Total Cost of Ownership of Plug-in Electric Vehicles Owned by
Early California Adopters in the 2010s

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Abstract

Total cost of ownership (TCO) analysis assesses the cost competitiveness of plug-in electric vehicles (PEVs) and internal combustion engine vehicles (ICEVs). The TCO literature characterizes an average driver to identify a future parity point where the ownership cost of a PEV is equal to or lower than an ICEV. This research had taken a different approach for TCO analysis, estimating costs of actual PEV early adopters in California between 2011 and 2020 using multi-year survey responses that provided valuable insights regarding vehicle purchase choice, driving and charging behavior, and sociodemographic attributes.

The TCO comparative analysis was done by vehicle segments (compact, mid-size, etc.), using selected models from the year 2018 and included incentives. The results show that the higher the segment was, the lower the annual mileage required to achieve a comparative TCO. For the mid-luxury segment, cost parity was achieved with only 10,100 annual miles, while for the subcompact segment, parity was reached when driving over 27,000 miles annually. As PEVs enter the mass market these days, these findings demonstrate the importance of incentive programs that are structured to benefit specific market segments that need them the most, rather than applying subsidies across all models, as done past decade to encourage early adoption.

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List of Abbreviations

AFLEET tool	Alternative Fuel Life-Cycle Environmental and Economic Transportation Tool
BEV	Battery electric vehicle
CARB	California Air Resource Board
CO_2	Carbon dioxide
CVRP	Clean Vehicle Rebate Project
DMV	Department of Motor Vehicles
EERE	Energy Efficiency & Renewable Energy
EIA	Energy Information Administration
EV rate	Electric vehicle rate
EVSE	Electric vehicle supply equipment
GHG	Greenhouse gas
HEV	Hybrid electric vehicle
ICEV	Internal combustion engine vehicle
LADWP	Los Angeles Department of Water and Power
LDV	Light-duty vehicle
MPGe	Miles per gallon equivalent MPGe
MSRP	Manufacturer suggested retail price
NHTS	National Household Travel Survey
PEV	Plug-in electric vehicle
PG&E	Pacific Gas & Electric
PH&EV Research Center	Plug-in Hybrid and Electric Vehicle Research Center
PHEV	Plug-in hybrid electric vehicle
RPV	Rooftop photovoltaic
SCE	Southern California Edison
SDGE	San Diego Gas & Electric
SMUD	Sacramento Municipal Utility District
TCO	Total cost of ownership
TOU	Time of use
UF	Utility factor
VMT	Vehicle miles traveled

ZEV	Zero-emission vehicle

1 Introduction

April 2022 marks the month with the world's highest monthly average of carbon dioxide (CO_2) levels in the atmosphere since recording started in 1958 (*1*). The Biden-Harris federal administration continues to allocate funding to lower U.S. carbon pollution, from investment in carbon capture storage technologies through the commitment of net-zero emissions federal procurements, intending to reach a net-zero emissions economy by 2050 (*2*–*4*). Recently, California Air Resource Board (CARB) released the Draft 2022 Climate Change Scoping Plan Update, which demonstrates a path to a carbon neutrality economy in California by 2045 or sooner (*5*). Transportation, as the sector that produces the highest greenhouse gas (GHG) emissions in recent years, and especially the light-duty vehicle (LDV) class, which accounts for 55% of the total U.S. transportation energy use, is bound to play a major role in achieving the federal and California State emission reduction goals (*6*, *7*). Over the past three decades, California legislated numerous bills, policies, regulations, and programs to achieve emission reduction from the transportation sector. This legislative work is supported by Executive Orders, which set adoption goals for zero-emission vehicles (ZEVs), including fleet electrification using battery electric vehicles (BEVs) and plug-in hybrid electric vehicles (PHEVs). An example of such legislation is the new Advanced Clean Cars II regulation offered by CARB, setting annual goals for new ZEV sales percentage from 2026 until reaching full market share in 2035, a continuum of the California flagship policy about ZEVs, with full or partial participation of additional 17 states (*8*). Indeed, California leads the ZEV diffusion in the U.S. (*9*).

Sales of new BEVs and PHEVs, collectively referred to as plug-in electric vehicles (PEVs), doubled in the past calendar year, from about 300,000 vehicles in 2020 to about 600,000 vehicles in 2021 in the U.S, while some auto-manufacturer, such as GM and Ford, experienced sales dropped in 2021 compared to 2020 (*10*, *11*). Many important factors influenced the increased PEV sales trend, among them was the greater number of offered PEV models for a lower purchase price in a recent couple of years. While PEV sales had been generally rising over the past decade in the U.S., the current affirming trend does not reflect early adopters' concerns in the early 2010s, when roughly the first modern BEVs were mass-produced and introduced in the North American market. One of the major concerns for buyers was the transition cost from internal combustion engine vehicles (ICEVs) to PEVs, as the purchase price of a PEV in the past decade was higher than of an ICEV. To overcome the capital cost barrier, incentive programs were implemented in the federal, state, and local strata.

Comparative analysis of the total cost of ownership (TCO) of PEVs and ICEVs is a common method to analyze the cost impacts of the shift from conventional vehicles, such as ICEVs and hybrid electric vehicles (HEVs), to alternative fuel vehicles, such as BEVs and PHEVs. Consumer-oriented TCO accounts for the vehicle purchase price, operating costs, and vehicle resale value (*12*). Traditionally, TCO studies characterize **an average driver** and identify a **future** parity point where the ownership cost of a PEV is equal to or lower than an ICEV and the factors that influence the cost parity of that representative driver (*13*, *14*). Estimating the future parity point requires a heavy set of assumptions, as seen in TCO studies with futuristic PEV models, featuring improved and cheaper technologies (*15*). Other studies considered only vehicle models that were offered in the market at the time of the analysis and estimated parities with variable ownership length (*16*). This research had taken a different approach for TCO analysis, finding occurrences of **past** cost parities of **actual** PEV early adopters. The Plug-in Hybrid and Electric Vehicle (PH&EV) Research Center conducted a multi-year online survey targeting new PEV owners (up to five years) in California between the years 2011 to 2020. The survey collected valuable data that was helpful to estimate the true TCO of the participants, including details about the owned vehicle, driving and charging habits of the main driver, utility provider, socio-demographic attributes, and details on the remaining household vehicles. Combining the survey data with multiple external datasets, the TCO was estimated for every participant individually. For estimating cost parities, operation costs were aggregated based on vehicle model, and travel behavior was assumed to be the same across the four powertrain types considered in this study (BEV, PHEV, HEV, and ICEV).

This study provides answers to the following research questions:

- What was the true TCO of Californian PEV early adopters between the years 2011 to 2020, and how did it change over time (year of initial purchase), driven miles, and income groups?
- What was the monetary saving (positive TCO) or loss (negative TCO) of drivers who chose a PEV over an ICEV or an HEV?
- What was the quantified role of federal and state incentives in the TCO of PEV drivers?
- Who were the drivers who gained positive or negative TCO by adopting a PEV?

Analyzing the costs of true adopters over the past decade raised a unique opportunity to evaluate the investment needed (if needed) by early adopters to propel the PEV market to its current sales volume, as early adopters are the main contributors to any technology diffusion process. Additionally, the TCO comparison analysis of different powertrain types demonstrated the necessity of the ZEV incentive programs, as offered during the analysis term (2011-2020), to discover if the willingness to pay a higher purchase price for new vehicle technologies resulted in an actual higher ownership cost.

This thesis is outlined as followed: Chapter 2 presents a literature review that covers the extensive work about consumer-oriented TCO studies in the automotive field and the different TCO comparison methods. Chapter 3, the methodology chapter, presents the TCO model. This chapter describes the cleaning process of the survey and online or paid data gathered to perform the analysis, and details all assumptions and calculations made. Chapter 4, the results chapter, shows descriptive statistics of the survey dataset and an overview of the estimated TCO across all survey participants and by income group. Furthermore, the chapter includes the TCO comparison between different powertrain types, and the identification of socio-demographic attributes of early adopters who benefited from the shift from conventional to alternative fuel vehicles. Chapter 5 discusses the significance of the research results and their policy implications, brings up the study limitations and possible future research, and concludes the findings. These chapters are followed by a reference list and a series of appendices showing the raw analysis results.

2 Literature Review

Research about the TCO of light-duty alternative fuel vehicles is vast and has been evolving over the past few years (*17*). Generally, the objective of the TCO methodology is to find under what conditions cost parities between comparable alternatives can be achieved. TCO analysis that is being performed on technology that is yet to penetrate the mass market, such as alternative fuel vehicles, seeks to find a parity at some future (or even present) point. TCO studies' methodology can be broadly classified as bottom-up (teardown) or top-down (aggregated) analysis. Studies using the top-down approach focused on several representative vehicle models that existed in the market at the time of the analysis (*13*, *16*, *18*–*20*). These studies estimated future vehicle purchase price as a percentage or a fixed cost reduction from the current manufacturer suggested retail price (MSRP) based on simplified assumptions (*12*, *19*, *20*), or, simply, extended the ownership length or annual vehicle miles traveled (VMT) to assess whether parity is achieved at a future time or with higher vehicle usage (*13*, *16*). Studies used the bottom-up approach to estimate current and future vehicle manufacturing and purchase costs required a rigorous set of assumptions regarding future technology developments, production volumes, and their associated costs, which lead to growing uncertainty in the analysis as the analysis term extends (*14*, *15*, *21*–*23*). My research focused on revealed costs occurred by PEV California drivers to estimate their TCO, avoiding the majority of future uncertain assumptions.

Analysis of past TCO of drivetrains is rare in the literature, and only two studies were found with past analysis (*24*, *25*). The first focused on California, Texas, the United Kingdom, and Japan from 1997 to 2015, and the second reviewed the Norway market between 1992 to 2019. While both studies used historic regional average gasoline and electricity prices, only the Norway study utilized documented information regarding vehicle residual value after three years of ownership. Palmer et al. characterized a driver with an annual VMT that varied across regions but was constant over time, while Figenbaum assigned VMT that increased every six years but was fixed for the entire country. While early studies considered average user characteristics, recent studies incorporated the effect of household characteristics and heterogeneity in travel demand (*26*–*28*), and a series of three other TCO studies used car movement data from 64 vehicles in Sweden to better assess the shifting cost from ICEV to PEV (*29*–*31*). Using the PH&EV multi-year survey, my study provided TCO estimation for all driver profiles that fully participated in the study, across counties, income levels, and driving attributes.

Vehicle comparison based on segment classification (i.e. compact, midsize, etc.), is a common strategy to evaluate the TCO of vehicles with different powertrain types (*13*, *16*, *18*, *19*, *26*, *32*, *33*). While some papers demonstrated pairwise comparisons of two powertrain types only (*26*, *33*), others did it in groups, using multiple powertrains (*13*, *16*, *18*, *19*). The choice of the models for comparison within each segment varies across the studies. One study chose vehicle models with the closest engine power (*18*), while another study picked the most efficient and popular model in each segment (*32*). Two other papers described resembled vehicles with similar technical attributes, preferably from the same automaker (*26*, *33*), and the rest simply chose the most popular vehicles in each segment (*13*, *16*, *19*). However, careful consideration of the trim level choice for each vehicle model is not always apparent. In their comparison, Breetz et al. chose the second to highest trim for the ICEV, and the second to lowest trim for the HEV (both models had five trim levels), which created an MSRP bias, favoriting the HEV over the ICEV.

To find resale value for different PEV models, some studies use online vehicle valuation tools, such as KBB.com or Edmunds.com (*16*, *26*, *33*). These studies derived the residual value by dividing the value that appears on the online tool by the MSRP. Since this calculation considers the advertised MSRP without subtracting federal income tax credit, purchase incentives, and other subsidies, it reflects a deflated residual value, which is also much lower than the residual value of ICEVs or HEVs. One study was found to acknowledge this caveat (*22*). Using the data from the PH&EV survey about leased vehicle down payment, monthly payment, and lease durations revealed the residual value as calculated by the dealerships, which better reflects the actual value of PEVs in the secondary market.

Overall, the TCO research findings varied across market and user contexts and methodologies. Two studies that assessed the German market and used similar ownership lengths agreed that comparative cost efficiency is greatly dependent on vehicle segment and annual VMT (*15*, *19*). Wu et al., who formed conceptual PEVs starting in 2014 using the bottom-up approach, found that parity can be achieved for high-mileage drivers in 2025. Letmathe et al., who employed existing models starting in 2016, concluded that parity can be achieved within the five years of ownership for the bigger or higher-end segments. Another two studies that focused on the U.S. market and used the bottom-up approach presented conflicting conclusions (*14*, *22*). Lutsey and Nicholas showed that parity between a sedan BEV and a sedan ICEV can be reached as early as 2024, while Hamza et al. determined that a cost parity at 2030 is possible only with an extreme favorable set of assumptions.

3 Methodology

To achieve individual TCO of PEV owners in California, comprehensive survey responses combined with paid and online data sources were utilized. This section details what databases were collected and how they were used to calculate ownership costs.

3.1 Online Survey

A multi-year online survey was conducted by the PH&EV Research Center and targeted new PEV owners (up to five years) in California. The participants were recruited from the Clean Vehicle Rebate Project (CVRP) database and California Department of Motor Vehicles (DMV) with the help of the CARB and were contacted through an email or a postcard between April 2015 and November 2020 in seven phases. During that period, 33,445 participants accessed the online survey of which 24,729 participants completed the survey (*34*).

In addition to vehicle details (make, model, trim, year, and odometer reading), household size and type, and socioeconomics and demographics attributes, the survey gathered in-depth information about driving and charging behavior of the new PEV and other vehicles in the household fleet, including commute and non-commute destinations and longest trip; charging locations (home, work, and public), charging level (level 1, level 2, and DC fast), charging recurrence, and their associated prices; and characteristics of the driver of each household vehicle. The survey asked about capital and reoccurring PEV purchase/lease costs, incentives received and their role in the purchase/lease decision, local utility company and its electricity rate, changes in electricity consumption and costs, installation of home charger, and the ownership of a rooftop photovoltaic system.

For this research, only new PEV purchasers were considered (no leasers or second-hand purchasers). After cleaning the data and omitting incomplete responses, the sample size was 11,505. Table 3.1 presents a summary of socio-economic statistics, alongside the 2017 National Household Travel Survey (NHTS) for California.

The PEV models covered in this study were purchased between the years 2011 to 2020, and their owners were considered early adopters. Early adopters carry a unique set of socioeconomic characteristics that do not apply to the mass market: they were mostly middle-aged males, highly educated, had a high income, owned a single-family home, and had a higher number of vehicles in their fleet (*35*–*37*). As seen in Table 3.1, this profile is applicable for the PH&EV survey and is aligned with the early adopter profile as described by the Innovation Theory (*38*). A comparison of the PH&EV survey results with the general population, using the 2017 NHTS for California, emphasized the early adopters' profile, which consisted of a higher percentage of educated and high-income males. In the PH&EV

survey, 65% were male, while in NHTS it was 48%. The majority of the PH&EV participants had a college, graduate, or professional degree (62%), whereas the vast majority of NHTS participants had a high school degree, GED, or less (92%). Similar skewness was seen for income, with almost half of the PH&EV participants within the middle-income grade (47%), and most of the NHTS respondents within the lowest income grade (67%).

Table 3.1. Socioeconomic Profile of PEV Households by PH&EV Survey and NHTS Data

		PH&EV		NHTS			PH&EV		NHTS
Variable	**Class**	**n**	**%**	**%**	**Variable**	**Class**	**n**	**%**	**%**
Gender	Male	7,458	65%	48%	Household size	1	1,355	12%	32%
	Female	3,990	35%	52%		2	4,711	41%	42%
	Decline to state	113	1%			3	1,951	17%	12%
Age group	29 or younger	632	5%			4	2,599	22%	9%
	30 to 39	2,551	22%			5+	944	8%	5%
	40 to 49	2,639	23%		Number of drivers	0			4%
	50 to 59	2,564	22%			1	1,675	14%	39%
	60 to 69	2,118	18%			2	7,800	67%	52%
	70 or older	961	8%			3	1,340	12%	7%
	Prefer not to answer	96	1%			4	629	5%	2%
Education	High school graduate, GED, or less	3,096	9%	92%		5+	117	1%	<1%
	College graduate	9,673	29%	5%	Number of vehicles	1	1,640	14%	32%
	Graduate or professional degree	10,899	33%	3%		2	5,749	50%	37%
	Prefer not to answer	9,787	29%			3	2,789	24%	16%
Income	$100,000 or less	1,670	16%	67%		4	986	9%	6%
	$100,000 to $199,999	4,788	47%	25%		5+	397	3%	3%
	$200,000 or more	2,469	24%	9%	PEV powertrain	BEV	6,795	59%	56%
	Prefer not to answer	1,326	13%			PHEV	4,766	41%	44%
House ownership	Own	9,883	85%	71%	Solar system	Yes	4,071	35%	
	Rent	1,575	14%	29%		No	7,490	65%	
	Other	103	1%						
House type	Detached house	9,482	82%						
	Attached house	1,235	11%						
	Apartment building	799	7%						

3.2 Evaluation Framework

As this research aimed to calculate the TCO of a new private passenger vehicle owner in California, many of the TCO model components were taken from the PH&EV survey, while others were estimated using various online sources. The vehicles reported in the survey were purchased between the years 2011 to 2020, and all costs were adjusted and capitalized to the year of purchase. The unit of TCO results is a dollar per mile driven. Figure 3.1 describes the TCO framework.

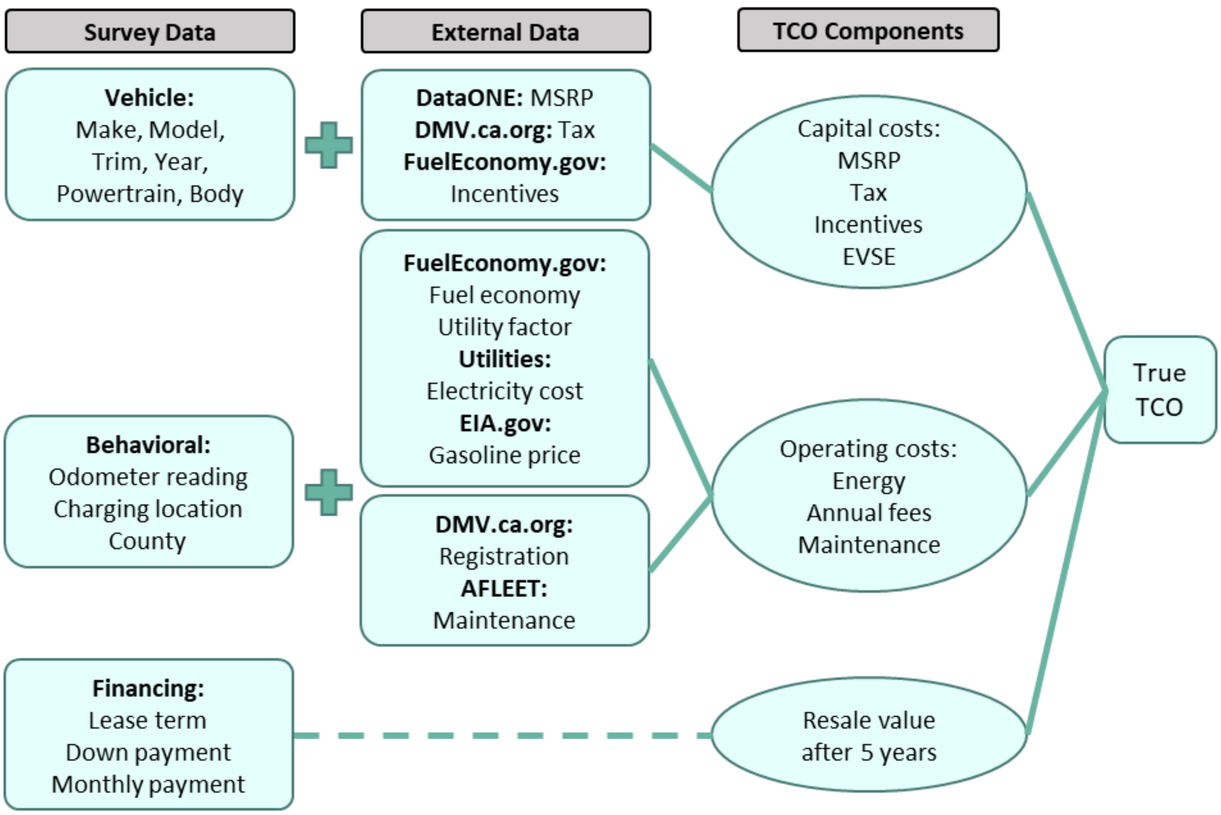

Figure 3.1. TCO Model

The survey data provides information about the vehicle, such as make, model, year, trim, powertrain, and body. Combined with data about MSRP, tax, incentive return, and electric vehicle supply equipment (EVSE) purchase cost and installation, the capital cost per mile driven was calculated as:

$$CC = MSRP \cdot TAX - INC + EVSE \tag{1}$$

Where, $MSRP$ = vehicle MSRP;

TAX = California vehicle purchase tax;

INC = incentive return; and,

$EVSE$ = home charging station purchase and installation cost.

