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CONSULTANT REPORT

Quantifying the Tangible Value of Public Electric Vehicle Charging Infrastructure

Prepared for: California Energy Commission
Prepared by: National Renewable Energy Laboratory

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ABSTRACT

The lack of public recharging infrastructure is an important barrier to the growth of the light-duty plug-in electric vehicle (PEV) market. Because the value of charging infrastructure is uncertain, especially during the early stage of market growth when low usage is more likely, it is difficult for decision makers to decide how much to invest in public charging stations. Quantifying the value of public charging infrastructure is essential for estimating the benefits to current PEV owners and projecting the effect on future PEV sales. This report estimates consumers' willingness to pay for public charging infrastructure based solely on the associated tangible value to current and potential PEV owners utility maximization. A basic theory of the tangible value of charging infrastructure is developed as a function of PEV type, range, recharging time, and existing infrastructure. Existing simulation studies provide functional relationships that measure the ability of charging infrastructure to enable additional miles of electrified travel. The willingness to pay for increased miles driven on electricity is then derived from econometric studies. The result is a set of three functions that can be used to calculate the willingness to pay for public charging infrastructure as a function of vehicle range, existing charging infrastructure, energy prices, income, and annual vehicle travel. Results show that the magnitude of willingness to pay for public electric vehicle charging is typically thousands of dollars. While this report quantifies the tangible value of public PEV recharging infrastructure from a consumer perspective, future work will assess overall consumer and societal benefits of charging infrastructure in supporting PEV adoption and decarbonizing the transportation sector.

Keywords: Electric vehicles, charging station, charging infrastructure, electric vehicle supply equipment, willingness to pay, e-miles

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EXECUTIVE SUMMARY

Measuring the value of public charging infrastructure to current and potential owners of plug-in electric vehicles (PEVs) is essential to weighing the benefits and costs of the infrastructure. The full value of PEV charging infrastructure relates to PEV adoption and use and includes several benefits. These benefits range from social value in reducing greenhouse gas emissions and other pollutants and displacing petroleum use in the transportation sector to consumer values that are tangible (for example, reducing the cost of operating vehicles or increasing the ability of these vehicles to satisfy travel demands) and intangible (such as enhancing awareness of electric vehicles and creating confidence in the viability and permanence of these vehicles). This report estimates consumers' willingness to pay for public charging infrastructure based solely on the related tangible value to current and potential PEV owners.

This report focuses on charging infrastructure available to the public rather than residential and workplace charging infrastructure where the great majority of PEV charging takes place. Even so, public charging infrastructure serves an important function by enabling additional electrified vehicle travel, especially for long-distance trips, and supporting PEV adoption for consumers that cannot reliably charge at home. By combining theory, results of simulation modeling, and econometric inferences about the value of charging stations and PEV range, this report develops a method for quantifying the tangible value of public charging infrastructure. The goal is to provide information to help guide public planning for and investments in infrastructure installation to help predict the effects of such investments on the sales of PEVs.

Key findings from this report include the following:

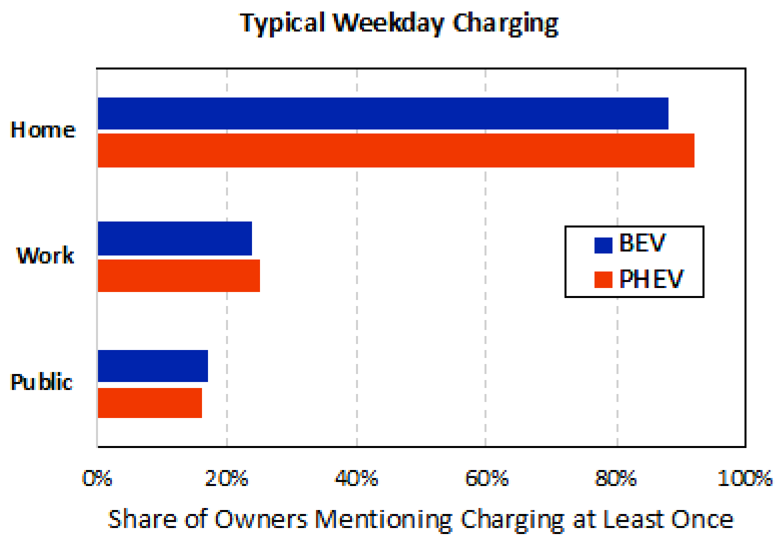
- Public charging infrastructure increases the value of PEVs to current and potential PEV owners by offsetting the effects of limited range and longer recharging times.
- Public charging can substantially increase PHEV use of electricity at the expense of gasoline use.
- For battery-electric vehicles (BEVs), increased public fast charging has been shown to enable more BEV travel, fitted reasonably well by a logarithmic function of the station counts, implying that the marginal value of a station decreases with the inverse of the number of stations.
- Also, the BEV electric miles enabled by public charging increases with the logarithm of the vehicle range. Therefore, the benefit of charging infrastructure decreases with increasing vehicle range.
- The electric miles of travel enabled by additional charging infrastructure can be translated into consumers' willingness to pay for those additional miles, leveraging econometric studies of the value of vehicle range.
- Willingness-to-pay functions are developed for different PHEV and BEV adopters (income levels) based on vehicle range, charging infrastructure availability, and power levels.
- Consistent with direct econometric estimates, public chargers can be worth thousands of dollars per BEV.

- For potential PEV purchasers, the value added by public charging infrastructure appears to be able to offset a large fraction of the perceived cost of the limited range and long recharging time of the BEV, thereby increasing the likelihood of purchase.
- A case study for a BEV with a range of 100 miles located in the Sacramento Area Council of Governments (SACOG) region is provided showing that the value of the existing public

direct-current, fast-charging infrastructure to the purchaser of a new BEV in California amounts to thousands of dollars and is similar in magnitude to the value of existing federal and state incentives for BEV purchasers.

While the majority of PEV recharging currently takes place at the vehicle's home base or workplace (Figure ES-1), public charging infrastructure increases the value of PEVs to current and potential PEV owners by offsetting the effects of limited range and longer recharging times.

Figure ES-1: Typical Weekday Charging Locations for PEVs in California



Source: NREL (data from California Energy Commission 2017)

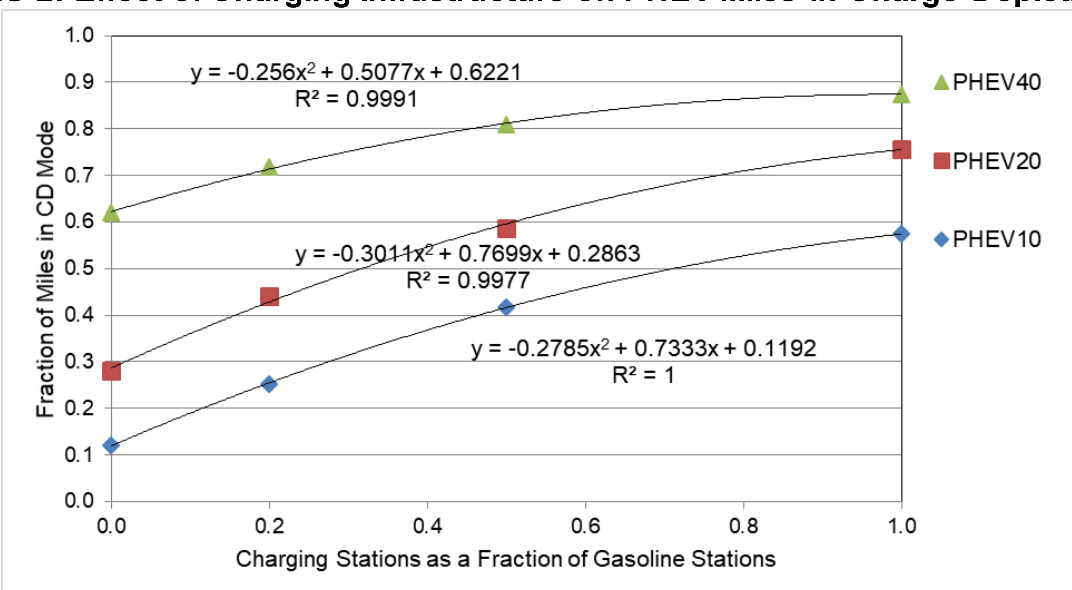
Public charging enables PEV owners to accomplish more of their travel demands with electric-powered vehicle travel. Fast charging is particularly valuable when charging time is valuable, such as on long-distance travel or during extended trip chains. The value of public charging infrastructure can be measured using the economic concept of willingness to pay. Because public charging infrastructure adds value to a PEV, consumers have a certain willingness to pay for it. The objective of this report is to define that willingness to pay in a way that allows it to be quantified.

The tangible value of public recharging infrastructure to PHEV owners is the fuel cost savings due to an increased opportunity to substitute electricity for gasoline. The cost savings from plugging in depend mainly on the usable battery storage capacity of a vehicle and the savings gained by substituting electricity for gasoline. But savings also depend on the geographical and temporal details of a PHEV owner's trip making, including the available battery capacity at the end of a trip and the time spent parked, as well as the availability of a charger at that time and place and the rate at which it can deliver electricity.

In contrast, BEV owners' willingness to pay for public charging infrastructure comes from enhancing the ability of the vehicle to satisfy the owner's demand for travel. The opportunity to charge between or during trips increases the ability of the BEV to accomplish the owner's travel objectives. For intraregional trips, Level 1 or Level 2 chargers may be enough for most daily travel. For inter-regional travel, where slower charging can significantly reduce the average speed of travel, fast charging is likely to be preferred. For BEVs, willingness to pay for public charging infrastructure depends on the distribution of daily travel distances, dwell times when BEVs are parked, the value of the traveler's time, and the availability of substitutes for BEV travel (for example, availability of a gasoline vehicle, other transportation modes, telecommunication). While the total willingness to pay for public charging increases as the number of chargers increases, the marginal value of another charger decreases as the amount of charging infrastructure increases and decreases with increasing vehicle range.

The availability of geographically and temporally detailed survey data describing the activity patterns of vehicles over an extended period has enabled highly realistic simulation modeling of the effects of limited range and recharging availability on the use of PHEVs and BEVs. Trip simulations by PHEVs indicate that public charging can substantially increase the use of electricity by these vehicles. Figure ES-2 summarizes the ability of charging infrastructure to increase the miles traveled by PHEVs in charge-depleting mode. The benefit appears to be greatest for shorter-range PHEVs and increases at a decreasing rate with increasing charger availability.

Figure ES-2: Effect of Charging Infrastructure on PHEV Miles in Charge-Depleting Mode



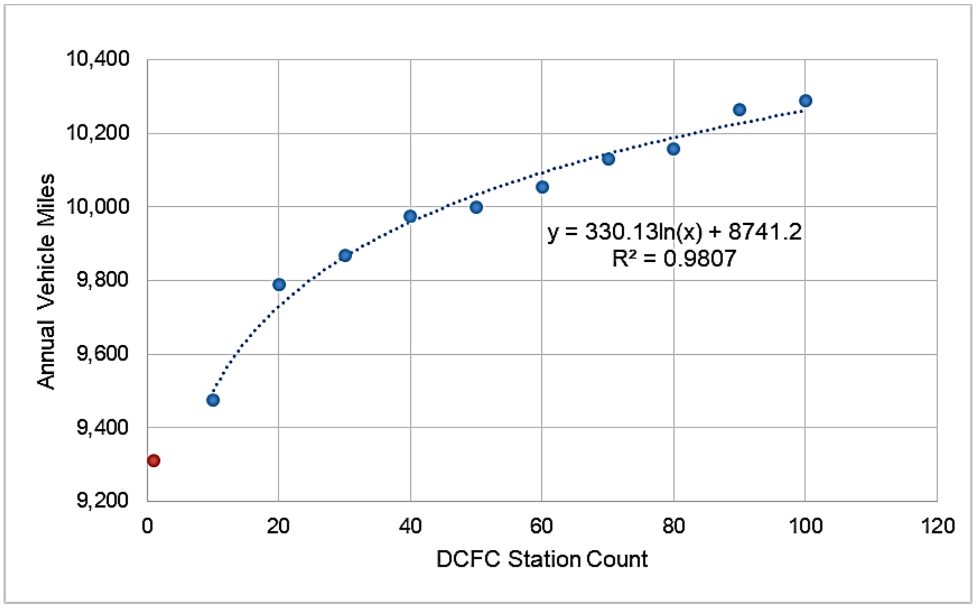
Source: NREL

For BEVs, the electric miles enabled by installing public charging were simulated in several studies. While how to best measure charger availability for a large population of vehicles remains a challenge, increased public fast charging has been shown to enable more BEV travel, fitted reasonably well by a logarithmic function of the station counts, implying that the marginal value of a station decreases with the inverse of the number of stations (Figure ES-3). Also, the fraction of annual conventional vehicle travel that can be accomplished by a BEV has been shown to increase with the logarithm of the vehicle range. However, the benefit of charging infrastructure decreases with increasing range (Figure ES-4).

The electric miles of travel enabled by additional charging infrastructure can be translated into consumers' willingness to pay for those additional miles leveraging econometric studies. Dozens of econometric studies have estimated consumers' willingness to pay for additional

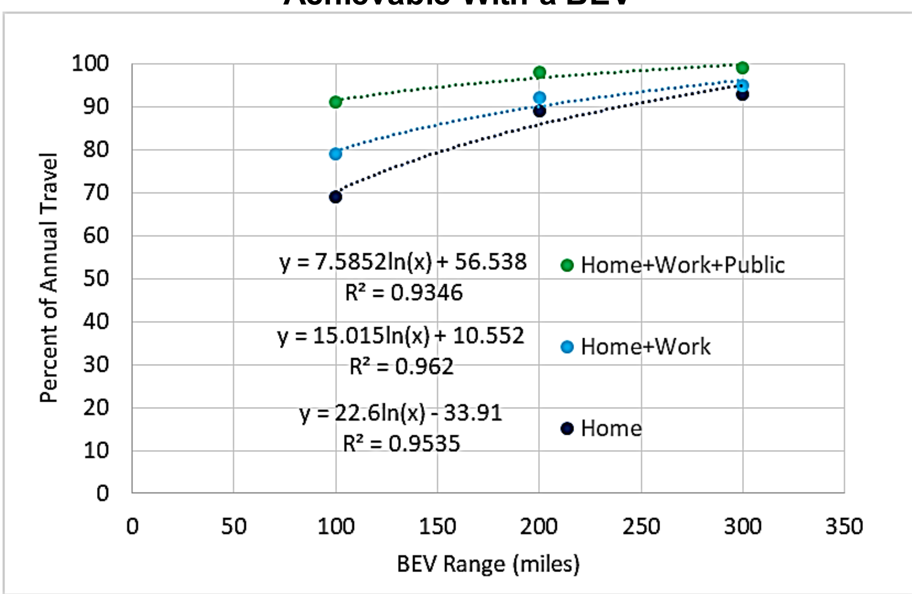
BEV range. Range and charging infrastructure enable additional electric miles. Willingness to pay for additional electric miles can be inferred from the value of range and can be applied to willingness to pay for charging infrastructure, provided the time cost of charging is considered.

Figure ES-3: Effect of DCFC Station Count on BEV Vehicle Miles Traveled



Source: NREL (data from Wood et al. 2015)

Figure ES-4: Effect of Range on Percentage of Conventional Vehicle Annual Miles Achievable With a BEV

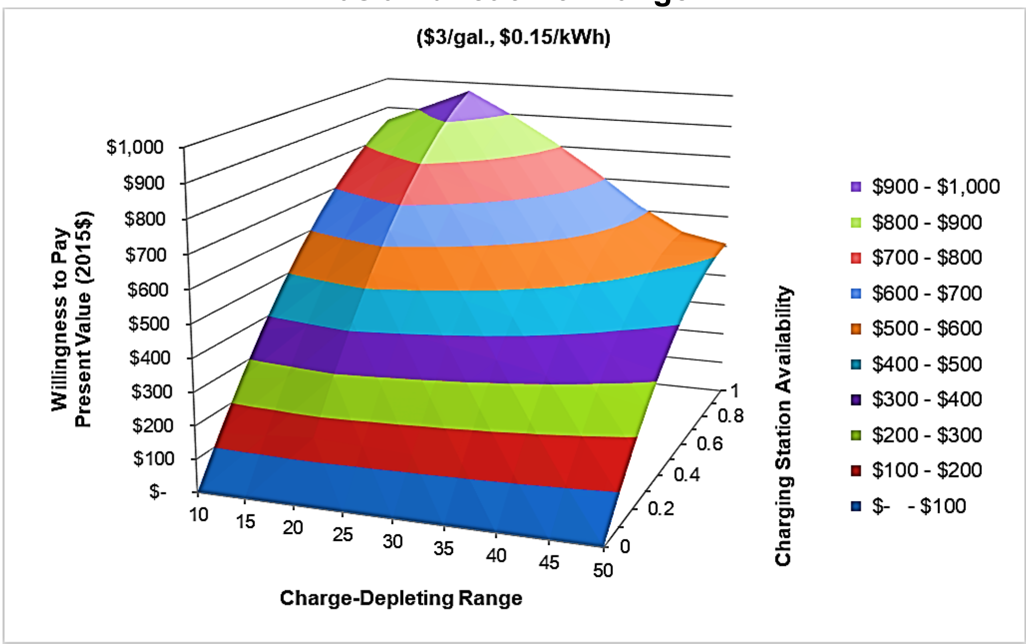


Source: NREL

Based on the analysis presented in this report, PHEV willingness to pay for recharging infrastructure increases at a decreasing rate as the number of charging stations available increases, exceeding an estimated $500 per PHEV20 when the number of charging stations exceeds 50 percent of "full availability" (Figure ES-5). In general, PHEV willingness to pay for charging infrastructure decreases with increasing nominal charge-depleting range.

