THESIS

UNDERSTANDING THE EFFECTS AND INFRASTRCUTURE NEEDS OF PLUG-IN ELECTRIC VEHICLE (PEV) CHARGING

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ABSTRACT

UNDERSTANDING THE EFFECTS AND INFRASTRCUTURE NEEDS OF PLUG-IN ELECTRIC VEHICLE (PEV) CHARGING

Plug-in electric vehicles (PEV) are any vehicle that uses electricity to propel the vehicle, potentially in combination with other fuels like gasoline, diesel or hydrogen. PEV offer the benefits of reduced dependence on foreign oil and decreased greenhouse gas emissions. While the benefits are numerous for this new technology, the drawbacks are not fully understood. The largest concern for the utility company is to understand the necessary infrastructure requirements to minimize their impacts on the electric grid. This study focuses on the infrastructure needs and effects and how to best control PEV charging. The results of these analyses show the fundamental disconnect between the consumer and the utility company.

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LIST OF ABBREVIATIONS

A	-	Ampere
AC	-	alternating current
AER	-	all-electric range
AFV	-	alternative fuel vehicle
CAFE	-	corporate average fuel economy
CD	-	charge-depleting
CO	-	carbon monoxide
CO2	-	carbon dioxide
CS	-	charge-sustaining
CV	-	conventional vehicle
DC	-	direct current
DOE	-	Department of Energy
EPRI	-	Electric Power Research Institute
EV	-	electric vehicle
GHG	-	greenhouse gas
HEV	-	hybrid electric vehicle
INL	-	Idaho National Laboratory
kW	-	kilowatt
kWh	-	kilowatt hour
NHTS	-	National Household Transportation Survey
NMTOC	-	non-methane total organic compounds
NO	-	nitrous oxide
NREL	-	National Renewable Energy Laboratory
OEM	-	original equipment manufacturer
PEV	-	Plug-in electric vehicle
PG&E	-	Pacific Gas and Electric
PHEV	-	Plug-in hybrid electric vehicle
SAE	-	Society of Automotive Engineers
SUV	-	sport utility vehicle
TCO	-	total cost of ownership
TOU	-	Time of use
UC Davis	-	University of California- Davis
UF	-	utility factor
US	-	United States
V	-	volt
V2G	-	vehicle-to-grid
VMT	-	vehicle miles traveled
ZEV	-	zero-emission vehicle

1.0 INTRODUCTION

Plug-in Hybrid Electric Vehicles (PHEV) is a type of hybrid-electric vehicle that can store and use electric energy from the grid to propel the vehicle. PHEV are an emerging technology that can help improve the sustainability of personal transportation. Some benefits to consumers of PHEV are a reduction in emissions[1,2], discounted utility rate structures[3], and decreased fuel consumption. PHEV are one of many suggested new vehicle technologies.

As an emerging technology, neither the negative or positive effects of PHEV are still fully understood. The main concerns over PHEV are possible increases in pollutants from increased usage of coal-fired power plants[4], increased peak load due to daytime and evening charging[5], uncertain infrastructure needs, increased cost of electricity generation[6] and maintenance[7], higher up-front costs, and uncertain payback periods[8]. These topics are being studied through both consumer and utility viewpoints.

Charging behavior is an area of particular interest because it directly affects both the utility and the consumer. Controlled charging behavior benefits utilities in that it reduces daytime demand. Three main charging scenarios are being researched. First, allowing consumers to freely charge based upon the assumption that they will choose to charge as directed, solely at-home, or during off-peak periods, as described by a TOU rate structure. Second, allowing consumers to charge at both their home and place of work. Third, individuals charge wherever they can and as often as they can. Currently, all three options are of concern to the utility company as understanding charging behavior directly affects their demand.

While residential charging behavior is likely to be sufficient for PHEV, electric vehicles (EV), a second type of PEV, will require a higher number of locations to charge. However, charging infrastructure is expensive, and where to build it and who will pay for it are two questions that are being asked. This same problem occurred in the mid-1990s with the introduction of the EV1 and RAV4 EV; significant expensive infrastructure was built and maintained within the state of California and much of it was never used[24]. This was due both to oversaturation of charging infrastructure, and infrastructure that was installed in less-than-ideal locations. Effective planning and installation is important to meet the needs of future EV drivers.

A new question that is arising is the rate (kW) at which the charging should take place. The PEV that are currently coming to market have the ability to charge at rates between 1.44 kW and 19.2 kW, and faster commercial charging rates of upwards of 50 kW may soon be available. These faster chargers are generally more expensive and can require additional electricity charges and transformer costs. In addition to costs, new infrastructure can also add challenges to electricity generation and grid management. The potential load changes and costs need to be analyzed before infrastructure is installed.

Actual consumer behavior is unknown; however, both EPRI and UC Davis have conducted interviews, panel discussions and sample studies with potential and actual early adopters. From 2006-2009 UC Davis conducted three different studies to better understand the acceptance[9], driver opinions[10], and consumer interface of PHEV[11]. In

2009, a group of expected early adopters from Southern California Edison customers were interviewed in order to better understand their fears, ideas and knowledge as to how they would operate and own a PHEV[12]. These particular studies give some answers as to how consumers will drive and charge their vehicles, what they are willing to pay for and who will purchase them.

PEV are not the only emerging technology in advanced vehicle technology. Many proponents of alternative vehicles are encouraging the spread and usage of hydrogen as a fuel source[13,14,15]. Hydrogen has some benefits over electricity when certain factors are weighted, namely the emissions associated with electricity generation. If electricity is primarily from coal-fired power plants, the emissions and cost associated with hydrogen can be significantly less than electricity. However, if nuclear and solar thermal are used as the primary power generation source, PHEV are more beneficial from both a cost and emissions (g/CO_2) standpoint[1]. Hydrogen is further hindered by its high fuel cell costs[16], expensive infrastructure needs[13], and fueling costs[14]. Due to its limiting factors, it is not treated as a feasible near-term solution in this paper.

PHEV offer the ability to sustain the light-duty vehicle fleet in spite of rising fuel costs, and act as stepping stone to pure EV technology. They offer both economic and environmental benefits, though their drawbacks are still not fully understood. Consumer acceptance, diffusion of vehicles and decreasing costs are necessary to ensure success to the technology. When analyzing PHEV it is important to understand the two parties that are affected by this emerging market: the utility company, who is responsible for meeting new demands, and the consumer's driving and fueling patterns.

1.1 Description of project

The goal of this project is to help better understand the near- and long-term capital costs, such as infrastructure needs, a capital cost, for PEV from both a utility and consumer standpoint. It is not yet understood what effects PEV will have on the US electric grid (and how to best control charging behavior) as the availability and rate of charging infrastructure increases, a variable cost. Consumers are also concerned as to what the utility of PEV (especially EV) will be. Through the use of a detailed model and simulation, we are able to produce results that quantify the infrastructure needs and effects of PEV on the electric grid and analyze them from both the consumer and utility perspective.

The following paper gives a background literature review (Chapter 2) of the current research being performed for PEV, and other AFV. A discussion of the initial findings and characteristics of the NHTS and US light duty vehicle fleet is presented in Chapter 3. Methods and models used to answer the above questions are described in Chapter 4. To quantify the need and benefit of charging infrastructure from both a utility and consumer standpoint by answering the following questions:

- What are the infrastructure requirements of PEV, what is the relative benefit in terms of consumer fueling price, and ZEV range capability to near-term, base case, increased infrastructure availability? (Chapter 5)
- For the three cases of charging availability, what ZEV-range has the largest benefit to higher charge rate infrastructure? Does the benefit increase significantly with the metric of cost per mile? (Chapter 6)

- Utility companies have a vested interested in vehicle charging behavior. Unlike private suppliers, it is not beneficial for vehicles to charge during peak periods of the day. Do current EV TOU rates send effective cost signals to consumers as to when they should charge their vehicles? (Chapter 7)
- From the perspective of the consumer, what benefit do these changes on the utility of PEV? Does the current SAE J2841 standard effectively capture the effects that near- and long-term infrastructure changes may have on the utility factor? (Chapter 8)

These outputs provide a thorough analysis of infrastructure and charging power. A brief sensitivity analysis to validate the results for a larger design space is shown in Chapter 9.

2.0 BACKGROUND

The following section attempts to further investigate and relate the previously mentioned topics and help describe the current research that is being performed.

2.1 Consumer charging behavior

The two main schedules that are being studied are an uncontrolled scenario, where the consumer can charge as they choose: if the vehicle is stopped at home, work or wherever a plug is available, it is assumed that the vehicle is charging. This is assumed to be the more economical decision for consumers (especially away from home where electricity is cheaper). Electricity is almost always less expensive than gasoline, and this disparity will likely only increase[17], thus encouraging more peak charging. The second (and preferred) method of charging (from a utility standpoint) is off-peak only charging, or controlled, when load demands are low. Off-peak charging has reduced cost, and demand for the utility and the consumer[20,21,22]. Uncontrolled and controlled charging are frequently compared to weigh the benefits and drawbacks to PEV from both a utility and consumer standpoint.

The two primary methods of controlling consumer charging behavior: TOU rates, such as those currently used by PG&E and dispatched controlled charging. TOU offer discounted electricity for off-peak periods, and the consumer ultimately decides when to charge. Dispatched controlled charging behavior is a utility system through a smart meter that directly controls whether the vehicle may charge or not. While controlled charging may work for PHEV, it may not meet all of the needs of EV and some additional daytime charging will have to take place. Both of these are feasible in the near-term.

Early adopters of PHEV are likely to be well-educated, environmentally conscious homeowners and early-adopters of technology[9,10,11,12]. In EPRI 2009[12], the individuals interviewed expressed a desire to follow the rules, only charge at night and help the environment. Additionally, these consumers said they “expected” to pay lower electricity rates at night because they felt that the cost savings of night charging was both beneficial to them and the environment, as well as convenient. Kurani[11] has supporting evidence to this claim: consumers generally charged at night, when they arrived home and expressed no inconvenience from evening charging, they equated it to “charging a cell phone or feeding the dog.” The study discovered that 70% of vehicles were plugged-in between 10 PM and 6 AM. These times represent delayed charging scenarios; yet they still have the potential to add to the evening peak. The initial buyers will require guidance as to how to charge, but are likely to charge as directed.

Despite the similar outcomes of the Kurani 2009 study and EPRI 2009 study, the consumers interviewed were from different scenarios. In the Kurani study, drivers of converted PHEV were not told whether or not the car should be charged, only that it could be charged. They were not given information on load shapes or potential environmental effects. Subjects charged and drove as they pleased. Once individuals realized that charging was beneficial, increased their fuel economy and decreased the need to visit the gas station, charging frequency increased. However, in the EPRI study, consumers were told what the consequences were of peak charging and groups answered as to what they said they would do. There is currently no public data set for what individuals would do if they were driving a PHEV and given information as to how to perform.

Consumer charging behavior directly affects such characteristics as emissions, grid load, infrastructure needs and financial benefits associated with driving a PHEV[8]. In order to best control consumer charging behavior, it is important to educate consumers about the environmental and economic impacts from their residential charging behaviors.

2.2 Demand, generation and emissions impacts of PHEV

PHEV can significantly reduce tailpipe emissions[18,19,20,21]. In Sioshansi's Ohio-based study, Markel's Colorado study and Jansen's study focusing on the western grid[18], all three conclude that vehicles charged from US-mix electricity (made up of roughly half coal) will increase emissions from generation sources, but decrease tailpipe emissions. Jansen claims that unless a cleaner generation source is used, GHG, NMTOC and CO emissions will all increase, and only the intensity of NO_x will decrease due to the use of secondary generation sources. Increased coal-fired power plant emissions are detrimental; however, they are more easily contained than tailpipe emission[19].

Wind generation is discussed as a better fit for PHEV due to its increase in off-peak generation and usage capabilities. Wind generation is not a consistent source of generation and opponents of wind often claim that reliance on wind generation will require more inefficient generators to meet the off-peak demand when the wind isn't blowing[1]. Proponents of V2G technologies claim that between wind and a significant PHEV saturation the off-peak load needs can be met[20,21]. New generation opportunities such as V2G and wind are possibilities that are being explored. These new technologies will require planning, infrastructure and financial support and are not a near-term solution[22].

Despite increased coal generation requirements, PHEV are cleaner vehicles that offer reduced tailpipe emissions when compared to both conventional vehicles (CV) and hybrid electric vehicles (HEV)[2]. When compared to competing technologies, such as hydrogen, when cleaner generation methods are used (e.g. nuclear, solar, wind) PHEV produce less emissions[1,23]. When PHEV are charged and controlled correctly, they can heavily reduce emissions as opposed to CV or HEV.

2.3 Residential infrastructure needs

PHEV offer consumers some of the benefits of electric vehicles (EV), but still allow for extended travel due to their dual fuel source. Also, unlike EV and hydrogen, they do not require as much infrastructure development. There are already 937 public charging stations available in California with varying levels of operability[24]. Approximately 50% of individuals surveyed from the Kurani 2008 study have access to 110V outlet within 25 feet from where they park their car[22] at home.

Level 1 home charging, or standard wall charging, is expected to cost between $200-$1000 (the higher end of the range occurs when installation of an outlet is necessary), making the availability of at-home charging feasible[25]. Level 2 chargers, one that is purchased and can charge at a rate of at least 3.33 kW, will cost, at minimum, roughly $2,000[25]. These chargers may not be necessary for most individuals who have easy access to a wall outlet.

Faster aging or increased maintenance of utility transformers and lines is a concern. Transformer aging in the hydro- Quebec market with one PHEV per household has been found to increase aging a fraction of a percentage point[26]. The study considered thermal loading, voltage regulation, transformer loss of life, losses, and harmonic distortion levels. Transmission costs are already included in most utility rate structures and a small increase is unlikely to be noticed by consumers.

Infrastructure development for Level 1 PEV charging is minimal. However, in some areas, Level 2 chargers are likely to be equivalent to 1.5-3 fully loaded households[27]. This is an obvious concern from a utility standpoint as a lack of preparation from the utility could lead to unnecessary disruptions for the utility.

Residential load shapes are highly sensitive to the frequency and rate at which PEV charge. Charging at work or commercial locations affects the intensity of home charging and lessens the load at home. In fact, one possible side effect of offering free commercial or work charging is the decreased frequency of at-home charging, where costs are directly charged to the consumer. Whether or not individuals choose to charge at home, work or commercial locations, and at what rate they do so, load shapes change. The relative improvement for workplace and public charging is dependent upon individual driving behavior.

2.4 Commercial and workplace charging infrastructure

While California has legacy charging stations from the older EV (EV1, RAV4EV), most states do not. These states will require additional infrastructure installations if the US market is to transition towards an all-EV[28] vehicle fleet. PHEV offer an advantage over hydrogen and all-EV since they do not require additional charging infrastructure.

The need for readily available workplace and commercial charging infrastructure (public charging) is a debated one and an issue that is not fully understood. Public charging alters both the residential load shape as well as the commercial load shape, and also makes it more difficult to understand what the peak load to the transformer will be. This added challenge makes it more difficult for utility companies to effectively plan for PHEV and EV.

Currently, the Department of Energy is investing millions of dollars to develop and install public charging infrastructure**Error! Bookmark not defined.** through the ChargePoint America program[29]. The location and rate of these chargers need to be analyzed in order to best utilize of the chargers. For instance, it may be more beneficial to have chargers at a grocery store or shopping mall as opposed to a gas station, since this is where individuals spend a significant part of their days. Strategic placement of public charging infrastructure can lead to charging locations that are efficiently used and convenient to consumers.

Developing workplace infrastructure is another concern. Significant workplace charging could cause an additional mid-morning peak, or worse, add to the afternoon peak (2PM-7PM). However, for some commuters, workplace charging might offer the ability to displace a significant enough amount of gasoline to make the purchase of a PHEV or EV economical. The choice to install workplace charging infrastructure and whether to charge the consumer a fee to charge their PEV is ultimately the company’s decision, although electricity tariffs and regulations may have a significant impact on their decisions.

2.5 Consumer expectations and knowledge of PHEV

Throughout 2006-2009 UC Davis conducted three studies to determine the market size and needs of PHEV. These studies, along with a 2009 EPRI report are currently the best available resource to understand near-term PHEV buyers' wants, needs and behaviors.

A major challenge to successful diffusion of PHEV or any alternative fuel vehicle (AFV) is education. In a 2008 UC Davis study, 2,373 new vehicle owners completed an online survey about their understanding and interest in PHEV. Of the respondents, 75% reported that they understood the dual fuel source of PHEV but many demonstrated little knowledge of what a PHEV was[10], often confusing PHEV for HEV. Since consumers have not yet formed strong opinions, there is an opportunity to steer them through proper charging practices. This lack of information from consumers is an opportunity to educate targeted populations in order to influence decision making.

The Chevy Volt is likely to be many consumers first interaction with a PHEV and positive social interactions can help encourage distribution of these vehicles. According to the 2009 Kurani study PHEVs communicate drivers values to other members of their social group. Some view this communication as a positive stigma, expressing their environmental friendliness, while others view the PHEV image as not fitting with their personal image. EPRI 2009 claims that HEV owners are less likely to be influenced by their friends (55%) than non-HEV owners (61%). This is likely to be because they have already made the decision to be early adopters of new technology. Social circles, no matter the stigma, certainly play a role in the diffusion of PHEV, and PEV as a whole.

Understanding the correct market to target as future buyers of PEV is a popular topic of discussion. The likely purchasers of the technology are generally agreed to be: educated, homeowners, early adopters and those interested in new technology[12]. It is also likely that current drivers of HEV will drive PEV. EV, as opposed to PHEV, are a very niche market with an expected limited number of vehicles to be sold. PHEV, however, are assumed to be a mass-market vehicle that meet consumers needs. Utility companies can study areas with high HEV levels to determine where greater infrastructure and demand areas will likely occur.

While environmental benefits of PEV are likely to be a factor to some, economic benefits and fewer, or zero, trips to the gas station are an influencing factor for others. Understanding the actual economic benefits and payback periods of purchasing a PEV are important, especially because of their higher up-front costs. In a 2006 NREL study, it was determined that gas would have to reach $5 a gallon in order for PHEV-10 to claim a payback period of 12 years[30]. The assumed long-term retail costs used by NREL are similar to those being used by OEMs, but do not include current tax incentives.

As both PHEV and EV enter the market in the coming years, it is important for consumers to have positive encounters with these vehicles. Through increased environmental and economic awareness, the potential for high adoption and acceptance rates of PEV is possible.

2.6 PEV as a near-term solution

PEV offer significant benefits over CV and HEV. Reduced pollution, dependence on foreign oil, and reduced fueling costs are a few of the known benefits to consumers. Automotive manufacturers have a separate set of benefits that PEV offer: increasing corporate average fuel economy (CAFE), and meeting the demands of forward thinking consumers. Because of PEV benefits, automakers are investing in these vehicles. Toyota, Nissan and Chevrolet have plans to release mid-size sedans in the next two years. SUVs, compacts and luxury vehicles are planned for the US market within the next 3 model years. These planned production vehicles show electrified transportation as a near-term solution and possibility.

PHEV have two distinct energy consumption types: charge-depleting (CD) mode and charge-sustaining (CS) mode. The vehicles in this study are assumed to operate as a pure-EV in CD mode up until the battery has been depleted. After the battery has been depleted, the vehicle operates in CS mode, or like a HEV, where regenerative braking is used to keep the charge-level of the battery nearly constant. Once PHEV are operating in CS mode, the gasoline engine is used to propel the vehicle with the assistance of the battery pack. EV, however, operate solely on electricity. As a result, the vehicles in this study are all considered to be ZEV-type PHEV until their range is depleted.