The extensive information regarding driving and charging behavior, as collected from the PH&EV survey, was used to calculate fuel costs as part of operating costs. The information includes odometer reading, share of charging location (home, work, and public) and type (level 1, level 2, and DC fast), and the location of the vehicle owner. Adding annual registration and maintenance costs, the total operating cost over the ownership period was calculated as:

$$OC = \sum_{n=1}^{N} \frac{FL + RG + MN}{(1+i)^n} \tag{2}$$

Where, FL = fuel cost;

RG = registration fee;

MN = maintenance cost;

i = interest rate (*39*); and,

n = ownership year.

It was assumed that the vehicles were owned for five years. While the 2020 U.S. average vehicle ownership length was 8.4 years (*40*), TCO studies used various durations, from five to 15 years, where the most frequent length was five or six years. Since PEVs are prevalent for only a decade, and major technology developments still occur, estimating the residual value of PEVs older than five years requires a broader set of assumptions that were preferably avoided. that we prefer to avoid. Therefore, for all vehicles, the resale value at the end of the fifth year was calculated as:

$$RV = \frac{\vartheta \cdot MSRP}{(1+i)^N} \quad (3)$$

Where, ϑ = percentage of the vehicle purchase price at the end of the ownership period; and,

N = ownership length.

Finally, the total TCO per mile driven over the ownership period was estimated as:

$$TCO = \frac{CC + OC - RV}{Total\, VMT} \quad (4)$$

The TCO presented was a total of costs over five ownership years, divided by the total miles driven in those years. With the choice to conduct a TCO analysis for an ownership length of five years, the analysis focused on the calculation and estimations of costs between 2011 to 2024. While the inflation rates for the years 2011 to 2021 were known, the inflation rates for the years 2022 to 2024 were estimated as the rolling average of the previous five years. At least for 2022, the estimated rate was possibly underestimated due to a sharp increase in the inflation rate shortly after the completion of the analysis.

3.3 Capital Costs

The capital costs include the vehicle purchase price, purchase tax, returned incentives, and the cost of purchasing and installing an EVSE.

3.3.1 Vehicle Purchase Price

Throughout 2017, the PH&EV survey used the Edmunds database to identify vehicle models owned by the survey participants. This database included MSRP information. Later, the survey utilized the fueleconomy.org database for the same purpose. However, this database had no information about MSRP. In addition, the survey asked the respondents to report their purchase price. When comparing the reported purchase price with MSRP from Edmunds, Figure 3.2 shows that for an individual MSRP, there was a range of purchase prices, possibly dependent on dealer markups, dealer discounts, and the purchasers' recollection.

To establish a consistent baseline representing the capital costs, an additional MSRP database was considered, namely DataONE (*41*). This database was merged with the PH&EV survey using the attributes of make, model, model year, trim, powertrain, and body. If several MSRPs were available for the unique combination of attributes, they were averaged. Figure 3.3 shows an excellent fit between the two databases and the merging process, with a high R-squared equal to 0.993. Therefore, this method was chosen to calculate capital costs.

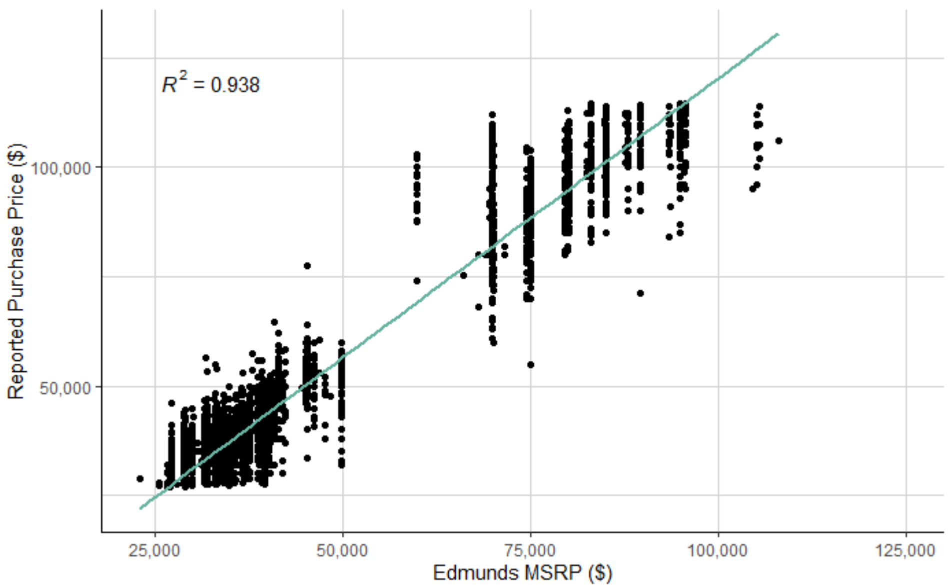

Figure 3.2. MSRP Validation: Reported Purchase Price Against Edmunds MSRP

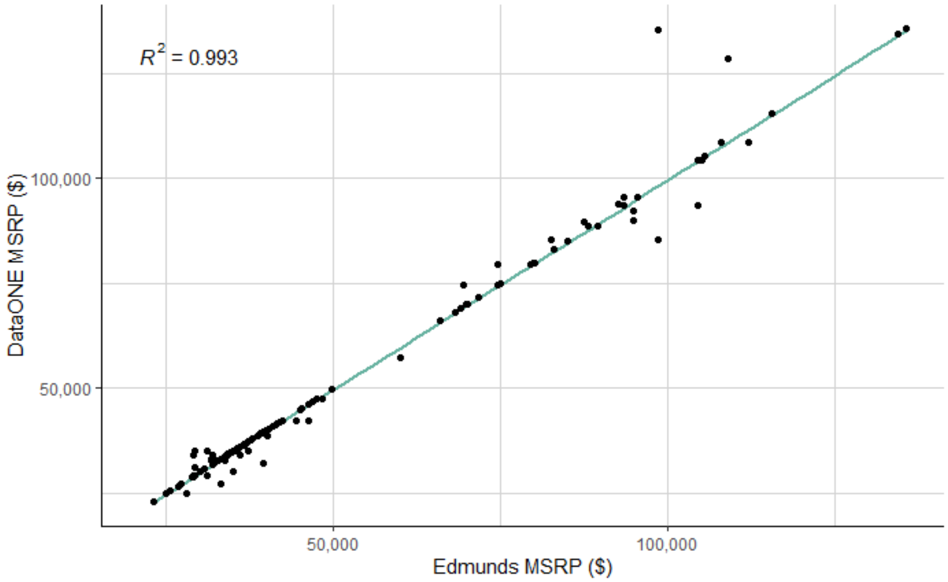

Figure 3.3. MSRP Validation: DataONE MSRP Against Edmunds MSRP

3.3.2 Tax Rate

The new vehicle purchase tax data was collected for the years 2011 to 2020 using the California DMV New Vehicle Registration Fee Calculator (*42*). For each county, a random zip code was chosen, assuming the tax rate was the same across zip codes within a county. The vehicle purchase date was set to January 1st of each year. In California, this tax varies by county, from 8.25% in various counties to 9.75% in Alameda County and Los Angeles County in 2011, and from 7.25% in counties like Colusa, El Dorado, Placer, and more, to 9.5% in Los Angeles County in 2020, as seen in Figure 3.4. Additionally, the tax fluctuates over the years, with some years it experiences an increase and in others a decrease, depending on the county.

The survey participants reported their household location by dropping a pin on a displayed map. The data was recorded as a pair of latitude and longitude values. Using the United States Census Bureau 2016 County Polygons (*43*), Federal Information Processing Standards (FIPS), and R software, each household dropped pin was matched with the appropriate county, and the county's tax rate was applied to the MSRP.

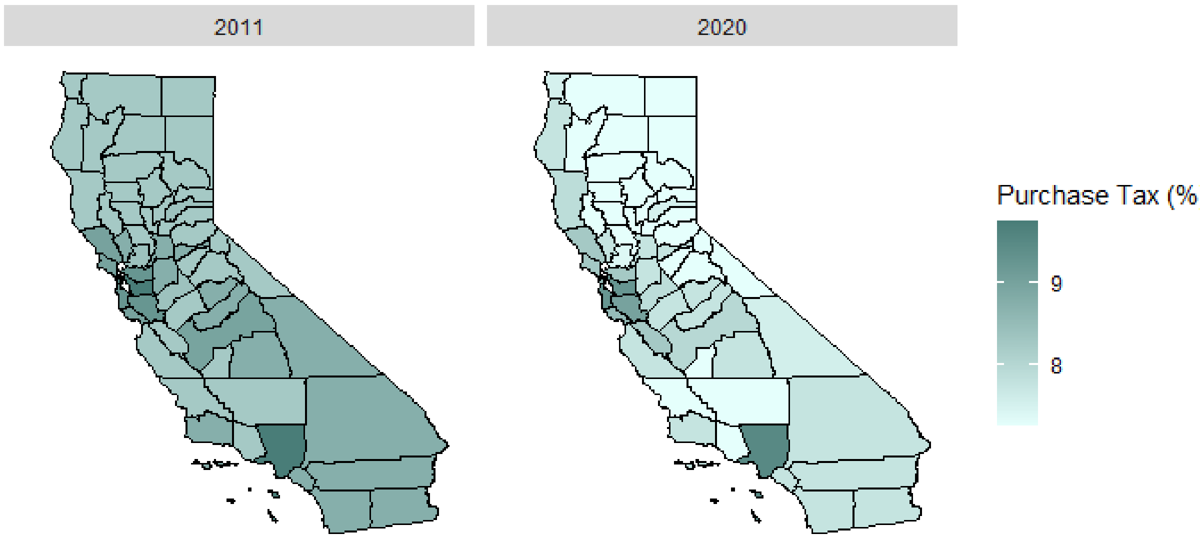

Figure 3.4. New Vehicle Purchase Tax by County in 2011 and 2020

3.3.3 Incentives

The PH&EV survey participants could report the incentive amount received from the federal income tax credit, state rebate, and local rebates.

The federal income tax credit is offered across all US jurisdictions and for all income levels for vehicles that were manufactured in 2011 or later. The credit of $2,500 to $7,500, phases out after a manufacturer sells 200,000 PEVs in the U.S. (*44*). The maximum amount given for each PEV model at any given time is publicly available (*45*). The option to report a new PEV purchase to gain the federal income tax credit is embedded in the major tax software, so the purchaser's due diligence is kept to a minimum. Therefore, it was assumed that every purchaser received the credit, and the high response rate for this question of 97.4% reinforced this assumption. When looking at the known maximum available credit amount per model, 7,234 (63%) respondents reported that amount. The missing or oddly-reported numbers were manually investigated and assigned a credit value as described below.

It is known that the federal tax credit is income-level dependent, where low-income households cannot fully take advantage of the entire tax credit, as their federal income tax can be lower than the credit amount (*46*). For respondents with an annual income greater than $50,000, the maximum tax credit was assigned. For respondents with an annual income lower than $50,000, the federal tax obligation might be lower than the available credit. No information regarding marital status was collected during the survey, and it was unknown if the survey respondents were more likely to file taxes individually or jointly. The average amount of federal tax obligation of a single filing and jointly filing for an income of $49,999 were averaged for each filing year. If the federal tax obligation was lower than the tax credit for a specific model at any given year, the federal tax obligation was assigned as the credit amount. If the federal tax obligation was higher than the tax credit, the maximum credit amount was assigned.

The state rebate program that was offered for all PEV purchasers was the California Clean Vehicle Rebate Project (CVRP), which was issued in 2010 (*47*). Starting in 2016, the project set an income cap, to ensure that rebates are allocated to low- to medium-income households, and a higher rebate amount is given to low-income households (*48*). Over the past decade, the program offers light-duty buyers a rebate of $2,500 for BEVs and $1,500 for PHEVs (with an addition of $2,000 for low-income households). The program continues to be revised beyond 2020, added a base MSRP cap and updated the rebate amount and the income cap (*49*).

In November 2016, CVRP set an income cap of $300,000 for joint filers. Households who earned more than the cap are not eligible to receive the CVRP rebate. From the survey data, households who purchased a PEV in the year 2019 were investigated. 67 households reported they earned more than $300,000 annually and purchased a new BEV that year, of which 44 (66%) of them reported receiving $2,500 as a state incentive, and 61 (91%) of them reported receiving an incentive between $500 to $3,500. The same was observed for new PHEV buyers with a high income. A total of 10 of them participated in the survey, where five of them reported receiving $1,500, and 9 of them reported receiving an incentive between $1000 to $2,500. According to the program guidelines, these participants should not be eligible for any rebate. Therefore, the CVRP incentive was manually applied based on the year of purchase and the reported income.

Clean Cars 4 All and Clean Vehicle Assistance Program are examples of local rebate programs which target low-income purchasers and disadvantaged communities in certain areas of California. The Clean Cars 4 All program ended in 2021, while Clean Vehicle Assistance Program still runs (*50*, *51*). Local programs that were offered past decade required the purchasers to actively seek them, meet a certain threshold, and go through an application process. In addition, there was a high rate of questionable reporting amounts in the survey by the participants. Therefore, the local incentives were excluded from the analysis. This exclusion fosters the ability to draw recommendations about future policies based on fixed values that apply to the general population rather than using district- or city-specific temporal benefits.

3.3.4 Electric Vehicle Supply Equipment (Charger)

Under the charging behavior section, the survey respondents were asked “How do you charge your {PEV model name} at home?”, and the given options were level 1 (“We're using a 120 V outlet at home”), converted level 1 (“We're using a converted 120 V cord to 240 V operation”), level 2 (“We're using a Level 2 (240 V) Charger at home”), or other (open text box). For level 1 charging, no additional costs were associated. For converted level 1, it was assumed that no infrastructure upgrade was done, and only an adapter was purchased by the 101 (<1%) respondents who chose this option. Having the generous assumption that the adapter is plugged into two alternating circuits, the cost of the converter was estimated to be $100. Almost half of the respondents (5,667 people, 49%) indicated they were charging their PEV using level 2. Assuming that level 2 EVSE required purchasing and installation, the assigned cost was $1,836, where $550 was paid for equipment and was paid $1,286 for installation (*52*).

3.4 Operating Costs

The main operating costs are energy expenditure, annual registration, and maintenance. While the last two are simpler to obtain, the first one requires a wide range of data sources.

3.4.1 Driving and Charging Behavior

The energy expenditure, both on gasoline and electricity, depends on the household driving and charging patterns. Using the survey assured representation of the California drivers' heterogeneity.

The survey respondents filled the current odometer reading, which was considered as the cumulative VMT. The participants also indicated the purchase month and year of the vehicle. As the completion date of the survey was known, it was possible to calculate the vehicle age. In the survey, vehicle age ranges between brand new vehicles to six years and four months, as Figure 3.5 shows. As the scope of this TCO analysis was total costs of five ownership years (and not year-by-year TCO), the total five-year (or 60 months) VMT was calculated using a monthly average VMT based on the reported data in the survey, per equation 6:

$$\text{Ownership length (month)} = \text{Purchase date } - \text{Survey date} \tag{5}$$

$$\text{Total 5 year VMT (mile)} = \frac{\text{Odometer reading (mile)}}{\text{Ownership length (month)}} \cdot 60 \text{ (month)} \tag{6}$$

While it is known that as a vehicle gets older, the less it is driven (*53*), this phenomenon cannot be sufficiently observed from the survey data. The calculation of total VMT using the monthly average odometer reading for vehicles owned more than five years suffered from an underestimation of the total VMT, and the VMT of vehicles owned less than five years suffered from an overestimation.

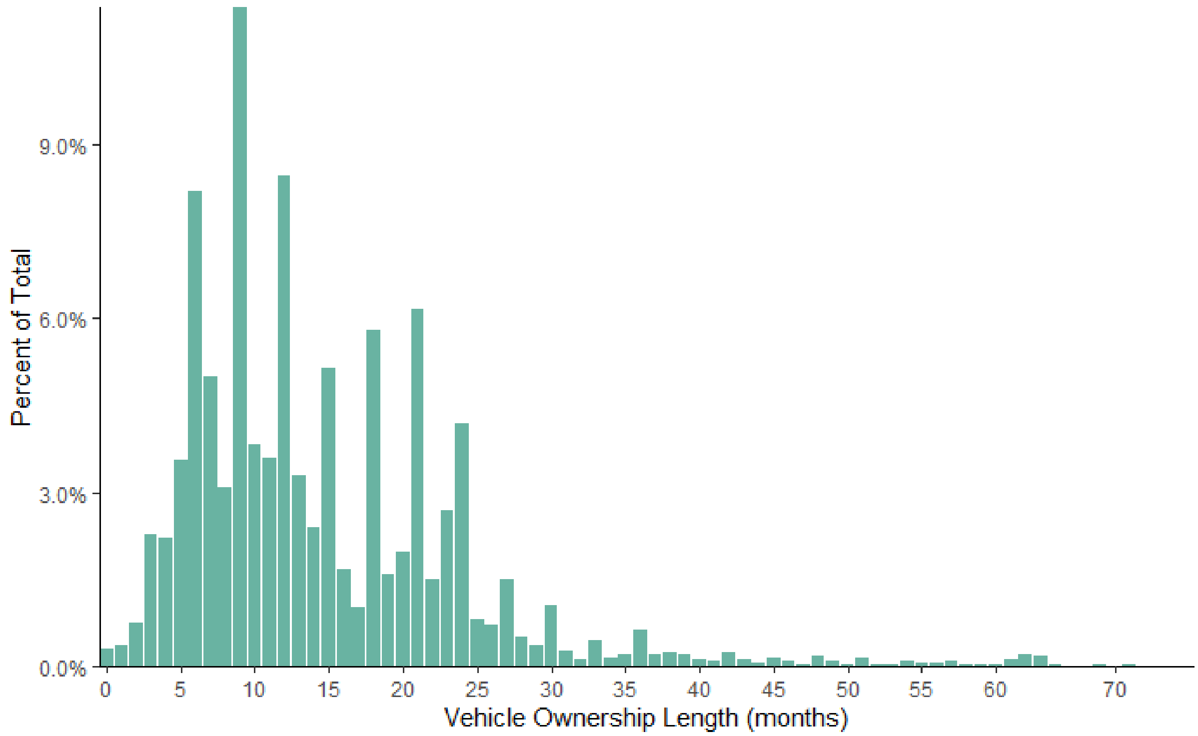

Figure 3.5. Vehicle Ownership Length of PH&EV Survey Participants

In the survey, the respondents were asked to fill a table representing their charging behavior the week before the survey. The respondents indicated whether or not they charged at the selected main location (home, work, and public) and at what level (level 1, level 2, DC fast), and at what days of the week (Monday through Sunday) each charging event happened, as shown in Figure 3.6. Adding the marked ticks by charging location and level and dividing them by the total amount marked ticks resulted in the likelihood percentage of each charging event happening, assuming that week was a representation of a five-year charging behavior. The charging behavior table was not available in the first phase of the survey, therefore, the average charging behavior of the second phase was applied to the first phase. Table 3.2 shows the average percentage of each charging event per phase, where all the events sum to 100%. It was seen that the percentage of charging at home declined over time, while work charging increased. Public charging percentage fluctuates, possibly because of the free Tesla Supercharging offered in earlier years for specific models.

