggregated data do not offer the flexibility to test for technological and behavioral uncertainties that may affect the cost of vehicle ownership. Finally, studies using top-down models often ignore the heterogeneity in vehicle-use at the household-level.

Given the constraints of the top-down models, researchers often use a bottom-up/teardown approach to estimate the vehicle purchase cost or the operating cost. (*7*, *19*–*21*). Teardown analysis of the vehicle purchase cost accounts for direct (e.g., production materials) and indirect costs (e.g., R&D) of production as well as the profit margin of the manufacturer and dealer. In this study, we adopt the bottom-up or teardown approach to estimate the purchase cost of BEVs and PHEVs. First, changes in vehicle production costs due to technology improvements can be closely analyzed using this approach such that the estimated future purchase price accounts for technology-related uncertainties. One thing to note is that while the bottom-up approach allows researchers to incorporate different distributions of the technology parameter in the cost analysis, it also makes the estimates sensitive to the distributional assumptions used in the analysis. As a result, the timeline for PEV cost parity may vary across studies based on the assumptions about the manufacturing cost components and technology uncertainties. Case in point: using the bottom-up/teardown approach for estimating the cost of PEVs, Lutsey and Nicholas (*7*) conclude that short-range battery-electric sedans can reach TCO parity with ICEVs as early as 2022. Going forward, considering rapid improvements in technology and cost reductions, BEVs in both the passenger car and the passenger truck segments are expected to reach cost parity by 2026. However, after critically reviewing the assumptions of the study by Lutsey and Nicholas (*7*), Hamza et al. (*20*) found in their TCO study that even with decreased battery costs, BEVs will not reach TCO parity in the next decade in any vehicle segment without a drastic increase in gasoline price (*20*).

In addition to vehicle capital costs, the cost of vehicle ownership for an individual depends on VMT, policy regulations, household fleet size, access to charging opportunities (for PEVs), and energy costs. All these factors lead to heterogeneity in TCO across consumers. Even though most of the studies using the teardown approach show a detailed analysis of the capital cost components of TCO, household characteristics and travel behavior influencing vehicle operating cost are usually incorporated using aggregate level data (e.g., average VMT, average electricity price, etc.). Recently, a limited number of studies have considered the effect of heterogeneity in travel behavior, household characteristics, and spatial variation in regulations and energy costs on TCO and TCO parity (*4*, *6*, *16*, *21*, *22*). Analyzing the TCO of PEVs in Italy, Scorrano et al. (*6*) find that BEVs can be cost-competitive relative to gasoline, diesel, or conventional hybrid vehicles with increased VMT, particularly when vehicle owners have access to a home charger and the BEV purchase price is subsidized (*6*). Similarly, in the context of the German car market, TCO analysis using vehicle segmentation and VMT scenarios by Wu et al. (*21*) suggests that BEVs can reach parity in all vehicle segments for drivers with high travel demand by 2025. Though these studies bring forth the importance of heterogeneity in operating cost in the cost parity calculation they mostly do not have a bottom-up model for the capital cost component. Except for the study by Wu et al. (*21*), none of the other TCO studies consider both the heterogeneity in vehicle operating cost and a teardown approach for estimating the vehicle manufacturing cost.

This study aims to contribute to the TCO literature by giving a comprehensive analysis of the capital cost and operating cost components of vehicle ownership from the OEM’s and consumers’ perspectives respectively. First, we incorporate the bottom-up/teardown approach for calculating the upfront vehicle capital cost accounting for the effect of R&D expenditure as well as the profit margin of the OEM and the car dealer. Due to the lack of data and uncertainties related to technology improvements, cost (or price) multipliers are adopted from the automotive literature to calculate indirect costs related to vehicle manufacturing (*19*, *20*, *23*). The multipliers assist to calculate the total manufacturing and purchase cost of a vehicle with new technologies. According to the technical studies reviewed here for the methodology and input parameters used for vehicle manufacturing cost calculations, R&D expenditure is on average equal to six percent of the manufacturing costs and the share of manufacturer profit is approximately five percent (*24*, *25*). This group of studies formed the basis for our estimation of cost multipliers for the R&D and manufacturer profit and thereby the future purchase cost of PEVs. Second, to account for the variation in operating costs we calculate the energy cost and thereby the TCO for consumers groups with different levels of travel needs. Finally, for a complete analysis of the cost of ZEV adoption targets set by the California government, we estimate the TCO for six market segments defined based on their sociodemographic characteristics and travel behavior.

The literature on TCO of PEVs often analyzes the cost of BEVs by different range categories (short-, mid-, and long-range). However, only a single range is generally considered for PHEVs (*7*, *20*, *21*). There are short- (e.g., Toyota Prius Prime with 25 miles) and long-range PHEV models (e.g., the Honda Clarity with 48 miles) in the market today. Research on the charging behavior and utility factor of PHEVs has shown that the range can influence plug-in behavior as well as eVMT (*26*–*28*). Consequently, the TCO of long- and short-range PHEVs can differ. Moreover, the Clean Vehicle Rebate Program (CVRP) that subsidizes PEV purchase in California has been modified to support longer-range PHEVs (*29*). Therefore, in our TCO analysis, we estimate the cost of ownership of short- and long-range PHEVs.

Table 1. Recent studies on TCO of PEVs and ICEVs

Source	Country	Period of study	Own Length (y)	Powertrain* (miles)	Vehicle Class	Vehicle Type	main TCO results
Lebeau et al. (2013) (18)	BE	2013 Future	7	ICEV (G, D), HEV, PHEV, BEV	PC: small, medium, premium	Representative models (best-selling)	BEV TCO is competitive with ICEV at the premium segment
Wu et al. (2015) (21)	DE	2014 2020 2025	6	ICEV (G, D), HEV, PHEV, BEV	PC: small, medium; PT: SUV	Conceptual vehicles	TCO parity of BEV with ICEV by 2025 for high annual VMT
Bubeck et al. (2016) (30)	DE	2015 2030 2050	12 (lifetime)	ICEV (G, D), HEV (F, M, G, D), PHEV (G, D), BEV, FCHEV	PC: small, compact, medium, executive; PT: SUV, minivan	Representative model	TCO parity of BEV with ICEV by 2030 for high annual VMT
Jakobsson et al. (2016) (*4*)	DE, SE	2020	NA	ICEV (G, D), BEV	NA	Representative model (comparable pairs)	No clear conclusion regarding TCO parity
Falcão et al. (2017) (*31*)	EU	2015	15 (lifetime)	ICEV (D), BEV	Minibus	Representative model (a comparable pair)	BEV TCO is 2.5 times higher than ICEV (D)
Letmathe and Suares (2017) (16)	DE	2016 2021	5	ICEV (G), HEV, BEV	PC: mini, small, medium, large, executive, luxury; PT: MPV, SUV	Representative models (most frequently registered)	Several BEVs and HEVs have lower TCO than ICEV without subsidy
Lévay et al. (2017) (*32*)	EU	2014	4	ICEV (G), PHEV, BEV	PC: mini, small, medium, large, sport; PT: SUV	Representative models (comparable pairs)	PEV TCO is slightly higher than ICEV in NL, FR, and UK
Mitropoulos et al. (2017) (*33*)	US	2015	10.6 (lifetime)	ICEV (G), HEV, BEV	Car, van, light-truck	Representative model (best-selling)	TCO parity of BEV with ICEV at 60K total VMT or higher
Palmer et al. (2017) (*34*)	UK, CA, TX, JP	1997 to 2015	3	ICEV (G, D), HEV, PHEV, BEV	PC: mid-size	Representative model	From 2013, BEV TCO is lower than ICEV, PHEV TCO is higher than ICEV (besides JP)

Source	Country	Period of study	Own Length (y)	Powertrain* (miles)	Vehicle Class	Vehicle Type	main TCO results
Breetz and Salon (2018) (15)	US	2011	5	ICEV (G), HEV, BEV	PC: mid-size	Representative model (best-selling)	BEV TCO is higher than HEV and ICEV
Danielis et al. (2018) (14)	IT	2017 2025	6	ICEV (G, D), HEV, BEV	PC: small, medium	Representative models (best-selling)	TCO parity of BEV with HEV for medium annual VMT without subsidy
Lutsey and Nicholas (2019) (7)	US	2018 to 2030	5	ICEV, PHEV (50), BEV (150, 200, 250)	Car, crossover, SUV	Conceptual vehicles	TCO parity of BEV with ICEV between 2022-2026. No parity between PHEV and ICEV
Scorrano et al. (2019) (6)	IT	2019	6	ICEV (G, D), HEV, BEV	PC: small, medium	Representative models (best-selling)	BEV TCO is competitive with ICEV for urban drivers who charge at home
Hamza et al. (2020) (20)	US	2018 to 2030	5	ICEV, PHEV (50), BEV (150, 200, 250)	Car, crossover, SUV	Conceptual vehicles	No TCO parity of BEV with ICEV by 2030
Hao et al. (2020) (*35*)	CN	2018 2025	10	ICEV, PHEV (50), BEV (100-250)	PT: SUV	Representative and conceptual vehicles	TCO parity of BEV with ICEV by 2025

* F = Full; M = Mild; G = Gasoline; D = Diesel

** Capital = purchase price, purchase tax, title; Operating = Fuel, insurance, maintenance, repair, annual fees and taxes; Maint = maintenance

Part 1: TCO Model Framework

In this section, we describe the general TCO model framework. First, we present the general framework of the model, its components, and the mathematical formulae for estimating the components. Second, we explain the teardown approach adopted to estimate the purchase cost of PEVs and ICEVs and the method to estimate the operating cost for the TCO analysis. Finally, we describe the market-level TCO calculation for three categories of driving behavior for the period 2020-2030. Here, the categories are defined in terms of miles traveled, similar to the TCO study by Scorrano et al. (*6*).

We calculate the TCO of a private vehicle owner in California, assuming the vehicle is financed new from an auto dealer and is owned for five years[4]. Though a shorter ownership period may lead to underestimation of the operational cost advantages of PEVs over ICEVs (e.g., lower maintenance costs), we choose to restrict the analysis to 5 years in alignment with most of the studies reviewed for the analysis. We consider three powertrain technologies and two main vehicles classes for the TCO analysis: a battery electric vehicle (BEV), a plug-in hybrid vehicle (PHEV), and an internal combustion engine vehicle (ICEV) using gasoline for passenger car (PC) and passenger truck (PT) segments (*36*).[5] As the electric range of a PEV can play an important role in the TCO estimates, we evaluate three BEV range categories: short-, mid-, and long-range, and two PHEV range categories: short- and long-range. As the purchase cost and fuel efficiency of gasoline vehicles vary by vehicle trim, we evaluate the TCO of two trim-levels: compact and mid-size ICEVs in the PC and PT segments. The TCO of each type of powertrain in the two vehicle classes (PC and PT) is primarily calculated at three time points: 2020, 2025, and 2030. Values for the interim years 2021-2024 and 2026-2029 are calculated linearly between the main analysis years. Figure 1 gives an overview of the TCO framework.

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[4] The current average ownership length in the U.S. is 8.4 years, according to www.iSeeCars.com. However, the different TCO studies use various durations, from five to ten years, where most of the studies choose five or six years.

[5] The categorization of passenger car and passenger truck is done based on the www.fueleconomy.gov database and the definition used in the 2019 study by Lutsey and Nicholas (*67*).

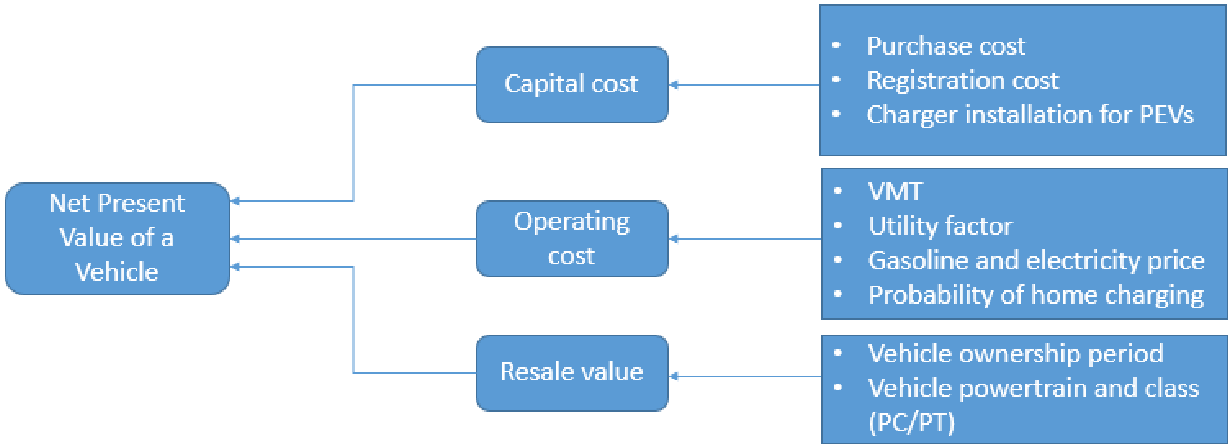

Figure 1. TCO framework

Considering our assumption that a vehicle is purchased new and financed with a loan, the purchase cost is subject to an annual percentage rate (APR). The APR represents the actual yearly cost of funds over the term of a loan including any fees or additional costs associated with a loan transaction. The remaining part of the one-time capital cost i.e., registration cost and cost of charger installation are paid post-purchase of the vehicle and after a charger is installed. Operating costs are incurred by vehicle owners annually during the ownership period. Finally, the resale value is realized one-time at the end of the ownership period. Given the varying timelines of the cost components, discounting and annualization adjustments are made to the cost components to obtain annualized TCO estimates. The estimation method and the adjustments are described here.

The annual capital costs of a vehicle with powertrain technology p and class c are calculated per *Equation 1*:

$$\boldsymbol{CC_{p,c}} = \frac{\boldsymbol{PP_{p,c} \cdot APR}}{\boldsymbol{1 - (1 + APR)^{-N}}} + \left(\boldsymbol{RG_{p,c} + HC_{p,c}}\right) \cdot \boldsymbol{CRF} \quad (1)$$

Where,

$PP_{p,c}$ = purchase price of a vehicle, assuming new vehicles are always financed;
APR = annual percentage rate of 5% (interest rate for loans considering an average credit score[6]);
N = ownership period; $\boldsymbol{RG_{p,c}}$= Initial vehicle registration cost
$HC_{p,c}$ = home charger installation cost;
i = real interest rate of 1.25% (interest rate of US treasury bonds with a residual maturity of five years as of February 2020[7]); and,

[6] Source: Bankrate. https://www.bankrate.com/loans/auto-loans/rates/. Accessed June 2020.
[7] Source: U.S. Department of The Treasury. https://www.treasury.gov/resource-center/data-chart-center/interest-rates/pages/TextView.aspx?data=yieldYear&year=2020. Accessed February 2020.

CRF = capital recovery factor (calculated as per *Equation 2*).[8]

$$\boldsymbol{CRF = \frac{i(1+i)^N}{(1+i)^N - 1}} \tag{2}$$

The recurring operating cost constitutes the annual fuel costs, annual insurance payments, and maintenance costs. The annual fuel cost of a vehicle with powertrain technology p and class c is calculated per *Equation 3*:

$$\boldsymbol{FC_{p,c} = UF_{p,c} \cdot AM \cdot FE_{elec,c} \cdot FP_{elec} + \left(1 - UF_{p,c}\right) \cdot AM \cdot FE_{gas,c} \cdot FP_{gas}} \tag{3}$$

Where,

$UF_{p,c}$ = utility factor (UF), the share of electric miles;
AM = annual vehicle miles traveled;
$FE_{elec,p,c}$ = energy consumption in terms of kWh per 100 miles;
$FE_{gas,p,c}$ = fuel efficiency in terms of gallons per mile; and
$FP_{elec \text{ or } gas}$ = price of electricity or gasoline.

For an ICEV, $UF_{p,c}$ is equal to zero. For a PHEV, $UF_{p,c}$ represents the share of electric miles, and $\left(1 - UF_{p,c}\right)$ represents the use of gasoline mode. For BEVs, $UF_{p,c}$ represents the share of miles driven with a BEV, while $\left(1 - UF_{p,c}\right)$ represents driving with an ICEV due to limited electric range. Assuming that the ICEV used in the case of insufficient BEV range is a part of the household fleet, we do not consider any rental cost in the calculation (*22*).

Summing up the fuel costs and other recurring cost components, the annual operating costs of a vehicle with powertrain technology p and class c is calculated per *Equation 4*:

$$\boldsymbol{OC_{p,c} = \frac{1}{N}\sum_{n=1}^{N}\frac{FC_{p,c} + AR_{p,c} + IN_{p,c,n} + MT_{p,c,n}}{(1+i)^n}} \tag{4}$$

Where,

$FC_{p,c}$ = annual fuel cost;
$AR_{p,c}$ = annual registration fee;
$IN_{p,c,n}$ = annual insurance premium (decreases with vehicle age); and,
$MT_{p,c,n}$ = annual maintenance cost (increases with vehicle age).

[8] The capital recovery factor represents the amount of equal payments to be received in N years such that the total present value of all these equal payments is equivalent to a payment of one dollar at present, given interest rate is *i*

The discounted and annualized resale value of a vehicle with powertrain technology p and class c is calculated per *Equation 5*:

$$RV_{p,c} = \frac{\vartheta.PP_{p,c}}{(1+i)^N} \quad (5)$$

Where,

$RV_{p,c}$ = resale value as a percentage *(ϑ)* of the purchase price of a five-year-old vehicle

Finally, the annualized TCO per mile of a vehicle with powertrain technology p and class c is calculated as per *Equation 6*:

$$TCO_{p,c} = \frac{CC_{p,c} + OC_{p,c} - RV_{p,c,}}{AM} \quad (6)$$

To estimate the timeline when PEVs can achieve cost parity with ICEVS in the two vehicle segments (PC and PT) without financial support, we do not consider any subsidy or tax credit in the TCO calculation.

Data and Methodology: TCO Estimation

Vehicle Manufacturing Cost Components and Purchase Price

To calculate the cost of manufacturing and the purchase price of a vehicle, we adopt the bottom-up/teardown approach (*19*). The data and method used to calculate the baseline and future values of different components of vehicle manufacturing and consumer purchase costs are detailed below.

Powertrain Specifications

The powertrain specifications considered in the calculation of the manufacturing cost of a vehicle are electric range, engine power, electric motor power, battery capacity, and electric efficiency. For the baseline year 2020, except electric efficiency, the values of all other powertrain components are derived from the corresponding powertrain data for PEV models available between 2018-2020. We take the average of the existing data to calculate the baseline values for the year 2020. Appendix A shows the complete list of vehicle models currently available in the market and their relevant specifications (*37*). Based on these vehicle models, the market average specifications are calculated. If a limited number of BEV models currently exist in the market for a certain category (i.e., BEV PC and PT long-range, and BEV PT mid-range), an extrapolation is made based on luxury models (like Tesla), to find electric power and battery capacity for those categories. The electric efficiency of a PEV model is calculated as the battery capacity divided by the electric range of the vehicle.

The electric range for future BEV models is set based on the desired range as revealed from a stated preference survey administered by the Plug-In Hybrid and Electric Vehicle (PH&EV) Research Center. The electric range for future PHEVs is set to align with the range requirements of the state rebate program. The California Clean Vehicle Rebate Program's (CVRP) minimum range requirement for PHEVs is 35 miles[9]. With policy support, we assume the range of future PHEVs will linearly increase up to 40 miles for short-range and up to 80 miles for long-range PHEVs by 2030. To keep the interpretation of the TCO results simple, we assume a linear increase in the electric range of PHEVs. The battery capacity for both BEVs and PHEVs is calculated such that it is proportional to the range increase but assuming constant electric efficiency. Though technology improvements may allow manufacturers to increase the electric range without proportionally increasing the battery size, larger battery packs will be required for long-range PEVs making the latter heavier and less fuel efficient than short- or mid-range PEVs. In other words, assuming technology improvements in battery capacity will result in an extended range, but the need for larger battery packs to allow for longer range PEVs can contradict the technology improvement, the electric efficiency for BEVs and PHEVs is kept constant for the future years. However, with an increased range and possibly increased vehicle weight, electric power must increase. Recent announcements of future BEV models reveal an increase in motor power (kW) compared to the existing models in the market[10,11]. With uncertainty regarding future electric motor power and the evolution of technology, we assume a 10 percent increase in electric motor power by 2025 and a plateau thereafter(*38*, *39*). In the case of future PHEV models, we use the data on electric power and range from existing BEV models in the PC segment. Fitting an exponential relationship between electric power and range to account for the increase in vehicle weight, we estimate the relationship between the two components. The estimated relationship is used to derive the value of electric power of future PHEV models (40-mile and 80-mile e-range). Lastly, assuming internal combustion engines supply the same amount of power in future years, the engine power is kept constant throughout the study period for ICEVs and PHEVs. However, for ICEVs, the impact of CAFE standards on fuel efficiency in future years is considered. Table 2. Powertrain Specifications summarizes all the technical vehicle specifications for the three types of powertrains, two vehicle classes (PC and PT), and the study period (2020-2030).