Because of PEV benefits, there are several PHEV and EV entering the market in the coming years. These vehicles offer a wide range of battery sizes and AERs with varying costs. Three vehicles will be analyzed as near term solutions with mass-market potential (Table 1).

Table 1 near term vehicle specifications

Vehicle make, mode and classification	*Charge-depleting (all-electric) range*	*Price*[1]
Toyota Plug-in Prius (PHEV)	13 miles (20.92 km)	Not released
Chevrolet Volt (PHEV)[31]	40 miles (64.37 km)	$41,000
Nissan Leaf (EV)[32]	100 miles (160.93 km)	$32,780

The data in Table 1 is not complete and is the best available data at the time of this paper. The all-electric ranges for the vehicles have been announced. CD and CS energy consumption is speculation at this point. Energy consumption data will not be complete and accurate until there is data available from real-world driving of these vehicles.

The three vehicles were selected here because they each offer different benefits and tradeoffs. The Toyota plug-in Prius offers the smallest AER, is speculated to be the least expensive[33] and is the vehicle that is most familiar with consumers. The Chevrolet Volt is a PHEV, and uses the gasoline engine as a backup; it is the most expensive of the vehicles. The Nissan Leaf offers the longest AER, and is a pure-EV, has no gasoline backup. Once the battery dies, the vehicle will require an electrical outlet to recharge. These vehicles are assumed to have similar charge-depleting electricity consumptions and different battery sizes. They are being compared here because they all are similarly sized, entering the market within a year of each other and have comparable performance characteristics.

[1] These priced do not include federal and state tax rebates.

2.7 Changes in the load shape

A major challenge of PEV is to understand their potential effect on the US electric grid, and how utility companies can predict and control future grid behavior. The utility company has the largest interest in doing so, as understanding demand and changes in load shape will directly affect their generation needs. Load shape will be easier to control for at-home charging only, where the installation of a smart meter or smart charger can better control demand. However, as the availability of charging locations increases and the charging rates change the load shapes will change. These changes are likely to occur in concentrated areas to begin with, but will likely spread as prices decrease and availability of PEV increase. This is the major concern for most utility companies as the concentration of PEV increases in their service territory.

For the following sections, the 2009 NHTS was used to simulate the driving and charging behavior of a full-penetration scenario for the US light duty vehicle fleet, represented as a mixture of PHEV-20, PHEV-40 and PHEV-60. As vehicles arrive at different locations, they are either allowed or denied charging, based on three cases (home charging, home and work charging, and all charging locations). Once a vehicle reaches a potential charging location, it may charge until the battery is fully charged, or the vehicle may depart before the battery is fully charged for the next trip. This gives an accurate representation of SOC and total charging, as well as providing accurate cost data for electricity. The total energy consumed by the driven vehicle fleet is summed and divided by the total number of driven vehicles, resulting in an average. The output of the analysis performed shows the effect of increasing charging locations and powers by graphing average vehicle loads (kW per vehicle) versus the time of day (0-24 hours).

2.7.1 Effects of increased charging locations

Home loads are easiest for utility companies to predict and control. Increasing the availability of charging locations changes the peak load for at-home charging (Figure 1).

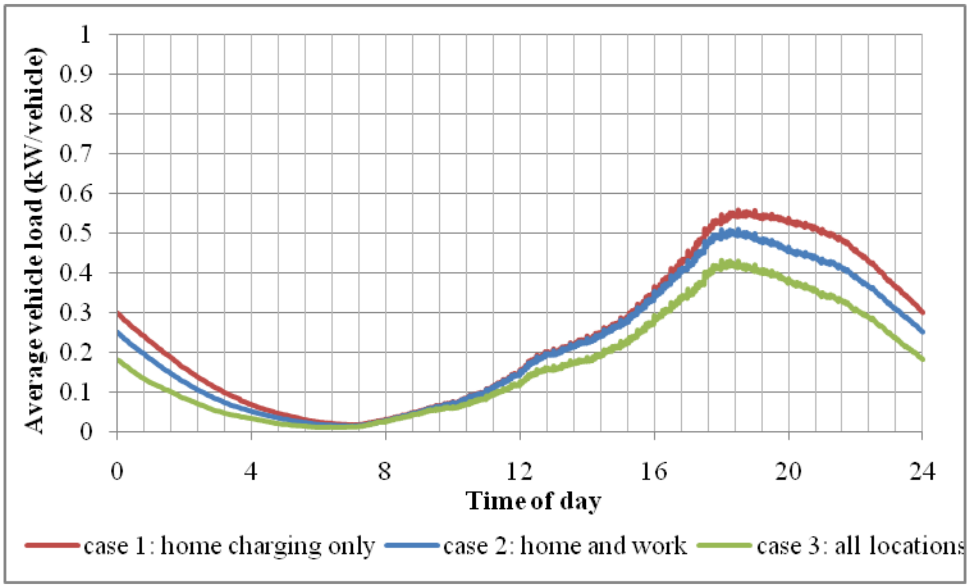


Figure 1 at-home charging loads for 1.44 kW charging rate

Figure 1 shows the home loads for the three charging availability scenarios, at 1.44 kW, a very near-term scenario, and one that the utility can directly control through dispatched charging.

The magnitude of the peak load increases for more restricted charging scenarios. The fewer charging locations that are available also results in a delayed peak for home charging. The at-home charging only scenario has both an increased peak (0.4 kW to 0.55 kW per vehicle), as well as a lengthier one, with demand continuing on until the early morning. This is perhaps the largest concern to residential electricity providers.

As the availability of away-from-home charging increases, the average total vehicle load increases (Figure 2).

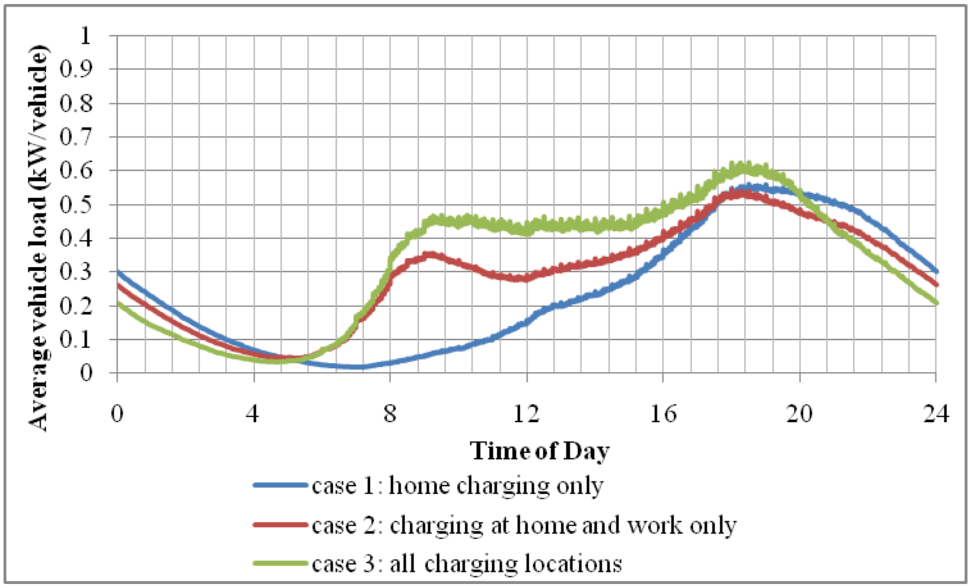


Figure 2 total average vehicle load for three base case scenarios at 1.44 kW

As availability of charging increases, it is likely that total charging will increase. This provides information to utility companies, since understanding demand is important. As the addition of infrastructure increases, the shift in demand also increases. For case 2 and case 3, peak demand shifts from .55 to .62 average kW per vehicle, a 10.7% increase, and decreases the length of peak for at-home charging. However, with the addition of more infrastructure, the magnitude of the load shapes increase during different parts of the day. The length of the peak for case 1 continues on until the early morning, whereas the overall load from the increased charging scenarios increases at both afternoon arrival times and in the morning. For case 3, charging at all charging locations, the load stays constant for much of the day, and has the highest peak in the early evening. This change in peak comes at a cost to the utility company, but is likely to reduce fueling costs to the consumer.

2.7.2 Effects of increased charging power

Many future-buyers of PEV are likely to install Level 2 chargers in their homes to maximize the benefit of their PEV. However, these increased charging powers alter the load shapes. Increasing the charging power availability for vehicles increases the magnitude of demand, which is not beneficial to utility companies (Figure 3), but many future drivers are likely to see a perceived benefit from quicker charging rates.

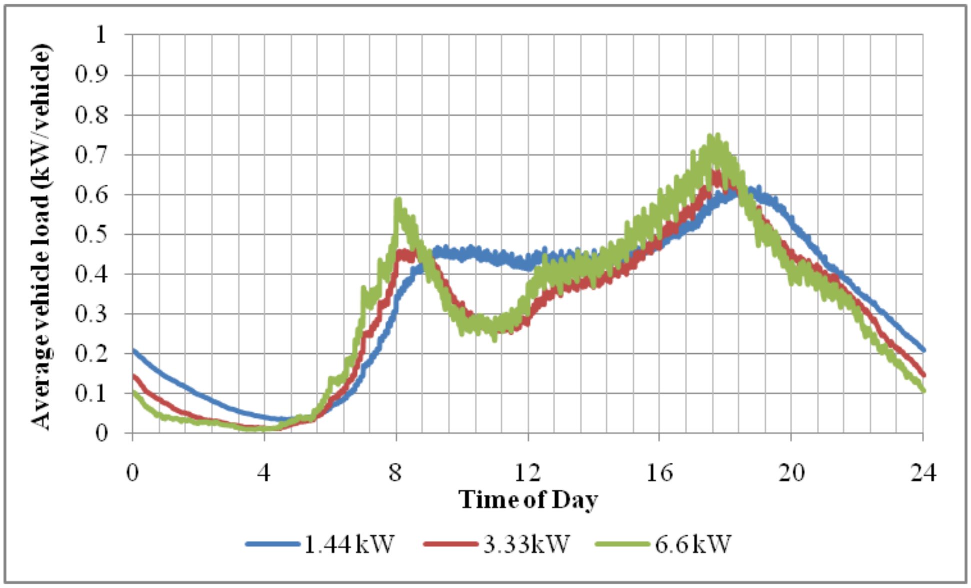


Figure 3 load shape for case 2: home and work charging at varying charge powers

As more power is used for charging, the magnitude of the overall average vehicle load increases, as does the magnitude of the peak. This information is expected, resulting in the increase on the home load, at peak times, from increased charging power[34]. These increased peaks all shorten the length of time required to charge. The 1.44 kW power has a longer peak throughout the day than the higher-rate chargers. The higher rate charge powers (3.33 and 6.6kW) show the shortened time to charge, as the load quickly drops around 7PM. The magnitude of the mid-morning peak is also higher, and quicker to "ramp up" as opposed to the lower charging rates. These load shapes are considered to be averages, and as the number of PEV increases in an area the magnitude of these quick changes will increase.

The higher charge powers are likely to pose challenges to utility companies by increasing the magnitude of the average vehicle load during potentially high load periods of the day. The utility is likely to prefer the decreased charging power, as it delays the peak load and spreads the magnitude of the peak to later in the evening when demand may not be as high. The low charging rate load keeps a relatively even load throughout the day. This is seen as a benefit from a utility perspective because this will reduce the demand on secondary, less efficient generation sources. To the consumer, the increase in charging rate is to be seen as a benefit: quicker charge times mean the vehicle is completely charged in less time, resulting in a perceived freedom from charging (this is especially true for EV as opposed to PHEV). The likelihood of individuals to install a charger will depend upon three factors: perceived benefit, cost of the charger, and availability of sufficient electrical service. In order for utility companies to get utility customers to charge at the ideal times and rates, incentives and education for consumers need to be put into place for a more controlled, predictable charging load shape.

3.0 DATA

3.1 The National Household Transportation Survey

The NHTS is a periodic, federally-funded survey of the US population whose purpose is to gather information on daily and long distance travel. For the 2009 NHTS, 150,147 households completed the survey. Individuals are surveyed regarding their household makeup, personal demographics, vehicle characteristics, and travel during an assigned travel day. The NHTS consists of four different files:

- The *vehicle file*, where specific information regarding vehicle characteristics is collected (e.g. annual mileage, vehicle age, odometer reading),
- The *household file*, where specific information pertaining to the household is collected (e.g. number of drivers, age of family members, income, number of vehicles owned),
- The *person file*, where every member of the household completes a survey and reports information pertinent to them only (e.g. race, age, distance to work, individual income, whether the individual is a driver or not),
- The *trip file*, every trip that is taken during the household's sampled day is recorded; regardless of the mode of transportation (e.g. walking, bus, driving).

Because every member of the family completes a self-reported person file and a trip file, there are duplicates of many of the trip entries with conflicting data. For example, *Household 103698 has four members of the family (A, B, C, D) and they all travel to breakfast, the gas station, drop C and D off at the mall, then A and B have lunch and return home, and C and D take the city bus home.*

All four members of the household will complete a trip file journal but might have different interpretations as to the time it took them, the distance traveled, and the amount of time spent at each location. These discrepancies are common within the dataset and need to be addressed.

3.1.1 An idle fleet

The NHTS surveys 150,147 households equally divided among 7 days (Sunday-Saturday) and then divide them evenly among the 12 months. The NHTS is then weighted to represent the entire US vehicle fleet. The files are all weighted under a *full sample weight* so as to represent the entire US population and vehicle fleet. The weightings must be used in order to have accurate information on travel patterns for the entire vehicle fleet. This sample should show how often vehicles are driven, where they are driven and, more importantly, the personal transportation needs of the country.

In order to electrify personal transportation it is necessary to understand the personal transportation needs and driving behaviors of the US vehicle fleet. Figure 4 shows the number of vehicles that were driven or remain parked (not driven) during the sampled NHTS days.

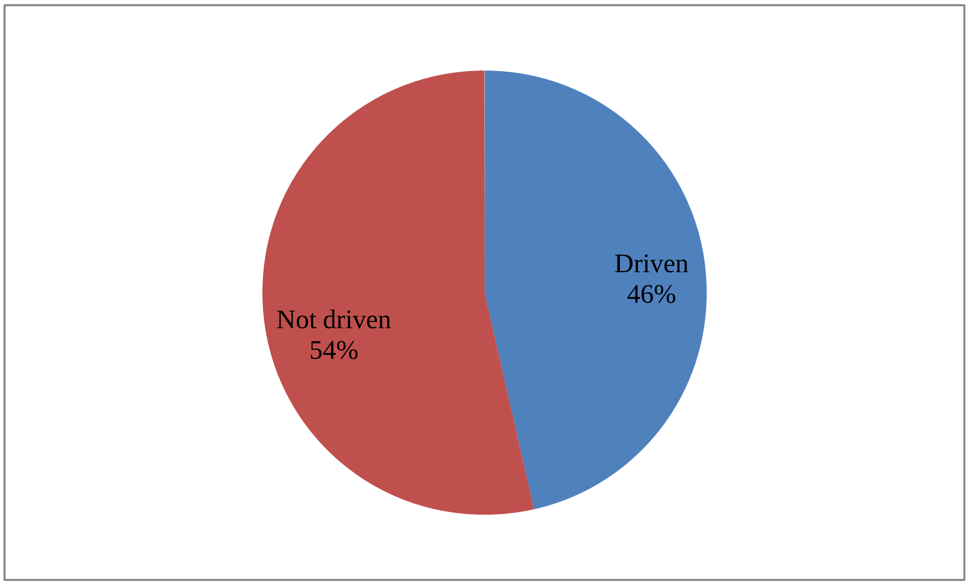


Figure 4 percentage of US vehicle fleet breakdown of driven and not driven vehicles (2009 NHTS)

The NHTS shows that, on average, a majority of vehicles are not driven on any given day. The likelihood of a vehicle being driven on any given day may be related to the day of the week sampled, age of the vehicle, number of vehicles in a household, or other factors. For this study it is only beneficial to look at driven vehicles from the NHTS. It is impossible for us to determine or study not driven vehicles' driving patters since we only have access to the travel trip data from their sample day. Of driven vehicles, the likelihood of a vehicle being parked during any given part of the day is extremely high (Figure 5).

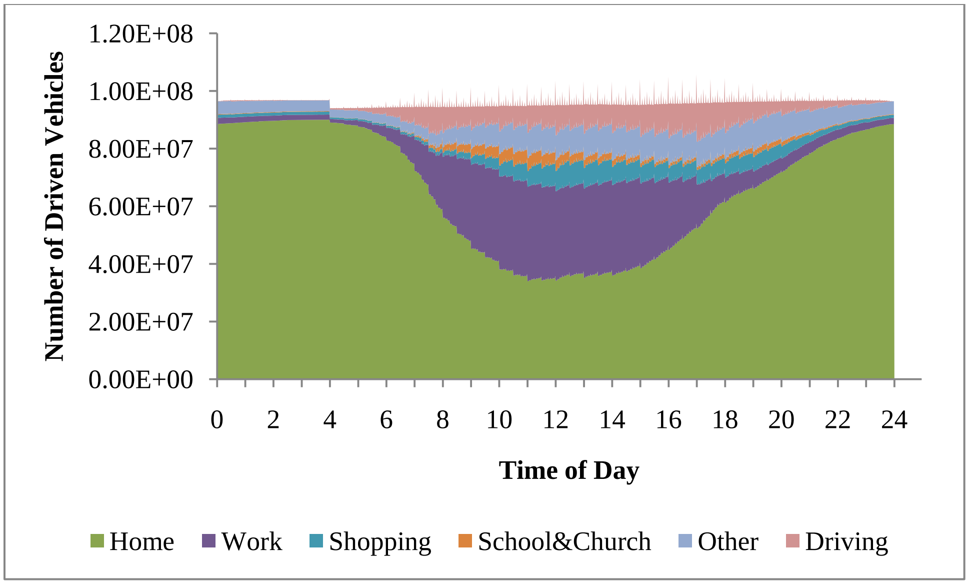


Figure 5 driven vehicle locations during the sample NHTS day (2009 NHTS)

Vehicles spend the majority of their useful lives parked at home and work. Because of this, in order to effectively analyze near-term charging infrastructure needs it is important to assess the needs of these two locations so as to maximize charging and minimizing loads.

Since driven vehicles are parked at home during the largest part of the day, let us assume it be the most likely charging location. The second place that vehicles are most likely parked is at the workplace. Both will be examined in the subsequent section.

3.1.2 Consistent driving patterns

The decision as to whether or not a household should own a PHEV or EV is easiest to understand by investigating the total driving distance of vehicles. While the three cases analyzed in this thesis offer a wide-range of AERs, it is important for households to understand their personal needs and daily driving behaviors. Figure 6 shows that more than 50% of vehicles are driven less than 30 miles a day and more than 75% of individuals drive less than 50 miles a day, and only 7% drive more than 100 miles. This data shows also that 93% of average driving day needs will be met with PHEV or EV entering the market in the near future, with an AER of less than 100 miles.