The contribution of public chargers to the value of a BEV is represented as the value of enabled electric miles. It depends on the same factors as the PHEV willingness to pay for electric vehicle supply equipment excepting fuel costs and depends on the value of an enabled mile and the value of reduced time to access a charger.

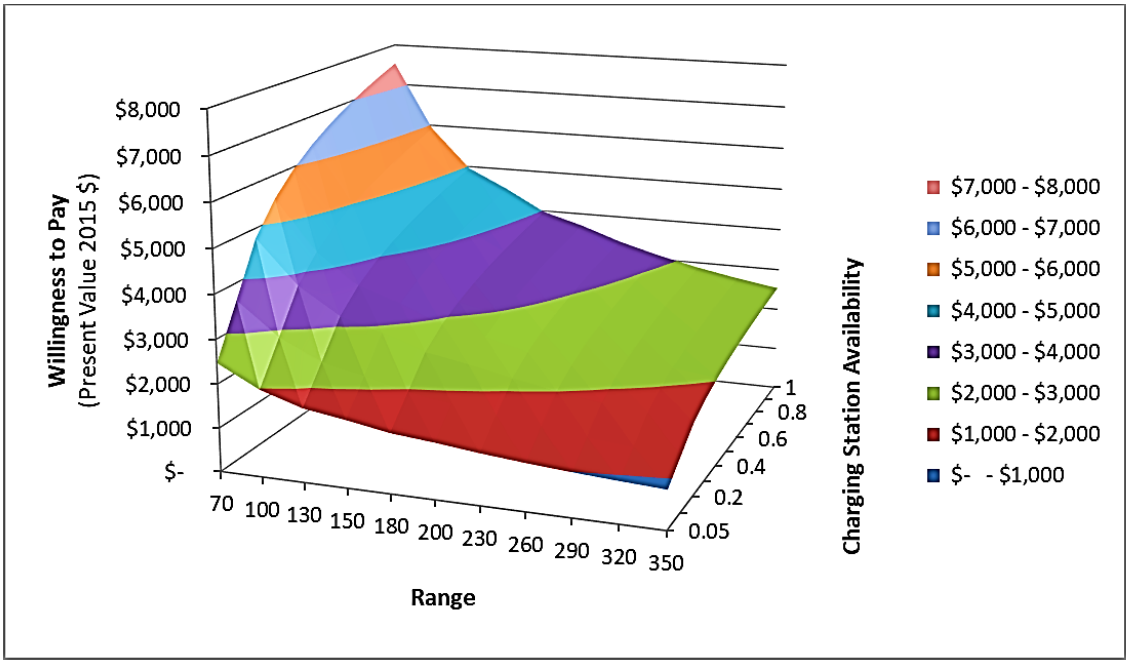
Figure ES-5: Illustration of PHEV20 WILLINGNESS TO PAY for Public Charging Stations as a Function of Range



Source: NREL. Assuming $3/gal for gasoline and $0.15/kWh for electricity.

The willingness-to-pay function illustrated in Figure ES-6 assumes a value of $0.50 per enabled mile, which is roughly consistent with an annual household income of $115,000 (the median household income of BEV owners in the 2016 California Vehicle Survey). Consistent with direct econometric estimates, public chargers can be worth thousands of dollars per BEV. Willingness to pay for public chargers for intraregional BEV travel decreases by about half as vehicle range increases from 100 miles to 300 miles.

Figure ES-6: Illustration of BEV WILLINGNESS TO PAY for Public Charging Stations for Intra-Regional Travel as a Function of Range for a Household with an Annual Income of $115,000

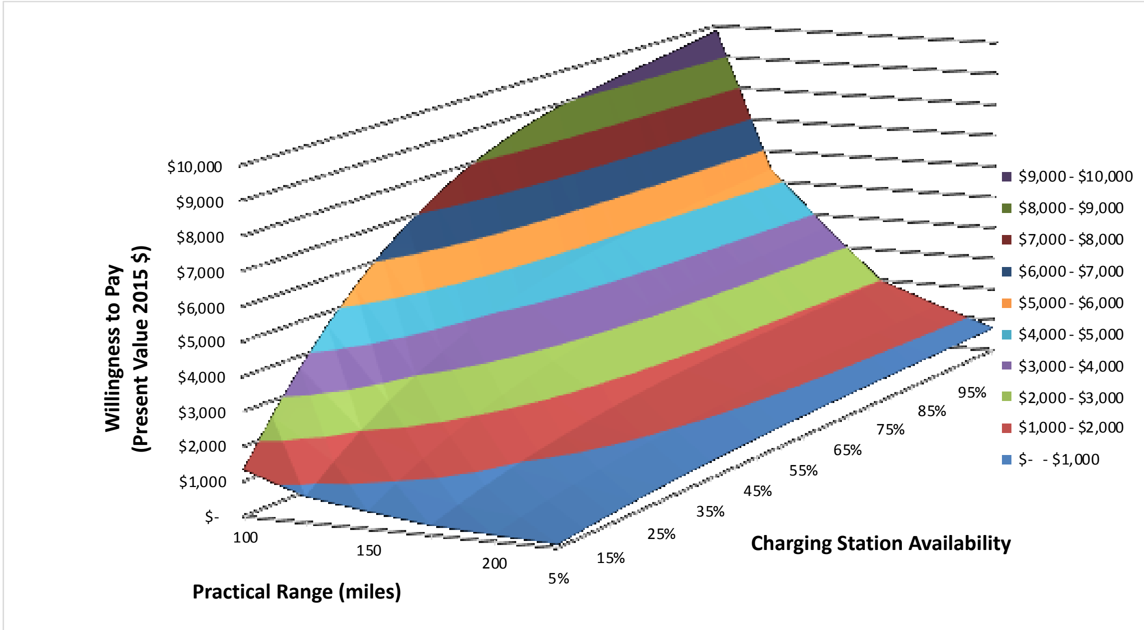


Source: NREL

The estimated value of inter-regional travel enabled by installing (only) DCFCs along inter-regional routes is illustrated in Figure ES-7. A value of $0.50 per enabled mile is again used, corresponding to a household income of $115,000. In this figure, charging station availability is measured as availability relative to a spacing of 40 miles on all intercity routes. Despite the infrequent nature of inter-regional travel, WILLINGNESS TO PAY can amount to thousands of dollars.

The intra- and inter-regional values of WILLINGNESS TO PAY for public charging infrastructure for BEVs shown above are additive. Although DCFCs are usable only by BEVs, public level 2 chargers contribute to the value of both PHEVs and BEVs.

Figure ES-7: Illustration of Willingness to Pay for Interregional Public DCFC Stations



Source: NREL

To summarize, public charging infrastructure creates value for owners and potential owners of PEVs. For PHEVs, it increases the miles in which the vehicle can be operated in charge-depleting mode, saving money by substituting electricity for gasoline. For BEV owners, it adds value by increasing the distance the vehicle can travel in one day, expanding the ability of the vehicle to provide mobility and access. For potential PEV purchasers, the value added by public charging infrastructure could offset a large fraction of the perceived cost of the limited range of the BEV and long recharging time, thereby increasing the likelihood of purchase.

Still, important issues remain. In particular, how best to measure charging station availability in an area, considering station design (number and power level of chargers), travel patterns, and the number and types of PEVs in the existing vehicle stock, remains a challenge. Econometric studies have used measures such as electric vehicle supply equipment per capita or per land area, but those metrics don't account for travel patterns and different need for charging. Alternatively, the ratio of public charging stations to gasoline stations has been proposed as a metric, but, while simple, the high-level aggregation doesn't convey information on the spatial distribution of chargers or the number and power levels of plugs, affecting possible wait times. Other issues in need of further research include simulation modeling focused on long-distance travel, allowing changes to trip-making behavior in simulations to maximize the benefits of PEVs, and investigation of the potential for queueing and the need to ensure the reliability of chargers.

CHAPTER 1: Introduction

Researchers have long recognized that adoption of alternative fuels and vehicles is hindered by the "chicken or egg" problem: consumers will not purchase alternative fuel vehicles (AFV) unless there is refueling infrastructure, but fuel suppliers are hesitant to build that infrastructure until enough alternative fuel vehicles are on the road (Sperling 1988; McNutt and Rodgers 2004; Gnann and Plötz 2015, Melaina et al. 2017). Consequently, unless the private benefits of AFVs are compelling, public policy intervention is necessary to initiate markets for AFVs and alternative fuels and sustain them during the early phases of development. This finding is especially true when the primary benefits are not private but public benefits, such as reduced greenhouse gas emissions, improved local air quality, and energy security. In that case, how to effectively and efficiently co-evolve the fuel and vehicle markets becomes a crucial question for public policy. Moreover, initial investments in refueling infrastructure trigger a positive feedback loop: as more vehicles are adopted the infrastructure utilization and profitability increase, inducing more investments that spur increased vehicle adoption.

Measuring the value of public charging infrastructure to current and potential owners of plug-in electric vehicles (PEV) is essential to weighing its benefits and costs. The full value of PEV charging infrastructure relates to PEV adoption and use and includes several benefits, ranging from social value in reducing greenhouse gas emissions and other pollutants and displacing petroleum use in the transportation sector to consumer values that are both tangible (e.g., reducing the cost of operating vehicles or increasing their ability to satisfy travel demands) and intangible (e.g., enhancing awareness of electric vehicles and creating confidence in their viability and permanence). This report estimates consumers' willingness to pay for public charging infrastructure based solely on its tangible value to current and potential PEV owners.

This report focuses on charging infrastructure available to the public rather than residential or workplace charging infrastructure that may or may not be available for use by the public. Although the great majority of PEV charging takes place at home or at work, public charging infrastructure serves an important function by enabling additional electrified vehicle travel, especially for long-distance trips. This report analyzes the tangible value of public PEV recharging infrastructure (also known as electric vehicle supply equipment or EVSE) to PEV owners and potential purchasers. The goal is to provide information to help guide public planning for and investments in EVSE deployment and to understand the likely impacts of such investments on the sales of PEVs. A second objective is to develop a method for incorporating the deployment of EVSE in random utility models of vehicle choice so that policies to support the co-evolution of vehicle and fuel markets can be rigorously analyzed. Apart from additional electric miles (e-miles), charging infrastructure also provides several intangible benefits in support of PEV adoption. EVSE enhances the visibility of electric vehicles and creates confidence in their viability and permanence, which can also influence adoption (Bailey et al. 2015). Public chargers also expand PEV market reach by enabling market segments that wouldn't otherwise consider purchasing a PEV, such as those without reliable access to home/workplace charging. These intangible aspects, however, are not considered in this report. While this report quantifies the tangible value of public PEV recharging infrastructure from a consumer perspective, future work will extend this study to assess overall personal and societal benefits of charging infrastructure in supporting PEV adoption and decarbonizing the transportation sector.

The report is organized as follows. Chapter 2 presents a simplified classification of the types of PEVs and EVSE and the locations where PEV recharging takes place. In Chapter 3 a basic theoretical model illustrates that the tangible benefit of public charging infrastructure is to increase the electric miles that can be accomplished by a PEV. The theory illustrates how infrastructure availability, range, and refueling time together enable additional electric miles of travel and reduce range anxiety (Rezvani et al. 2015). All three variables are important and must be included in an integrated framework. Theory also provides insights about the functional relationships among the key factors and how the value of recharging infrastructure is likely to vary across consumers and from place to place (e.g., Reid and Spence 2016). In Chapter 4 simulation studies using geographically and temporally detailed data on vehicle use are used to quantify the increase in electrified vehicle travel by different types of PEVs enabled by charging infrastructure. Simulation studies also provide insights about the interdependency of range and charging infrastructure. The studies are used to calibrate mathematical functions relating the quantity of public charging infrastructure to incremental electric miles of travel for plug-in hybrid electric vehicles (PHEVs) and for battery electric vehicles (BEVs) in intra- and inter-regional travel. In Chapter 5 the value of electrified travel enabled by recharging infrastructure is inferred from econometric studies that have estimated the values of public charger availability, range, and recharging time. In Chapter 6 insights from theory, simulation modeling, and econometric analysis are combined to produce a set of three functions that calculate the willingness to pay for public charging infrastructure as a function of vehicle attributes, existing charging infrastructure, energy prices, and annual vehicle travel for PHEVs and for BEVs in intra- and interregional travel. The report concludes with a discussion of promising areas for further research.

CHAPTER 2:
Types of Vehicles, Infrastructure, and Recharging Opportunities

Public charging infrastructure increases the value to vehicle owners of PEVs. The benefits of publicly available EVSE depend on the rate at which it can deliver electricity and the types of vehicles that use it. PEVs powered entirely by an electric motor drawing from an onboard battery pack are referred to as all-electric vehicles (EVs) or BEVs and are powered entirely with electricity from an external source. PHEVs are PEVs that also have internal combustion engines. Distinctions are typically made between PHEVs in which the internal combustion engine provides the primary motive power and allows for extended range and those in which the electric motor provides all or virtually all the motive power. In the theory presented below, the tangible value of EVSE to either type of PHEVs is to enable greater substitution of grid electricity for gasoline. Because of this, we differentiate PHEVs solely based on their capacity to store electricity on board. This is usually done in terms of "all-electric" or "charge-depleting" range — that is, PHEV20 or PHEV40 indicate enough electricity stored on board for 20 or 40 miles of all-electric operation. The tangible value of public chargers to BEVs is increasing the miles a BEV can travel in a day. Like PHEVs, we differentiate BEVs based on the associated range in miles (e.g., BEV100, BEV200).

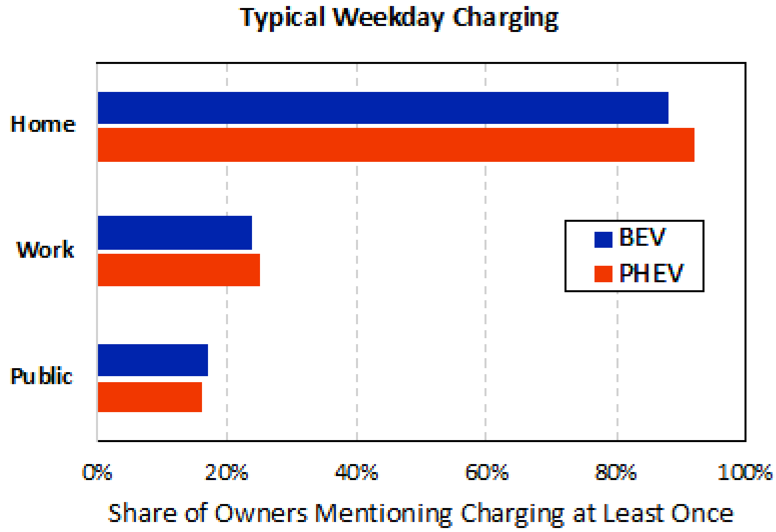
Because charging a PEV takes much longer than refueling a conventional gasoline vehicle, places where vehicles remain parked for extended periods of time present attractive opportunities for charging. Because of this, the literature typically distinguishes between home, workplace, and public charging. Data on charging locations consistently show that the great majority (80 percent–90 percent) of charging is done at home (INL 2015), with workplace charging a distant second (Figure 1).

Figure 1: PEV Recharging Pyramid

Source: National Research Council (NRC 2015, Figure 5-1)

Recent data from the 2016 California Vehicle Survey generally supports the recharging pyramid concept shown in Figure 1 (California Energy Commission 2017). With 12 percent of the population, 11.35 percent of the 2016 light-duty vehicle (LDV) stock (IHS Markit 2017), and 47.38 percent of the 2016 PEV LDV stock (IHS Markit 2017) of the United States, California has 24 percent of the public PEV charging stations and 30 percent of the outlets for charging PEVs (AFDC 2018a). In the 2016 California Vehicle Survey (California Energy Commission 2017), 159 BEV owners and 156 PHEV owners responded to questions about where and when they charged their vehicles on a typical weekday. Figure 2 shows the percentage of locations mentioned at least once by the respondents. The overwhelming majority mentioned charging at home, followed by workplace (19 percent) and public charging (12 percent–13 percent) (Figure 2).