The cost of the battery is a major determinant of the cost of a PEV powertrain. At present, lithium-ion (Li-ion) batteries are the most suitable and affordable battery technology for the automotive industry. Experts agree that this technology will remain popular in the next decade or more, and it is hard to predict how soon the solid-state battery technology will replace Li-ion batteries in commercially produced PEVs (*40*–*44*). Therefore, for now, we assume the use of Li-ion batteries in PEVs through 2030. There is an effort to mass-produce a higher energy density cathode, noted as NMC811 Li-ion batteries within the next five years. This improved cathode with a lower amount of cobalt is not only expected to bring down the price of PEVs by $2400 but is also predicted to improve the energy density by 10 percent (*45*). For simplicity, to account for the increase in the BEV range, we assume a linear increase in battery capacity of up

[9] Source: California Clean Vehicle Rebate Program. https://cleanvehiclerebate.org/eng/faqs/why-don%E2%80%99t-i-see-my-vehicle-eligibility-list-0. Accessed December 2020.
[10] Source: EVAdoption. https://evadoption.com/future-evs/new-electric-vehicles-in-2020/. Accessed June 2020.
[11] Source: Pocket-lint. https://www.pocket-lint.com/cars/news/140845-future-cars-and-upcoming-electronic-cars-of-the-future-coming-soon. Accessed June 2020.

to 10 percent by 2025 and a plateau afterward. Assuming constant electric efficiency, the increase in battery capacity for PHEVs is assumed to be proportional to the range requirements.

Table 2. Powertrain Specifications

		BEV						PHEV				ICEV			
		PC			PT			PC		PT		PC		PT	
		Short	Mid	Long	Short	Mid	Long	Short	Long	Short	Long	Compact	Midsize	Compact	Midsize
2020	Range (mile) [A]	<200	200<x<300	>300	<250	250-350	>350	25	50	22	34				
	Engine Power (kW) [A]							95	76	97	140	120	150	160	210
	Electric Power (kW) [A]	100	180	226	150	270	340	58	135	58	76				
	Battery Capacity (kWh) [A]	36	60	68	64	77	85	9	18	10	16				
	Electric Efficiency (kWh/mile) [B]	0.28	0.25	0.21	0.31	0.28	0.24	0.36	0.36	0.46	0.46				
	Fuel efficiency (MPG) [A]							43	43	35	35	28	32	25	20
2025	Range (mile)	<200	200<x<300	>300	<250	250<x<350	>350	33	65	31	50				
	Engine Power (kW) [A]							95	76	97	140	120	150	160	210
	Electric Power (kW) [C]	110	198	249	165	297	374	61	142	61	82				
	Battery Capacity (kWh) [C]	40	66	75	70	84	94	12	23	14	23				
	Electric Efficiency (kWh/mile) [B]	0.28	0.25	0.21	0.31	0.28	0.24	0.36	0.36	0.46	0.46				
	Fuel Efficiency							43	43	35	35	35	39	31	24
2030	Range (mile)	<200	200<x<300	>300	<250	250<x<350	>350	40	80	40	80				
	Engine Power (kW) [A]							95	76	97	140	120	150	160	210
	Electric Power (kW) [C]	110	198	249	165	297	374	63	149	63	96				
	Battery Capacity (kWh) [C]	40	66	75	70	84	94	14	29	18	37				
	Electric Efficiency (kWh/mile) [B]	0.28	0.25	0.21	0.31	0.28	0.24	0.36	0.36	0.46	0.46				
	Fuel Efficiency							43	43	35	35	36	40	31	24

Note:
A: market average of 2018-2020 models;
B: electric efficiency= Battery capacity/ electric range
C: for BEVs, battery capacity and electric power increases 10% by 2025 and then stays constant. In the case of PHEVs, future values of electric power are estimated from the relation between range and electric power of BEV PCs. Subsequently, battery capacity of PHEVS in 2025 and 2030 is calculated as efficiency (assumed same as baseline year) *range

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Battery and Powertrain Costs

Battery pack cost for the different PEV range categories is calculated using the mid-range BEV PC with 60 kWh battery capacity as a reference case. The battery pack cost is calculated for class c vehicle per Equation 7 (*20*):

$$\boldsymbol{BPC_c}(\$) = \left[\boldsymbol{BPC_{avg}}\left(\$/_{\boldsymbol{kWh}}\right) + \frac{\boldsymbol{60(kWh) - BC(kWh)}}{\boldsymbol{60(kWh)}} \cdot \boldsymbol{BPC_{avg}}\left(\$/_{\boldsymbol{kWh}}\right) \cdot \boldsymbol{0.023}\right] \cdot \boldsymbol{BC_c(kWh)} \quad (7)$$

Where,

BPC_{avg} = average battery pack cost;
BC_c = battery capacity of a vehicle from class c; and 0.023= battery pack size scaling factor

If the battery capacity is higher than 60 kWh, the cost per pack reduces, and vice versa. For 2020, the battery pack cost is equal to 161 $/kWh, which is the industry average cost (*46*). In the literature, several predictions of Li-ion battery pack cost are found. For 2025, the minimum prediction is 82 $/kWh (*47*), and the maximum prediction is 133 $/kWh (*19*). For 2030, the minimum prediction is 62 $/kWh (*47*) and the maximum prediction is 112 $/kWh (*48*). The average value of the above predictions is taken for each analysis year, $107.5 and $97/kWh for the years 2025 and 2030, respectively. Since PHEVs carry a relatively smaller battery (or a more expensive type of battery), there is an additional cost adjustment for the battery pack cost (0.061). The battery pack cost for a PHEV is calculated as per Equation 8 (*20*):

$$\boldsymbol{BPC_{PHEV,c}}(\$) = \boldsymbol{BPC_c}(\$) \cdot \left(\boldsymbol{1} + \frac{\boldsymbol{60(kWh)}}{\boldsymbol{BC_c(kWh)}} \cdot \boldsymbol{0.061}\right) \quad (8)$$

Cost estimates for all other powertrain components are calculated based on the study by UBS Evidence Lab (19), hereon referred to as the UBS study, where the costs estimates for each vehicle manufacturing component was calculated based on a teardown analysis of a Chevrolet Bolt with an electric motor power of 150 kW and a Volkswagen Golf (ICEV) with an engine power of 127 kW. For the analysis here, the costs of the powertrain components (other than battery pack cost) have been scaled based on the engine or electric motor power detailed in Table 2.Based on the teardown analysis of the cost of Chevrolet Bolt in the UBS study (19), a cost reduction of 10-25 percent is predicted for the electric powertrain components (components other than the battery pack) due to economies of scale, technology improvements, and competition. The reductions suggested by the UBS study are implemented here for the vehicle models in 2025. We assume costs of the powertrain components other than the battery pack remain constant between 2025 and 2030. No cost changes are applied to the manufacturing cost components for the gasoline powertrain in the study period (2020-2030). Changes in capital cost/ purchase cost of ICEVs is modeled through increased cost of research and development for the OEMs subjected to the CAFE regulation (as described below).

Other Direct, Indirect, and R&D Costs

Estimates for other direct costs (warranty provision, assembly staff costs, direct materials, and supplier components) are taken from the UBS study (*19*) and scaled up by 6.0 percent for the PC segment and 21.0 percent for the PT segment across all powertrain technologies. The scaling is primarily done to reflect the efficiency standards in the US and the larger footprint of U.S. vehicles (*7*). Considering the Chevrolet Bolt, by 2025, the UBS study (*19*) suggests a cost reduction of 28.6 percent for warranty provision and a cost reduction of 6.2 percent for supplier components. These reductions are adopted in the analysis for the years 2025 and 2030.

Indirect costs encompass depreciation and amortization (D&A), selling, general, and administration (SG&A), and research and development (R&D). For ICEVs, indirect costs are set to 20.5 percent of direct costs across all analysis years (*7*), with about a third of the indirect costs associated with R&D expenses (*24*). For BEV-PC and PHEV-PC, estimates of D&A and SG&A costs for the year 2020 are taken from the UBS study (*19*). We observe that on average, across the range categories of BEVs and PHEVs, the direct costs of BEV-PT are higher by 28 percent than BEV-PC, and the direct costs of PHEV-PT are higher by 10 percent than PHEV-PC. Therefore, the indirect cost of BEV-PT and PHEV-PT are equal to the indirect costs of BEV-PC and PHEV- PC multiplied by 28 percent and 10 percent, respectively. For 2025, the UBS study (*19*) predicts a cost reduction of 50.0 percent for D&A, which was adopted in the analysis for the year 2025. No change in D&A costs is assumed between 2025 and 2030. SG&A expenses remain the same across all analysis years.

In this study, we consider R&D expenditure as a major cost component in PEV manufacturing. We assume that a five-year R&D investment is equally distributed among the new PEVs sold globally over five-years. Therefore, an increase in the global market share of PEVs results in economies of scale for the OEM, and a lower share of the R&D expenses is passed on to the purchase price. For the base year 2020, we applied the R&D costs reported in the UBS study (*19*) for all the PEVs. For the analysis years 2025 and 2030, we sum the predicted new PEV sales (global) for years 2021-2025 and 2026-2030 respectively. Since there is a range of predicted values for global PEV sales in the 2020-2030 period, we consider both the minimum and the maximum value while calculating the total number of PEV sales during the study period. The minimum prediction of global sales of new PEVs is 8.5 million and 26 million in 2025 and 2030, respectively (*49*). The maximum prediction of global sales of new PEVs is 24.5 million and 43 million in 2025 and 2030, respectively (*50*). For each prediction, a linear interpolation is applied from 2020 to 2025 and from 2025 to 2030, to calculate the number of new sales for the interim years. Considering the average of the maximum and minimum predicted values for each year, the cumulative global PEV sales are assumed to be 58 million in 2025 and 136 million in 2030.

Based on the recent R&D investments announced by Daimler, Volkswagen, and Ford for their PEV production line, the total R&D expenditure over five-years is set at $11B[12,13]. The main automotive companies are assumed to each have a five percent share (not considering Tesla) in the global PEV market[14,15]. Based on these assumptions and considering the R&D expenditure is equally distributed across the PEVs manufactured during the study period, the R&D cost per vehicle for 2025 is calculated as $4,725 and $1,776 for 2030 ($11B divided by five percent of the number of new PEV sales). By 2030, therefore, R&D should constitute between 5 to 6 percent of manufacturing costs instead of the present-day 19 to 22 percent (*19*, *24*, *25*).

OEM Profit Margins and Dealer Markups

The literature on dealer markup for ICEVs has identified factors like search friction, asymmetric information, and competition among co-located distributors as important determinants of the markup amount (*51*–*54*). In a recent study on the economics of dealer agglomeration, Murry and Zhou (*51*) found that search friction on average can generate a markup of $333 per vehicle. Dealer markup for ICEVs can also differ by vehicle size, with dealers offering larger discounts on smaller cars (*55*). In the absence of data to track search costs or competition, to keep the TCO model simple we set the dealer markup proportional to vehicle size for the PEV and ICEV models analyzed here. We assumed a five percent mark-up for PC compact and PC midsize, 10 percent for PT compact, and 15 percent markup for PT midsize ICEVs. Since BEVs do not require periodical maintenance like ICEVs, car dealers may lose a major source of income from parts and services (*56*). Hence, the dealer markup on BEVs is assumed to be higher than ICEVs, equal to 15 percent (*19*). Dealer markup for PHEV is assumed to be between BEVs and ICEVs, with 10 percent for the PC and 15 percent for the PT segment.

Past research on pricing in the auto industry suggests that similar to auto dealers, the market power of auto manufacturers or original equipment manufacturers (OEMs) can differ by vehicle size and segment (*55*). Market power and profit margin earned by an OEM in a given market may also differ by manufacturer's nationality due to their factor market decisions as well as depending on their import competition (*57*, *58*). Going by the current market trends, the study by ICCT on the cost of PEVs, and Argonne National Lab study on the indirect costs of OEMs, we assume that the earnings before income tax (EBIT) for any profitable vehicle type (mostly conventional fuel vehicles) is 5 percent (*7*, *24*). We consider the 5 percent profit margin for all categories of ICEVs analyzed here. We assume that PEVs are currently sold at loss by the OEMs. According to the UBS study (*19*), auto manufacturers like Chevrolet incur a loss of 15 percent per vehicle (Chevrolet Bolt) at the EBIT level. Based on the UBS study findings, in this study, we use a 15 percent profit/loss margin for BEVs in the baseline year 2020 and a loss of 10 percent

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[12] Source: Business Insider for FCA and Daimler. https://www.businessinsider.com/promises-carmakers-have-made-about-their-future-electric-vehicles-2020-1. Accessed March 2020.

[13] Source: Ford. https://corporate.ford.com/articles/sustainability/new-generation-electric-vehicles.html. Accessed March 2020.

[14] Source: Car Sales Statistics for Daimler. https://www.best-selling-cars.com/brands/2019-full-year-global-mercedes-benz-sales-worldwide/. Accessed March 2020.

[15] Source: Investopedia for Ford. https://www.investopedia.com/articles/markets/123015/ford-vs-chevy-comparing-business-models-and-strategies-f-gm.asp. Accessed March 2020.

is assumed per PHEV. However, with the reduction of battery costs in future years and economies of scale, PEVs are assumed to be profitable by 2030.

Total Purchase Cost

From the preceding discussion of the technical specifications of the three powertrain technologies and the cost components, the purchase price of a vehicle with powertrain technology p and class c is calculated as per Equation 9:

$$\boldsymbol{PP_{p,c}} = \left[\boldsymbol{BPC_{p,c}} + \boldsymbol{PT_{p,c}} + \boldsymbol{OD_{p,c}} + \boldsymbol{IN_{p,c}}\right] \cdot \boldsymbol{EBIT_{p,c}} \cdot \boldsymbol{DM_{p,c}} \tag{9}$$

Where,

$BPC_{p,c}$ = battery pack cost,
$PT_{p,c}$ = other powertrain costs, either electric or gasoline or both,
$OD_{p,c}$ = other direct costs,
$IN_{p,c}$ = indirect costs,
$EBIT_{p,c}$ = OEM EBIT,
$DM_{p,c}$ = dealer markup,

Corporate Average Fuel Economy (CAFE) and carbon dioxide emissions standards require automotive companies to raise the fuel efficiency of their ICEV fleet. Assuming rising compliance costs for manufacturers, the cost of fuel efficiency improvements and thereby the purchase price of ICEVs can be expected to increase with tightening CAFE standards (*59*). To reflect the effect of the fuel efficiency standard on the purchase price of future ICEVs a 1.8 percent and 4.0 percent increase is assumed in the year 2025 and 2030, respectively (*60*).

Other Capital Costs Components

Post-purchase, the cost of vehicle registration is a one-time cost and thereby a part of the capital cost component of TCO. We assume that the registration tax for new vehicle purchase (both PEVs and ICEVs) is equal to 9.0 percent; the average of the new vehicle registration fee in San Francisco County (8.5 percent), and Los Angeles County (9.5 percent), as calculated from the California DMV New Vehicle Registration Fee Calculator[16].

Assuming households can install a charger at home, the cost of charger installation becomes part of the capital cost of a PEV. The cost of Level 1 home charger installation is $0 and $1,836 for a Level 2 charger. Assuming 16 percent of BEV owners install Level 1 charger, and the rest (84 percent) install a Level 2 charger, the average installation expense is assumed to be $1,542 for BEV owners during the study period (*61*, *62*). For PHEVs, we assume all owners install Level 1 charger in 2020, and linearly shift to Level 2 charger, up to 84 percent by 2030. The average cost of installation is accordingly calculated for each analysis year.

[16] Source: California Department of Motor Vehicles. https://www.dmv.ca.gov/wasapp/FeeCalculatorWeb/newVehicleForm.do. Accessed February 2020.

Operating Costs

The operating cost component of the TCO estimate includes the fuel, registration, insurance, and maintenance costs. As past studies have shown, there is generally considerable variation in the operating costs of a given vehicle due to heterogeneity in travel behavior (*51*). In other words, the TCO of an ICEV or a PEV will be different for a household with high travel demand compared to one with low annual miles traveled. To account for the variability in travel demand and its impact on TCO, we define three consumer/driver groups based on their annual VMT. The three groups are defined using the 2017 National Household Travel Survey (NHTS) California Add On data. We consider the annual mileage traveled by California households using vehicles of model years 2010 and newer (*63*). Given the distribution of the miles traveled, the average annual mileage of the first two quantiles represents the low-VMT category with 6,000 miles. The annual mileage of the third quantile represents the average-VMT category, with 12,000 annual miles traveled. For the high-VMT category, we consider the average VMT of the fourth quantile with 20,000 miles. TCO is estimated for the three VMT categories.

Fuel Costs

The effect of heterogeneity in travel demand on operating costs is reflected in the annual fuel cost of households. The fuel cost for an ICEV/PHEV or the cost of recharging a BEV/PHEV will vary across households based on their travel demand, the price of gasoline in their area of travel, the rate of electricity, and the fuel and the electric efficiency of the gasoline and electric vehicle respectively. For the market-level analysis of TCO, in the baseline year 2020, we assume that the price of gasoline to be $3.68 per gallon, the average California gasoline retail price in 2019.[17]. For future years, the price of gasoline is assumed to go up to $3.86 per gallon by 2030, based on the predictions of the Energy Information Administration (EIA).[18] The cost of electricity for PEV charging is assumed to be the average of the "off-peak" rates of the EV rate plans offered by the three main electricity providers in California: PG&E, SDG&E, and SCE. The household electricity rate used for the TCO analysis is equal to $0.17 per kWh.[19,20,21]In terms of charging location, for the market-level TCO analysis in Part 1, we assume that PEV owners charge their vehicles only at home during the "Off-Peak" time. In part 2 of the study where we analyze the TCO of different market segments, we consider the heterogeneity in charging costs among apartment dwellers and single-family homeowners. Based on EIA's predictions about

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[17] Source: U.S. Energy Information Administration, Weekly Retail Gasoline and Diesel Prices. https://www.eia.gov/dnav/pet/pet_pri_gnd_dcus_sca_w.htm. Accessed June 2020.

[18] Source: U.S. Energy Information Administration, Annual Energy Outlook 2020, Table 12. https://www.eia.gov/outlooks/aeo/. Accessed June 2020.

[19] Source: Pacific Gas and Electric Company. https://www.pge.com/en_US/residential/rate-plans/rate-plan-options/electric-vehicle-base-plan/electric-vehicle-base-plan.page. Accessed June 2020.

[20] Source: San Diego Gas & Electric Company. https://www.sdge.com/residential/pricing-plans/about-our-pricing-plans/electric-vehicle-plans. Accessed June 2020.

[21] Source: Southern California Edison. https://www.sce.com/residential/rates/electric-vehicle-plans. Accessed June 2020.

changes in the electricity rate, in Part 1 of the study we assume that it remains constant until 2030.[22] In part 2 of the study, we consider changes in electricity rate for the 2020-2030 period.

Data on the fuel efficiency and electric efficiency of gasoline vehicles and PEVs are obtained from the EPA database. The fuel economy value for the powertrain and vehicle categories evaluated here is equal to the average fuel efficiency of vehicles of the model year 2018 or later. In addition to the gasoline price, electricity rate, and fuel efficiency of the vehicles, the fuel cost of PHEVs depends on the share of electric miles driven, referred to as the utility factor (UF). The UF for PHEVs is calculated using the data from Environment Protection Agency (EPA). It is the average utility factor of all the PHEV models evaluated by the EPA. In the case of BEVs, though the share of electric miles is 100 percent, we assume that there can be scenarios when the range of the BEV may not be sufficient for a trip. In such scenarios, households would have to use an ICEV. The share of days when the BEV can be used is defined as the utility factor for BEVs. Past studies have assumed that if the range of a BEV is insufficient for a trip, household will rent an ICEV with the average fuel economy (*3*). Considering the case of a multi-vehicle household, we assume that the ICEV used for the non-BEV days is part of the household fleet and we do not consider any rental cost (*22*)(*4*). Single-vehicle households with BEVs may need to rent a vehicle, but to keep the estimation simple in Part 1 of this report, we consider the scenario of multi-vehicle households and keep the above assumption. The average fuel efficiency of a gasoline car and the gasoline prices mentioned earlier are used to estimate the fuel cost incurred in the non-BEV days. PEV fuel economy and UF is kept constant through the analysis years. On the other hand, the fuel economy of ICEVs is assumed to increase by 23% in 2025, and 27% by 2050, as suggested by the CAFE regulations (*60*, *64*). The UF and the fuel efficiency values used in this study are presented in Table 3.