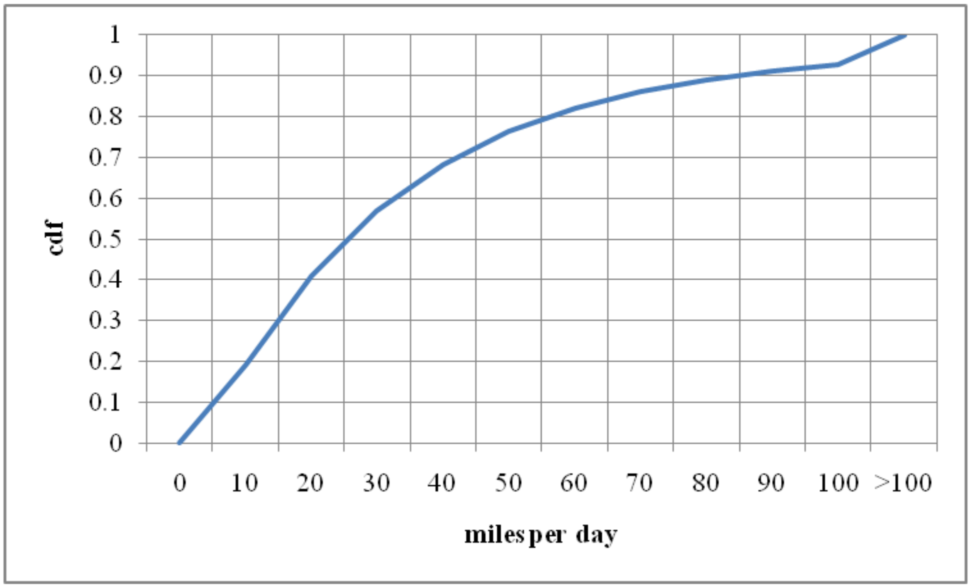


Figure 6 daily miles traveled by driven vehicles in the 2009 NHTS

While it is important to understand average daily driving distances, it is equally as important to understand where vehicles are parked at the start and end of their driven days. If the majority of vehicle charging is to take place in the home it is necessary to understand how many vehicles start and end their days at home and how most of them are utilized on a day-to-day basis. Figure 7 shows that 90% vehicles start and end their days at home. However, there is roughly 10% discrepancy as to whether vehicles will start and end their days at home (4.4% of vehicles end at home but do not start at home and 4.9% of vehicles start at home but do not return home). This is most important for EV where the vehicle depends upon access to charging and the user may have to make additional plans to charge at the end location.

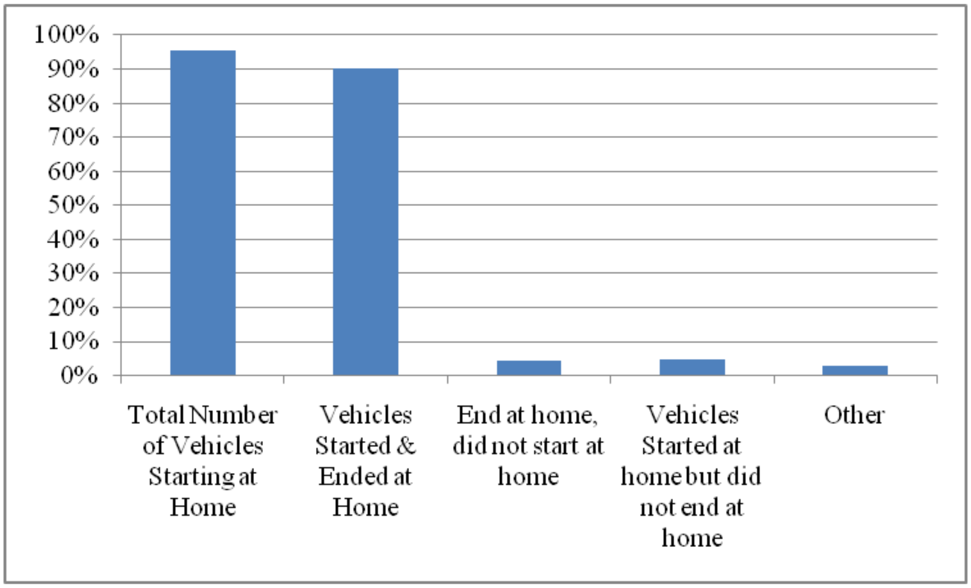


Figure 7 vehicle start and end locations from the 2009 NHTS

If the assumption is made that home charging is the sole method of charging for the majority of PEV owners it is most important to understand how many vehicles are arriving at home at any given hour of the day. Figure 8 shows both a cumulative distribution of arrival times and the hour-by-hour distribution of vehicles arrive at home between 5-7PM. This includes the entire driven vehicle set. If charging is not delayed or controlled, then the peak load will likely increase, for utilities that already experience a late-afternoon peak.

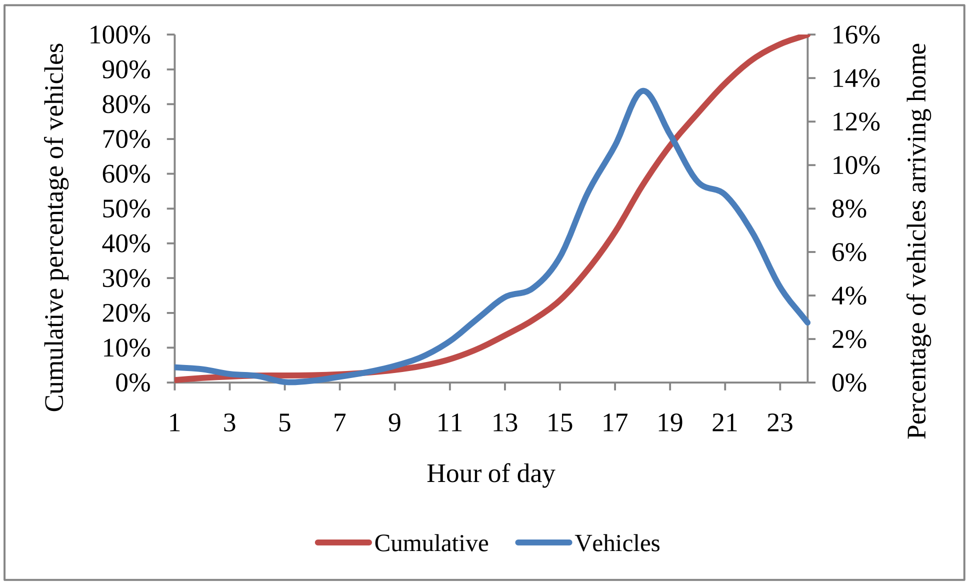


Figure 8 home arrival times for driven vehicles in the 2009 NHTS

If home charging is assumed to be the majority of charging availability, the second most common will be workplace charging. It is important to understand the driving patterns of commuters. One metric that is easy to use from the NHTS is reported distance to work (Figure 9).

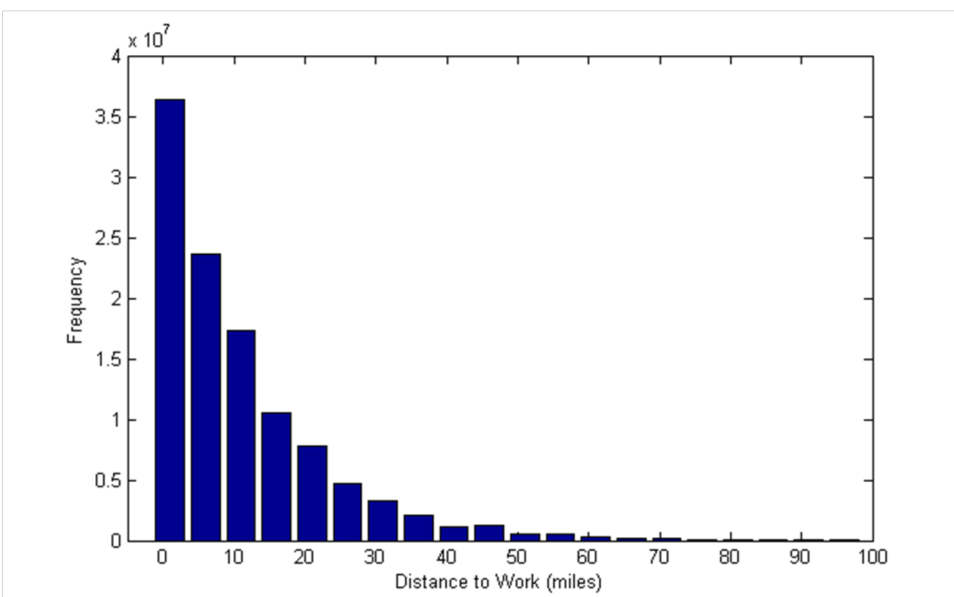


Figure 9 unweighted distance to work distribution from the 2009 NHTS

Figure 9 shows a very clear distribution of reported distance to work, with the average being at 11.3 miles. This shows that most commuters needs are likely to be met with either at-home charging only, or home and work charging and using a low-AER vehicle.

In order to understand the effect of the PEV on the grid, it is important for us to understand the charging behaviors, the locations where charging is available and the cost to charge these vehicles. The decision to place charging infrastructure at different locations will depend heavily on what type of vehicle is being considered (and specifically its AER), the cost of the charging infrastructure and the concentration and type of PEV in the area.

4.0 METHODS

The analysis for this study was performed in the MATLAB programming environment. The chapter describes the methods were used to model charging and driving behaviors using the 2009 NHTS dataset.

4.1 Vehicle Days

The NHTS is an important, and arguably the best, resource for understanding average daily travel behavior of the US vehicle fleet. However, since the households are only sampled on one day, it is impossible to know what their actual day-to-day travel behaviors look like. Self-reporting contributes error to the data which must be considered in any analysis, however, the dataset is still treated as statistically accurate (n=1). As mentioned in section 3.1, individuals that are on the same trip often have different perceptions as to the time and distance they traveled on the same trip. In order to address this error a special vehicle day weight, *w*, was applied to each vehicle within the dataset:

$$w = W * \frac{1}{n}$$

Where *W* is the full sample weight that is initially applied to the NHTS dataset, to represent the full US vehicle fleet, and *n* is the number of people that are linked to each vehicle trip, resulting in 943,315 vehicle days analyzed. By using this weighting, the full sample weight is still retained and this removes the reporting errors that occurred from vehicles with multiple individuals in the vehicle, where the vehicle may have been reported at more than one location at the same time.

4.2 Vehicle age and comparing not driven and driven vehicle samples

Due to the nature of the data, it was necessary to use only the driven vehicle data. However, in order to understand whether or not this was actually representative of the entire fleet needed to be determined. Of the many reported vehicle characteristics, the annual VMT is the most relevant, since it should show how vehicles are driven throughout their lives and on a yearly basis (Figure 10).

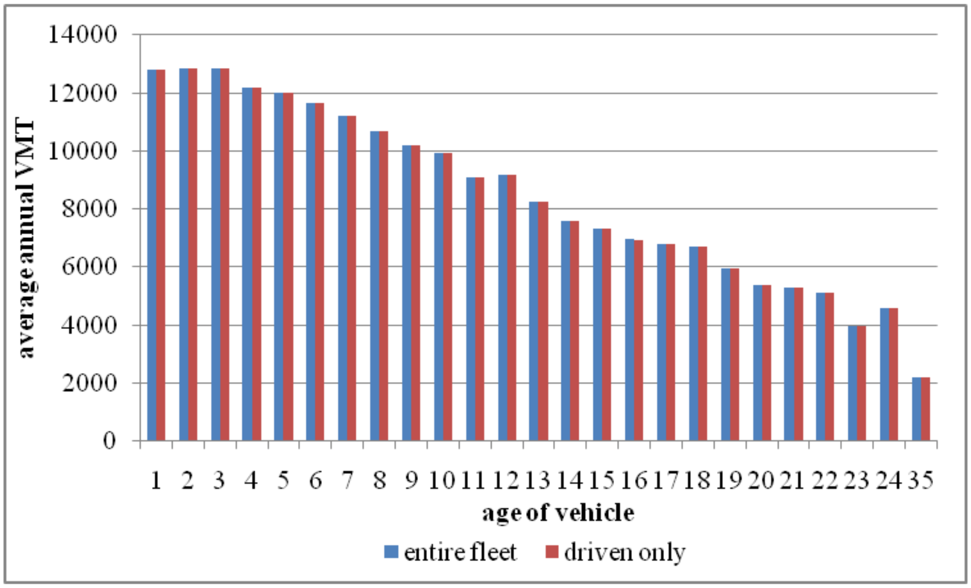


Figure 10 comparison of driven versus not driven vehicle annual VMT by age

Figure 10 shows that there is less than 0.01% difference between the averaged reported annual VMT of driven or not driven vehicles on the sampled day. However, it does show the very clear decline in annual VMT relative to the age of the vehicle. This shows the difference in driving behaviors between older and newer vehicles. With a steadily declining average annual VMT it is likely that older vehicles will be driven less. As the vehicle ages, the likelihood of it being parked on the given sample day is increasingly high (Figure 11).

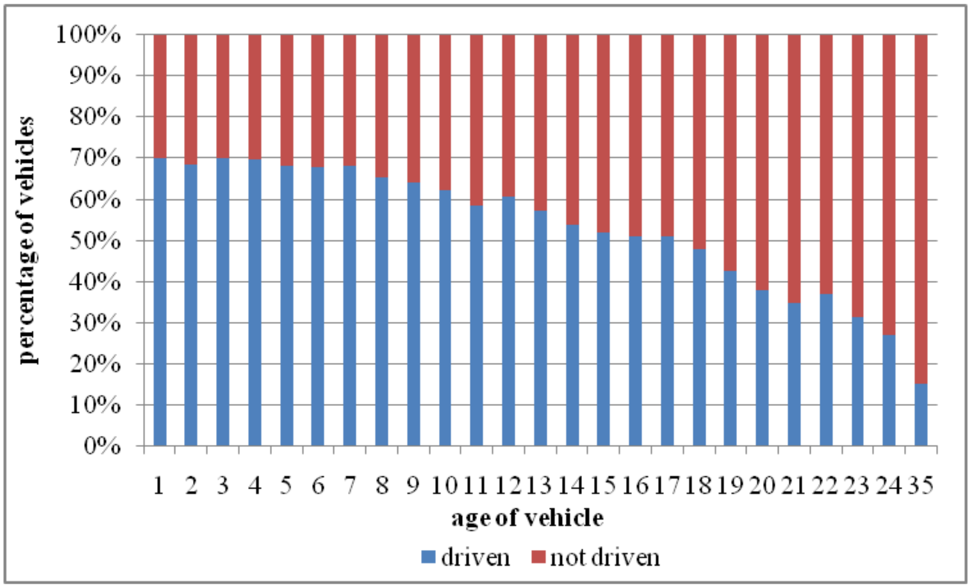


Figure 11 driven versus not driven vehicles by age

Eighty-five percent of vehicles at age 35 were not driven on the sampled NHTS days, this compared to age 1 vehicles, where 70% of vehicles are driven on the sample day. This data shows that driving behaviors are clearly different for older and newer vehicles, but not necessarily driven or not driven vehicles.

4.3 ZEV-range vehicles

PEV are an emerging technology. However, as with any new technology, it is impossible to know the real-world energy consumption and performance of these vehicles. And, since these vehicles consume electricity and gasoline, formal comparison between the performance of conventional vehicles and PEV is not possible at this time. Computer simulation of drive cycles is currently the best data source available.

To simplify the calculations used in this study, the types of vehicles analyzed operate in pure-EV mode until the battery is depleted, or as ZEV. There is assumed to be a linear depletion of the battery for all vehicles with the distance driven. In real-world driving once the battery in an EV is depleted, the vehicle must be refueled at an electrical outlet to move. However, that is not considered to be the case for this analysis. For this study, it is impossible for vehicles to be completely depleted, all vehicles are theoretically PHEV, and are equipped with gasoline engines to propel them if their needs are not met by the current charging scenario. In order to ensure that these values represent real world driving, they are based off of the SAEJ1711 composite fuel economy. This was done to simplify the calculations and analyze the actually needs of near-term PEV, and in effect eliminates speed and driving type from the SOC calculation and treats all vehicles as PHEV.

4.4 Utility Factor

The utility factor is a measure of a PEV likelihood of consuming electricity or gasoline as a fuel. It is the standard developed by the SAE to "provides the mileage weighted probability that the vehicle is in CD mode. In other words, if a fleet of test vehicles was deployed to every person in the NHTS, the Utility Factor weighting would attempt to estimate the total miles driven in depleting mode divided by the total miles"[35]. The utility factor is calculated using the NHTS data, and assumes that vehicles drive in perfect charge-depleting mode (all-electric) up until they have reached their specified AER. The vehicle then operates in charge-sustaining mode and consumes gasoline. The following equation is used to form the J2841 UF curve for PHEV:

$$UF = 1 - \exp\left(-\left[C1 * \left(\frac{x}{norm_{dist}}\right) + C2 * \left(\frac{x}{norm_{dist}}\right)^2 + \cdots + C9 * \left(\frac{x}{norm_{dist}}\right)^9\right]\right)$$

Where,

Table 2 utility factor values used in J2841

Value	*Fleet UF*
norm_dist	399.9
C1	10.52
C2	-7.282
C3	-26.37
C4	79.08
C5	-77.36
C6	26.07
C7	0
C8	0
C9	0

This equation produces the following curve (Figure 12):

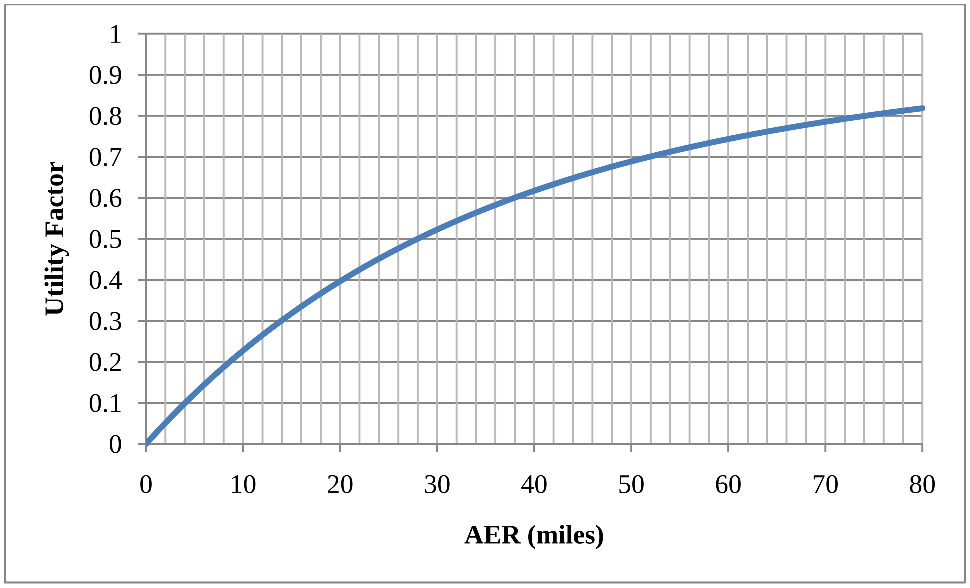


Figure 12 SAE J2841 utility factor curve

A high AER vehicle will have a utility factor that approaches 1.0 since most vehicle days total driving distance will be less than the AER. The utility factor is used as one metric to compare different driving behaviors and infrastructure needs for this study. The equation for the NHTS of the utility factor is listed below, as described by the SAEJ2841 standard:

$$UF_{SAE}(AER) = \frac{\sum_{d \ni S} \min(d, AER)}{\sum_{d \ni S} d}$$

where AER is the charge-depleting range of the vehicle, d is the vehicle distance miles traveled, and *S* is the total number of vehicles considered in the set. If $d \leq AER$ the UF is equal to 1, or if $d > AER$, the UF is simply the value that results from the AER divided by the total distance traveled. This version of the utility factor assumes charging once per day. For the vehicle day set, *S*, the minimum of either the total distance driven, *d*, or the *AER* of the vehicle is summed for each vehicle in the NHTS and divided by the sum of every distance, *d*, driven. The UF is a valuable calculation to determine the estimated utility of a PHEV.

