ELECTRIC POWER RESEARCH INSTITUTE

Total Cost of Ownership Model for Current Plug-in Electric Vehicles

2013 TECHNICAL REPORT

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Abstract

The plug-in electric vehicle (PEV) market has grown dramatically in the past three years, but the central question concerning PEV acceptance in the marketplace still remains: When compared to a hybrid or conventional vehicle, is a PEV worth the additional up-front cost to consumers? Given the incomplete understanding of changes in driving patterns due to vehicle purchases, the baseline analysis described in this report does not model customer adaptation, nor does it attempt to address non-tangible PEV ownership benefits. However, this analysis *does* use data that is new to EPRI transportation modeling in order to estimate the range of values for customers with different driving patterns. The baseline analysis relies on a cost-of-ownership model that examines only current vehicles, current fuel prices, and a relatively conservative set of customer values. In particular, two PEVs, the Chevrolet Volt and Nissan LEAF, are analyzed in comparison with a limited set of current conventional and hybrid vehicles. Following are key results of the analysis:

- With current incentives and prices, financial factors should not be a deterrent to a PEV purchase for most buyers.
- The LEAF is less expensive than competing options on average, but has a wide variation in value for different drivers, suggesting that battery electric vehicles will require more careful consideration when making a purchase decision.
- The sensitivities suggest that increases and decreases in gasoline prices will have a significant impact on the relative costs of PEVs, but that state incentives or rebates and equivalent vehicle price changes will have an even larger impact on cost tradeoffs.

Keywords

Plug-In Electric Vehicle (PEV)
PEV Market
Chevrolet Volt
Nissan LEAF
Electric Transportation Modeling
Cost-of-Ownership Model
PEV Customer Acceptance
PEV Charging

Executive Summary

The mainstream market for plug-in electric vehicles (PEVs) has quickly grown from initial market introduction of two models in late 2010 to widespread availability of a variety of vehicles today. Given the cost premium associated with PEVs, there is considerable uncertainty about how sales will evolve over time. This EPRI report attempts to address one of the key questions surrounding the acceptance of PEVs in the marketplace: When compared to a hybrid or conventional vehicle, is a PEV worth the additional up-front cost to consumers?

This question is difficult to answer due to significant differences between PEVs and conventional vehicles that affect how they will be perceived and used by customers. PEVs are typically plugged in at home and charged overnight instead of being refueled at a gas station, so they are typically more convenient than conventional cars for short range driving. However, they can be relatively inconvenient for long-range driving, depending on the vehicle design. An investigation of conventional tools and methods for evaluating customer valuation of vehicle technologies showed that existing tools were inadequate for analyzing the differences between conventional vehicles and PEVs. This report describes the development of and initial results from a cost-of-ownership model created to analyze the impact of these differences.

Modeling Customer Diversity

The biggest limitation of current tools and methods for analyzing vehicle value is that they do not explicitly model driver diversity or driver adaptation to vehicle differences. While it is clear that different drivers have different driving needs and different personal situations that could significantly affect their personal valuation of a given vehicle, limited data is available to inform analyses of these differences. These differences are particularly important when considering PEVs since the availability of home charging may be a critical barrier to a vehicle purchase, and unique personal driving patterns may make a PEV a favorable or unfavorable choice. Understanding these differences is important because customers are likely to self-select PEVs based on their own perception of the suitability or unsuitability of a vehicle for their own needs. “Forcing” a vehicle onto a customer as part of a modeling exercise would likely overstate the costs of a PEV purchase while understating the benefits.

In addition to differences between drivers, the purchase of a vehicle may significantly change a driver's vehicle usage. This adaptation will likely happen in general—for example, purchase of an off-road vehicle may open up new travel opportunities. Adaptation to the characteristics of a PEV is particularly important because a PEV is most useful within the limits of its electric driving range. Preliminary studies of early PEV purchasers suggest that adaptation to the unique characteristics of these vehicles frequently occurs and is often seen as a benefit rather than a limitation. However, more study is needed to understand how adaptation will occur as PEVs expand into the mass market.

Given the incomplete understanding of changes in driving patterns due to vehicle purchases, this analysis does not model customer adaptation. However, this analysis *does* use data that is new to EPRI transportation modeling in order to estimate the range of values for customers with different driving patterns. These data are preliminary but already provide important insights about this value variation. Such insights strongly suggest that traditional vehicle valuation and market adoption tools will not be adequate for modeling PEV adoption.

Vehicle Comparison Scope

One key difficulty in understanding the fleet market impact of PEVs is that there is considerable uncertainty about how PEV characteristics and usage will change over time. In order to reduce this uncertainty, this analysis is restricted to examining only current vehicles, current fuel prices, and a relatively conservative set of customer values. In particular, two current PEVs, the Chevrolet Volt and Nissan LEAF, are analyzed in comparison with a limited set of current conventional and hybrid vehicles. No financial value is estimated for less tangible PEV benefits such as commuter lane access, home recharging convenience, and a smoother more pleasant driving experience—all of which previous EPRI analysis has found to be important to potential vehicle buyers but difficult to value.

The baseline scenario assumes that only home charging is available. Other scenarios with increased charging availability are discussed, but these results are not used for the primary value comparisons. This assumption reflects the fact that although some customers already have workplace charging and some areas already have reasonable public charging availability, most current customers will not have these benefits for some time.

This limited scope does not capture the significant current optimism about future improvements in vehicles or charging availability, but it does provide a snapshot of the present situation and identifies focus areas for future data acquisition and model development.

Key Results of the Analysis

- **With current incentives and prices, financial factors should not be a deterrent to a PEV purchase for most buyers.** In terms of both total lifetime costs and monthly outlay, PEVs are typically within +/- 10% of comparable hybrid or conventional vehicle options. Because increased capital costs are well balanced by operating cost savings, the decision to purchase a PEV can usually be made based on personal values rather than financial limitations, assuming that the purchase of any vehicle is within a customer's financial capabilities. However, the analysis revealed that some drivers have driving patterns that are poorly matched to the characteristics of a given PEV and would experience a negative impact from a PEV purchase.
- **The LEAF is less expensive than competing options on average, but has a wide variation in value for different drivers, suggesting that battery electric vehicles will require more careful consideration when making a purchase decision.** In the worst case, the Volt can be operated in hybrid mode with roughly the same range and usage characteristics as other hybrid vehicles, so the risk of a significant negative impact is relatively low. Because the LEAF is a battery electric vehicle, it has a fixed range limitation that may result in significant cost or inconvenience for some customers given current charging availability. However, the relatively low capital costs for the LEAF and very low operating costs mean that well-matched drivers can incur substantially lower costs with the LEAF than other available options. These variations indicate that tools to help inform customers of potential savings will be particularly important for battery electric vehicles. Additionally there appears to be significant potential for customers to affect their ownership costs through adaptation.
- **The sensitivities suggest that increases and decreases in gasoline prices will have a significant impact on the relative costs of PEVs, but that state incentives or rebates and equivalent vehicle price changes will have an even larger impact on cost tradeoffs.** The analysis indicates that capital costs and operating costs are reasonably well balanced at the current time for most vehicle comparisons. Changes in the price of gasoline will affect this balance and will cause significant changes in payback time, but will result in relatively small changes in total ownership costs or monthly expenditure. Favorable state incentives or equivalent changes in capital costs for vehicles will have a larger impact than fuel prices, significantly improving payback time, total ownership cost, and monthly expenditure.

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Section 1: Introduction

This report discusses the current state of lifecycle costs for a selection of plug-in electric vehicles (PEVs) available at the present time. These relative costs are interesting to analyze since PEVs typically have higher up-front costs than comparable conventional vehicles (CVs) but have lower operating expenses. Understanding the tradeoff as it exists today and analyzing the primary factors in this tradeoff will help in understanding the long-term prospects for widespread PEV adoption.

This analysis differs from other recent cost analyses in some important ways:

- **Feature-matched conventional comparison vehicles.** The comparison vehicles chosen for the tradeoff analysis are not necessarily the closest conventional vehicle option, since current PEVs differ in important ways from conventional vehicles which are superficially similar.
- **Realistic driving patterns**. The cost and value of a PEV can vary significantly depending on how an individual driver's mileage changes from day to day. This analysis uses driving patterns measured over a full year in order to more closely approximate the usage patterns of real drivers.
- **Varied purchase options.** Most cost analyses focus on the tradeoff between up-front capital cost and operating costs over time, which approximates the case of a cash purchase of a new vehicle. Although this is an important purchase option this paper also investigates costs for auto loans since financing is much more common [1].
- **Financial discount rate.** In order to compare present costs to future benefits, a discount rate is typically used in economic analyses to recognize that a dollar in the present is typically more valuable than a dollar in the future. There are many factors that can affect the discount rate, including risk margins and perceived customer preference, but in this analysis discounting is performed on a financial basis only.

Table 1-1 shows a comparison between this cost analysis and other PEV cost analyses.

Table 1-1
Comparison of Study Scope and Assumptions[1]

		Simpson, 2006	Lemoine et al,. 2008	AEO, 2009	EPRI, 2004	Al-Alawi & Bradley, 2012	NY Times, 2012	FuelEconomy.gov, 2012	EPRI, 2012
Study Scope	**Vehicle Class**	Midsize sedan	Compact Car, Full-size SUV	Low drag, midsize	Midsize Car, Full-size	Compact Car, Midsize	2012 MY Vehicles	2012 Hybrid Models	2012 MY Vehicles
	Comparison Vehicles	$ 28,773			$20,500-23,000		2012 MY Vehicles		Average HEV,
	Basis of Comparison Vehicles						Chassis		Comparable class,
	PHEV Type	HEV, PHEV2-60	HEV, PHEV20	HEV, PHEV5-60	EV, HEV, PHEV20	HEV, PHEV5-60	2012 MY Vehicles	2012 MY Vehicles (HEV	2012 MY Vehicles
	Battery Type	Li-Ion	NiMH	Li-ION	NiMH	Li-Ion	Li-Ion, NiMH (depending	Li-Ion, NiMH (depending on	Li-Ion, NiMH (depending
	Economic Year	2006$	2008$	2007$	2003$	2010$	?	?	2012
Vehicle Usage Assumptions	**Vehicle Miles Traveled (VMT) Model**	15,000 mi*year-1, constant	11,000 mi*year-1, constant	14,000 mi*year-1, constant	117,000, 150,000 mi lifetime	12,000 mi year-1 for Cars, 15,000 mi year-1 for light trucks	15,000	Varies	Varies, 150,000 lifetime
	Vehicle Life	15 years	12 years	6 years	10 years	5 years, 13 years	?	?	150,000 miles
	Charging Assumption	Full recharge each day	Full recharge each day	Full recharge each day	Full recharge each day	Full recharge each day	?	?	home and workplace
	Utility Factor (UF) type	1995 NPTS-derived UF,	250 days year-1 fueled by	None, 37% of VMT	26% of VMT assumed	SAE J2841 UF	?	?	NREL Puget Sound
	Fuel Economy Method	Modified J1711, EPRI	MWP Weighted,	105 mpg CD, 42 mpg CS	UF weighted	UF weighted gasoline	TrueCar.com	EPA-rated	UF weighted gasoline
	Electricity Consumption	0.093 kWh/mile for	?	37% of VMT	26% of VMT assumed	UF weighted electricity	TrueCar.com	EPA-rated	UF weighted electricity
	EPA Adjustment of Fuel Economy	Yes	None	None	Yes	Yes	?	Yes	Yes
Modeled Components of Ownership Costs	**Gasoline Cost Model**	$5.00 gallon	$2.00 gallon, $3.00 gallon,	$3.00 gallon, $4.00 gallon,	$1.75 gallon	Forecasted over vehicle	$3.85 gallon	Varies	$4.00 gallon
	Electricity Cost Model	$0.09kWh	$0.05 kWh, $0.10 kWh,	$0.10 kWh	$0.05kWh	Forecasted over vehicle	?	Varies	$0.12 kWh
	Incremental Cost Model	EPRI, 2001	EPRI, 2001 corrected	Includeds tax credit	EPRI, 2001; ANL	EPRI, 2001; Kalhammer	N/A	N/A	N/A
	Vehicle Salvage Value Model	None	None	None	Battery only	Entire vehicle has resale	None	None	None
	Maintenance Cost Model	None	None	None	Yes	Yes	None	None	Yes
	Insurance Cost Model	None	None	None	None	Yes	None	None	None
	Registration Renewal Cost	None	None	None	None	Yes	None	None	None
	Loan Model	None	None	None	None	Yes	None	None	Yes
	Tax Model	None	None	None	None	Yes	None	None	Yes
	Discount Rate	None	16%, corrects for vehicle	10%	8%	6%	None	None	5% for first 5 years, 8%
Consumer Preference Model	**Lease**	None	None	None	None	None	None	None	Yes
	Metric of preference	Payback Period-based	Payback Period-based	Benefits-based	Benefits-based	Payback Analysis,	Payback Period-based	Payback Period-based	Lifetime Total Cost of
	Purchase	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
	Real Vehicle Data Used	None	None	None	None	None	None	None	Yes

The results generally indicate that PEVs are competitive at current costs with subsidies for many customers. These subsidies are expected to decrease over time, but it is also expected that PEV components will become less expensive and more efficient in the coming years as production quantities are increased and learning and standardization occurs. For example, battery packs are the most expensive part of current PEVs, and current EPRI research indicates that battery costs can

[1] This chart is modeled after work completed by Al-Alawi & Bradley [2].

decrease significantly as production quantities increase [3, 4]. As these changes occur, the cost comparisons described in this paper will change. This paper should be seen as a snapshot of a continually evolving analysis.

Diversity of Customer Needs and Circumstances

In analyzing the cost tradeoff for current PEVs it is important to understand not only the average cost differences between vehicle types but also the variation in cost for different consumers. The variation in value of PEVs for different consumers can be quite high, especially at this early stage of market introduction when charging is not generally available or may be expensive to supply at home. Another important source of cost variation is the differences in driving patterns between individual drivers.

The total cost of ownership of a PEV can vary substantially between two drivers based on driving pattern consistency, even when their average amount of driving is the same. For example, Figure 1-1 shows the sorted daily driving distances for each vehicle in the dataset used in this report (described in detail below), with two usage traces highlighted. Both of these vehicles were driven about 10,000 miles per year, but their different travel patterns cause them to have different values for a plug-in hybrid electric vehicle with 40 miles of electric range (PHEV40). For the vehicle represented by the black curve, 83% of driving days are less than 40 miles, and 77% of total miles traveled were in the first 40 miles of daily driving. With this travel pattern, a PHEV40 can operate most of the time on electricity. For the vehicle represented by the red curve, only 53% of driving days are less than 40 miles. The large number of long driving days for the red car means that only 50% of driving would be on electricity. The difference between these driving patterns will have a significant impact on the value experienced by these vehicle owners.

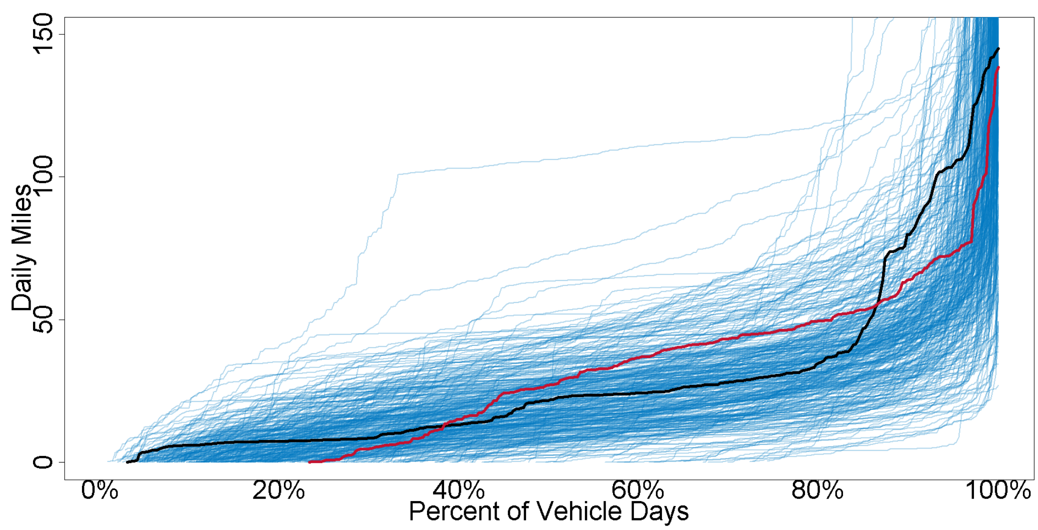

Figure 1-1
Driving Traces in Study Dataset

In order to handle this variation in driving patterns, the analysis in this report was performed in an unconventional way. Instead of using the vehicle driving data to calculate averages which were then used to calculate costs, the cost was separately calculated for each vehicle and scenario, and the resulting costs from each case were then averaged. For simple cases, the result of averaging scenario-based costs was the same as the result of averaging vehicle driving data directly. However, for complex cases averaging scenario-based costs leads to both an average result and a variance around this average. This variation shows that some vehicle purchasers would be substantially better off with a PEV purchase than the average, while others would see substantially less financial benefit. Interestingly, a battery electric vehicle (BEV) appears to have a much larger variability in cost than a PHEV. This observation indicates that a BEV can be very beneficial in some cases but very poor in others, while a PHEV has a relatively stable cost and lower risk.

Vehicle Purchase Models

In this study two types of vehicle ownership models were analyzed: purchasing the vehicle with cash up front or financing over a 60-month period. There are other ways to finance a vehicle, including leasing, but these two purchase options illustrate tradeoffs typical of those that customers must make.

Total cost of ownership is evaluated over a vehicle lifetime of 150,000 miles, which means that each vehicle has a different lifetime in terms of calendar years. Vehicles are typically resold multiple times over their life, but the value of future fuel savings is reflected in the resale value of used vehicles, so ownership can be reasonably modeled as one continuous lifetime [5].

Section 2: Methods & Assumptions

The sections below describe the critical assumptions used in this report and the characteristics for the PEVs and the comparison vehicles.

All vehicle prices are based on either model year (MY) or 2013 Manufacturer Suggested Retail Price (MSRP) for zip code 94304 (Palo Alto, CA). All vehicle pricing includes a 7.2% sales tax, and tax credits and installation costs for the Electric Vehicle Supply Equipment (EVSE) as appropriate. The Nissan LEAF and Chevrolet Volt benefit from a $7,500 federal tax credit, assumed to be taken at the time of purchase. For the Nissan LEAF a cost of $1,500 is added at the time of purchase for the assumed installation of a Level 2 EVSE. The Chevrolet Volt is assumed to charge at Level 1, so no EVSE cost is applied.

The study assumptions are summarized in Table 2-1.

Table 2-1
Assumptions Used Throughout Baseline Cost Analysis

Constant	Value used
Inflation rate	3%
Real interest rate	2%
Real discount rate (t <= 5 years)	2%
Real discount rate (t > 5 years)	5%
Cost of standard gasoline	$3.62 gallon^{-1}
Cost of electricity	$0.12 kWh^{-1}
Loan period	60 months/5 years

Table 2-1 (continued)
Assumptions Used Throughout Baseline Cost Analysis

Constant	Value used
Replacement vehicle fuel economy[2]	24 miles*gallon^{-1}
EVSE cost (BEV only)[3]	$1,500
Sales tax[4]	7.2%
Vehicle lifetime [8]	150,000 miles

The gasoline prices were calculated based on a 12 month average between January 23, 2012 and January11, 2013 of national gasoline prices [9]. The auto loan period is arbitrary but is a typical value. It is assumed that all electricity is priced at the U.S. residential average[5]. Fuel prices are not adjusted to reflect potential future changes.

Vehicle Comparison Choices

PEVs are currently more expensive than conventional vehicles to purchase, but if the total lifetime cost of these vehicles is fully calculated they can be cost-competitive. Calculating this tradeoff requires that the PEV be compared to a conventional vehicle that is feature-competitive, so one important difference between this cost comparison and many other comparisons is that the PEVs are not necessarily paired with the closest conventional vehicle, especially not the base model of the closest conventional vehicle. Electric-drive powertrains are quiet, smooth, and relatively free of maintenance and repair, so they are more comparable to luxury-level powertrains than the cost-engineered powertrains often used in economy cars. Additionally, current PEVs come standard with features not present in the base models of their conventional counterparts, such as navigation systems, seat warmers, and telematics. The section below describes how comparison vehicles were created for each of the PEVs analyzed. The Prius Plug-in has promising initial sales and interesting comparison characteristics, but was not included in this version of the analysis due to limited data on vehicle operation.