Registration, Insurance, and Maintenance Costs

While the registration, insurance, and maintenance cost vary by vehicle class (economy vs luxury), powertrain (ICEV vs BEV), and vehicle type (compact, SUV, etc.), to keep the analysis simple we assume that these cost components, do not change over the period of analysis.

The registration cost is assumed to be a linear function of the purchase price before tax, as presented in Equation 10. The function is based on the California DMV New Vehicle Registration Fee Calculator for ICEVs and PEVs purchased in December 2019 and located in the San Francisco area (i.e., zip code 94115).[22]

$$\boldsymbol{REG_{PEV} = 0.0086 \cdot {}^{PP_{p,c}}/_{TAX} + 160.71} \tag{10}$$

$$\boldsymbol{REG_{ICEV} = 0.0086 \cdot {}^{PP_{p,c}}/_{TAX} + 140.71}$$

[22] Source: U.S. Energy Information Administration, Annual Energy Outlook 2020, Table 1. https://www.eia.gov/outlooks/aeo/. Accessed June 2020.

The insurance premium is calculated with the AAA calculator for a single 35-year-old male who lives in the San Francisco area (zip code 94115).[23] The insurance includes all recommended policies: liability coverage, comprehensive, and collision. We collect insurance cost data for different vehicle ages (from one- to five-year-old) and different annual miles traveled (low-, average-, and high-VMT) for the basic trim of vehicle models in each vehicle category analyzed here. The MSRP we assume is similar to the purchase price estimated in this study. The baseline is the ICEV-PC (Toyota Camry) with monthly insurance costs detailed in Table 4. For all other vehicle categories, a scaling factor is used to adjust the insurance cost of the vehicle model, based on the ratio of the insurance cost of each category and the insurance cost of ICEV-PC, as detailed in Table 5. We assume that by 2030, the insurance cost multiplier of PEVs will be equal to the insurance cost multiplier of ICEVs (1.00 for PC and 1.02 for PT).

The maintenance costs per driven mile and vehicle age for the different powertrains and classes are from the AFLEET Tool by Argonne National Lab[24], and are detailed in Table 6.

[23] Source: AAA. https://quote.digital.csaa-insurance.aaa.com. Accessed June 2020.
[24] Source: Argonne National Lab. https://greet.es.anl.gov/afleet_tool . Accessed Jun. 17, 2020.

Table 3. Utility factor and fuel economy

	BEV						PHEV				ICEV			
	PC			PT			PC		PT		PC		PT	
	Short	Mid	Long	Short	Mid	Long	Short	Long	Short	Long	Compact	Midsize	Compact	Midsize
Utility Factor	0.93	0.95	0.97	0.93	0.95	0.97	0.57	0.57	0.55	0.55				
Fuel Economy (kWh/100 mile)	29	29	29	29	29	29	33	33	38	38				
Fuel economy (MPG), 2020							43	43	35	35	28	32	25	20
Fuel economy (MPG), 2025							43	43	35	35	35	39	31	24
Fuel economy (MPG), 2030							43	43	35	35	36	40	31	24

Table 4. ICEV-PC insurance cost

	Monthly Insurance Cost ($)		
Year of Ownership	**Low-VMT**	**Average-VMT**	**High-VMT**
1	184	201	218
2	182	198	215
3	179	195	211
4	174	189	204
5	168	182	196

Table 5. 2020 Insurance Multipliers

BEV						PHEV				ICEV			
PC			PT			PC		PT		PC		PT	
Short	Mid	Long	Short	Mid	Long	Short	Long	Short	Long	Compact	Midsize	Compact	Midsize
Chevrolet Bolt			Kia Niro			Toyota Prius Prime		Chrysler Pacifica		Toyota Camry		Honda CR-V	
1.15	1.15	1.15	1.2	1.2	1.2	1.05	1.05	1.1	1.1	1	1	1.02	1.02

Table 6. Maintenance cost per mile

	BEV		PHEV		ICEV	
Year of Ownership	**PC**	**PT**	**PC**	**PT**	**PC**	**PT**
1	0.059	0.070	0.062	0.073	0.064	0.076
2	0.064	0.076	0.067	0.080	0.070	0.083
3	0.086	0.102	0.090	0.107	0.094	0.111
4	0.106	0.126	0.112	0.133	0.116	0.137
5	0.127	0.151	0.134	0.159	0.139	0.164

Resale Value

The resale value for each vehicle type is calculated with data from Kelly Blue Book[25]. The resale value is the average of private party and trade-in values of a five-year-old (2015) vehicle in a “very good condition”, with standard trim and equipment, and annual mileage of 12,000 miles located in the San Francisco area (zip code 94115). Table 7 presents the 2020 resale value for each vehicle category, and the model(s) used to collect the data. For vehicle segments with a non-existing or limited number of models available in the market, the resale value is calculated using linear extrapolation. We assume the depreciation in the value of PEVs will be equal to the depreciation of ICEVs by 2030, reflecting PEV preference that is similar to ICEVs in the used car market.

Table 7. 2020 resale value of a five-year-old vehicle

BEV						PHEV				ICEV			
PC			PT			PC[D]		PT[E]		PC		PT	
Short[A]	Mid[B]	Long	Short[C]	Mid	Long	Short	Long	Short	Long	Compact[F]	Midsize[F]	Compact[G]	Midsize[G]
23%	33%	38%	38%	39%	45%	40%	40%	45%	45%	50%	50%	55%	55%

Note:
A: BEV-Short PC- Nissan Leaf
B: BEV-Mid PC- Chevrolet Bolt
C: BEV-Short PT- Kia Niro
D: PHEV PC- Toyota Prius Prime
E: PHEV PT- Chrysler Pacifica
F: ICEV PC- Toyota Corolla & Honda Civic for Compact segment; Toyota Camry & Honda Accord for Midsize PCs
G: ICEV PT- Toyota Rav4 & Honda CRV for Compact segment; Toyota Highlander & Honda Pilot for Midsize PTs

[25] Source: Kelly Blue Book. https://www.kbb.com/whats-my-car-worth/?ico=kbbvalue. Accessed June 2020.

Results: Market-level TCO Analysis

In this section, we first present the results of the teardown analysis of manufacturing and purchase cost of PEVs and ICEVs for the study period 2020-2030. Second, we describe how cost competitive PEVs can be compared to ICEVs in the future for the three VMT categories described earlier (low-, mid-, and high-VMT).

Teardown Analysis of Purchase Price

The results of the purchase cost calculation using the cost teardown approach are presented in Figure 2. The bars on the positive side of the x-axis show the different cost components involved in manufacturing. The bars on the negative side of the horizontal axis represent the loss suffered by an OEM from PEV manufacturing in 2020. As mentioned above, we assume that OEMs start earning a profit on PEV manufacturing by 2030. Total purchase cost in the baseline year 2020 is represented by a yellow diamond mark. **Comparing the estimated purchase cost of the three types of powertrains across vehicle segments, we observe that the initial purchase price of an ICEV is always lower than a PEV, for all vehicle segments during the study period (2020-2030).** In 2020, the purchase cost of a BEV-PC short-, mid-, and long-range is $31,624, $37,354, and $39,754, respectively. With higher powertrain (including battery) and R&D costs, BEV-PC short-range is 35 percent more expensive to purchase than a comparable compact ICEV, and BEV-PC long-range is 60 percent more expensive to purchase than a comparable midsize ICEV. The purchase cost of a PHEV-PC short-range is $30,578 and a long-range is $33,226, which is 31 to 34 percent higher than the purchase price of ICEVs. A similar trend is observed for the PT class in 2020, where a compact ICEV costs 37 percent less than a BEV short-range, and a midsize ICEV is cheaper by 45 percent than a BEV long-range.

By 2030, as the powertrain and R&D costs reduce with economies of scale, the difference in purchase cost between an ICEV and a BEV declines compared to 2020. However, the latter is still more expensive than ICEVs. Assuming OEMs would make a profit of 5% for all powertrain types, we observe that the purchase cost of a PHEV is higher than an ICEV by 14 to 18 percent for the PC segment and by 6 to 7 percent for the PT segment. However, in the case of passenger trucks, the short-range PHEV PT becomes more cost-competitive than the mid-size ICEV in the PT segment. The purchase cost of a BEV is more than a comparable ICEV by 13 to 35 percent in both the PC and the PT segment. For the PC segment in 2030, we observe that the PHEV and BEV short-range have approximately similar purchase price.

The breakeven or the tipping point for PEVs is not only subjected to the technological and supply-side uncertainties of the PEV production process but also depends on the ICEV manufacturing costs. To account for the uncertainties in the manufacturing cost of ICEVs, we perform a scenario analysis focusing on the role of CAFE standards on the purchase cost of ICEVs. We simulate a pro-environment policy scenario, where we assume that the 2012 CAFE standards of 54.5 mpg are enforced by 2030. As a result of the stringent standards, OEMs may have to invest in more fuel-efficient internal combustion engine technologies or vehicle design. As a result, the ICEV purchase price is assumed to increase by 5.7 percent by 2030, similar to the assumption made by Lutsey et al. in their cost assessment of 2025-2030 light-duty vehicles in the US (*60*).We also simulate a scenario where CAFE standards are revoked in 2020 (worst-case scenario) and ICEV manufacturers have zero compliance costs. Figure 3 shows the changes in purchase price throughout the analysis years for the PC segment, where the 'sensitivity-bar' indicates the results of the policy-oriented scenario analysis. ICEV purchase price steadily goes up, with the rise in compliance costs for manufacturers. The bottom of the 'error-bar' illustrates the purchase price of ICEVs in the worst-case scenario where the CAFE standards are revoked. The top of the 'sensitivity-bar' illustrates the purchase price of ICEVs in case of stringent CAFE standards as set in the 2012 regulation. According to the 2012CAFEstandard regulation, the fleetwide (cars & trucks) average fuel efficiency of an OEM's should be 54.5 mpg to avoid any penalties.[26] **According to Figure 3, the purchase price of ICEVs from the PC segment remains lower than PEVs in the study period, even when CAFE standards are stricter.**

The purchase price of PEVs decreases over time, and it is not affected by the CAFE standards, as shown in Figure 3. The kink observed in the year 2025, or the change in slope between the years 2020-2025 to 2025-2030, is created by several of our assumptions. For BEVs, the electric power and the battery capacity increase between the years 2020 to 2025, and remain the same between the years 2025 to 2030. These powertrain specifications greatly contribute to the production cost of a vehicle; the higher they are, the higher the purchase price is. From 2025 to 2030, these specifications plateau which dictates a more moderate slope in this period compared to the previous years. For PHEVs, the increase in OEM profit between the years 2025 and 2030 is higher than the increase between 2020 and 2025. Therefore, the rate of decline in the purchase price of PHEVs from 2025 to 2030 is lower than the years before.

For the PT segments, as Figure 4 shows, irrespective of the CAFE standards, short-range PHEVs reach parity with mid-size ICEVs by 2023, but the gap widens due to increased compliance costs. Additionally, short-range BEV is predicted to be cost-competitive with mid-size ICEV passenger trucks by 2030 when CAFE standards are more stringent. Long-range PHEVs experience an increase in purchase cost between the years 2025 to 2030. The price of a bigger battery pack to support the long-range requirements of 2030 along with the cost of higher electric power exceeds the reduction in battery cost between 2025 and 2030. Therefore, an increase in the purchase price is observed for PHEVs.

To understand how uncertainties related to battery costs will influence the manufacturing costs and consequently the purchase price of PEVs we do scenario analysis concerning battery cost values. For this scenario analysis, the minimum and maximum predicted battery pack costs are incorporated into the purchase price of PEVs. Figure 5 and Figure 6 show the results for the PC segment, and Figure 7 and Figure 8 show the results for the PT segment. Even with the minimum battery pack cost prediction, the cost competitiveness of PEVs in terms of purchase cost does not improve. ICEVs in the PC segment continues to have the lowest purchase price for the study period (Figure 5). For the PT segment, Figure 7 and Figure 8 reinforce the result that the purchase cost parity of short-range PHEVs with mid-size ICEV occurs around 2023. The parity of short-range BEV passenger trucks with mid-size ICEV can starts as early as 2029 if

[26] https://nepis.epa.gov/Exe/ZyPDF.cgi/P100EZ7C.PDF?Dockey=P100EZ7C.PDF

battery pack costs reduce to the minimum predicted value. On the contrary purchase price parity may not be reached in the case of high battery pack costs.