The UF in this study is calculated differently than the two previous methods. Since this study increases the availability of charging locations, it is assumed that the utility of the vehicle will change. As a result, a new UF is used:

$$UF_{new}(AER) = \frac{\sum_{d \ni S} miles_{CD}}{\sum_{d \ni S} miles_{total}}$$

The UF_{new} is used in this study to compare the increase or decrease in effectiveness of the 2009 NHTS under different charging and infrastructure scenarios. It is also compared to the UF_{SAE}. The utility factor can also be used to compare factors that may affect driving behavior of vehicles, such as annual vehicle miles traveled, age of vehicle, distance to work, etc[36]. This is a widely accepted standard to uniformly compare PEV and their total benefit to consumers.

4.5 Cost per mile ($\$*mi^{-1}$)

Comparison of HEV, CV, EV and PHEV is sometimes difficult because of their varying fuel consumption types. However, one common metric is cost, and the easiest comparison is the metric of cost per mile ($\$*mi^{-1}$).

$$\frac{cost}{mile} = miles_{CD} * \frac{kWh}{mile} * \frac{\$}{kWh} + miles_{CS} * \frac{gallon}{mile} * \frac{\$}{gallon}$$

Where, $miles_{CD}$ are the number of miles driven in CD mode (only electricity is consumed) and $miles_{CS}$ is the total number of miles driven in CS mode (only gasoline is consumed). This metric calculates the total amount spent on both gasoline and electricity for all AER, charging scenarios and charge powers for the entire NHTS, but does not take into account round-trip efficiency of the charger battery system. The values used are for 2012 dollars and prices, to accurately represent near-term forecasted values. The cost per mile metric is a valuable, easy calculation to use, and has the ability to relate all types of vehicles and fueling patterns.

4.6 Understanding the achieved benefit

To effectively compare the improvement from increased infrastructure, charging power and AER, it is necessary to create a useful metric to quantify the overall benefit achieved by making a defined set of changes. For this study, the chosen metric is the "increase in the percentage of vehicle days who receive net benefit from the change", calculated as:

$$B = \frac{P_1 - P_2}{P_1}$$

where, P_1 is the percentage of vehicle days whose needs were met by the base case scenario, and P_2 is the percentage of vehicle days whose needs were met by the new scenario. The result, B, is the benefit that is achieved by making the change from P_1 to P_2. The benefit, or increased benefit, is dimensionless and is still only representative of vehicle days and not individual's long term driving behavior.

4.7 Vehicle charging benefit model

In order to understand the benefit of high-rate charging and public charging infrastructure, we must analyze the gain given to consumers with a higher frequency of charging locations as well as higher rate chargers for different AER. To best simulate the necessity of high charging rates, a time resolved vehicle charging scenario is simulated for every vehicle day in the NHTS dataset. The flow chart in Figure 13 shows the model.

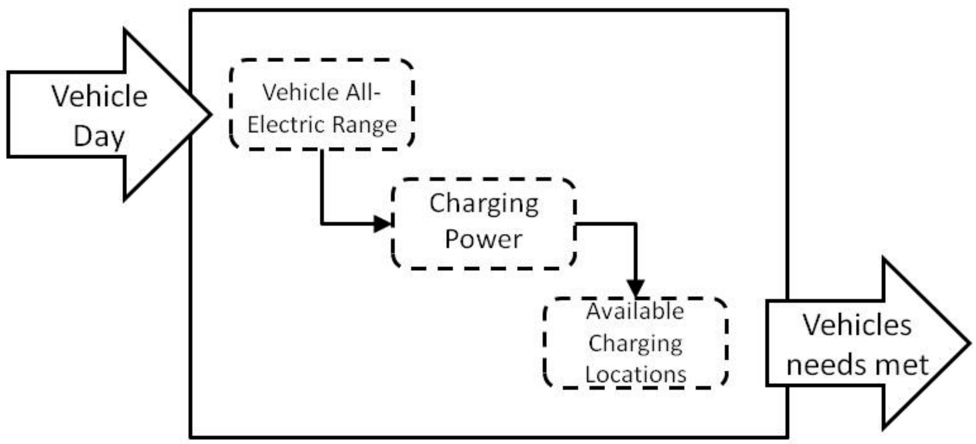


Figure 13 vehicle charging benefit method

The following parameters are used for this model:

Table 3 variable values (Source: EIA.gov, EPRI 2001)

Variable	*Value*
Charger efficiency	0.9
Electricity cost	\$0.1066 (\$ *kWh^{-1})
Gasoline	\$2.666 (\$*$gallon^{-1}$)
Charge-depleting energy consumption	280 (Wh*mi^{-1})

The charge-sustaining fuel economy changes for different ranges of PHEV [2]. The EPRI 2001 study is based off the SAE J1711 calculations for fuel economy and comparison of CV, HEV0, HEV20 and HEV 60. A linear relationship, with an R^2 value of 0.98 was found to calculate the CS fuel economy of the vehicles with the different

AER that were used in this study (Figure 14). HEV20 and HEV60 are equivalent to a, respectively, PHEV-20 and PHEV-60, and an HEV0 is a traditional HEV.

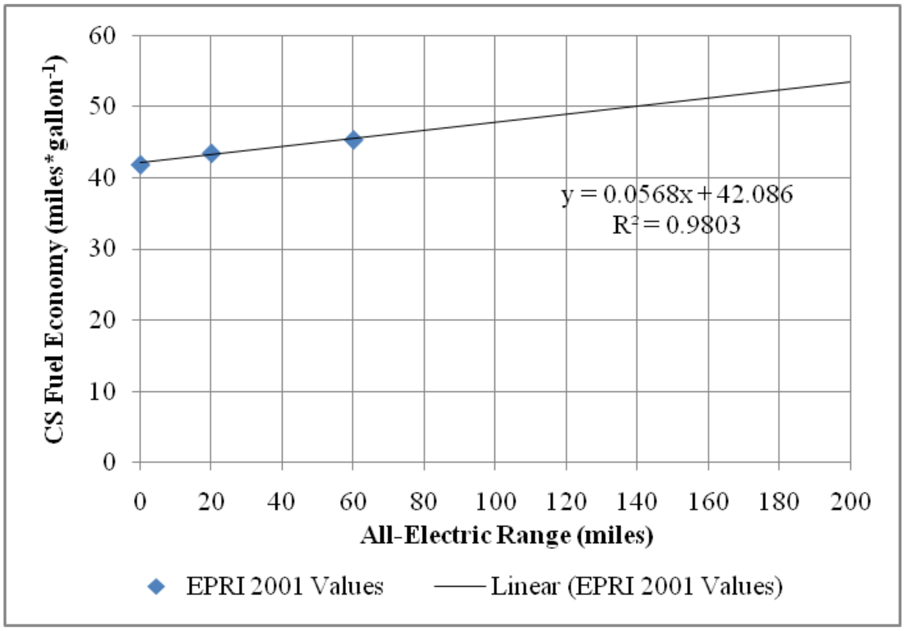


Figure 14 charge-sustaining fuel economy values used

In order to ensure that these values represent real world driving, they are based off of the SAEJ1711 composite fuel economy,

$$0.55 * FE_{urban} + 0.45 * FE_{highway} = Composite\ Fuel\ Economy$$

Using the combined fuel economy shows an accurate representation of average US vehicle fleet driving behaviors.

4.7.1 Vehicle all-electric range

Both PHEV and EV with varying AER are likely to be available soon. In order to analyze the largest range of acceptable charging infrastructure, the following AER were used: 10, 20, 30, 40, 50, 60, 70, 80, 90, 100, 150, and 200 miles. These represent both near- and possible long-term PEV.

4.7.2 Charging power

The charging powers that are currently available are Level 1 AC and Level 2 AC. Level 1 AC is considered to be 1.44 kW, or charging from a standard 120V outlet at 12A efficiency. Level 2 charging is considered to be: 3.33kW, 6.6kW, 9.6kW and 19.2 kW. However, OEMs are displaying and offering faster charging options with charging rates upwards of 50 kW (Level 3 AC). These faster charging options are more likely to be long-term public charging infrastructure and are not considered in this study. 1.44 kW is assumed to be the least expensive to install and all other rates will require purchase and installation of a charger and potentially upgrades to electrical services. All five of these charging rates are analyzed for three different charging scenarios.

4.7.3 Available charging locations

Three types of charging locations are used in this study. From the NHTS it is easiest to quantify these into 3 groups: home, work and all other locations (school, church, restaurants, malls, etc.). The descriptions within the NHTS are too numerous to truncate, and, as a result, are binned to three categories: home, work and everywhere else. This attempts to capture both near- and long-term charging scenarios.

Due to the nature of the NHTS, it is important to place the charging scenarios into three different scenarios. Near term, it is likely that an individual will charge solely at home (case 1) and possibly at work (case 2), where costs are incurred by either the consumer or employer. Long term it is possible that charging infrastructure will be available wherever the car is parked (case 3), at some cost to the consumer. This infrastructure may be made available at different charging powers. In order to gain a full understanding of the benefit of away-from-home charging, three scenarios are analyzed within the model:

- case 1: home charging only, the vehicle is only allowed to charge at locations it reported as 'Home' from the NHTS,
- case 2: home and work charging, the vehicle can charge at both places reported as home and as work,
- case 3: all locations, the vehicle can charge at any location where the vehicle is parked,

The state of charge of the vehicle requires time to charge at each of these locations, and does not assume instantaneous charging. Time to connect & disconnect the vehicle from the charging station is assumed to be small and is therefore neglected. The study also assumes that the driver never fails to connect the vehicle to the charging station whenever charging is modeled.

The vehicle charging benefit model is a combination of charging locations, charging rates and AER. All combinations are analyzed in order to get a thorough understanding of the needs of PEV:

$$n_{AER} * n_{charging\ locations} * n_{charging\ rates} = 180\ combinations$$

Where n_{AER} is the number of AER analyzed (12), $n_{charging\ locations}$ is the number of charging scenarios analyzed (3), and $n_{charging\ rates}$ is the number of rates analyzed (5). It is assumed that PHEV and EV are going to have different infrastructure needs, since PHEV can be fueled by both electricity and gasoline and EV can only be fueled by electricity.

The output of the model is the percentage of vehicle days that the gasoline engine stays off, and is thus, met by the constraints. Secondly, the utility factor as well as the total fueling costs incurred are output for analysis. The goal of this analysis is to discover what is necessary for near- and long-term success of PEV by comparing all near- and long-term possible scenarios, and at what economic benefit is achieved to the consumer.

4.8 Vehicle energy use model

Designing PHEV-specific TOU rates which can help utilities realize these proposed economic benefits requires consideration of the interactions between the stochastic distribution of driving and fueling behaviors, the utility TOU rate structures, and consumers' decision making process. Since TOU rates are likely to affect at-home charging only, that is all this model considers. The vehicle energy use model proposes a computational analysis which incorporates submodels to represent the effect of these considerations. It uses a subset of the 2001 NHTS. As shown in Figure 14, the analysis is made up of three subcomponent analyses: a vehicle energy use model, a utility rate structure model, and a consumer behavior decision tree. The input to the analysis is a proposed TOU rate structure, the output from the model is a metric of the effectiveness of that TOU rate structure. Each submodel is described in the sections that follow.

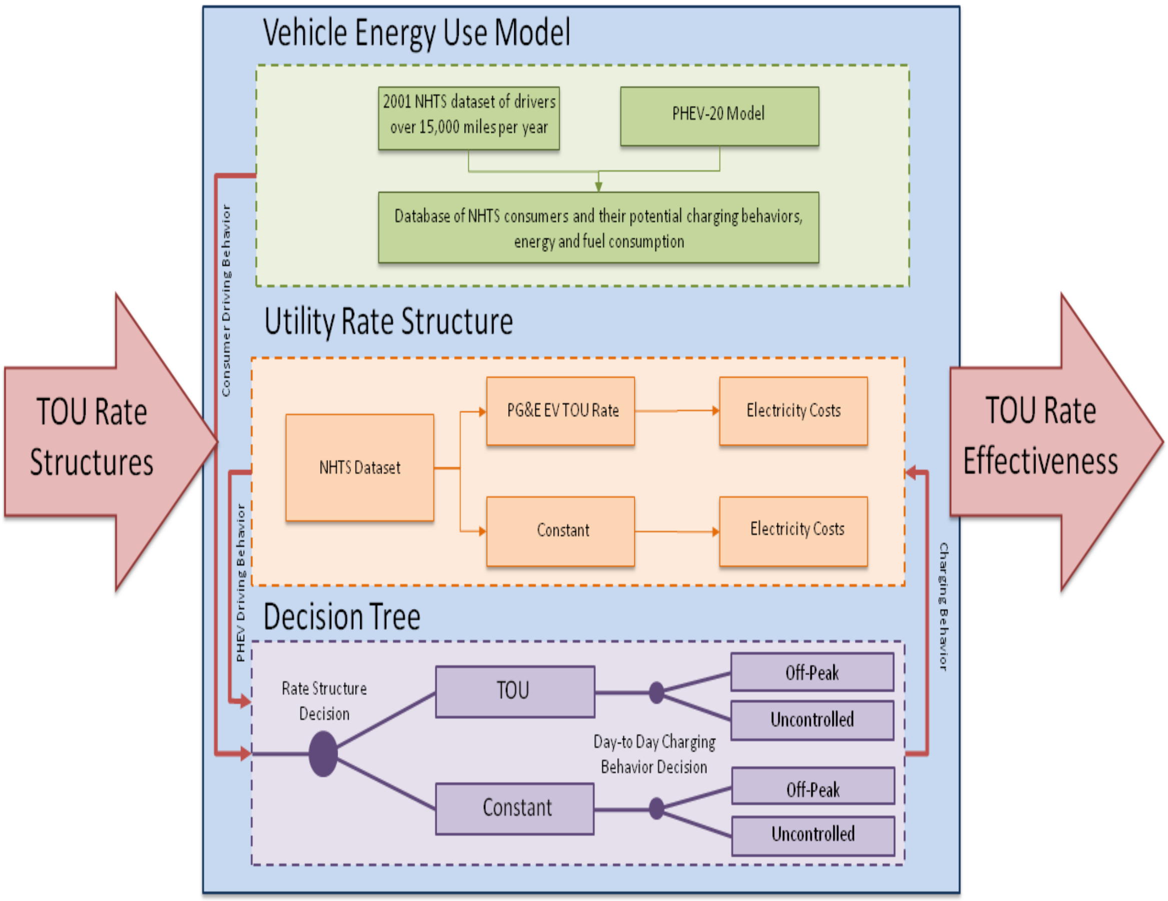


Figure 15 diagram of the structure of TOU rate effectiveness

4.8.1 Vehicle energy use model

The vehicle energy use model calculates the time-resolved driving state, charging state of charge electricity consumption, and gasoline consumption for a representative fleet of vehicles. The energy use model is populated with the driving behavior of potential EV and PHEV owners using a subset of the 2001 NHTS.

For this study, the subset of the NHTS is populated with the day trips of vehicles that drove more than 15,000 miles per year as these vehicles are most likely to realize the lifecycle cost benefits of PHEV and EV and are therefore most likely to be representative of EV and PHEV driving patterns[32]. This subset of trips consists of N=5,332 day trips.

To model the energy consumption of the vehicle, the vehicle energy use model simulates the charging state electricity consumption, and gasoline consumption of each vehicle in the NHTS subset using the vehicle driving state (driven, parked or charging) as an input. Table 4 defines the characteristics of the example PHEV. The example PHEV is operated as a mid-size ZEV-capable PHEV with 20 miles of ZEV[5]. Upon full discharge of the battery (after 20 miles), the vehicles operates in a charge sustaining mode in which no net electricity is consumed. This model assumes that the PHEV can only charge at the driver's home, and that each vehicle is individually metered and billed. These assumptions correspond to a near-term relevant scenario in which there exists negligible public charging infrastructure, and that the utility cannot communicate one household's TOU rate to other public or private chargers.

Table 4 list of vehicle characteristics and corresponding parameter used

Vehicle Characteristic	*Value*
Charge-sustaining fuel economy	37 mpg (6.34 L $(100km)^{-1}$)
Charge-depleting electricity consumption	0.36 ACkWh $mile^{-1}$ (0.21 ACkWh km^{-1})
Charging rate	1.2 kW @ 110 VAC
Gasoline cost	\$2.55 $gallon^{-1}$ (\$0.674 L^{-1})
Charge-depleting (all-electric) range	20 miles (32.2 km)

Figure 16 shows a sample comparison of a single vehicle's driving state, charging state, fuel consumption and electricity consumption under the two vehicle charging scenarios. In the first scenario (uncontrolled), the vehicle charging is not controlled by the utility, and the vehicle is allowed to charge whenever it is present at its home charger. For the off-peak charging scenario, the vehicle may only charge after the off-peak rate period begins, at 12AM. This charging is either controlled by consumer with the use of a timer, or is dispatched by the utility. The driving state as a function of time is the input to the vehicle energy use model from the NHTS subset. This vehicle makes two trips on the NHTS sample day which end at home: one trip of 23 miles, and one trip of 13 miles. Under the uncontrolled charging scenario, the two stops at home over the course of this day lead to two charging events. For the off-peak charging scenario, the vehicle is allowed to recharge only after the off-peak rate period begins, at 12AM. The output of the vehicle energy use model is the time resolved electricity consumption and gasoline consumption of this vehicle under the two charging scenarios. Comparing their consumptions shows that charging scenario can affect the energy consumption of the vehicle. In general, charging off-peak reduces charging frequency, thereby reducing electricity consumption and increasing gasoline consumption.

By performing this simulation for every vehicle in the NHTS subset, the vehicle energy use model outputs the time-resolved driving state, charging state, electricity consumption, and gasoline consumption to the utility rate structure model and the consumer decision tree model.

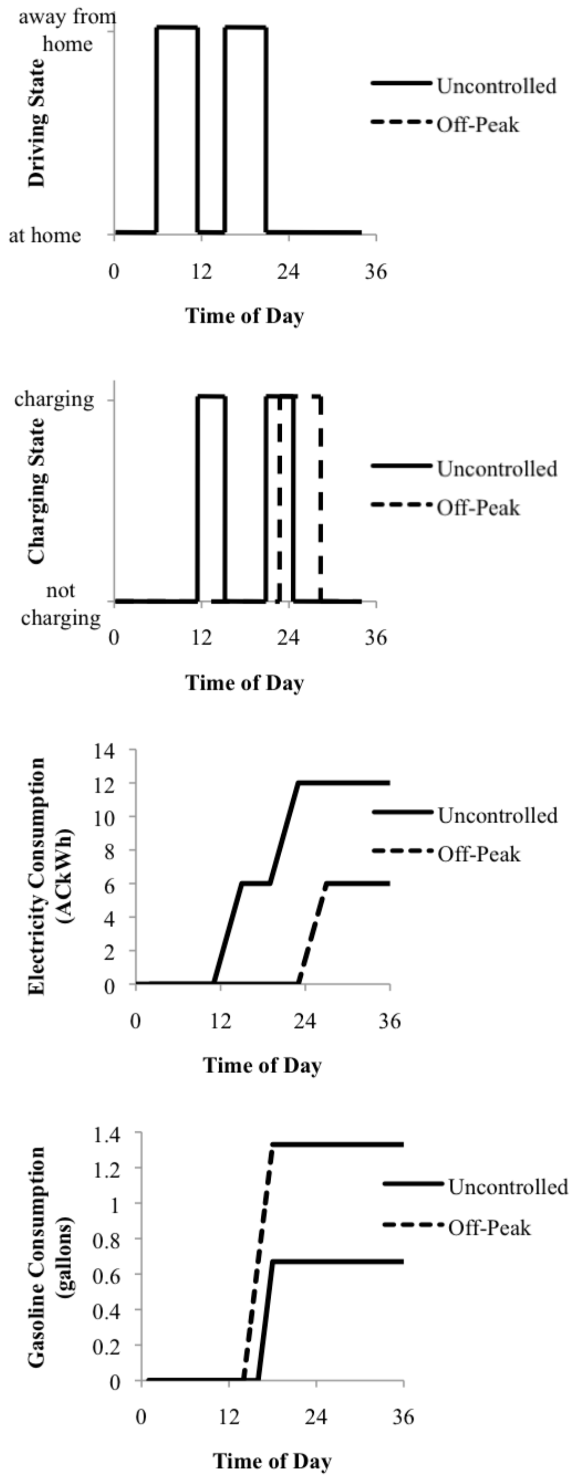


Figure 16 Plot of 30 hours with driving/stopped at home, electricity and gas consumption for a sample of the 2001 NHTS

4.8.2 Consumer decision tree model

In order to understand and evaluate consumer charging behavior, this model assumes that the charging behavior for each consumer is determined by two decisions.