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[2] For BEVs, there may be days where the vehicle cannot complete the daily driving needs. These are considered to be "replacement days," which are described in more detail below

[3] Installed EVSE can vary between $500 and $6,000. The decision to use $1,500 for the EVSE installed cost is based on advertised costs from both Toyota and Ford of $1,500 for a typical installed EVSE [6].

[4] Based on a weighted average of state sales tax rates [7].

[5] This may not be accurate for non-residential charging – such as at the workplace or through a charger subscription network (such as Coulomb's ChargePoint Network, or NRG's eVgo network) – which can range from free to $90/month for all-inclusive charging. However, the baseline scenario assumes all charging is done at home and the majority of charging will be done at home in other scenarios.

Average Conventional Vehicle and Average Hybrid

Although each of the automakers for the PEVs analyzed in this report make vehicles which could be used for comparisons, four vehicles similarly sized and equipped were used to generate a average conventional vehicle and average hybrid. This allows both of the PEVs to be compared against the same set of reference vehicles. The details of the comparison vehicles are listed below in Table 2-2 and Table 2-3. The specific models and options packages selected are at a relatively high equipment level in order to be comparable with current PEV offerings.

Table 2-2
MSRP and Combined EPA Fuel Economy for Four Vehicles Used to Create the Average Conventional Vehicle

Vehicle	Honda Civic EX	Chevrolet Cruze LTZ	Ford Focus Titanium	Volkswagen Passat	Average Conventional Vehicle
Manufacturer's Suggested Retail Price	$24,141	$24,980	$25,285	$25,595	$25,000
Combined Fuel Economy (miles / gallon)	32	27	31	25	29

Table 2-3
MSRP and Combined EPA Fuel Economy for Four Hybrid Electric Vehicles Used to Create the Average Hybrid

Vehicle	Ford Fusion Hybrid	Honda Civic Hybrid	Toyota Camry Hybrid XLE	Toyota Prius IV	Average Hybrid
Manufacturer's Suggested Retail Price	$31,710	$26,490	$35,438	$28,995	$30,658
Combined Fuel Economy (miles / gallon)	39	44	40	50	43

Table 2-3 (continued)
MSRP and Combined EPA Fuel Economy for Four Hybrid Electric Vehicles Used to Create the Average Hybrid

Vehicle	Ford Fusion Hybrid	Honda Civic Hybrid	Toyota Camry Hybrid XLE	Toyota Prius IV	Average Hybrid
Manufacturer's Suggested Retail Price	$31,710	$26,490	$35,438	$28,995	$30,658
Combined Fuel Economy (miles / gallon)	39	44	40	50	43

2013 Chevrolet Volt

The Chevrolet Volt is the first extended-range electric vehicle introduced to the market, so it has most of the performance advantages of a purely electric vehicle (such as smooth and quiet operation and instantaneous torque response) while still allowing the fast and convenient refueling of a gasoline vehicle for longer trips. The Volt is equipped with a 16 kWh battery, seats four adults, and has an electric driving range of 38 miles. The baseline Volt comes "fully loaded" with an LCD display, Bluetooth capabilities, and a luxury-grade drivetrain, so it is positioned at a relatively premium level compared to other vehicles within the compact vehicle class.

The price and fuel economy of the Chevrolet Volt and the generic conventional and hybrid comparison vehicles are shown below in Table 2-4. The fuel economy for the Volt is the combined city/highway fuel economy in charge sustaining mode; gasoline-only usage in actual operation averages over 100 mpg of gasoline and can range into thousands of miles per gallon for some drivers [10].

Table 2-4
MSRP and Combined EPA Fuel Economy of the Chevrolet Volt, and Average Comparison Vehicles (Average Conventional Vehicle (CV) and Average Hybrid Vehicle (HEV))

Vehicle	Chevrolet Volt	Average CV	Average HEV
Manufacturer's Suggested Retail Price	$39,995	$25,000	$30,658
Purchase Price (After Taxes, Credits, Destination Charges and EVSE Installation)	$35,200	$26,800	$32,865
Combined Charge Sustaining Fuel Economy (miles / gallon)	37	29	43
Combined Electricity Consumption (AC Wh / mile)	360	N/A	N/A
Vehicle Powertrain Type	Extended-Range Electric Vehicle	Internal Combustion Engine	Hybrid Electric Vehicle

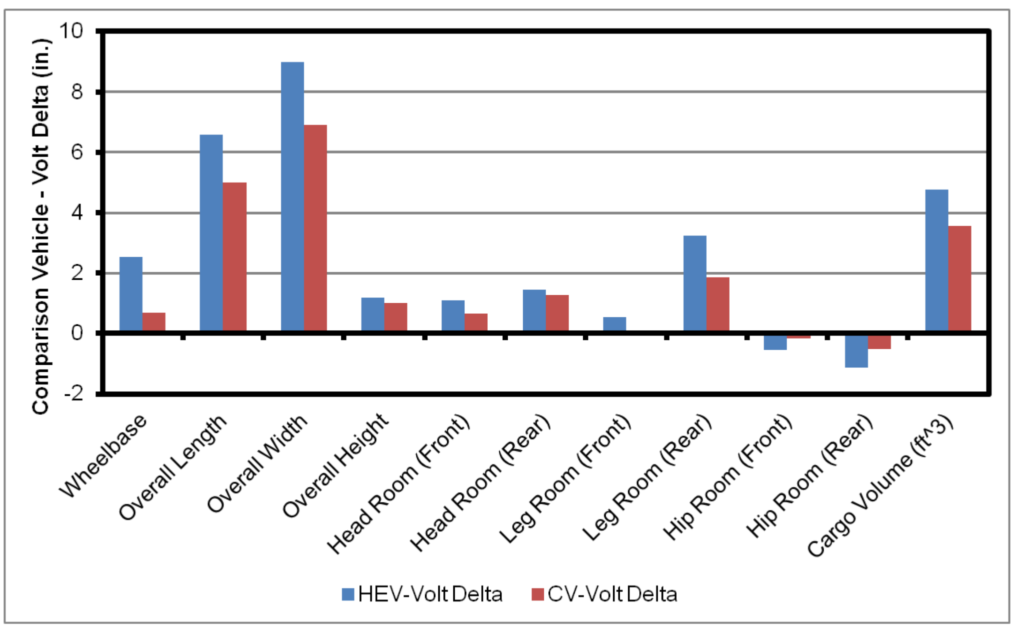

Figure 2-1
Relative Dimensions of the Chevy Volt and Comparison Vehicles

In general, the interior dimensions of the comparison vehicles are comparable to that of the Chevrolet Volt. The differences in dimensions and cargo volume are relatively small and can be attributed to aesthetic design decisions, battery size, and aerodynamics.

2013 Nissan LEAF

The 2011 Nissan LEAF entered the U.S. vehicle market in late 2010 as the first commercially available BEV sedan since the previous generation of BEVs was withdrawn from the market in the early 2000s. In 2013, the full-charge range of the Nissan LEAF was increased from an EPA rated 73 miles to an EPA rated 84 miles. The Nissan LEAF is equipped with a 24 kWh battery, seats five adults and is built on a similar chassis to the Nissan Juke, Cube or Sentra; however, the vehicle platform is unique. The mid-level LEAF SV comes "fully loaded" with a navigation system, Bluetooth capabilities, and heated seats. Additionally, the LEAF powertrain is smooth and quiet, so it is relatively luxurious compared to other vehicles in the compact car class. In this analysis the LEAF is compared to the average conventional vehicle and conventional hybrid. The characteristics of these vehicles are shown below in Table 2-5 and the relative dimensions are shown in Figure 2-2.

Table 2-5
MSRP and Combined EPA Fuel Economy of the Nissan LEAF and Average Comparison Vehicles (Average Conventional Vehicle (CV) and Average Hybrid Vehicle (HEV))

Vehicle	Nissan LEAF SV	Average CV	Average HEV
Manufacturer's Suggested Retail Price	$31,820	$25,000	$30,658
Purchase Price (After Taxes, Credits, Destination Charges and EVSE Installation)	$29,022	$26,800	$32,865
Combined Charge Sustaining Fuel Economy (miles / gallon)	N/A	29	43
Combined Electricity Consumption (AC Wh / mile)	289	N/A	N/A
Vehicle Powertrain Type	Battery Electric Vehicle	Internal Combustion Engine	Hybrid Electric Vehicle

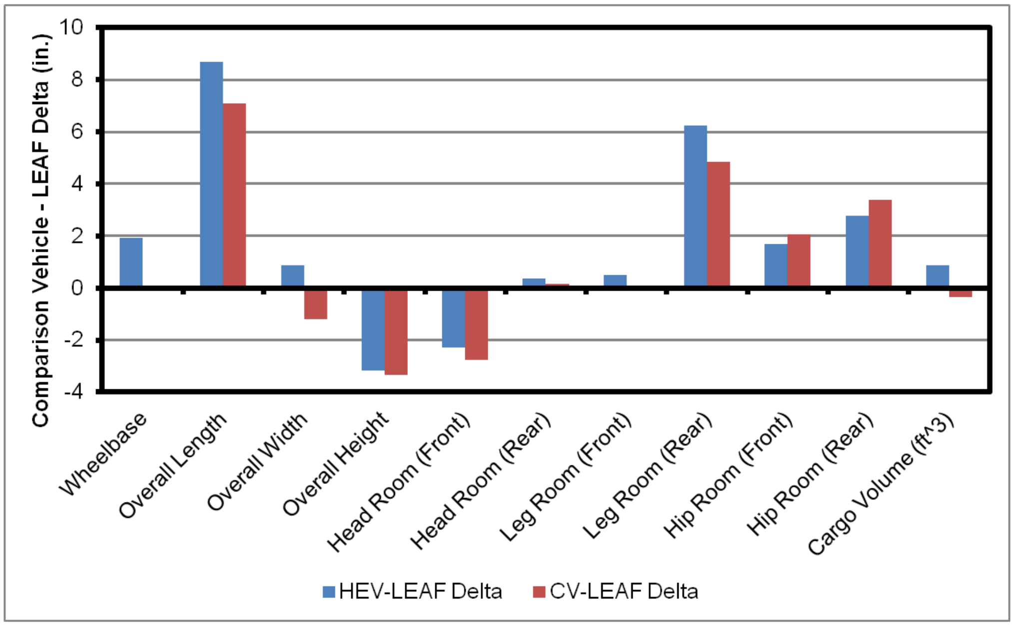

Figure 2-2
Relative Dimensions of the Nissan LEAF and Comparison Vehicles

The LEAF has more headroom than the comparison vehicles, but has less room in the rear seats. The differences overall are relatively small, and are comparable to variation within vehicle classes for conventional vehicles.

Representation of Driving

In the past, EPRI analysis has focused on utility factors derived from the National Household Travel Survey (NHTS) [11]. While the NHTS has a national scope and is well executed, it has the significant drawback of only providing one sample day of driving for each vehicle and driver. This is particularly problematic when analyzing total cost of ownership of BEVs, since driving pattern consistency can have a substantial effect on the applicability of a BEV even if average driving patterns are the same.

To address this shortcoming of the NHTS, a separate dataset was used that contained a longitudinal sample of driving data for a more limited number of vehicles. This data was collected in the Puget Sound area of Seattle, WA between November 2004 and April 2006 for around 400 vehicles in 275 households. All vehicles used in this study have at least one year of sampled driving data. This data is made publicly available by the National Renewable Energy Lab (NREL) [12]. Similar to the NHTS, the NREL dataset is based on driving data taken from conventional vehicles, so it is unclear how well the driving behavior measured in these surveys matches the real-world driving behavior of PEVs. Appendix A shows a comparison between this dataset and the 2009 NHTS, showing that this data appears to be a reasonable match for urban driving in the NHTS for vehicles driven between 6,000 and 14,000 miles per year, so this analysis focuses on this subgroup. This subgroup represents about

45% of NHTS drivers and a majority of NHTS miles, but underrepresents high-mileage drivers and low-mileage drivers, which are poorly represented in the NREL dataset. The lack of publicly available longitudinal datasets with more national scope and inclusion of a wider range of drivers is a significant shortcoming that should be addressed in future work.

As with previous EPRI analysis, this model assumes that all vehicles are replaced with a PEV and that these vehicles are driven and charged in the same pattern as the original vehicle, subject to charging availability. Unlike previous analyses, if the modeled vehicle is a BEV, analysis is performed before leaving the home location to ensure that the BEV can return home without fully depleting the range. If not, this series of trips is assumed to be performed with a conventional gasoline vehicle, and these miles are considered 'replacement miles.' The number of unique days on which replacement miles occur is also recorded so that the cost for a replacement vehicle, such as a rental car, can be quantified (a household replacement is assumed in the baseline case in this report with no daily vehicle use cost).

The gasoline and electricity usage is dependent upon both total miles driven and availability of charging. Two charging scenarios are considered in this analysis: home charging and home plus workplace charging.

Each of the driving traces from the NREL data is simulated separately for each vehicle and charging scenario, and then the aggregate performance of the fleet is calculated from the average of all vehicles. In some cases, statistics are presented for the variation in cost deltas between different drivers.

Fueling Costs

Fueling costs for gasoline and electricity are calculated by multiplying the fuel use for each simulated vehicle by the fuel cost. The fuel costs and fuel use are assumed to stay the same over the vehicle life.

Maintenance Costs

Maintenance costs are an additional operating cost considered in this study. Maintenance costs are the costs for regular services required to ensure the continued reliable operation of a vehicle, such as oil changes and inspections. Maintenance costs do not include repair costs, which happen unexpectedly due to failures in a vehicle component.

Maintenance costs are calculated using the less severe mileage-based maintenance schedule in each vehicle's manual and the service costs for zip code 94304 (Palo Alto, CA), taken from Edmunds.com [13]. Brake pad replacement and brake fluid flush, unless otherwise performed in the maintenance schedule, is done every 40,000 miles for conventional vehicles. Costs for brake service are estimated by using ConsumerReports.org, for area code 94304 [14] (these costs are not listed on Edmunds.com). Since HEVs and PEVs have regenerative braking and thus less wear on the brake pads, no brake pad replacement is assumed to happen throughout the 150,000 year ownership period, but brake fluid flushes are performed every 40,000 miles [15]. More information on cumulative lifetime maintenance costs are shown in Appendix B.

Unmodeled Operating Costs

There are some operating costs that were not included in the calculation of total ownership cost in this analysis. The omissions were due to a lack of data or a modeling judgment that these costs were not significant differentiators between different vehicle types. These costs include the cost of tire replacement, insurance costs, repair costs, and salvage costs. Tire replacement costs and insurance costs are significant, but there is limited information on how these costs occur for individual consumers and it is expected that these costs will be similar for comparable vehicles. Insurance costs vary based on the initial cost of the vehicle, but this variation in costs appears to be secondary to variations in cost due to location and driver history. Salvage cost or value is not included in this study due to a high degree of uncertainty about future materials prices.

Repair costs are a significant cost that ideally would be included in this model, but limited data is available for repair costs for PEVs, or even for conventional vehicles. Initial data on PEV reliability is positive – Ford has reported that there have been no electric motor failures in the drive system of the Escape Hybrid, which is similar to the powertrains in PEVs [16]. Current PEV powertrains have unusually long warranties for the battery packs, as shown in Table 2-6, and in ZEV states.

Table 2-6
Battery Warranty Information for PEVs Analyzed in this Study

Vehicle	Battery Warranty
Chevrolet Volt	8 years/100,000 miles
Nissan LEAF	8 years/100,000 miles

For PEVs, the potential cost of battery replacements is a significant uncertainty since limited data is available on long-term reliability and the battery is critical to the operation of the powertrain. Batteries are also a relatively high percentage of the total vehicle costs for PEVs and are known to exhibit degradation over time. However, newer battery chemistries have demonstrated improved durability. The trajectory of degradation is also important in understanding whether or not vehicle owners actually replace the battery, but is not well-characterized. For example, it seems unlikely that a battery will be replaced if the vehicle is otherwise near the end of its service life. Also, if degradation is gradual and small it may not be perceived as significant by the customer, especially for PHEVs [16]. Understanding these relative costs is an important area for future research.

There are many non-monetary values associated with PEVs which are not quantified in this study. For example, states and towns are offering single-occupant High Occupancy Vehicle lane access, insurance cost reductions, and discounted premium parking. These benefits vary from state to state and can result in time savings for the consumer that varies on a case-to-case basis[6].

Discount Rate

The selection of a discount rate is a significant factor in lifetime cost studies, particularly over long timeframes. The discount rate represents the 'time value of money,' a recognition that a dollar one year from now is typically worth less than a dollar today because today's dollar could be invested in a variety of ways such that it will be worth more than a dollar after a year has passed. Additionally, discounting can account for the fact that any potential investment is riskier than holding onto cash. A discount rate is used to discount future costs and savings to calculate the 'Net Present Value' (NPV) of expenditures over the entire lifetime of the car. Figure 2-3 below shows the effects of varying discount rates on 1 unit of value over 20 years. For example at a 5% discount rate $1 saved 20 years from now is worth approximately $0.38 saved today.

The selection of a discount rate is always difficult since rates often include assumptions about the consumer value of future money, which can differ substantially from strict financial concepts of rate of return on investment. This selection is particularly problematic now, since interest rates are at a historically low level while inflation is at a more typical level, making the real risk-free rate of return (a typical reference point) near 0%. For example, vehicle customers often finance a car with an auto loan. Current automotive loan rates are around 3% with an inflation rate of less than 2%, so the real discount rate for future savings would be on the order of 1%.

For this study, a real discount rate of 2% is used for five years and is then increased to 5%, reflecting the judgment of the authors that the current historically low interest rate levels will persist for some time but that the economy will return to more normal levels within the next five years.

The discount rate is used to modify future costs using the following formula for net-present value (NPV) calculation:

$$NPV_t = \frac{c_{annual}}{(1+r)^t}$$

Where, c_{annual} is the annual cost including fuel expenditures, maintenance, and costs associated with vehicle replacement; t is the time passed in years from 2013, and r is the discount rate. The costs for all future years of the vehicle lifetime are then summed up for each vehicle option and these are then compared to calculate total savings or deficits.

[6] State incentives vary and some states do not have incentives. More information on local and state incentives can be found through Plug-in America [17] or the Electric Drive Transportation Association (EDTA) [18].