For the last 7 days, please indicate when your [redacted] was charged at each of the following locations:

	Home	At work while working			Non-Work		
	Level 2	Level 1	Level 2	DC Fast	Level 1	Level 2	DC Fast
Monday (Yesterday)	☐	☐	☐	☐	☐	☐	☐
Sunday (Day before yesterday)	☐	☐	☐	☐	☐	☐	☐
Saturday (3 days ago)	☐	☐	☐	☐	☐	☐	☐
Friday (4 days ago)	☐	☐	☐	☐	☐	☐	☐
Thursday	☐	☐	☐	☐	☐	☐	☐
Wednesday	☐	☐	☐	☐	☐	☐	☐
Tuesday	☐	☐	☐	☐	☐	☐	☐

Figure 3.6. Charging Behavior Table from the PH&EV Survey

Table 3.2. The Average Percentage of Charging Events per Survey Phase

Survey Phase	Survey Dates	Home	Work Level 1	Work Level 2	Work DC Fast	Work Total	Public Level 1	Public Level 2	Public DC Fast	Public Total	Total
1	Apr 2015 - Sep 2015	81.5%	1.2%	5.3%	1.3%	7.8%	1.6%	3.6%	5.5%	10.7%	100%
2	May 2016 - Jul 2016	81.5%	1.2%	5.3%	1.3%	7.8%	1.6%	3.6%	5.5%	10.7%	100%
3	Aug 2016 - Oct 2016	77.5%	3.8%	10.3%	0.9%	15.0%	0.7%	3.0%	3.7%	7.5%	100%
4	Jun 2017 - Aug 2018	76.1%	3.7%	10.8%	0.7%	15.2%	0.7%	4.6%	3.5%	8.7%	100%
5	Oct 2017 - Nov 2017	74.5%	4.4%	12.9%	0.4%	17.7%	2.0%	4.7%	1.0%	7.8%	100%
6	Aug 2018 - Apr 2019	73.5%	2.9%	12.6%	1.8%	17.3%	0.9%	4.6%	3.6%	9.1%	100%
7	May 2020 - Oct 2020	73.8%	2.4%	12.4%	2.5%	17.3%	0.9%	3.8%	4.3%	8.9%	100%

The utility factor (UF), defined as the fraction of VMT using the electric mode of a vehicle, is measured between zero to one. This measure is dependent on battery technical attributes and the driver's behavior (*54*, *55*). For BEVs, the UF was assumed to be equal to one. For PHEVs, the values published by the Office of Energy Efficiency & Renewable Energy (EERE) were assigned for each model and year (*56*). It was found that for long-range PHEV (over 30 miles), the EERE UF values were close to actual drivers' UF in California. For lower range PHEVs, the EERE UF values were overestimated (*57*). In addition to UF, the EERE fuel economy values (in mi/kWh for BEVs and PHEVs and mi/gal for PHEVs) were also added to the Survey dataset based on vehicle model, year, trim, and powertrain.

3.4.2 Energy Costs

Past average of all grades of retail gasoline prices ($/gallon) for California and predictions for a future average price of motor gasoline were published by the U.S. Energy Information Administration (EIA) (*58*, *59*). Based on the reference case, the ratio between each future year (2022 to 2024) and a past year (2021) was applied to the 2021 gasoline price to calculate the 2022 – 2024 gasoline prices. Past and future average gasoline prices for California are presented in Figure 3.7.

To estimate gasoline prices per county over time, first, the average retail gasoline cost per county and the average of California State for a particular day (March 28, 2022) were recorded (*60*). Then, the ratio between each averaged county price and the average state price was calculated, as presented in Figure 3.8. The calculation shows that Modoc County had the lowest ratio of 0.90, hence, the cheapest gasoline in California that day. Mono County had the highest ratio of 1.14, hence, the most expensive gasoline. These ratios, as of March 2022, were used as a proxy for the entire analysis length. Each county ratio was multiplied by the California historical and future retail gasoline price to obtain the county retail gasoline price over time.

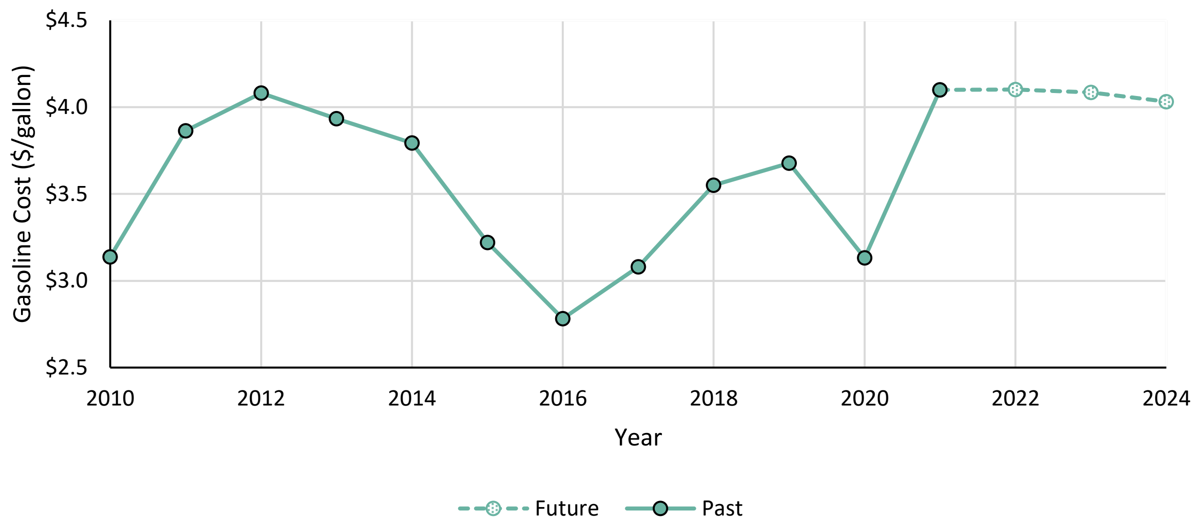

Figure 3.7. Past and Future Average Retail Gasoline Price in California

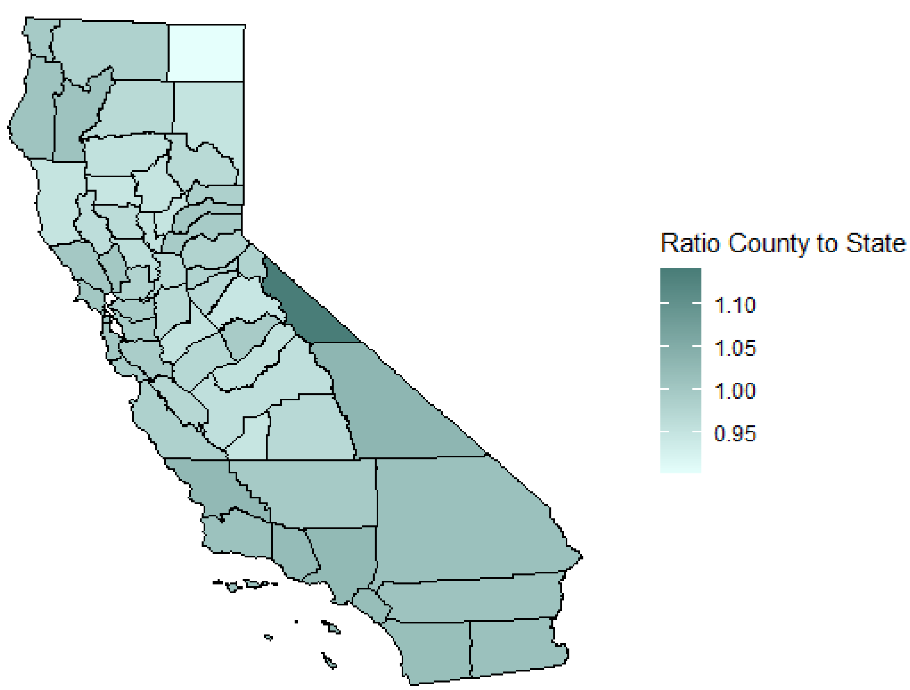

Figure 3.8. The ratio Between County Average and State Average Retail Gasoline Price

To assign a home electricity rate, the information about the electric utility company and the rate program collected by the survey was incorporated. The survey respondents could choose between three possible electric plans: flat rate, time of use (TOU), and special electric vehicle (EV) rate. The respondents also provided information about whether or not they were using a timer to charge their vehicle.

The survey respondents chose from a dropdown menu with 19 options the local electric utility company that serves them, with the option to specify a company that was not on the menu. In total, over 60 companies were reported. To simplify the data collection process of historical and current electricity rates of various programs from different utilities, the data was collected from the five most reported utilities, which were Pacific Gas & Electric (PG&E) (43.1%), Southern California Edison (SCE) (27.3%), San Diego Gas & Electric (SDGE) (11.9%), Los Angeles Department of Water and Power (LADWP) (7.2%), and Sacramento Municipal Utility District (SMUD) (3.3%). For respondents who were served by any other company (7.2%), the average rate of the five popular companies was assigned.

Each utility company publishes a Rate Schedule that details the current rates of their plans, which is updated multiple times a year. Historical Rate Schedules since 2011 were collected from the five popular utilities and summarized per plan type. For each plan type (flat, TOU, and EV), the different utilities could offer several programs, some of which were newly introduced, and others were retired between 2011 to 2021. For example, PG&E introduced in August 2013 two EV rate plans, named EV Rate A and EV Rate B. In July 2019, an additional plan was introduced, named EV2. All plans of the same type were averaged per peak mode (Peak, Part-Peak, and Off-Peak), if applicable. The rate data collection did not include the fixed minimum meter charge, low-income energy rates (CARE), and the California Climate Credit.

The residential rate for home vehicle charging for each survey participant was assumed based on the following logic:

- If indicated EV plan and timer charging → Average of off-peak rates from EV plans

- If indicated EV plan and no timer charging → Average rate of all peak rates for EV plans
- If indicated TOU plan and timer charging → Average of off-peak rates from TOU plans
- If indicated TOU plan and no timer charging → Average rate of all peak rates for TOU plans
- If indicated Flat Rate plan → Average of tier 2 rates from Flat Rate plans

When historical data was not available online, the earliest documented rate was applied to any missing previous year. Future rates were calculated using the average growth rate for the years 2020 – 2025 of residential electricity rate per utility company, as published by the California Energy Commission (*61*). Figure 3.9 to Figure 3.13 present the historical and future rates for each utility company. A dashed line in past years represents missing data that was filled manually, and in future years, a dashed line represents a prediction.

For work (any level) and public level 1 charging events, it was assumed the charging was for free. The rate of public level 2 charging events was equal to the average of the EVgo lowest advertised pricing for guests and basic members during off-peak and on-peak hours. This rate was equal to $0.35/kWh, as of March 2022. Similarly, the rate of public DC fast charging events was equal to the guests and pass members rate in ElectrifyAmerica stations, which was $0.43/kWh in March 2022. An annual factor and a location factor were applied to the above rates to reflect the change in electricity rate over the years and across service locations, based on the average rate charged in California every analysis year and by each utility company. Figure 3.14 presents the annual factor as a percentage of the base year 2022. The sharp increase between the years 2019 to 2022 indicates the effect of the pandemic on the annual average electricity rate.

Specific Tesla models at specific years were eligible for unlimited free Tesla Supercharging. These models were assigned free public charging (*62*). The literature shows that households with a rooftop photovoltaic (RPV) system save, on average, 25% of their electricity consumption, after subtracting capital and installation costs (*63*, *64*). Survey respondents could indicate if their household had an RPV system, so the saving was applied to their energy costs.