The first decision that each consumer will make is whether to sign up for a vehicle-specific TOU electricity rate. This decision is made infrequently, usually upon purchase of the vehicle and upon installation of the charger. Next, the consumers must make daily decisions about how and when to charge their vehicle. This decision is simplified into two possible choices: charging during the off-peak rate block, or charging immediately upon parking the car at the home charger.

These two decisions are nested into a decision tree, representing the assumption that consumers are unlikely to regularly change their rate structure, but their decision about charging behavior can be changed daily on the basis of daily driving habits.

The decision tree model of consumer charging behavior results in 4 possible decision states for each day the vehicle is charged:

- The consumer chooses a TOU electricity rate for their vehicle and charges off peak,
- The consumer chooses a TOU electricity rate for their vehicle and charges immediately upon parking the car at the home charger ,
- The consumer chooses a constant electricity rate for their vehicle and charges off peak ,
- The consumer chooses a constant electricity rate for their vehicle and charges immediately upon parking the car at the home charger.

Feeding these 4 possible decision states to the vehicle energy use model and the utility rate structure model allows for the evaluation of the PHEV fuel and electricity costs under each decision combination: so the model runs for 4 different iterations.

4.8.3 Utility rate structure model

The utility rate structure model evaluates the costs to the consumers of their vehicle electricity use and evaluates the impacts of the vehicle's charging behavior on the electric grid.

Two utility rate structures are analyzed in the baseline analysis: an EV TOU rate and a constant rate based off of the average residential rate. The costs per unit energy for these two rates structures are shown in Table 5. The rates, and the "peak", "part-peak", "off-peak" classifications, represent current EV TOU and residential rate structures in the Pacific Gas and Electricity service territory[3]. This example TOU rate structure represents a simplification of actual TOU rate structures. For example, this analysis assumes that EV charging will not move the consumer among baseline usage blocks and that peak demand pricing is not in effect. Although this simplified TOU rate structure does not perfectly represent any TOU rate in entirety, it is representative of the key aspects of TOU rate structures that utilities hope will cause consumer shift charging times to meet utility objectives.

Table 5 Modeled default EV TOU rate structure and constant rate structure

Time of day	*Default EV TOU rate ($/kWh)*	*Constant rate ($/kWh)*
12AM-7AM (off-peak)	0.05140	0.18259
7AM-2PM (part-peak)	0.10811	0. 18259
2PM-9PM (peak)	0.29583	0. 18259
9PM-12AM (part-peak)	0.10811	0. 18259

By interfacing the utility rate structure model with vehicle energy use and consumer behavior models, the fuel cost to each vehicle in the NHTS subset can be modeled under each state of the decision tree.

4.8.4 Metrics of decision making

As described in the background section, an effective TOU rate would provide economic incentives for a consumer to 1) choose to be billed using a TOU rate, and 2) choose to charge during the off-peak period.

For each vehicle (*k*) in the 2001 NHTS subset, a given cost metric (*c*) can be evaluated at each of the four states of the decision tree ($c_{TOU,offpeak}$, $c_{Const,offpeak}$, $c_{TOU,uncontrolled}$, and $c_{Const,uncontrolled}$). The effectiveness of the TOU rate structure decision can then be quantified by calculating the fraction of the NHTS subset where it is less expensive to charge off peak using the TOU rate than it is to charge at will using the constant electricity rate. This metric measures how many of the 2001 NHTS subset trips are economically incentivized to choose the TOU rate structure.

$$E_1 = \frac{1}{N}\sum_{k=1}^{N}\left(c_{TOU,offpeak}(k) < c_{Const,uncontrolled}(k)\right)$$

The effectiveness of the charging time decision can be quantified by calculating the fraction of the NHTS subset for which it is less expensive to charge during off-peak periods as compared to an uncontrolled charging scenario. This metric measures how many of the NHTS respondents choose to participate in the off peak program, while knowing that they receive a TOU rate.

$$E_2 = \frac{1}{N}\sum_{k=1}^{N}\left(c_{TOU,offpeak}(k) < c_{TOU,uncontrolled}(k)\right)$$

These decisions are nested so that E_1 represents the effectiveness of the TOU rate if one allows each consumer to periodically choose whether or not to enroll in a TOU rate. If one assumes that the decision to enroll in a TOU is sticky and cannot be reevaluated once it is made, then E_2 will represent the effectiveness of the TOU rate in reducing the cost while making the daily decision to charge the vehicle either at off-peak times or at other times, as needed. Where the effectiveness of the TOU rate is high, it represents a mutually beneficial condition for both consumers and utilities. Consumers will receive robust price signals that direct them towards decisions that reduce their costs, and utilities get a large number of consumers who charge off-peak, thereby minimizing their impact on the electric grid.

5.0 INFRASTRUCTURE REQUIREMENTS OF PEV

Due to PEV dual fuel source it is important to understand future-consumers charging and infrastructure needs. It is popularly assumed that EV will require more infrastructure than PHEV because their only source of fuel is electricity. In order to gain insight as to the true infrastructure needs, the 2009 NHTS dataset is used it to simulate the vehicle charging benefit model. The percentage of vehicle day needs that were met (whether or not the gasoline engine turned on) for each AER at 1.44 kW charging power for the three different infrastructure cases from section 4.8.3 was calculated. Figure 17 shows the increase in needs met for increasing infrastructure for the most near-term scenario.

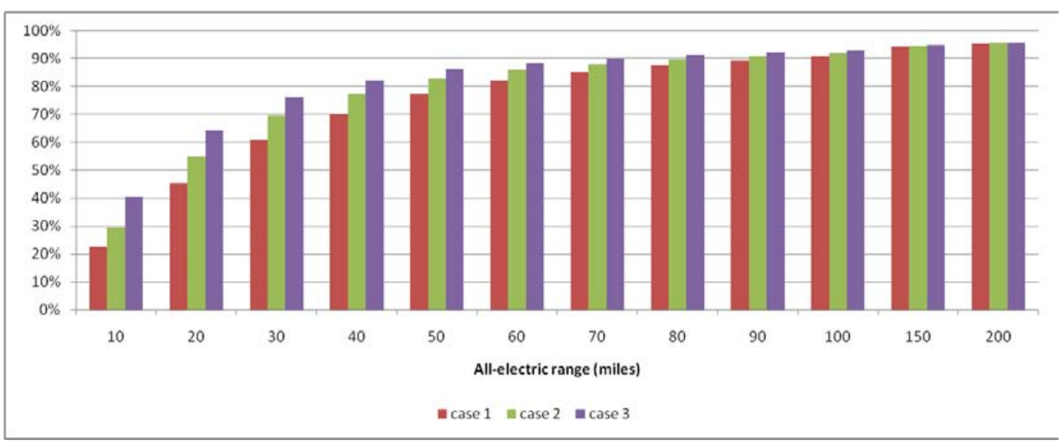


Figure 17 comparison of needs met for 1.44 kW charging infrastructure

Figure 17 compares the percentage of vehicle days whose needs are met from increasing the infrastructure availability of PEV (y-axis) as compared to each AER analyzed (x-axis). The overall benefit is highest for low-AER vehicles, nearly doubling the number of vehicle days needs met for a PHEV-10, and drops to less than 5% difference for vehicles with above 70 mile AER. This shows the very small benefit achieved for increasing infrastructure for near-term EV, like the Nissan Leaf, but high increase for low- to mid-AER vehicles.

5.1 Benefits of increased infrastructure

Current drivers of EV and PHEV maximize their electric miles driven by carrying an extension cord and charging wherever they can. As described in section 5.6, the benefit metric:

$$B = \frac{P_1 - P_2}{P_1}$$

The benefit, B, is calculated by comparing the change between two points: P_1 and P_2. In this case, it is comparing the number of vehicle days needs met from home charging only (case 1, P_2) to the number of vehicle days needs met a higher availability of charging locations (case 2 or case 3, P_1). This is plotted for each AER analyzed. Figure 18 shows the benefit increase of home to home and work, and home to charging at all charging locations at 1.44 kW, a very near-term scenario.

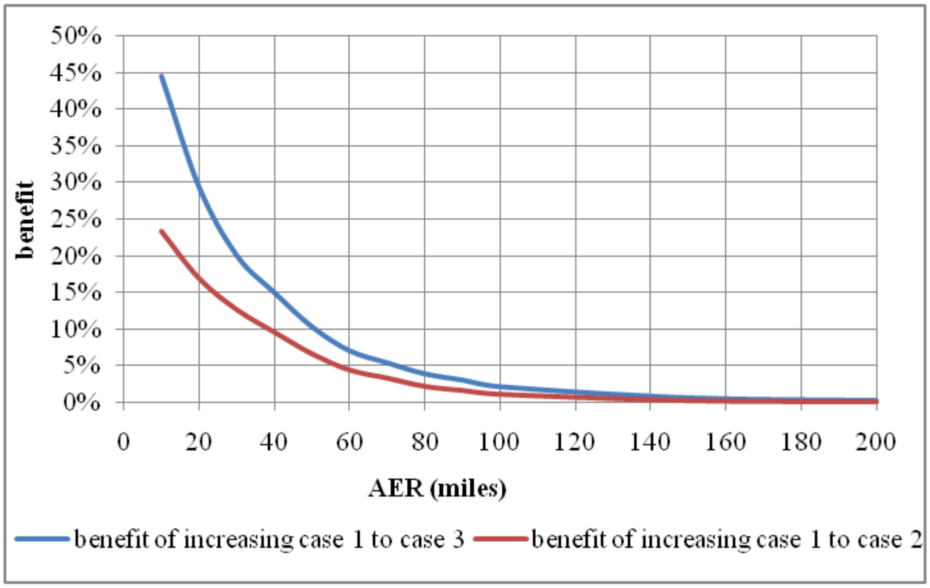


Figure 18 comparison of possible charging locations at 1.44 kW

The increase in availability for charging has a significant effect in the benefit seen by PEV drivers. The benefit *metric* increases when moving from increasing charging availability at home only to home and work charging (23%) and an even larger benefit to increasing charging availability to all locations (44%). Again, the largest benefit is for low-AER vehicles. The relative increase for vehicles over 50 miles AER drops to less than 5% for home and work charging, and 70 miles for charging at all charging locations. In order to maximize the number of people that would benefit from increased infrastructure availability utility companies should invest in low-power, high availability of electrical infrastructure.

Infrastructure comes at cost and as such, this must be addressed. The maximum benefit to consumers is seen for increasing the infrastructure to every commercial location, however, this is not a near-term, feasible scenario. For level 1 charging, each charger is assumed to cost $200. This is a fixed cost. The average cost per vehicle for a very near-term scenario is shown below (Figure 19).

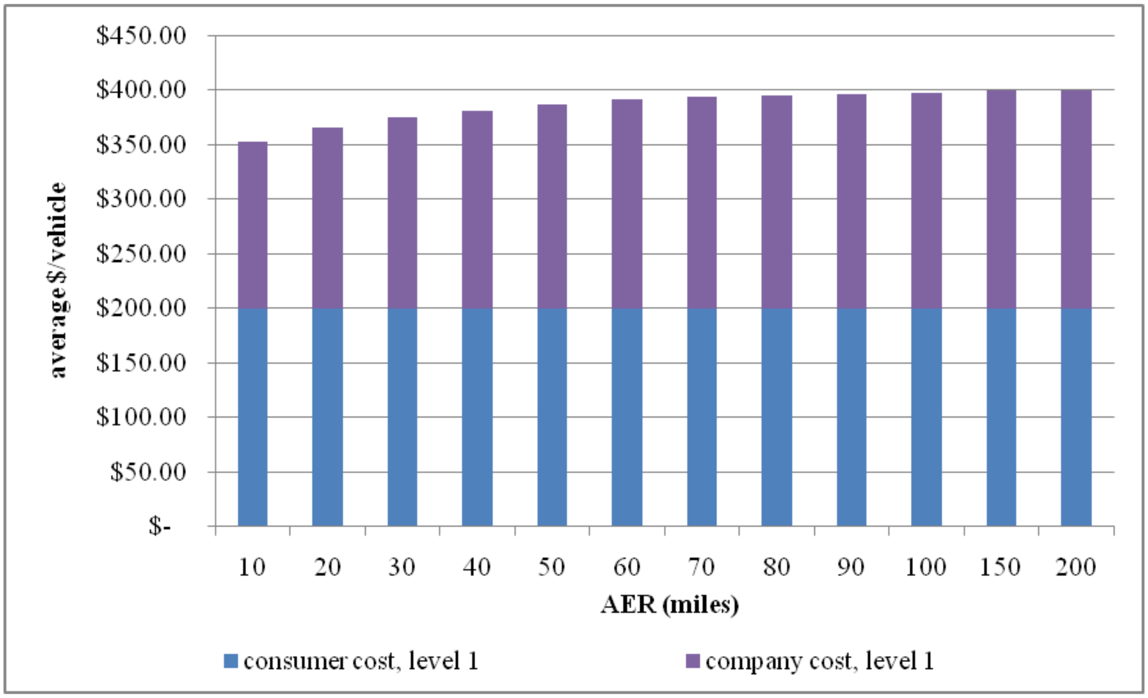


Figure 19 average $/vehicle cost for near-term charging scenario at 1.44 kW

Figure 19 shows the cost for installing large amounts of infrastructure for low-AER vehicles. Mid-range PHEV, such as the Chevy Volt, shows a fixed cost of $200/vehicle for home charging (a cost incurred directly to the consumer upon the purchase of the vehicle) and an average of $180/vehicle for the case 2 charging scenario, a cost shared by the consumer and employer. These are one-time costs and take into account the higher benefit for low-AER vehicles. The increase in charging availability comes at a financial cost to both the consumer and employer, but is likely to have long-term benefits by reducing future fueling costs and tailpipe emissions.

The increased benefit achieved by increasing the availability of charging infrastructure is of value to future drivers of PHEV. This benefit does not take into consideration varying charging power and does not analyze how reliably drivers connect their vehicles to charging stations. The effects of this analysis may seem of value to most consumers and utility companies: as the availability of infrastructure increases, the benefit metric increases. Large amounts of infrastructure are ideal to low-AER vehicle owners as it allows them to maximize their electric drive potential.

To summarize, there is a 44% increase in the benefit metric for increasing the charging availability from home to all locations for low-AER vehicles. For high-AER vehicles the benefit is less than 3%. Therefore, we can conclude that, from this definition of the benefit, more charging stations is of benefit to low-AER vehicles rather than high-AER vehicles, as previously assumed. It is still important to recognize that drivers of high-AER vehicles will want, or think they require charging locations. As such, this should still be considered when utility companies and municipalities begin investing in infrastructure.

6.0 INCREASED AER AND CHARGING POWER

As the AER increases, there are changes to both the benefit metric by increasing the number of charging stations, as well as increasing the charging rate of the stations. The change in the benefit metric (section 4.6) used to compare different scenarios.

The vehicle days from the 2009 NHTS were used and imputed into the vehicle charging benefit model. The output of the model compares the number of vehicle days within in the NHTS whose needs were met by the specified AER, charging power, and charging availability. Additional outputs can be found in Appendix A.

6.1 Effects of increased AER and charging power

When analyzing the effects of increased AER and charging power, the trends are primarily from increasing infrastructure. However, there are two significant findings. First, as the AER increases, the total number of trips that can be completed solely off of electricity increases. At a high AER, the effect from the amount of infrastructure becomes small. Second, charging rate is not as significant, and causes very little difference. These results are displayed in Figure 20. The dotted lines are for case 1, the dashed lines are for case 2 and the solid lines are for case 3. The percentage of vehicles who were fueled solely off of electricity is graphed versus the AER (Figure 20).

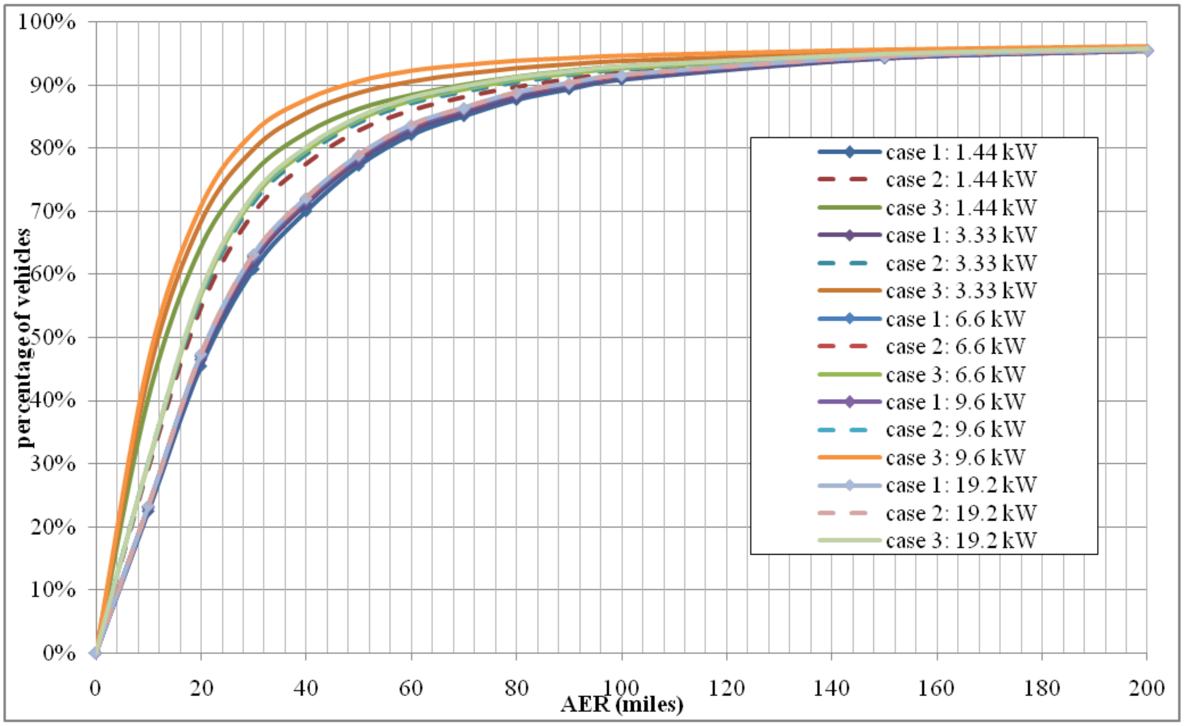


Figure 20 vehicle charging benefit model results for all cases

For case 1 charging, by increasing the AER from 10 to 20 miles, close to half of all vehicle days needs will be met by the charging speed and availability scenario, and for the case of the Chevrolet Volt, with an AER of 40 miles, 70% of vehicle days needs are met by just using 1.44 kW charging power, and at-home charging, the most basic, near-term charging scenario. If a household installs a 3.33kW charger, the percentage increases 1.17%. The benefit of charging power for low-range vehicles and at-home charging has a 22.5-23.3% change for 10 mile AER. The other extreme is a 5% increase between 100 mile AER and 200 mile AER, from 90.8% (at 1.44 kW, 100 mile AER) 95.5% (19.2 kW, 200 mile AER), making the benefit of doubling the AER and increasing charging power, small. These same trends are seen for both case 2 and case 3. Figure 20 shows that the benefit of increasing the AER of PEV for all potential charging scenarios is independent of charging power.