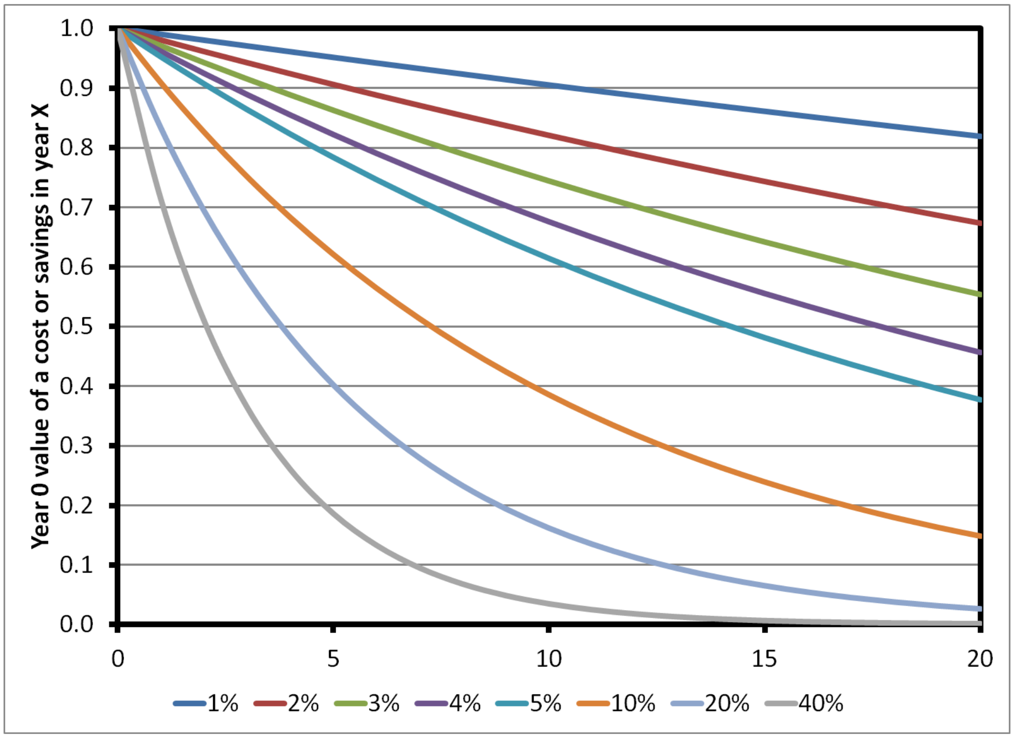

Figure 2-3
Effects of Discount Rate on Net Present Value Calculation, over a 20-Year Period

Section 3: Results: Cash Purchase

The first method of vehicle acquisition analyzed is outright purchasing of the vehicle, which is commonly used in ownership cost comparisons, although often implicitly. This method assumes that the vehicle purchaser pays the full capital cost up front, and then pays for operating expenses over time. Figure 3-1 illustrates cumulative expenditures for a sample cash purchase. Most efficiency technology purchases have a similar characteristic: costs are higher up front for the more efficient technology, but reduced operating expenses will result in savings over time. The time at which cumulative expenses for the more efficient option are less than the default option is often called the 'payback time.' In this section, total cost of ownership is reported since this a key indicator of relative affordability. Payback time is reported in Section 4 for the financed purchase case since this is a much more common vehicle acquisition method and therefore is more representative of customer experience.[7]

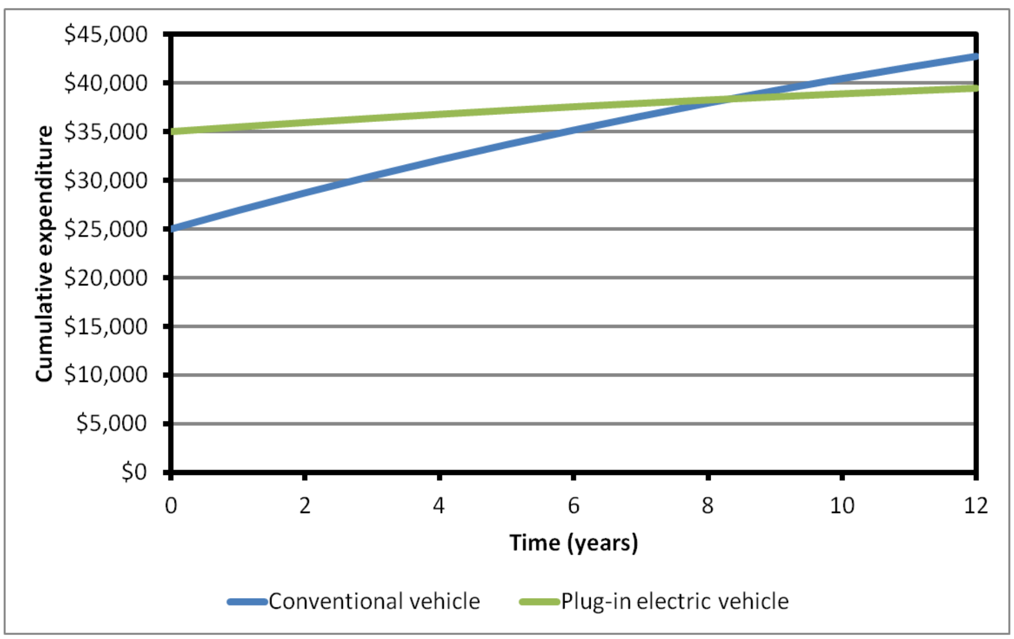

Figure 3-1
Cash Purchase Example

[7] Due to financing costs payback time will always be less for the cash purchase method than for the financed purchase method.

The primary results from the cash purchase analysis are:

- **Current PEVs with incentives are roughly comparable in cost to competitive options over the life of the vehicle.** Although there are interesting differences between vehicles and a range of values for each vehicle comparison based on different driver circumstances, overall lifecycle cost differences are on the order of 10-20%, which is comparable to the difference between option packages and powertrains for an individual vehicle or between roughly similar vehicles such as midsize sedans and small sport utility vehicles.
- **The Volt is cost competitive.** The Volt is somewhat less expensive than the average conventional vehicle and average hybrid for most drivers. The variation in cost differences is significant, but the risk of significant negative cost impact is relatively low.
- **The LEAF is very cost competitive, although there is substantial variation between different drivers.** The LEAF is on average significantly less expensive than the average conventional vehicle and average hybrid. However, the variation of cost differences across driving patterns is very high, indicating that it will be important to help drivers assess the potential value of a LEAF purchase before they buy.

Data Presentation and Additional Assumptions

The results of the purchase analysis show total expenditures for the vehicle broken down into five categories:

- Purchase – the total amount spent on the upfront purchase of the vehicle. This includes the MSRP, delivery charges, sales tax, incentives, and installation of an EVSE if applicable.
- Maintenance – cost to maintain the vehicle, estimated from each vehicle's ownership manuals. This maintenance includes brake pad replacement and fluid flush every 40,000 miles for conventional vehicles, unless otherwise dictated in the owner's manual. HEV and PEV maintenance does not include a brake pad replacement, but does include regular brake fluid flushes.
- Operation – Gasoline – the total operation costs accrued throughout the vehicle lifetime from gasoline purchases
- Operation – Electricity – the total operation costs accrued throughout the vehicle lifetime from electricity purchases
- Replacement – this category is only for the LEAF and includes the total amount of gasoline used by an alternative vehicle on replacement days, assuming a fuel economy of 24 mpg.

The model also does not include some significant ownership costs, including tires, license and registration, insurance, and salvage value. These are left out for both reasons of uncertainty and simplicity, as described in more detail in Section 2. These baseline results do not include any additional state incentives, but these incentives are discussed in the sensitivities in Section 5.

Most analyses of total ownership costs use average driving data to calculate average ownership costs. In this analysis the payback analysis was performed for each vehicle in the sample individually, and then the ownership costs of all of these samples were averaged. This calculation allows an investigation of the variation in ownership costs in addition to the average ownership costs and reveals interesting differences in ownership costs for different vehicle usages, particularly in the case of the LEAF.

Chevrolet Volt

The first vehicle analyzed is the Chevrolet Volt, which is compared to two other vehicles: a generic conventional vehicle, and a generic hybrid. Of the vehicles analyzed in this study, the Chevrolet Volt has the highest upfront purchase price. Therefore, in order for the Volt to make financial sense to most consumers over the lifetime of the vehicle, the savings from operation and maintenance need to exceed the additional upfront cost. Figure 3-2 shows the average total cost of ownership for the Volt relative to the comparison options. The results indicate that gasoline expenditure is substantially reduced to the point that the higher capital cost is recovered. The Volt is the lowest cost option overall, but the differences between the lifetime cost of the Volt and the generic conventional vehicle and generic hybrid are small. As later analysis in Section 4 shows, this means that the payback crossover point comes relatively late in the vehicle life.

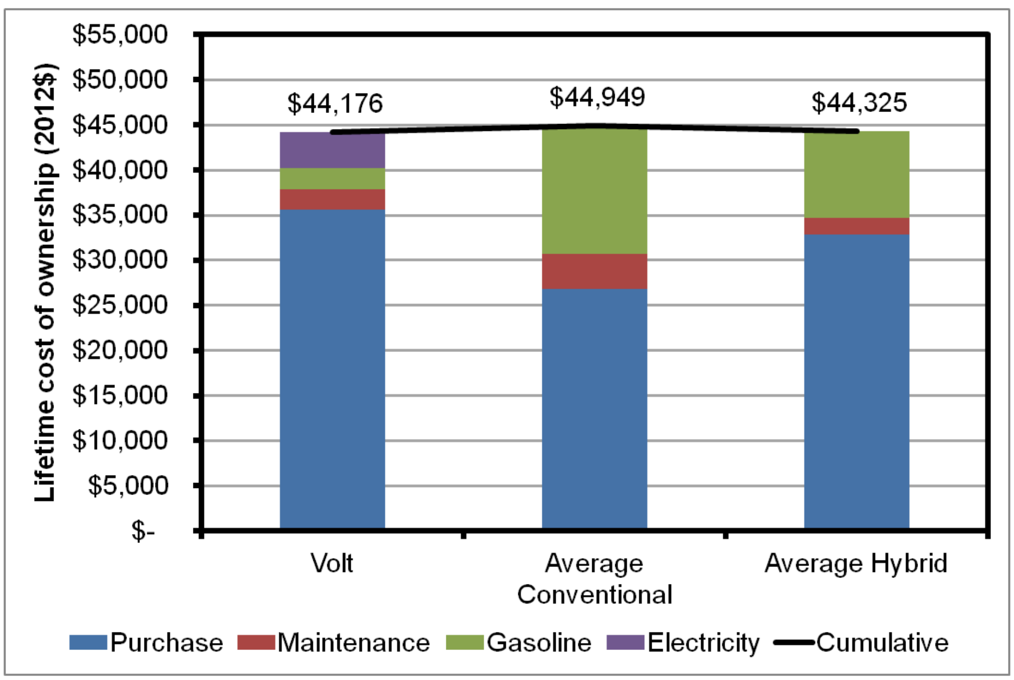

Figure 3-2
Average Total Cost of Ownership for the Volt and Comparison Vehicles

Figure 3-3 shows how the ownership costs of the Volt differ from the ownership costs of each comparison vehicle. Moreover, it shows how those cost differences vary depending on driving patterns. In this figure, each section of each column represents 20% of the driver population in the study sample. The $0 data point on the Y axis represents the total cost of the Volt over its lifetime using home charging only, and positive data points indicate costs higher than the Volt while negative data points indicate costs lower than the Volt.

The chart also shows the difference in ownership costs if workplace charging is available. When workplace charging is added to the scenario it provides benefit for some customers, but because the Volt has high all-electric range that allows electricity to be used for typical commutes the average value of workplace charging is relatively low. The value generally comes from days when other driving activity is added to normal commuting (note that the data points beyond $1,000 comes from only a few drivers).

The cost difference between the Volt and the generic hybrid vehicle and between the Volt and the generic conventional vehicle illustrates how individual drivers' circumstances vary.

When compared to the average conventional vehicle, the average lifetime cost of the Volt is about $775 lower (as shown previously in Figure 3-2), but the variation in savings or deficits is relatively high. The chart shows that 20% of Volt drivers save roughly $1,500 to $2,200 relative to the conventional vehicles. Only about 20% of Volt drivers are worse off than the average conventional vehicle, although a few drivers are almost $1,500 worse off since their driving patterns are particularly unfavorable for the Volt.

When compared to the average hybrid, the average lifetime cost of the Volt is almost equal (as shown previously in Figure 3-2), but the variation around this value shows that about 60% of Volt buyers receive financial benefit, while 40% of Volt buyers are worse off because their driving patterns are unfavorable for the Volt. Those Volt drivers who are better off see a cost advantage of up to $1,200 compared to the average hybrid. Roughly 20% of those who have higher expenses with the Volt see a widely varying cost disadvantage, roughly $500 to $1,800, depending on their driving patterns.

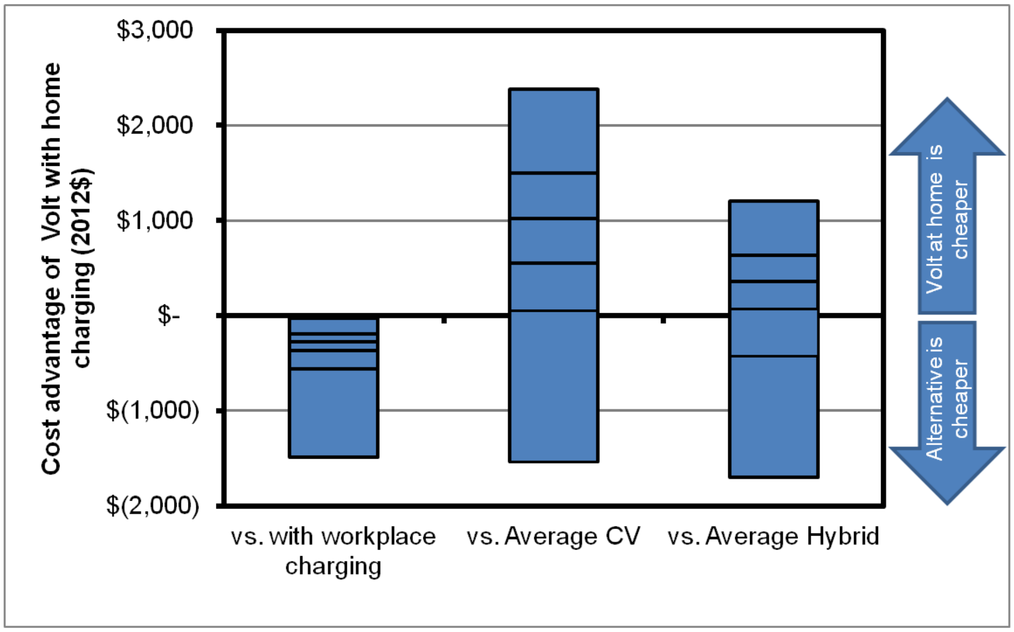

Figure 3-3
Cost Difference Variation for Volt Alternatives

Overall the lifetime cost difference between the Volt and the comparable options indicates that the increased capital cost of the Volt is well-balanced by fuel savings. There is variation in lifetime costs, but it is important to note that the total variation in each case is less than 5% of total costs up or down.

Nissan LEAF

The Nissan LEAF is an interesting vehicle to compare to other vehicles since it is a BEV and therefore has a cost that is difficult for many drivers to estimate since operating costs and usage characteristics are different than conventional vehicles. For the baseline comparison, it is assumed that the LEAF charges only at home with a Level 2 charger. Driving days that exceed the range of the LEAF are assumed to be driven with a conventional vehicle with a fuel economy of 24 mpg with no daily usage cost, which implicitly assumes that the LEAF is one of multiple cars in a household [19]. Increased replacement costs are analyzed in the sensitivities considered in Section 5.

In this analysis the LEAF is compared to two vehicles: an average conventional car, and an average hybrid car. The average lifecycle cost for the LEAF and each comparison vehicle is shown in Figure 3-4. On average the LEAF is less expensive than the generic conventional vehicle and generic hybrid vehicle by over $7,000.

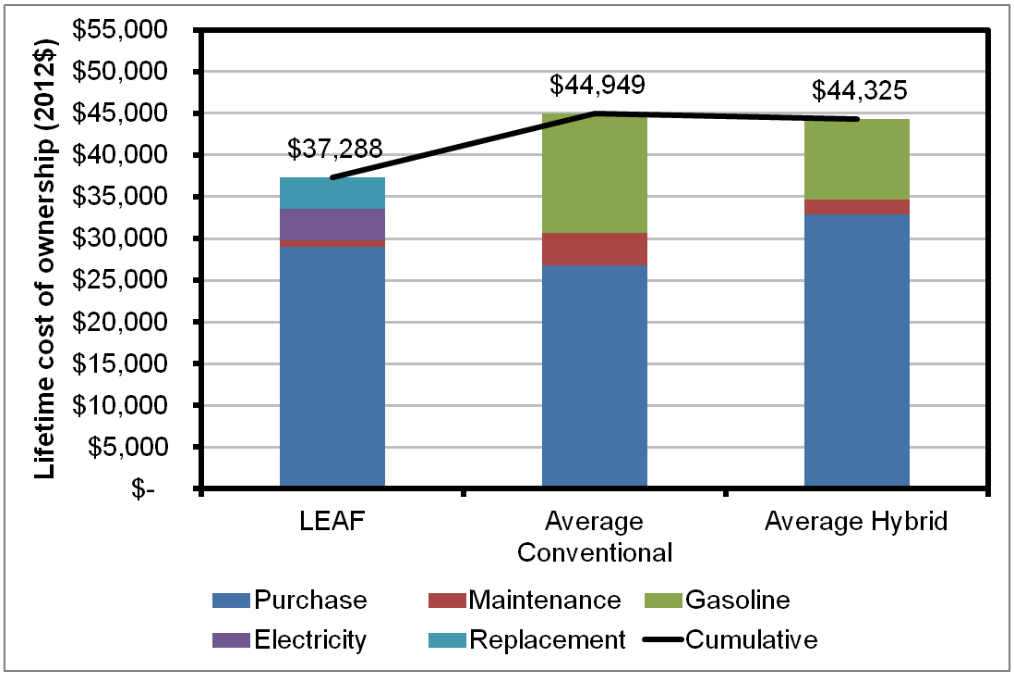

Figure 3-4
Average Total Cost of Ownership for the LEAF and Comparison Vehicles

Figure 3-5 shows the variation in cost between the LEAF and comparable options by showing the range of cost for different segments of the population, with each box in each column representing 20% of the population. The variation in cost difference between the LEAF and other options is around 25% of the total lifetime costs, so the variation is quite high compared to the Volt. Due to the significant cost advantage of the LEAF almost all customers experience a lower cost with the LEAF, but some are much better off, highlighting the need for identification of the best potential customers.

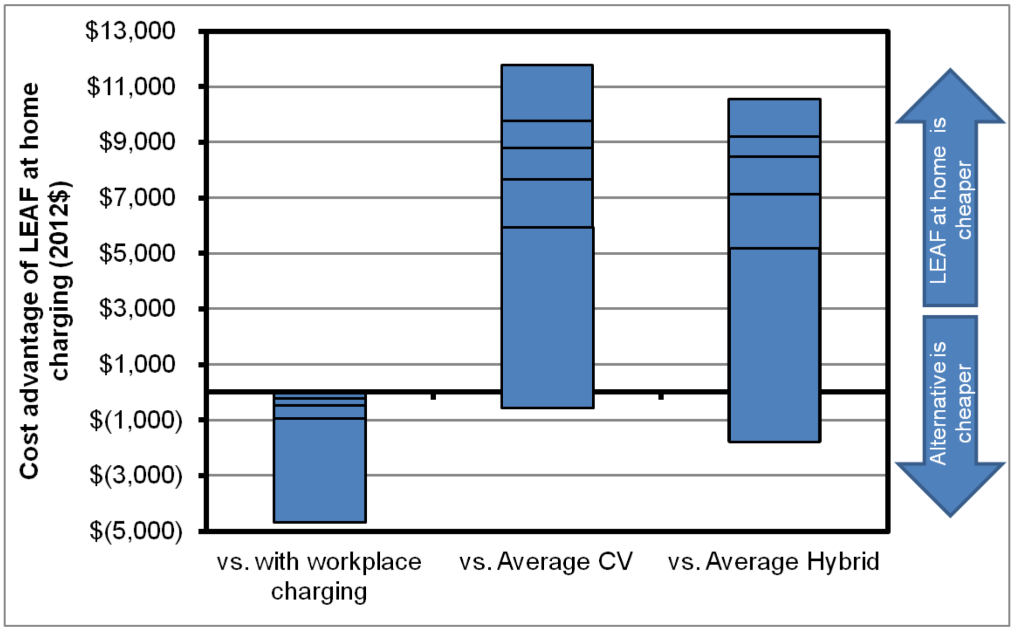

Figure 3-5
Cost Difference Variation for LEAF Alternatives

Due to the importance of replacement value and the high potential uncertainty in the estimation of this value, a more detailed analysis was performed. Figure 3-6 shows the variation of replacement cost by quintile for various charging assumptions. Each box in each column represents 20% of the vehicle population, and a red line is drawn at $3,800, the average lifetime replacement cost in the analysis above.

As implied by Figure 3-5, Figure 3-6 shows that much of the replacement cost is experienced by a relatively small percentage of the population. In the base scenario with home charging only, around 60% of the population has less than the average replacement cost and about 40% of the population has replacement cost greater than the average, but some negatively impacted users have much higher replacement costs. Increased charging availability helps to bring down replacement cost and increase the portion of the population that would benefit from a LEAF. Workplace charging decreased the average replacement cost by $700, to $3,100. Moreover, adding charging to 50% of public locations visited on longer driving days or adding supplemental fast charging in addition to the home-only case has the effect of bringing average costs down to about $2,800 and bringing a total of about 70% of the population below the baseline average replacement cost. In each of these improved cases, around 30% of the driving population remains above the average cost with a substantial portion with very high replacement costs. The availability of a higher efficiency replacement vehicle (the rightmost column) significantly improves costs for the least favorable drivers, and has even higher benefit than increased charging infrastructure for the most favorable drivers.