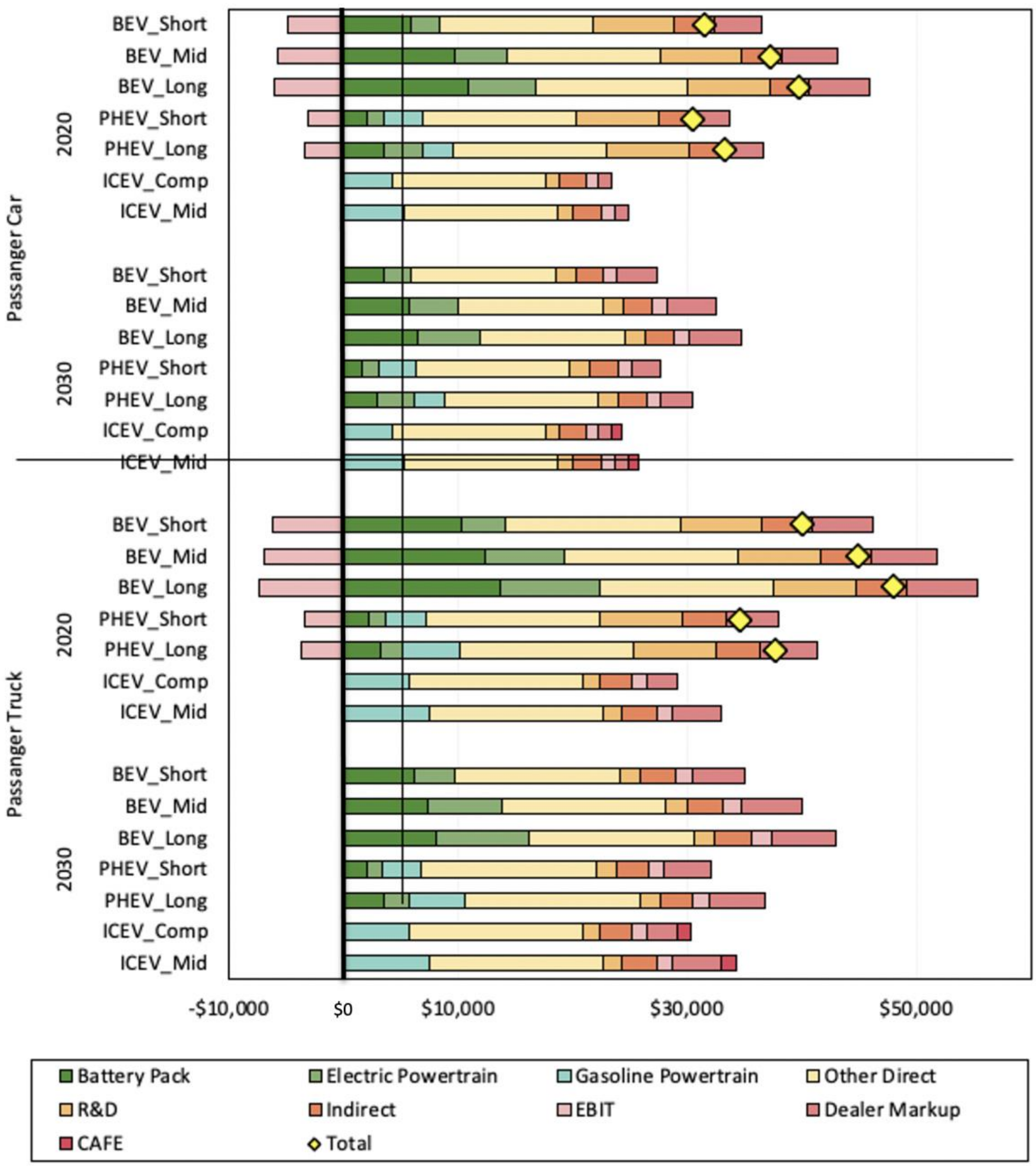

Figure 2. 2020 and 2030 vehicle purchase price breakdown

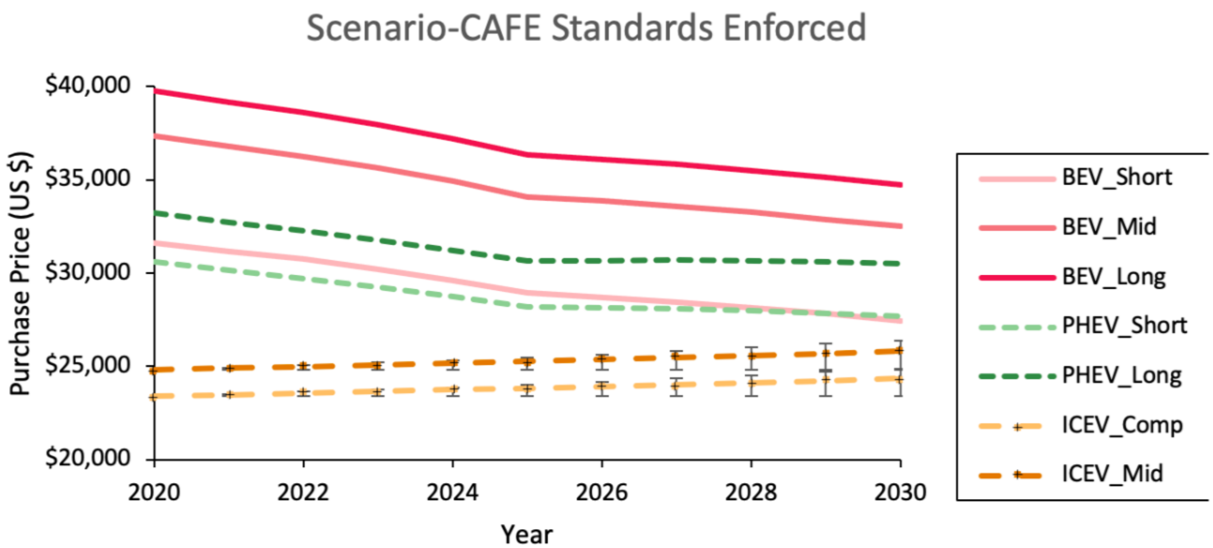

Figure 3. 2020-2030 passenger car purchase price

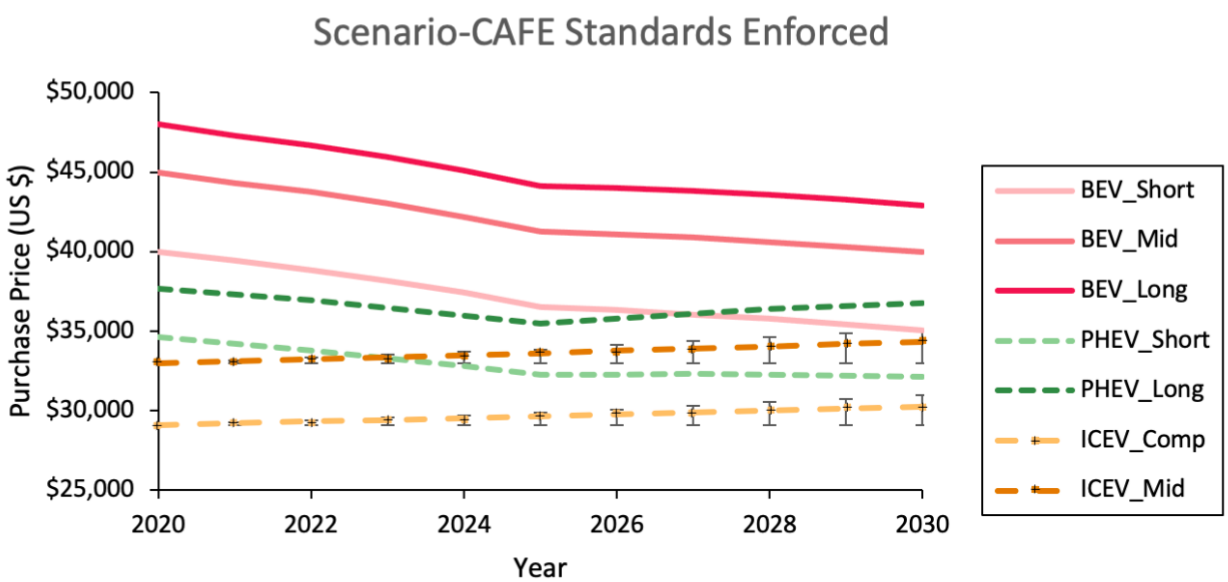

Figure 4. 2020-2030 passenger truck purchase price

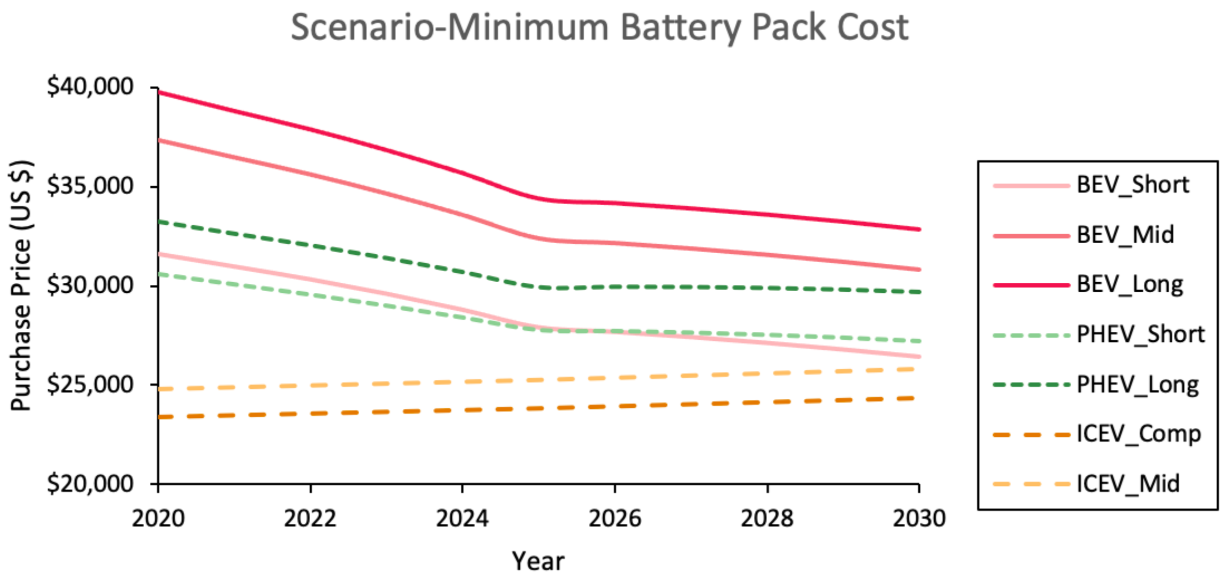

Figure 5. 2020-2030 passenger car purchase price

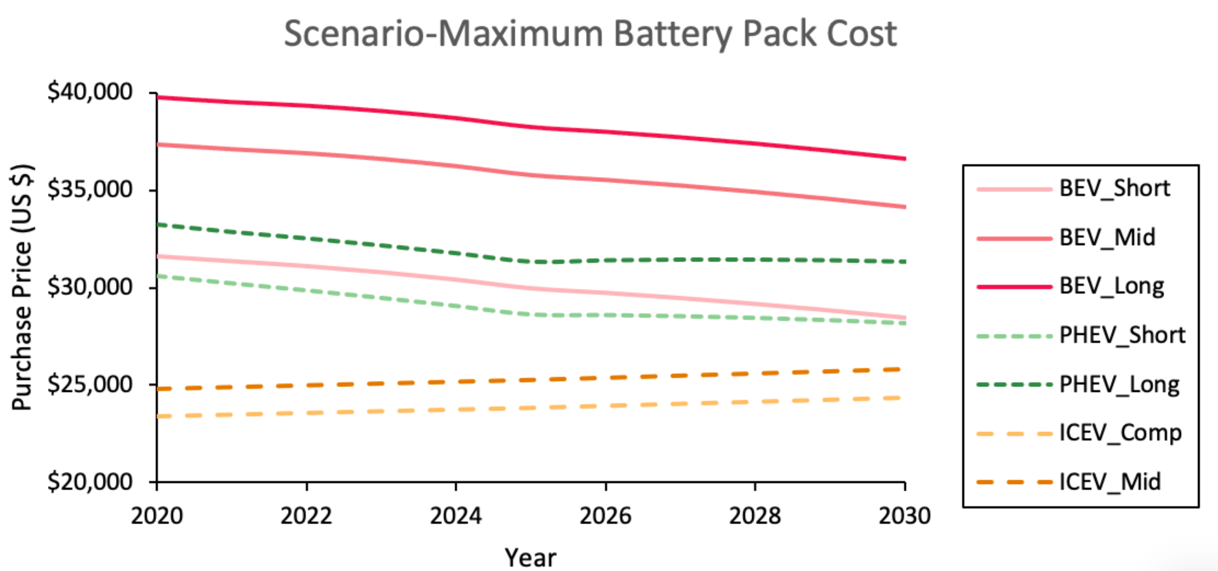

Figure 6. 2020-2030 passenger car purchase price

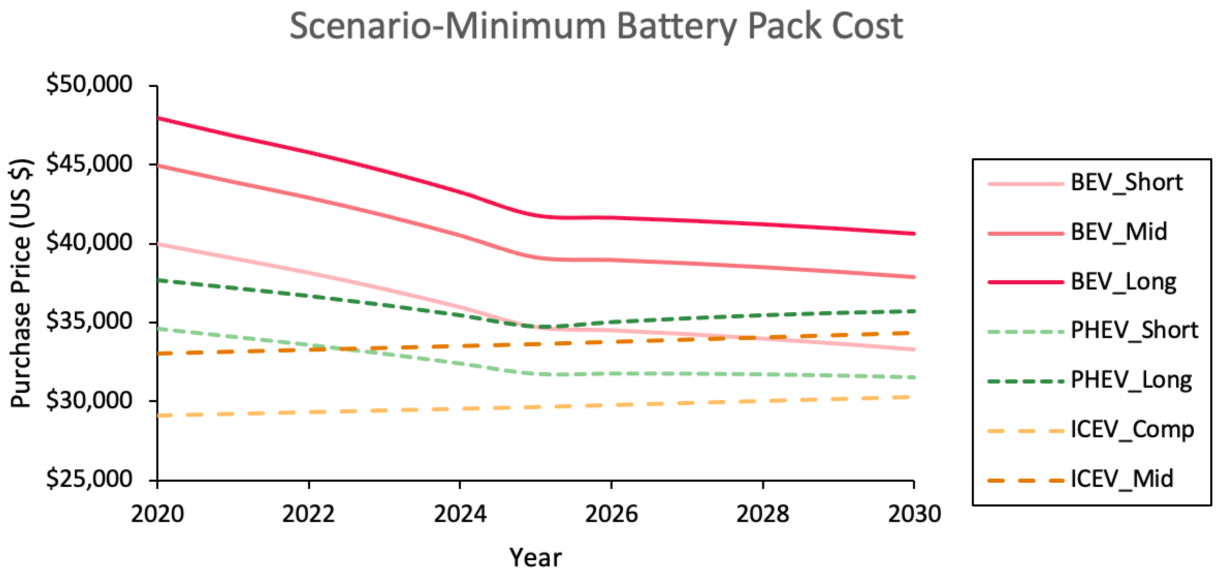

Figure 7. 2020-2030 passenger truck purchase price

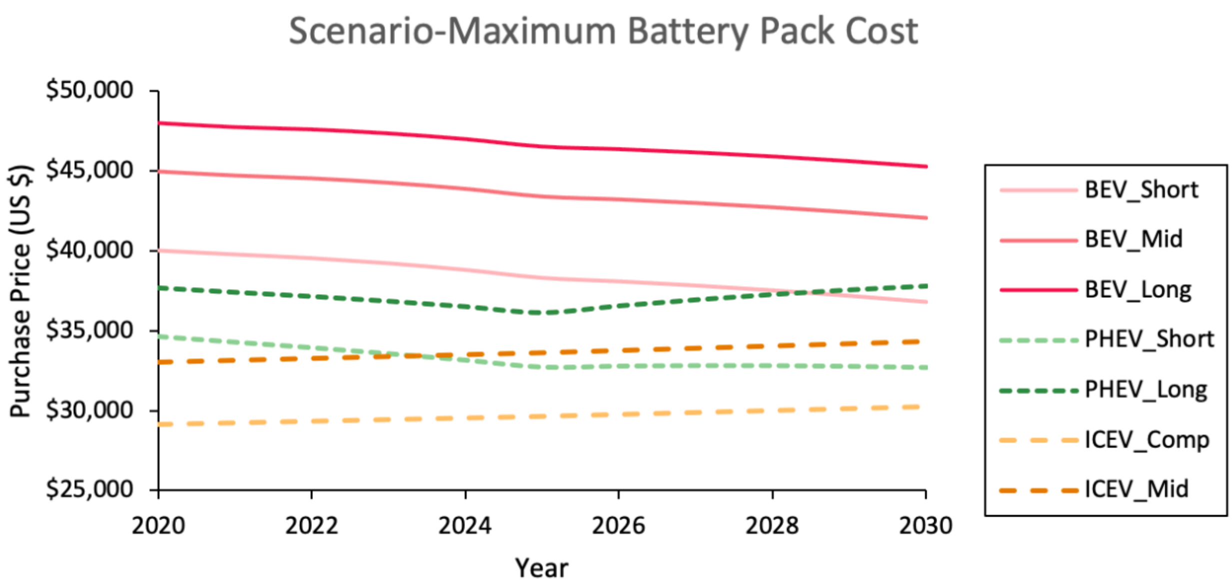

Figure 8. 2020-2030 passenger truck purchase price

Cost Competitiveness of PEVs

The annual TCO per mile analysis includes all cost components discussed above along with the other capital cost components, operating costs, and the resale value. Figure 9 shows the analysis results for the three VMT categories. In the baseline year 2020, purchasing and operating a BEV from the PC segment with average annual VMT (mid-category) leads to per-mile expenses that are higher by 30 to 35 percent compared to a comparable ICEV. The TCO per mile of PHEVs in the PC segment is higher by 12 to 18 percent. Considering the PT segment and the mid-VMT category, TCO parity is achieved between the PHEVs (both short- and long-range) and the mid-size ICEVs as well as between the short- and mid-range BEV PT and the mid-size ICEV.

In general, considering the current predictions about the market conditions and technology improvements, low VMT will benefit from holding an ICEV in any vehicle category over the next decade. By 2030, drivers in the high-VMT category with a PC can get the same annual TCO per mile for a short-range BEV as with a compact or a mid-size ICEV. Similarly, drivers in the high-VMT category can get cost parity between a short-range PEV in the PT segment and an ICEV from the compact-SUV segment without any incentives. **Based on the analysis results, by 2030, high mileage drivers can in general benefit financially from the ownership of a PEV from the passenger car or truck segment.**

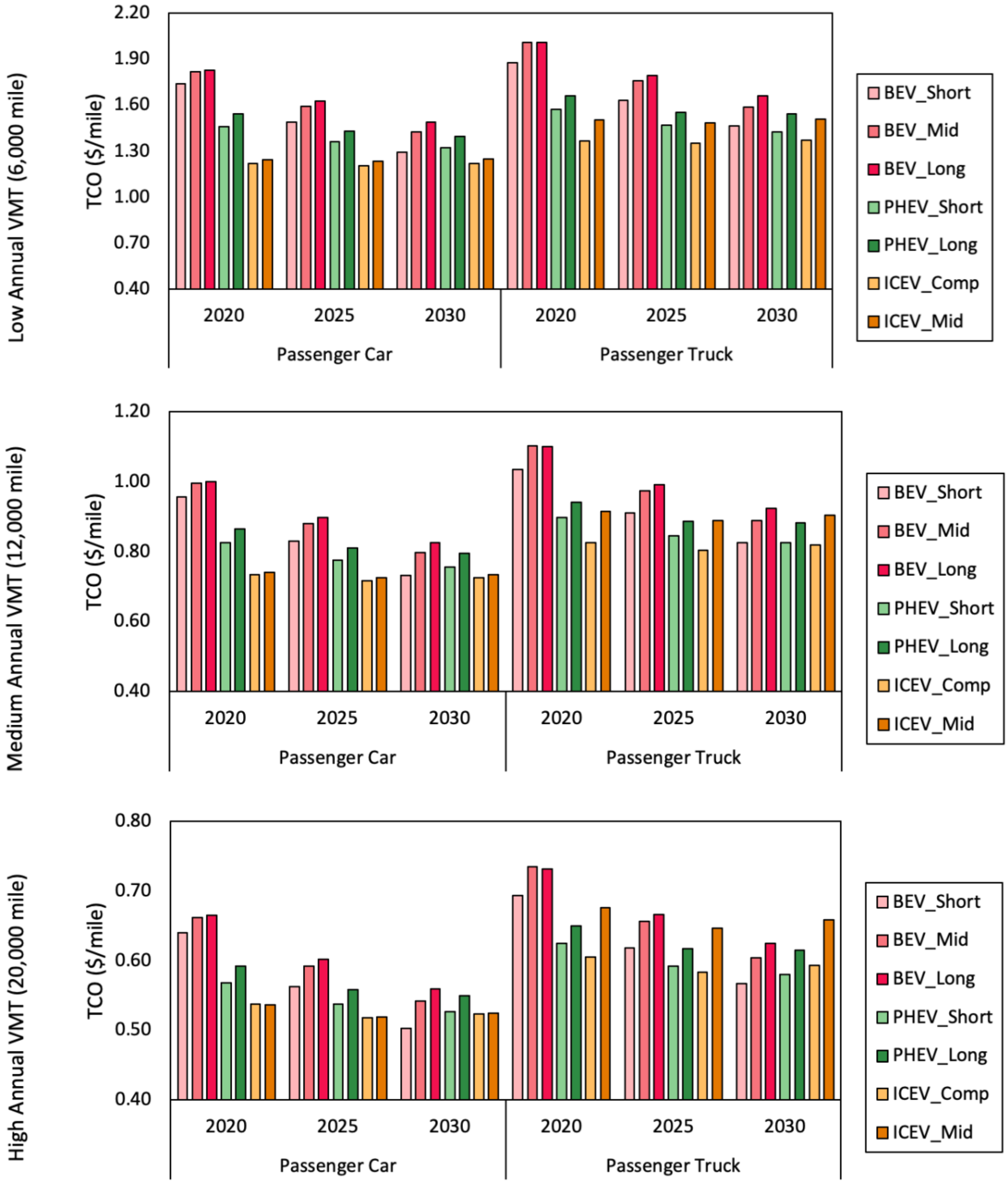

Figure 9. TCO/mile for average market groups in years 2020, 2025, and 2030

Part 2: Cost of Electrification of the Light-duty Vehicle Fleet in California

A major concern associated with achieving the target of 100% ZEV sales by 2035 or a zero-carbon transportation system by 2045 is the cost of transitioning from an ICEV-dominated fleet to one where almost 100% of the vehicles are ZEVs. As observed in the market-level TCO analysis in Part 1, given the predictions of battery cost improvements and current policy regulations, PEVs will not reach purchase price parity in any of the vehicle categories. However, as the operating cost of PEVs is lower than ICEVs, overall cost competitiveness can be achieved under certain scenarios, particularly if there is high-travel demand. This section will evaluate the cost of a specific fleet transition scenario ("ultra-low carbon scenario) based on the ZEV adoption model described in Appendix B. Details about the ultra-low carbon scenario and assumptions about the penetration rate of BEVs, PHEVs, and fuel cell electric vehicles (FCEVs) has been discussed in a recent study by Brown et al. where the authors analyzed possible policy options that could, if combined, put the state on the pathway to a carbon-neutral transportation system by 2045 (*65*). Here, we will rely on the adoption scenarios and the assumptions for the FCEV market used in the study by Brown et al. but restrict our analysis to 2030 for consistency with Part 1 of this study. Considering ZEV allocation under the "ultra-low carbon" scenario, we compare the monetary cost of transitioning to ZEVs to the cost of continuing with a comparable ICEV fleet for the years 2020 to 2030 for the six categories of household defined based on annual household income (less than $75,000, $75,000-$200,000, and greater than $200,000) and dwelling type (single-family/apartment & others). The details of the TCO calculation, including assumptions and references can be accessed at DRYAD (https://doi.org/10.25338/B80D10).

The market-level TCO analysis in Part 1 of this study accounted for the difference in cost of PEV adoption for three VMT categories. But VMT is not the only source of heterogeneity in the cost of adoption. As a recent study from Norway has shown, sociodemographic characteristics are a strong predictor of the vehicle portfolio (*66*). Socio-demographic characteristics like household income and dwelling type can influence a household's vehicle fleet size and composition, access to charging infrastructure at home, work, and public/non-work locations along with total VMT. Thereby, here in the analysis of the cost of electrification, we try to capture these additional sources of heterogeneity, estimating the TCO benefits for the six household categories accounting for differences in the ability to install chargers, charging probability at home, and dependence on public chargers.

The market-level TCO analysis in Part 1 included only PEVs. To model the cost of electrification of California's LDV fleet for the period 2020-2030, we include FCEVs as these vehicles are expected to be an integral part of the fleet. Also, the cost of electrification analysis includes all the ZEVs in order to align it with the ZEV allocation mechanism described in Appendix B and the electrification goals of California (net-zero carbon emission from the transportation sector by 2045). The cost of electrifying the LDV fleet of California in the 2020-2030 period under the "ultra-low carbon" scenario is demonstrated as follows:

We first demonstrate how the fall in vehicle price of existing ZEV technologies (BEVs, PHEVs, and FCEVs) from 2020 to 2030 impact the capital cost and consequently the total cost associated with the electrification process. The purchase price of BEVs and PHEVs for the period 2020 to 2030 are the ones estimated using the teardown approach (Figure 2). For ICEVs, we take the manufacturer suggested retail price (MSRP) of the 10 highest selling models from the compact and midsize segment of passenger cars and passenger trucks (base trim-level) for the year 2020. Assuming, the OEM profit margin is incorporated in the MSRP, we only assume that there is a dealer margin of 5% for PCs and 10% for PTs. Also, for FCEVs we incorporate the dealer markup. To include the effect of CAFE standards on future ICEV purchase price we assume that there is a 2% rise in price by 2025 and a 4% increase by 2030. As mentioned earlier, the purchase price of FCEVs are taken from the study by Brown et al. (*65*). The vehicle purchase prices for all the powertrains considered in Part 2 of the analysis are provided in Table 8. The capital cost component of TCO estimates for BEVs and PHEVs also include the cost of charger installation. The probability of Level 2 charger installation may vary across income groups and between single-family owners and apartment dwellers. This difference in probability is considered in the estimation of expected cost of charger installation for the six household segments. The probability of charger installation is obtained from the multi-year cohort survey of PEV owners in California administered by the Plug-in Hybrid & Electric Vehicle (PH&EV) Research Center at UC Davis. Assuming that home chargers do not follow similar ownership patterns as household PEVs and there is no used market for chargers, we do not consider a resale value for chargers.