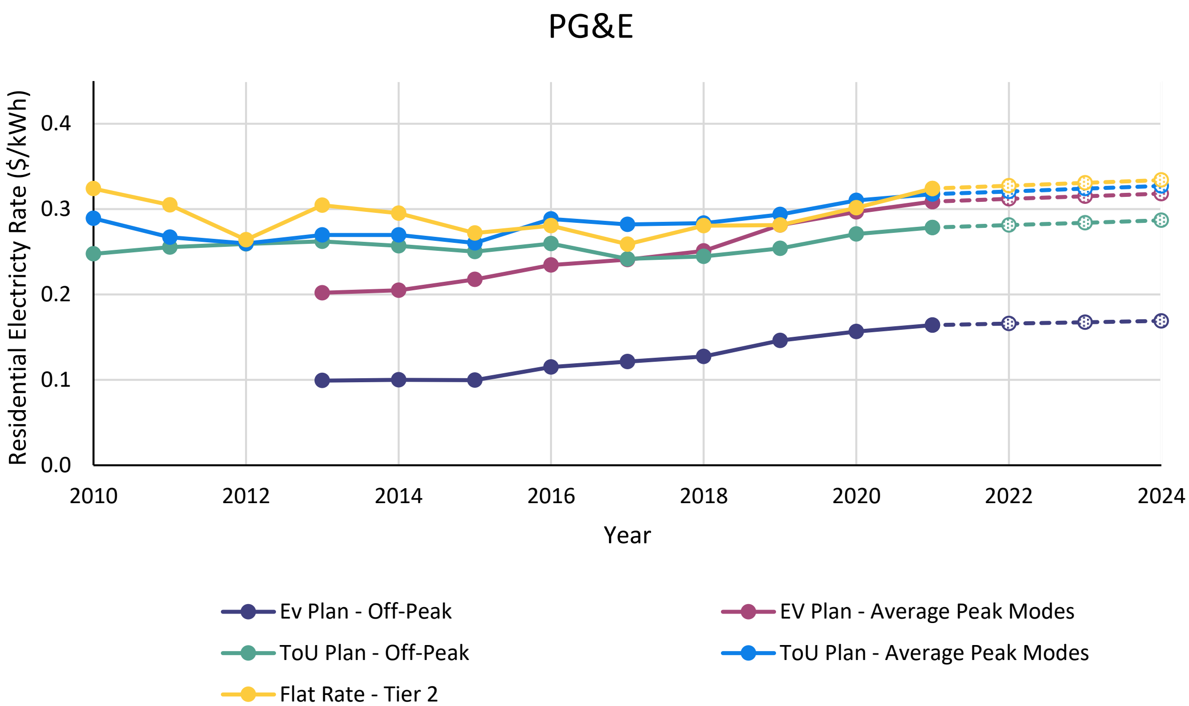

Figure 3.9. Historical and Future Residential Electricity Rate of PG&E

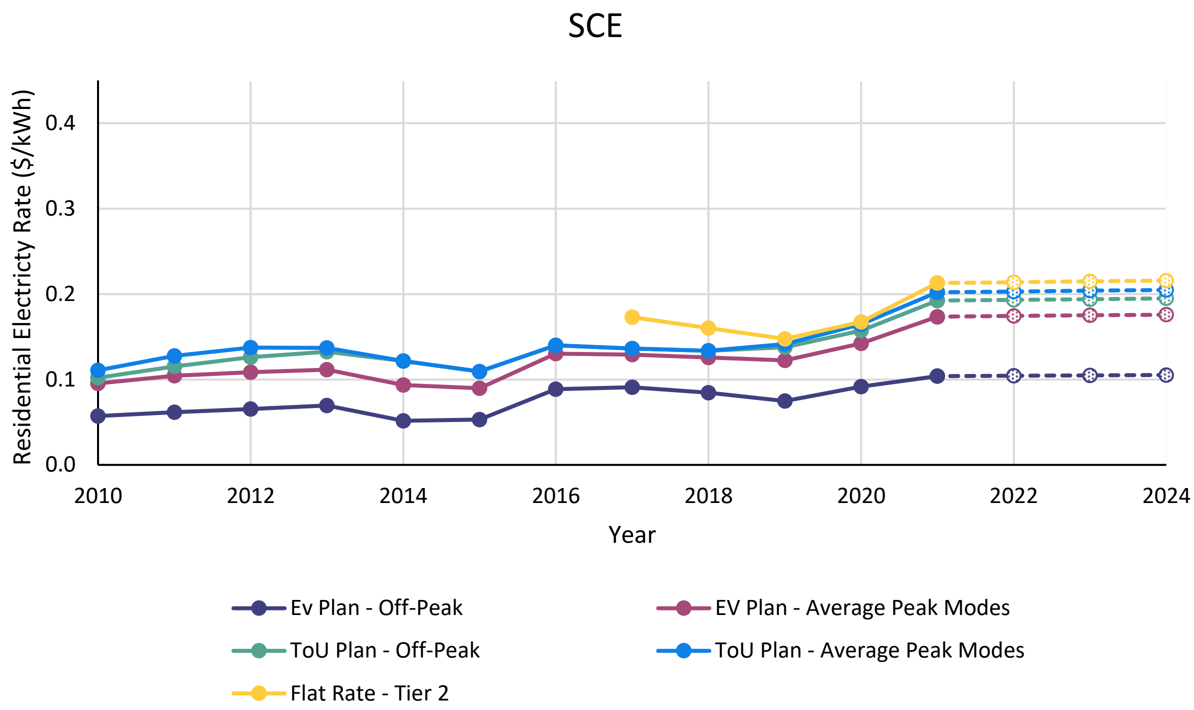

Figure 3.10. Historical and Future Residential Electricity Rate of SCE

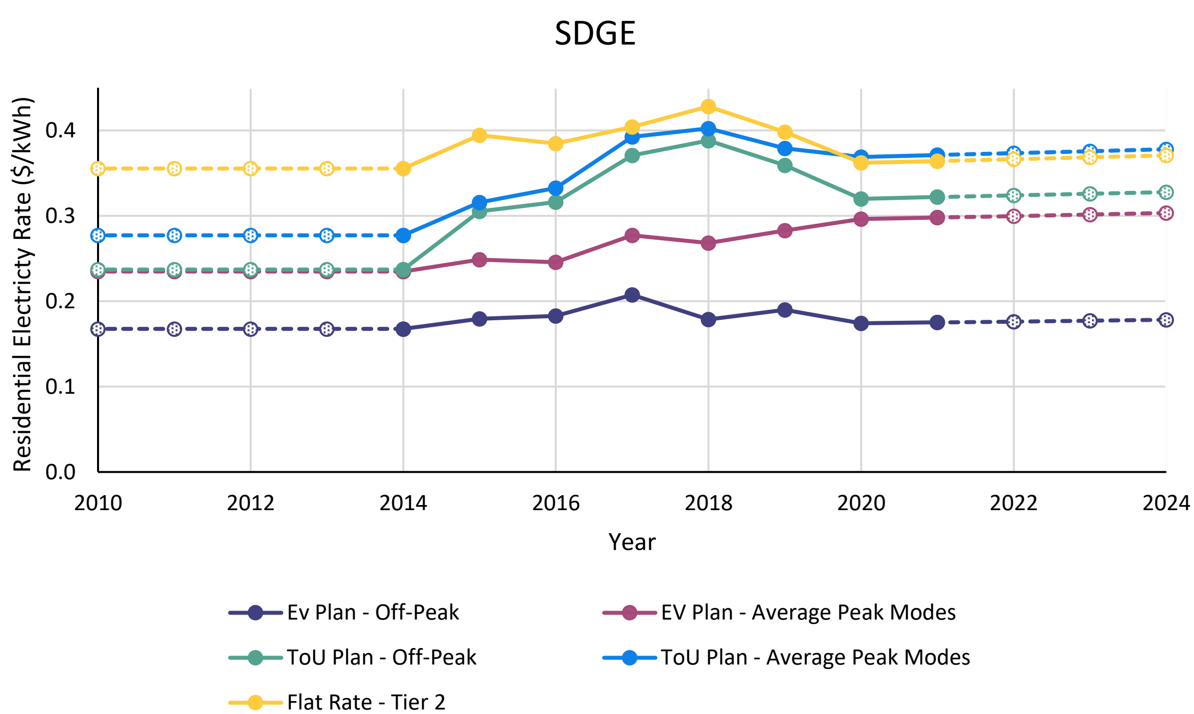

Figure 3.11. Historical and Future Residential Electricity Rate of SDGE

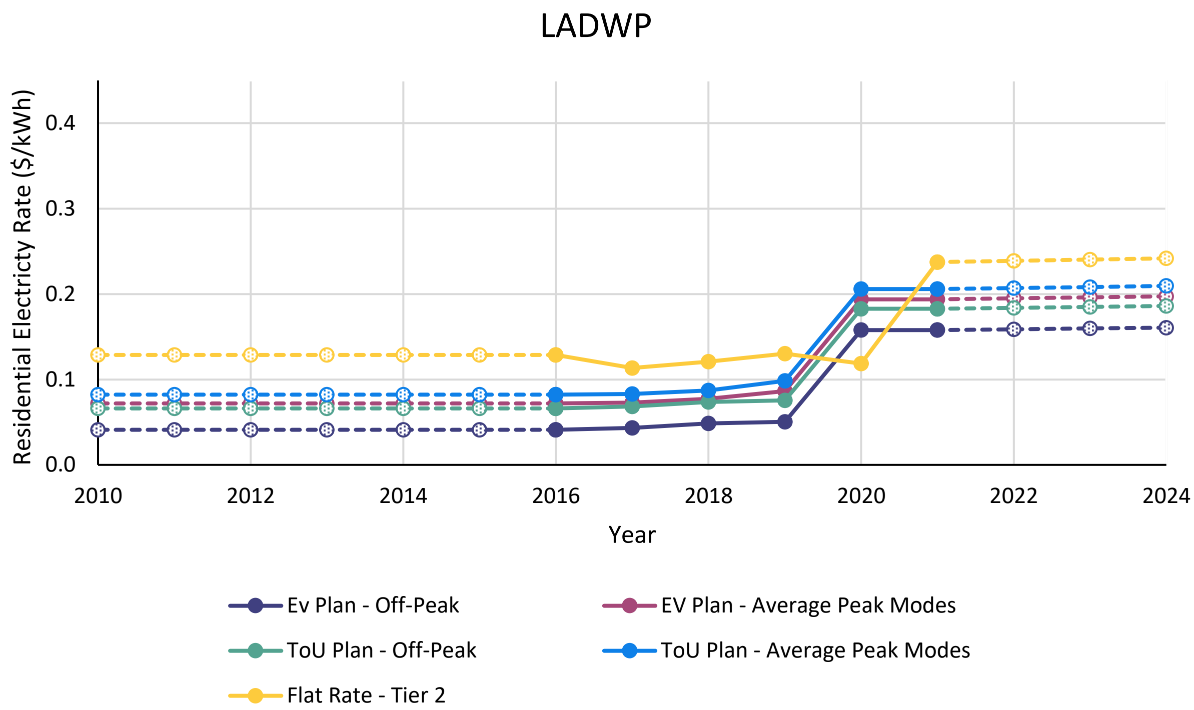

Figure 3.12. Historical and Future Residential Electricity Rate of LADWP

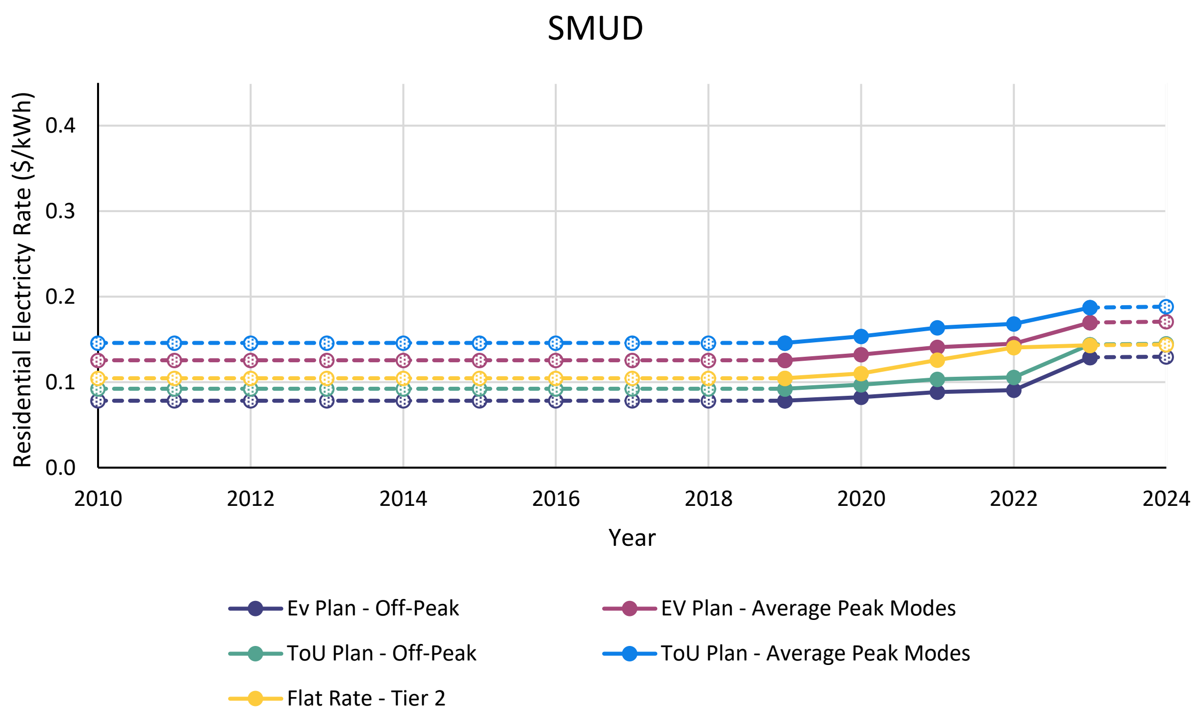

Figure 3.13. Historical and Future Residential Electricity Rate of SMUD

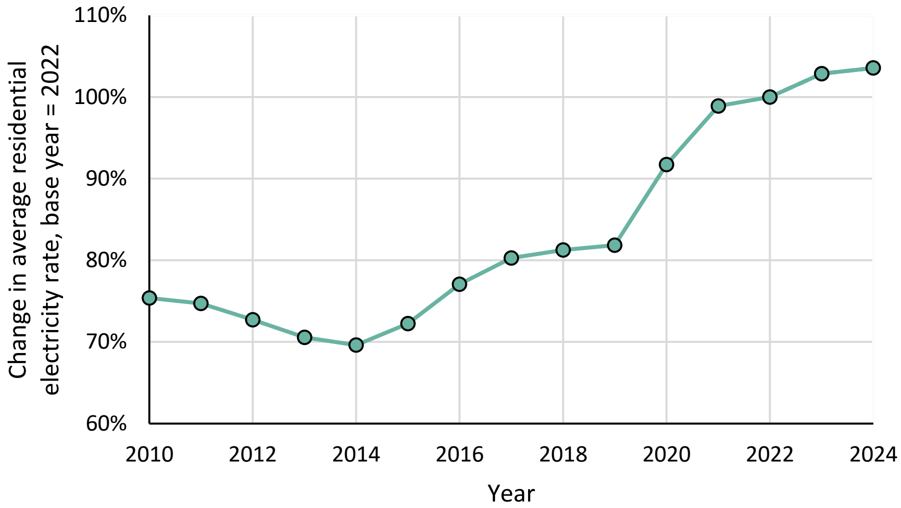

Figure 3.14. Annual Change in Average Residential Electricity Rate in California (2022 base year)

The total energy cost for PEVs was calculated per Equation 7:

$$EC = \sum_{t=2011}^{2024} \sum_{loc} \sum_{level} UF \cdot \frac{1}{\mathrm{Eff}\left(\frac{mi}{kWh}\right)} \cdot VMT(mi) \cdot CE_{loc,level} \cdot CR_{t,loc,level}\left({}^{\$}/_{kWh}\right) \cdot INF \cdot RPV + \sum_{t=1}^{5} \sum_{county} (1-UF) \cdot \frac{1}{\mathrm{Eff}\left(\frac{mi}{gal}\right)} \cdot VMT(mi) \cdot GAS_{t,county}\left({}^{\$}/_{gal}\right) \tag{7}$$

$$UF = \begin{Bmatrix} 0.288 - 0.888 & PHEV \\ 1 & BEV \end{Bmatrix} \tag{8}$$

$$RPV = \begin{Bmatrix} 0.75 & \text{for home charging events if RPV exists} \\ 1 & \text{else} \end{Bmatrix} \tag{9}$$

Where, t = ownership year;

loc = charging location type (home, work, and public);

$level$ = charging level (level 1, level 2, and DC Fast);

UF = utility factor (Equation 8);

Eff = vehicle energy efficiency;

VMT = annual VMT;

$CE_{loc,level}$ = charging event type in terms of location and level;

$CR_{t,loc,level}$ = charging rate per year, location type, and level;

INF = inflation rate between the year of purchase and the year of charging;

RPV = factor indicates if a household had an RPV system (Equation 9);

$county$ = California counties; and,

GAS = retail gasoline price in a given year and county.

3.4.3 Annual Registration Fees

Similar to the tax rate, also the annual registration fees were taken from the California DMV New Vehicle Registration Fee Calculator (*42*). The data was collected for the years 2011 to 2022, where the future years (2023 – 2024) were assumed to be equal to 2022. The same zip code from the tax data collection was used to find the fees. Also here, the vehicle purchase date was set to January 1st of each year. The annual registration fee charged by the DMV is a compound of state and local fees. The state fees are Registration Fee, California Highway Patrol Fee, Vehicle License Fee, Alternative Fuel Fee, and Current Transportation Improvement Fee. The Registration Fee is a fixed amount across all counties that increased over the years, from \$31 in 2011 to \$63 in 2022. Similarly, California Highway Patrol Fee increased from \$22 in 2011 to \$29 in 2022. The Vehicle License Fee is a percentage of the vehicle MSRP, 1.16% before 2011, and 0.65% afterward. The Alternative Fuel Fee is a fixed \$3 charge across all counties and years. The Current Transportation Improvement Fee started in 2018 and it classifies vehicles into five levels based on their MSRP: up to \$4,999; \$5,000 to \$24,999; \$25,000 to \$34,999; \$35,000 to \$59,999; and, \$60,000 or above. The first level does not have any associated fees, the second level fee was \$50 in 2018-2020 and \$55 in 2021-2022. The third, fourth, and fifth levels fees were \$100, \$150, \$175, respectively, in 2018-2020, and \$110, \$165, \$192 in 2021-2022. The local fees varied from county to county, and included, but were not limited to, County Service Authority For Freeway Emergencies Fee, Fingerprint ID Fee, Air Quality Management District, Auto Theft, DUI Crime Deterrence Program, Abandoned Vehicle Fee, and more. The total amount of all local fees ranged from \$1 in Mariposa County to \$15 in San Mateo County in 2011, and from \$1 in Mariposa County to \$25 in

Merced County in 2022. The total amount of fees fluctuated over time in some counties and stayed constant in others.

3.4.4 Maintenance

The Alternative Fuel Life-Cycle Environmental and Economic Transportation (AFLEET) Tool by Argonne National Lab was used to estimate the maintenance cost per driven mile, vehicle age, and vehicle body for the different powertrains (*65*). The AFLEET Tool 2013 was used for vehicles owned from 2011 to 2013 and the AFLEET Tool 2016 was used for vehicles owned between 2014 to 2016. From 2017 and forward, AFLEET was published annually until 2020 and used for accordingly maintenance years. To estimate the maintenance cost in future years (2021 to 2024), the costs from AFLEET Tool 2020 were applied.

3.5 Resale Value

This study presents a novel approach to estimating the resale value of a vehicle with a new powertrain technology that does not exist in the market long enough to establish a secondary market, such as PEVs. Unlike the existing literature, no online resale value calculators nor averaged residual values for different technologies were utilized. Instead, the leased vehicle data from the PH&EV survey was used. The approach presented here subtracts the federal income tax credit from the MSRP, as this credit passes through to the next buyer, to avoid the deflated resale values used in the literature (*66*).

7,846 new leased vehicles for three years were identified from the survey dataset, which covers about 250 different vehicle models. Each leased vehicle had data about the down payment and the monthly payment. By using a leasing calculator (*67*), the residual value after three years can be retrieved, using Equation 10.

$$Residual\ value\ _3(\$) = \frac{\frac{Monthly\ Pay}{1 + Tax\ Rate_t} \cdot Length - Cap \cdot Length\ \cdot MF - Cap}{Length \cdot MF - 1} \tag{10}$$

$$Cap = MSRP - Incentives - Down\ Payment \quad (11)$$

Where, $Monthly\ Pay$ = monthly payment from the survey;

$Tax\ Rate$ = average tax rate in California for a given year t;

$Length$ = length of lease in months (36);

Cap = capitalized cost required for monthly payment calculation (Equation 11);

MF = Money Factor, which is the interest rate for leasing purposes (0.125%);

$MSRP$ = MSRP of a vehicle from DataOne;

$Incentives$ = federal income tax credit; and,

$Down\ Payment$ = down payment from the survey.

Since this is the residual value after three years of ownership, and the analysis called for a residual value after five years, another calculation step was required. It was assumed that PEVs depreciate 25% after the first year and at a constant rate every year afterward. Knowing the residual rate after three years, the constant depreciation rate for any year greater than one can be easily calculated. Using the first and constant depreciation rates, the resale value after five years can also be calculated for each vehicle. For simplicity, all of the five-year residual values of the same vehicle group were averaged and used across all analysis years. The vehicle groups were divided by the powertrain (BEV, PHEV, HEV, and ICEV), body (passenger cars, including sedans, coupes, hatchbacks, and more, and light-duty trucks, including SUVs and vans), and vehicle class (standard and luxury). Table 3.3 details the calculated resale values.

The combined resale value of HEVs and ICEVs was found on Kelly Blue Book using the top five popular vehicle models in California in 2020 (Toyota Corolla, Toyota Camry, Honda Civic, and Honda Accord for passenger cars, and Toyota RAV4, Honda CRV, Toyota Highlander, and Honda Pilot for light-duty trucks). The resale value was the average of private party and trade-in values of a five-year-old vehicle (2016-2020) in a “very good condition”, with standard trim and equipment, and annual mileage of 12,000 miles in San Francisco County (zip code 94115). Table 3.3 details the gathered resale values.

Table 3.3. Average Resale Value of Five Years Vehicle per Powertrain, Body, and Class

	Passenger Car		Light Duty Truck	
	Standard	Luxury	Standard	Luxury
BEV	0.32	0.28	0.38	0.34
PHEV	0.29	0.29	0.31	0.31
HEV or ICEV	0.50	0.50	0.55	0.55

3.6 TCO Comparisons

The main objective of this study was to find the share of California drivers that financially benefited by their choice to purchase a new PEV over a combustion engine vehicle, and who were they. To answer these questions, selected PEV models were compared to selected ICEV or HEV comparable models in different vehicle segments. The comparison analysis focuses on the most extensive data collection year, which was 2018. The trim level for each model was carefully chosen, based on the specification of each trim, to propose as similar as possible comparisons.

A couple of assumptions were made to answer the research questions: a new ICEV or HEV would have been purchased instead of the new PEV and the substitute ICEV or HEV was driven similarly to the PEV in terms of annual VMT (*68*). Average local values were used for gasoline price, electricity cost, and DMV registration fees that were not dependent on the MSRP. Any other TCO component was estimated based on the TCO model presented in the Methodology section.

To identify the users who gained a positive TCO compared to the ones who did not, the annual VMT in which a parity occurred was used. Per comparison, vehicle owners who drove more miles annually than the parity point had a positive TCO, and the ones who drove less had a negative TCO. For each group, the sociodemographic attributes were examined, such as home ownership status, home type, number of vehicles at home, and more.

4 Results

The results presented in this section show a summary of the sample data after cleaning and the estimated TCO of this sample. The TCO is shown over time, annual VMT, and by powertrain type. A deeper analysis was performed on the relationship between TCO, income level, and vehicle characteristics. Finally, comparisons were made between selected PEV and non-PEV models to understand if California drivers could financially benefit from the purchase of a PEV, what were the role of the federal income tax credit and the state incentive in these parities, and who were the PEV driver who benefited by their early-adoption choice.

4.1 Descriptive Statistics

To understand the profile of early PEV purchasers who filled the survey, hereby key sociodemographic attributes for the study's sample of 11,505, faceted by vehicle powertrain, BEV or PHEV, across the analysis term (2011-2020). Figure 4.1 and Figure 4.2 present the distribution of gender and age, excluding non-binary gender and "Decline to state" options due to low sampling. The middle age groups of 30 to 39, 40 to 49, 50 to 59, and 60 to 69 were approximately equally dominating the PEV market, with a share of 20% to 30% for each group. That was applicable for both binary genders (female and male) and powertrains (BEV and PHEV). Similarly, Figure 4.3 and Figure 4.4 show the distribution of house ownership (own or rent) and house type (detached house, attached house, such as duplex and fourplex, and apartment). The general trend among the survey respondents was an increasing percentage of PHEV owners who lived in an attached house or an apartment, whether it was owned or rented. Over the years, more and more households with low- and medium-income (up to $200,000 per year) purchased a PEV, as anticipated with the increasing offered models under a wider price tag and the nature of market penetration. The income group of $100,000 to $200,000 dominated the sample for both powertrain types, as shown in Figure 4.5 and Figure 4.6. The number of households with a single vehicle in their fleet (excluding motorcycles and motorhomes), which was a PEV only, increased over the years, a positive trend for adoption showing trust in this new technology, as seen from Figure 4.7.