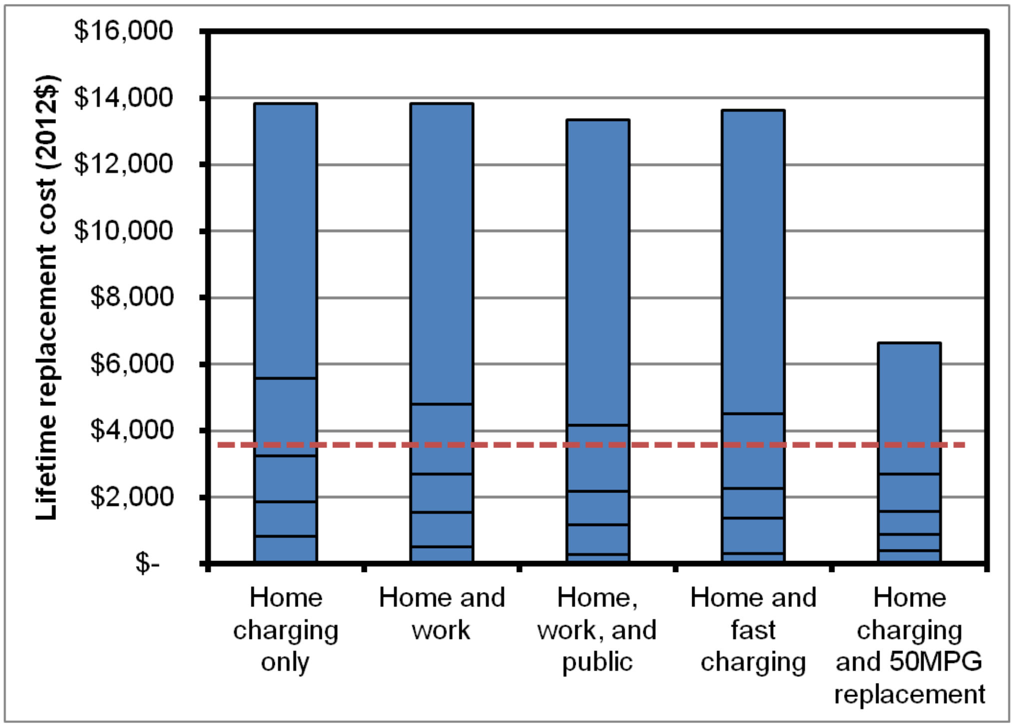

Figure 3-6
Replacement Cost for LEAF with Varied Charging Assumptions

Figure 3-6 and the analysis above indicate that self-selection will be very important for the purchase of vehicles with characteristics like the LEAF. Some drivers are much better off than average, so it would be advantageous to develop techniques that can identify these drivers and clarify their value proposition. Additionally, the variability in value indicates that drivers may have considerable control over the lifetime cost of a BEV. This analysis assumed that driving patterns were unchanged from the baseline driving pattern, but given the wide range of potential replacement costs it is also likely that drivers can substantially influence their costs by altering their driving patterns.

Section 4: Results: Financed Purchase

For many TCO studies the cost comparison is performed assuming that an initial capital cost is traded off with operational cost savings over time. However, over 70% of vehicle purchases in the United States are financed, so this is a much more common purchase option [1]. This section investigates the results of financing a vehicle purchase on the stream of payments required for PEVs and conventional vehicles.

Figure 4-1 shows a rough loan and operating cost payment scenario that illustrates the cumulative expenditure for a vehicle buyer using the same sample costs used in Figure 3-1. The monthly expenditure is much higher during the finance period as the vehicle purchase cost is paid back. After the finance period only operating costs are incurred. If the total cost of ownership of the PEV option is lower than the total cost of ownership of the conventional vehicle option then at some point during the life of the vehicle the total expenditure for the PEV will be lower than for the conventional vehicle. This point is typically called the *payback time* for the increased capital expenditure. In this report the analysis of financed purchase cost revolves around two aspects: the total monthly outlay during the loan period and the payback time. The monthly outlay during the loan period is important because it is a critical indicator of affordability. Regardless of total lifetime costs, if a cost difference overwhelms a customer's vehicle expenses budget it will be difficult for the customer to make a purchase, so fuel savings must balance out payments relatively closely. Payback time is calculated because it is an important measure of how quickly the customer can be expected to perceive the value of increased efficiency.

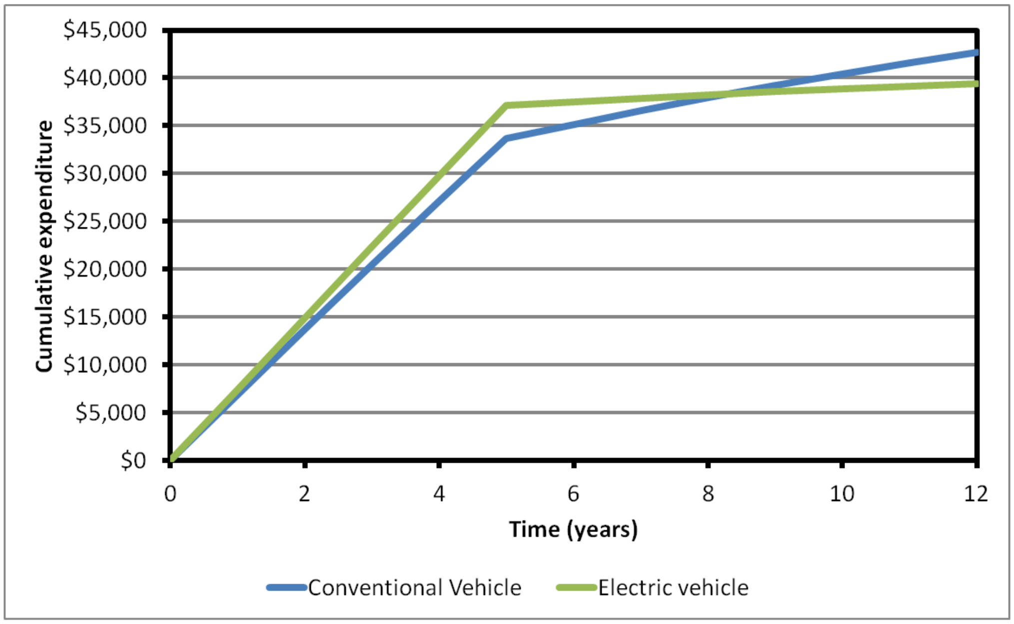

Figure 4-1
Financed Purchase Example

The primary results from the financed purchase analysis are:

- **Current plug-in electric vehicles are generally competitive on a monthly cost basis.** Although there are substantial differences between options and substantial variation within each comparison group based on driver circumstances, in general the range of monthly payments between all options is approximately $100, or about 15%. This indicates that increased capital expenses are relatively well matched by fuel savings. If a purchase of a new vehicle is within a customer's budget, then the purchase decision can be guided by personal preference and values rather than on cost differences alone.
- **The Volt has a slightly higher monthly cost during the finance period than the average conventional vehicle and average hybrid, and an extended payback period.** Relative to the average conventional vehicle and average hybrid, payback takes a long time for most customers if it occurs at all, but this is partly a reflection of the more premium market positioning of the Volt that the comparison vehicles
- **The LEAF is very cost competitive against the average hybrid and average conventional vehicle.** Due to the competitive capital costs and very low operating costs of the LEAF it achieves lower monthly costs than the average conventional vehicle and average hybrid, leading to rapid payback.

Additional Assumptions

In this analysis each sample driver is evaluated separately, and then the results are averaged to calculate the average monthly expenditure during the first 5 years of the loan period. Each vehicle is assumed to have an auto loan for the entire upfront price of the vehicle, at a 5% nominal interest rate over 60 months, which is typical or high for current rates. The federal tax credit[8], sales tax, and EVSE installation, where appropriate, are assumed to happen immediately and are included in the financed cost. The ownership is assumed to be over 150,000 miles for each case, resulting in different ownership timeframes for each vehicle sample.

Chevrolet Volt

Figure 4-2 shows the average monthly expenditure during the loan period for three comparison vehicles: the Volt, average conventional vehicle, and average hybrid vehicle. Due to its relatively high capital cost the Volt monthly expenditure is higher than the average conventional vehicle and average hybrid. However, the total spread between the lowest cost and highest cost is approximately $110 per month, so it is likely that if a customer strongly desired a particular vehicle and had the financial means to buy a car in this class the expenditure difference would not be a primary constraint. The average conventional vehicle is the least expensive option by approximately $70 per month, despite being among the most expensive options in the total cost comparison in Figure 3-2. This gap occurs because roughly 20% of costs for the average conventional vehicle are due to operating costs, which continue after the loan period is over. These increased monthly expenditures after the loan period will eventually overcome the increased total expenditure during the loan period. Figure 4-3 shows the variation in payback time for different drivers for each vehicle relative to the Volt. Because each driver has a different driving pattern, payback time varies.

[8] In general it can take some time for the tax credit to be filed and deducted. However, this can have either a positive or negative effect on the results discussed here depending on the time of purchase.

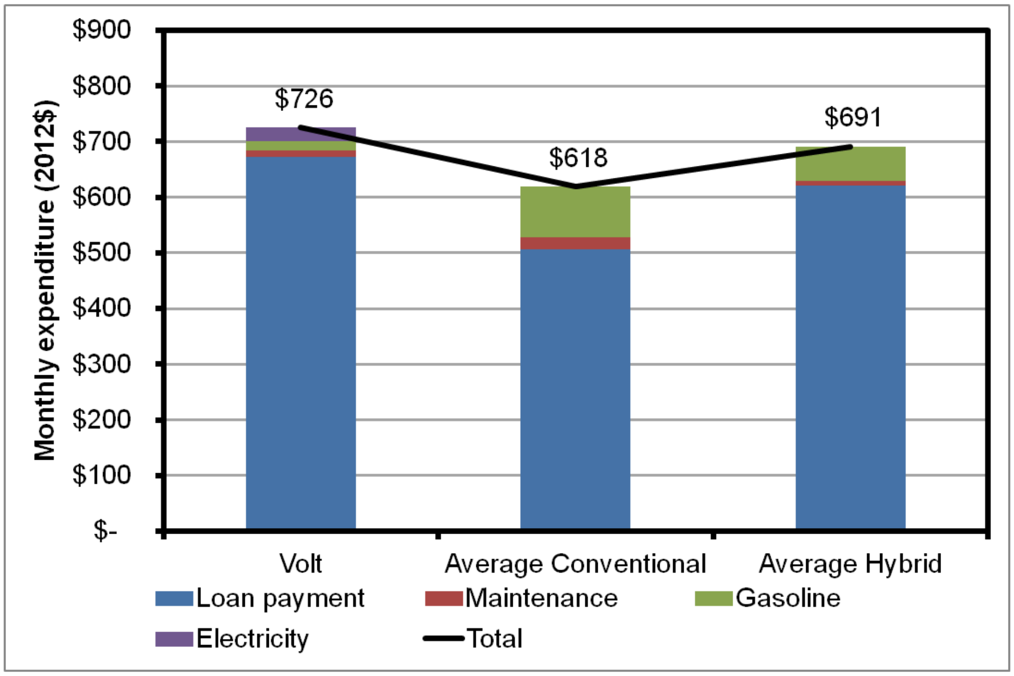

Figure 4-2
Average Monthly Expenditure for Volt and Comparison Vehicles during the Finance Period

Figure 4-3 shows that payback for the Volt is achieved within 11-16 years for 30% of drivers. Around 65% of drivers do not achieve payback within 20 years, which effectively means that payback will not be achieved. This may be surprising considering the total cost advantage the Volt had in Figure 3-3, but since financing costs effectively increase the capital cost of each vehicle, the higher initial expenditure of the Volt is difficult to overcome.

The relatively long payback time calculated for the Volt may make the cost comparison seem quite unfavorable. However, an important aspect of the difference between these vehicle options is that the monthly expenditure difference is relatively low, so non-financial considerations, or variations in fuel costs (analyzed in Section 5) may be more important. Figure 4-4 shows the variation in the difference in monthly expenditures between the Volt and the comparison options during the loan period; each box in each column represents 20% of drivers. With the exception of the Volt and average conventional vehicle comparison, the variation in expenditure difference is relatively low and total differences are also low. For the Volt and average conventional vehicle comparison, the gap is about $110 in favor of the conventional vehicle, a difference of about 15%. This gap is substantial, but likely low enough that a purchase decision could be made based on values and personal preferences rather than financial factors.

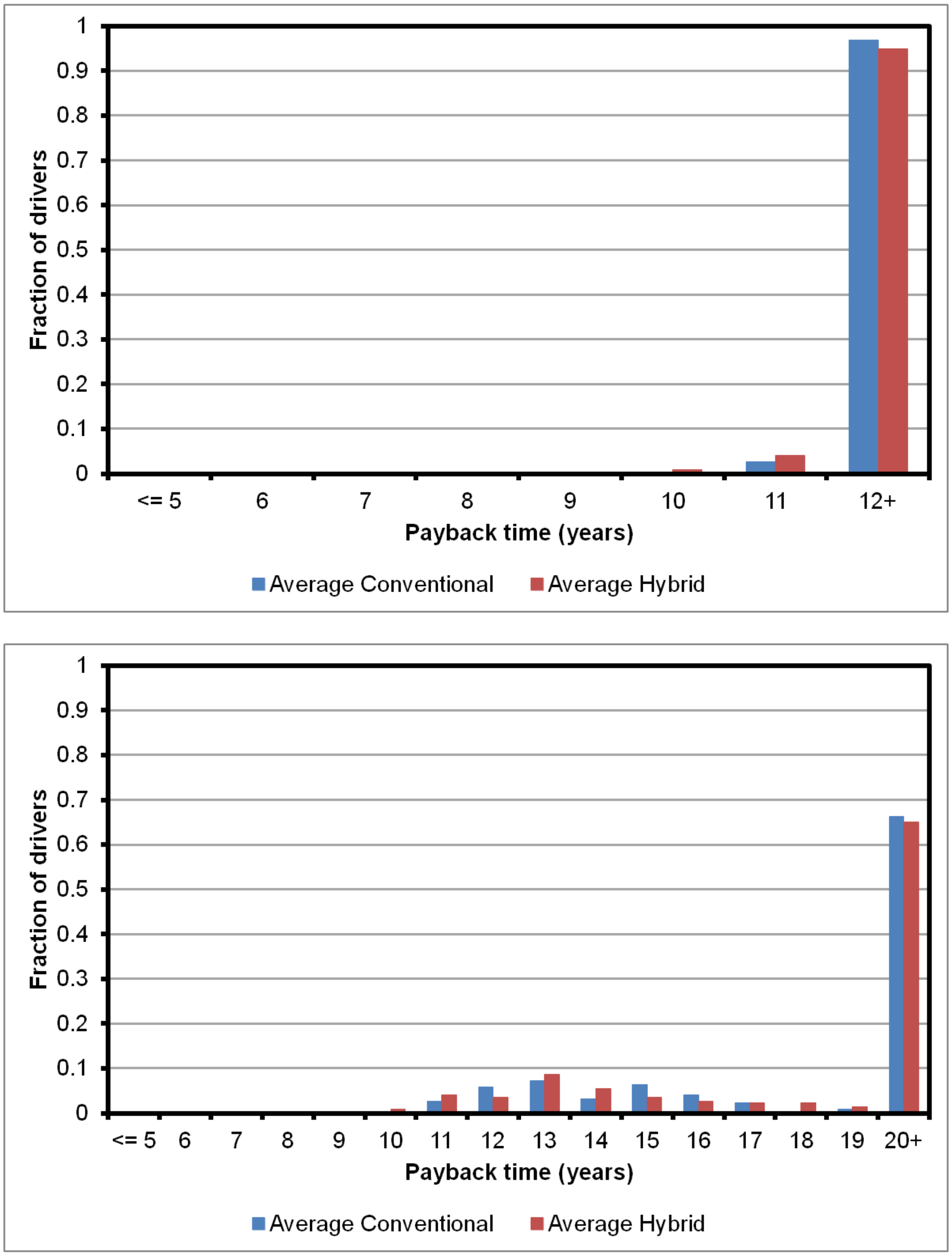

Figure 4-3
Payback Time Variation for Volt Relative to Comparison Vehicles

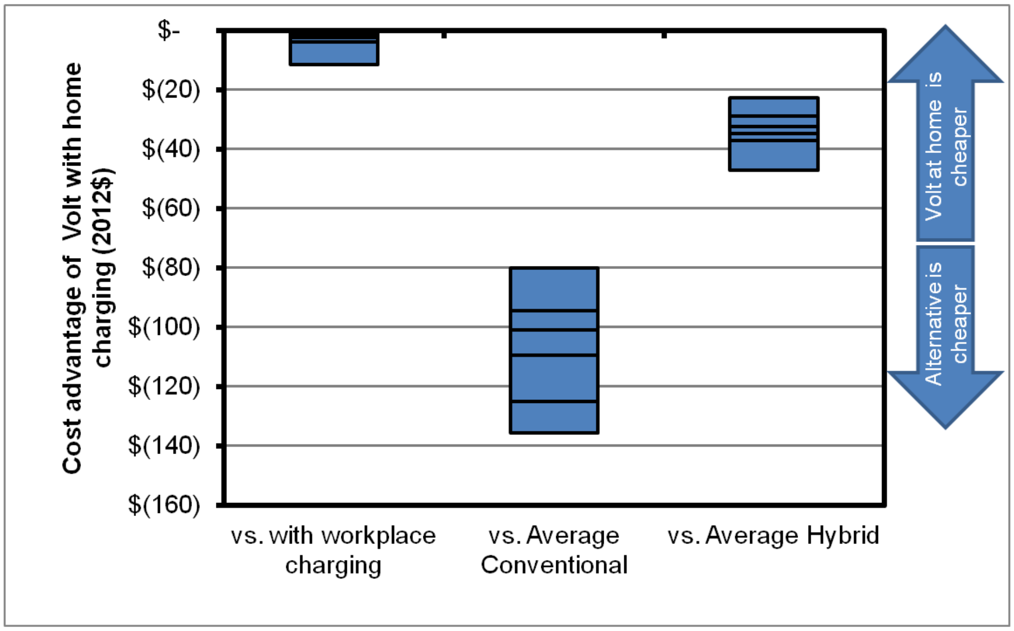

Figure 4-4
Monthly expenditure difference between the Volt and Comparison Options during the Finance Period

Nissan LEAF

Figure 4-5 shows the average monthly expenditure for three vehicles: the LEAF, an average conventional vehicle, and an average hybrid. The total expenditure for each of these options is roughly comparable — the total cost spread is less than $100/month. The LEAF has capital costs between the average conventional vehicle and average hybrid vehicle, but due to its very low operating costs it is the least expensive vehicle in terms of monthly expenditure.