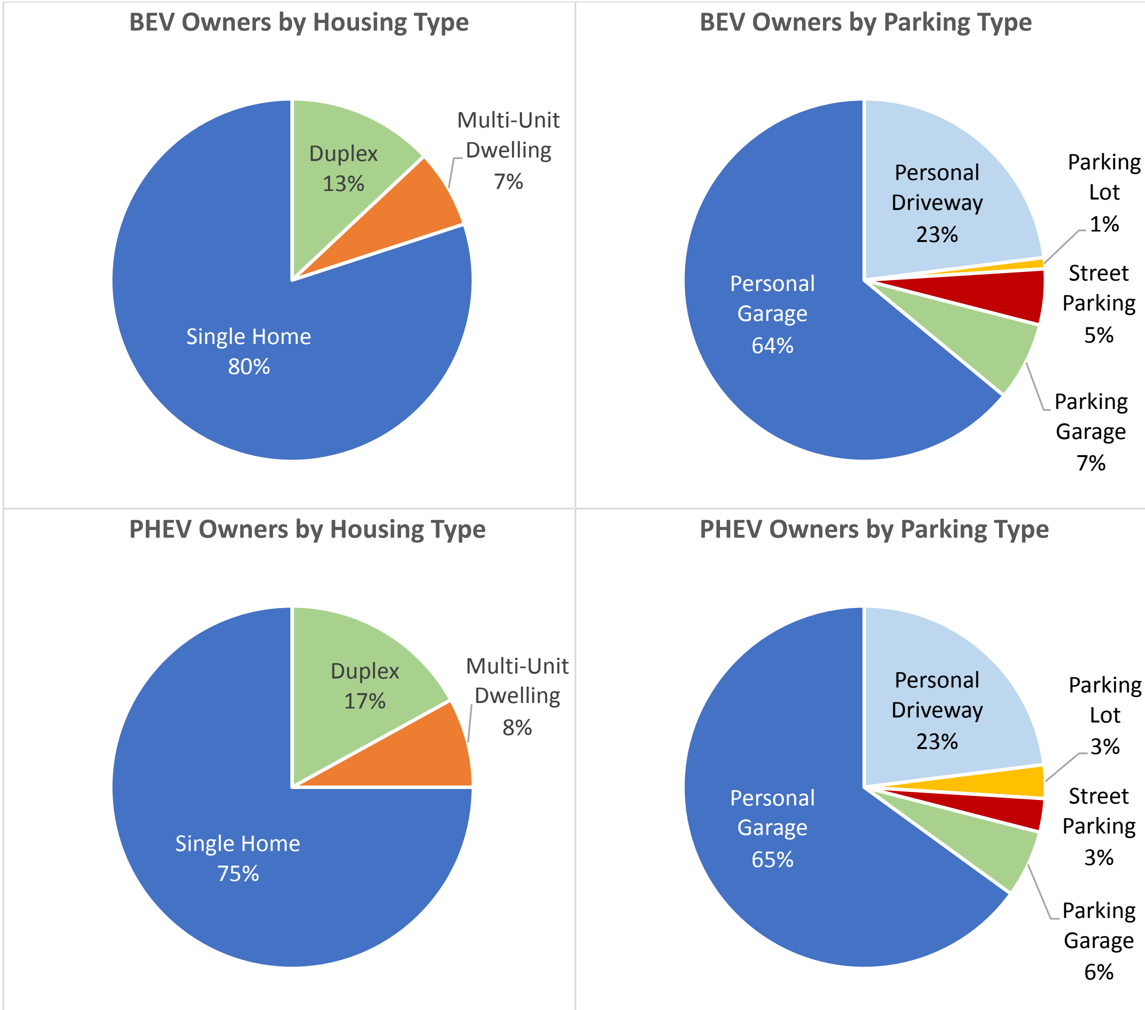
Figure 2: Typical Weekday Charging Locations for PEVs in California



Source: NREL (data from California Energy Commission 2017)

The simulation models and econometric analyses cited throughout this report make important assumptions about where and how PEVs will be charged. In general, they assume that vehicles begin a day having been fully charged at their home base. This appears to be a reasonable approximation for current owners of PHEVs and BEVs, the overwhelming majority of whom live in single-family or duplex homes and have either a private garage or driveway in which to charge their vehicles (Figure 3) (California Energy Commission 2017). However, the pattern may change in the future as more multiunit-dwelling residents become PEV owners. Most studies also assume that charging at work and other locations is opportunity charging and therefore not time-sensitive. However, the charging location data shown in Figure 2 suggest there is a nonnegligible amount of primary charging done at nonresidential chargers. For the present, it seems reasonable to assume that home-based charging is available to almost all PEV purchasers and that the time required to charge at home or at work is not time constrained and therefore has little or no cost.

Figure 3: 2017 BEV and PHEV Owners by Type of Housing and Parking



Source: NREL (data from California Energy Commission 2017

Three types of EVSE are generally recognized (AFDC 2018b):

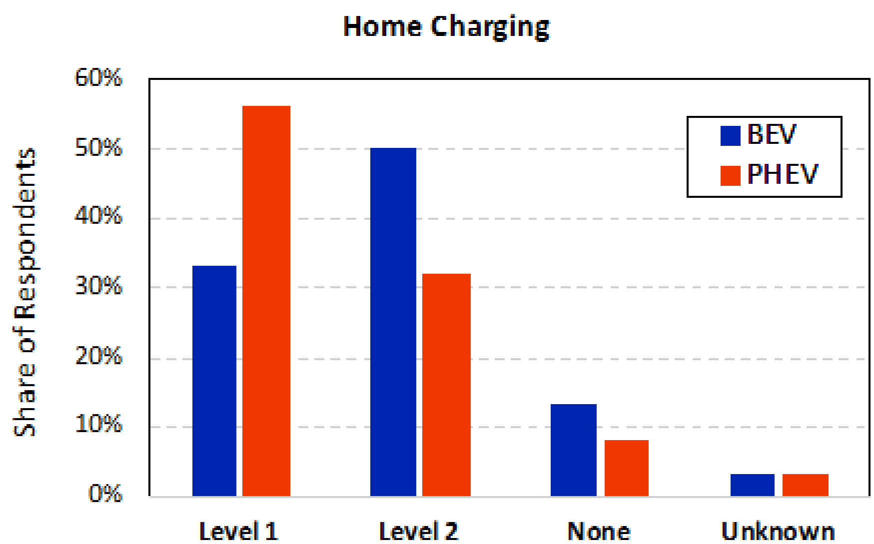
1. Level 1, which uses a standard 120-volt (V) source that can be found in any household and can supply 2–5 miles of range per hour of charging at about 1.4–1.92 kilowatts (kW)
2. Level 2, which requires a 240 V source and can supply 10–60 miles of range per hour at 7.2–19.2 kW
3. Direct current fast charging (DCFC), which requires a 480 V source and can supply 60–100 miles of range in 20 minutes at 40–130 kW.[1]

While charging behaviors vary across geography, housing stock, and vehicle types and will likely evolve over time, in 2015 the National Research Council posited that the vast majority of

[1] Extreme fast charging technology is being developed that can deliver electricity at up to 400 kW or more (Chehab 2017). While this new technology still faces technological and economic challenges it has the potential to deliver 200 miles of EV range in just over 15 minutes.

PEV recharging will likely continue to be done at the home base of the vehicle or workplace in the near term (Figure 1, from NRC 2015, Figure 5-1).[2] These are locations where vehicles tend to dwell unused for several hours at a time. Recharging at either Level 1 or Level 2 rates is therefore convenient and cost-effective because time is not a constraint. The 2016 California Vehicle Survey indicates that 57 percent of BEV owners and 40 percent of PEV owners purchased home rechargers or otherwise upgraded their home electrical system. The remainder relied on preexisting electrical outlets. Figure 4 summarizes the residential charging equipment used by the respondents of the 2016 California Vehicle Survey (California Energy Commission 2017): about half of BEV users reported to have used Level 2 residential chargers, while only 30 percent used Level 1. For PHEV drivers, however, Level 1 was reported to be used by more than 55 percent of respondents, with only 30 percent reporting to have used Level 2 chargers at home. Less than 10 percent of PHEV drivers and 13 percent of BEV adopters didn't report residential charging. In addition to the possibility of simple nonresponse, another reason for the sizeable fractions reporting no residential charging may be that the survey includes mostly innovators and early adopters who may not be a sound basis for extrapolation to the mass market.

Figure 4: Typical 2017 Residential Charging Equipment for PEVs in California



Source: NREL (data from California Energy Commission 2017)

On the other hand, nonresidential fast charging is most useful when time is constrained (i.e., most valuable). For PEVs with long recharging times (mainly BEVs), it is therefore useful to treat infrastructure for interregional travel (predominantly DCFCs) differently from infrastructure for intraregional travel (predominantly Level 1 and Level 2 chargers). To keep

[2] Ubiquitous home charging might not be feasible in the long term as PEVs are sold to consumers that don't have access to residential charging solutions (e.g., single-family homes without a plug available near the parking spot, multiunit dwellings, or street parking). Previous studies have shown that lack of residential charging greatly affects the need for public charging (Wood et al. 2017a), impacting the estimates leveraged in this study.

the theory simple, two types of EVSE are considered below: slow (a mixture of Levels 1 and 2) and DCFC.

Measuring recharging infrastructure is challenging because of the complexity of EVSE and related deployment. In addition to the kinds of EVSE deployed (three is already a simplification, considering the three connector types [Combined Charging System, CHAdeMO, and Tesla] and vehicle-specific charging power capabilities), the location relative to vehicle travel patterns and dwell times is critically important. Measurement is made more complex by the potential for sharing of EVSE by multiple vehicles (California Energy Commission 2018), as well as potential scheduling conflicts, queuing, and wait times, plus the likelihood that PEV owners will change their travel behavior to get the greatest benefit from their vehicles. Unfortunately, neither the simple theoretical model described in Chapter 3, nor the complex simulations in Chapter 4, nor the review of econometric analyses in Chapter 5 provide a complete answer to the question of how best to measure charging infrastructure.

CHAPTER 3: Theory

Quantifying the value of public charging infrastructure to current and potential owners of PEVs is important to designing efficient and effective policies to support the coevolution of the vehicle and fuel supply markets. Public charging infrastructure is valuable because it reduces the disadvantages of the limited storage capacity of a PEV and longer refueling time. Public charging infrastructure adds value to PEVs by reducing their range and refueling disadvantages relative to conventional vehicles. The key premise of this report is that the value of public charging infrastructure can be measured using the economic concept of willingness to pay.

Willingness to Pay in Vehicle Choice Models

In economics, the value of a good to a consumer is measured by the consumer's willingness to pay for it. "Willingness to pay" is defined as the maximum amount of money an individual would agree to give up to obtain a good or avoid a bad (Varian 1992). It can be measured by the difference between an individual's satisfaction, or utility, $u(p, w)$, at a reference level of prices, represented by a vector, p_0, and income, w_0, and a different level of prices and income, p^*, w^*. For policy analysis, it is useful to measure utility in dollars using an indirect or money utility function. The indirect utility function $U(p_0;\, p^*, w_0)$ measures the amount of income the consumer would need at prices p^* to be as well off as at prices p_0 and income w_0. Willingness to pay can also be measured by the integral under the consumer's demand function from price level p_0 to price level p^*. Marginal willingness to pay is defined at the maximum amount a consumer would pay for the next unit of a good or service (e.g., one additional charging station). Total willingness to pay is the cumulative value (total utility) of the entire consumption of a good or service (e.g., the combined value of all charging stations).

Consumers' vehicle choices are often modeled by random utility models, in which vehicle i's utility to a typical consumer is represented by a function of the associated attributes ($\boldsymbol{x}$), those of the decision maker ($\boldsymbol{y}$), the context of the choice ($\boldsymbol{z}$), and a random term (ε_i) that represents factors not explicitly included in the utility function (Train 2009). The price of a vehicle would be an element of $\boldsymbol{x}$, say x_p, and availability of public charging would be an element of $\boldsymbol{z}$, say z_i. Let $U(\boldsymbol{x}, \boldsymbol{y}, \boldsymbol{z}, \boldsymbol{\beta})$ be a representative utility function that, for simplicity, is assumed to be linear with coefficients $\boldsymbol{\beta}$.

Equation 1

$$U_i(\boldsymbol{x}, \boldsymbol{y}, \boldsymbol{z}, \boldsymbol{\beta}) = \sum_{i=1}^{n_x} \beta_i x_i + \sum_{j=1}^{n_y} \beta_j y_j + \sum_{k=1}^{n_z} \beta_k z_k + \varepsilon_i$$

If the error term, ε_i, in Equation 1 is assumed to have a type 1 extreme value distribution,[3] the probability P that a consumer will choose vehicle type i is given by Equation 2, in which j indexes all possible vehicle choices.

Equation 2

$$P_i = \frac{e^{U_i}}{\sum_{j=1}^{N} e^{U_j}}$$

In such a model, the marginal willingness to pay for a change in attribute x_i is equal to its marginal utility divided by the negative of the marginal utility of price. In the case of the simple linear utility function of Equation 1, this is $\beta_i/(-\beta_p)$. Because the price of a vehicle is in present dollars, a dollar of price can be assumed to equal a dollar of current income. Thus, in general, the marginal willingness to pay for an increase in charging infrastructure is equal to the ratio of marginal utilities.

Equation 3

$$WTP = -\frac{\partial U / \partial x_i}{\partial U / \partial x_p}$$

Among the vehicle attributes (x_i) in Equation 1 are the range and recharging time of a PEV. For today's electric vehicles these attributes are inferior to those of a conventional vehicle. Because public recharging infrastructure serves to offset some of the range and refueling disadvantage of a PEV relative to a conventional vehicle, the maximum value of public infrastructure is expected to be less than the total range and recharging disadvantage of a PEV.

A shortcoming of the simple linear utility function of Equation 1 is that it assumes a constant marginal value of every attribute and a constant marginal utility of income. In general, the marginal utility of income tends to decrease with increasing income (Layard et al. 2008), leading to an increasing marginal willingness to pay for attributes as income increases, all else equal. Therefore, consumers with different incomes will value all attributes differently. In some models, this conclusion is reflected in price coefficients, β_p, that vary either by type of vehicle (e.g., luxury vs. economy) or across individuals. In addition, the value of time varies with income (e.g., Brownstone and Small 2005) making the cost of access time and recharging time dependent on income. Consequently, willingness to pay for public charging infrastructure will vary with income.

In Chapters 4 and 5 of this report, information from simulation modeling and econometric analyses is used to synthesize equations that calculate a consumer's total, as opposed to marginal, willingness to pay for public charging infrastructure. For BEVs, public infrastructure offsets part of the cost of shorter range and longer refueling time relative to a conventional

[3] Type 1 extreme value distribution is also referred to as the Gumbel distribution. The probability density function formula is $f(x) = \frac{1}{\beta} e^{\frac{x-\mu}{\beta}} e^{-e^{\frac{x-\mu}{\beta}}}$, with μ the location parameter and β the scale parameter.

gasoline vehicle. For a PHEV, public infrastructure adds to the energy cost savings of a vehicle by enabling more miles to be traveled in the lower-cost charge-depleting mode. Because total willingness to pay is measured in present value dollars, in theory it should have the same effect on consumers' vehicle choices as the price of the vehicle. As such, total willingness to pay (V_p) could be directly entered in the indirect utility function of a random utility model multiplied by the negative of the price coefficient of the model.

Equation 4

$$U_i(\boldsymbol{x_i}, \boldsymbol{y}, \boldsymbol{z}, \boldsymbol{\beta}) = -\beta_p V_{ip} + \sum_{i=1}^{n_x} \beta_k x_{ik} + \sum_{j=1}^{n_y} \beta_j y_j + \sum_{k=1}^{n_z} \beta_k z_k + \varepsilon_i$$

For PHEVs, only one measure of willingness to pay enters the utility function. For BEVs, two willingness-to-pay measures are derived, representing infrastructure for intra- versus interregional travel. If correctly estimated, their values should be additive. There is some overlap between the two because interregional EVSE, even if located only along intercity routes, will serve some intraregional traffic and vice versa. Including only DCFCs located along intercity routes outside of metropolitan areas when measuring interregional willingness to pay should be an effective strategy for reducing such double counting. For example, a recent national infrastructure analysis (Wood et al. 2017a) makes just such a separate accounting. Wood et al. (2017a) estimated that an adequate charging infrastructure would include 4,900 DCFCs in larger cities, 3,200 in towns, and 400 along interstate corridors to provide basic coverage and support 15 million PEVs.

The total willingness-to-pay estimates are a function of the attributes of vehicles (range and, for PHEVs, fuel economy), consumers (income, annual vehicle miles traveled) and geographical factors (infrastructure availability). Depending on the form of discrete choice model, the price coefficient may also vary, adding to the heterogeneity of preferences. Even so, consumers' preferences are likely to differ from the calculated willingness-to-pay values. Discount rates (used to discount costs and benefits over the life of a vehicle) vary from one person to another. Perceptions of public charging availability will also vary. Moreover, information perceived by consumers might differ from unbiased assessment, making awareness and personal preference important factors. Therefore, it may be desirable to estimate the coefficient of total willingness to pay along with other coefficients of a model rather than assuming that the negative of the price coefficient is always the correct value.

Factors That Determine Willingness to Pay for Recharging Infrastructure

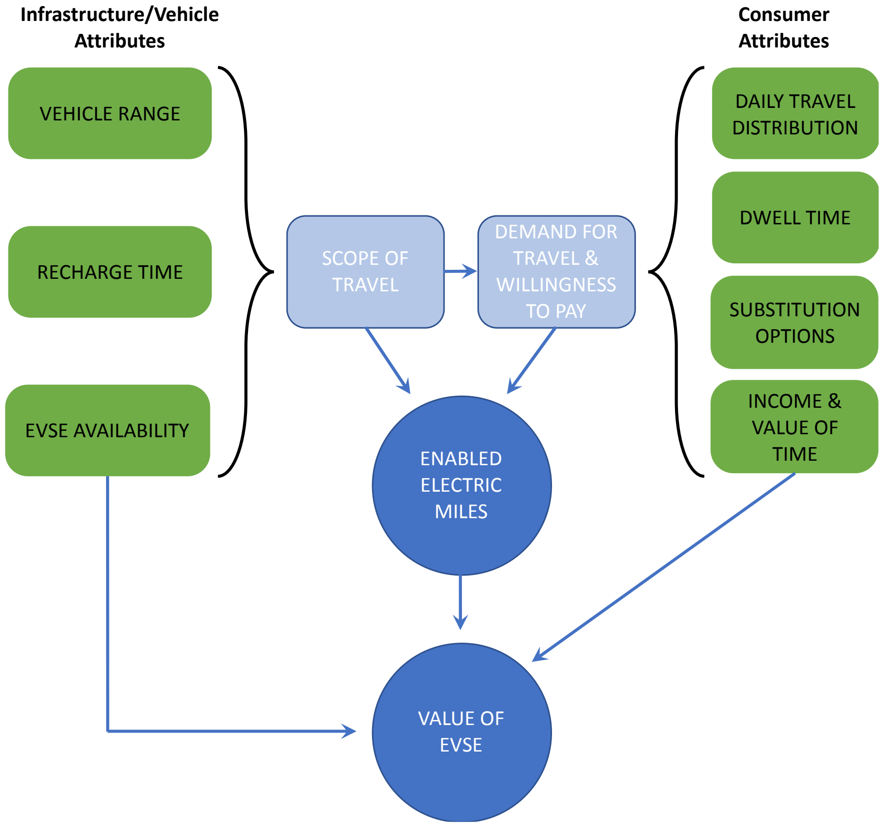
The value of public charging to a consumer depends on three vehicle attributes: (1) whether the PEV can operate only on electricity (BEV) or can also be powered by conventional fuels (PHEV), (2) the range of the PEV when using electricity, and (3) the time required to recharge. The incremental value of additional public charging stations also depends on their location, the amount of EVSE already in place, and the number of PEVs. The value of EVSE also depends on consumers' attributes: (1) income and the value of time, (2) availability of other vehicles, and (3) demand for travel and the ability to substitute other goods and services for automobile travel.