Table 8. Purchase price of BEVs, PHEVs, ICEVs, and FCEVs (2020-2030)

	BEV						PHEV				ICEV				FCEV	
	Passenger car			Passenger Truck			Passenger car		Passenger Truck		Passenger car		Passenger Truck		Passenger car	Passenger Truck
	Short	Mid	Long	Short	Mid	Long	40-mile	80-mile	40-mile	80-mile	Compact	Midsize	Compact	Midsize		
2020	$34,470	$40,918	$46,153	$44,101	$52,937	$57,871	$34,329	$37,510	$38,799	$42,342	$24,125	$34,030	$29,338	$43,857	$47,675	$60,250
2021	$33,048	$39,332	$44,397	$42,439	$51,065	$55,870	$,343	$36,471	$37,800	$41,413	$24,221	$34,165	$29,454	$44,031	$46,378	$58,537
2022	$31,684	$37,808	$42,708	$40,840	$49,259	$53,938	$32,385	$35,460	$36,826	$40,504	$24,317	$34,300	$29,571	$44,205	$45,117	$56,873
2023	$30,376	$36,342	$41,084	$39,302	$47,516	$52,073	$31,455	$34,477	$35,878	$39,615	$24,413	$34,436	$29,689	$44,381	$43,890	$55,256
2024	$29,122	$34,933	$39,521	$37,821	$45,836	$50,273	$30,551	$33,522	$34,954	$38,746	$24,510	$34,573	$29,807	$44,557	$42,696	$53,685
2025	$27,920	$33,579	$38,018	$36,396	$44,214	$48,534	$29,673	$32,593	$34,054	$37,896	$24,608	$34,710	$29,925	$44,734	$41,535	$52,159
2026	$27,964	$33,578	$37,954	$36,419	$44,187	$48,471	$30,131	$33,146	$34,605	$38,765	$24,703	$34,845	$30,041	$44,908	$40,780	$51,219
2027	$28,007	$33,577	$37,891	$36,442	$44,160	$48,408	$30,596	$33,708	$35,165	$39,655	$24,799	$34,981	$30,158	$45,083	$40,040	$50,296
2028	$28,051	$33,576	$37,828	$36,465	$44,133	$48,345	$31,068	$34,279	$35,733	$40,564	$24,896	$35,117	$30,275	$45,258	$39,312	$49,390
2029	$28,094	$33,575	$37,764	$36,488	$44,106	$48,282	$31,548	$34,861	$36,311	$41,495	$24,993	$35,254	$30,393	$45,434	$38,598	$48,500
2030	$28,138	$33,574	$37,701	$36,511	$44,079	$48,220	$32,034	$35,452	$36,898	$42,447	$25,090	$35,391	$30,512	$45,611	$37,897	$47,626

Second, we demonstrate how changes in fuel price, difference in travel behavior, and heterogeneity in accessibility to charging infrastructure can impact the operating cost of gasoline and ZEVs over the study period. The assumptions related to changes in cost of charging BEVs and PHEVs at non-home locations due to vehicle-to-grid integration as well as the cost of refueling FCEVs are taken from the study by Brown et al.(*65*). Accounting for the transition to renewable energy sources in California at the electricity grid-level and the potential of economical daytime charging, a higher proportion of charging events and thereby VMT is assumed to be electrified with workplace charging in the later years. Data on gasoline price predictions is from the U.S. Environment Protection Agency, and the difference in access to charging infrastructure by household category is derived from the multi-year cohort survey of PEV owners in California administered by the Plug-in Hybrid & Electric Vehicle Research Center at UC Davis. Details on the assumptions and data sources can be found in the excel workbook with the TCO calculations (https://doi.org/10.25338/B80D10). We also account for the difference in annual VMT across the six household categories, but we assume they remain constant over the years (2020-2030). In other words, we assume that households have the same number of vehicles and drive them in a similar fashion as now. This is a strong assumption about travel and vehicle choice behavior, but it was required to keep the analysis simple and understandable. The data on annual VMT for the six household categories and their sub-categories based on vehicle ownership are estimated using the 2019 California Vehicle Survey data[27]. Figure 10 gives the estimated average annual VMT of the six household groups analyzed here. Note, hereon, in all the figures AH refers to “apartment- high income (> $,200,000)”, AM refers to “Apartment-mid income ($75,000-$200,00), AL refers to “apartment-low income (<$ 75,000)”, SH refers to “Single family-high income (> $,200,000)”; SM refers to “Single family-mid income ($75,000-$200,00)”, and SL refers to “Single family-low income(<$ 75,000)”.

[27] "Transportation Secure Data Center." (2021). National Renewable Energy Laboratory. Accessed [05.27.21]: www.nrel.gov/tsdc.

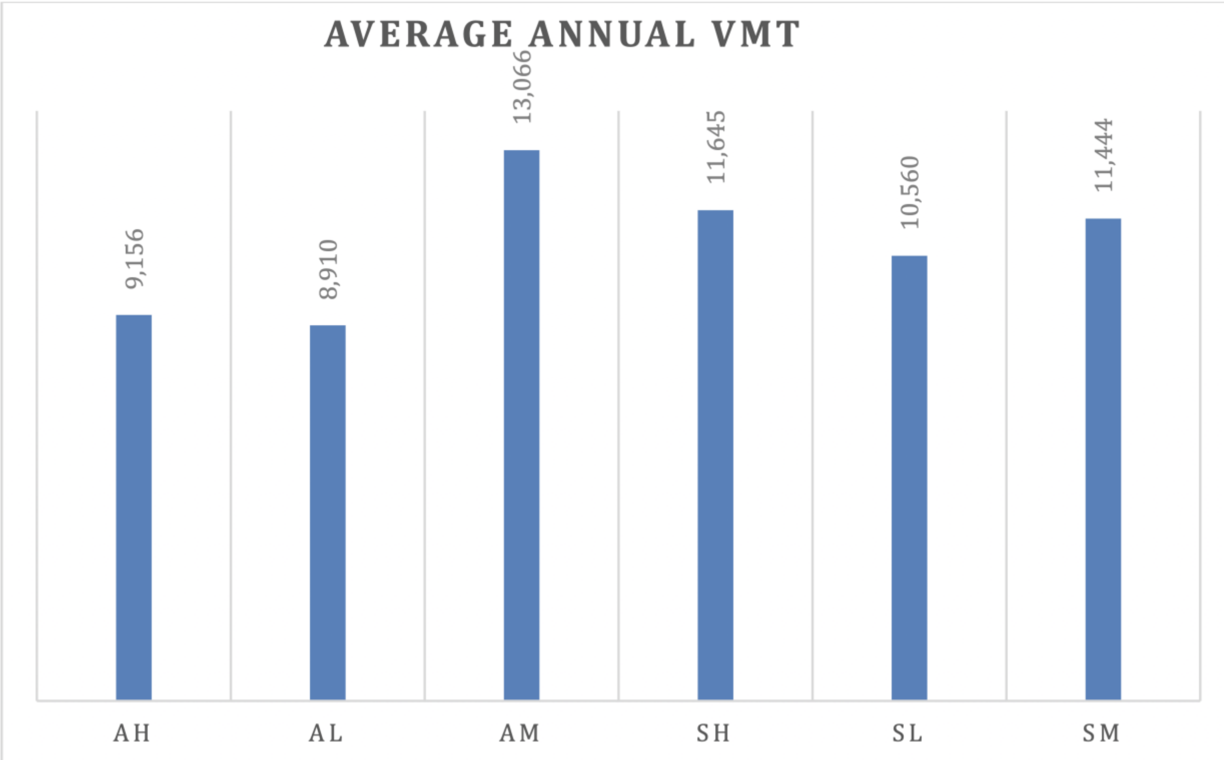

Figure 10. Average annual VMT estimates from California Vehicle Survey (2019)

Finally, annualized TCO of twelve ZEV options (short-, mid-, long-range BEV PC and PT, short (40)- and long (80)-range PHEV PC and PT, FCEV PC and PT) and the cost of adoption at the fleet-level is evaluated for the LDV electrification scenario demonstrated in Appendix B (but restricted to the 2020-2030 period). Once again, to keep the cost calculation aligned with Part 1 of the study, a vehicle ownership period of 5 years is assumed. Accordingly, the resale value of the vehicle is estimated based on the vehicle depreciation rate assumed in the 2019 AFLEET Tool by the Argonne National Laboratory (https://greet.es.anl.gov/afleet_tool).

In the allocation mechanism described in Appendix B, each of the six household groups are allocated a type of ZEV (BEV/PHEV/FCEV) each year based on their income, dwelling type, existing fleet size, and number of ZEVs already adopted. However, there is no differentiation between passenger cars/ trucks/ long-range/mid-range/short range vehicles in the allocation mechanism. Since vehicle cost differs across these segments- PC versus PT or short-range vs mid-range, or mid-range versus long-range, for the TCO analysis, we differentiate between these vehicle segments. Households are allotted a passenger car (PC) or truck (PT) based on a fleet transition scenario described in Table 9.

Table 9. ZEV allotment Rule for TCO Comparison (Demonstration of a Possible Scenario)

Household Type (Fleet size + # PEVs/ZEVs)	ZEV allotted: vehicle segment and type of ZEV	Comparable Gasoline Vehicle
1 vehicle + 0 PEV (No PEV adopted)	FCEV- PT	Gasoline PT
2/3/4/5 vehicles + 0 PEV (No PEV adopted)	FCEV- PC	Gasoline PC
1 vehicle + 1st ZEV	ZEV-PT (LR BEV-PT/PHEV 80- PT)	Gasoline PT; Mid-size Gasoline PT for BEV LR PT, PHEV 80 PT
2/3/4/5 vehicles + 1st ZEV	ZEV-PC (MR BEV- PC/ PHEV 40 PC)	Gasoline PC
2/3/4/5 vehicles + 2nd ZEV	ZEV-PT (LR BEV-PT/ PHEV 80-PT)	Gasoline PT; Mid-size Gasoline PT for BEV LR PT, PHEV 80 PT
3/4/5 vehicles + 3rd ZEV	ZEV-PC (MR BEV-PC/PHEV 40 PC)	Gasoline PC
4/5 vehicles + 4th ZEV	ZEV-PT (SR BEV-PT/PHEV 40 PT)	Gasoline PT; Mid-size Gasoline PT for PHEV 80 PT
5 vehicles + 5th ZEV	ZEV-PC (SR BEV-PC/PHEV-40 PC)	Gasoline PC

According to the ZEV adoption model described in Appendix B, in the year 2020, 54% of the PEV-owning households had only one PEV in their fleet and were mainly single-family home dwellers in the high- and middle-income category. Considering the ZEV allotment rule based on household fleet composition of Table 9 and the ZEV adoption model in Appendix B, majority of the PEVs are allocated to single-family homeowners in the high- and mid-income category between 2020 and 2030. Moreover, though the technology matures over time, range anxiety may still play a role in the ZEV adoption decision whereby, households with multiple vehicles adopt BEVs and PHEVs. As a result, with the ZEV allotment rule of Table 9, these multi-vehicle single family homeowners are allocated mid-range BEVs and PHEV 40 passenger cars in the scenario demonstrated here. This allocation mechanism will play a strong role in the results described below. One thing to note, the results shown here is a demonstration of the cost of electrifying California's LDV fleet under one possible scenario (ZEV adoption under "ultra-low carbon" scenario +ZEV allotment rule described above). The cost of electrification will differ under an alternative scenario (e.g., if ZEV adoption is accelerated or more long-range BEVs/PHEVs are encouraged, etc.).

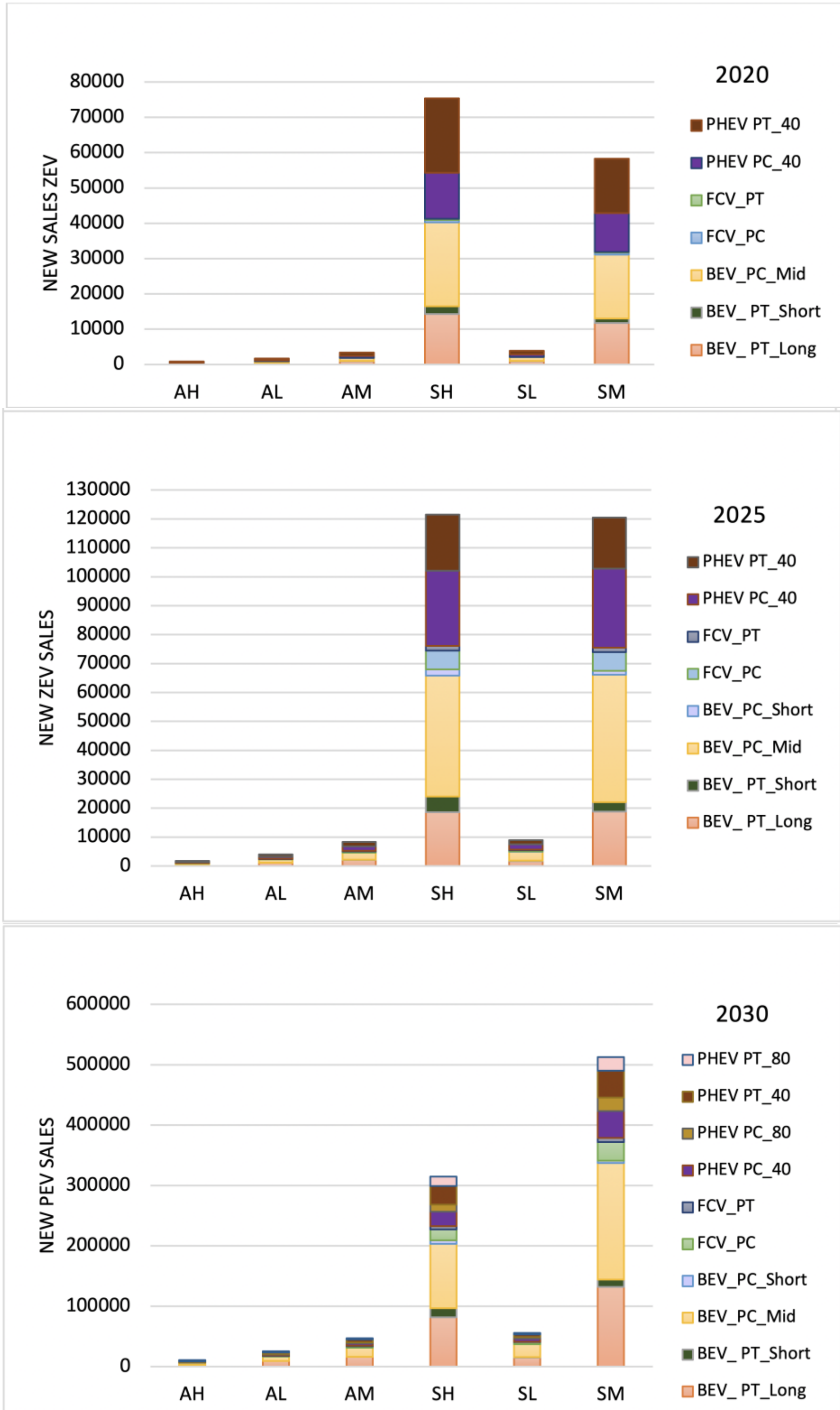

Figure 11. ZEV allocation across household groups in 2020,2025, and 2030

Result: Cost of Electrification of the Light-duty Vehicle Fleet in California (2020-2030)

The trend of capital cost differences between ZEVs and ICEVs that need to be incurred for transitioning to a ZEV-dominant fleet in California corresponds to the ZEV allocation pattern observed in Figure 11. The difference in upfront capital cost between ZEVs and ICEVs falls over the years for all household groups. However, the gap between ZEV and comparable ICEV capital cost falls at a higher rate between 2020 and 2025 than in the later years. This can be driven by the fact that until 2025, ZEVs are adopted primarily by multi-vehicle households, thereby allocated mid-range BEV passenger cars and PHEV cars with 40-mile range. The cost of both the vehicle types falls over the time period in comparison to the cost of the comparable ICEV (compact ICEV-PC). Beyond 2025, as more single-vehicle households enter the market and multi-vehicle households adopt their second and third PEV, long-range passenger trucks get allocated. The price of the long-range ZEV passenger trucks continues to be high in the 2020-2030 period and thereby the price difference between ZEVs and comparable ICEVs (midsize PTs) are lower. **Overall, we observe that over the years though the average upfront annualized capital cost of ZEVs remains higher than comparable ICEVs for all the household categories, it reduces on average by 56% from the year 2020 to 2045 in response to the fall in the cost of the ZEV technologies and economies of scale (**Figure 12**).**

The capital cost difference between ZEVs and ICEVs vary across household segments due to the difference in their ability to install a Level 2 charger at home. The expected cost of charger installation is higher for households in single-family homes, with higher income, and adopting BEVs. As a result, we observe that the capital cost difference is lower for apartment dwellers and low-income households. Moreover, in the latter years as a household adopts multiple PEVs, the cost of charger installation is shared across multiple PEVs making the capital cost for additional PEVs lower. Here, in the TCO analysis we assume that each household will install only one Level 2 charger, there is no depreciation. These are strong assumptions and if there is depreciation, households will need to install additional chargers and that will raise the cost of adopting multiple PEVs. Future studies in this area should account for this possible scenario.

We do account for charger congestion in terms of lower probability of access to home Level 2 charger in a multi-PEV household. However, the effects of charger congestion will reflect in the operating cost than in the capital cost component of TCO.

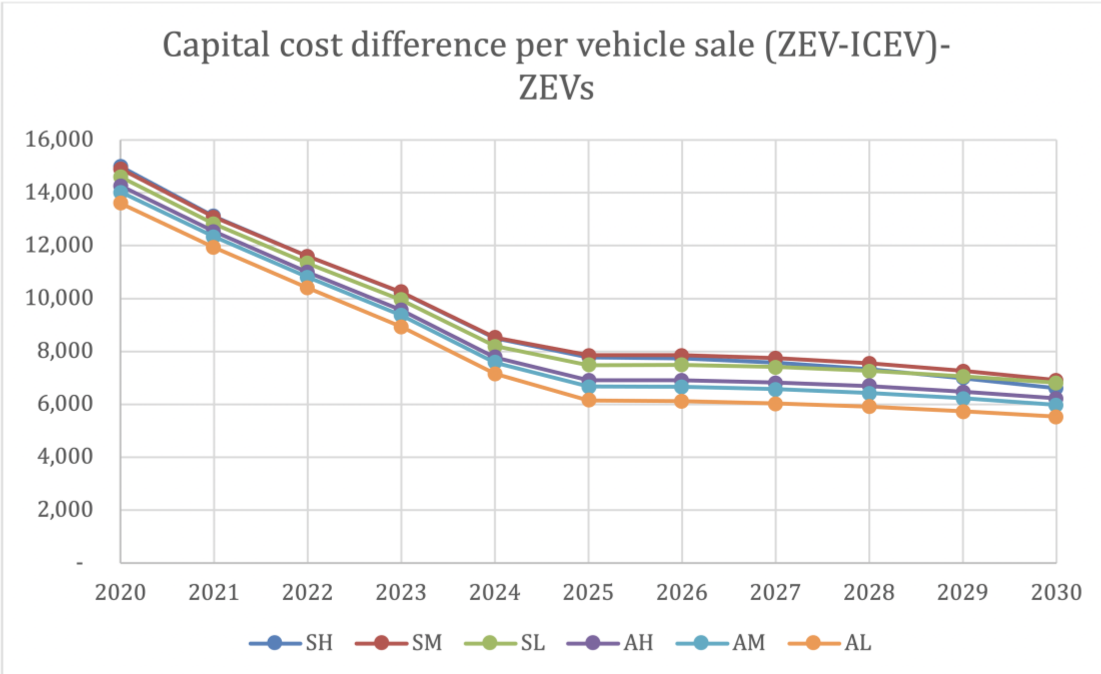

Figure 12. Average capital cost difference between a ZEV and an ICEV-fleet

In terms of operating costs, though ZEVs always have a lower cost of operation than gasoline vehicles, the difference reduces until 2025 and increases thereafter (Figure 13). The inverted u-shape can be a result of multiple factors. First, both gasoline prices and cost of charging at home, work, and DC fast chargers go up between 2020 and 2025. Post 2025, assuming greater penetration of renewable energy into the electricity grid mix and vehicle-to-grid integration as in the study by Brown et al., cost of charging at work and DC Fast charger decreases, while gasoline cost continues to rise. The estimates in the figure indicate that the rise in operating cost of ICEVs due to increase in gasoline price can exceed the cost savings obtained from fuel efficiency improvements. Moreover, we observe that middle income apartment dwellers (AM) with the highest annual VMT have the highest operating cost benefits from switching to a ZEV, while the high-income apartment dwellers (AH) with lower VMT have lower fuel cost savings. This is consistent with the results in Part 1 of the study, past literature on VMT and TCO benefits (*6*), and the VMT distribution in Figure 10.