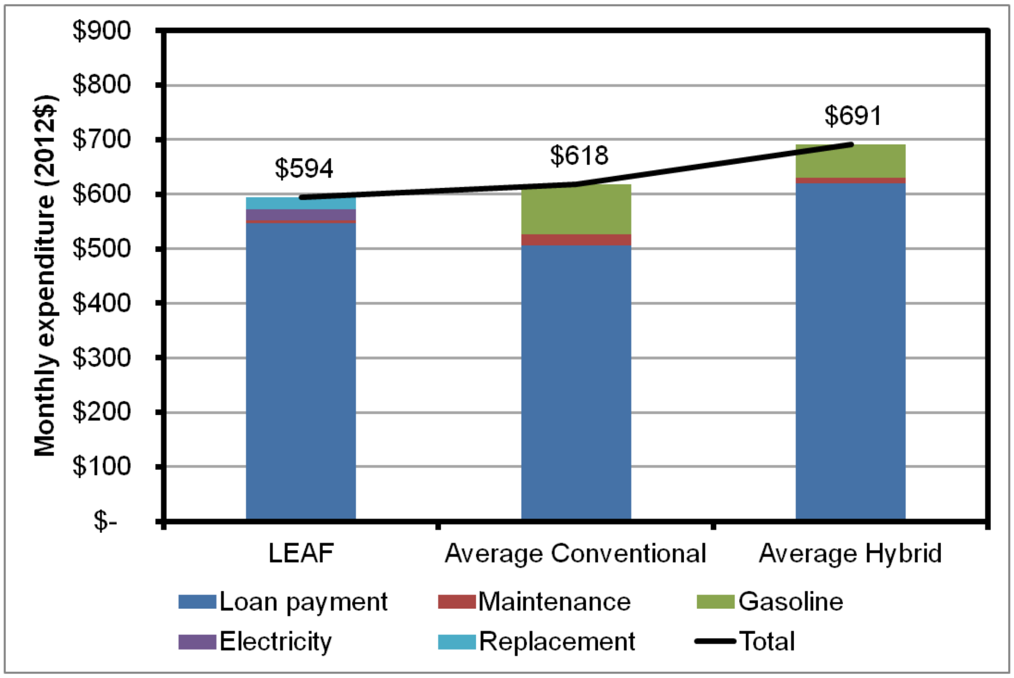

Figure 4-5
Average Monthly Expenditure for LEAF and Comparison Vehicles during the Finance Period

Figure 4-6 shows the payback time variation for different drivers. The capital cost for the LEAF is relatively closely matched to the capital cost of the average hybrid and CV while operating expenditures of the LEAF are lower. As a result, almost all drivers achieve payback within the loan period.

Figure 4-7 shows the monthly expenditure difference for this comparison set. Costs for the LEAF are lower in almost all cases, but there is considerable range in the expenditure differences for the LEAF relative to the other options.

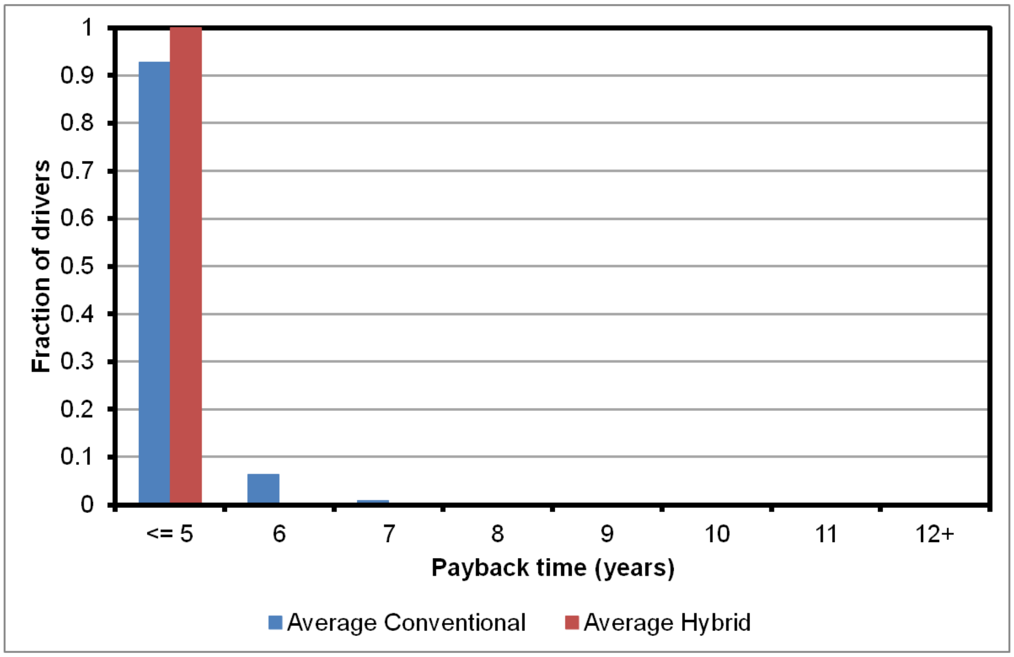

Figure 4-6
Payback Time Variation for LEAF Relative to Comparison Vehicles

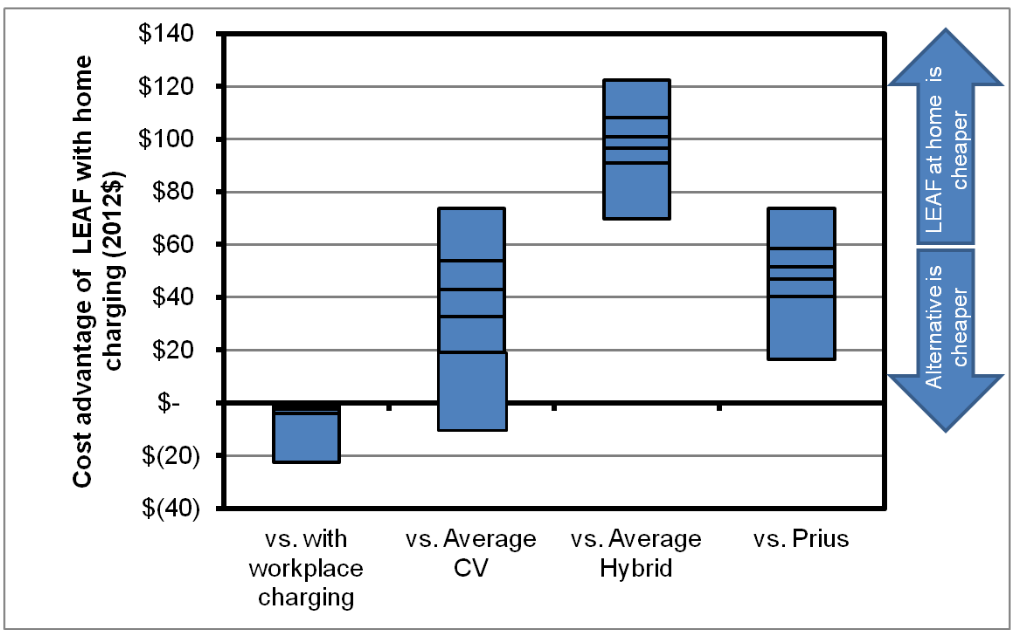

Figure 4-7
Payment Difference between the LEAF and Comparison Options during the Finance Period

Section 5: Sensitivity to Assumptions

In any analysis it is important to ensure that the results are minimally affected by reasonable variation in uncertain assumptions. Since this analysis is based on current data, uncertainty in the assumptions should be relatively low. However, future fuel prices can differ substantially from the price today and incentives can vary between different locations. After investigating the sensitivity to different assumptions, three sensitivity scenarios were selected for discussion below:

- **Gasoline price sensitivity.** Gasoline costs are a significant fraction of total ownership costs for conventional vehicles and even for hybrids, and gasoline prices can vary significantly within the lifetime of a vehicle. In order to investigate the effect of gasoline prices, the analysis was performed for prices one dollar higher and one dollar lower than the 12-month average of $3.62/gallon.
- **Replacement cost sensitivity.** The baseline analysis assumed that the LEAF was one vehicle in a multicar household which included a gasoline-powered vehicle so that a replacement vehicle would be available without a daily usage cost. In order to estimate the effects of replacement vehicle costs, the analysis was rerun assuming daily usage fees of $10/day and $20/day.
- **PEV incentive sensitivity.** The most critical components of ownership cost comparisons are the initial capital costs for the different vehicle options. Although these costs are relatively fixed in the near term, they can vary for different customers and between different regions based on a number of factors including demand, availability, and local market conditions. For PEVs, one aspect that can vary substantially from region to region is the state purchase incentive. In order to investigate the effects of these additional incentives, the analysis was rerun for a purchase in California, which has state vehicle incentives, EVSE installation incentives, and historically higher gasoline prices, all of which contribute to more favorable market conditions.

The results from these sensitivity analyses are presented below, abbreviated when possible.

Gasoline Price Sensitivity

The price of gasoline has recently been volatile so it is impossible to examine a range of future costs. In order to investigate the potential effect of gasoline price variance, the payback analysis was performed for gasoline costs of $2.62 and $4.62/gallon, one dollar higher and lower than the baseline cost of $3.62/gallon.

Note that all gasoline prices are in 2012 dollars, so the price actually paid by consumers in future years would rise over time with inflation in all of these cases but the relative cost ratios would remain the same.

Overall the results indicate:

- **As expected, PEVs become more favorable as gasoline prices rise.** With lower gasoline prices, the Volt and LEAF have a lower total cost advantage and may have a cost disadvantage, and achieving payback will take an extended time period. With higher gasoline prices, the low gasoline usage of the PEVs gives these vehicles a substantial cost advantage. However, due to the close balance of capital costs and operating costs, payback may still take 10 years or more for some customers.

Chevrolet Volt

Figure 5-1 shows the average total cost of the Volt and its comparison vehicles with varying gasoline costs. The vehicles that use more gasoline are more sensitive to the price of gasoline, so as gasoline prices rise the hybrids become more favorable than the generic conventional vehicle, and the Volt becomes even more favorable. As gasoline prices fall, the capital costs become dominant and the generic conventional vehicle becomes the lease expensive option.

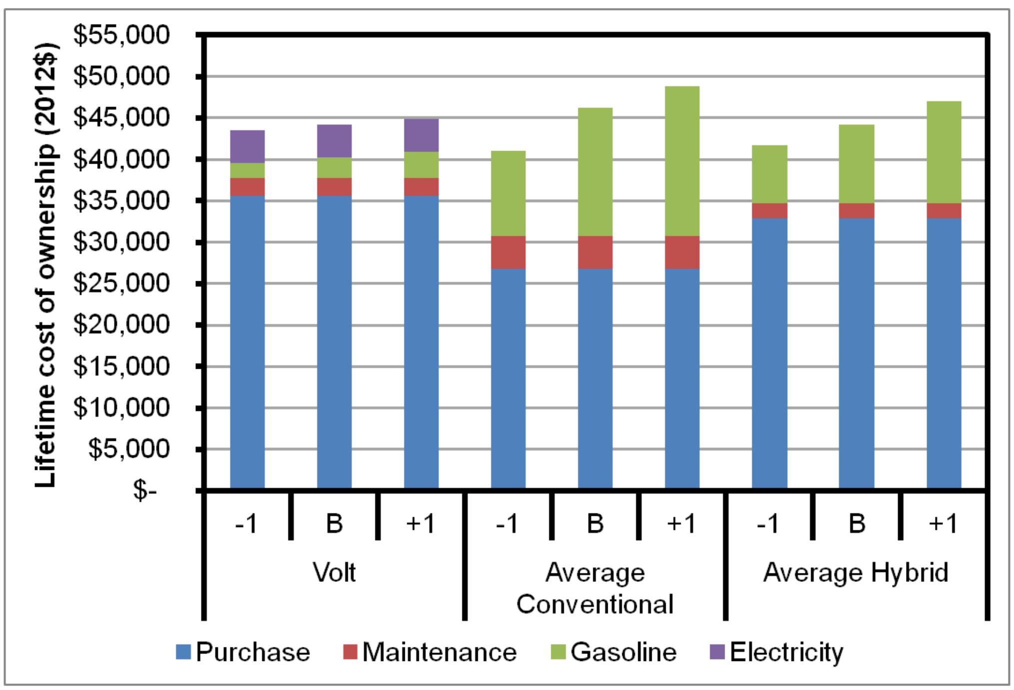

Figure 5-1
Average Total Cost of Ownership for the Chevrolet Volt and Comparison Vehicles with Gasoline Prices of +/- $1

Figure 5-2 and Figure 5-3 show the variation in lifetime cost differences for these two gasoline cost cases. As indicated above, Figure 5-2 shows that with less expensive gasoline the Volt is more expensive than the average conventional vehicle and average hybrid vehicle for all drivers.

If gasoline costs rise, the Volt has a substantial cost advantage on average and is less expensive than the comparison vehicles for almost all drivers.

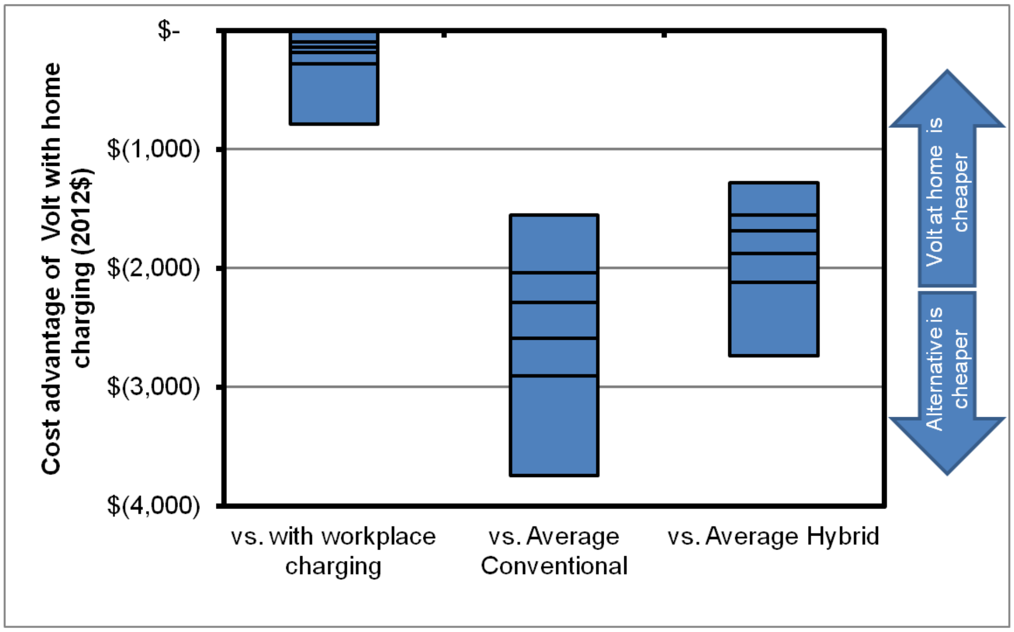

Figure 5-2
Cost Difference Variation for Chevrolet Volt Alternatives with Gasoline Prices of $2.62/gallon

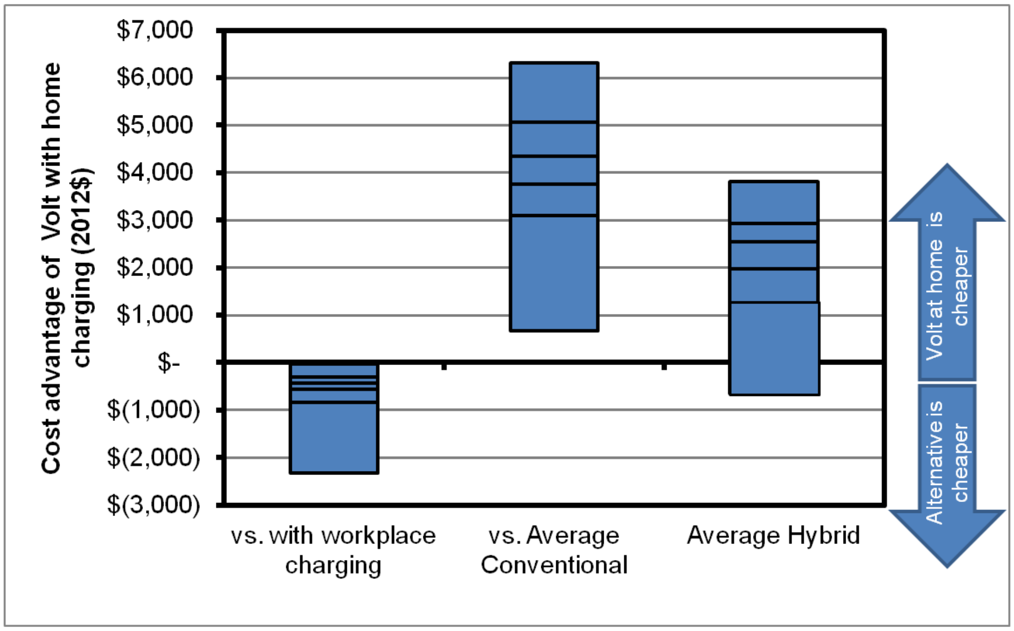

Figure 5-3
Cost Difference Variation for Chevrolet Volt Alternatives with Gasoline Prices of $4.62/gallon

The Volt loan comparison results in similar sensitivity to gasoline prices. Figure 5-3 shows the average monthly expenditure during the loan period for the Volt and the comparison vehicles. Interestingly, even with high fuel prices the cost of gasoline is overwhelmed by the loan payments, so the Volt is a more expensive option on a monthly basis in all cases. However, the variation in gasoline prices has a significant impact on payback time. Figure 5-5 shows the payback time variation for a gasoline price of $2.62/gallon. As indicated by the total cost analysis above, the Volt is more expensive for all customers. Figure 5-6 shows the payback time variation for a gasoline price of $4.62/gallon. As expected, payback is substantially accelerated. However, the additional cost of financing has a significant effect on the capital/operating cost tradeoff and decreases the clear cost advantage seen in Figure 5-3.

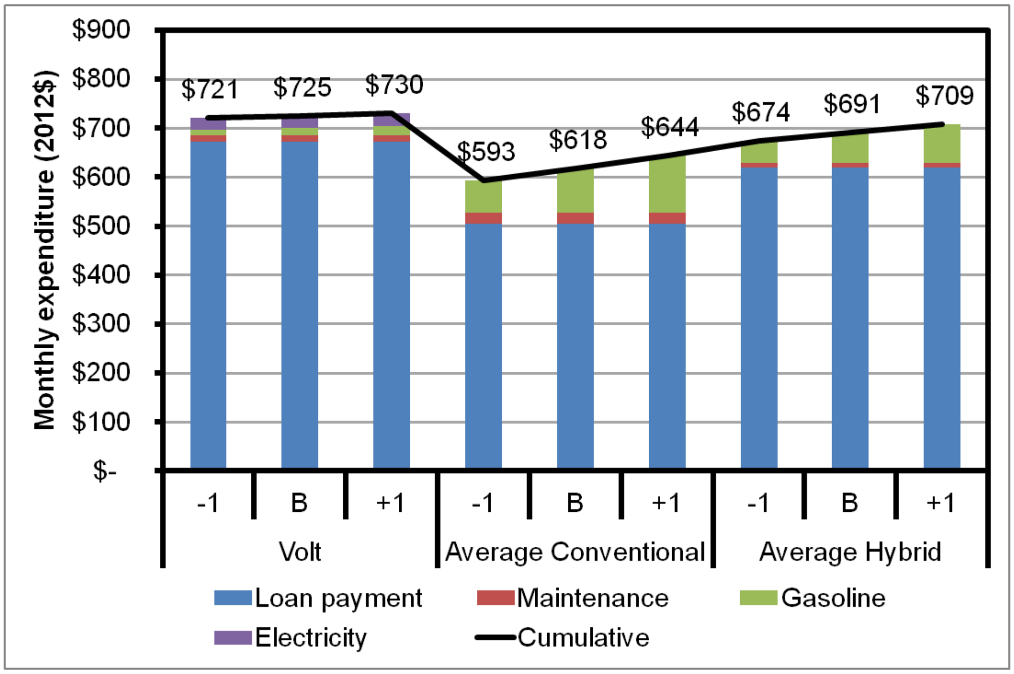

Figure 5-4
Average Monthly Expenditure for Chevrolet Volt and Comparison Vehicles during the Finance Period with Gasoline Prices of +/- $1