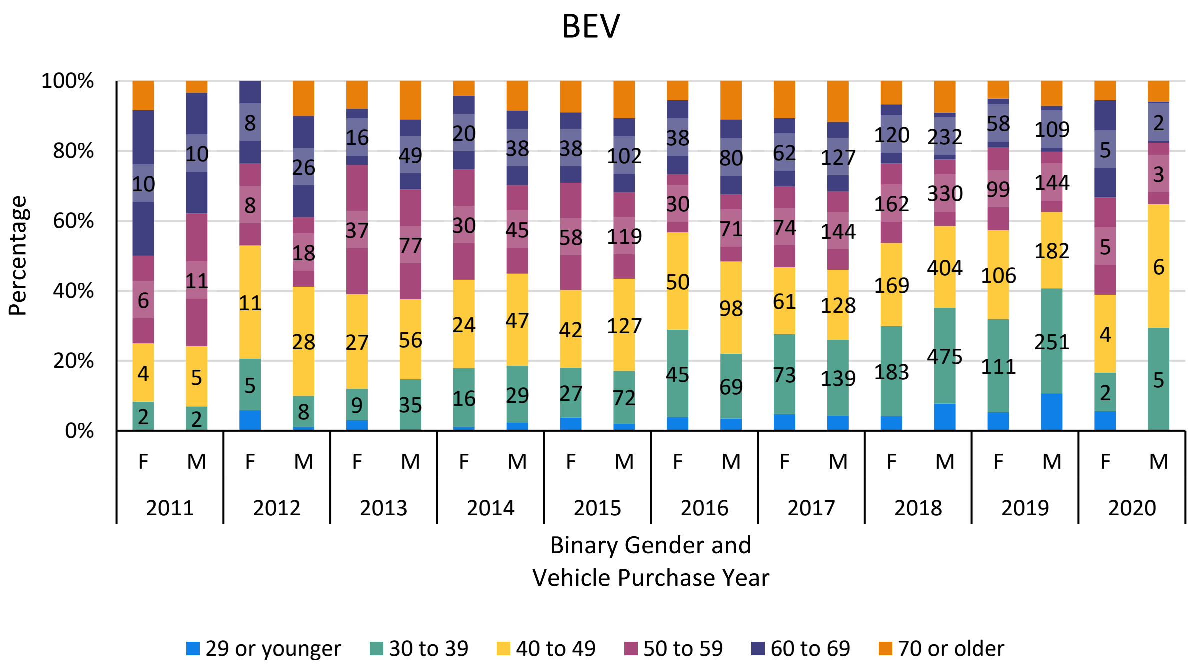

Figure 4.1. BEV Sample Distribution by Age, Binary Gender, and Purchase Year

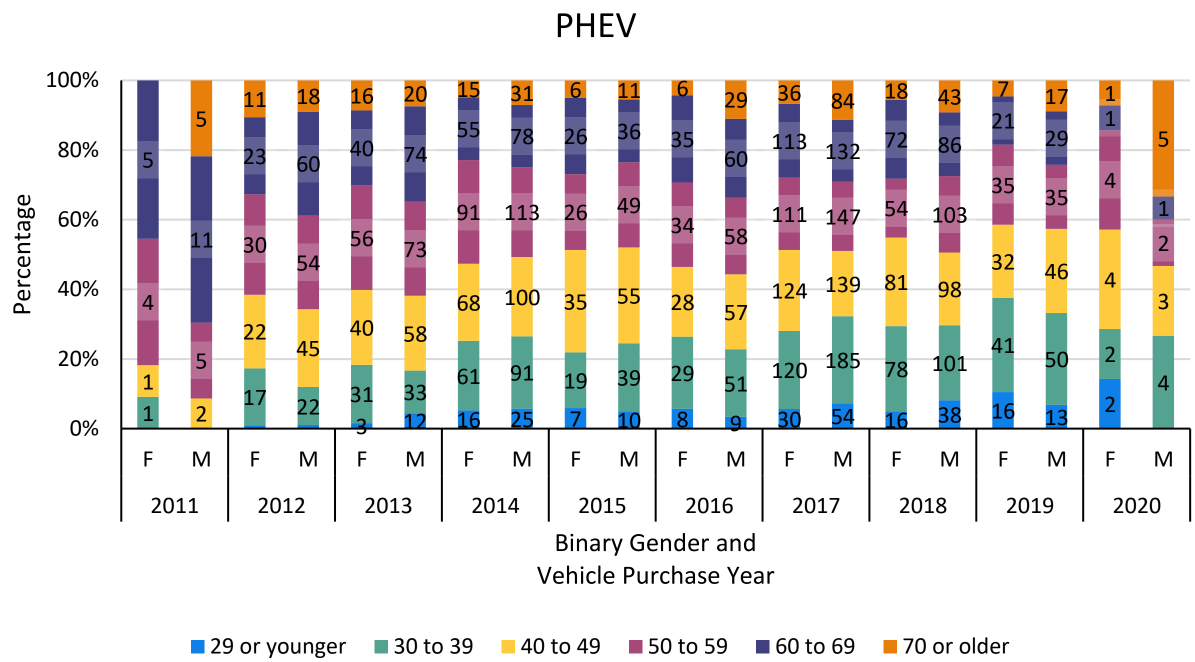

Figure 4.2. PHEV Sample Distribution by Age, Binary Gender, and Purchase Year

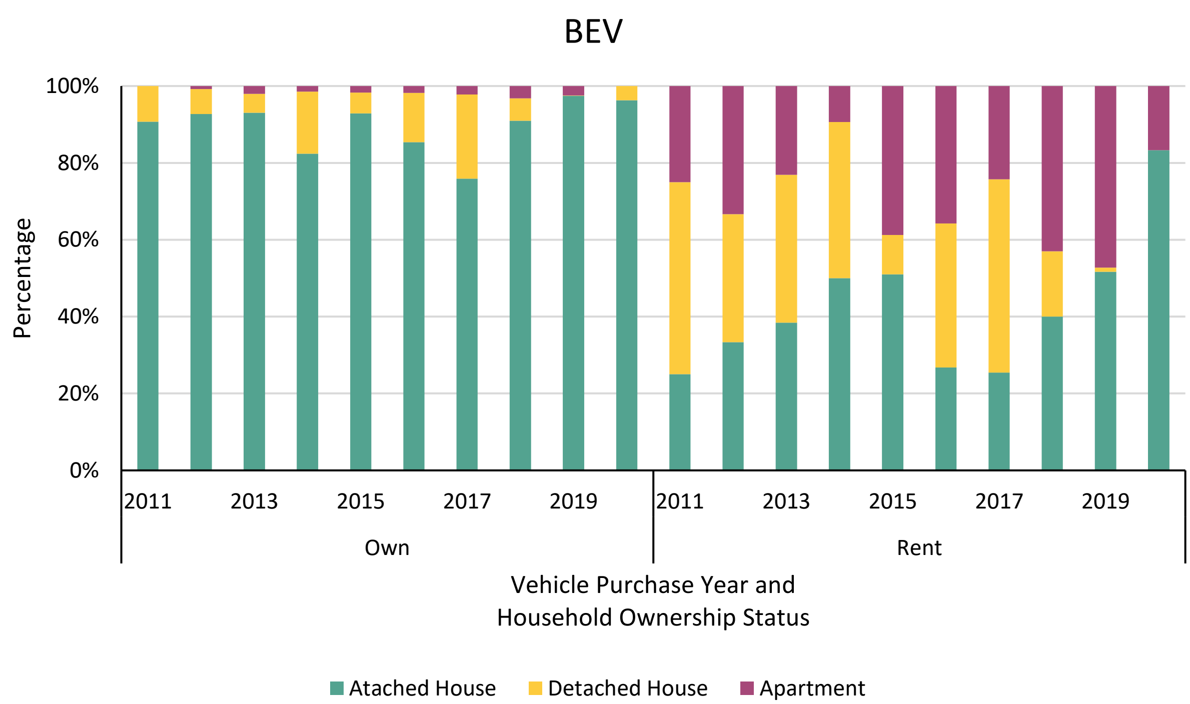

Figure 4.3. BEV Sample Distribution by House Type, Household Ownership Status, and Purchase Year

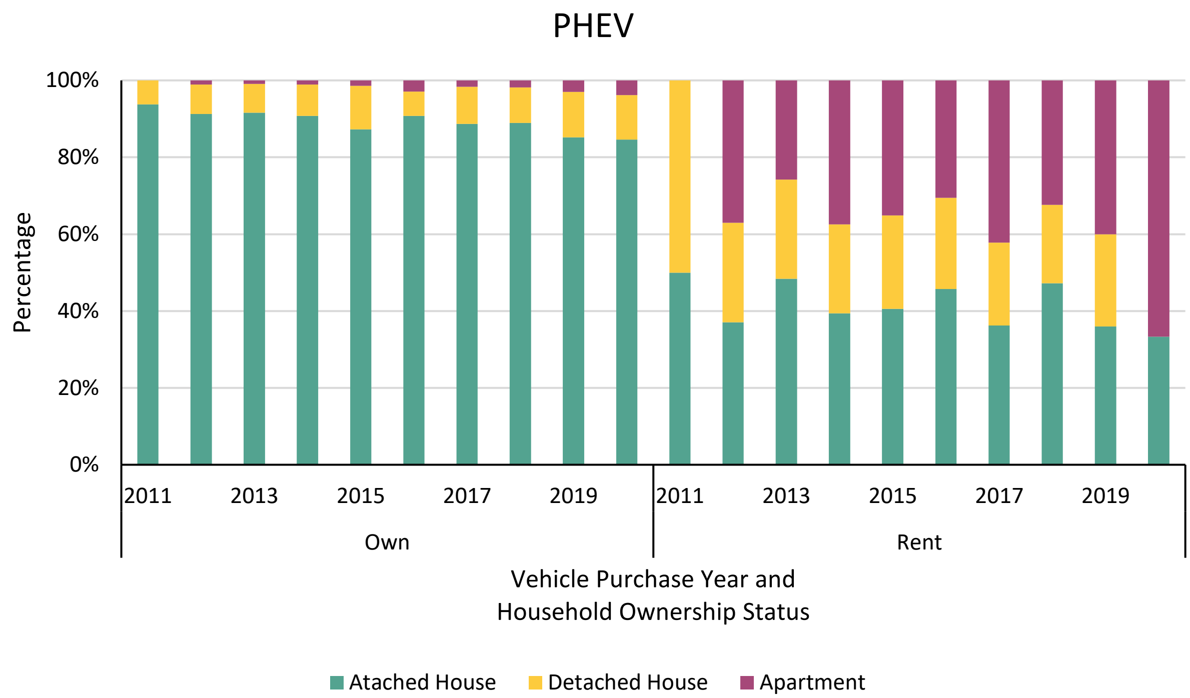

Figure 4.4. PHEV Sample Distribution by House Type, Household Ownership Status, and Purchase Year

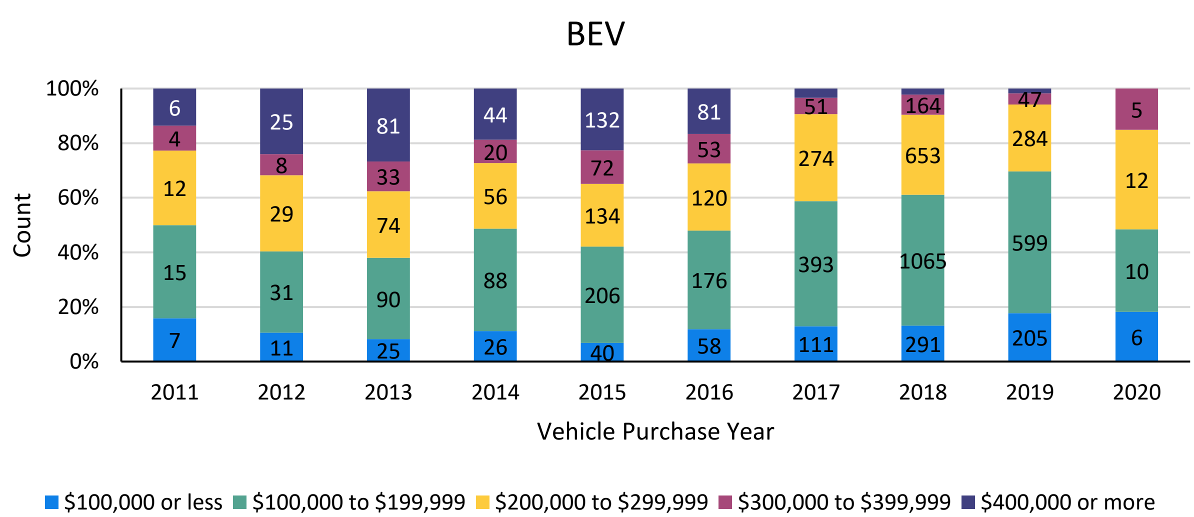

Figure 4.5. BEV Sample Distribution by Income and Purchase Year

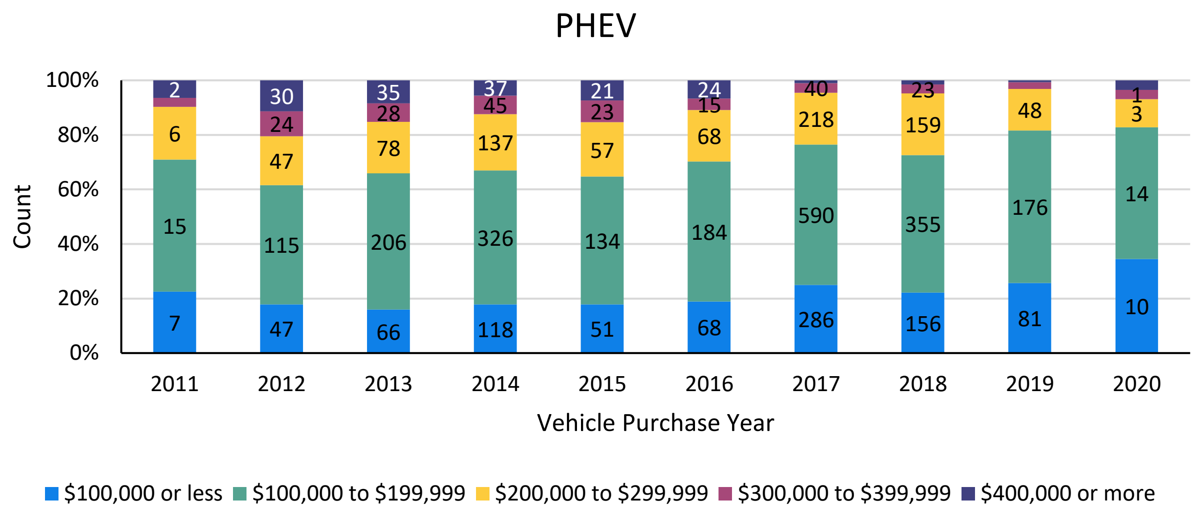

Figure 4.6. PHEV Sample Distribution by Income and Purchase Year

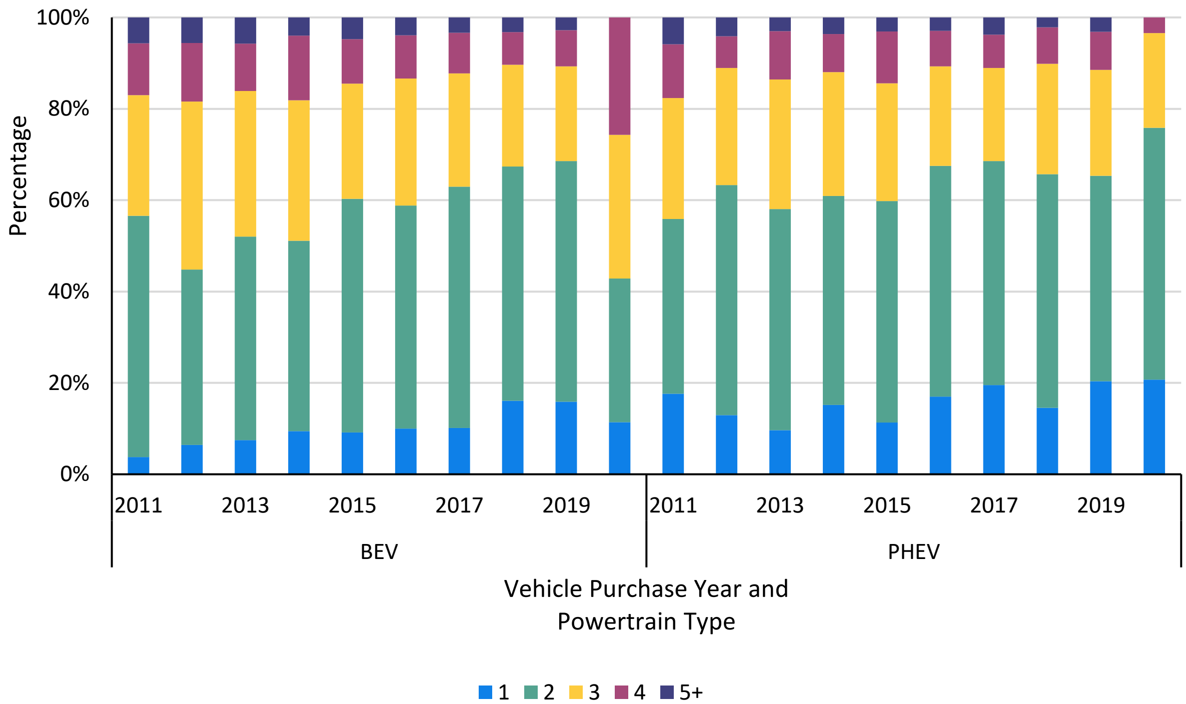

Figure 4.7. Sample Distribution by Household Fleet Size, Powertrain Type, and Purchase Year

4.2 TCO Overview

TCO was estimated for an ownership length of five years and is presented in the form of US dollars per driven mile, adjusted for the year of purchase. Figure 4.8 presents the TCO estimation of the entire sample, faceted by powertrain type. For BEVs, the TCO ranges from $0.26/mile to $4.83/mile, and for PHEVs, it ranges from $0.29/mile to $2.23/mile. The higher BEV TCO was mainly driven by higher capital cost compared with PHEV, as Figure 4.9 suggests. The popular PHEVs had an MSRP of about $30,000, such as Chevrolet Volt, Toyota Prius Prime, and Ford C-Max. The popular BEV models had an MSRP of about $35,000, such as Nissan LEAF and Chevrolet Bolt, and the popular Tesla Model 3 had an MSRP of about $45,000. Figure 4.10 shows that the distribution of annual VMT between the two powertrain types was similar, ranging from 4,100 miles to 27,700 for both powertrain types, with a median of 12,500 miles. The similar distribution suggests that BEVs and PHEVs were similarly driven. The annual fuel expenditure, as seen in Figure 4.11, also shows a similar range, where the BEV distribution was skewed towards the lower end with the absence of gasoline expenditure. The BEV energy expense ranges from $0 (free DC Fast charging by Tesla) to $3,750 per year, and the PHEV fuel and energy expenditure ranges from $85 to $3,350.