The value of recharging availability to the owner of a dedicated BEV is that it extends the ability of the vehicle to access opportunities in space and time (i.e., to provide mobility and accessibility). From a different perspective, it increases the number of trips the consumer would like to take for which the BEV is a desirable mode of travel. Range accomplishes the same purpose. Range and fuel availability are, to a certain extent, substitutes. A vehicle with longer range can accomplish a greater number of trips with less recharging infrastructure. The expansion of recharging infrastructure enables the same number of trips to be accomplished by a vehicle with shorter range. Both range and recharging infrastructure reduce time spent recharging but in somewhat different ways. Increased range decreases the number of recharging events while recharging infrastructure reduces the time and distance required to access a station. The value of reducing the number of recharging events also depends on the time required for recharging per event and the value of time spent charging. Together, range, refueling time, and refueling availability interdependently determine the non-monetary cost of refueling.

The cost of time spent recharging is context dependent. The cost of time spent charging at home, overnight when a vehicle is not needed, may be limited to the time it takes to plug and unplug the vehicle, making it more convenient than refueling a gasoline vehicle at a filling station. Similarly, the time cost of charging at work or anywhere a vehicle is parked for an extended period may also be negligible. On the other hand, the time cost of an unanticipated need to recharge, or recharging during a long-distance trip, could be substantial. The term "range anxiety" was coined to represent the fear of an unanticipated recharging requirement, at which recharging infrastructure might or might not be available. Part of the value of visible, public recharging infrastructure appears to be in reducing this fear (NRC 2015; Rezvani et al. 2015; Axsen et al. 2015; Franke and Krems 2013).

This section presents a mathematical exposition of the tangible factors that affect consumers' willingness to pay for recharging infrastructure. The relationships between the factors are illustrated schematically in Figure 5. Vehicle range affects the geographical scope of travel achievable by a vehicle, which is affected similarly by the availability of recharging infrastructure. Range, recharging time, and infrastructure availability affect the average speed of travel through the time required for recharging, a function of the number, access time, and duration of required recharging stops. Consumers' willingness to pay for EVSE infrastructure depends on their travel behavior (i.e., travel demand, which depends on many factors including vehicle range and geography) as reflected in desired daily travel distributions (including long-distance travel and times when vehicles are parked), their options for substituting for travel by the vehicle in question, and the value of time spent in travel-related activities. Consequently, consumer preferences for EVSE will vary geographically.

Figure 5: Factors Affecting Consumers' Willingness to Pay for EVSE Infrastructure



Source: NREL

For PHEVs, the value of recharging infrastructure is chiefly the fuel cost savings available by substituting a greater amount of electricity for gasoline, although for some PHEV owners, there are additional benefits in terms of altruism and self-identity from using what is perceived to be a more environmentally benign form of energy (Axsen et al. 2015; Hackbarth and Madlener 2013).

The value of public EVSE for BEVs is considered next. The effect of range and EVSE on the scope of travel is considered first because while range itself enables greater mobility, provision of EVSE can have the same effect. Range also strongly affects the willingness to pay for EVSE infrastructure through the effects on the frequency of recharging. The key result is that the marginal willingness to pay for range varies with the inverse of range (1/R) and depends on EVSE availability and charging time as well (Dimitropoulos et al. 2013). Likewise, the marginal value of additional EVSE in terms of increasing mobility is shown to decrease as EVSE infrastructure coverage increases. The fact that the marginal value varies with 1/R implies that the total value increases with the logarithm of R. Because the fundamental values of inter- and intraregional refueling availability differ (Melaina et al. 2013) they are analyzed separately. The key result for interregional EVSE infrastructure is that each additional station increases the daily distance that can be accomplished by a BEV by a decreasing amount. There are two reasons for this. First, the number of stations required to provide a given increase in the radius of feasible daily travel increases more rapidly than the radius. Second, the number of trips consumers take tends to decrease exponentially with distance.

PHEV Willingness to Pay for Recharging Infrastructure

PHEVs can refuel with gasoline as well as electricity and thus can take advantage of the ubiquitous gasoline refueling infrastructure and short gasoline refueling time. The tangible value of public recharging infrastructure to PHEV owners is therefore the cost savings on energy due to an increased opportunity to substitute electricity for gasoline (assuming that electricity is cheaper than gasoline, on a per-mile basis). Nicholas et al. (2017) found that the frequency of PHEV charging by drivers in a California survey was positively related to the electric range of the PHEV. In addition, when gasoline prices decreased, PHEV owners plugged in less frequently. Out of 156 PHEV owners in the California Vehicle Survey, only 2 reported that they never charged their vehicles (California Energy Commission 2017). Both have PHEVs with small electric ranges: one reported an electric range of 4 miles and the other 11 miles.

The cost savings from plugging in depend on (1) the charge-depleting range of the PHEV (a function of the usable battery storage capacity), (2) the savings gained by substituting grid electricity for gasoline (a function of the price of gasoline, p_G, the price of electricity, p_E, and the energy consumption when using gasoline, e_g, and when using electricity, e_E, both in kWh/mile), and (3) the probability that EVSE is available at the end of a trip, P_i, the rate at which the recharging infrastructure available at the end of trip i can deliver electricity to the vehicle, A_i, and the time the vehicle spends parked, d_i, before beginning trip $i+1$, multiplied by the fraction of that electricity that can be used before the next recharging event, f_i. Let c_i be the usable remaining electricity stored in the battery of the vehicle at the end of trip i.[4] The value of public charging infrastructure is the sum of savings over all trips, appropriately discounted over time.[5]

Equation 5

A. $WTP = V = \sum_{i-1}^{N} P_i Min(d_i A_i, C - c_i)(p_G e_G - p_E e_E) f_i$

Equation 5 requires knowing each individual's trip making over time and the probability of each type of EVSE being available each time the vehicle is parked. It also requires constraining the amount of recharging to the remaining spare capacity of the battery. However, it illustrates a few useful points and, researchers have simulated just such calculations using detailed vehicle use data. First, the value of public charging infrastructure increases linearly with the probability that a recharger is available where vehicles are likely to end trips. Assuming chargers are well located, the probability of charger availability should be proportional to the density of chargers. Willingness to pay also increases linearly with the amount of time vehicles are parked at the end of a trip up to the time required to fully recharge the battery. This period will depend on the available battery capacity when the vehicle is parked and the charging rate. Value also increases with increasing battery capacity, other things equal. Finally, savings depend on the fuel costs per mile of gasoline and electricity and the efficiency of the vehicle in charge-depleting and charge-sustaining modes. Equation 1

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[4] For simplicity, the possibility of stopping to recharge during a trip is omitted.

[5] To simplify Equation 1, the PHEV is assumed to use only electricity when operating in charge-depleting mode. In reality, most PHEVs will use some gasoline in charge-depleting mode with the amount of gasoline use per mile generally decreasing as the charge-depleting range increases. Redefining pe to be the cost per mile (including both gasoline and electricity) in charge-depleting mode corrects the simplification.

assumes that all PHEV charging is "convenience charging" (i.e., it occurs at a time and place where a vehicle would otherwise be parked for an extended period). Under other circumstances, the cost of time to access charging significantly reduces the net value.

Because of the more limited battery capacity of PHEVs and the assumption of convenience charging, it may also be reasonable to assume that Level 2 and DCFC chargers count equally. Wood et al. (2017b) found Level 1 charging to be enough for most workplace charging, but Level 2 was preferred for public PHEV charging, and PHEVs were found not to need DCFC.

BEV Willingness to Pay for Recharging Infrastructure

BEV owners' willingness to pay for public charging infrastructure differs from that of PHEV owners in that the value does not come from savings on energy costs, but rather from enhancing the utility of the vehicle. The effect of EVSE on the scope of BEV travel (the distance it can travel after leaving home base) is considered first, followed by the effect of recharging time. Finally, the effect of range on refueling frequency is considered and shown to be inversely related to the value of EVSE for BEVs.

Range and Scope of Travel

For BEVs, the value of additional interregional recharging infrastructure is that it expands the ability to reach destinations farther from the home base of the vehicle. A distinction is made between the practical range of a fully charged BEV, R, and the associated scope, S, the area accessible by the vehicle in a day including available recharging infrastructure. First, it is shown that adding stations increases the scope of travel at a decreasing rate per station. Second, because the frequency of trip-making decreases with increasing trip length beyond the mode of the trip length distribution, the value of additional stations decreases more rapidly with increasing scope. In Chapter 4, empirical analyses of continuously monitored vehicle travel in Seattle and other cities are reviewed that illustrate how the number of trips enabled by the expansion of public EVSE decreases rapidly as the investment in infrastructure is increased.

Consider a potential BEV owner who can regularly recharge at home. For simplicity, a region with a rectangular (square) road system (grid) is assumed. A BEV with a practical range of 2R can reach any point on the grid in a square centered on the home base with sides $R\sqrt{2}$ (area = $2R^2$) and return to the home base.[6] Adding chargers that can fully recharge the vehicle expands the area that can be reached.[7] Adding four DCFCs at the corners of the original square expands the total area that can be reached to $8R^2$ (red squares), an increase of $8R^2$ -

[6] In reality, the range of a BEV is not constant but depends on ambient temperature, use of heating and air conditioning and other accessories, driving style, terrain, traffic conditions, and battery degradation (e.g., Wood et al. 2017a, p. 31). The range of conventional vehicles is also affected by such factors but to a lesser degree.

[7] In general, charging at DCFC stations is slowed when a vehicle reaches roughly 80 percent of its battery capacity to avoid damage to the battery. In addition, chargers will need to be located within the maximum practical range of a vehicle to be of practical value to BEV drivers. The authors overlooked these factors for the sake of simplifying the mathematical model and will reintroduce them subsequently.

$2R^2 = 6R^2$ (Figure 6).[8] The added number of stations is 4 times the original number (1), but the area increases by a factor of 3 ($6R^2/2R^2$). Expanding again by adding a layer of eight stations increases the area to 5 times the original size ($2R^2$) for an added area to added station ratio of 5/8 (green squares). Continuing to add layers of rectangles around the perimeter of the existing reachable area, it becomes clear that the number of stations is an arithmetic progression with increment of 4 while the added area is a progression with increment of 2. The incremental distance always increases by R but the number of stations required increases with n+4. The n^{th} ratio and limit as n approaches infinity is given by Equation 6.

Equation 6

B. $$\frac{a_1+(n-1)2}{a_1+(n-1)4} \; and \; \lim_{n\to\infty} \frac{a_1+(n-1)2}{a_1+(n-1)4} = \frac{1}{2}$$

The ratio converges on 1/2 quickly; after just two layers it is 5/8 and by five layers it is 11/20. If the authors assume that potential destinations are uniformly distributed in space, in the limit each station increases the scope of the vehicle by half as much as the first station. Using the consumer's own distribution of daily travel as a function of distance should produce a more realistic estimate of trips enabled by adding EVSE stations. In either case it is clear the value to a consumer of each additional EVSE station is not constant but decreases as the number of EVSE stations increases (He et al. 2015).[9]

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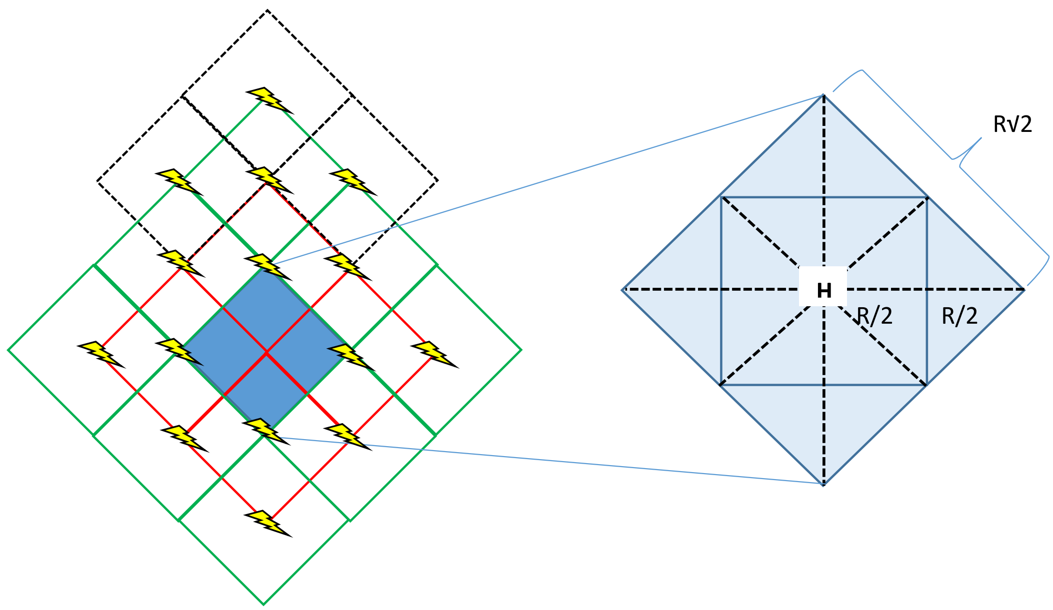
[8] In this theoretical exposition and in the simulation analyses discussed in Chapter 4, it is assumed that charging stations are located in a coordinated and optimal way. In reality, charger locations will be less than optimal.

[9] The stations added far from one consumer's home will have value for other consumers in other locations. Still, this model provides some insights about the value of EVSE for intercity travel and for the direction of relationships for intraregional travel if not for the exact functional form.

Figure 6: Areas Reachable From a Home Base (H) Without EVSE (blue square) and With Added EVSE (red, green, and black squares) Assuming a Rectangular Street Grid (lightning bolt symbols indicate charging station locations)



Source: NREL

From the perspective of added range (R, radius), the distance that can be traveled in all directions that is added per charging station is given by Equation 7, which goes to zero as n approaches infinity.

Equation 7

C. $$\lim_{n\to\infty} \frac{R}{1+(n-1)\,4} = 0$$

Let n=1 be the home base charger and $n \in$ N the total number of charging stations. The number of charging stations added at each stage is 4(n-1) and the total number of EVSE stations at stage m are sum from n=2 to m of 4(n-1).

At each stage, expanding the range of an EV by R requires adding four more stations than were required at the previous stage. Thus, the total number of stations required to increase the effective range of a BEV m multiples of R is given by Equation 8.

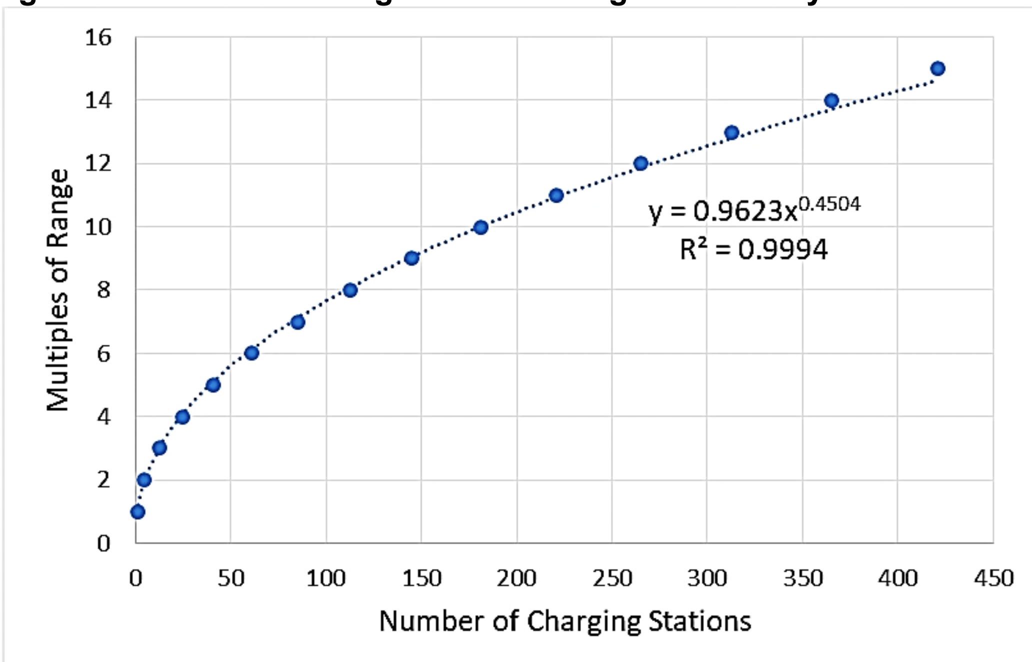
Equation 8

D. $$n = \sum_{i=1}^{m} 4i$$

Figure 7 illustrates the effect of adding charging stations to increase the effective range in all eight directions illustrated in Figure 6 for a 100-mile-range BEV. In theory, the number of stations required is proportional to the inverse of vehicle range: if 220 stations were required to enable a 1,000-mile trip by a BEV100, only 110 stations would be needed for a BEV200.