If the dividing line between PHEV and EV is considered to be 80 miles AER, the maximum benefit to EV by increasing charging rate is 2.97%, at the most extreme scenario (comparing case 1 charging to case 3 charging). This still shows that 6% of vehicle day needs are still not by met by allowing charging everywhere. And, although this percentage is low, it is more important for some drivers than others. It is important for utility companies and municipalities to install infrastructure for consumer peace-of-mind as well as the consumers that do need it.

6.2 Increased charging power as a benefit

Understanding the benefit for increasing the charging power is important as there is a high cost associated with installing faster chargers, potentially detrimental effects to the US electric grid and uncertain load shapes from high concentrations at public locations. The most near-term scenario is home charging only at 1.44 kW or perhaps 3.33 kW. The availability of public infrastructure, especially higher powers, is likely to be limited for the near-term scenario. Figure 21 shows all benefits of increasing charge power for the three charging scenarios by showing the increase in the percent of people who benefit (y-axis) versus the AER (x-axis).

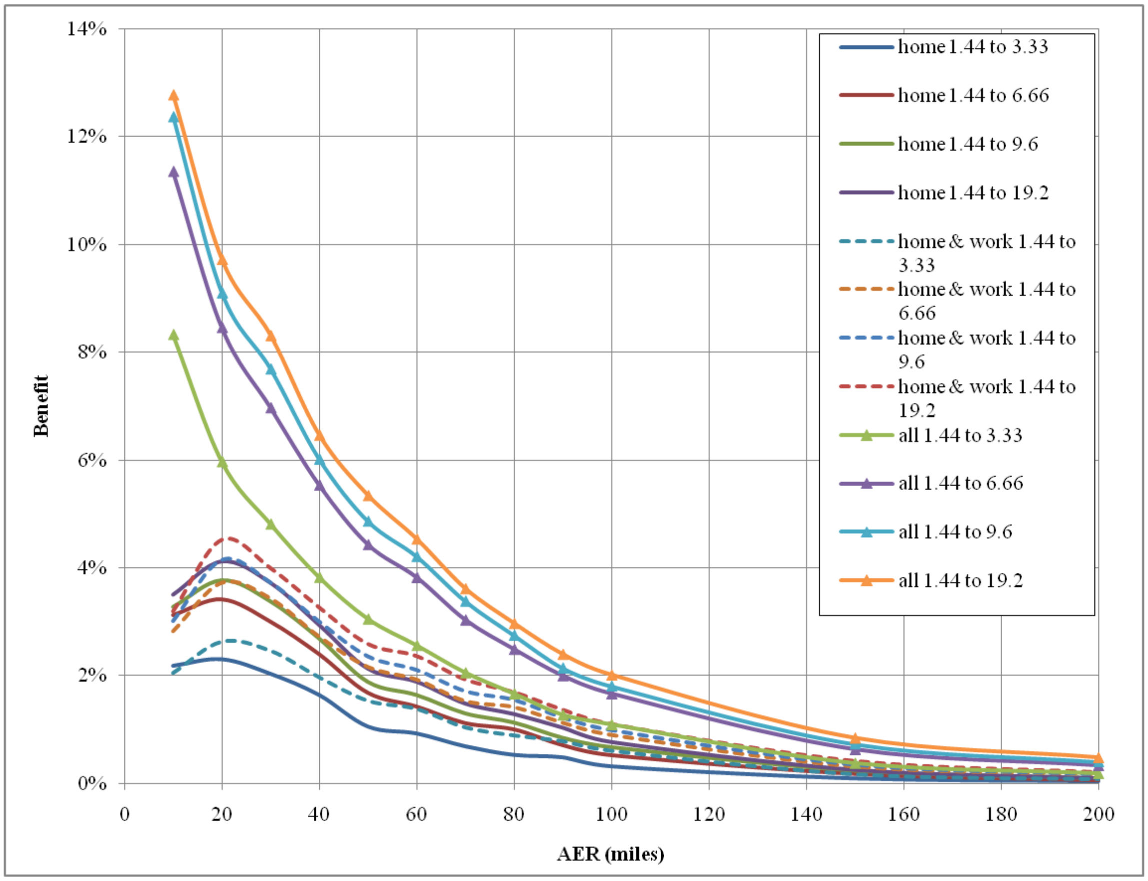


Figure 21 comparison of increased charge power

The results of increasing charging power as compared to different locations show a few clear trends. First, the overall benefit for increasing charging power for both the home charging and home and work charging scenarios is limited to less than 4.5% benefit for all scenarios. This maximum occurs at 20 mile AER for the scenario of increasing home and work charging power from 1.44 kW to 19.2 kW. This benefit does not consider increased infrastructure cost. The trend continues to show a negative rate of change, and at 70 mile AER the benefit is less than 2% for increasing charge power. This is very insignificant, and the benefit decreases for less than 1% for all scenarios at 100 mile AER. The small benefit to high-AER vehicles is almost completely independent of charging location and charging power.

The trend changes for allowing charging at all charging locations and increasing the charging power. Instead of a peak at 20 mile AER the maximum benefit is at the lowest AER, 10 miles, at 12.7% for 19.2 kW, and steadily decreases as the AER increases. The benefit for these decreases steadily and by 60 mile AER, the benefit is less than 5% for all scenarios. The maximum increase is at 20 miles for both at home charging and home and work charging, with 4.1% and 4.5% of vehicle days benefiting by increasing the charging rate from 1.44 kW to 19.2 kW, respectively. The largest benefit of increased charging rate is in after charging infrastructure has already been increased: the number of charging locations available to vehicles is 12.7% for charging at all charging locations, and a 10 mile AER. This benefit drastically decreases as the AER increases. These values again show the relatively small benefit achieved by increasing charging power under any charging availability scenario.

Again, it is important to analyze the costs associated with level 1 and level 2 infrastructure (Figure 22).

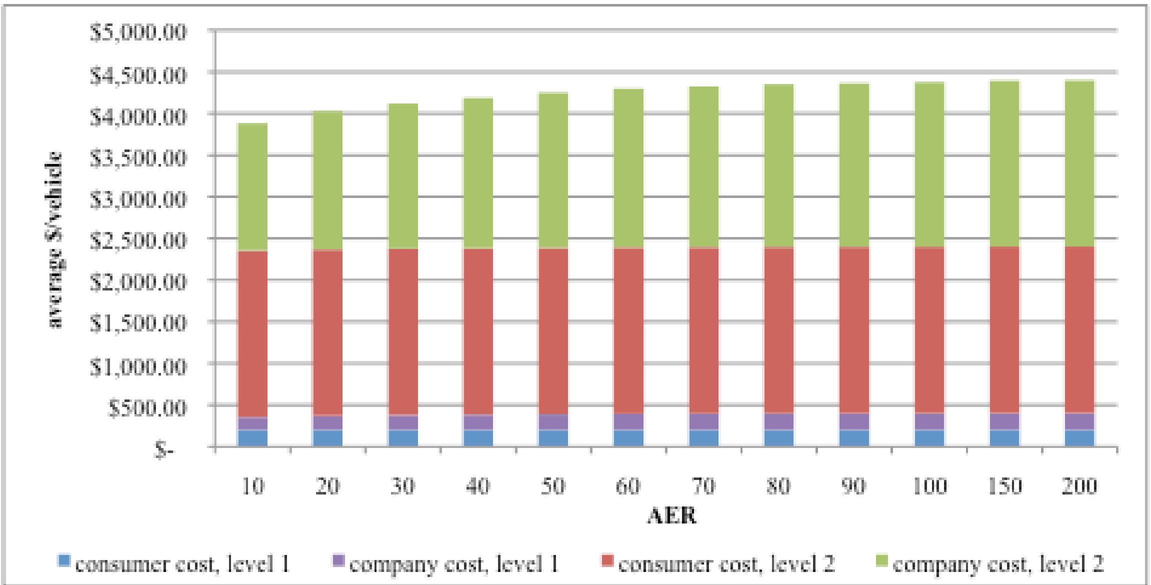


Figure 22 average cost per vehicle for near-term charging scenarios

The benefit metric shows a reduced need for high-AER vehicles, and a higher benefit for increasing charging locations. However, as previously stated, it is not feasible in the near-term to increase the number of charging stations to all locations. It is beneficial to assess near-term infrastructure and costs associated with increased charging power. From INL, level 1 charger installation cost is $200 and level 2 (3.33kW) installation cost is $2,000. The average cost per vehicle comparison of case 1 and case 2 is shown in figure 22, with the average cost per vehicle (y-axis) and the AER available (x-axis).

While some consumers may believe there to be a significant benefit to installing level 2 chargers, it is unlikely that they will ever recoup the cost that is required to install them. The average cost per vehicle is, on average, ten times that of level 1 charging and has a very small benefit to most vehicles. Level 2 charging is may not be practical for most users in the near term but must still be installed in well-planned locations.

The benefit to vehicles of having charging infrastructure dramatically decreases as the AER increases. For low range AER, the benefit may be significant (between 44.5 and 49.1%). This is almost completely independent of charging power (Figure 23).

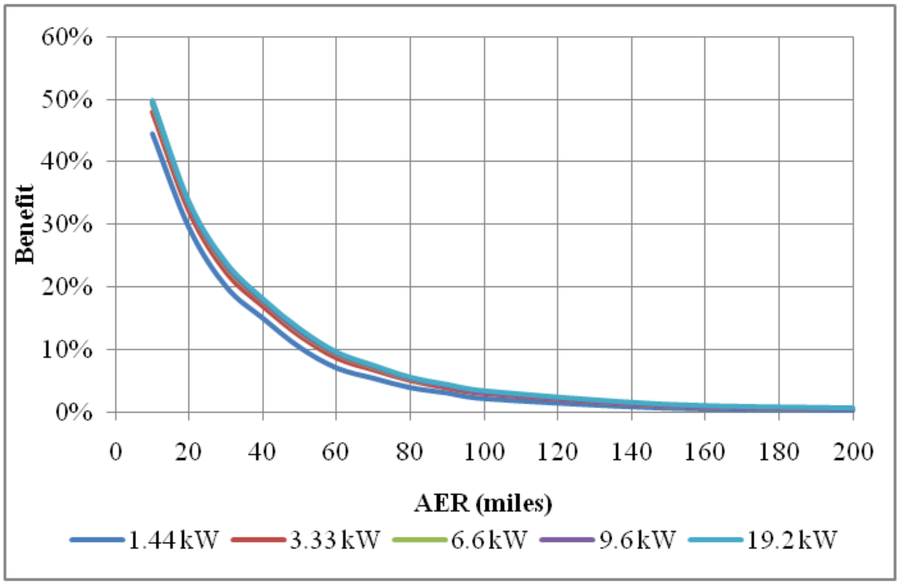


Figure 23 benefit of increasing charging availability from home only to all locations

Figure 23 shows the maximum benefit (y-axis) to increasing charging locations (case 1 to case 3) versus the AER (x-axis). This occurs at the lowest AER. This shows that the majority of vehicle days are spent taking short trips. Vehicles with a low-range AER and high charging availability will benefit most, and this is completely dependent of charging power.

High rate charging infrastructure is expensive, adds stress to the electric grid by peaking at inopportune times and has an insignificant benefit to most vehicle days. With a benefit of less than 13% for all scenarios, this does not warrant the increase in cost associated with installing high-rate chargers. This is especially true for vehicles charging at home only. It is important for consumers to realize the low benefit achieved for level 2 charging which does not justify the cost for 98% of Volt buyers and 99% of Leaf buyers.

6.3 Cost per mile as a metric

For many consumers, it is likely that one of the main benefits of PEV will be a reduction in fueling costs and a reduced number of trips to the gas station. The higher the AER of the vehicle, it is assumed that total refueling costs will decrease, since electricity is significantly less expensive than gasoline. However, the benefit should be significant since the cost of increasing the AER (which is increasing the size of the battery) is significant. The metric of cost per mile is calculated for the 180 combinations listed in the vehicle charging benefit model to compare the benefit achieved by increasing AER from the consumer perspective (Figure 24).

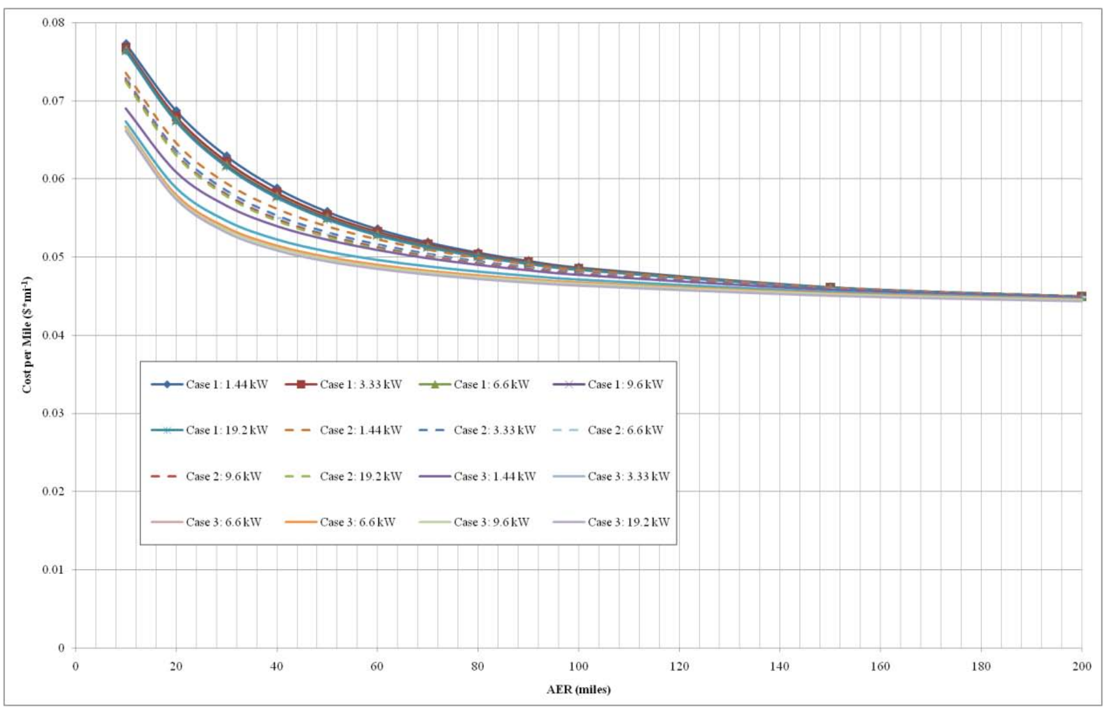


Figure 24 cost per mile output for charging scenario and power combinations

Figure 24 is the average cost per mile calculated for the vehicle day. This shows similar results to the previous analysis: increasing the availability of charging infrastructure has the largest benefit to consumers, and increasing the charging power has a relatively small impact. The benefit is most significant for low-AER vehicles. However, the cost difference is small, and is unlikely to justify the cost of installation of high rate charger: 14.45% difference when comparing 10-mile AER case 1 charging at 1.44 kW as compared to case 3 at 19.2 kW. The benefit is unsubstantial as the AER increases. For most vehicles this is an insignificant difference and unlikely to warrant the increase in purchasing cost of a high AER vehicle.

To summarize, the largest benefit seen for consumers is from an increase in low-power charging infrastructure. A high availability of low-power outlets should provide a sufficient amount of infrastructure for most PEV. For the near-term EV with a 200 mile AER and a heavy saturation of high-level 2 charging will not meet the needs of 4% of average vehicle days. This could result in a vehicle owner having to rent a car 2-3 days a month, or forcing individuals to participate in car sharing programs. The results of this section show that for most vehicle days, the most benefit is achieved by a high-availability of level 1 charging in combination with low and mid-range PHEV.

7.0 TOU RATES AS A METHOD OF CONTROLLING RESIDENTIAL CHARGING BEHAVIOR

For the vehicle energy use model, the following metrics were calculated for a subset of the 2001 NHTS,

- Consumer electricity costs (considering only electricity),
- Consumer cost per mile ($/mi, considering the costs of electricity and gasoline),

The effectiveness of the default EV TOU rate can then be calculated for these two cost metrics.

7.1 Electricity costs as a price signal

Utility bills represent the easiest financial line of communication between the utility company and the consumer. Whether these bills are communicated in real time, or monthly, they can only represent the costs of electricity used by the PHEV. A TOU model is a pricing signal sent by the utility through utility bills to consumers that increases electricity prices during peak hours when the grid may be already highly loaded. The off-peak charging period is the lowest cost. The original outputs of the model show a strong (100%) signal, for the metric of the electricity bill, sent to consumers by choosing off-peak electricity (Appendix B).

Despite the strength of the economic signal communicated to the consumer through the utility bill, electricity costs to the consumer are an inadequate cost metric for PHEV. Because PHEV are fueled by both gasoline and electricity, the utility bill provides an incomplete assessment of the actual fueling costs incurred by the consumer, of operating the vehicle as gasoline fueling costs are not currently communicated through the utility bill.

7.2 Cost per mile as a price signal

A more relevant metric of PHEV operating costs is the total fueling cost per unit distance. For PHEV, the calculation of cost per mile must include both electricity and gasoline costs. The TOU rate analysis can be used to calculate the cost per mile for every daily trip in the NHTS subset, and for the four decision states.

For the metric of cost per mile, the consumer's decision making process is more muddied than was the case using the metric of utility costs. There exists significant overlap between the cost per mile for each of the 4 decision states.

To first understand the decision whether or not to enroll in an EV TOU rate, we can calculate the effectiveness of the EV TOU rate decision. The effectiveness of the TOU rate structure decision is E_1 = 95%. In other words, for 5% of drivers, the EV TOU rate structure will lead to average higher costs per mile than will a constant rate structure.

From these analyses of PHEV, we can see that the legacy EV TOU rate sends strong price signals to the consumers using the metric of cost per mile. Both decision states are lower, while still giving a slight benefit to an EV rate structure decision as well as off-peak charging.

7.3 TOU rates as signal to consumers

The results of the vehicle energy use model analysis has shown that the modeled default EV TOU rates provides economic incentives to PHEV owners to help control their at-home charging behavior. The economic signal sent by the utilities is carried by the electricity bill. This analysis has shown that the electricity bill provides a signal encouraging PHEV owners to charge during off peak periods using the EV TOU rate. By performing the analysis using the cost metric of cost per mile (which is most relevant to PHEV owners), this analysis has shown that approximately most consumers will pay less if they choose to behave as the utility would prefer.

7.4 TOU rates and gas prices

PHEV fueling costs are dictated by both electricity and gasoline fueling prices, the utility can only control and incentivize electricity costs. To achieve thoroughly robust and effective control of PHEV charging behavior the TOU rate must reduce the charging costs of vehicle that charge during the off peak period to the degree that the discount in electricity costs can overcome the increased gasoline consumption that comes with delaying PHEV charging until the off-peak period. These TOU rates must be resistant to changes in gasoline prices.

A strong TOU rate will show high rate structure decision effectiveness (E_1) for the cost metrics of cost per mile regardless of the cost of gasoline. This implies that consumers will see an economic incentive to choose the TOU rate and charge off-peak. A strong TOU rate will also show high charging decision effectiveness (E_2) for the cost metrics of both electricity costs and cost per mile, regardless of the price of gasoline. Such a TOU rate implies that the price signals that are transmitted to the PHEV consumer through their electricity bill will lead the consumer to charge their vehicle in a way that minimizes their cost of operating the PHEV and reduces their vehicle's impact on the electric grid.