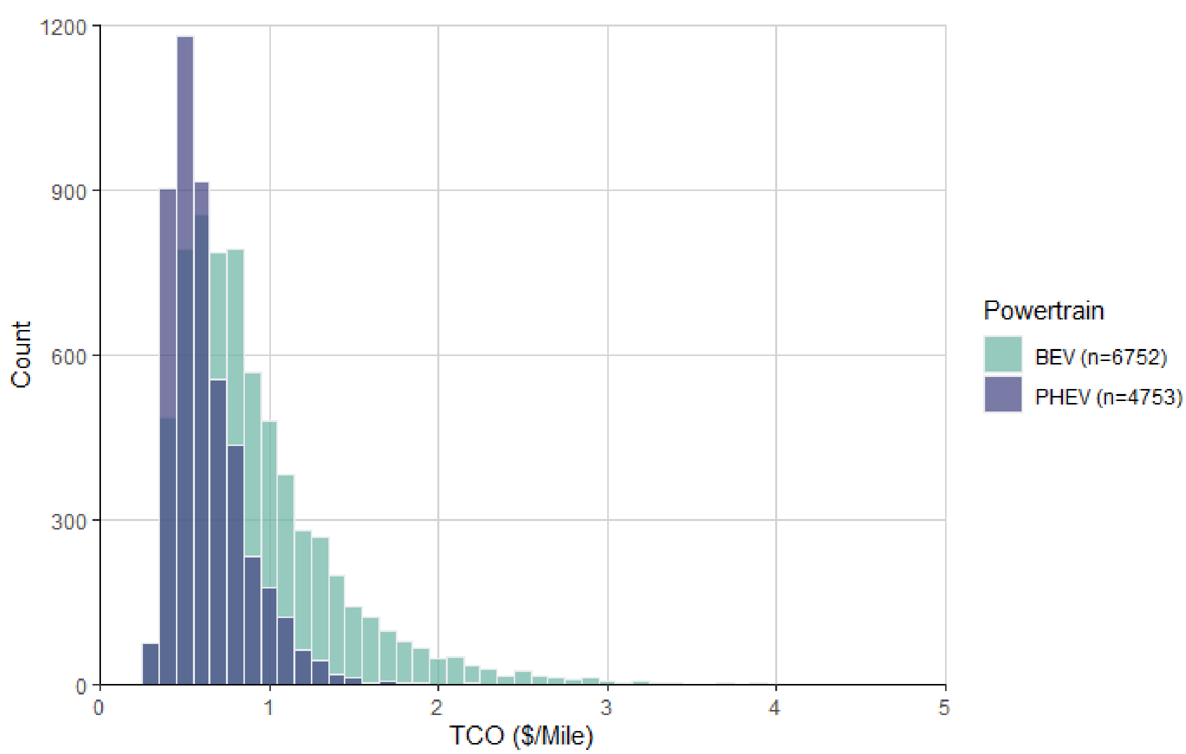

Figure 4.8. TCO Results of Survey Sample (California PEV Owners between 2011-2020)

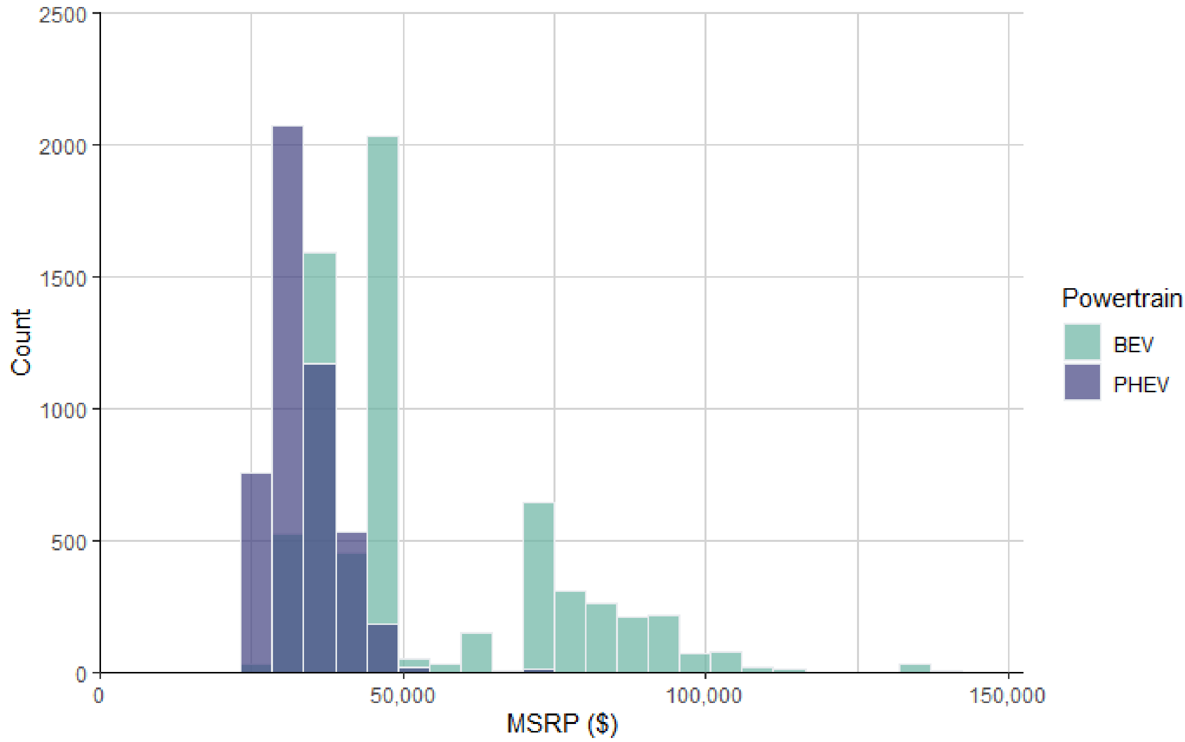

Figure 4.9. PEV MSRP Distribution of Survey Sample

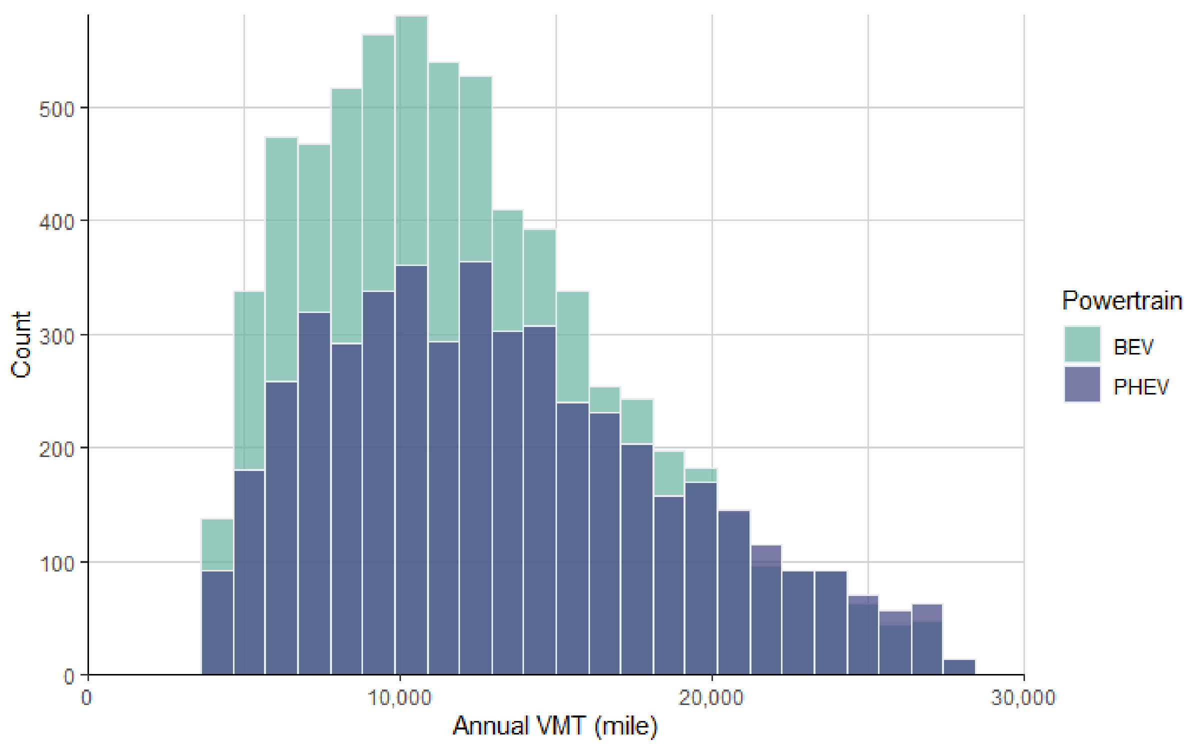

Figure 4.10. Annual PEV VMT Distribution of Survey Sample

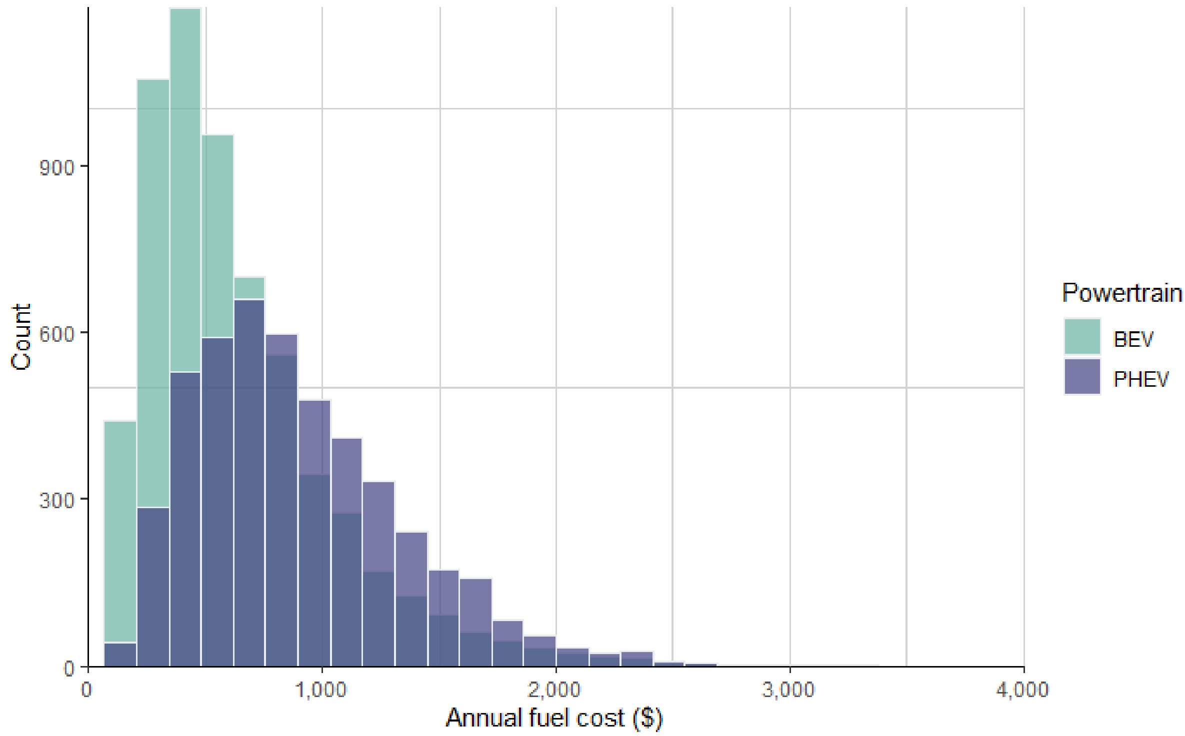

Figure 4.11. Annual PEV Fuel Cost Distribution of Survey Sample

As the MSRP plays a major role in the overall TCO, to track the TCO trend over time, the vehicle sample was split into standard and luxury auto manufacturers. The standard manufacturers were Ford, Honda, Hyundai, Kia, Mitsubishi, Nissan, Smart, Subaru, Toyota, and Volkswagen, and the luxury manufacturers were Audi, BMW, Cadillac, Chrysler, Jaguar, Mercedes, Tesla, and Volvo (written alphabetically). Figure 4.12 shows that the median BEV TCO per year of standard manufacturers fluctuates around $0.5/mile to $0.6/mile during the analysis term, and for PHEVs, it fluctuates between $0.5/mile to $0.55/mile. The TCO of luxury BEVs decreases over time with the introduction of cheaper models under the same luxury brand. Of course, the luxury TCO was always higher than the standard TCO.

As expected, the TCO per mile decreases with the increase of annual VMT, as shown in Figure 4.13. For BEVs, drivers who drove 4,100 miles annually had a TCO of $0.26/mile and $0.41/mile for standard and luxury classes, respectively. Drivers who drove over 27,000 miles a year, had a TCO of $1.65/mile and

$4.83/mile for the two classes. Tesla Model 3 (all trims) was clustered separately for this plot, as this model's TCO falls between the standard and the luxury clusters.

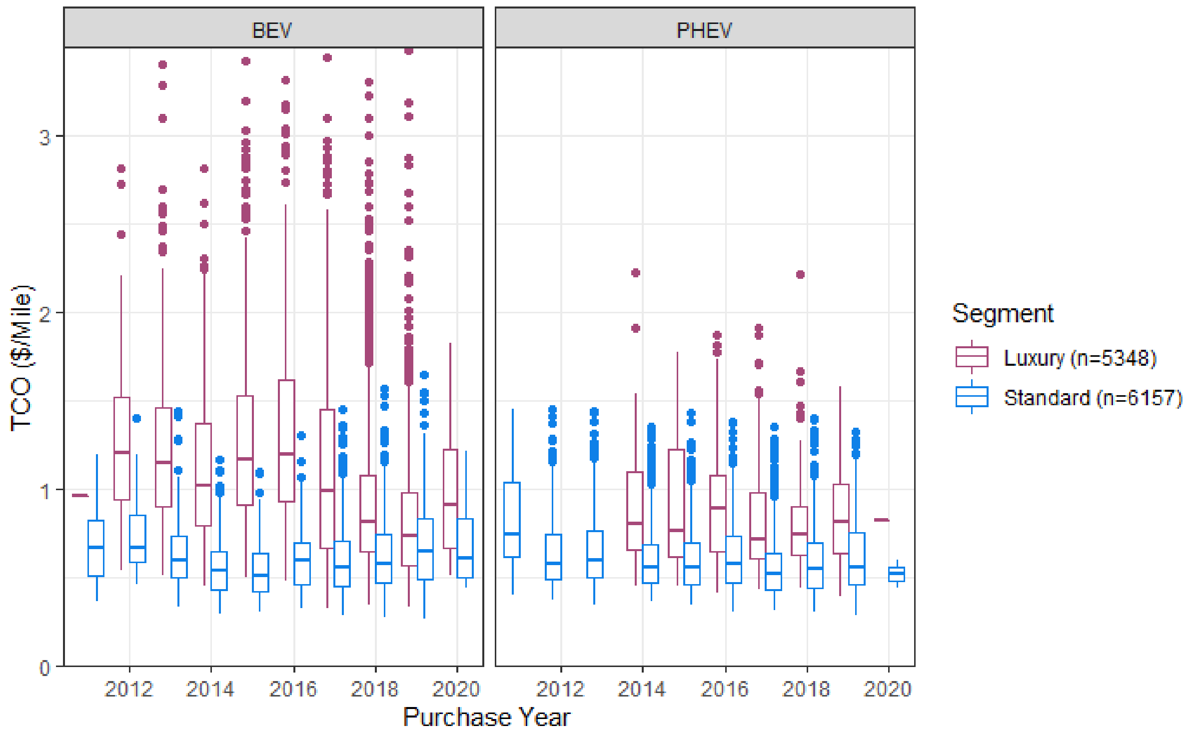

Figure 4.12. TCO by Vehicle Purchase Year, Powertrain Type, and Manufacturer Class

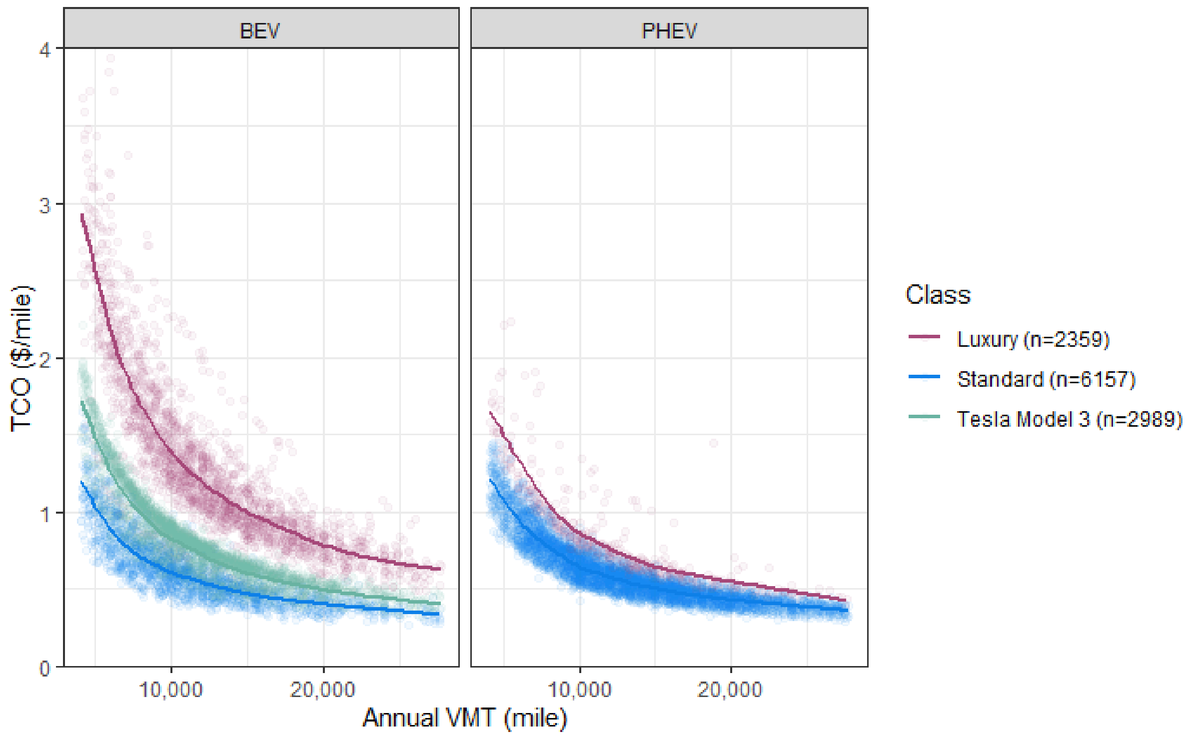

Figure 4.13. TCO versus Annual VMT by Powertrain Type

Looking at the relation between BEV TCO and income level, it is seen that an increase in income positively correlates with higher TCO, driven by higher capital costs, as seen in Figure 4.14 and Figure 4.15. The fuel efficiency of the purchased BEVs, in terms of miles per gallon equivalent (MPGe), decreases with the increase in income level (Figure 4.16). Despite that, the energy expenditure shows a negative trend with higher income (Figure 4.17). Tesla Model S and Model X were the most popular vehicles purchased by the highest income level, capturing 72% of the highest-income sample. These two models were eligible for unlimited free Tesla Supercharging (also called DC fast charging) during the analysis term. Despite the vehicles' worst energy efficiency, these vehicles' owners spent the least on energy. This special perquisite, which benefited mainly high socioeconomic households and is not offered these days, skews the results in favor of BEVs.