The value of charging stations will decrease with distance from a home because the probability of taking trips that would use the station decreases with distance. The decrease in interaction with distance, "distance decay," has been called the "first law of geography" (Eldridge and Jones 1991). The simplest distance decay model implies that the probability (p_{ij}) of a trip from an origin (i) to a destination (j) will vary directly with the size (M) of the destination and inversely with the square of the distance (d_{ij}) from the origin: $p_{ij} = k\, M_j/(d_{ij})^2$. In practice, exponents for M_j and d_{ij} are estimated empirically. This implies that the value of charging infrastructure, especially for intercity trips, will decrease with increasing distance from the home base of a vehicle. On the other hand, the value of a trip is likely to increase with its length. In the theory of EVSE value for interregional travel, the effect of distance decay is represented by the frequency distribution of daily vehicle travel by distance, as explained below.

Figure 7: Theoretical Long-Distance Range Enabled by DCFC Stations



Source: NREL

The simple theory just presented takes the perspective of a single vehicle. The marginal benefit to that vehicle of adding one more EVSE clearly decreases as the number of EVSE increases. But if the presence of others is allowed, the certainty of decreasing marginal benefit is less obvious. Additional charging stations confer benefits on other vehicles, increasing their value. However, once a boundary is drawn around the inhabited area, additional charging stations beyond that boundary will have decreasing marginal benefits, as in the single BEV example. In that case, EVSE will have multiple users, which raises two additional issues: (1) sharing EVSE increases the benefit per unit, but (2) multiple users create the possibility of scheduling conflicts and waiting time, which would reduce the benefit to those in the queue. These two phenomena have important implications for measuring EVSE infrastructure. Sharing implies that the value of each charger increases with the ratio of BEVs to chargers. Congestion implies the opposite. For example, NREL and the California Energy Commission (2018) quantified these phenomena in a simulation of statewide charging needs in 2025. The assessment found a range of needed chargers: from a minimum of ~9,000 DCFCs to meet coincident demand and up to ~25,000 DCFCs if each were to be shared among two BEVs daily.

The value of increased range depends on the frequencies and values of longer trips, which are strongly correlated with annual mileage. Empirical studies reviewed by Liao et al. (2017) found that consumers' preferences for range are correlated with annual miles traveled. Annual miles enabled by charging infrastructure that extends vehicle range can be estimated from daily travel distributions by weighting the probability of a trip by the length (L) and dividing by total daily vehicle miles of travel (D). Greene (1985) fitted Gamma distributions to household data to represent daily vehicle travel and Lin et al. (2012) showed that the Gamma provided good estimates of energy use by PEVs. Tamor et al. (2013) combined normal and exponential probability distributions to more flexibly approximate daily travel. Plötz et al. (2017) compared Gamma, Weibull, and lognormal distributions and concluded that the Weibull provided better fits to daily travel distributions.

Using the Weibull cumulative distribution function, the fraction of daily trips enabled by charging infrastructure that increases vehicle range from R_0 to R is given by Equation 9, where λ is the scale parameter of the trip distribution and k determines the shape of the distribution.

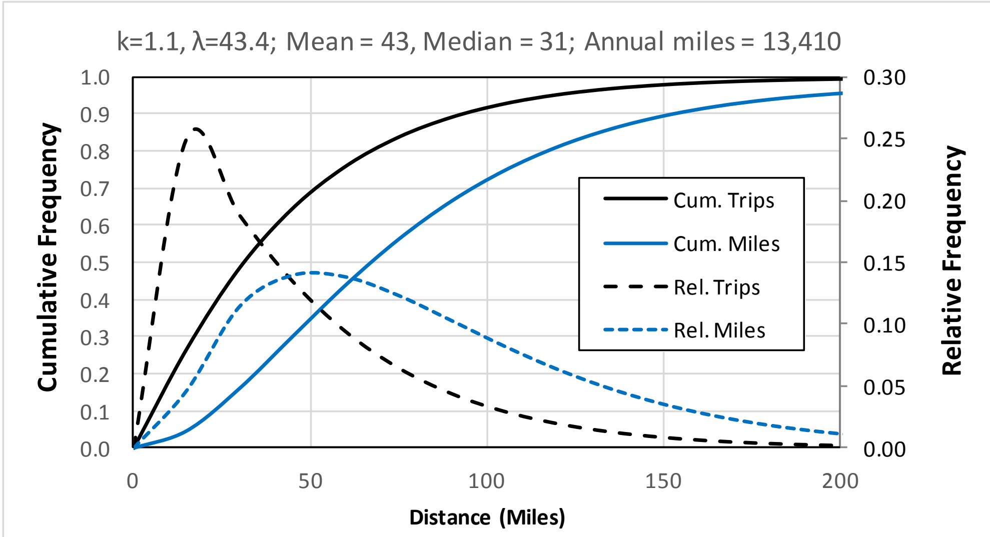
Equation 9

E. $$p(R, R_0) = \left(1 - e^{-\left(R/\lambda\right)^k}\right) - \left(1 - e^{-\left(R_0/\lambda\right)^k}\right) = e^{-\left(R_0/\lambda\right)^k} - e^{-\left(R/\lambda\right)^k}$$

Figure 8 illustrates the probability density and cumulative density functions of a hypothetical Weibull trip distribution function with parameters k = 1.11 and λ = 39. These parameters were chosen to approximate the annual trip distribution of an average light-duty vehicle in California. The distribution implies average daily miles of travel of about 43 and median of 31 and annual vehicle miles traveled (VMT) of about 13,400 miles, similar to that of a typical light-duty vehicle in California (NHTS 2018) or a 2-year-old passenger car in the United States. (Davis et al. 2017, Table 8.8; NHTSA 2006, Table 7).[10] The distribution of annual miles by trip length (blue lines in Figure 8) is the distribution of trips weighted by trip distance.

[10] The mode of the distribution is also consistent with the NHTS 2017 data on household vehicle trips.

Figure 8: Hypothetical Weibull Cumulative (CDF) and Probability Density (PDF) Trip Distributions



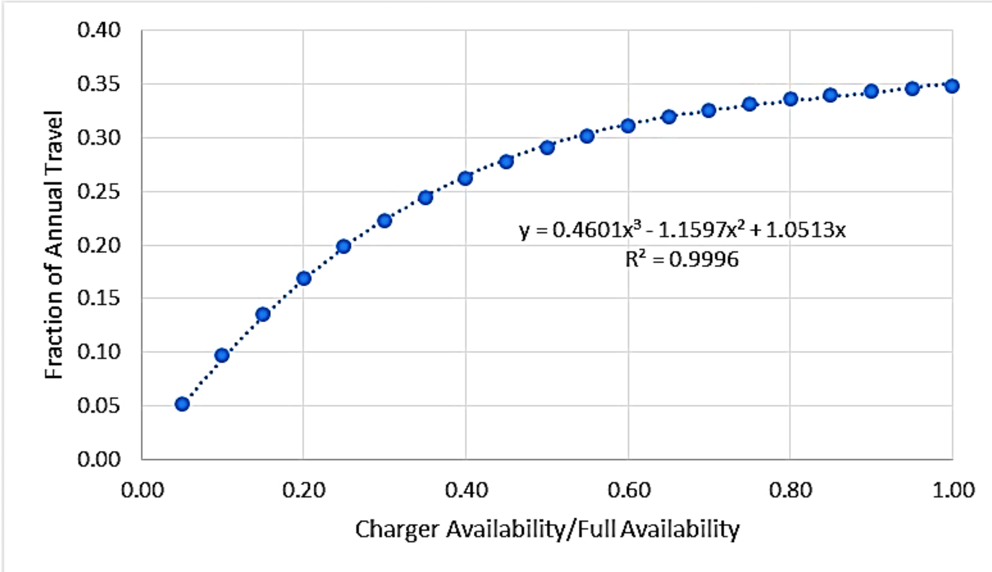
Source: NREL

The annual miles added by extending vehicle range can be computed by transforming the daily travel distributions to daily vehicle miles distributions, calculating the expected daily miles of travel added by increasing vehicle range using Equation 9, and multiplying by 312.[11] The resulting estimated enabled miles are reasonably closely approximated by a cubic polynomial of the increase in range (Figure 9) with intercept of zero and almost as well by a logarithmic function of availability.[12] This theoretical result is broadly consistent with the marginal value of range decreasing with 1/R in that enabled miles increase at a decreasing rate as range increases. Recharging takes time, which can add to the cost of PEV use on longer trips, an issue addressed in the following section.

[11] The hypothetical trip distance distribution does not include days on which no trips are taken. Data cited in Melaina et al. (2016, p. 30) indicate that a better assumption is that vehicles are used only 312 days per year, on average (312 * 42.536 = 13,271). Each DCFC is assumed to increase the range of BEVs on average by 1.5 miles.

[12] The logarithmic function, although simpler, is not used for calculating willingness to pay because it creates an anomaly at very low levels of charger availability. However, the logarithmic approximation is used in estimating the effect of charger availability on long-distance travel in chapter 6.

Figure 9: Miles of Travel Enabled Beyond a 75-Mile Range Using Hypothetical Weibull Distribution



Source: NREL

EVSE Convenience and Recharging Time

The value of infrastructure also depends on the convenience of recharging, which is represented as the time cost of recharging or, alternatively, the overall speed of travel. For long-distance travel, the average speed of travel establishes a limit on how much travel can be accomplished in a day. If a traveler can average 60 miles per hour for 15 hours per day, the limit would be 900 miles. If a BEV has a practical range of 100 miles and requires an additional 20 minutes to recharge (these values being chosen to simplify the calculations), the average speed is reduced to 100 miles/(120 minutes/60 minutes)hour = 50 miles per hour. At this velocity the upper bound on daily travel would be 750 miles. If recharging required 3 hours and 20 minutes, average speed would be reduced to 20 miles per hour and the daily maximum distance to 300 miles.[13] On the other hand, a BEV with a 300-mile range and 20-minute recharge time would travel at an average speed of 56.25 miles per hour, could travel 844 miles in 15 hours, and would stop three times, including the end of the trip. To accomplish the same trip the 100-mile-range BEV would have to stop nine times. This implies that the intercity range of an EV depends on the speed of recharging and that the need for intercity EVSE is inversely proportional to EV range.

The time cost of refueling depends on range, access time to a charger, t_a, and recharging time, t_r. A function relating the time cost of recharging (C_a) to the time per event ($t_a + t_r$), the value of time (w), the rate of travel ($m(t)$) in distance per time, vehicle lifetime (L), and

[13] This assumes the recharge time at the end of the trip would be considered part of the trip by the driver. In reality, it might be used as leisure time.

discount rate (r) was derived by Greene (2001).[14] In continuous time the relationship is given by Equation 10.[15]

Equation 10

$$\text{F.}\quad C_a^* = \int_{t=0}^{L} \frac{w(t_a+t_r)m(t)}{R} e^{-rt} dt = \frac{w(t_a+t_r)}{R} \int_{t=0}^{L} m(t) e^{-rt} dt = w(t_a + t_r) M \frac{1}{R}$$

In Equation 10, M is discounted future miles of travel. From this perspective, the value of range is in reducing the time cost of travel. At low range levels, the value of increased range (in terms of reduced time spent refueling) decreases rapidly (with the inverse of range) as range increases. The fact that the value of range (from this perspective) varies with the inverse of range was also noted by Dimitropoulos et al. (2013), who point out that few econometric estimations of willingness to pay for range use this functional form. Instead, most estimate the value of range as a linear function of R, which could cause biased estimates of willingness to pay or, at least, limit the ranges over which the estimates could be roughly valid.

The time to access public EVSE depends on the number (or density) of EVSE units.[16] Several studies have estimated the time required to access an alternative fuel station as a function of station availability. None is specifically focused on access to EVSE. On the one hand, one would not expect the time required to get to a station given an origin, destination, and route of travel to depend on the type of fuel. On the other hand, the geography of EVSE locations is likely to differ from that of gasoline stations (e.g., EVSE located at shopping malls or restaurants), and the time required to complete a charge could make queuing time an important consideration in addition to access time. Based on a simulation analysis of automobile trips in Sacramento, California, Nicholas et al. (2004) showed that the time required to access fuel in the metropolitan area decreased at a decreasing rate as the number of stations was increased. Existing gasoline stations were sequentially removed from the simulation in order of related impact on total travel time, starting with the station whose removal caused the smallest increase. Nicholas et al. (2004) found that a simple power function of the ratio (f) of remaining stations (n) to the total number of stations (N) fit the decrease in access time well. Multiplying access time by the value of time (w) results in a power function for the cost of limited fuel availability within a metropolitan region as a function of the number of alternative fuel stations divided by the number of existing gasoline stations.

Equation 11

$$\text{G.}\quad C_3 = wK\left(\frac{n}{N}\right)^{\alpha} = wKf^{\alpha}$$

[14] As noted above, in reality the value of time is likely to be very different for access time and recharge time.

[15] Equation 6 is most appropriate for BEVs rather than bifuel PHEVs. For PHEVs, range would have to be redefined as charge-depleting or all-electric range.

[16] It also depends on the availability of a charger; that is, whether the EVSE unit is already in use or inoperable. Redundancy is not covered in this report but would increase the required number of EVSE units as an inverse function of downtime.

Greene (1998) found that either a power function or exponential function fit stated preference survey data on the perceived cost of limited fuel availability. Melaina et al. (2013) also found that power functions fit results of stated preference surveys from four major United States metropolitan areas. The cost functions differed somewhat across the cities and were somewhat higher than the results of Nicholas et al. (2004). The cost of having only 1 percent as many charging stations as gasoline stations in a metropolitan area ranged from $2,000 to $3,000, present value. Costs at 10 percent availability ranged from about $1,000 to $1,500. Greene et al. (2004) used Nicholas et al.'s (2004) results together with a value of time of $20/hour to estimate a cost of $2,500 at 0.5 percent availability, decreasing to $500 at 10 percent availability.

The value of travel time has been extensively studied and found to vary substantially across individuals and across types of travel and the context of travel. The U.S. Department of Transportation recommends estimating the value of time spent traveling as a function of hourly earnings (Belenky 2011).

Equation 11 expresses the cost of limited fuel availability per refueling event as a function of the relative availability of infrastructure. Translating this limited fuel availability cost to a present value cost per vehicle requires estimating the number of refueling events over the lifetime of a vehicle and discounting to present value. A decreasing exponential function of age provides a reasonable approximation to annual miles over the lifetime of a vehicle (NHTSA 2006). Let M_0 be the usage of a new vehicle, in miles per year and δ be the rate of decrease per year. Let L be vehicle lifetime and r the annual discount rate. The present value cost of access time to a recharging station is given by Equation 12, in which M is discounted lifetime miles of travel. The value of increased fuel availability is the difference between the cost at f_0, the initial or reference availability, and at f.

Equation 12

H. $$C_1^* = wKf^a \int_{t=0}^{L} \frac{1}{R} M_0 e^{-(\delta+r)t} dt = wKf^a \frac{M_0}{R} \frac{1}{\delta+r}\left[1 - e^{-(\delta+r)L}\right] = wKf^a \frac{M}{R}$$

For BEVs with home or workplace recharging, most recharging will be done at home or at work. This finding does not change the functional relationship shown in Equations 11 and 12 but it does greatly reduce the miles of travel affected, resulting in many fewer recharging events and a lower time cost of recharging.

Combined Effects of Range, Charging Time, and Public Infrastructure

Combining the effects of range, recharging time, and range-enabling infrastructure leads to a formula that is a product of (1) the effect of I units of EVSE infrastructure on enabled electric annual vehicle miles traveled (eVMT) as a fraction of conventional vehicle travel, $h(I)$, (2) the effect of range on diminishing the impact of adding infrastructure, $k(R)$, (3) the annual miles of vehicle j, M_j, and (4) a factor to convert annual willingness to pay to lifetime willingness to pay, D_j. The term in brackets contains the value per mile of enabled travel, v, and the time cost of recharging. In Equation 13, $t_a{}^*$ and $t_r{}^*$ are defined as reductions in time from an initial level.

Equation 13

$$\text{I.} \quad WTP = h(I)k(R_i)M_j\left(v_j + w(t_a + t_r)\frac{1}{R_i}\right)D_j$$

Equation 13 provides estimated willingness to pay for a total level of infrastructure of I in present value dollars. The marginal willingness to pay is the derivative of willingness to pay with respect to I. If $h(I)$ is a logarithmic function of I as Figure 9 suggests, say $a_0 + a_1 ln(I)$, then $dWTP/d_I = a_1/I$, an inverse function of I. That is, the marginal value of the next charger decreases with the inverse of the installed infrastructure. Because the willingness to pay for I charging stations has units of dollars, it can be converted to utility by multiplying by the coefficient of price in a random utility model. Willingness to pay is a function of the logarithm of the amount of infrastructure, the range of the vehicle, the consumer's miles of travel, value of time, and discount rate. Because price coefficients may vary across vehicles or as a function of income, the effect of willingness to pay on the choice of a PEV will also.

In theory, the value of enabled EV travel can be estimated by equating vehicle travel enabled by range to travel enabled by EVSE. The value of increased EV range has been estimated by numerous econometric studies, and willingness-to-pay estimates have been analyzed by Dimitropoulos et al. (2013) and Greene et al. (2017). The possibility of using econometric estimates for this purpose is explored in Chapter 5.

Summary of Recharging Theory

The development of even the simplified theory of PEV recharging presented above leads to some inferences about the value of public charging infrastructure.