In order to evaluate the sensitivity of TOU rates as gas prices change, the model was run for gasoline prices varying from $1-20/gallon. While $20/gallon in the U.S. is unlikely, it is not in the foreseeable future. Gasoline prices are expected to rise as demand increases. The rate decision effectiveness (E_1) and charging decision effectiveness (E_2) were calculated and compared.

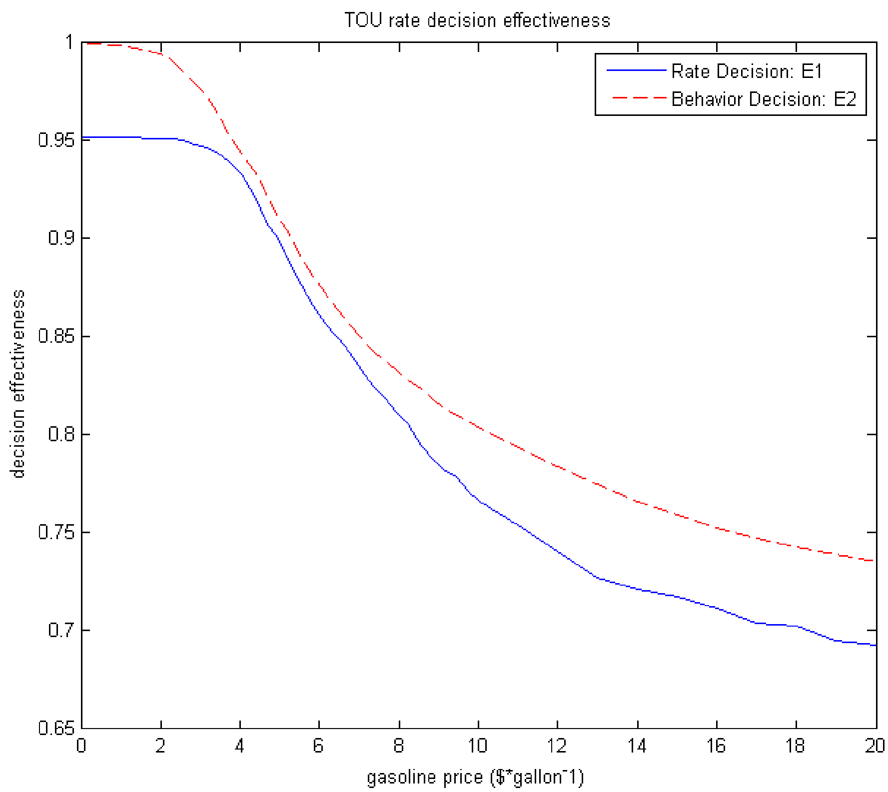


Figure 25 effectiveness of rate structure and charging behavior

The utility bill of all customers will be lowest if they charge off-peak using the TOU rate as opposed to the default constant rate, showing an effectiveness of 100%. This is of primary benefit to the utility, as it is less likely that the grid will be overburdened by disruptions in use. In addition, Figure 25 shows the tradeoff for the cost per mile metric that limits the effectiveness of TOU rates as a means for controlling PHEV charging behavior with regards to the price of gasoline. Despite the high prices of gasoline, still an effectiveness of 68% can be achieved. This is because of the large number of low mileage days driven by consumers. Vehicles that drive more than 20 miles a day will benefit from increased charging frequency, whereas consumers, who drive small amounts, regardless of gasoline prices, will still benefit from using a TOU rate and charging off-peak.

TOU rates are very strong in showing a significant influence to consumers and helping to control charging behavior. Secondly, TOU rates are weak in persuading individuals to choose a TOU rate. Regardless of the gasoline price, vehicles are better off charging during off-peak hours. These vehicles are likely to driven small amounts throughout the day and do not deplete their battery. The advantage of inexpensive electricity as compared to expensive gasoline is the major cost factor for consumers who deplete their battery. The TOU rates are not resistant to rising gasoline prices.

To summarize, TOU electricity rates do provide pricing signals through the electricity bill directing by PHEV owners to enroll in the TOU rate and to charge during the off-peak period. As gasoline prices increase, consumers who deplete their battery are better off by charging at will. This minority is best served by choosing a constant rate structure and charging at their convenience. From the NHTS, it is impossible to determine whether or not this is accurate for all drivers, or simply the portion that depleted the battery for the sample day.

7.5 Effects of consumer education

Utilities possess tools other than TOU rates that can help to control the charging behavior of PHEV owners. The education of consumers as to what types of charging behavior are desired by the utility can influence charging behavior without resorting to economic incentives. Researchers have found that future-buyers and early-adopters of PHEV will be educated homeowners, of higher socioeconomic status and environmentally conscientious[9,10,11]. As a result, these studies suggest that the purchasing of PHEV is not dependent upon the availability of discounted electricity. Instead, the environmental benefits, community benefits, and long-term electricity rate benefits of controlled charging will influence the charging behavior of consumers along with the economic incentives that come with TOU rates.

8.0 CHANGES IN THE UTILITY FACTOR

The utility factor, which is the current SAE standard for comparing the utility of PHEV at different AER, is another metric by which to compare PHEV. It compares the amount of electric and non-electric miles driven for varying ranges of PHEV.

For this study, the utility factor was used to compare to the benefit of both increasing charging infrastructure and charge power, for near-term scenarios. The 2009 NHTS vehicle days were placed into the vehicle charging benefit model and the utility factor was calculated using the following method:

$$UF = \frac{\sum miles_{CD}}{\sum miles_{total}}$$

This method is slightly different than the SAE J2841 equation (described in section 4.4) since it considers all miles driven in CD mode (as opposed to just the AER of the vehicle) and allows vehicles to charge as restricted by the varying charging scenarios. The same set of AER, charging powers and charging scenarios are examined to show the benefit in the utility of PHEV to consumers.

8.1 Effects of increased charging locations

The most near-term scenario is allowing 1.44 kW charging at either home or all locations. The model assumes that as a vehicle arrives at a location it is able to charge; until the vehicle either departs for its next trip, or the battery is full. Figure 26 shows the utility factor for both scenarios (case 1 and case 3) and the relative improvement that is achieved by increasing charging availability.

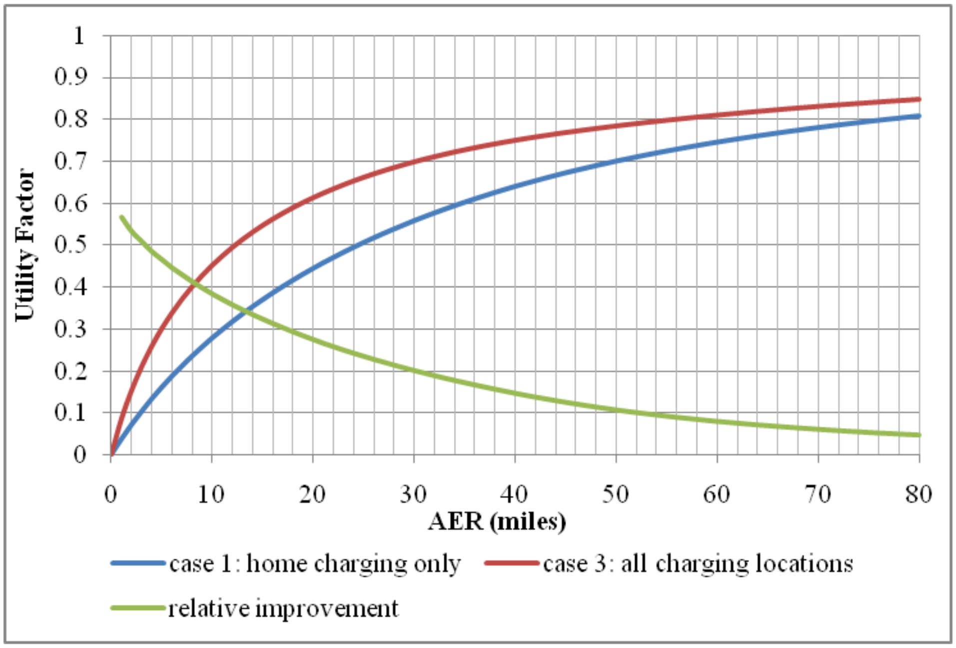


Figure 26 comparison of charging location and relative improvement to the utility factor at 1.44 kW

The benefit for increasing charging locations is very high for low-AER vehicles, 57% for a 1 mile AER, and 38% for a 10-mile AER. The return decreases to 14.5% for 40-mile AER, and 4.6% for an 80-mile AER. The benefit of increased charging availability, for low-range AER is significant to consumers, even at a very low charge power.

8.2 Effects of increased charging power

Increasing the charging power does not provide much benefit to the utility factor (Figure 27).

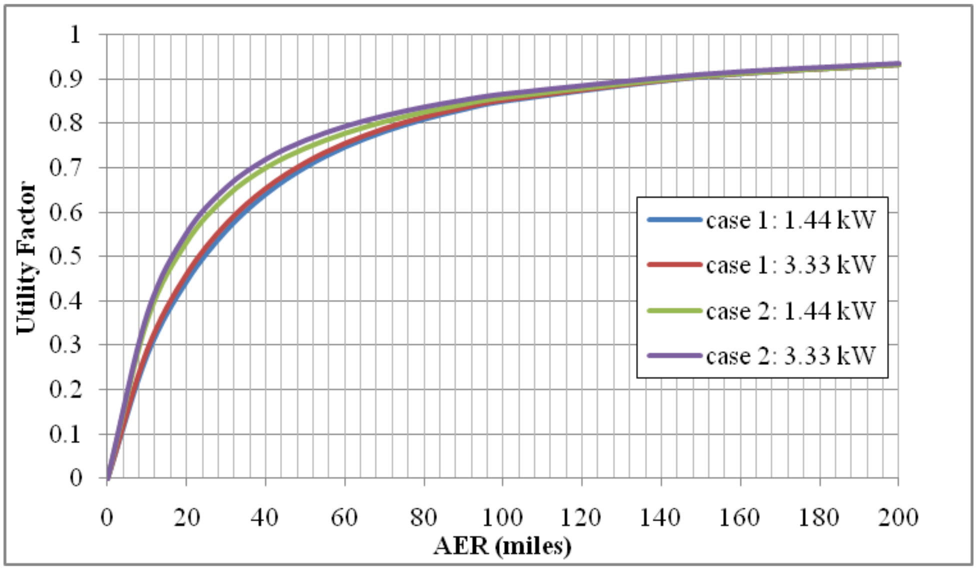


Figure 27 utility factor comparison of home charging, increased charging power and increased charging location

The maximum benefit achieved is by increasing the amount of charging locations, not by increasing the charging power. This is seen in Figure 27, which shows a comparison of 1.44 kW and 3.33 kW for both case 1 and case 2 charging. The increase for at-home charging only between 1.44 and 3.33 kW is minimal regardless of AER, with a maximum benefit of 1.6%. The maximum increase occurs at a 20 mile AER: the difference between 1.44 kW home charging and 3.33 kW charging at all charging locations is 21.2%. The difference between allowing home charging and charging at home and work locations is present, regardless of charging power; and this benefit is highest for low-AER vehicles.

8.3 Effects of increased charging as compared to SAE J2841

The vehicle charging benefit model presented provided the results to 15 different near-term charging power and location scenarios. The utility factor was computed and compared to the current SAE J2841 standard (Figure 28).

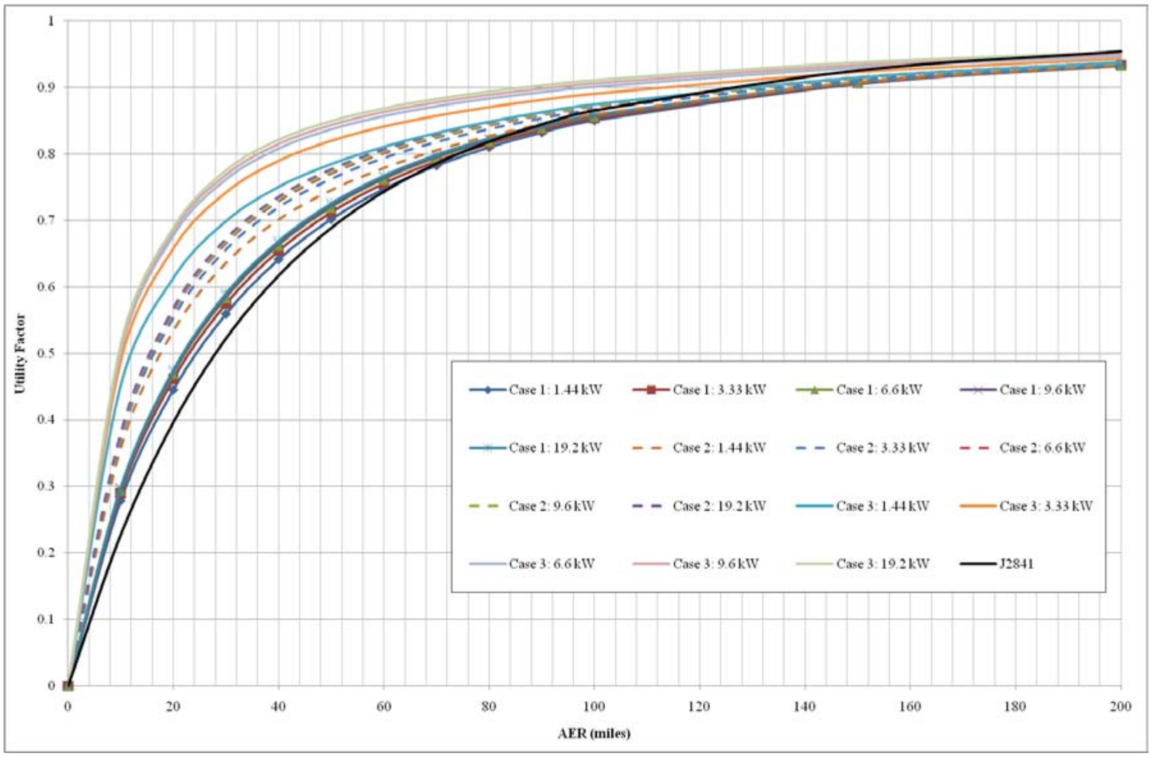


Figure 28 calculated utility factor for 15 scenarios and compared to SAE J2841

Figure 28 shows similar results to the previous two scenarios, that increased charging availability has the largest increase in utility of PHEV. The results of case 3 charging, combined with low level 2 charging powers has an increase in the utility factor, especially at values of low-AER. The largest increase for case 3 charging is between 1.44 kW and 6.6 kW with a difference of 6.4% at 20 mile AER. This is small compared with the largest increase between charging availability for case 1 charging at 1.44 kW to case 3 charging at 19.2, which has its largest difference of 24.4%, again at 20-mile AER. Increasing the availability of high level 2 charging has the largest benefit to the utility of PHEV.

In this comparison of the utility factor, it is important to understand that the SAE standard assumes at home charging only, once per day, at a charging power of 1.44 kW. However, this is an unlikely near-term scenario. Figure 28 shows the significant difference between both near- and long-term charging scenarios and the SAE standard. For low-AER, the SAE estimate greatly underestimates the utility factor for all scenarios. While near-term it is unlikely that there will be a full saturation of 19.2 kW chargers, it is probable that individuals with low-AER vehicles will maximize their electric drive potential by charging as often as possible. As the AER increases, the difference between the SAE standard and the calculated utility factor values decreases, and eventually over estimates the actual values (Figure 29).

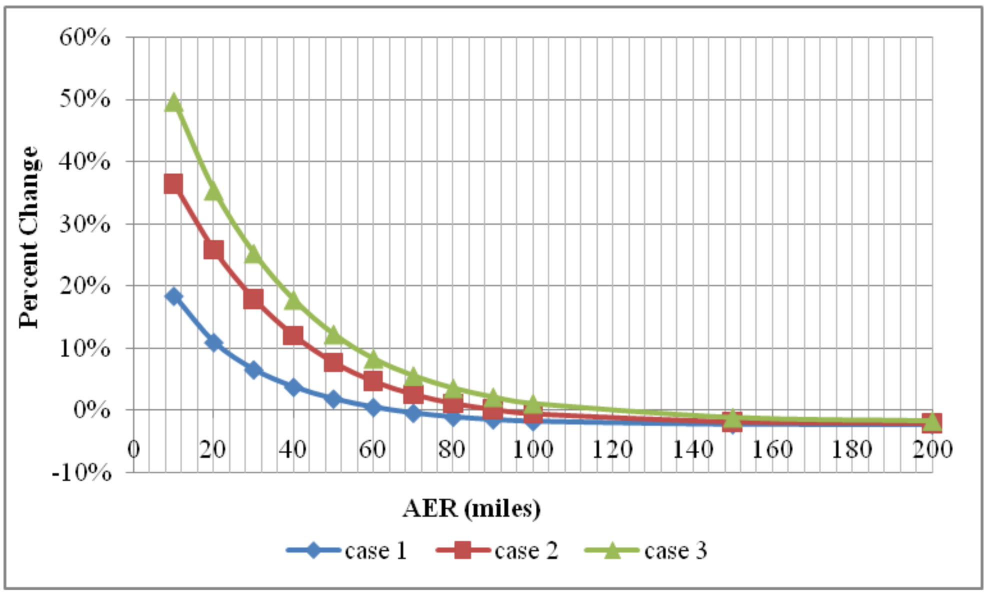


Figure 29 percent change of 1.44 kW charging scenarios to SAE J2841

Figure 29 shows the calculated difference between the SAE standard and the calculated values for the three most near-term charging scenarios at 1.44 kW charging power for all AER. These are scenarios that individuals with EV and converted PHEV are currently using. The simulated values show between an 18.3-49.6% underestimation of the actual utility of 10 mile AER PHEV. This is a large difference, which shows the inaccuracy of the current SAE standard.

The SAE standard should reflect actual driving and charging behaviors of future PHEV owners. While this data is not currently available it can be assumed from the above analysis that PHEV owners are likely to charge at low-rates as often as they can, or as long as there is an available outlet. This has an effect on the calculation and value of the utility factor, as the CD mode range will be less than the total number of miles driven in CD mode. This is a more accurate representation of the utility and user acceptability of PHEV.

9.0 SENSITIVITY ANALYSIS

PEV are a near-term solution for increasing the sustainability of personal transportation. These vehicles offer benefits of increased fuel economy, reduced dependence on foreign oil, decreased refueling cost by utilizing inexpensive electricity and a reduction in tailpipe emissions. Understanding the near- and long-term effects of PEV to both consumers and utility companies is very important for the successful diffusion of these vehicles.

In order to maximize the benefit of these findings, it is important to test the sensitivity of this analysis to the rest of the design space of PEV. Understanding the possible sources of error and calculating the sensitivity of the results to these values is a valuable test. Sensitivity calculations were performed on both the charger efficiency used (90%) and the CD energy consumption (280 $Wh*mi^{-1}$). The selection to use CD energy consumption and charger efficiency was chosen because of their importance in understanding the effects to both the utility and consumer. The main benefit of computer simulation is the ease at which to re-create the results. These assumptions can help determine the size of the design space for which the results are valid.

The comparisons were made for near-term PEV. Three vehicles to simulate that represent the near-term vehicles were compared: Nissan Leaf, Chevrolet Volt and Toyota

Plug-in Prius. These vehicles have an AER of 100, 40 and 13 miles, respectively. A charging power of 1.44 kW and home and work charging availability was examined.

9.1 Charger efficiency

An initial value of 0.9 was used for the charger efficiency. 90% efficiency is a near ideal scenario, and it is important to understand the effects that lower efficiencies will have. The values were analyzed for both the range from 0.8-0.9 for the selected near-term vehicles (Table 6).