Figure 4.14. BEV TCO per Income Group

Figure 4.15. BEV capital costs per Income Group

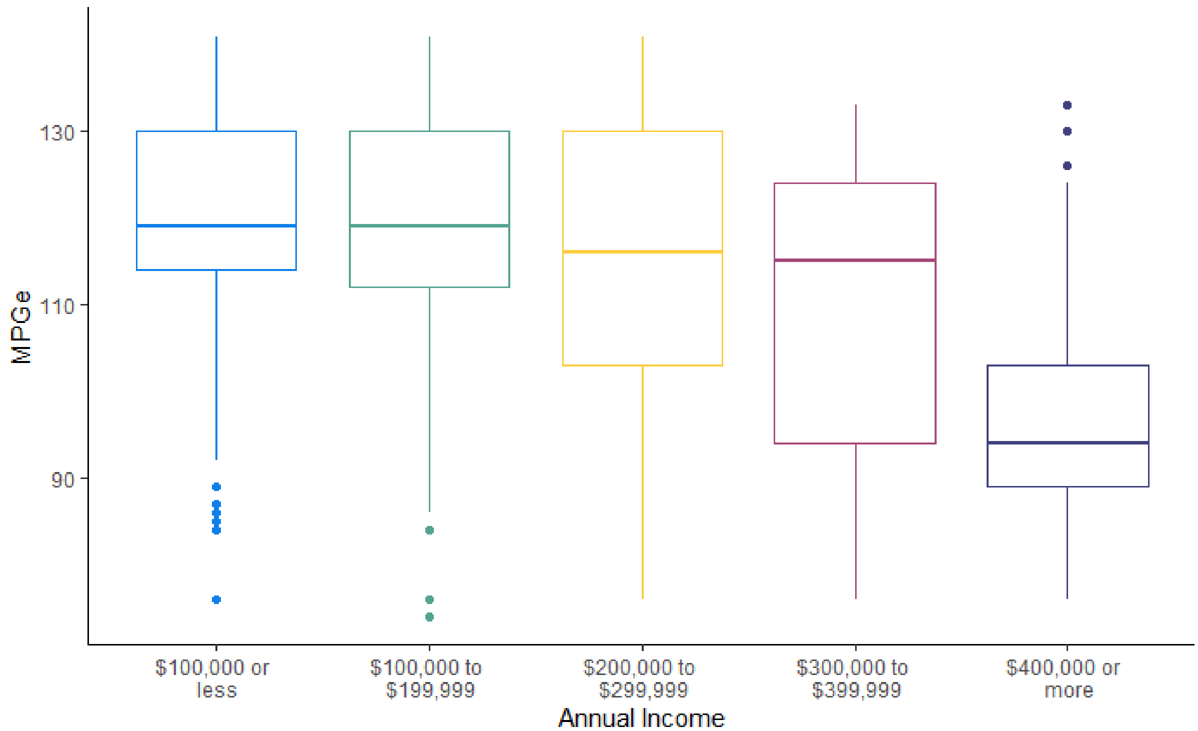

Figure 4.16. BEV Fuel Efficiency per Income Group

Figure 4.17. BEV Energy Expenditure per Income Group

4.3 TCO Comparisons

To understand whether California drivers monetarily enjoy their PEVs, the TCO comparison analysis results are presented against annual VMT, which ranges from 4,000 to 28,000 miles, the lowest and highest annual mileage calculated based on the survey odometer records. This analysis focused on the year 2018, which was the year with the highest response amount.

The comparisons were made within the near-luxury, mid-size, compact, and subcompact segments, as defined by the California New Car Dealers Association (*69*). For the chosen vehicles, if a PEV and non-PEV models were offered, they were compared (for example, Toyota Prius Prime PHEV and Toyota Prius HEV). If a non-PEV powertrain was not offered for a specific PEV model, a matching non-PEV model within the same segment from the same manufacturer was chosen (for example, Nissan LEAF and Nissan Sentra). If a manufacturer does not offer non-PEV models, the matching model was one of the top-selling models in California (*69*). For example, Tesla Model 3 and BMW 3-series.

The trim level for each model was carefully chosen. In the simple case, where the same trim was offered across multiple powertrain types, that same trim was selected. For example, the trim Platinum for Ford vehicles. For the Toyota Prius comparison, although the model was offered in multiple powertrains, the trim level naming was different. Looking at the specification sheet for the different trims, it was found the Premium PHEV trim was most similar to the Three HEV trim. In another case, for the comparison of Tesla with BMW, the middle trim was chosen. For Tesla Model 3, it was the Long Range trim. For BMW 3-Series, it was the 330i xDrive trim.

The comparison analysis includes the following vehicles for each segment:

- Near luxury
  - BEV: Tesla Model 3 Long Range (MSRP: $49,000)
  - ICEV: BMW 330i xDrive (MSRP: $43,450)

- Mid-size
  - PHEV: Ford Fusion Energi Platinum (MSRP: $41,400)
  - HEV: Ford Fusion Platinum (MSRP: $37,370)
  - ICEV: Ford Fusion Platinum (MSRP: $36,990)
- Compact (Nissan)
  - BEV: Nissan LEAF SV (MSRP: $32,490)
  - ICEV: Nissan Sentra SV (MSRP: $19,085)
- Compact (Toyota)
  - PHEV: Toyota Prius Prime Premium (MSRP: $29,000)
  - HEV: Toyota Prius Three (MSRP: $26,735)
- Compact (Chevrolet)
  - PHEV: Chevrolet Volt LT (MSRP: $33,220)
  - ICEV: Chevrolet Cruze LT (MSRP: $21,720)
- Subcompact
  - BEV: Chevrolet Bolt LT (MSRP: $36,620)
  - ICEV: Chevrolet Spark 2LT (MSRP: $17,475)

Figure 4.18 to Figure 4.23 reveal that the higher the segment was (and the more expensive the vehicle was), the lower annual VMT was required to achieve a comparative TCO with a non-PEV vehicle. That has an important equity implication, where **households who could afford higher segment vehicles, were the ones who were most likely to profit by choosing a PEV over an ICEV** or HEV while incentives were offered without restrictions. Furthermore, within the given analysis term, **the lower the segment is, the more important incentives were for achieving TCO parity**.

Tesla Model 3 Long Range, a near-luxury model, the most popular vehicle in the survey, owned by 14% of the respondents, achieved TCO equivalency with the BMW 330i xDrive after 10,100 annual miles only, as seen from Figure 4.18. According to the survey, 62% of the respondents drove more than 10,100 miles a year with their Tesla Model 3 Long Range. If the federal income tax credit and the state incentive were not given in 2018, a comparable TCO was achieved when driving more than 26,000 miles annually.

For the mid-size segment, Figure 4.19shows that the Ford Fusion Energi Platinum PHEV reaches a TCO comparison with Ford Fusion Platinum ICEV just under 16,000 annual miles with incentives, and a little above 20,000 miles if incentives were not offered. A TCO equivalency, within the VMT range, was not reached between the HEV and PHEV models of the Fusion.

The compact segment had several popular vehicles, and Figure 4.20 shows the TCO comparison for Nissan. For the SV trim, Nissan LEAF SV BEV reaches a comparable TCO with Nissan Sentra SV ICEV after 14,600 miles with incentives. This comparable pair had the second-highest difference in MSRP, as the LEAF costs $13,405 more that the Sentra. Yet, the VMT equality point was equivalent to a daily commute of 36.5 miles only, assuming the accepted 200 workdays a year with no other driving performed in that vehicle. In the survey, 28% of the LEAF SV owners profited by choosing to purchase this model over a similar ICEV.

For Toyota and Chevrolet PHEVs, although high annual milage was required to achieve TCO parity, 10% of their owners financially benefited by owning a PHEV, as seen in Figure 4.21 and Figure 4.22, correspondingly. Toyota comparison includes the Prius Prime Premium PHEV and Prius Three HEV. Using the combustion driving mode, these models had a similar fuel efficiency. With an MSRP difference of only $2,265, the two models achieve TCO parity after 21,000 annual miles with incentives. Despite a much higher MSRP difference of $11,500 for the Chevrolet models, Volt LT PHEV and Cruze LT ICEV, achieved TCO parity at a similar milage of 22,000 miles, due to the lower fuel efficiency of the Cruze compared with the Volt.

The subcompact segment presents the highest difference in MSRP, a difference of $19,145, for the models Chevrolet Bolt LT BEV and Chevrolet Spark 2LT ICEV, as shown in Figure 4.23. As a result, TCO comparison was achieved only if driving over 27,000 miles per year.