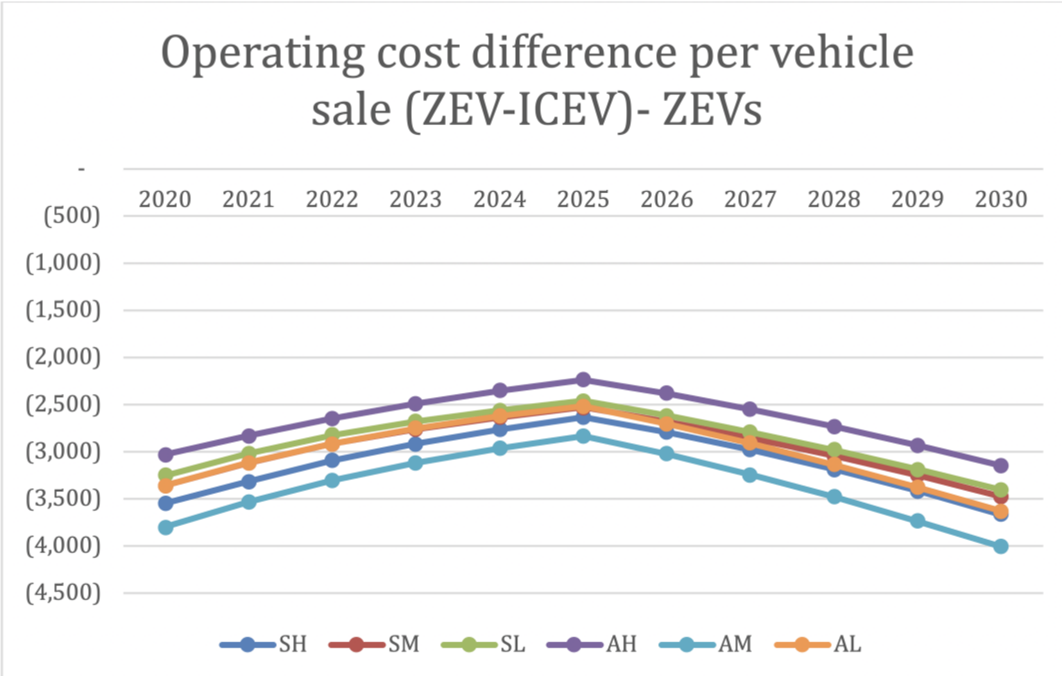

Figure 13. Average operating cost difference between a ZEV and an ICEV-fleet

Finally, summing up the capital cost, operating cost, and the resale value of a ZEV fleet for the six household categories we observe that at the fleet-level, until 2030, the average total cost of adoption of ZEVs remains higher than a comparable ICEV fleet for the apartment high-income group and detached home dwellers belonging to all income categories (Figure 14). **Cost parity is achieved only by the group with high annual VMT (Middle income apartment dwellers) and lower income households with multiple vehicles.** In the ZEV adoption model described in Appendix B, a small share of low-income apartment dwellers participates in the ZEV market in the 2020-2030 period, mostly multi-vehicle households getting their first PEV/FCEV. According to the ZEV allocation rule in Table 9, these households are allocated comparatively shorter range PEVs from the passenger car segment, raising the potential to reach cost parity by 2030.

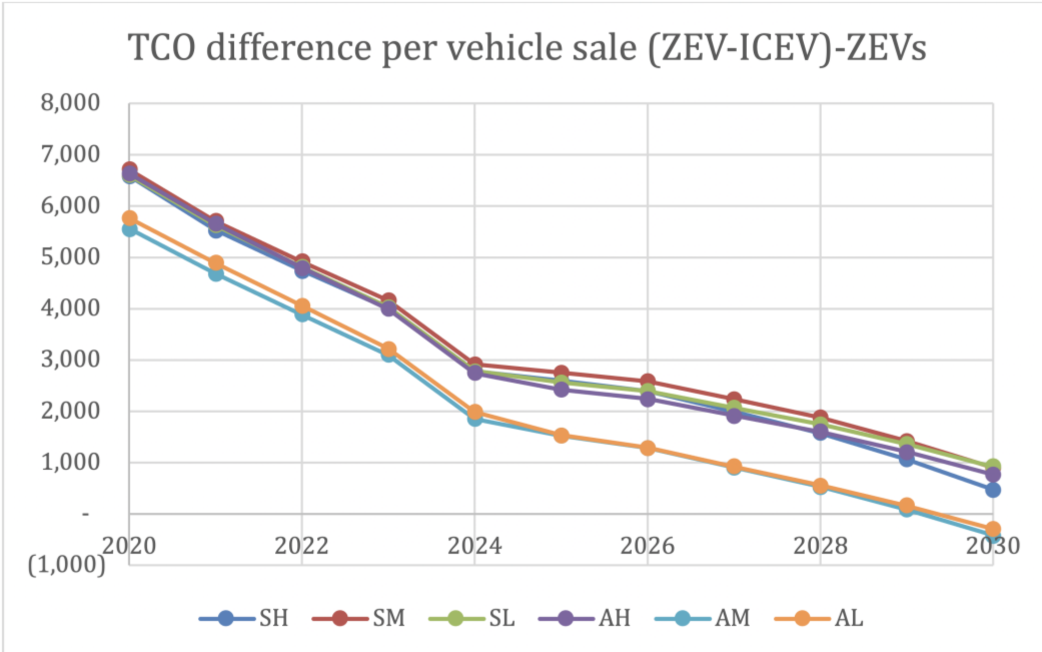

Figure 14. Average TCO difference between a ZEV and an ICEV-fleet

Overall TCO and thereby the total cost of ZEV transition varies by market segment. However, it can also vary at the household-level based on their fleet composition which in turn determines the cost of charger installation, the probability of access to home chargers, and the dependence on public chargers. In the other words, even when the average TCO falls for a particular household category, some individual households in that category may benefit from electrification of their household fleet, while others may not. As a result, the share of households in each of the six categories that benefit from switching to a ZEV rather than a comparable ICEV will vary over the years. As observed in Figure 15, in the initial years, when households add their first ZEV (mostly mid-range PC allocated), the share of households benefiting from electrification rises for all six household categories, with a higher share of low- and mid-income apartment dwellers benefitting in the early years than other household groups. This can be explained by the higher VMT of the mid-income apartment dwellers and the type of ZEV allotted to the multi-vehicle households in these two groups. Post-2025, as the share of economical daytime workplace charging goes up and the upfront capital cost falls, the share of households benefiting from electrification rises. Beyond 2025, 35% to 50% of the households incur TCO benefits across the six household categories compared to less than 10% in the initial years.

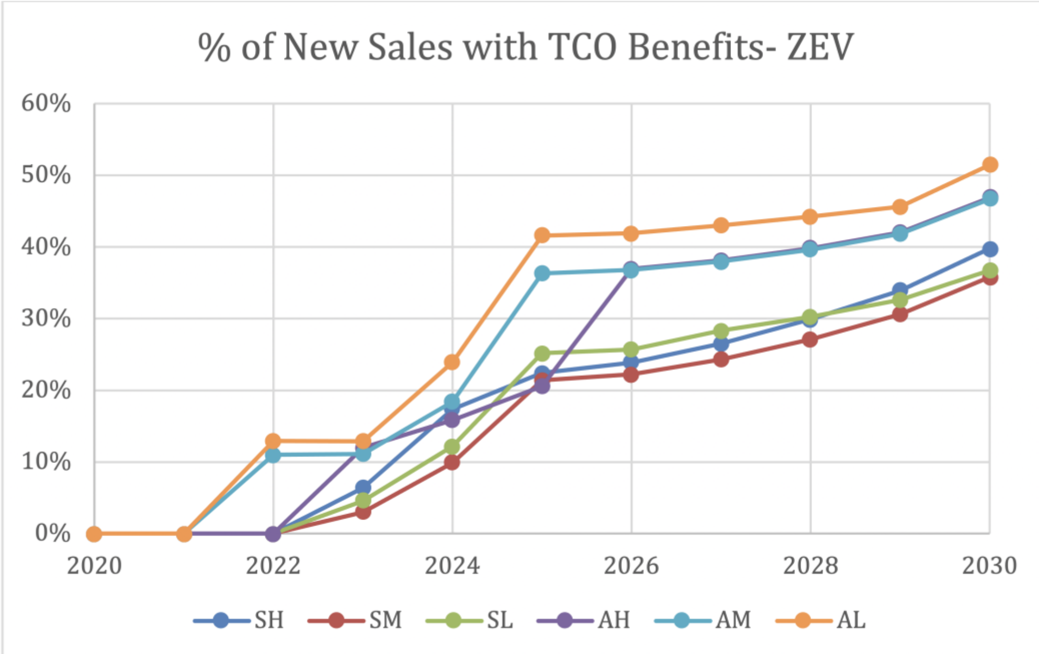

Figure 15. Proportion of household with TCO benefits from purchasing ZEVs

Conclusion

Policy implications of the TCO modeling and cost of transition analysis

The primary motivation behind the market-level TCO analysis and the demonstration of a possible scenario of cost of electrification was to bring forth some of the important market characteristics and barriers that policymakers need to consider in transitioning the current California fleet to an almost 100% ZEV-fleet by 2045. The rate of diffusion of PEVs and FCEVs over the next decade will depend on whether the ZEV options are cost-competitive with the conventional fuel vehicles and how much “followers” in the adoption process benefit from electrification. As illustrated in this study, cost competitiveness and the TCO benefits are subjected to both technology and user-behavior related uncertainties. While the results presented here will alter based on how the ZEVs are allotted to households in the different categories, the share of new and used vehicles assigned to each household category, or with a change in the other TCO model assumptions, we believe that the policy implications illustrated here will continue to hold.

First, ZEVs have been subsidized over the past decade by the federal and state government to encourage adoption. As the purchase price of ZEVs fall due to improvements in battery technology or powertrain components, policymakers expect to be able to phase out these subsidies and incentives. However, as we observe in Figure 12, cost parity is not achieved by most household types until 2030. Moreover, in terms of TCO benefits, there will be some households at all time points who will continue to need incentives to adopt ZEVs as they do not benefit from switching to these vehicles, potentially due to their travel needs, access to charging facilities, or other fleet characteristics, as observed in Figure 15.

Second, considering the expected reduction in the purchase price of PEVs over the next decade, TCO savings from PEV adoption will depend on the operating cost savings offered by the powertrains. The operating cost of PEVs depend not only on the miles traveled but also on the cost of vehicle charging. As our comparative analysis of operating costs for ZEVs and ICEVs show, the cost savings from switching to ZEVs fall in the later years as low-income households and apartment dwellers adopting these vehicles are more dependent on non-home charging infrastructure. As charging at public infrastructure can be expected to remain more expensive than home-charging, it is important to consider policies that will allow higher access to overnight/at-home charging for low-income households and apartment dwellers.

Lastly, as our vehicle allocation scenario and TCO results indicate, low-income households may need access to cheaper used ZEVs in the market to be able to meet cost parity and replace their ICEVs with these vehicles. As the maintenance cost of PEVs is considerably lower than ICEVs over the vehicle lifetime, the operating cost savings from a used PEV can be substantial. Thereby, to encourage electrification among the lower-income households, a robust used car market for ZEV vehicles will be important.

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Data Management

Products of Research

The project used existing survey and logger data collected by the PH&EV center in UC Davis to simulate vehicle use and charging behavior models. In addition, the project used public data like 2019 California Vehicle Survey and auto industry reports for the technology cost predictions. No new data was collected for the project. All the data has been managed by the PI of the project.

Data Format and Content

The data used for the TCO estimation and cost of electrification analysis are stored as Excel files. There is no individual/household-level data with identifiable information.

Data Access and Sharing

The PI and the PH&EV center will retain the right to manage the data. The data used for the calculation of vehicle manufacturing costs and market-level TCO of PEVs is available on the Dryad data repository at https://doi.org/10.25338/B80D10.

Reuse and Redistribution

The data used for the calculation of vehicle manufacturing costs and market-level TCO of PEVs is available on the Dryad data repository. Suggested citation:

> Chakraborty, Debapriya; Tal, Gil; Buch, Koral (2021), Total Cost of Ownership of Plug-in Electric Vehicles Calculations Data sheet, Dryad, Dataset, https://doi.org/10.25338/B80D10

Appendix A: Market Models and Specifications

Table 10. 2018-2021 BEV models in the US and their specifications

Make	Model	Year	Range (mile)	Battery Capacity (kWh)	Electric Power (kW)	Segment	Class	Range Category
MINI	Cooper SE Hardtop 2 door	2020	110	32.6	135	PC	standard	short
MINI	Cooper SE Hardtop 2 door	2021	110	32.6	135	PC	standard	short
Kia	Soul Electric	2018	111	30	81	PC	standard	short
Kia	Soul Electric	2019	111	30	81	PC	standard	short
Ford	Focus Electric	2018	115	33	107	PC	standard	short
Volkswagen	e-Golf	2020	123	55.7	100	PC	standard	short
Hyundai	Ioniq Electric	2018	124	28	88	PC	standard	short
Hyundai	Ioniq Electric	2019	124	28	88	PC	standard	short
Volkswagen	e-Golf	2018	125	35.8	100	PC	standard	short
Volkswagen	e-Golf	2019	125	35.8	100	PC	standard	short
Nissan	Leaf (40 kW-hr battery pack)	2020	149	40	110	PC	standard	short
Nissan	Leaf (40 kW-hr battery pack)	2019	150	40	110	PC	standard	short
Nissan	Leaf	2018	151	40	110	PC	standard	short
Hyundai	Ioniq Electric	2020	170	38.3	100	PC	standard	short
Nissan	Leaf SV/SL (62 kW-hr battery pack)	2019	215	62	160	PC	standard	mid
Nissan	Leaf SV/SL (62 kW-hr battery pack)	2020	215	62	160	PC	standard	mid
Tesla	Model 3 Standard Range	2019	220	54	211	PC	standard	mid
Tesla	Model 3 Standard Range	2020	220	54	211	PC	standard	mid
Nissan	Leaf (62 kW-hr battery pack)	2019	226	62	160	PC	standard	mid
Nissan	Leaf (62 kW-hr battery pack)	2020	226	62	160	PC	standard	mid
Chevrolet	Bolt EV	2018	238	60	150	PC	standard	mid
Chevrolet	Bolt EV	2019	238	60	150	PC	standard	mid
Tesla	Model 3 Standard Range Plus	2019	240	54	211	PC	standard	mid
Kia	Soul Electric	2020	243	64	201	PC	standard	mid
Tesla	Model 3 Standard Range Plus	2020	250	54	211	PC	standard	mid
Chevrolet	Bolt EV	2020	259	66	150	PC	standard	mid
Tesla	Model 3 Mid Range	2018	260	62	202	PC	standard	mid

Make	Model	Year	Range (mile)	Battery Capacity (kWh)	Electric Power (kW)	Segment	Class	Range Category
Tesla	Model 3 Mid Range	2020	264	62	211	PC	standard	mid
BMW	i3s (94Ah)	2018	107	33.2	125	PC	luxury	short
BMW	i3 (94Ah)	2018	114	33.2	125	PC	luxury	short
BMW	i3	2019	153	42.2	125	PC	luxury	short
BMW	i3s	2019	153	42.2	135	PC	luxury	short
BMW	i3	2020	153	42.2	125	PC	luxury	short
BMW	i3s	2020	153	42.2	135	PC	luxury	short
Porsche	Taycan Turbo S	2020	201	79.2	290	PC	luxury	mid
Porsche	Taycan Turbo	2020	201	93.4	170	PC	luxury	mid
Porsche	Taycan 4S Perf Battery Plus	2020	203	93.4	120	PC	luxury	mid
Polestar	2	2021	233	78	150	PC	luxury	mid
Tesla	Model S 75kWh	2018	249	75	270	PC	luxury	mid
Tesla	Model S 75D	2018	259	75	386	PC	luxury	mid
Tesla	Model S 75D	2019	259	75	386	PC	luxury	mid
Tesla	Model 3 Mid Range	2019	264	62	211	PC	luxury	mid
Tesla	Model S Standard Range	2019	285	75	400	PC	luxury	mid
Tesla	Model S Standard Range	2020	287	75	398	PC	luxury	mid
Tesla	Model 3 Long Range Performance AWD (20in)	2020	299	75	358	PC	luxury	mid
Tesla	Model 3 Long Range Performance AWD (19in)	2020	304	75	358	PC	luxury	long
Tesla	Model 3 Long Range	2018	310	75	202	PC	luxury	long
Tesla	Model 3 Long Range AWD	2018	310	75	335	PC	luxury	long
Tesla	Model 3 Long Range AWD Performance	2018	310	75	349	PC	luxury	long
Tesla	Model 3 Long Range	2019	310	75	211	PC	luxury	long
Tesla	Model 3 Long Range AWD	2019	310	75	335	PC	luxury	long
Tesla	Model 3 Long Range AWD Performance	2019	310	75	358	PC	luxury	long
Tesla	Model S P100D	2018	315	100	568	PC	luxury	long

Make	Model	Year	Range (mile)	Battery Capacity (kWh)	Electric Power (kW)	Segment	Class	Range Category
Tesla	Model S P100D	2019	315	100	568	PC	luxury	long
Tesla	Model 3 Performance AWD	2021	315	75	321	PC	luxury	long
Tesla	Model 3 Long Range AWD	2020	322	75	335	PC	luxury	long
Tesla	Model 3 Long Range Performance AWD (18in)	2020	322	75	358	PC	luxury	long
Tesla	Model S Performance (21in Wheels)	2019	325	100	400	PC	luxury	long
Tesla	Model S Performance (21in Wheels)	2020	326	100	398	PC	luxury	long
Tesla	Model 3 Long Range	2020	330	75	211	PC	luxury	long
Tesla	Model S 100D	2018	335	100	386	PC	luxury	long
Tesla	Model S 100D	2019	335	100	386	PC	luxury	long
Tesla	Model S Performance (19in Wheels)	2019	345	100	400	PC	luxury	long
Tesla	Model S Performance (19in Wheels)	2020	348	100	398	PC	luxury	long
Tesla	Model 3 Long Range AWD	2021	353	75	293	PC	luxury	long
Tesla	Model S Long Range	2019	370	100	398	PC	luxury	long
Tesla	Model S Long Range	2020	373	100	398	PC	luxury	long
Tesla	Model S Long Range Plus	2020	402	100	568	PC	luxury	long
Kia	Niro Electric	2019	239	64	150	PT	standard	short
Kia	Niro Electric	2020	239	64	150	PT	standard	short
Hyundai	Kona Electric	2019	258	64	150	PT	standard	short
Hyundai	Kona Electric	2020	258	64	150	PT	standard	short
Audi	e-tron	2019	204	95.3	313	PT	luxury	short
Volvo	XC40 AWD BEV	2021	208	75	150	PT	luxury	short
Audi	e-tron Sportback	2020	218	95.3	313	PT	luxury	short
Jaguar	I-Pace	2019	234	90	294	PT	luxury	short
Jaguar	I-Pace	2020	234	90	294	PT	luxury	short
Tesla	Model X 75D	2018	238	75	386	PT	luxury	short
Tesla	Model X 75D	2019	238	75	386	PT	luxury	short
Tesla	Model X Standard Range	2020	258	75	398	PT	luxury	short
Tesla	Model X Performance (22in Wheels)	2019	270	100	568	PT	luxury	mid
Tesla	Model X Performance (22in Wheels)	2020	272	100	580	PT	luxury	mid

Make	Model	Year	Range (mile)	Battery Capacity (kWh)	Electric Power (kW)	Segment	Class	Range Category
Tesla	Model X P100D	2018	289	100	568	PT	luxury	mid
Tesla	Model X P100D	2019	289	100	568	PT	luxury	mid
Tesla	Model Y Performance AWD (21in Wheels)	2020	291	75	377	PT	luxury	mid
Tesla	Model X 100D	2018	295	100	386	PT	luxury	mid
Tesla	Model X 100D	2019	295	100	386	PT	luxury	mid
Tesla	Model X Performance (22in Wheels)	2021	300	100	424	PT	luxury	long
Tesla	Model Y Performance AWD	2021	303	75	312	PT	luxury	long
Tesla	Model X Performance (20in Wheels)	2020	305	100	580	PT	luxury	long
Tesla	Model Y Performance AWD	2020	315	75	358	PT	luxury	long
Tesla	Model Y Long Range AWD	2020	316	75	361	PT	luxury	long
Tesla	Model X Long Range	2019	325	100	398	PT	luxury	long
Tesla	Model Y Long Range AWD	2021	326	75	270	PT	luxury	long
Tesla	Model X Long Range	2020	328	100	398	PT	luxury	long
Tesla	Model X Performance (20in Wheels)	2021	341	100	424	PT	luxury	long
Tesla	Model X Long Range Plus	2020	351	100	398	PT	luxury	long
Tesla	Model X Long Range Plus	2021	371	100	369	PT	luxury	long