1. The availability of public charging infrastructure, PEV range, and recharge time are interdependent.
2. For BEVs, willingness to pay for EVSE infrastructure depends on the distribution of daily travel, dwell times when BEVs are parked, the value of the traveler's time, and the availability of substitutes for BEV travel (e.g., availability of a gasoline vehicle, other transportation modes, telecommunication). Less tangible benefits, such as reduced range anxiety, are also important but more difficult to quantify and model.
3. Other things equal, the marginal value of infrastructure decreases as vehicle range increases.
4. Other things equal, the marginal value of EVSE decreases according to the inverse amount of installed EVSE.
5. For PHEVs, the value of EVSE infrastructure consists chiefly of energy cost savings from substituting grid-produced electricity for gasoline use.
6. For BEVs, the value of EVSE consists primarily of enabling additional vehicle miles of travel, augmented by reduced time required to access recharging and, for faster charging infrastructure, reduced charging time.

An important issue that has not been resolved is how best to measure infrastructure availability. Melaina et al. (2016) and Wood et al. (2017a) measured charging infrastructure relative to the number of PHEVs and BEVs on the road. Based on the theory presented and analyses reviewed, another appropriate metric would be the availability of a charger at a location where it is most useful to the PEV driver. Assuming that chargers are located where PEV drivers are most likely to use them, two appropriate and simple metrics for intraregional travel could be the number of chargers divided by area or by the length of roadways in the region.

For interregional travel, charger availability might be best measured in terms of chargers per mile. Wood et al. (2017a) evaluated spacing DCFCs at intervals of 40, 70, and 100 miles along interstates. They concluded that 400 stations providing 2,500 connectors at a spacing of about 70 miles between stations would provide adequate coverage for a fleet of 15 million PEVs. Kontou et al. (2017) analyzed the optimal location of charging stations along a linear corridor while estimating the optimal range of BEVs. Kontou et al. (2017) obtained data on daily trip distances from the United States 2009 National Household Travel Survey.[17] The estimated optimum consisted of BEVs with a range of 204 miles and charging stations spaced 172 miles apart (84 percent of the range of the BEVs). Social value was maximized when all the chargers were installed as early as possible. A similar result was obtained by Nie et al. (2016). Appropriately spacing chargers along a route is part of the solution, but the more difficult question is how to ensure availability when a vehicle requires it and avoid lengthy waiting times. Melaina et al. (2016) measured charger infrastructure in terms of EVSE units of different types per PHEV and per BEV. Until this subject is adequately analyzed, charging stations per 100 intercity route miles appears to be a useful metric.

[17] National Household Travel Survey: http://nhts.ornl.gov.

CHAPTER 4: Insights From Simulation Models

The availability of geographically and temporally detailed survey data describing the activity patterns of vehicles over an extended period has enabled highly realistic simulation modeling of the effects of limited range and recharging availability on the use of PHEVs and BEVs. By combining Global Positioning System (GPS) tracking with automated data transmission and processing, researchers have learned not only about trip distances, but about timing, locations, and time spent parked. These lessons have enabled modelers to quantify effects of EVSE on vehicle travel and develop empirical insights about functional forms, usually conditional on the travel patterns of conventional gasoline vehicles.

Most simulation studies make the following simplifying assumptions:

1. PEVs are driven like conventional vehicles to the extent that the range and charging infrastructure allows.
2. PEVs have access to charging at home.
3. At the beginning of a travel day, PEVs leave home fully charged.[18]
4. The deployment of public charging infrastructure is done in a coordinated and optimal manner.
5. Queueing at charging stations is usually not considered.
6. PEV range is a constant fraction of rated range even though it is known to be affected by ambient temperature, heating and A/C use, traffic conditions, and other factors.
7. At the beginning of each day, vehicle operators have perfect foreknowledge of the trips they will make.

Although not universally true, available data indicate that these assumptions are reasonable approximations, except for optimal EVSE placement to date. A potentially important limitation of nearly all simulation analyses is that they do not consider changes in the observed travel behavior of conventional vehicle drivers that PEV drivers might make to improve the utility of PEVs, such as additional planned stops for recharging (Neubauer and Wood 2014). Notwithstanding, simulation modeling has developed empirical relationships between range, recharging time, and EVSE deployment that, together with econometric evidence described below, provides a reasonable basis for estimating the value of public EVSE that can also be used in calibrating random utility models of vehicle choice. Simulation studies analyzing PHEV

[18] More precisely, PEVs leave home either fully charged or with sufficient charge to accomplish the travel requirements of the day if the requirements can be accomplished with less than a full charge.

electric miles enabled by EVSE are considered first, in the PHEVs and EVSE section, followed by analyses of the effects of EVSE on the utility of BEVs in the BEVs and EVSE section.

PHEVs and EVSE

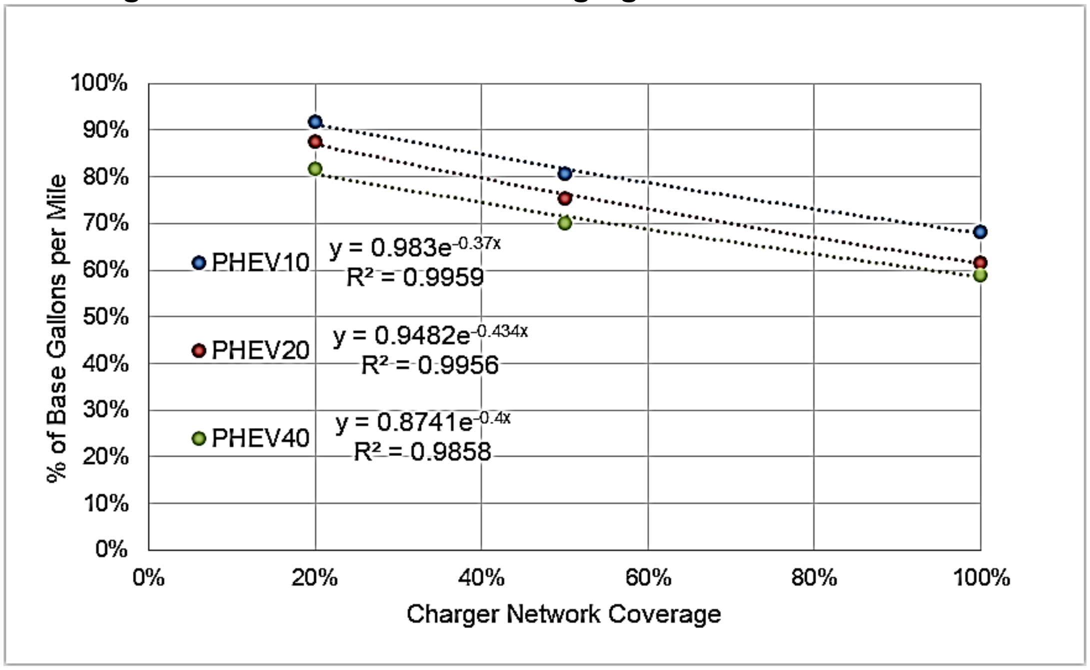
Although the maximum possible benefit of workplace and public recharging for PHEV owners could be in the thousands of dollars over the lifetime of a vehicle, practically achievable benefits are more likely to be numbered in hundreds of dollars (Lin and Greene 2011). By means of a simulation analysis of the daily driving of 229 conventional vehicles in Austin, Texas, Dong and Lin (2012) found that an extensive public recharging network could reduce PHEV gasoline use by more than 30 percent and reduce energy costs by more than 10 percent without changing the usage patterns of the vehicles. Their analysis assumed that each vehicle began the travel day with a full charge. They also assumed all public chargers were Level 2 (6 kW of power). Kontou et al. (2015) analyzed the interdependency of PHEV range and workplace charging. They found that the provision of workplace charging *increased* the optimal PHEV range from 16 to 22 miles to take advantage of greater gasoline savings. Providing a variety of PHEV ranges enabled greater savings than providing workplace charging, however, by accommodating the heterogeneity of travel patterns.

Reductions in PHEV gasoline use per mile relative to reference gasoline consumption based on Dong and Lin (2012) are shown in Figure 10. The estimates have been fitted by exponential functions of charger network coverage.[19] The derivatives of all the functions are negative, indicating that the marginal benefits of EVSE infrastructure decrease with increasing coverage. "Charger network coverage" is defined as the probability that a charger will be available when the vehicle parks. Thus, "coverage" applies to all places where vehicles are parked and could benefit from recharging (that is, it is not the number of charging stations as a percentage of gasoline stations). The amount of charge depends on the dwell time at the parking location and the battery capacity of the vehicle. PHEV40s are estimated to save more gasoline, but Dong and Lin's (2012) results suggest that the marginal benefit of increased EVSE infrastructure is about the same for PHEV40s, PHEV20s, and PHEV 10s (Figure 10). Recent evidence on PHEV charging in California indicates that the quantity of energy obtained per charge by a PHEV is nearly proportional to battery capacity (Tal 2019). Thus, if charging events increase in proportion to the availability of charging for all types of PHEVs, fuel savings should increase at a faster rate for PHEVs with higher battery capacities.

Dong and Lin's (2012) simulation assumes that PHEVs will take advantage of the opportunity to charge whenever it is available and would reduce their gasoline use. However, analysis of actual charging behavior by California PHEV owners shows that electric miles by PHEVs with low electric range are only about 40 percent (PHEV10) to 60 percent (PHEV20) of that implied by the standard utility factors (SAE 2841) used by Dong and Lin (2012). On the other hand, owners of PHEV40 vehicles are achieving 85 percent to 90 percent of the standard utility factors (Tal et al. 2018). Thus, the potential savings by PHEV20s and especially PHEV10s shown in Figure 10 are likely overestimated.

[19] If it is important that the functions equal 100 percent at zero coverage, quadratic functions can be substituted.

Figure 10: Effect of Public Charging on PHEV Gasoline Use



Source: NREL (data from Dong and Lin 2012)

The effect of charging network coverage on miles traveled in charge-depleting mode can be calculated from the related effect on gasoline use given (1) gasoline consumption per mile in charge-depleting (e_d) and charge-sustaining (e_s) modes, (2) the base share of miles in charge-depleting mode at 0 percent coverage (f_0), and (3) the ratio of gasoline use at coverage level I to gasoline consumption at 0 percent coverage ($F(I)$). Let $f(I)$ be the fraction of miles traveled in charge-depleting mode at coverage I and M be annual miles of travel. $F(I)$ as a function of $f(I)$ is given by Equation 14.

Equation 14

J. $$F(I) = \frac{(1-f(I))M e_s + f(I) M e_d}{(1-f_o) M e_s + f_o M e_d}$$

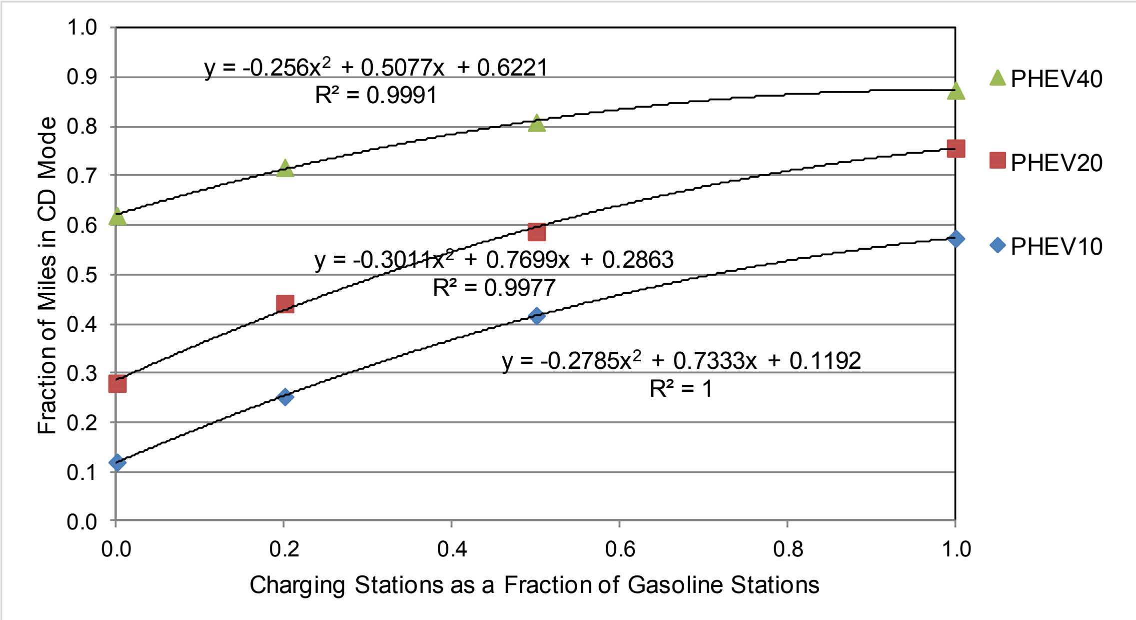
Solving for $f(I)$, the fraction of miles in charge-depleting mode at coverage I gives Equation 15.

Equation 15

K. $$f(I) = \frac{F(I)\left[\frac{1-f_o}{e_d/e_s} + f_o\right] - \frac{e_s}{e_d}}{1 - \frac{e_s}{e_d}}$$

The relationships in Figure 11 were calculated using Equation 15, inserting fuel consumption rates and values of $F(I)$ from Dong and Lin (2012) and utility factors (defined as the base share of miles in charge-depleting mode) for PHEV10/20/40 from Tal (2019).[20] The data points are well approximated by quadratic functions over the range 0 to 1.

Figure 11: Effect of Charging Infrastructure on PHEV Miles in Charge-Depleting Mode



Source: NREL

The effect of range on the benefits of public and work recharging opportunities for PHEVs was measured by Wood et al. (2017b, fig. 16) by means of simulation analysis. Adding workplace charging to home-based charging increased average electric miles by about 13 percent for PHEVs with a 20-mile charge-depleting range (Figure 12, green line). Adding ubiquitous public charging opportunities enabled another 11 percent for the PHEV20 vehicle (red line) for a total benefit for both types of charging opportunities of about 24 percent (blue line). In all cases benefits declined with roughly the inverse of the square root of charge-depleting range, indicating that increasing PHEV battery capacity reduces rather than increases the benefits of EVSE. Reduced need for recharging away from the home base appears to outweigh the increased capacity to store energy on board. The value added by public charging in addition to workplace charging appears to be almost the same as the value of adding workplace charging to home charging.

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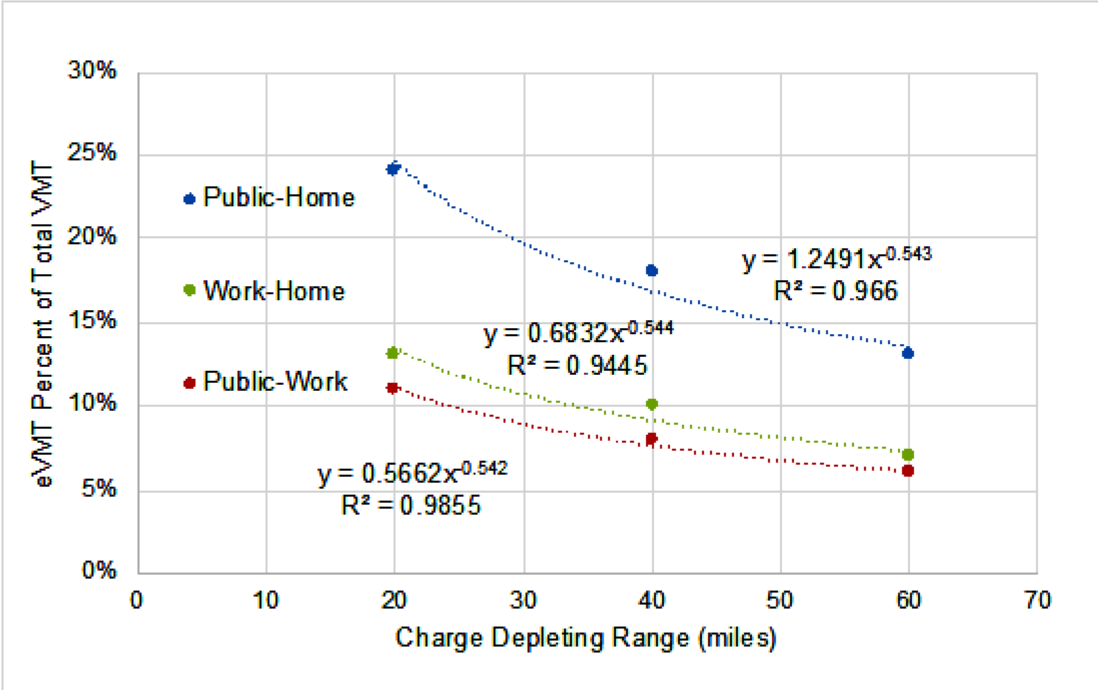
[20] Dong and Lin (2012) provide only the utility factor for the PHEV20 used in their analysis. However, Dong and Lin's (2012) PHEV20 utility factor is almost identical to Bradley and Davis's (2011) alternative to the SAE J2841 utility factor. We have substituted more recent factors based on California PHEVs (Tal, 2019).