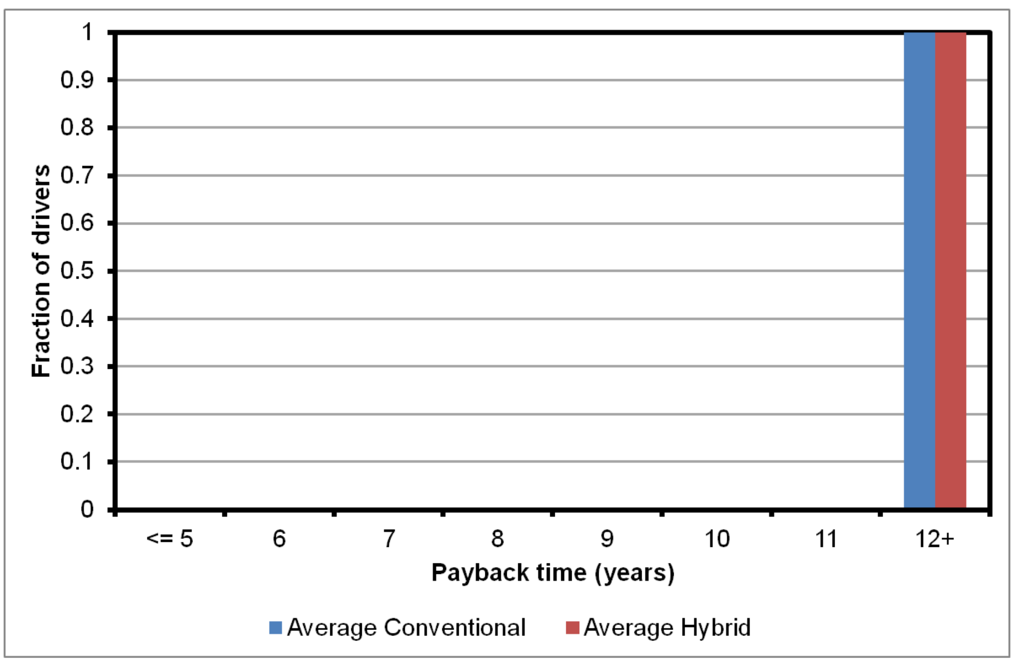

Figure 5-5
Payback Time Variation for Volt Relative to Comparison Vehicles with Gasoline Prices of $2.61/gallon

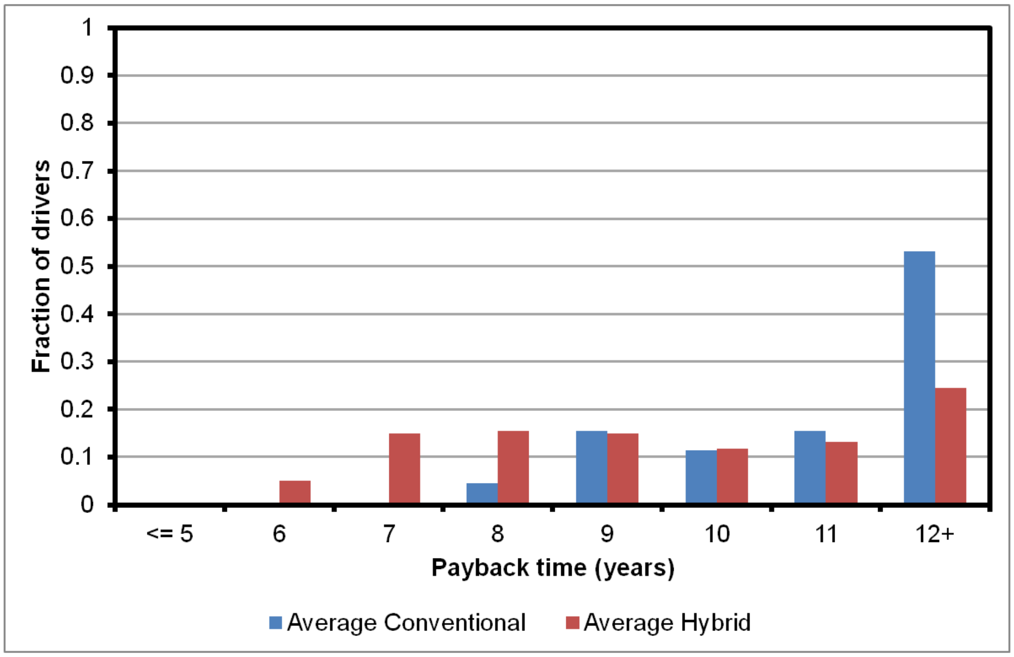

Figure 5-6
Payback Time Variation for Volt Relative to Comparison Vehicles with Gasoline Prices of $4.61/gallon

Nissan LEAF

Figure 5-7 shows the average total cost of ownership for the Nissan LEAF and its comparison vehicles with varying gasoline prices. As expected, the sensitivity of the comparison vehicles to the price of gasoline is higher than the sensitivity of the LEAF, but perhaps surprisingly the sensitivity of the LEAF is not zero in this comparison. This nonzero value is due to the assumed use of a gasoline replacement vehicle on driving days beyond the range of the LEAF.

Figure 5-8 shows the variation in total cost differences between the Nissan LEAF and its comparison vehicles for gasoline costing $2.62/gallon. The LEAF is less expensive than the average conventional vehicle and average hybrid vehicle for a majority of drivers, but for a lower amount than in the baseline case.

Figure 5-9 shows the same comparison for a gasoline cost of $4.62/gallon. In this scenario the LEAF is less expensive than the average conventional vehicle and average hybrid for almost all drivers.

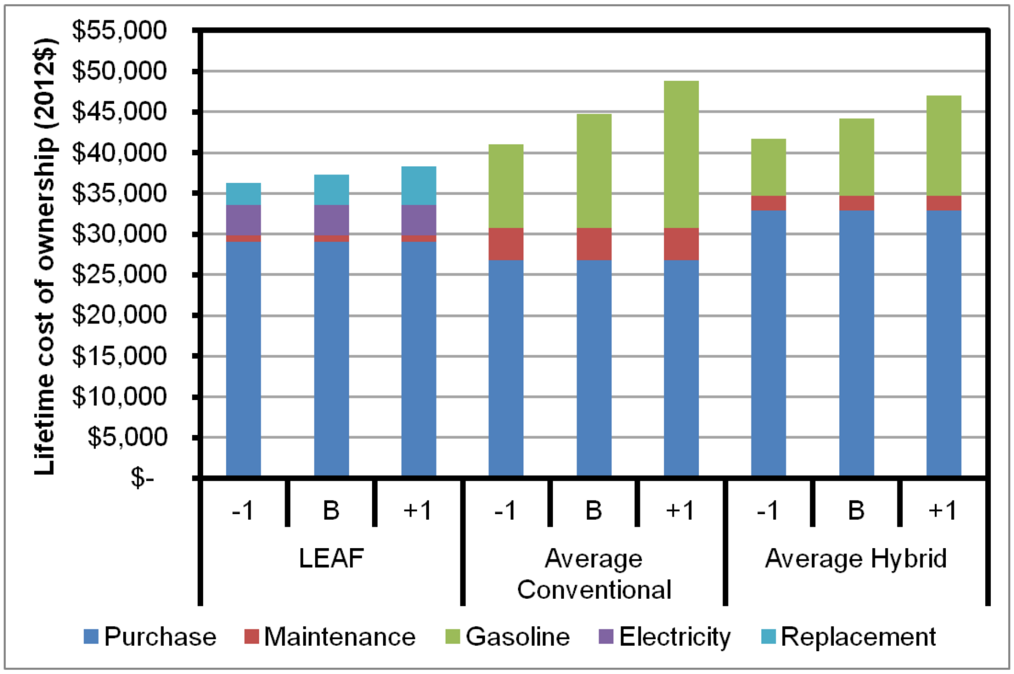

Figure 5-7
Average Total Cost of Ownership for the Nissan LEAF and Comparison Vehicles with Gasoline Prices of +/- $1

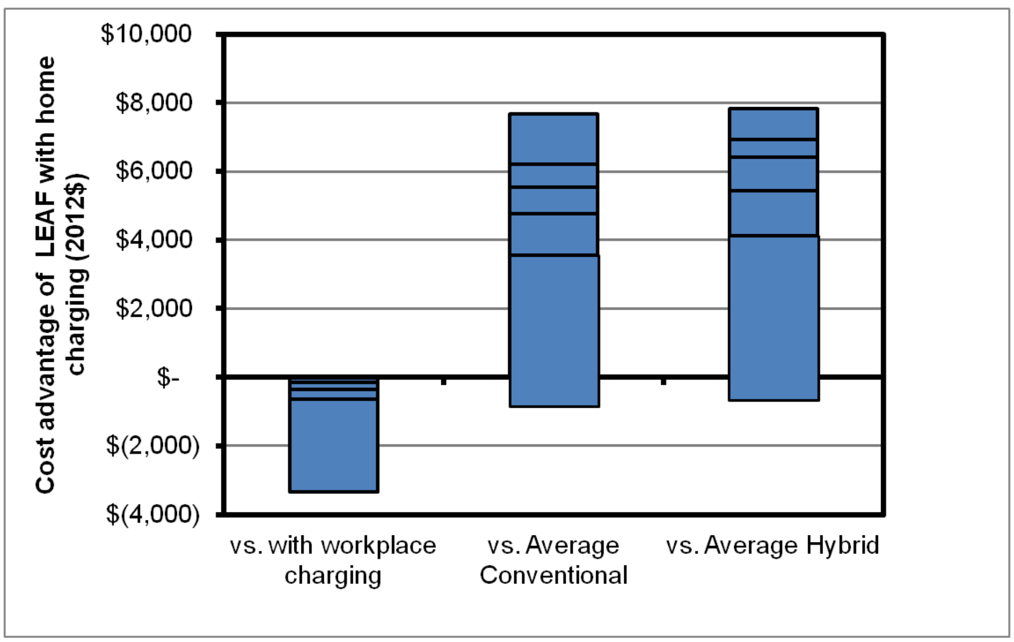

Figure 5-8
Cost Difference Variation for Nissan LEAF Alternatives with Gasoline Prices of $2.61/gallon

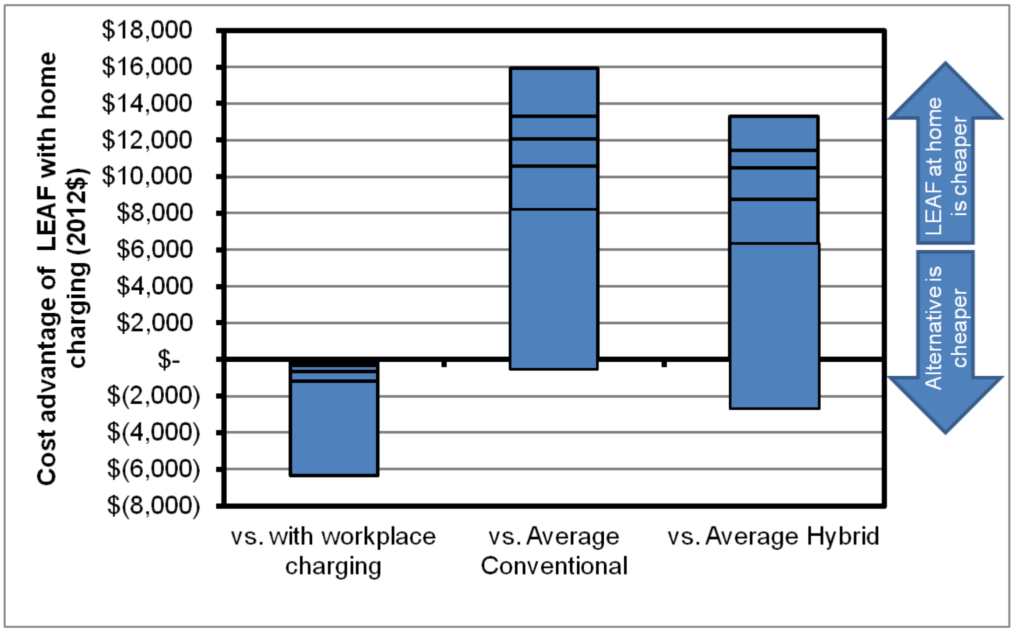

Figure 5-9
Cost Difference Variation for Nissan LEAF Alternatives with Gasoline Prices of $4.61/gallon

Varying gasoline prices have a similar effect on the comparison between a financed purchase of a LEAF and its comparison vehicles: the lower sensitivity of the LEAF to the price of gasoline means that its relative costs improve substantially with increased gasoline costs. Figure 5-10 shows the average monthly costs during the financing period for the LEAF and its comparison vehicles. Figure 5-11 and Figure 5-12 show the payback period in each case. With a gasoline price of $2.62/gallon, payback relative to the average conventional vehicle happens over 6-9 years (all drivers see payback within the financing period relative to the generic hybrid). With a gasoline price of $4.62/gallon, payback occurs within the finance period for almost all drivers.

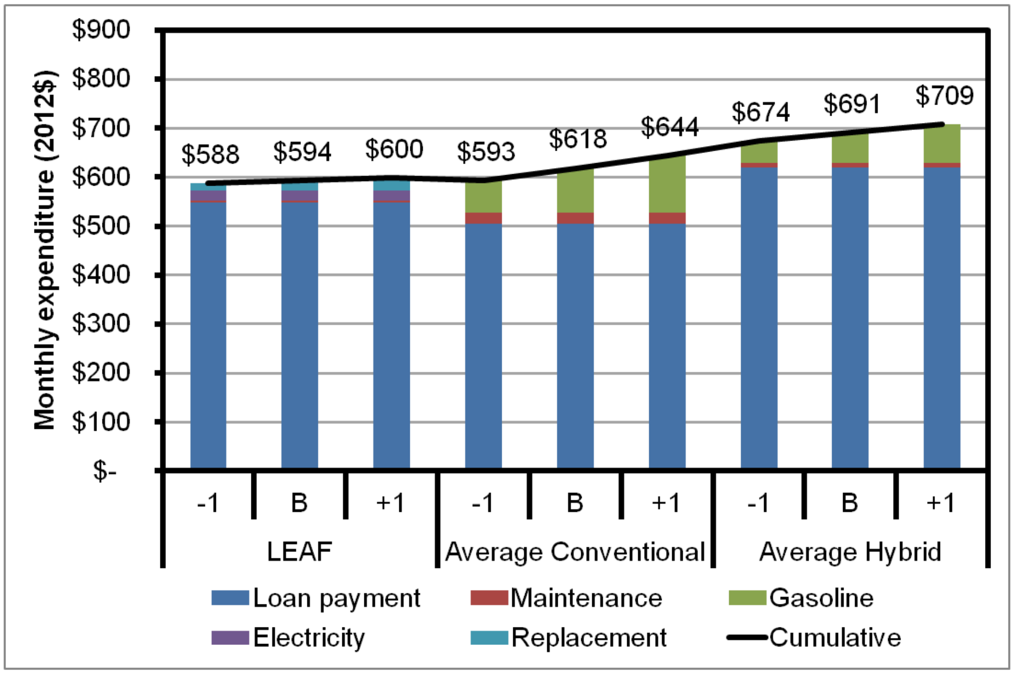

Figure 5-10
Average Monthly Expenditure for Nissan LEAF and Comparison Vehicles during the Finance Period with Gasoline Prices of +/- $1

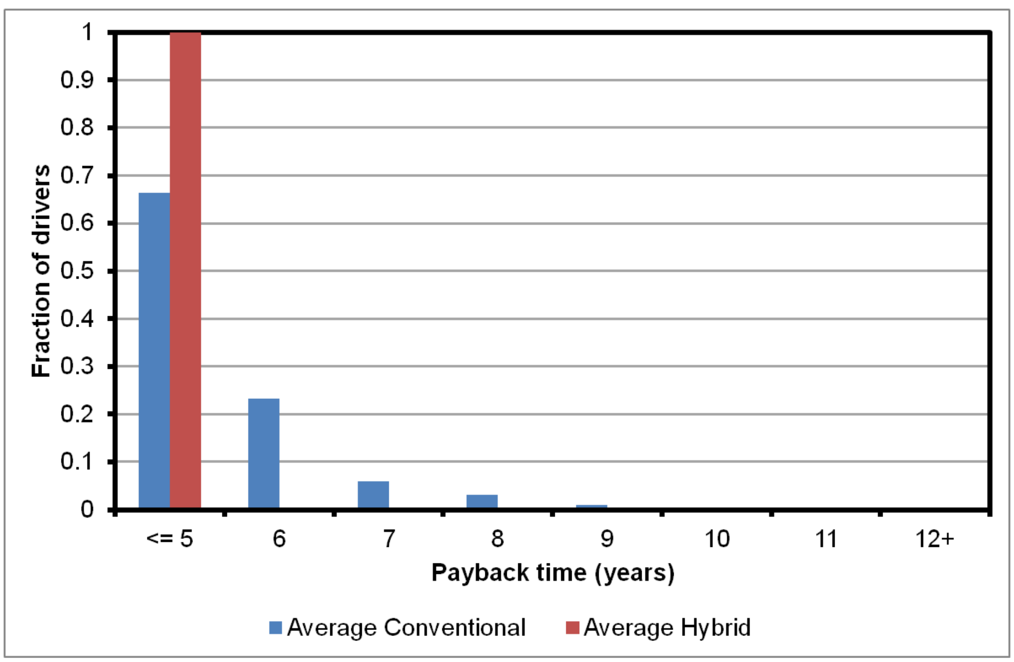

Figure 5-11
Payback Time Variation for the LEAF Relative to Comparison Vehicles with Gasoline Prices of $2.62/gallon

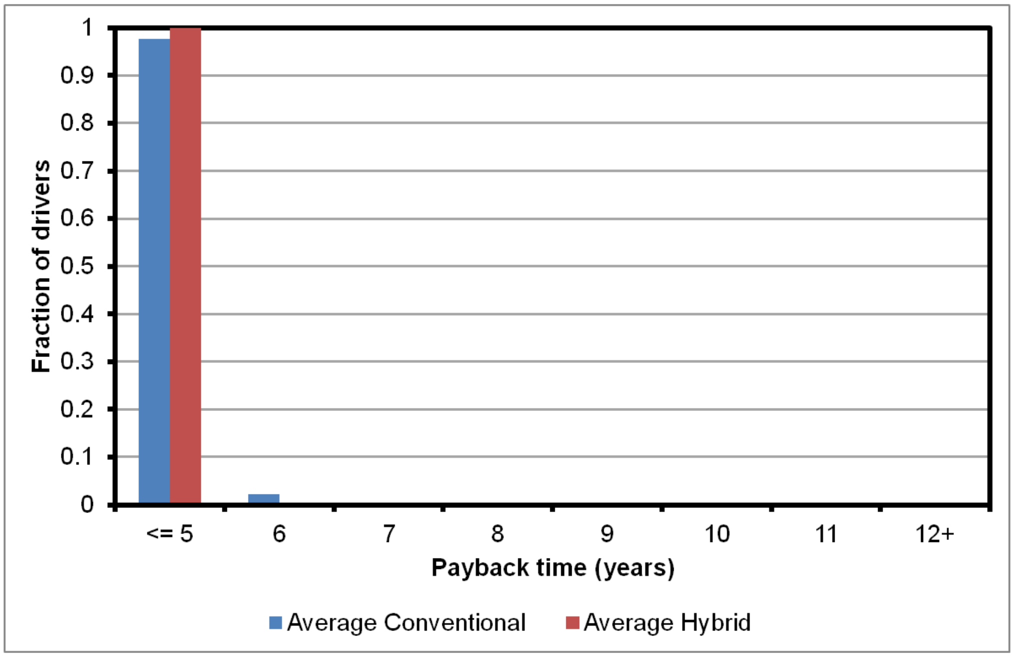

Figure 5-12
Payback Time Variation for the LEAF Relative to Comparison Vehicles with Gasoline Prices of $4.62/gallon

Replacement Cost Sensitivity

One important assumption in this analysis is that the potential buyer of a LEAF has a second car available for use with no daily use fee. In reality there will be some customers who would like to purchase the LEAF as an only car and it is likely that even in households with multiple vehicles there will be some days in which all vehicles will be required to drive beyond the range of the LEAF. It seems likely that self-selection will substantially mitigate this effect — drivers who drive intensively will likely avoid the purchase of a vehicle that will not meet their mobility needs. However, in order to estimate the effects of a daily use fee, the analysis for the LEAF was rerun assuming a daily use fee of $10/day and $20/day for an alternate vehicle (also at a mileage of 24 mpg). The results indicate:

- **A daily use fee has a significant effect on average costs.** Each $10/day increment increased average total ownership cost by about $2,200.
- **Most of the additional costs from a usage fee were incurred by relatively few drivers.** The majority of drivers were relatively unaffected by the usage fee, implying that self selection could be very important in reducing overall costs even if a usage fee is incurred.

- **Analyses based on average usage will likely overstate real costs of replacement days.** The wide variation between different drivers emphasizes the importance of driver self-selection. If analysis is based on average driving patterns alone, it will likely substantially overstate the cost impacts of long driving days.