Table 11. 2018-2021 PHEV models in the US and their specifications

Make	Model	Year	Range (mile)	Battery Capacity (kWh)	Electric Power (kW)	Engine Power (kW)	Segment	Class	Range Category
Ford	Fusion Energi Plug-in Hybrid	2018	21	7.6	69	105	PC	standard	short
Hyundai	Ioniq Plug-in Hybrid	2018	29	8.9	32	78	PC	standard	short
Hyundai	Sonata Plug-in Hybrid	2018	28	9.8	50	115	PC	standard	short
Kia	Optima Plug-in Hybrid	2018	29	9.8	50	100	PC	standard	short
MINI	Cooper SE Countryman All4	2018	12	7.6	65	100	PC	standard	short
Toyota	Prius Prime	2018	25	8.8	75	70	PC	standard	short
Ford	Fusion Energi Plug-in Hybrid	2019	26	9	68	105	PC	standard	short
Ford	Fusion Special Service Vehicle PHEV	2019	26	9	68	105	PC	standard	short
Hyundai	Ioniq Plug-in Hybrid	2019	29	8.9	32	78	PC	standard	short
Hyundai	Sonata Plug-in Hybrid	2019	28	9.8	50	115	PC	standard	short
Kia	Optima Plug-in Hybrid	2019	29	9.8	50	100	PC	standard	short
MINI	Cooper SE Countryman All4	2019	12	10	65	100	PC	standard	short
Toyota	Prius Prime	2019	25	8.8	75	70	PC	standard	short
Ford	Fusion Energi Plug-in Hybrid	2020	26	9	68	105	PC	standard	short
Ford	Fusion Special Service PHEV	2020	26	9	68	105	PC	standard	short
Hyundai	Ioniq Plug-in Hybrid	2020	29	8.9	45	78	PC	standard	short
Kia	Optima Plug-in Hybrid	2020	28	9.8	50	115	PC	standard	short
MINI	Cooper SE Countryman All4	2020	18	10	65	100	PC	standard	short
Toyota	Prius Prime	2020	25	8.8	53	70	PC	standard	short
MINI	Cooper SE Countryman All4	2021	18	10	65	100	PC	standard	short
Toyota	Prius Prime	2021	25	8.8	75	70	PC	standard	short
Chevrolet	Volt	2018	53	18.4	135	75	PC	standard	long
Honda	Clarity Plug-in Hybrid	2018	48	17	135	77	PC	standard	long
Chevrolet	Volt	2019	53	18.4	135	75	PC	standard	long
Honda	Clarity Plug-in Hybrid	2019	48	17	135	77	PC	standard	long
Honda	Clarity Plug-in Hybrid	2020	48	17	135	77	PC	standard	long
Honda	Clarity Plug-in Hybrid	2021	48	17	135	77	PC	standard	long
Audi	A3 e-tron	2018	16	8.8	80	110	PC	luxury	short
BMW	330e	2018	14	7.6	83	135	PC	luxury	short

Make	Model	Year	Range (mile)	Battery Capacity (kWh)	Electric Power (kW)	Engine Power (kW)	Segment	Class	Range Category
BMW	530e	2018	16	9.2	83	135	PC	luxury	short
BMW	530e xDrive	2018	15	9.2	83	135	PC	luxury	short
BMW	740e xDrive	2018	14	9.2	83	158	PC	luxury	short
Mercedes	C350e	2018	9	6.4	60	180	PC	luxury	short
Porsche	Panamera 4 e-Hybrid	2018	16	14.1	70	243	PC	luxury	short
Porsche	Panamera 4 e-Hybrid Executive	2018	16	14.1	70	243	PC	luxury	short
Porsche	Panamera 4 e-Hybrid ST	2018	16	14.1	70	243	PC	luxury	short
Porsche	Panamera Turbo S e-Hybrid	2018	14	14.1	70	243	PC	luxury	short
Porsche	Panamera Turbo S e-Hybrid Executive	2018	14	14.1	70	243	PC	luxury	short
Porsche	Panamera Turbo S e-Hybrid ST	2018	14	14.1	70	243	PC	luxury	short
Volvo	S90 AWD PHEV	2018	21	9.2	99	224	PC	luxury	short
BMW	530e	2019	16	12	83	135	PC	luxury	short
BMW	530e xDrive	2019	15	12	83	135	PC	luxury	short
BMW	740e xDrive	2019	14	9.2	83	158	PC	luxury	short
BMW	I8 Coupe	2019	18	11.6	96	170	PC	luxury	short
BMW	I8 Roadster	2019	18	11.6	96	170	PC	luxury	short
Mercedes	S560e	2019	19	13.5	90	180	PC	luxury	short
Porsche	Panamera 4 e-Hybrid	2019	14	14.1	70	243	PC	luxury	short
Porsche	Panamera 4 e-Hybrid Executive	2019	14	14.1	70	243	PC	luxury	short
Porsche	Panamera 4 e-Hybrid ST	2019	14	14.1	70	243	PC	luxury	short
Porsche	Panamera Turbo S e-Hybrid	2019	14	14.1	70	243	PC	luxury	short
Porsche	Panamera Turbo S e-Hybrid Executive	2019	14	14.1	70	243	PC	luxury	short
Porsche	Panamera Turbo S e-Hybrid ST	2019	14	14.1	70	243	PC	luxury	short
Volvo	S60 AWD PHEV	2019	22	10.4	99	233	PC	luxury	short
Volvo	S90 AWD PHEV	2019	21	10.4	99	189	PC	luxury	short
Audi	A8 L	2020	17	14.1	100	230	PC	luxury	short
BMW	530e	2020	21	12	83	137	PC	luxury	short
BMW	530e xDrive	2020	19	12	83	137	PC	luxury	short
BMW	745e xDrive	2020	16	12	83	207	PC	luxury	short
BMW	I8 Coupe	2020	18	11.6	105	170	PC	luxury	short

Make	Model	Year	Range (mile)	Battery Capacity (kWh)	Electric Power (kW)	Engine Power (kW)	Segment	Class	Range Category
BMW	I8 Roadster	2020	18	11.6	105	170	PC	luxury	short
Mercedes	S560e	2020	19	13.5	90	270	PC	luxury	short
Porsche	Panamera 4 e-Hybrid	2020	14	14.1	70	243	PC	luxury	short
Porsche	Panamera 4 e-Hybrid Executive	2020	14	14.1	70	243	PC	luxury	short
Porsche	Panamera 4 e-Hybrid ST	2020	14	14.1	70	243	PC	luxury	short
Porsche	Panamera Turbo S e-Hybrid	2020	14	14.1	70	243	PC	luxury	short
Porsche	Panamera Turbo S e-Hybrid Executive	2020	14	14.1	70	243	PC	luxury	short
Porsche	Panamera Turbo S e-Hybrid ST	2020	14	14.1	70	243	PC	luxury	short
Volvo	S60 AWD PHEV	2020	22	11.6	99	233	PC	luxury	short
Volvo	S90 AWD PHEV	2020	21	11.6	99	189	PC	luxury	short
Volvo	V60 AWD PHEV	2020	22	11.6	99	180	PC	luxury	short
Audi	A7 quattro	2021	24	14.1	105	165	PC	luxury	short
Audi	A8 L	2021	18	14.4	100	150	PC	luxury	short
BMW	330e	2021	23	12	80	135	PC	luxury	short
BMW	330e xDrive	2021	20	12	80	135	PC	luxury	short
BMW	745e xDrive	2021	17	12	83	167	PC	luxury	short
Volvo	S60 AWD PHEV	2021	22	11.6	99	233	PC	luxury	short
Volvo	S90 AWD PHEV	2021	21	11.6	99	189	PC	luxury	short
Volvo	V60 AWD PHEV	2021	22	11.6	99	230	PC	luxury	short
Cadillac	CT6 Plug-In	2018	31	18.4	120	170	PC	luxury	long
Karma	Revero	2018	37	20.8	300	150	PC	luxury	long
Karma	Revero	2019	37	20.8	300	150	PC	luxury	long
Karma	Revero GT (21-inch wheels)	2020	61	28	350	175	PC	luxury	long
Polestar	1	2020	52	34	223	230	PC	luxury	long
Polestar	1	2021	52	34	223	243	PC	luxury	long
Kia	Niro Plug-in Hybrid	2018	26	8.9	32	104	PT	standard	short
Mitsubishi	Outlander PHEV	2018	22	12	60	87	PT	standard	short
Kia	Niro Plug-in Hybrid	2019	26	8.9	32	104	PT	standard	short
Mitsubishi	Outlander PHEV	2019	22	12	60	87	PT	standard	short
Subaru	Crosstrek Hybrid AWD	2019	17	8.8	88	102	PT	standard	short

Make	Model	Year	Range (mile)	Battery Capacity (kWh)	Electric Power (kW)	Engine Power (kW)	Segment	Class	Range Category
Kia	Niro Plug-in Hybrid	2020	26	8.9	45	104	PT	standard	short
Mitsubishi	Outlander PHEV	2020	22	12	60	87	PT	standard	short
Subaru	Crosstrek Hybrid AWD	2020	17	8.8	88	102	PT	standard	short
Chrysler	Pacifica Hybrid	2018	33	16	89	164	PT	standard	long
Chrysler	Pacifica Hybrid	2019	32	16	89	164	PT	standard	long
Chrysler	Pacifica Hybrid	2020	32	16	89	105	PT	standard	long
Ford	Escape FWD PHEV	2020	37	14.4	36	128	PT	standard	long
Toyota	RAV4 Prime 4WD	2021	42	18.1	174	131	PT	standard	long
BMW	X5 xDrive40e	2018	14	9.2	83	210	PT	luxury	short
Mercedes	GLC350e 4matic	2018	10	8.7	85	150	PT	luxury	short
Mercedes	GLE550e 4matic	2018	10	8.7	85	245	PT	luxury	short
Porsche	Cayenne S e-Hybrid	2018	14	14.1	70	245	PT	luxury	short
Volvo	XC60 AWD PHEV	2018	18	9.2	99	235	PT	luxury	short
Volvo	XC90 AWD PHEV	2018	19	9.2	99	235	PT	luxury	short
Land Rover	Range Rover PHEV	2019	19	12.4	105	221	PT	luxury	short
Land Rover	Range Rover Sport PHEV	2019	19	12.4	105	221	PT	luxury	short
Mercedes	GLC350e 4matic	2019	10	8.71	85	150	PT	luxury	short
Porsche	Cayenne e-Hybrid	2019	13	14.1	99	245	PT	luxury	short
Volvo	XC60 AWD PHEV	2019	17	10.4	99	235	PT	luxury	short
Volvo	XC90 AWD PHEV	2019	17	10.4	99	235	PT	luxury	short
Audi	Q5	2020	20	14.1	105	185	PT	luxury	short
Bentley	Bentayga	2020	18	17.3	100	230	PT	luxury	short
BMW	X3 xDrive30e	2020	18	12	80	134	PT	luxury	short
Land Rover	Range Rover PHEV	2020	19	13	105	193	PT	luxury	short
Land Rover	Range Rover Sport PHEV	2020	19	13	105	193	PT	luxury	short
Lincoln	Aviator PHEV AWD	2020	21	13.6	74	294	PT	luxury	short
Mercedes	GLC350e 4matic	2020	22	13.5	90	145	PT	luxury	short
Porsche	Cayenne e-Hybrid	2020	14	14.1	99	240	PT	luxury	short
Porsche	Cayenne e-Hybrid Coupe	2020	14	14.1	99	240	PT	luxury	short
Porsche	Cayenne Turbo S e-Hybrid	2020	12	14.1	99	240	PT	luxury	short

Make	Model	Year	Range (mile)	Battery Capacity (kWh)	Electric Power (kW)	Engine Power (kW)	Segment	Class	Range Category
Porsche	Cayenne Turbo S e-Hybrid Coupe	2020	12	14.1	99	240	PT	luxury	short
Volvo	XC60 AWD PHEV	2020	19	11.6	99	233	PT	luxury	short
Volvo	XC90 AWD PHEV	2020	18	11.6	99	233	PT	luxury	short
Land Rover	Range Rover PHEV	2021	19	13	105	221	PT	luxury	short
Land Rover	Range Rover Sport PHEV	2021	19	13	105	221	PT	luxury	short
Lincoln	Aviator PHEV AWD	2021	21	13.6	74	294	PT	luxury	short
Volvo	XC60 AWD PHEV	2021	19	11.6	99	235	PT	luxury	short
Volvo	XC90 AWD PHEV	2021	18	11.6	99	235	PT	luxury	short
BMW	X5 xDrive45e	2021	31	24	83	210	PT	luxury	long

Table 12. Specification of ICEV models in California (Top 5 in sales Q2 2020)

Make	Model	Year	Engine Power (kW)			Segment	Class	Range Category
			min	max	avg			
Honda	Civic	2020	118	134	126	PC	standard	compact
Toyota	Corolla	2020	104	126	115	PC	standard	compact
Nissan	Sentra	2020	111		111	PC	standard	compact
Hyundai	Elantra	2020	95	150	123	PC	standard	compact
Kia	Forte	2020	110	150	130	PC	standard	compact
Mazda	3	2020	139		139	PC	standard	compact
Volkswagen	Jetta	2020	110		110	PC	standard	compact
Subaru	Impreza	2020	113		113	PC	standard	compact
Honda	Accord	2020	143	188	166	PC	standard	midsize
Hyundai	Sonata	2020	134	142	138	PC	standard	midsize
Toyota	Camry	2020	151	224	188	PC	standard	midsize
Kia	Optima	2020	133	183	158	PC	standard	midsize
Mazda	6	2020	139	169	154	PC	standard	midsize
Nissan	Altima	2020	136	176	156	PC	standard	midsize
Subaru	Legacy	2020	136	194	165	PC	standard	midsize
Ford	Fusion	2020	130	183	157	PC	standard	midsize
Volkswagen	Passat	2020	130		130	PC	standard	midsize
Chevrolet	Malibu	2020	119	186	153	PC	standard	midsize
Honda	CR-V	2020		142	142	PT	standard	compact
Toyota	RAV4	2020		151	151	PT	standard	compact
Mazda	CX-5	2020	139	169	154	PT	standard	compact
Subaru	Forester	2020		136	136	PT	standard	compact
Chevrolet	Equinox	2020	102	188	145	PT	standard	compact
GMC	Terrain	2020	127	188	157	PT	standard	compact
Kia	Sportage	2020	135	179	157	PT	standard	compact
Volkswagen	Tiguan	2020		137	137	PT	standard	compact
Ford	Escape	2020	135	186	161	PT	standard	compact
Nissan	Rogue	2020		127	127	PT	standard	compact
Hyundai	Tucson	2020	120	135	128	PT	standard	compact
Kia	Telluride	2020		217	217	PT	standard	midsize

Hyundai	Palisade	2020		217	217	PT	standard	midsize
Honda	Pilot	2020		209	209	PT	standard	midsize
Hyundai	Santa Fe	2020	138	175	157	PT	standard	midsize
Subaru	Outback	2020	136	194	165	PT	standard	midsize
Toyota	Highlander	2020		220	220	PT	standard	midsize
Honda	Passport	2020		209	209	PT	standard	midsize
Subaru	Ascent	2020		194	194	PT	standard	midsize
Volkswagen	Atlas	2020	175	206	191	PT	standard	midsize
Ford	Explorer	2020	224	298	261	PT	standard	midsize
Toyota	4Runner	2020		201	201	PT	standard	midsize

Appendix B: Fleet electrification scenario modeling

The electrification of the privately-owned light duty vehicle fleet is central to the plan to create a carbon-neutral transportation sector in California by 2045. In order to expand zero-emission vehicle (ZEV) or PEV ownership, the state will need to overcome three key obstacles: decreasing the costs of adopting electric vehicles to enable more households to adopt their first electric vehicle, expanding the range of models available to allow more households to fully electrify their fleets, and finally providing a statewide charging and hydrogen fueling network to support the travel needs of ZEV-only households. This section presents a scenario for the spread of PEV ownership across all California households based on the vehicle sales and fleet makeup scenario shown in Figure 16 and Figure 17.[28] The "ultra-low carbon" scenario observed in Figure 16 and Figure 17 was developed as part of a study done for California Environmental Protection Agency to identify the strategies required to achieve the 100% ZEV transition goal (*65*). In order to achieve a net-zero emission LDV fleet by 2045, it is assumed that BEVs will dominate but PHEVs will reach close to 20% market share and Fuel Cell Electric Vehicles close to 15% market share by 2040 (Figure 16). The sales shares were translated into fleet or stock shares of vehicles. By 2030, ZEVs are a relatively small share of the stock of all vehicle types except transit buses. Stock shares lag sales shares, with ZEVs reaching no more than 30% of stock by 2030 except for buses. They reach about 15% stock share of LDVs and less than 15% for all truck types (Figure 17). The stock of PEVs (BEVs and PHEVs) is set such that the state achieves the goal set by former governor Jerry Brown of 5 million ZEVs on the road by 2030 and 100% ZEV sales by 2035.

Fleet electrification is modeled at the household level, with adoption of the first household ZEV modeled separately from adoption of second and later vehicles. Wealthier households in single-family homes with larger fleets adopt their first ZEV sooner than households in other groups. Households that have adopted their first ZEV are eligible to add more ZEVs to their fleet at the rate of up to one per year until all of their ICEVs have been replaced by ZEVs. This analysis divides households into six categories, grouped by income level (under $75,000, $75-200,000, or above $200,000 per year) and housing type (single-family or multi-unit). For the initial adoption step, these six categories are collapsed into four to roughly match the adoption categories identified in Lee et al. (*9*): residents of multi-unit dwellings in the top two income categories are modeled together, and residents in the lowest income category are modeled together irrespective of housing type. Each category is further subdivided by number of household vehicles (1, 2, 3, 4, or 5+).

[28] The fleet makeup described in the two figures are adopted from a recent California EPA report https://doi.org/10.7922/G2MC8X9X

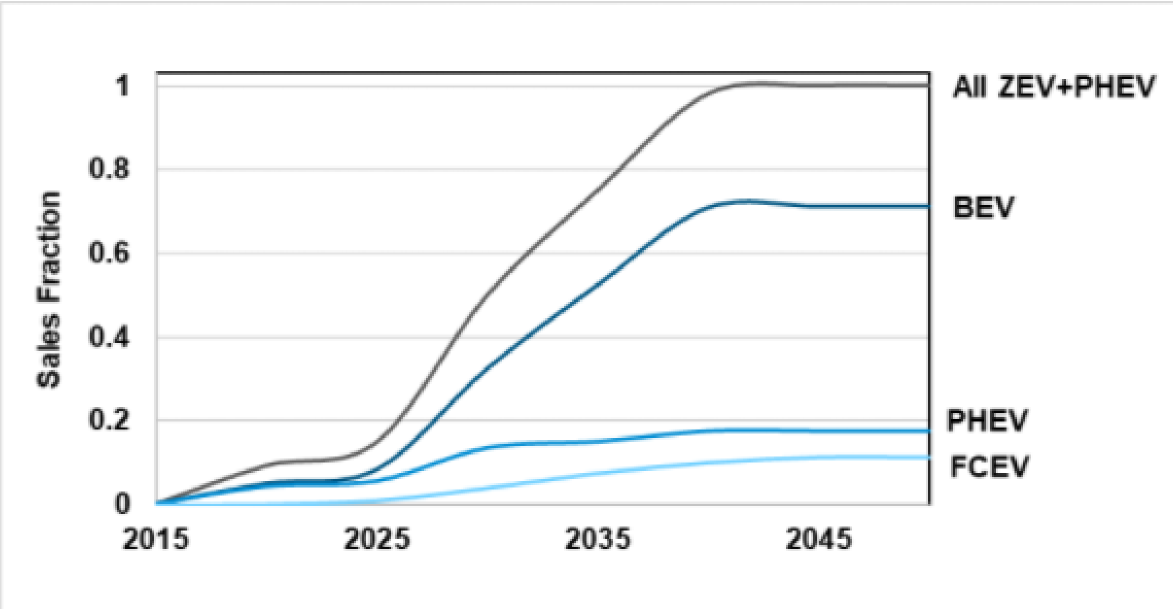

Figure 16. Ultra-Low carbon Scenario- LDV ZEV sales shares in California

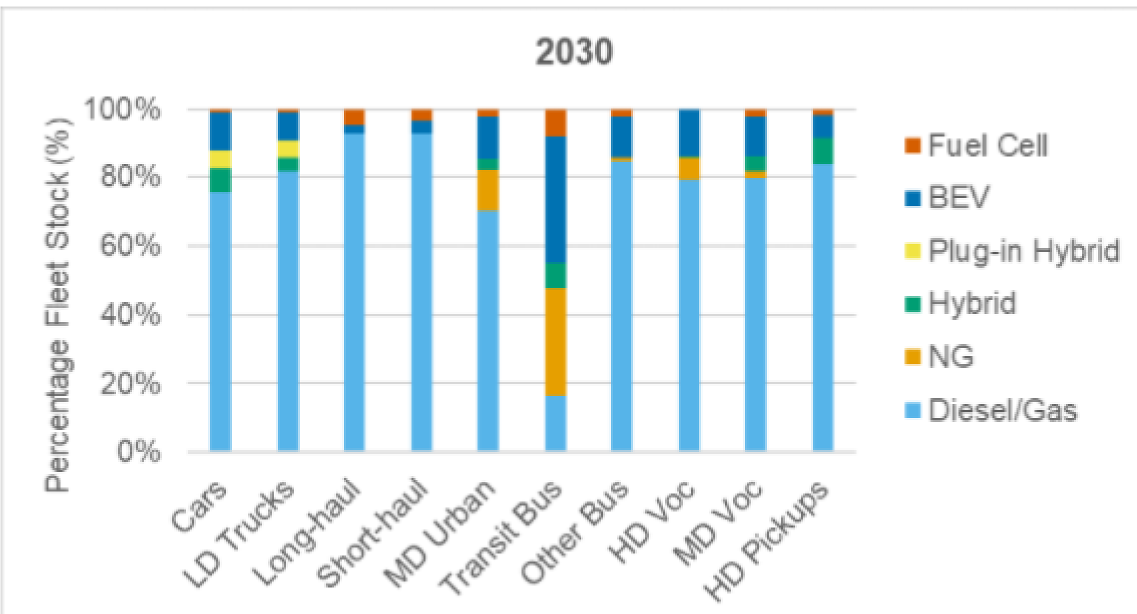

Figure 17. Stock shares in the ultra-low carbon scenario for the vehicle fleet in 2030

Since the American Community Survey does not provide cross-tabulations of these sociodemographic characteristics, statewide totals for each household category were generated using synthetic population methods at the census tract level with data from the American Community Survey and the 2019 California Vehicle Survey. The resulting synthetic population was aggregated to statewide totals for all further steps of analysis. The statewide total number of households and vehicles in each group are shown in Table 13, with the rough order in which each household type begins to electrify their household fleets shown in the "Rank" column.