Figure 12: Effect of Charging Infrastructure and Electric Range on PHEV eVMT



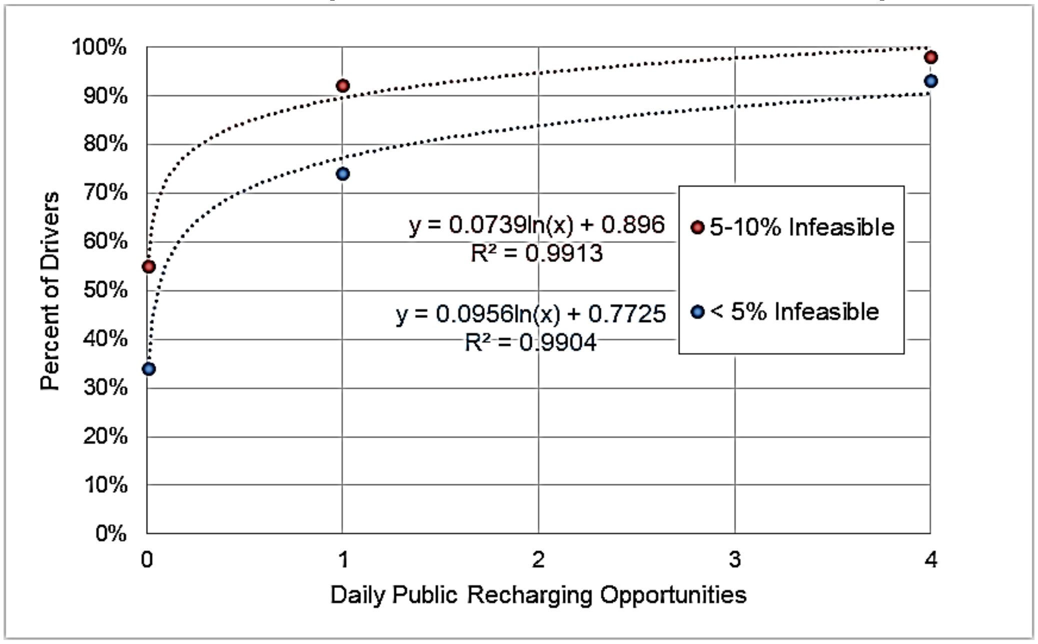
Source: NREL

By incorporating the estimated changes in eVMT into Equation 14 and adding prices and vehicle efficiencies, the value of EVSE to PHEV owners can be quantified.

BEVs and EVSE

Analyzing the trip-making behavior for 382 vehicles in the Seattle area with more than half a year of GPS-tracked travel data, Dong and Lin (2014) found that adding just one opportunity for public recharging (in addition to home recharging) greatly improved the ability of BEVs to satisfy household trip making. The fraction of drivers for whom a BEV could accommodate at least 95 percent of trips increased from about 35 percent to about 75 percent (Figure 13). With charging available everywhere, the fraction increased to more than 90 percent. A logarithmic function of daily charging opportunities appears to describe the results reasonably well. Dong and Lin's (2014) calculations assumed what is now a relatively modest nominal range of 76 miles and that drivers would use only 80 percent of that. With increased range the feasibility of BEVs increases, but the value of public recharging decreases as shown below. The analysis assumes that a charger is available to the driver during the longest time the vehicle is parked away from home, wherever that may be. Thus, even the one recharge per day case assumes a relatively high degree of charger availability. Five percent of days infeasible is 17 days per year. Unless another vehicle can be easily substituted for the BEV, this may not be acceptable to many drivers. A potentially important conclusion of Dong and Lin's (2014) analysis is that to achieve BEV market shares in the vicinity of 50 percent, at least one daily opportunity for public (away from home) recharging should be available.

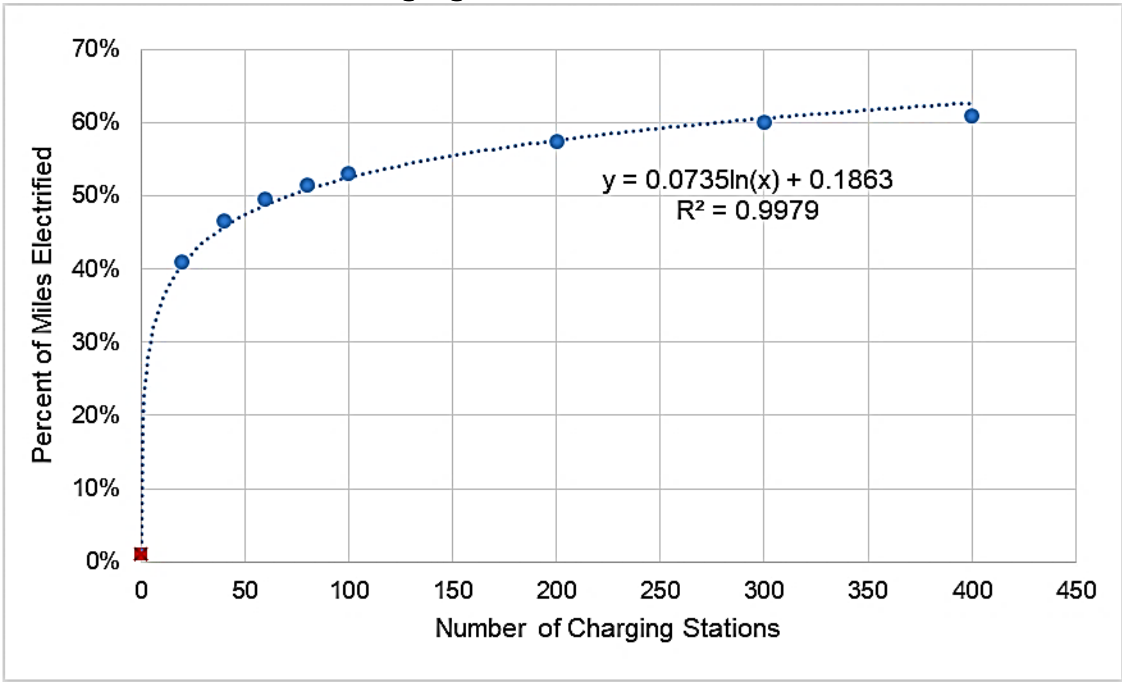
Figure 13: Effect of Public Recharging Opportunity on the Fraction of Drivers Who Could Accomplish at Least 95 Percent of Their Trips



Source: NREL (data from Dong and Lin 2014). Note: In this graph, "4" daily public recharging opportunities represents Dong and Lin's "charge everywhere."

The logarithmic relationship between BEV utility and EVSE is also supported by Shahraki et al.'s (2015) analysis of the potential to electrify taxi miles in Beijing. Using actual, timed GPS data on the activities of 11,880 taxis, the authors selected optimal locations for "slow" and "fast" charging stations, separately. The increase in electrified miles enabled is well fitted by a logarithmic function of the number of chargers added. (Note: the square red data point is not from Shahraki et al. [2015] but was added to drive the curve close to {0,0}.) Figure 14 shows only the effect of adding slow chargers; the effect of adding only fast chargers has a similar shape but enables nearly 20 percent more miles to be electrified. Given that taxis typically travel many more miles per year than household vehicles do, the ability of the logarithmic function to also describe the taxi simulation results is encouraging.

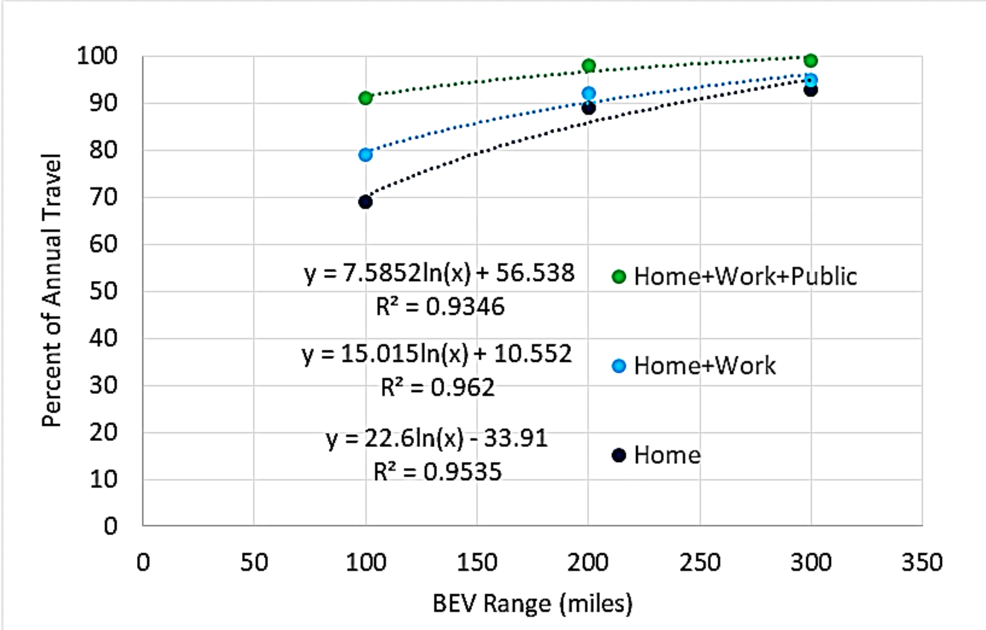
Figure 14: Effect of Slow Charging EVSE on Electrification of Taxi Miles in Beijing



Source: NREL (data from Shahraki et al. 2015)

The value of home, work, and public charging for BEVs with ranges of 100, 200, and 300 miles was estimated by Wood et al. (2017b) for 20,177 vehicles in the 2011 Massachusetts Travel Survey. The effect of range on the fraction of conventional vehicle travel that could be accomplished by the BEV is shown in Figure 15, with different curves for home charging only, home plus workplace charging, and home, workplace, and public charging. The change in the fraction of annual VMT as a function of range is described by logarithmic equations that can be used to project the effect of a one-mile increase in range at a given range.

Figure 15: Effect of Range on Percentage of Conventional Vehicle Annual Miles Achievable With a BEV



Source: NREL

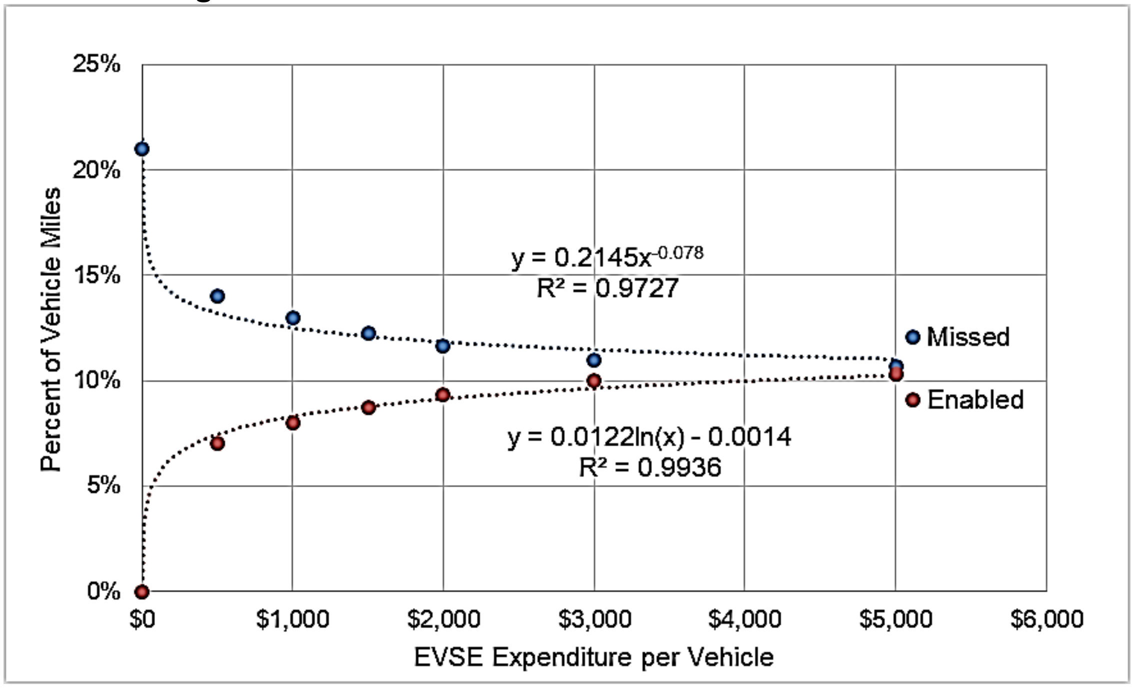
EVSE Availability, Power Levels, and Vehicle Utility

Also analyzing the Seattle data, Neubauer and Wood (2014) simulated the effects of various combinations of home, workplace, and public infrastructure on BEV utility, measured as the percentage of original trips taken that could be accomplished by a 75-mile-range BEV. Deployments of Level 1, Level 2, and DCFC plugs were analyzed. Like Dong et al. (2014), drivers were assumed to have perfect knowledge of future trip making as well as vehicle performance, including state of charge at the end of each trip. The study also assumed no change in trip-making behavior to accommodate the limited range of BEVs. The analysis was limited to vehicles whose annual mileage in the original data set exceeded 8,000 miles per year, and drivers were divided into three sets: (1) Set A with a BEV utility factor of 80 percent or more, (2) Set B, the remaining vehicles exceeding 8,000 miles/year, and (3) Set C consisting of drivers who made a work trip on at least 200 days per year. Assuming drivers would require 15 miles of range at the end of any trip as a safety margin, the analysis found that for Set A anytime home charging at Level 2 offered minimal benefits over Level 1: an increase in utility from 86 percent to 88 percent of trips in Year 1 and no increase by Year 10 of the vehicle life. For the commuter Set C, adding workplace charging to home Level 1 anytime charging increased utility by 3 percent to 7 percent, depending on the limitations on workplace charging and vehicle age. For a subset of drivers with longer commutes, workplace charging made a much greater difference, and most of the benefit of workplace charging was due to that subset of commuters. Comparing everywhere, anytime availability of public charging to Level 1 home-only charging, the study found that public Level 1 charging increased vehicle utility by 6 percent to 9 percent, while public Level 2 charging increased utility by 11 percent to 15 percent.

Neubauer and Wood (2014) note that their results are sensitive to individuals' degree of range anxiety (measured by reserve miles required at the end of a trip) and depend critically on two key assumptions: (1) no change in conventional vehicle trip-making behavior to accommodate BEV recharging, and (2) drivers having perfect knowledge of trip making and vehicle performance. Their results confirm that under optimal conditions (perfect foreknowledge and limited range anxiety), BEVs can satisfy most of the travel needs of most drivers. Two important inferences follow from their analysis: (1) the average benefits of workplace and public charging are much smaller than they are for a subset of individuals who take many long-distance trips, and (2) reduction of range anxiety and increased peace of mind may be important components of the value of public EVSE.

Using a GPS database of trips by 275 Seattle households operating 445 vehicles for as long as 18 months, Dong et al. (2014) calculated optimal locations for Level 1, Level 2, and DCFC chargers by minimizing the number of missed trips subject to a budget constraint on expenditures on EVSE. All vehicles were assumed to be converted to BEVs. Missed trips were defined as those that the BEV would be unable to take due to lack of remaining range. The data included dwell times when vehicles were parked and assumed that drivers knew all the trips they would be taking on any given day. Home chargers were assumed to be Level 1. The study produced two important results for valuing EVSE. First, the great majority of missed trips and vehicle miles can be accommodated with modest expenditures on EVSE if it is optimally located. While a power function fits the reduction in missed VMT well, a logarithmic function fits the increase in VMT enabled even better. Figure 16 shows the percentage of missed or enabled vehicle miles, which is much greater than the percentage of trips because the missed trips are the longer ones. At a $500 expenditure per vehicle fewer than 5 percent of trips are missed. Second, the benefit in terms of reduced missed trips and miles decreases rapidly with increasing investments and then levels off (Figure 16). About 70 percent of the vehicle miles enabled by a $5,000 per vehicle investment in EVSE were enabled by the first $500 invested.

Figure 16: Effect of EVSE Investment on Missed VMT



Source: NREL (data from Dong et al. 2014)

In addition, the optimization results implied that at $500 per vehicle, more than 95 percent of the budget for public charging would be spent on Level 1 charging stations, and at $1,000 per vehicle more than 70 percent would be spent on Level 1 chargers with the rest going to Level 2 chargers. At $1,500 per vehicle, most expenditures would be on Level 2 chargers, but nothing would be spent on DCFCs until expenditures exceeded $2,500 per vehicle. Because there is little benefit to be gained beyond an expenditure of $1,500 per vehicle, it may be reasonable for modeling vehicle choice to assume fixed shares of Level 2 and Level 1 charging to support intra-regional travel. Based on Dong et al. (2014), a Level 2 share of 10 percent to 20 percent would be appropriate. Dong et al.'s (2014) EVSE cost estimates are somewhat dated. (They were based on studies published in 2013 and 2005.) Recent data on the charging behavior of California BEV owners show that use of Level 1 charging decreases sharply with increasing vehicle range (Tal 2019). Owners of Nissan Leaf vehicles rated at 73 miles of range obtained 30 percent of their energy from Level 1 charging. When the range increased to 107 miles, Leaf owners used Level 1 charging for only 13 percent of their energy requirement. Use of Level 1 charging by Tesla Model S owners was 2 percent or less (Tal 2019).