It should be noted that the driving data available is relatively limited so there are factors that could either increase or decrease the effects of a usage cost. For example, areas with higher proportions of rural drivers would likely have a higher impact from replacement days due to longer driving distances. Costs could be decreased if a driver changed his driving pattern due to the purchase of a LEAF. This adaptation effect is separate from self-selection and has been seen in early deployments, but it is uncertain how large this effect will be as BEVs enter the mass market.

Figure 5-13 shows the average total cost of ownership for the LEAF and its comparison vehicles for the baseline and for additional LEAF scenarios with a daily use fee of $10/day and $20/day for a replacement vehicle. The additional daily use fee adds about $2,200 to the average total ownership cost for the LEAF, making it less competitive relative to the comparison vehicles. However, Figure 5-14 an Figure 5-15, which show the variation in cost differences across drivers, indicate that a large proportion of drivers who benefited from the LEAF in the baseline analysis in Figure 3-5 still generally benefit, but the drivers who were negatively affected by the LEAF are now more negatively affected. So most of the negative impacts of a daily use fee were incurred by the portion of drivers who were already worse off, implying that self-selection will likely be even more important than in the baseline analysis as replacement costs rise.

The pattern of impacts is similar in the loan purchase case, so the results are not reproduced here. As implied in Figure 5-14 and Figure 5-15, the main impact of a usage cost on payback is that there is a general increase in payback times, and there are also some drivers who see no payback.

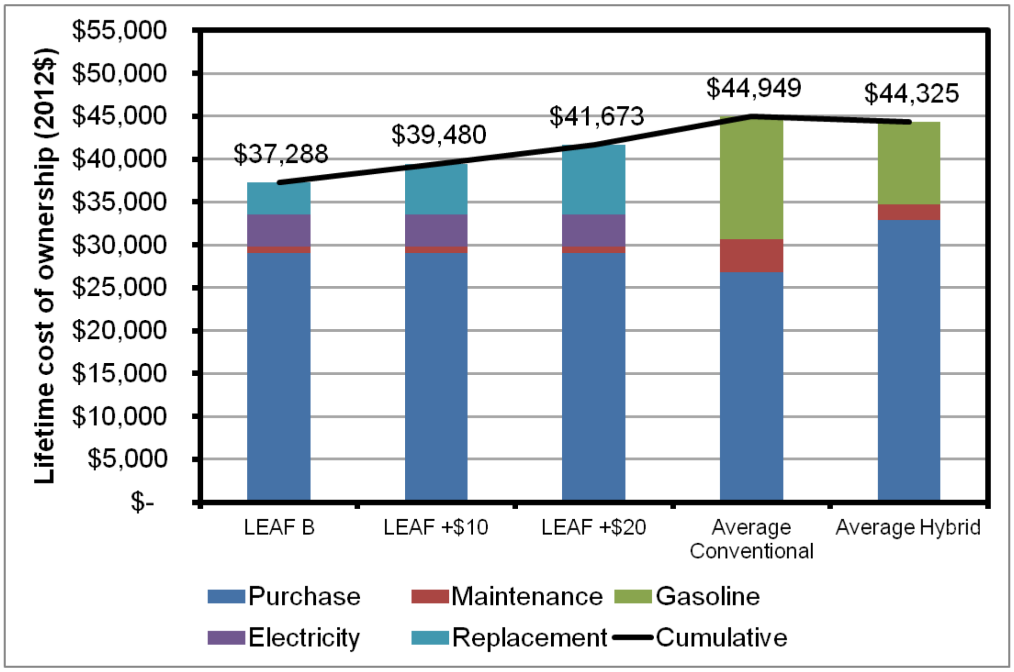

Figure 5-13
Average Total Cost of Ownership for the Nissan LEAF and Comparison Vehicles with a Replacement Cost of $10/day and $20/day ("LEAF B" is the baseline of $0/day)

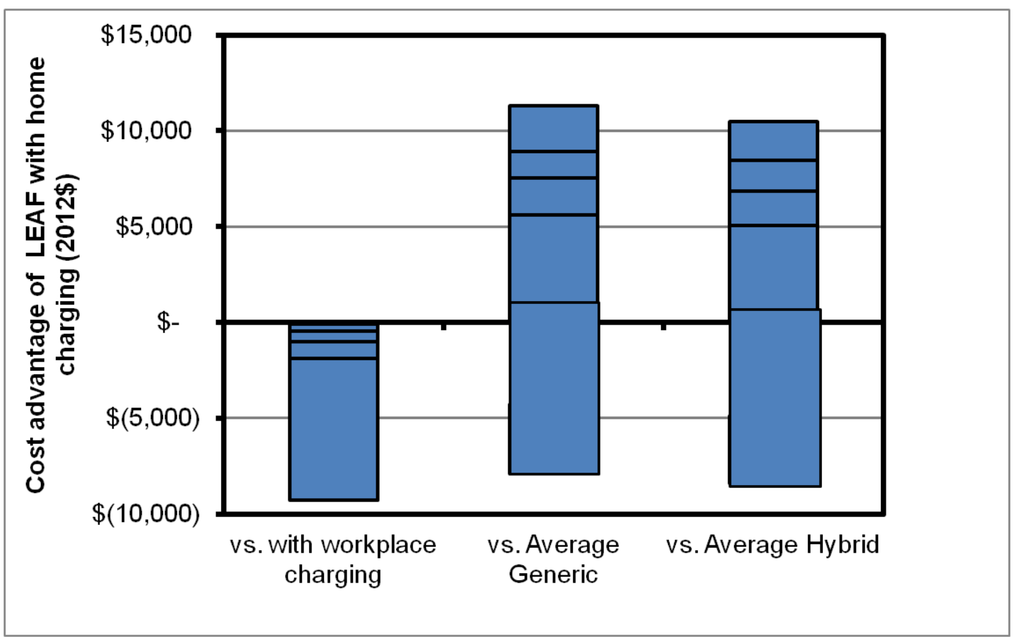

Figure 5-14
Cost Difference Variation for the LEAF and Comparison Vehicles with a $10/day Usage Fee

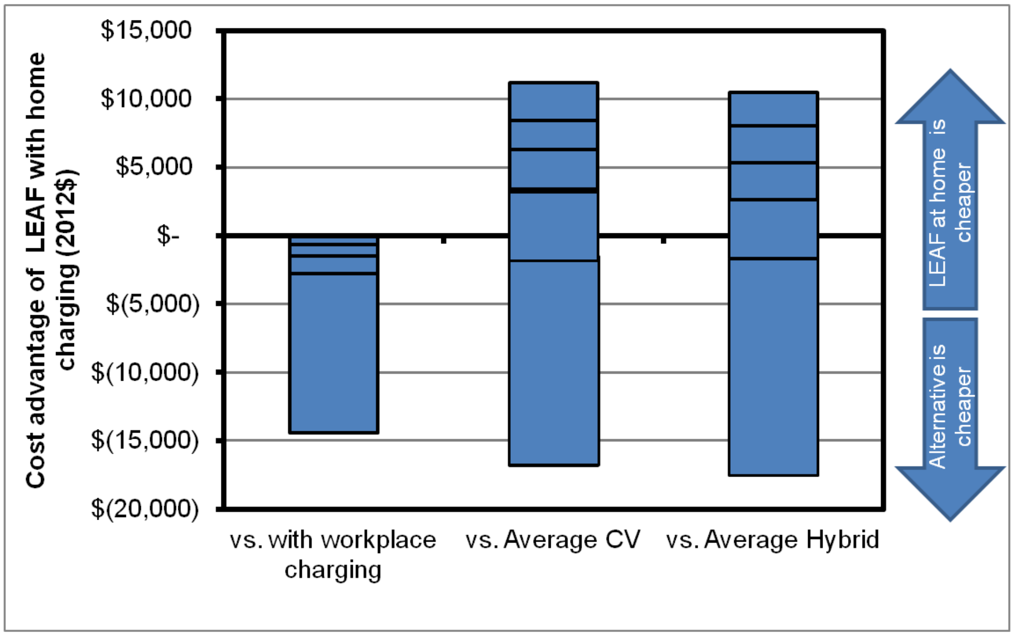

Figure 5-15
Cost Difference Variation for the LEAF and Comparison Vehicles with a $20/day Usage Fee

PEV Incentive Sensitivity

The most influential sensitivity for PEV cost comparisons is PEV capital cost. Although it is likely that capital costs for PEVs will decrease over time, it is difficult to speculate when reductions will occur or by how much. However, there are currently interesting variations to analyze due to state incentives. A wide range of state incentives or rebates are available, from no incentive in most states to $6,000 in Colorado and $7,500 in West Virginia [17, 18]. To explore the effects of these incentives, the analysis was run for California, which has notable market conditions:

- A state vehicle incentive of $1,500 for the Volt and $2,500 for the LEAF is available.
- An EVSE installation incentive covers 50% of the installation cost of an EVSE, and various programs are available for free EVSE installation. For this scenario, the EVSE cost for the LEAF was reduced from $1,500 to $750 (the baseline Volt cost estimate assumed an EVSE was not installed at home).
- Gasoline is typically more expensive in California than the nationwide average. Based on the 12-month rolling average a gasoline price of $4.04/gallon was used, 43 cents higher than the national average.
- Low-cost off-peak electricity is available. However, due to the generally higher electricity costs in California this discount brings the costs down to $0.10/kWh, 2 cents less than the national average.

The results indicate that these changes have a significant impact on the relative costs of PEVs. In particular:

- **The Volt is very cost competitive.** The Volt is substantially less expensive in terms of average total ownership cost for all drivers. Payback on financed purchase is also achieved for almost all drivers, although payback happens over an extended period relative to the conventional vehicle for the least favorable drivers.
- **The LEAF is the most cost competitive option.** The reduced capital cost of the LEAF in California due to the large state incentives and already-low operating costs make the LEAF significantly less expensive than the competitive options on average. All drivers in this sample achieve payback within the financing period.

Chevrolet Volt

Figure 5-16 shows the comparison in average total ownership costs in California. The Volt is substantially less expensive than the comparison vehicles due to the favorable market conditions. However, a significant portion of the total expenditures for competitive options is for gasoline, which is spread out over the full vehicle life. Figure 5-17 indicates that during the five years of the finance period the monthly expenditures are similar for each of the options, with an average cost advantage of $40-$70/month for the generic conventional vehicle. This means that even though the Volt is less expensive over time, payback will occur after the financing period is over. Figure 5-18 shows that the Volt will occur over 8–15 years relative to the conventional vehicle. Relative to the average hybrid, payback for the Volt happens during the finance period for all drivers.

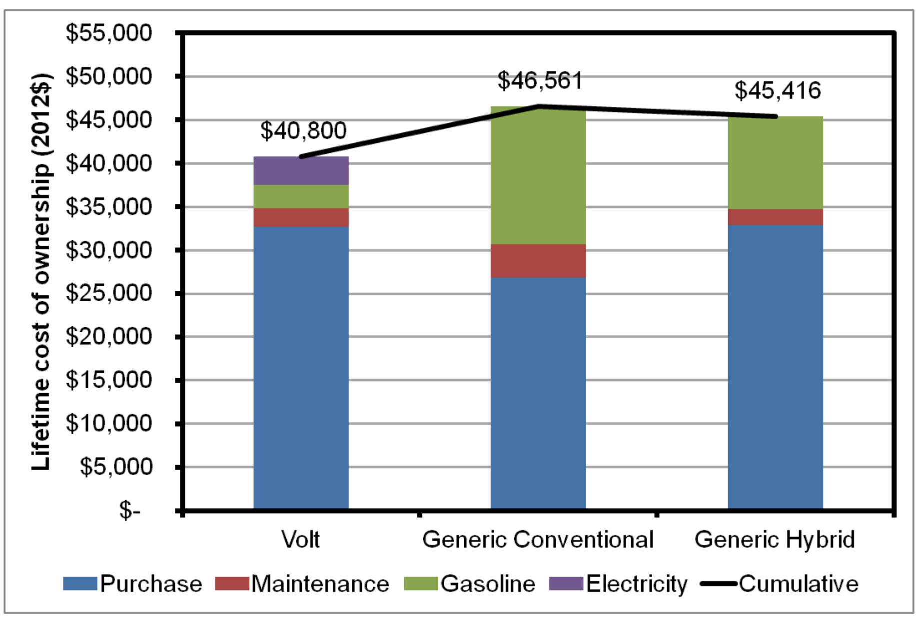

Figure 5-16
Average Total Cost of Ownership for the Chevrolet Volt and Comparison Vehicles in California

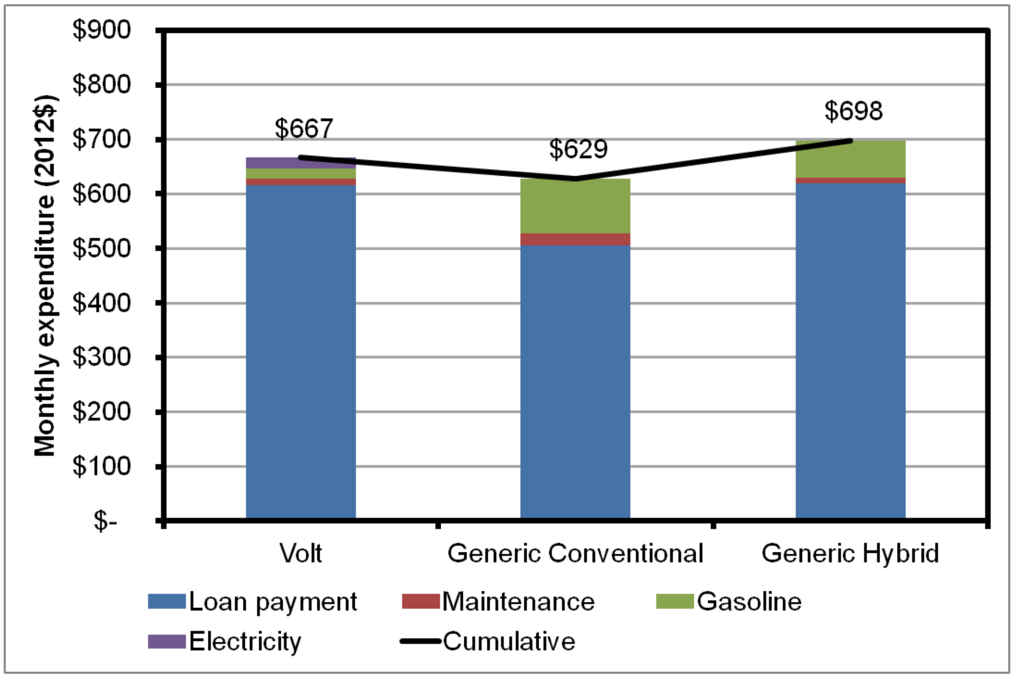

Figure 5-17
Average Monthly Expenditure for Chevrolet Volt and Comparison Vehicles during the Finance Period in California

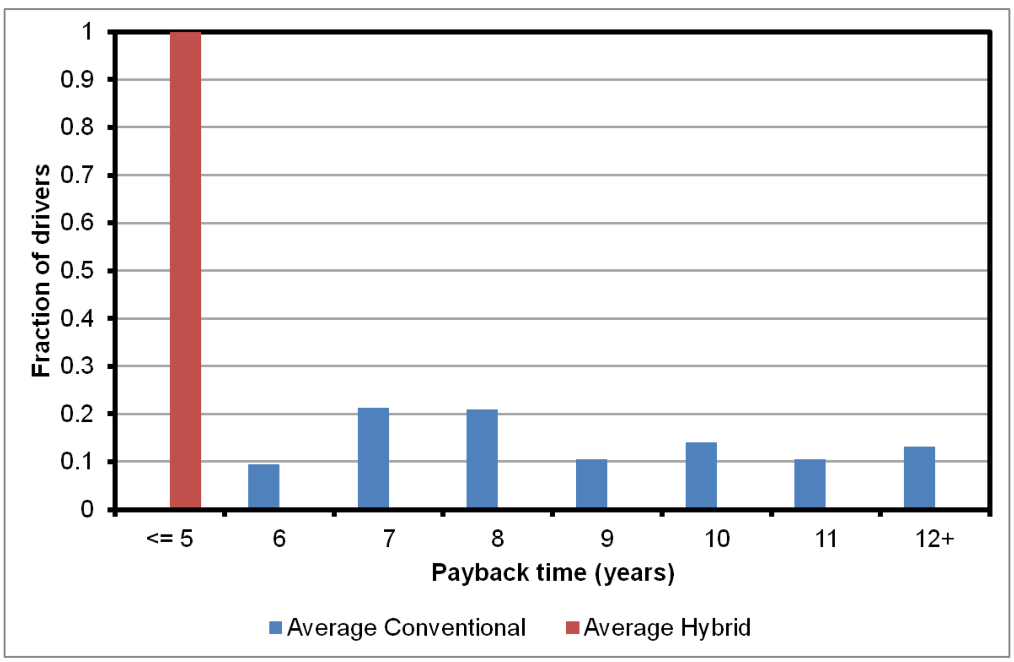

Figure 5-18
Payback Time Variation for the Chevrolet Volt Relative to Comparison Vehicles in California

Nissan LEAF

The additional state incentives in California are substantial—in this analysis the combined benefit of $3,250 is almost 10% of the total ownership costs. As shown in Figure 5-19, this difference combined with the fuel cost advantage in California make the LEAF about $11,000 less expensive than the other comparison vehicles. Due to the relatively low capital cost of the LEAF in California, the monthly cost during the finance period is also lower than competing options so payback will be achieved quickly. Figure 5-20 shows the comparison of monthly costs, and Figure 5-21 shows the payback time for the LEAF. All sample drivers achieve payback within the financing period. These results indicate that the relative costs are quite favorable for the LEAF in California.