Table 6 sensitivity for charger efficiency

Charge depleting range (miles)	*% change*	*$/mi range*
13	0.30%	0.22%
40	0.27%	0.31%
100	0.05%	0.08%

Table 6 shows the percent change in outputs for both the benefit metric described in section 4.6 as well as the change in the metric of cost per mile for the entire 2009 NHTS. The sensitivity represented is from assuming a charging efficiency of 90% as opposed to a lower value of 80%. This is a small value for both the metric of vehicle days needs met and cost per mile.

9.2 Wh/mile

For the CD energy consumption, an initial value of 280 Wh*mi^{-1} was used. This is a likely value for near-term mid-size PEV. However, one aspect that this study does not take into account is the increase in energy consumption relative to vehicle weight. The vehicle weight is likely to increase as the battery size increases. The range of CD energy consumptions that this analysis is sensitive to needs to be determined, since real-world values are still unknown. The results of the analysis performed in this thesis are valid for the values from 250-300 Wh*mi^{-1} (table 7).

Table 7 error calculations CD energy consumption

CD range (miles)	*low % range*	*low $/mi range*	*high % range*	*high $/mi range*
13	-1.87%	4.33%	-0.74%	2.75%
40	-1.59%	6.99%	0.60%	4.41%
100	-1.04%	8.47%	1.01%	5.32%

The initial value used was 280 Wh*mi^{-1} and compared to 250 Wh*mi^{-1} (low range) and 300 Wh*mi^{-1} (high range). The sensitivity of altering the charge depleting energy consumption is much larger than that from the charger efficiency.

The sensitivity analysis performed for the charge efficiency and CD energy consumption show the range for which this analysis is robust. These results are not limited by either the charger efficiency or the CD energy depletion.

9.3 Treating the NHTS as n=1

As stated previously, there is some associated reporting error with the dataset. However, this is the best dataset available for transportation statistics and one that is respected and valued. The error range associated with this dataset is assumed to be minimal and not within the ability or scope of this project, as the dataset is treated as statistically accurate (n=1).

The errors associated with the NHTS are from both the respondents of the survey and those performing the sampling. There is assumed to be an unknown amount of error with the self-reporting of surveys. The use of the vehicle day weightings attempts to get rid of this, but it does alter the weights assigned by the NHTS. Secondly, while the NHTS is performed and executed by very qualified individuals, there is the possibility of over-sampling a specific group. The 2009 dataset is relatively new and some weightings are still being changed to best reflect the travel patterns of the US vehicle fleet. Lastly, this analysis is for average US daily travel, and should not to be taken as representative of specific individuals. Without a larger dataset it is impossible to make these conclusions. Overall, the NHTS is still the best free, publicly available dataset and the errors are generally ignored.

9.3.1 Driving behaviors

One of the main sources of error for this analysis is the accuracy of driving behaviors. The model does not differentiate individuals varying driving patterns and behaviors, so the metric of energy consumption is a representation of the average and not necessarily applicable to all individuals. The model assumes that current drivers of compact vehicles and large sport utility vehicles have identical driving patterns which may or may not be true in a real-world scenario. However, the NHTS is currently the best dataset available and the analysis reflects the usefulness of the data.

10.0 SUGGESTIONS FOR FUTURE WORK

10.1 Thorough TCO

Total cost of ownership is a valuable metric to compare the benefits of charging infrastructure because it effectively compares everything through the metric cost throughout the vehicles lifetime. Secondly, it would be beneficial to have access to actual energy usage data from real-world driving patterns as well as linear daily driving and charge frequency data. A thorough TCO model would allow us to take consumer behaviors and calculate associated cost from driving, charging and refueling behaviors.

10.2 Larger database

The NHTS currently offers the best free, publicly available dataset for average US daily travel. However, since households are only sampled on one random travel day, it is impossible to determine their actual daily travel patterns. As a result, understanding whether or not PHEV or EV will or won't meet an individual's needs is impossible to tell. The NHTS provides a clear insight to average US daily travel, but does not provide answers as to whether or not transportation can be electrified.

A second problem with the NHTS is lack of seasonal data provided. The NHTS makes an effort to evenly sample during the entire calendar year, as well as equal representation of weekday versus weekend travel. The initial results of the NHTS show that there is little difference between long distance travel during holiday months (May, July, November, and December) and other months of the year. If individuals are assumed to have more long-distance travel during holiday weekends, and these individuals drive EV, the availability of rental cars will be limited during these times. This may or may not be true, but the level of detail that is provided within the dataset does not provide solid evidence one way or another.

While the NHTS is a national dataset, there are datasets that may become available in the near future that would provide linear month data for a small number of vehicles in certain cities. This, ideally, would provide clarity as to the actual timing and frequency of long distance travel for most individuals.

The results of this investigation show that even for a heavy saturation of level 2 infrastructure, 4% of vehicle days needs would not be met. This would mean that on 2-3 days a month, households would have to use a different household car, rent a car, or participate in a car sharing program. However, this data reflects average US vehicle daily travel, as opposed to what actual individuals drive. The individuals within the dataset that travel more than 200 miles on their sample day may or may not travel that frequently (an assumed 2-3 days a month). Without longitudinal long-term data, it is impossible for us to make conclusions on individual travel, as opposed to average daily travel.

The availability of linear long-term data would likely provide answers as to actual travel needs for individuals. A dataset with long-term data, with the addition of the NHTS, could better inform researchers how to effectively electrify transportation and meet the needs of most individuals. Effectively using this data and achieving valuable results will be a challenge, but one that is necessary in order to make verifiable claims regarding individual travel behaviors and needs.

11.0 CONCLUSION

Two models were used to analyze the near- and long-term effects of PEV drivers. The benefit to consumers from changes in charging locations, AER, charging power and TOU rates were analyzed to determine the achieved benefit to consumers under a variety of scenarios.

Conventional wisdom would suggest that EV have a higher dependency and benefit to charging infrastructure than PHEV, however, that is not the case. The availability of more charging locations has a higher benefit to consumers and vehicles with low-AER. The low-AER vehicles are likely to be PHEV which have the ability to refuel from both gasoline and electricity. These same vehicles are likely to come at the lowest cost to consumers. From the consumer perspective, it seems logical, that near-term drivers of EV have higher needs for infrastructure than PHEV. The results found in this study support that PHEV will benefit more from infrastructure than EV.

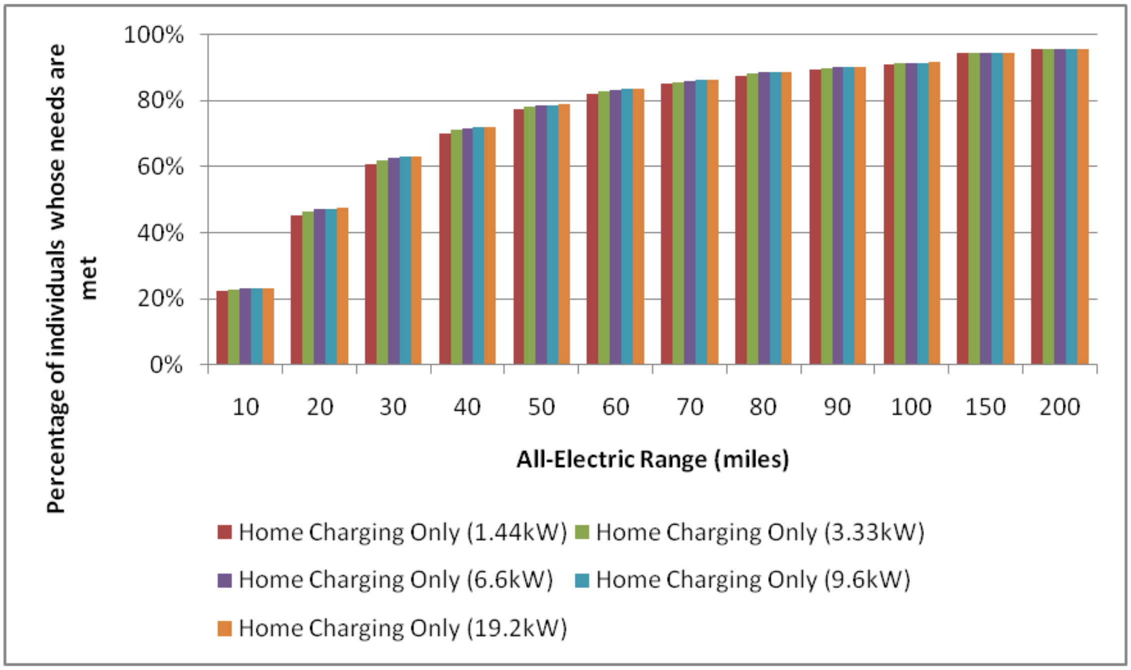
However, from the utility company standpoint, the reduction in benefit for high-AER vehicles will likely result in limited infrastructure installed. This is especially true if it is assumed that utility companies are responsible for paying for the installation, planning and purchasing of charging equipment. Utility companies have an even further decreased incentive to install and provide architecture if their service area has a high concentration of high-AER vehicles as opposed to low-AER vehicles.

Utility companies currently are able to predict penetration of PEV in certain areas by examining current areas with a high number of HEV. They are concerned with uncertain concentrations and charge times. The cost of installing this equipment is very high and without assurance that the equipment will be used and have a reasonable payback period, it is doubtful that utility companies will pay for much infrastructure.

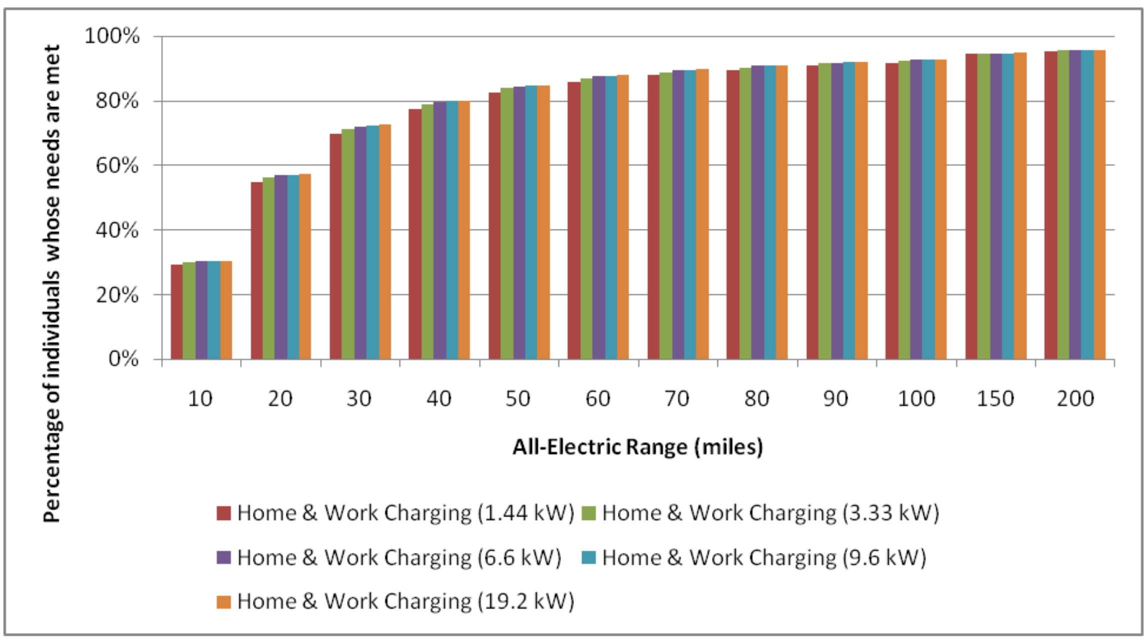
A portion of the burden of preparing infrastructure for PEV falls upon the utility companies. As a result, it is necessary for the companies to have a clear understanding (or best- and worst- case scenario) of potential penetration scenarios within their service territory. The larger the penetration of PEV, the more severe the load shifts and changes will be. Utility companies must inform consumers and future buyers of PEV as to best practice scenarios. They must educate consumers as to the true necessity of high rate chargers. In order for controlled, ideal charging to occur benefits and incentives and education programs need to be put into place.

As an emerging technology, it is impossible to know for certain what economic and environmental effects (both positive and negative) will actually happen. Research in the area is very centered upon best and worst case scenarios, analyzing a spectrum of data and attempting to understand both viewpoints: from the utility and the consumer. In order to understand and best promote PEV it is important to educate consumers about the technology and proper charging behaviors.

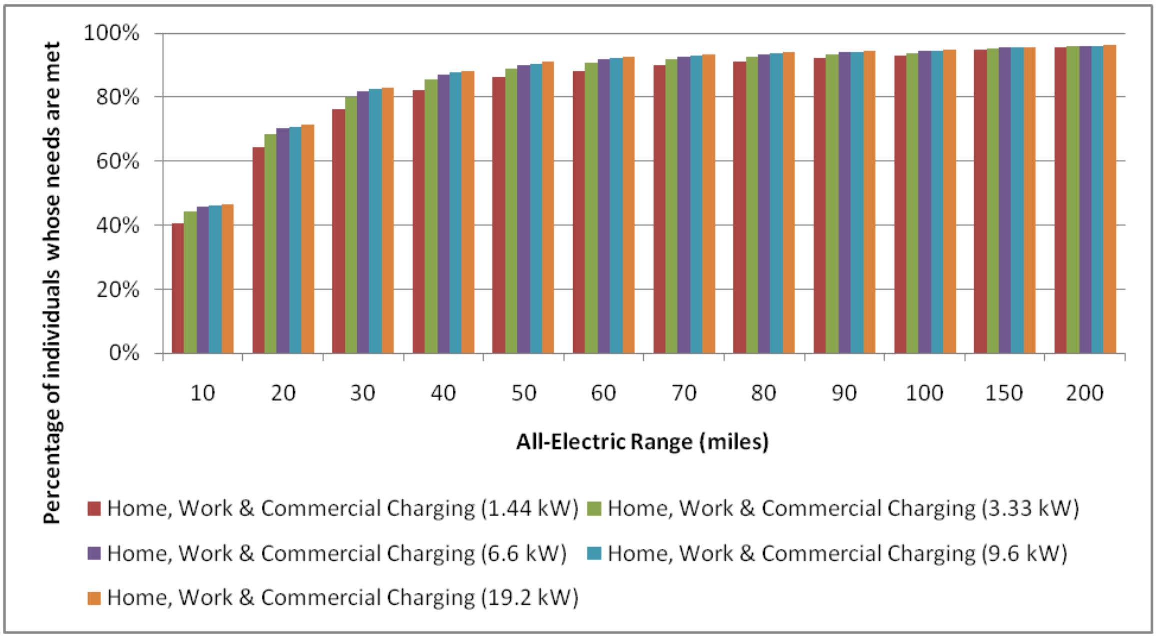
APPENDIX A: ORIGINAL OUPUTS OF THE VEHICLE CHARGING BENEFIT MODEL



Appendix Figure 1 home charging only

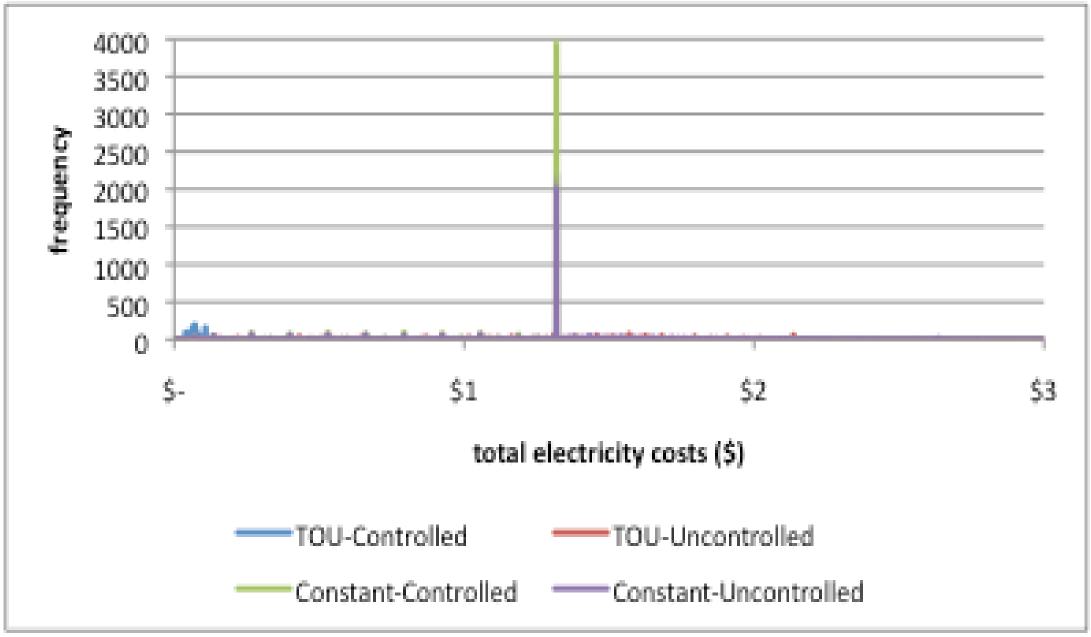


Appendix Figure 2 home and work charging

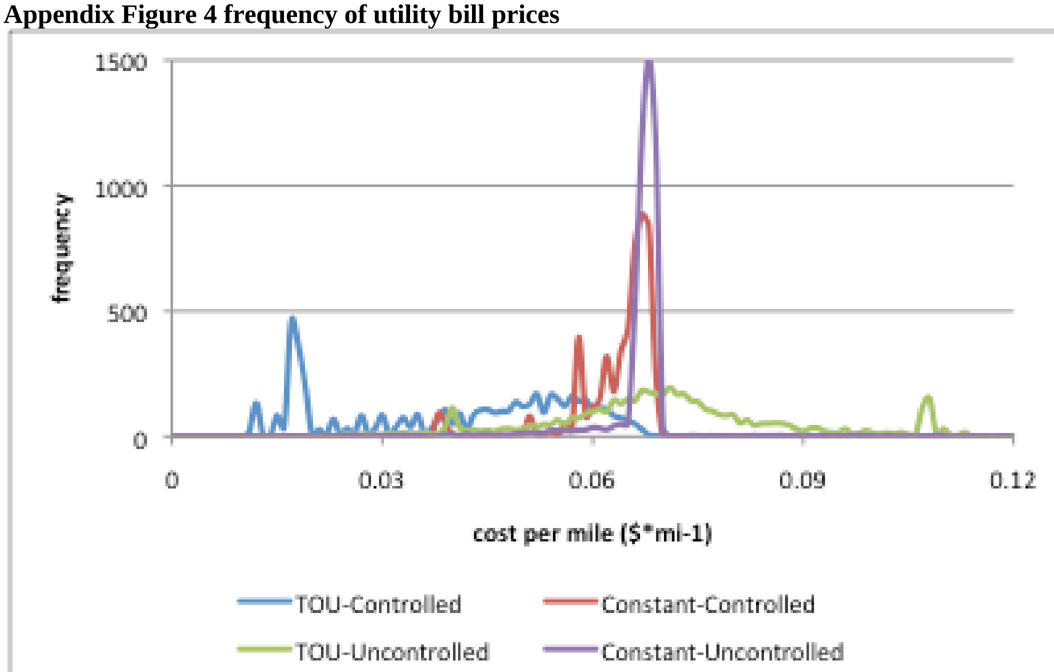


Appendix Figure 3 all charging locations

APPENDIX B: OUTPUTS OF THE VEHICLE ENERGY USE MODEL



Appendix Figure 4 frequency of utility bill prices



Appendix Figure 5 frequency of cost per mile

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