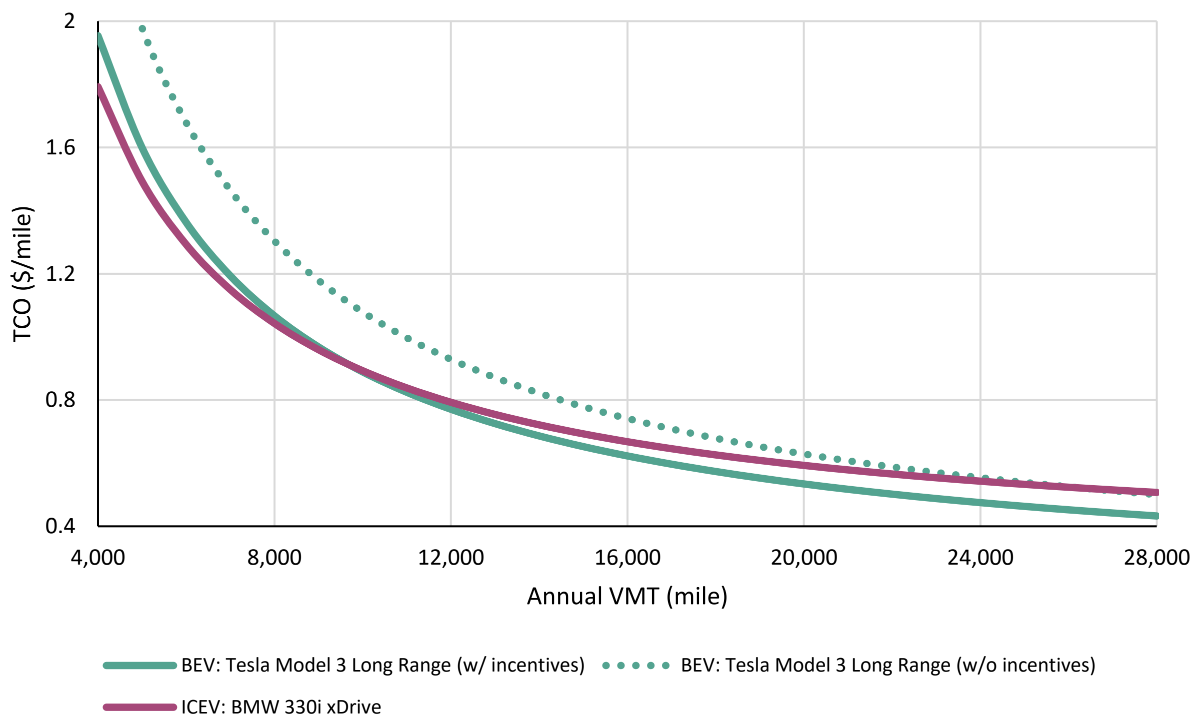

Figure 4.18. TCO Comparison for Near-Luxury Segment in 2018

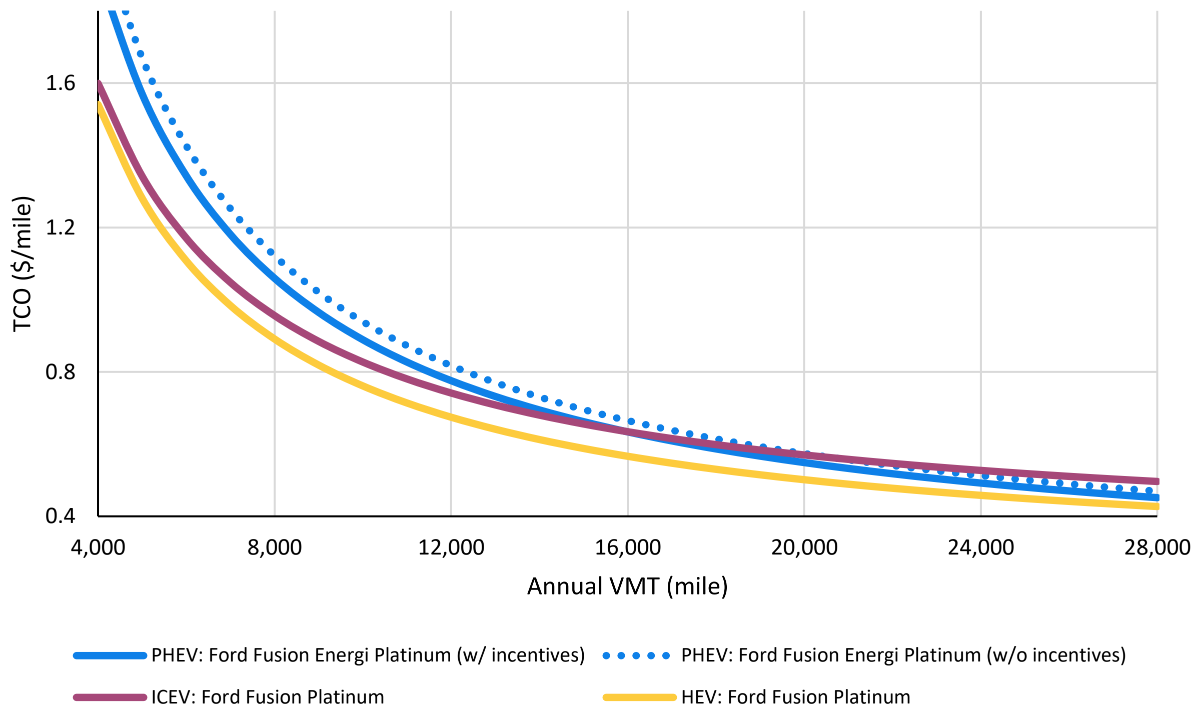

Figure 4.19. TCO Comparison for Mid-Size segment in 2018

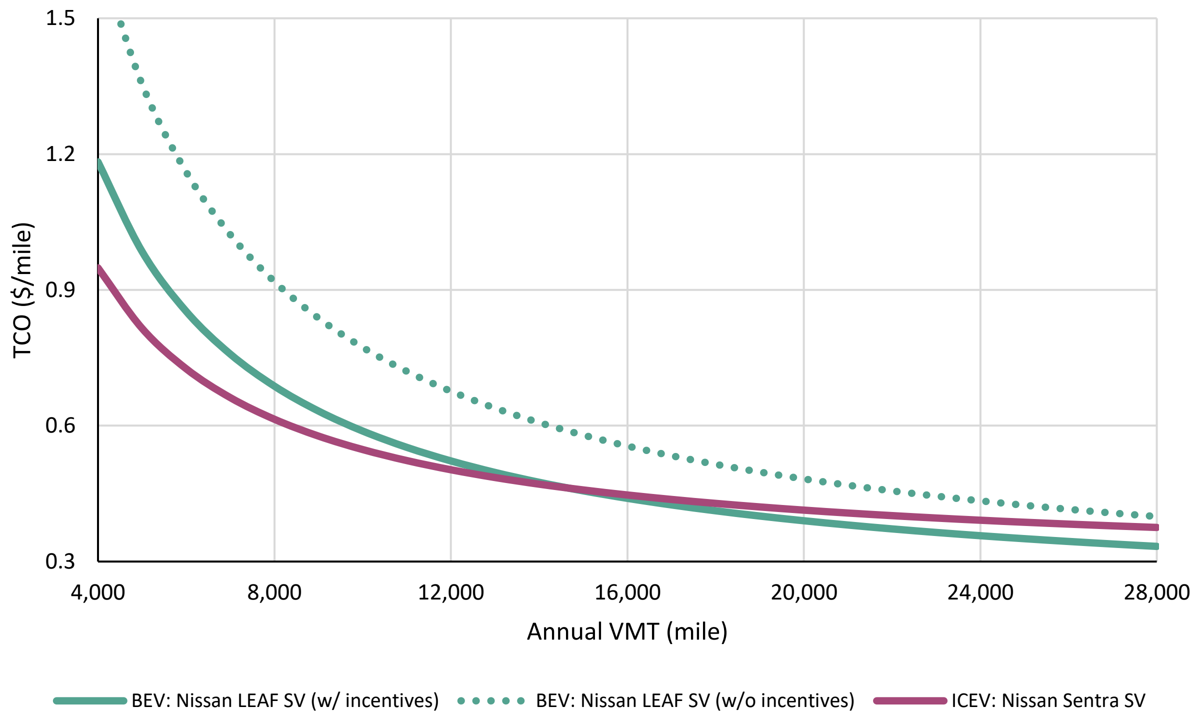

Figure 4.20. TCO Comparison for Nissan Compact Segment in 2018

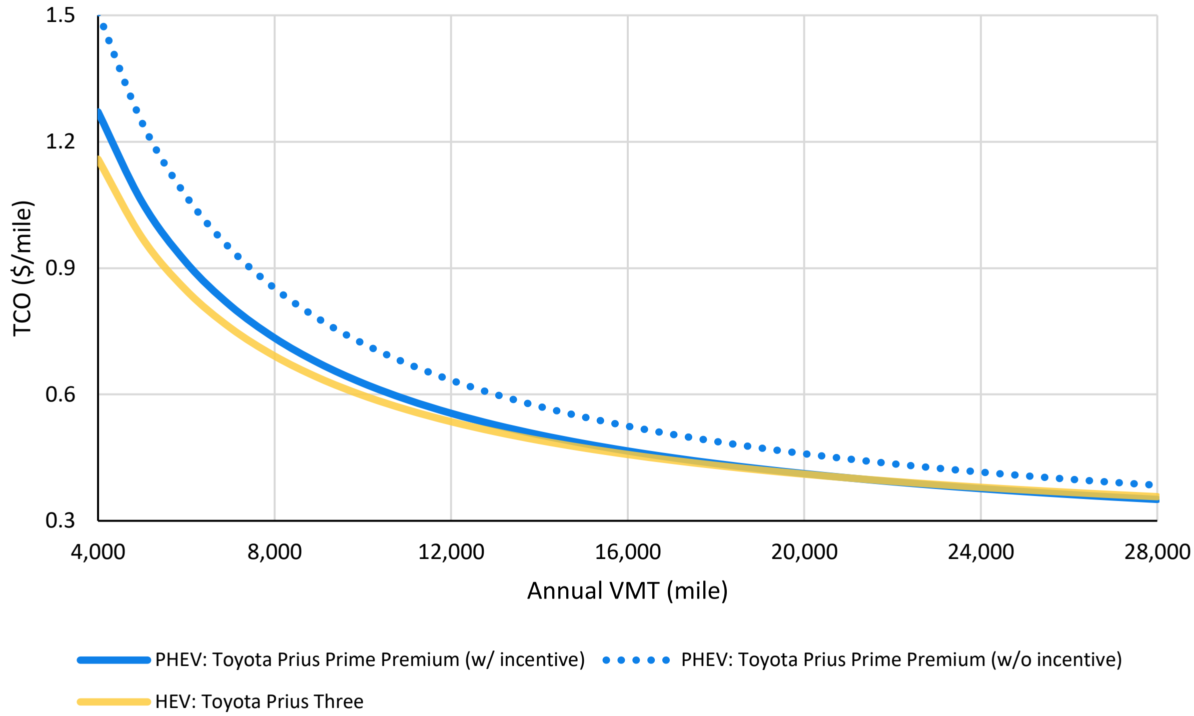

Figure 4.21. TCO Comparison for Toyota Compact Segment in 2018

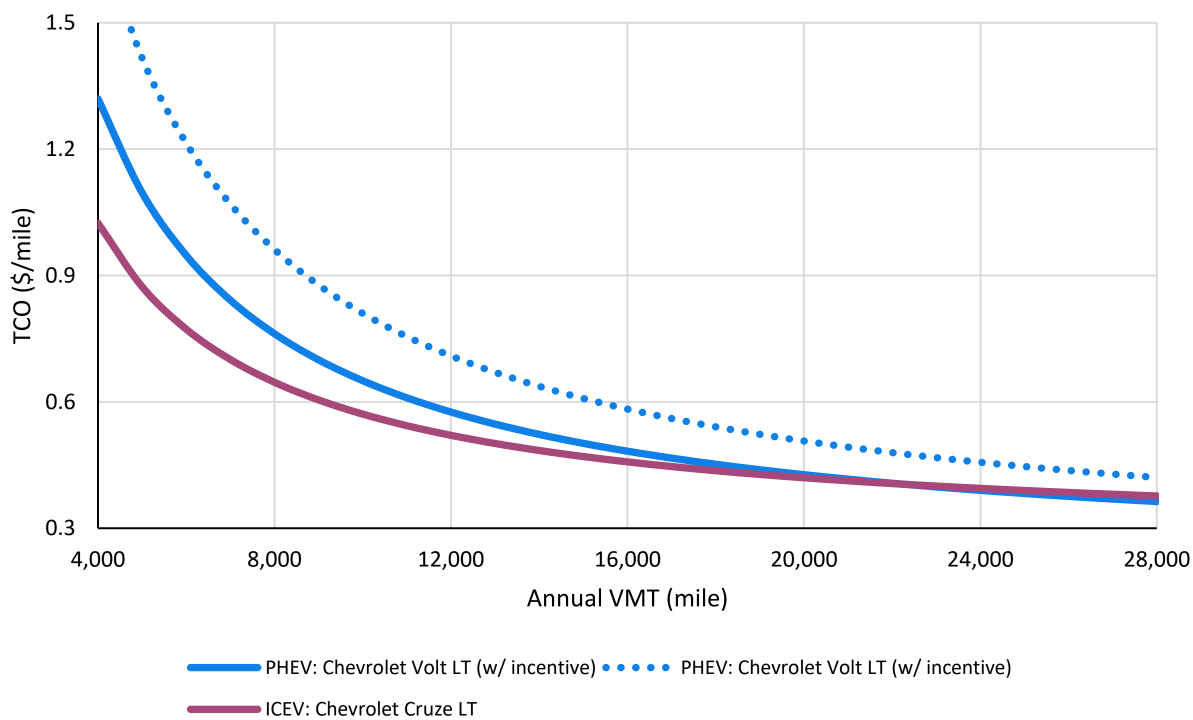

Figure 4.22, TCO Comparison for Chevrolet Compact Segment in 2018

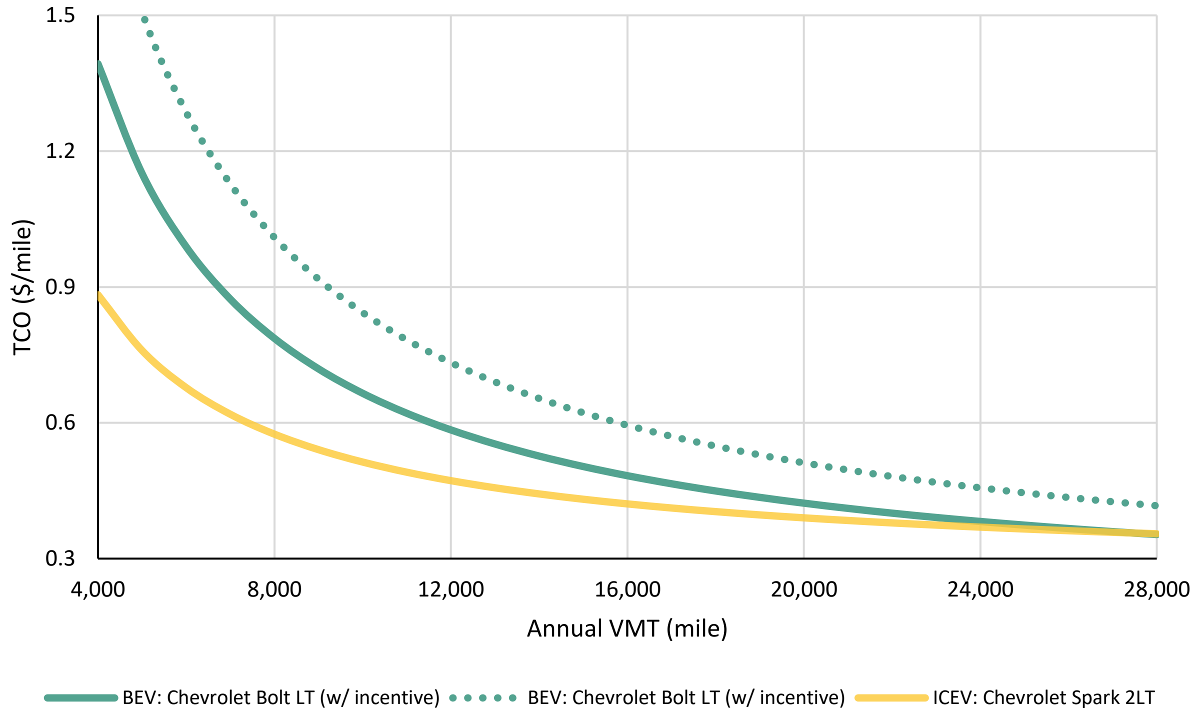

Figure 4.23. TCO Comparison for Subcompact Segment in 2018

The last remaining question to be covered is the characterization of the Californian drivers who were financially advantaged or disadvantaged by their choice to purchase a new PEV over a new non-PEV. While the most popular model in the sample in 2018 was the Tesla Model 3 Long Range, which was owned by 1,647 respondents, the second most popular vehicle (besides the Standard trim of Model 3) was Chevrolet Volt LT, with 146 owners only. Other models chosen for the comparative analysis were owned by 30, or fewer, survey participants, which can lead to low sampling errors. Therefore, this section focuses on the two most popular models in the survey, Tesla Model 3 Long Range BEV and Chevrolet Volt LT PHEV. Focusing on only two vehicle models created anecdotal conclusions that were not suitable for broad policy recommendations or trend identifications. However, with the novelty of the survey data and the analysis performed on it, these snapshot conclusions should be introduced in the TCO literature.

The Tesla Model 3 Long Range BEV owners who financially benefited from purchasing a new BEV, were characterized similarly to the owners who did not benefit from this purchase, as measured by TCO per driven mile. Both groups were mostly homeowners (a little over 80%) and lived in single-family houses. The income distribution was also similar between the groups. A little over half of each group had only two vehicles in their household. Overall, 62% of Tesla Model 3 owners reached parity with the equivalent ICEV.

The Chevrolet owners showed a slight difference between the drivers who experienced a monetary advantage (10% of the sample, or 15 owners) to the ones who did not (90% of the sample, or 131 owners). Of the financially advantaged group, 20% were renters, compared with 10% of the financially disadvantaged group. As the rental market is dominated by apartment rentals, there were more Volt owners who gained positive TCO and lived in apartments compared to Volt owners who had negative TCO. While the share of dual vehicle households was similar between the two financial beneficence status groups, the share of households with three or four vehicles was higher for benefited Volt owners compared with the ones who did not, which implies that, despite the vehicle household inventory, the Volt was driven far enough (over 22,000 miles a year) to be an economical choice.

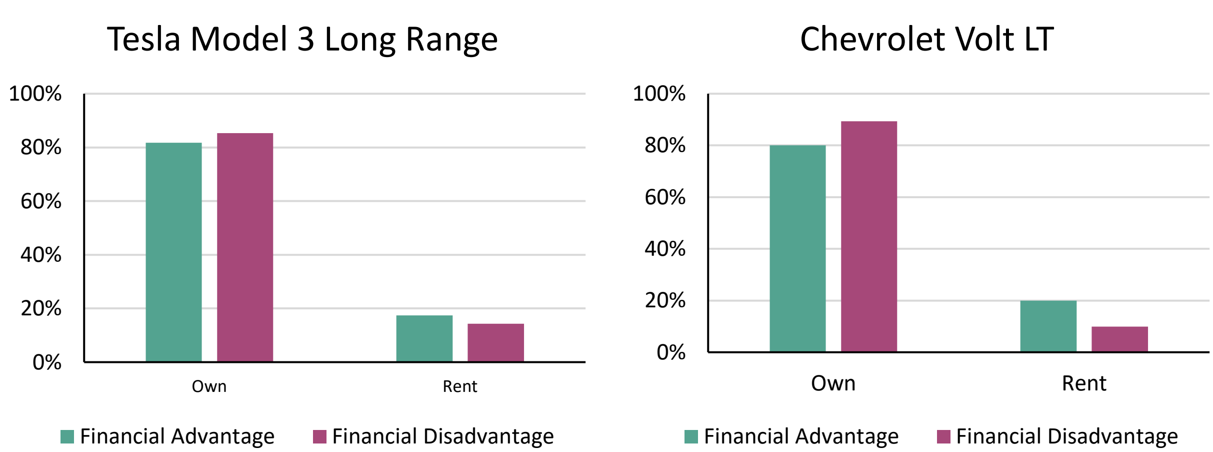

Figure 4.24. Homeownership Status per TCO Beneficence Status for Two 2018 Vehicle Models

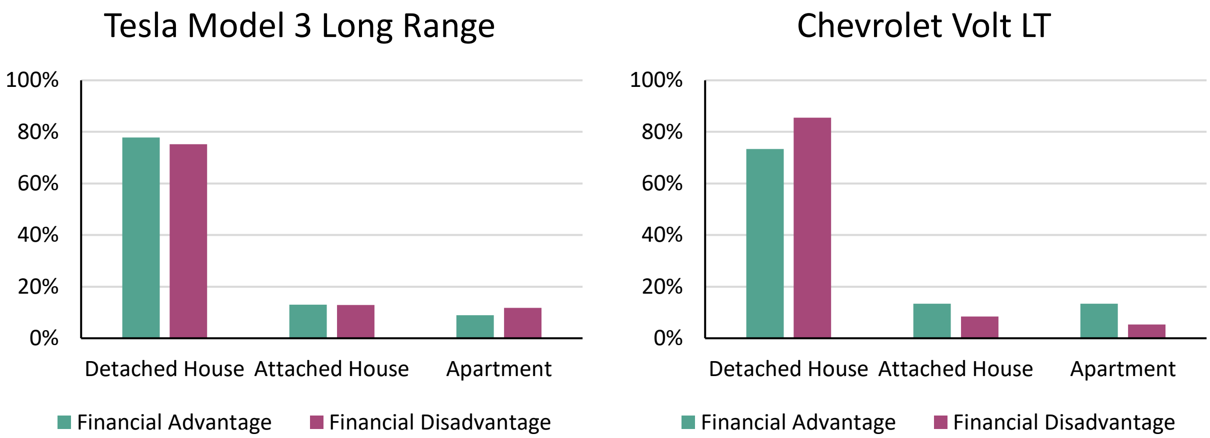

Figure 4.25. House Type per TCO Beneficence Status for Two 2018 Vehicle Models

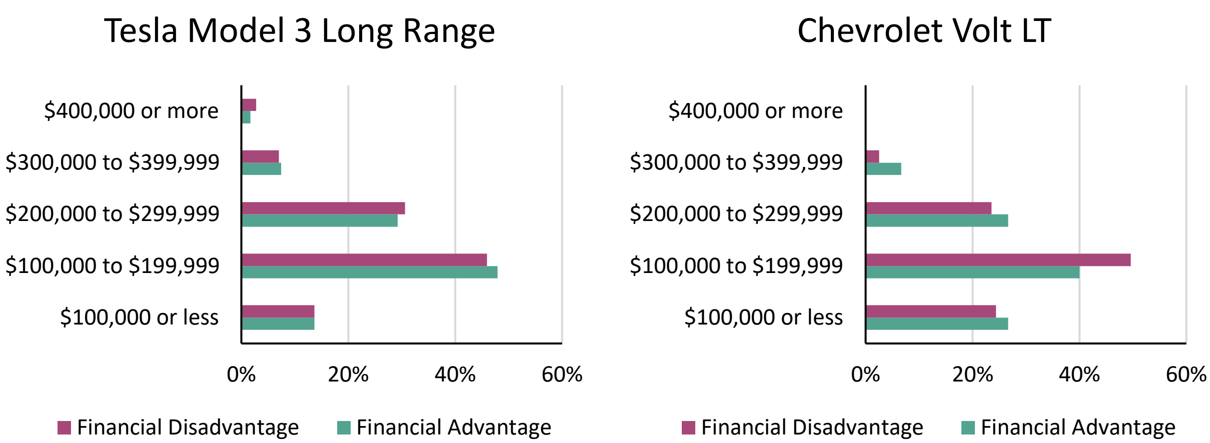

Figure 4.26. Income Level per TCO Beneficence Status for Two 2018 Vehicle Models

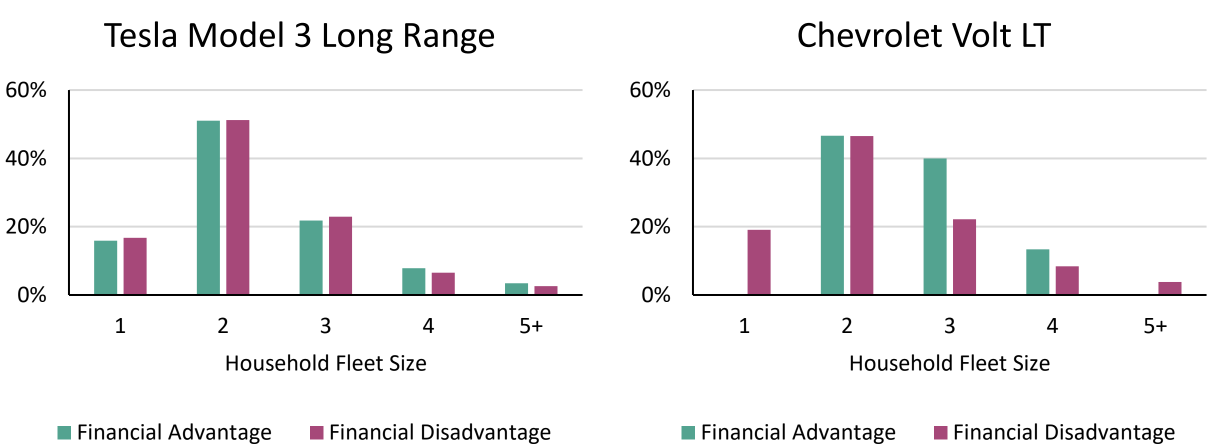

Figure 4.27. Fleet Size per TCO Beneficence Status for Two 2018 Vehicle Models

5 Discussion and Conclusions

This study seeks to estimate the ownership cost of real PEV owners in California using the PH&EV PEV owners survey. The surveyed owners purchased their vehicle between the years 2011 and 2020, hence, are considered early adopters of the new powertrain technologies. Assuming an ownership length of five years, the TCO estimation includes capital and operation costs and resale value. The capital costs are MSRP, tax, federal and state incentives, and purchase and installation of an EVSE. Energy expenses, annual registration fees, and maintenance are included in the operation costs.

The ability to estimate TCO for real drivers and aggregate the results based on sociodemographic characteristics differentiates this study from the existing literature, which uses a typical driver with an average driving behavior that had country-level average expenses.

The results show that TCO ranged from $0.26/mile to $4.83/mile, and was depending on the selected vehicle model and trim, driving behavior, and residency location. The TCO comparisons completed in this study were between different drivetrain technologies represented by different vehicle models purchased in 2018. A corresponding ownership cost for a BEV and an ICEV in the mid-luxury segment was reached for drivers who drove 10,100 miles a year and received the federal income tax credit. Similarly, for the compact segment, a BEV needed to be driven over 14,600 miles annually to financially benefit from this purchase. Sociodemographic comparisons between Tesla Model 3 Long Range owners who were financially advantaged by their vehicle purchasing choice with the disadvantaged owners showed that both groups were similarly distributed among income levels, the number of cars in their household, housing type, and housing ownership status.

Overall, before the pandemic disrupted the economy and drastically affected vehicle purchase pricing, and while federal and state incentives were fully offered, there were PEV owners who financially made a sensible vehicle purchase decision in 2018. Based on the TCO estimations presented in this paper, 62%

of Tesla Model 3 Long Range owners and 28% of Nissan LEAF SV owners reached a cost parity. Without governmental subsidy, studies predicted a cost parity only after 2024 or even 2030 for the average driver (*22*, *70*). The role of PEV incentives is strongly echoed by this strike difference in parity finding of 6 to 12 years at least. Moreover, per this study's results, cost parity was not reached for most selected models with the lack of incentives.

With more than two and a half million PEVs sold in the USA since 2010 (*71*), the PEV market enters the mainstream crowd. While three OEMs phased out from the federal income tax credit program and CVRP set an income cap, the 2020-2021 global chip shortage drove auto prices up, increasing the purchase price of the anyway expensive PEVs. In parallel, to ensure the implementation of the 2020 California executive order to phase out new combustion engine vehicle sales by 2035, CARB proposed an update for the ZEV mandate, named Advanced Clean Cars II Regulations, to comprise new vehicles from 2026 to 2035. Aside from the regime processes, gas prices experienced a sharp increase of about 50% in the past year, which can demonstrate Bushnell et al. results, who found that an increase in gasoline prices had a greater effect on the decision to purchase a BEV compared with an increase in electricity prices (*72*). As a result, the mainstream market will soon be forced to purchase expensive vehicles, if a new car is desired or needed. The described invadable developments, combined with these research results, pose affordability and equity concerns and raise the question regarding the adequate policy steps federal and state governments should do to assure the sale decreasing of polluting vehicle technologies to combat GHG emissions.

According to the results, among the compared segments, the mid-luxury segment reached parity with the lowest annual driven miles. Purchasing a mid-luxury vehicle is associated with a lifestyle choice rather than a mobility need. Hence, future incentive programs should be structured such that these programs will support the purchase of a BEV rather than the purchase of a mid-luxury vehicle by the mass market, to drive equity. This finding reinforces the CVRP MSRP cap of eligible LDV models. While

Tesla models are not eligible for the federal income tax credit since 2020, the purchasers of boutique OEM models, such as Lucid and Karma, are still eligible for the federal subsidy. With the evolving PEV market, there might be a need to reconsider the federal incentive for such vehicles. New PEV incentive policies should accommodate vehicle TCO which is dependent on the brand and the trim to reach greater adoption across different market segments.

Yet, early adopters, whether they purchased a luxury or a standard model, established the essential PEV second-hand market. This market opens up purchasing opportunities for driver segments who are interested or are capable of acquiring a vehicle under a stricter budget. During the analysis term (2011 – 2020), incentivizing all PEV models without MSRP caps was crucial to reaching the current PEV market state. The incentives received by the original owners are embodied in the used PEV prices, which drive these prices down and pass through the benefits to the next owner.

Despite using data from real vehicle owners, many assumptions were required to estimate their TCO, such as the ownership length and UF for PHEVs. Thus, the TCO estimated in this study represents true costs on an average. After cleaning the dataset, it was found that about a quarter of the respondents did not provide their odometer reading, and were removed from the analysis, which caused a significant loss of information. This contributed to the inability to draw conclusions related to specific vehicles since most models had a small sample size per vehicle trim and purchasing year. However, the analysis done in this study can be used to further characterize market segments over time, rather than investigating specific models or vehicle segments as done in this study. Future research can include clustering work of sociodemographic attributes to discover which market segments financially benefit (or not) by their choice to purchase a new PEV and by how much. The survey also asked the participants whether or not their new PEV replaced an older existing vehicle, and which vehicle model was that. This information can be helpful to estimate the change in TCO with the purchase of a PEV and bring novel insight to the "willingness to pay" literature (in the field of PEVs), which currently focuses on stated preferences and lacks revealed preferences.

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