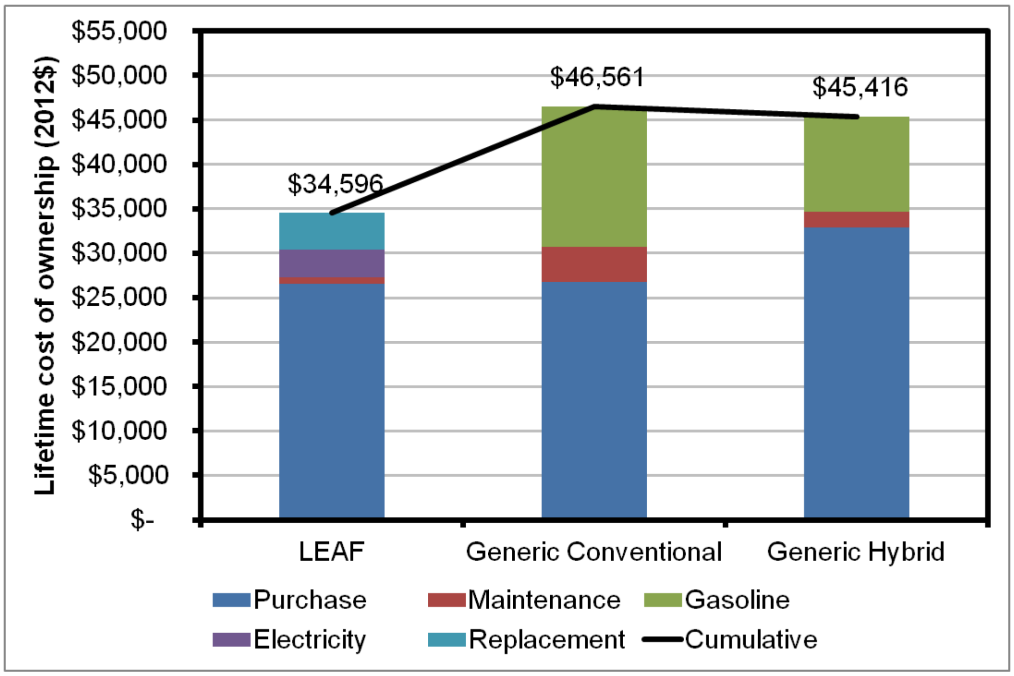

Figure 5-19
Average Total Cost of Ownership for the Nissan LEAF and Comparison Vehicles in California

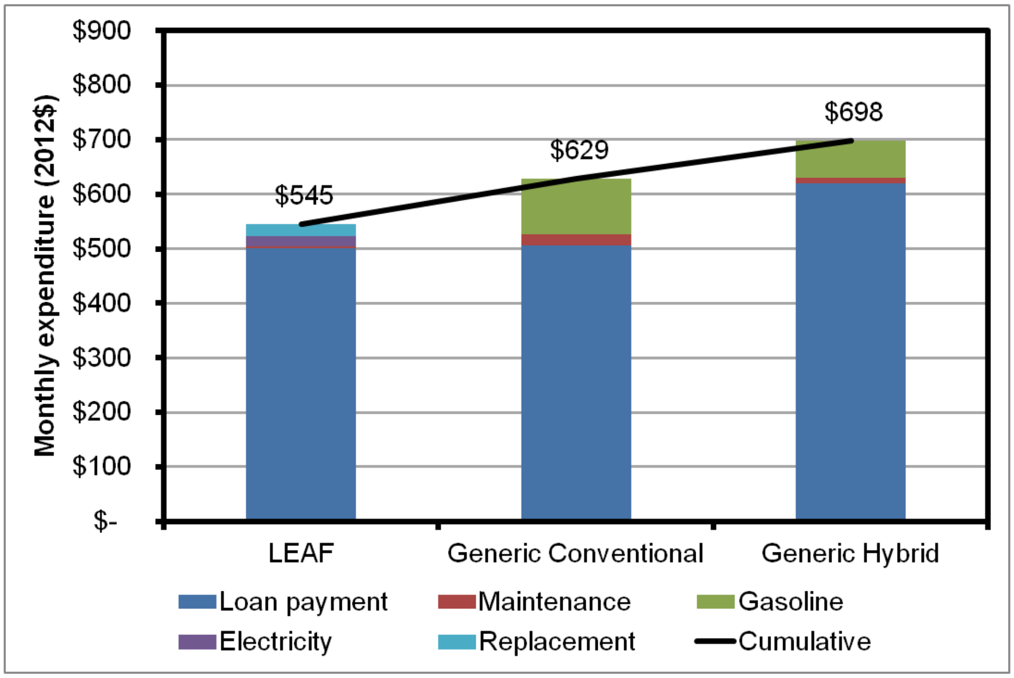

Figure 5-20
Average Monthly Expenditure for the Nissan LEAF and Comparison Vehicles During the Finance Period in California

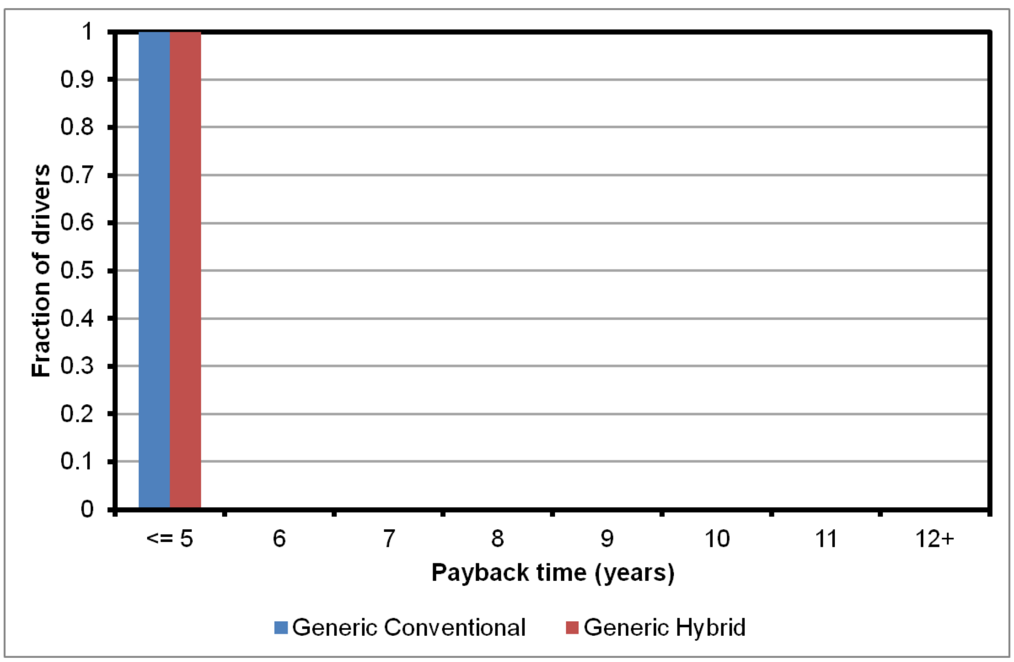

Figure 5-21
Payback Time Variation for the Nissan LEAF Relative to Comparison Vehicles in California

Section 6: References and Bibliographies

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Appendix A: Comparison of National Household Travel Survey and Puget Sound Datasets

The National Household Travel Survey (NHTS) has often been used for vehicle analysis applications by EPRI and other organizations. However, for this study the NREL Puget Sound dataset [12] was used to better characterize the lifecycle costs associated with driving PEVs, since it provided a longitudinal driving sample for each vehicle, which allowed analysis of both driving pattern intensity and consistency. The NHTS has the advantages of national scope and well-structured demographic weighting, but only samples each household for one driving day. The ability to analyze driving over an extended time period is particularly important for understanding the operating cost of BEVs, since driving consistency can have a particularly high impact on BEV costs. However, the Puget Sound dataset has some disadvantages: it is based on electronically captured data so it is not always clear why an unexpected behavior occurred and it only covers a limited geographical area so it does not exactly match expected national driving patterns. These disadvantages are discussed in more detail below.

One unexpected characteristic of the Puget Sound data is that a large number of cars were away from home for long periods. Although this behavior is possible, previous analysis of the NHTS indicates that it is unusual [11]. Since locational data was removed from the Puget Sound data to insure privacy of the participants, it is impossible to determine whether this unexpected behavior is due to bad data capture or an actual driving pattern that included long periods away from home. Since the baseline analysis assumed home charging as the only charging source, long periods away from home would be unachievable for BEVs and unlikely for PHEVs. For this analysis, drivers who were away from home for too long or for a large number of days per year were excluded. As shown in Figure A-1, this was a relatively small number of drivers, relatively equally distributed across different annual miles traveled bins. The remaining vehicles, in blue, were used in this analysis.

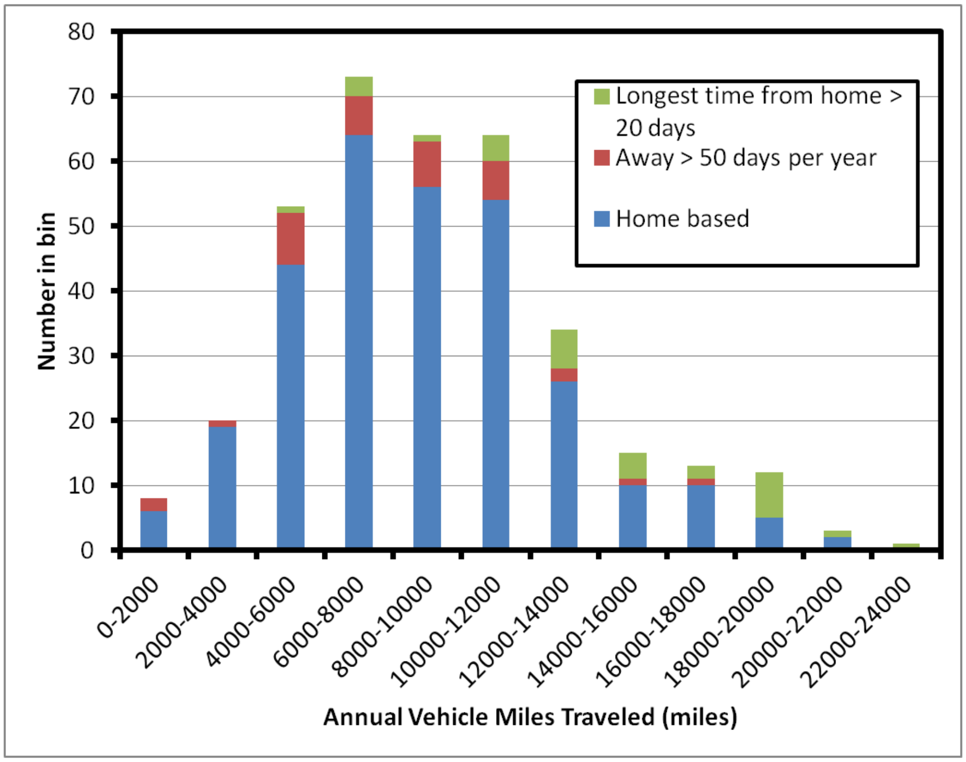

Figure A-1
Distribution of Annual Driving in Puget Sound Dataset for Drivers Used and Excluded

The NREL Puget Sound dataset was then compared to three subsets of the NHTS population: vehicles ten years and younger ('NHTS young'), vehicles in an urban area ('NHTS urban') and vehicles meeting both of these characteristics ('NHTS young & urban'). These metrics were chosen based on the fit of the data as well as the characteristics of Puget Sound. One of the most important characteristics of driving patterns for cost comparisons is the driving intensity, or the annual amount of vehicle miles traveled. Figure A-2 shows the driving intensity for the NHTS samples and the Puget Sound dataset. The Puget Sound dataset is grouped towards the center of the distribution, while the NHTS has a higher percentage of vehicles with low driving intensity and a higher percentage of vehicles with higher driving intensity. It is a concern that high-intensity vehicles do not appear to be well represented in the Puget Sound data. However, it is possible that the NHTS is overestimating driving intensity. Since the NHTS samples only one driving day, annual mileage is imputed. Figure A-3 shows the average one-way commute for each sample and Figure A-4 shows the average daily distance for both samples, which both indicate that the Puget Sound dataset is a relatively close match for the NHTS, despite the apparent lack of high intensity drivers in Figure A-2. Given the limitations of these datasets, the Puget Sound vehicles with between 6,000 and 14,000 miles per year are used for this analysis. This sample has good coverage in the Puget Sound dataset, represents about 45% of the NHTS sample, and corresponds reasonably well with the average annual vehicle mileage of 11,800 miles per year calculated from the Transportation Energy Book for the year 2009 [20], although it likely excludes some high-intensity vehicles. More research will be required to create a representative national sample appropriate for future analyses.

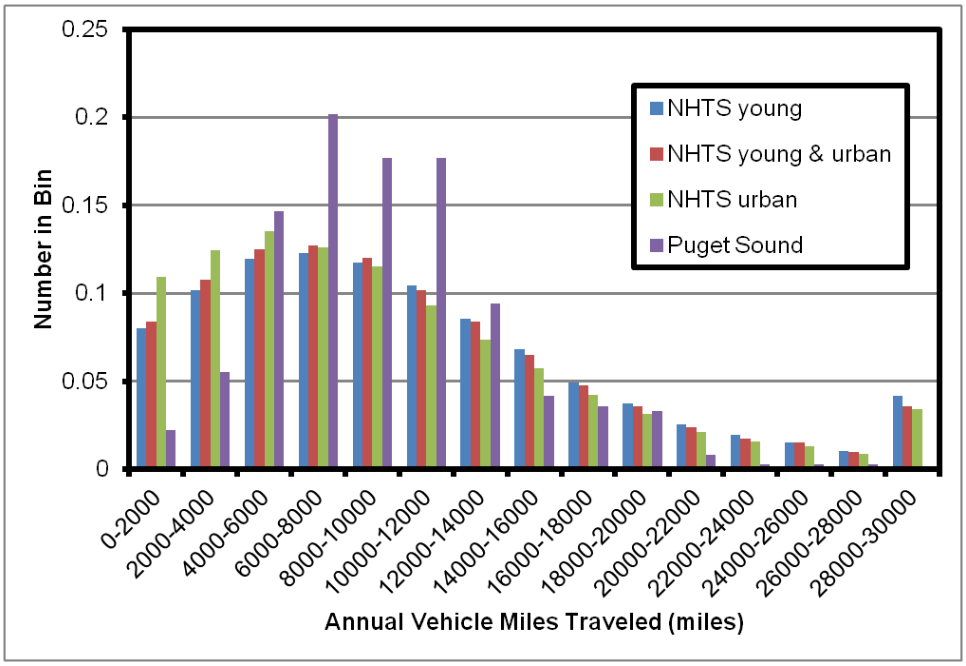

Figure A-2
Comparison of Annual Miles Between the Puget Sound Dataset and the NHTS

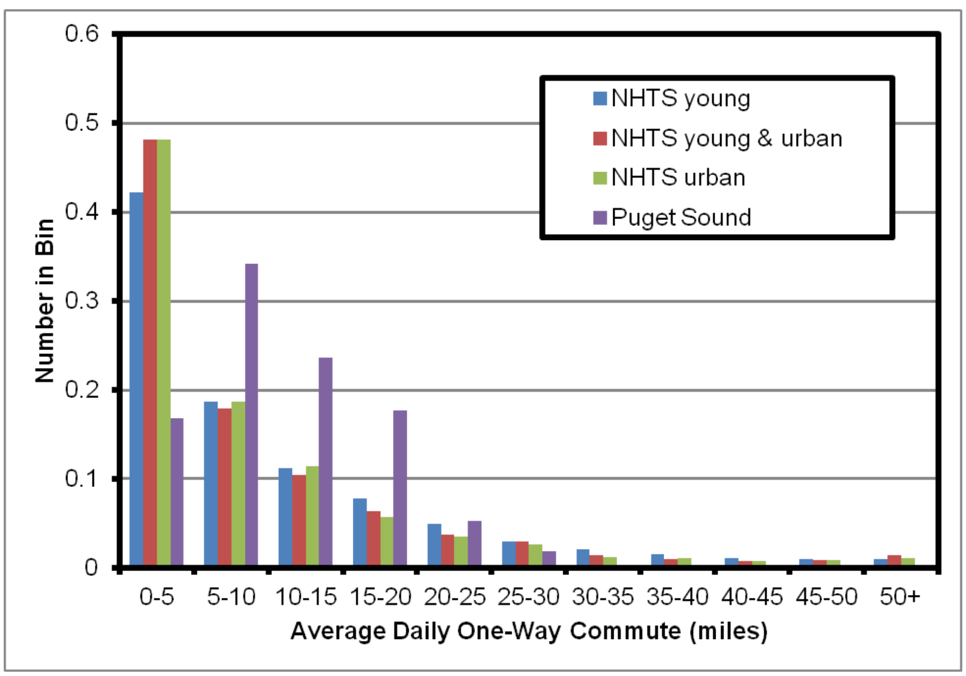

Figure A-3
Distribution of Average Daily One-Way Commute for Both the Selected NHTS Subsets and the Puget Sound Data

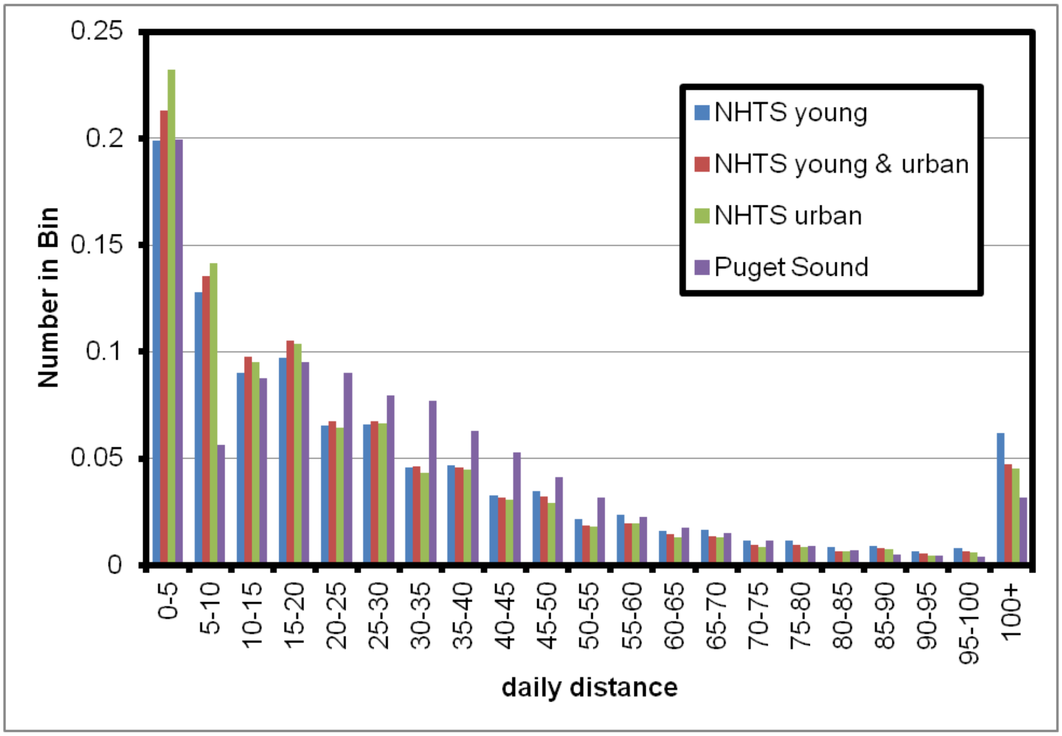

Figure A-4
Distribution of Daily Total Miles Driven for Both the Selected NHTS Subsets and the Puget Sound Data

Appendix B: Maintenance Cost Model

The model used to estimate maintenance schedules is based on owner's manuals for Model Year (MY) 2012 vehicles. The pricing is from Edmunds.com for zip code 94304 (Palo Alto, CA) for all vehicles [13]. While most maintenance schedules analyzed had an option for time duration, a mileage-based model was chosen for a lifetime maintenance schedule of 150,000 miles. Since maintenance costs could not be averaged for the generic comparison vehicles, the generic hybrid uses the maintenance schedule for the Toyota Prius, and the generic conventional vehicle (CV) uses the maintenance schedule for the Chevrolet Cruze. The following figure shows the annual maintenance costs for the four vehicles in the study.

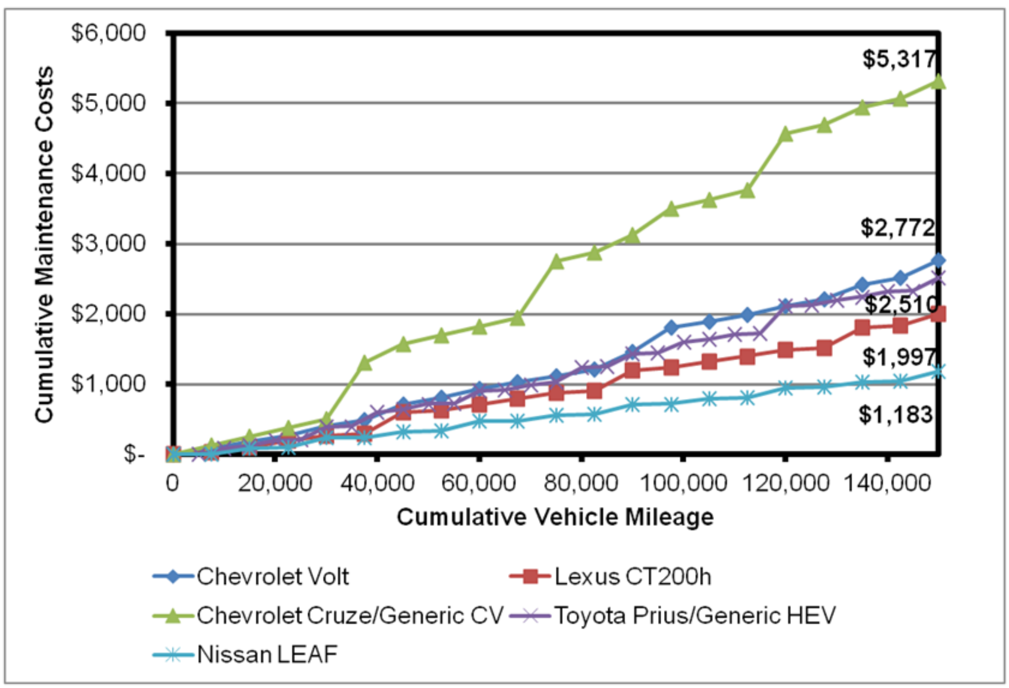

Figure B-1
Cumulative Lifetime Maintenance Costs (2012$), Mileage Based, for Vehicles Used in Stud

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