Table 13. Total households and vehicles in the four groups used for fleet electrification modeling

Rank	Household Income (annual)	Home Type	Total Households in California	Total Vehicle
1	> $200k	Single family	1,135,000	2,999,000
2	$75-200k	Single family	3,506,000	8,365,000
3	> $75k	Multi-Unit	1,257,000	2,084,000
4	< $75k	Any	7,056,000	13,116,000

This ZEV adoption model rests on a number of key assumptions:

1. Electrifying the first vehicle in a household is the key step in adoption, since it requires an investment in charging infrastructure and for household members to adapt their behavior to a new technology. The estimated number of first-vehicle adoptions in each household category is estimated using a Bass diffusion of innovations model adapted from Lee et al. (*9*).
2. Income and housing type are the primary controls on electric vehicle adoption. Wealthier households that can afford to purchase new vehicles and install charging infrastructure at home will adopt ZEVs sooner than households that cannot afford to invest or live in a house where charging infrastructure cannot be installed. Multi-vehicle households will convert their first vehicle sooner than single-vehicle households, but will electrify their household fleet one vehicle at a time.
3. Relative proportions of household types and vehicle ownership patterns will not change over the study period. If vehicle ownership decreases, that will be most significant among the households with the largest vehicle fleets, who will e.g., downsize from 5 to 4 vehicles. This sort of change would not substantially impact these results.
4. Electrification is permanent: once a household has replaced an ICEV with a ZEV, they will never replace that ZEV with an ICEV.
5. Every new vehicle sold replaces an existing vehicle, and there is little to no friction in the market for used ZEVs. A small fraction of households account for most new vehicle sales, and most other households primarily purchase vehicles used. As a result, new ZEV sales and the corresponding replacement of an ICEV will occur in different households. By assuming that the market for used ZEVs work separate from the new sales, we can attribute all new ZEVs sold to one of three events: electrifying the first household vehicle (and thus requiring an infrastructure investment, where possible), replacing

additional ICEVs in households that already have at least one ZEV, and replacing retired ZEVs.

Fleet Electrification Modeling Results

Based on the assumptions stated above and the order of electrification given in Table 13, Figure 18 shows the adoption of ZEVs separated by home type. BEVs account for most of the electrification, and PHEVs and FCEVs support the electrification of households that cannot charge vehicles at home or require more range than affordable BEVs can provide. Even by 2045, about a quarter of the LDV fleet will still require liquid fuel at least occasionally.

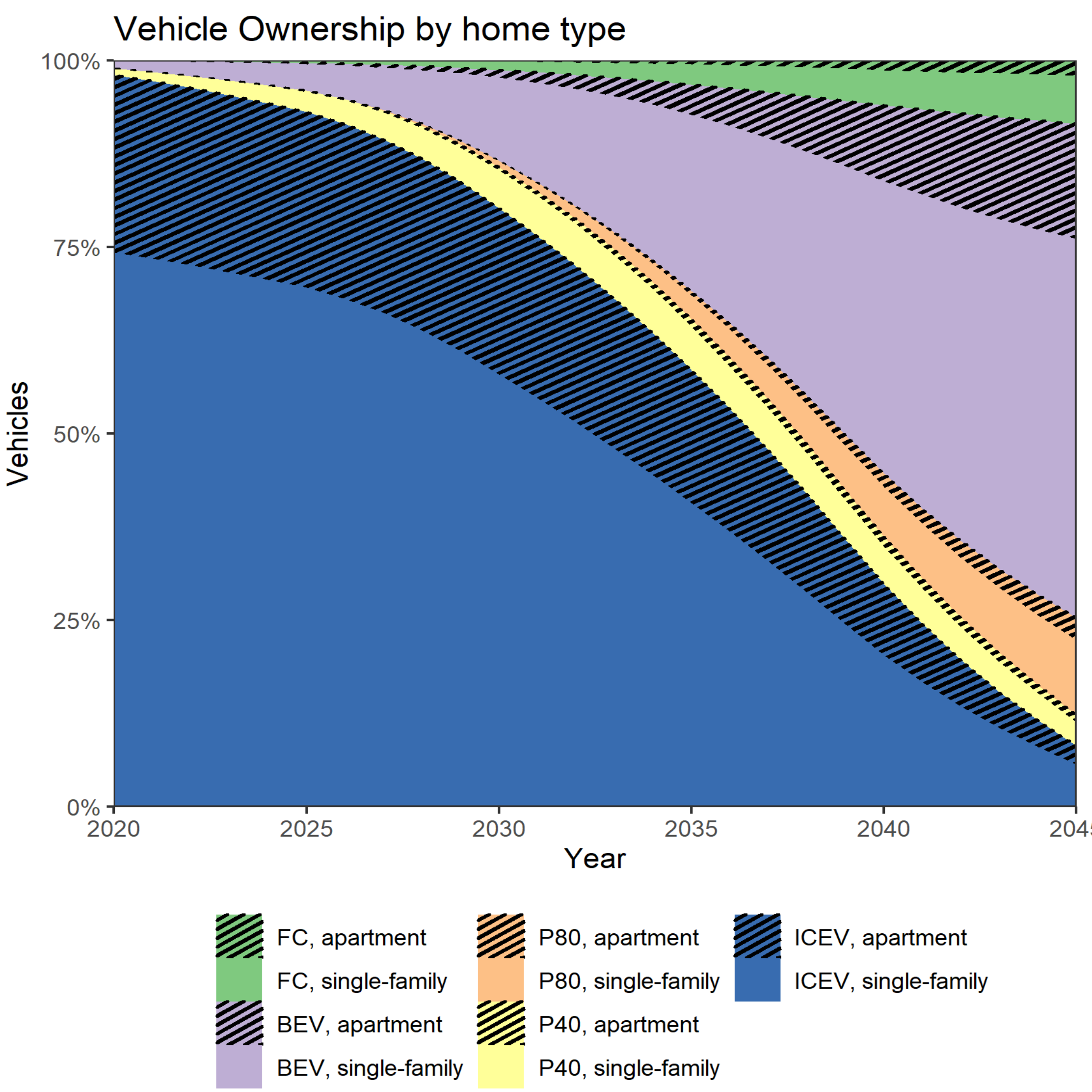

Figure 18. Adoption of First Vehicle by household group and fleet size (P40: PHEV 40-mile e-range; P80: PHEV 80-mile e-range; FC: fuel cell electric vehicle)

The ZEV adoption model described here assumes that adoption will be most rapid among high-income households in single-family homes and slowest among people who cannot afford either new vehicles or home chargers (Figure 19). show the rate of adoption by household type. According to the ZEV allocation scenario, ZEV adoption through 2025 will remain heavily concentrated among high-income households with single-family homes and middle-income households in single-family homes with at least 3 household vehicles (Figure 20). Growth from 2025-2030 will expand into middle- and high-income households in apartments and become nearly universal among middle- and high-income residents of single-family homes. From 2030 to 2035, adoption will begin expanding into all household categories, and at least 20% of all groups except low-income households will have at least one ZEV by this point. By 2040, at least 60% of households in all groups except low-income households with only one vehicle will own at least one ZEV. The challenges of being fully ZEV-dependent mean that single-vehicle households are expected to lag in adoption by 5 years behind 2-vehicle households and by as much as 10 years behind households with larger fleets.

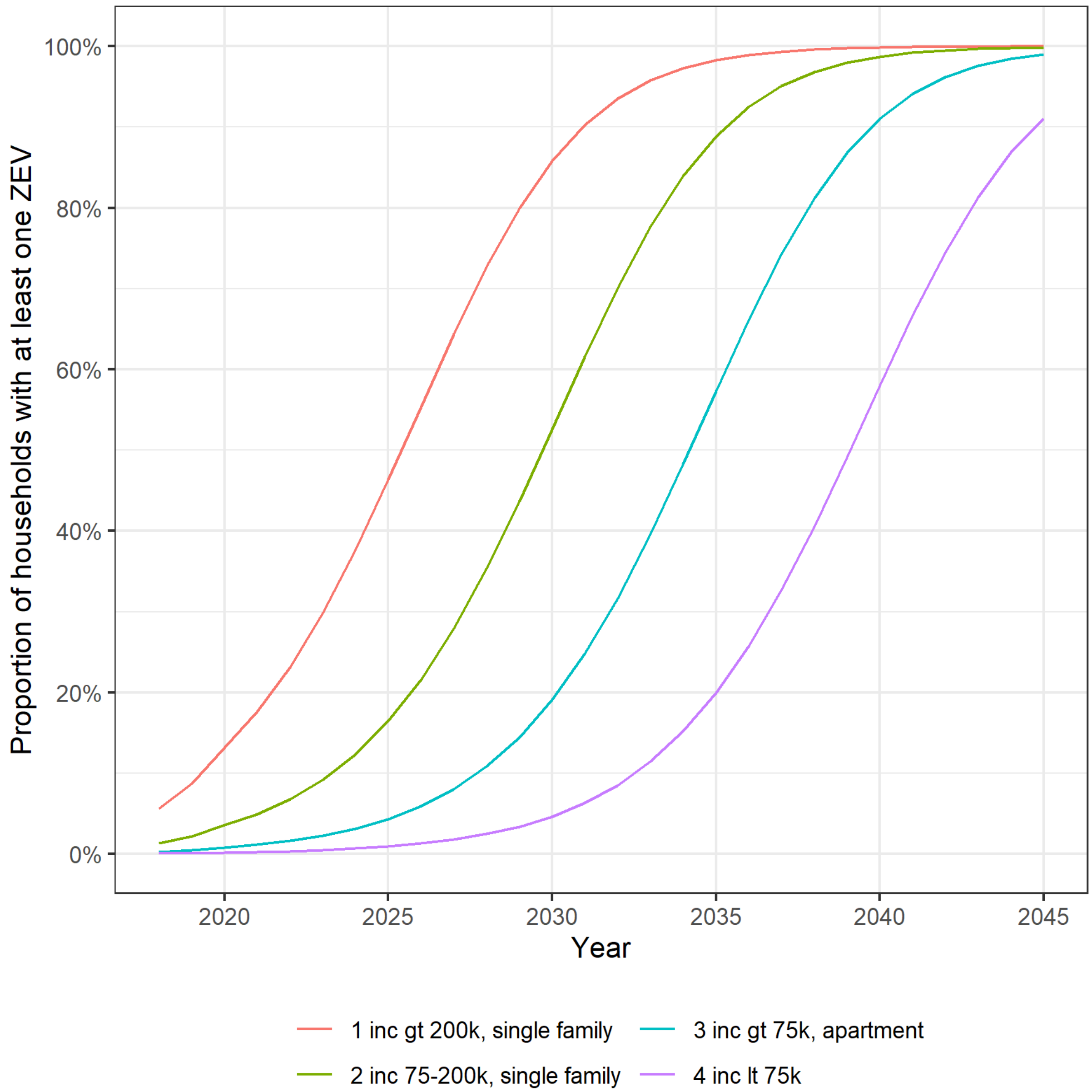

Figure 19. Adoption of first ZEV by household type

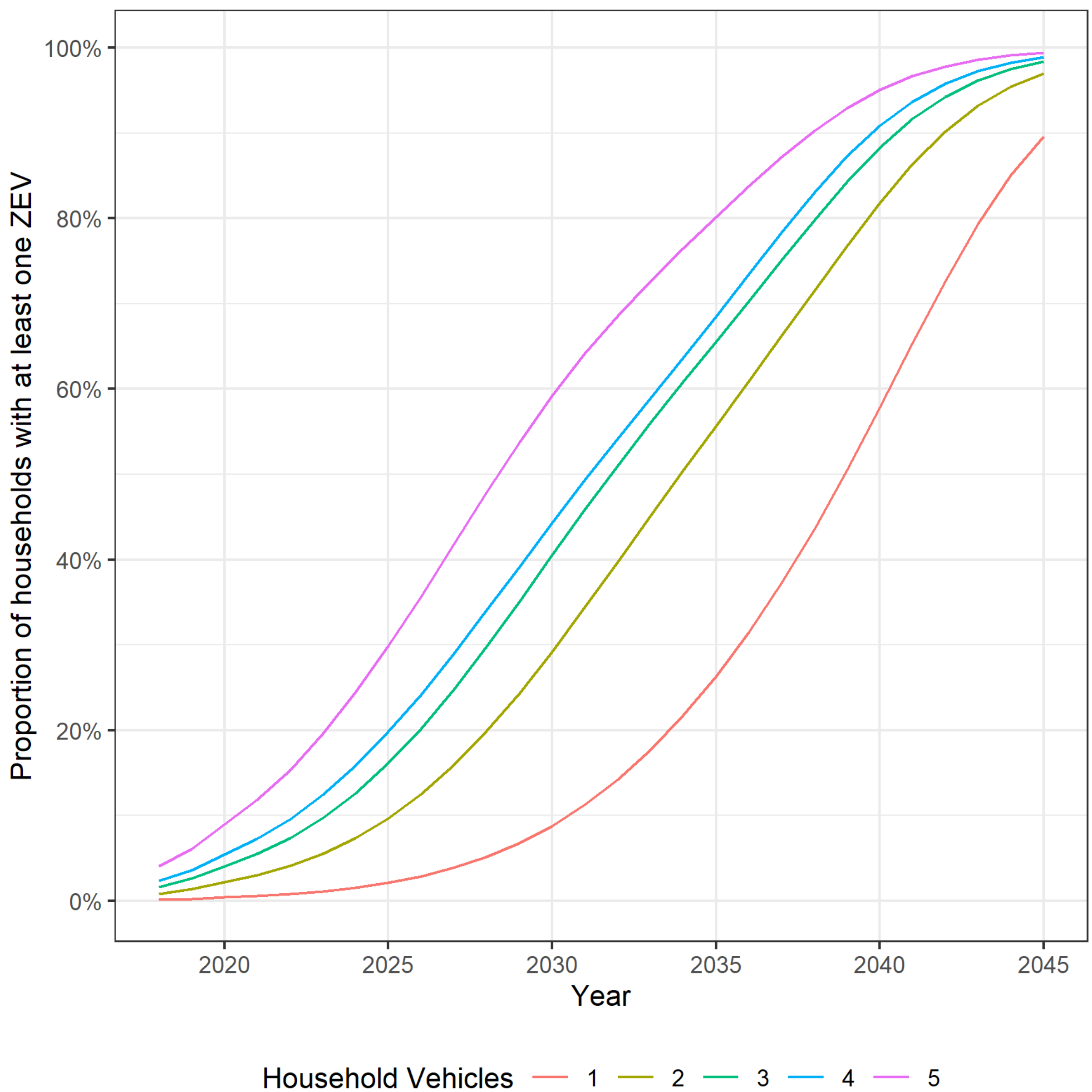

Figure 20. Adoption of first ZEV by number of household vehicles

Considering the ZEV allocation mechanism of the ZEV adoption model, Figure 21 shows the total number of ZEVs by household category. We use these estimates for calculating the cost of electrification of the LDV fleet in the main report.

Limitations of the ZEV allocation mechanism described here: This model did not incorporate a few important factors that could significantly affect the adoption of PEVs into California households. Specifically, there are many aspects of the secondary market that could impact both the new and used markets in CA. One potential scenario is a strong new PEV market in CA and simultaneously comparatively weaker markets in neighboring states could lead to a larger than typical flow of used vehicles to the secondary markets outside of California. There are also unknown factors at the federal level, such as changing CAFE standards, national ZEV regulations, or extending ZEV purchase incentives that would all affect the market growth nationally and in California, but are not included in the model.

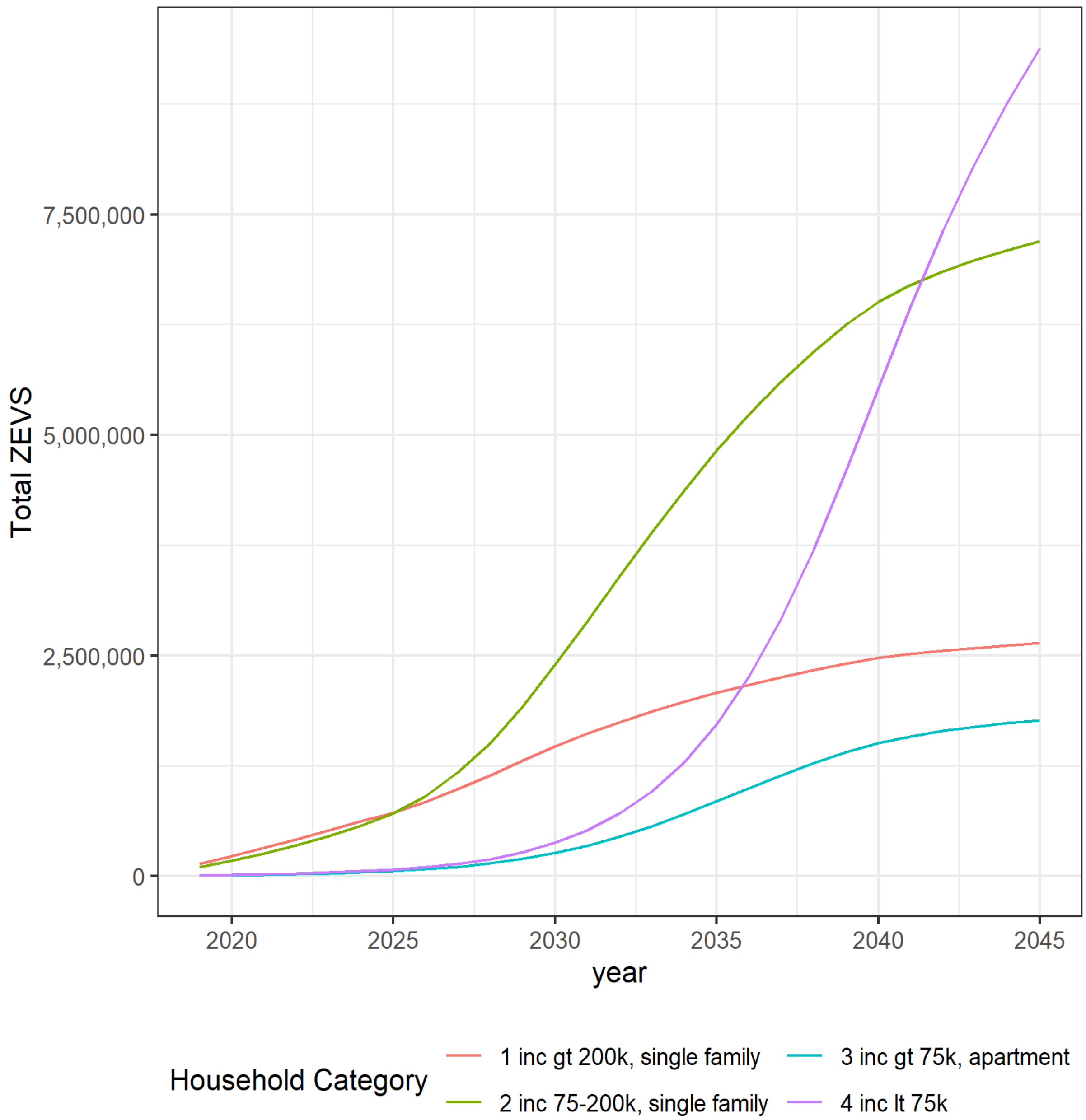

Figure 21. Total ZEV ownership by household category