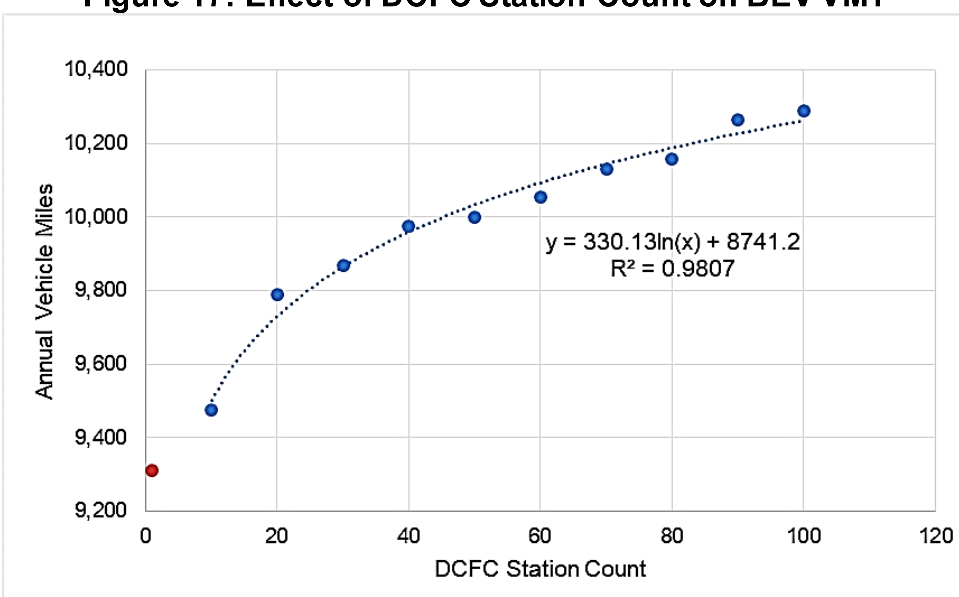
A possible explanation for the failure to select DCFCs in Dong et al.'s (2014) simulation is that the study relied on the dwell locations and times of conventional gasoline vehicles. BEV drivers might have stopped sooner on a long trip to take advantage of the opportunity to use a DCFC. Early experience with DCFCs indicated that the most heavily used DCFCs were those along major commuter routes in Seattle and San Francisco, suggesting that BEV drivers visited these locations specifically for extending the range of their vehicle (EV Project 2015). Recent evidence from California indicates a sharp uptick in DCFC use for EVs when they travel more than 100 miles from their home base, indicating that DCFCs are important facilitators of long-distance travel by BEVs (Tal 2019). Because the simulation method does not allow any changes in trip patterns, it probably does not accurately reflect the benefits of investments in

DCFC infrastructure. Nie and Ghamami (2013), for example, estimated the optimal location and power level for charging stations along a highway connecting Chicago, Illinois, and Madison, Wisconsin, and found that all optimal solutions consisted entirely of DCFCs.

The benefits for enabling additional vehicle travel by BEVs by installing only DCFCs were simulated by Wood et al. (2015) using location- and time-specific vehicle travel patterns for 317 vehicles in the Seattle metropolitan area. There are roughly 2.5 million vehicles in the Seattle metropolitan area, so each vehicle in the study represents 7,500 to 8,000 vehicles. All public charging was assumed to be DCFC in the analysis. Total VMT enabled as a function of the DCFC station count is shown in Figure 17. Base VMT with no DCFC stations (but universal Level 2 home recharging) is shown by the red dot (9,310 miles/year). The simulated effects (blue dots) are fitted reasonably well by a logarithmic function of the station counts, implying that the marginal value of a station decreases with the inverse of the number of stations. The intercept term of the equation in Figure 17, 8,741, is roughly comparable to but less than the estimated miles of driving achievable with only home recharging (9,310).

To maintain the same ratio of charging stations to vehicles, 10 DCFC stations per 317 vehicles linearly extrapolates to 75,000 to 80,000 DCFC plugs for the entire Seattle metropolitan area. If each station, for example, had five connectors, only 15,000 to 16,000 DCFC stations would be required. Wood et al. (2017a) estimated that only five or six connectors (i.e., one DCFC station in this example) would be required per thousand vehicles. Under these alternative assumptions, only about 2,500 stations would be required. Recent detailed simulation modeling for California has shown that the number and configuration of charging stations needed to enable full usage of electric vehicles depends on a variety of factors, including local parking, availability of home charging, charging technology, driver preferences and ability to share public fast-charging stations, pricing, and use of PEVs by transportation network companies (Bedir et al. 2018). Still, estimating the demand for charging infrastructure requires continued research and analysis.

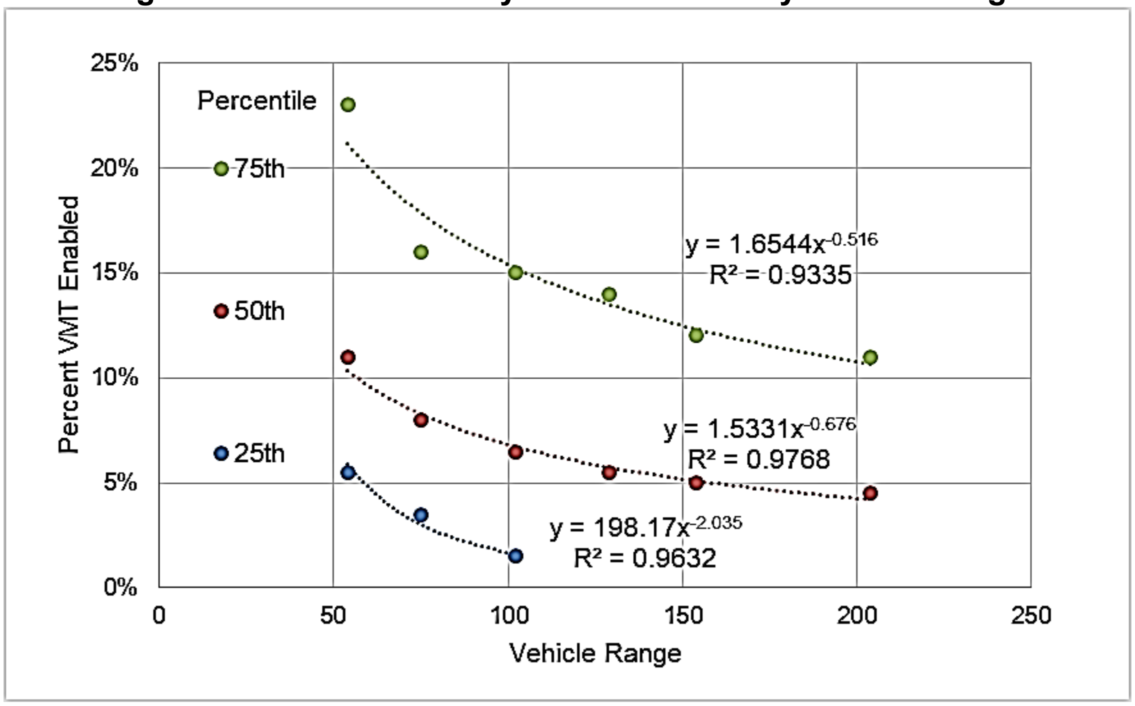
Figure 17: Effect of DCFC Station Count on BEV VMT



Source: NREL (data from Wood et al. 2015)

Wood et al. (2015) also analyzed the effect of vehicle range on the benefits of public charging infrastructure. Like the PHEV simulations of Wood et al. (2017b), VMT added decreased with roughly the inverse of the square root of vehicle range. Figure 18 shows the effect of range for three percentiles of drivers, with the twenty-fifth percentile having the lowest annual mileage and the seventy-fifth percentile having the highest mileage of the three groups. VMT added for the fiftieth percentile (median) driver is about half that of the seventy-fifth percentile and about twice that of the twenty-fifth percentile.

Figure 18: VMT Enabled by DCFC Stations by Vehicle Range



Source: NREL (data from Wood et al. 2015)

Summary of Insights From Simulation Studies

In addition to providing essential quantitative relationships between public EVSE installation and enabled eVMT, simulation studies suggest three insights that may be useful for incorporating charging infrastructure into vehicle choice models.

1. Consumers' willingness to pay for public EVSE infrastructure is likely to be heterogeneous depending on consumers' daily trip length distributions. Because the probability of intensive daily use is strongly correlated with annual VMT, annual VMT may serve as a reasonable proxy for more complex trip distributions.
2. A reasonable simplification for purposes of vehicle choice modeling may be to assume that (1) DCFCs are used primarily for interregional recharging, and (2) a mix of Level 1 and Level 2 chargers in fixed proportions satisfies most of the requirements for intraregional recharging.
3. The willingness to pay for EVSE infrastructure that enables intraregional BEV travel can be assumed to increase with the logarithm of investment in public recharging infrastructure or the logarithm of an appropriate measure of the number of EVSE units

installed (e.g., EVSE per area, EVSE per miles of roadway, or EVSE per existing gasoline stations).

Estimating the cost of trips that cannot be satisfied by the AFV depends on the options available to the consumer. If the household owns other vehicles, the least costly solution might be to substitute a non-AFV for the AFV for the longer trips. If the household does not own other vehicles or if substitution is not a good solution on the day in question, renting a non-AFV is an option (Dong and Lin 2014). If other vehicles are available on other days, rescheduling could be an attractive solution. Otherwise, an alternative destination might be chosen, or the trip might be foregone. A more promising approach seems to be to estimate the value of BEV miles *enabled* by EVSE. The value of enabled miles offsets a portion of the cost of the limited range and longer recharging time of a BEV. The available simulation analyses provide an empirical basis for quantifying the number of enabled miles (eVMT). Given the analogous effects of range and EVSE on extending the scope of a BEV, econometric estimates of the value of extended range might then be used to value the additional EV miles.

Substituting a logarithmic function of installed EVSE based on the simulation analyses into Equation 16 produces a functional form for the value of trips enabled by EVSE for BEVs that can be calibrated. In both the Dong et al. (2014) and Shahraki et al. (2015) studies, the number of vehicles and the area are fixed. Thus, in both cases enabled miles increase with the logarithm of the number of stations per area (X), since ln(I/X) = ln(I)-ln(X) and ln(X) is a constant. Equation 16 provides the form to be calibrated, in which a_0 and a_1 are constants to be estimated from the simulation analyses. The w, M, and X variables may be specific to a geographical area, and R and t_r terms are intended to be based on the vehicle and EVSE.

Equation 16

L. $$WTP = \left(a_0 + a_1 ln\left(\frac{I_j}{X_j}\right)\right)\left(\frac{b_0}{R_i^{b_1}}\right) M_j \left(v_j + w_j(K(f_0^a - f^{a_2}) + t_r)\frac{1}{R_i}\right) D_j$$

Chapter 5 explores what the econometrics literature can state about the value of an enabled mile of travel (as a function of range).

CHAPTER 5: Insights From Econometric Analyses

The theory and simulation studies discussed above provide useful functional forms for calculating willingness to pay for public charging stations. However, they do not include all infrastructure-related factors that may influence car buyers' choices. Simulation studies can estimate the miles of travel enabled by increased vehicle range or by additional recharging infrastructure, but they cannot estimate consumers' willingness to pay for those additional miles. Econometric studies can estimate willingness to pay but often with substantial uncertainty due to the limitations of available data and the difficulty of controlling for all relevant factors. Studies that attempted to directly measure the value of public EVSE are reviewed first, followed by studies that estimated the value of increased range.

Econometric studies of the value of EVSE infrastructure in vehicle choice models were briefly reviewed by Liao et al. (2017). They note that researchers have represented infrastructure availability in different ways: density of charging stations per area, distance from home to the closest station, and presence at home, work, or public places. They report that most studies show a significantly positive effect of EVSE infrastructure on the probability of choosing a PEV, with one study finding a diminishing marginal utility of EVSE availability, as predicted by theory (Achtnicht et al. 2012). None of the studies reviewed distinguished between DCFC and slower-charging EVSE. All the studies reviewed, however, were based on stated preference surveys rather than actual purchase decisions.

Li et al. (2017) estimated a model in which EV sales and the number of charging stations were simultaneously determined, using quarterly data for the period 2011 to 2013 from 353 United States Metropolitan Statistical Areas. A log-log form was used in which charging station availability was measured as the number of public stations in the metropolitan area. The number of public charging stations was consistently a statistically significant predictor of EV sales under a variety of model formulations and estimation methods. The authors' preferred instrumental variables estimation results indicated that a 10 percent increase in the number of charging stations would result in an 8.4 percent increase in EV sales, on average. However, the value, or willingness to pay, for charging stations decreased with the number of stations in operation. At the Metropolitan Statistical Area average of 22.6 stations for the 2011–2013 period, the price-equivalent value of one additional station was $961. The value decreased to $795 at 27.3 stations (the 2013 average) and would be only $68 if a Metropolitan Statistical Area contained 320 stations. Although the study made appropriate efforts to control for omitted variable effects, the possibility remains that the number of public stations is affected by unobserved factors such as differences in local public sentiment toward and knowledge of EVs.

Most empirical estimates of willingness to pay for recharging infrastructure, reduced recharging time, and increased vehicle range come from random utility models of vehicle choice (Greene et al. 2017). In these models, the desirability, or utility, of a vehicle is a function of the associated attributes (**x**), as well as those of the decision maker (**y**), and the context of the decision (**z**), plus unobserved utility represented by a random variable (**ε**). Let each category of variables be represented by vectors, **x**, **y**, and **z**, respectively, and utility be a function all three types, U(**x**,**y**,**z**)+**ε**, as in Equation 1. The willingness to pay (WTP) for a unit increase in public charging infrastructure, call it z_I, is the negative of the derivative of U with respect to that variable relative to the vehicle price, x_p.

Equation 17

M. $$WTP = -\frac{\partial U/_{\partial z_I}}{\partial U/_{\partial x_p}}$$

The numerator of Equation 17 has units of "utils" per unit of attribute i, and the denominator units are utils per present value dollar, which makes the units of willingness to pay dollars per unit of attribute i. The coefficient of price is negative, and the negative sign ensures that WTP >0 if i is a desirable attribute.

Economic theory strongly suggests that the willingness to pay for increased range, and therefore the value of additional infrastructure, should increase with increasing income.[21] Fundamentally, this is a consequence of the relaxing of an individual's budget constraint causing an outward shift in the demand curve of any good. In Equation 17 this would be reflected in a decrease in the absolute value of $\partial U/\partial x_p$.[22] As the denominator of Equation 17 decreases in absolute value, willingness to pay increases, all else equal. However, out of 23 recent econometric studies of the value of range, only four allowed willingness to pay for range to vary with income. The implications of the four studies for modeling willingness to pay for charging infrastructure are discussed in the "Vehicle Range" section of this chapter.

Achtnicht et al. (2012) estimated the willingness of German consumers to pay for availability of electric vehicle recharging at existing refueling stations based on a stated preference survey. By construction, the willingness to pay for a 1 percentage point increase in recharging availability was represented as a linear function of stations offering EVSE as a percentage of existing conventional refueling stations. The high willingness to pay and low willingness to pay values shown in Figure 19 differentiate between individuals who stated upper bound prices for the vehicle they intended to buy either above (high) or below (low) the sample median price. Given the date of the stated preference survey (2007–2008) it is likely that many respondents were unfamiliar with EVs. More importantly, the survey did not mention the option of home recharging. Considering this, perhaps the most useful conclusions from the study are that recharging availability is important to car buyers but that the marginal willingness to pay decreases with increasing fuel availability, as theory predicts.

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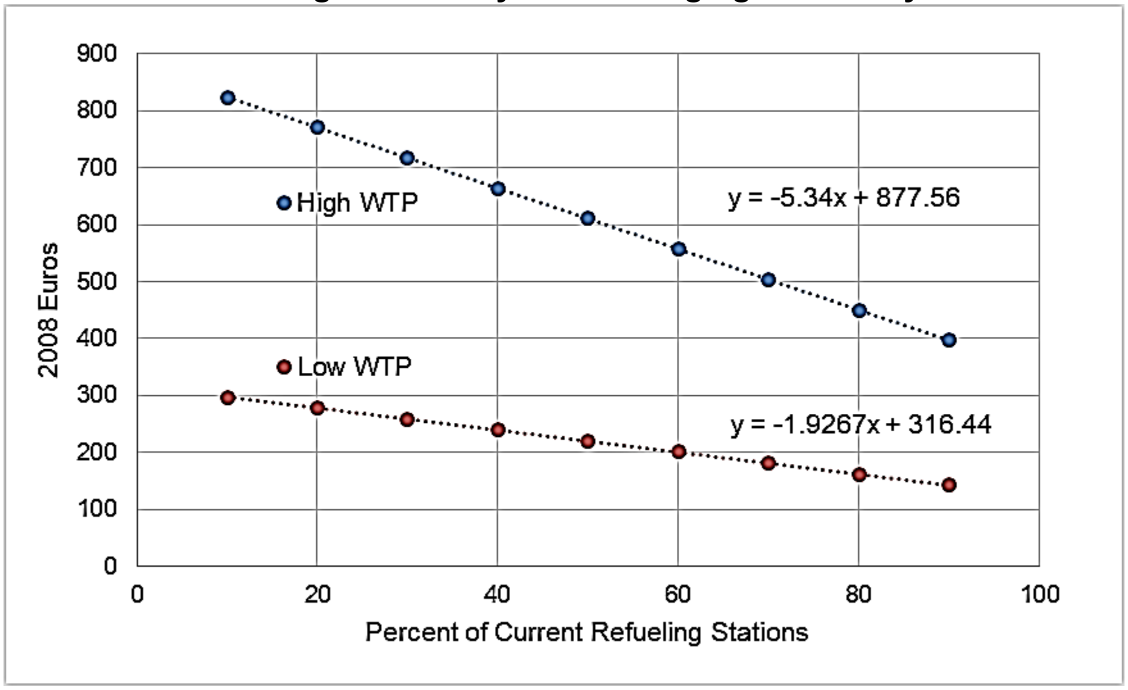
[21] This follows directly from the assumption that range is a normal good (consumers prefer more of it to less of it). Demand for a normal good increases with increasing income, and since a consumer's demand function describes quantity demanded as a function of price, it follows that an increase in income increases the price a consumer is willing to pay for any given quantity (Varian 2010, Ch. 6).

[22] Utility, defined as happiness, does not seem to increase over time with increasing income as it does across individuals and societies at a given point in time (Easterlin 2005). This may be because aspirations increase in step with income (Easterlin 2001). This does not imply that demand for goods will not increase over time with increasing income. However, the satisfaction derived from increased consumption may not increase.

Figure 19: Estimated Willingness to Pay for Recharging Availability at Service Stations



Source: NREL

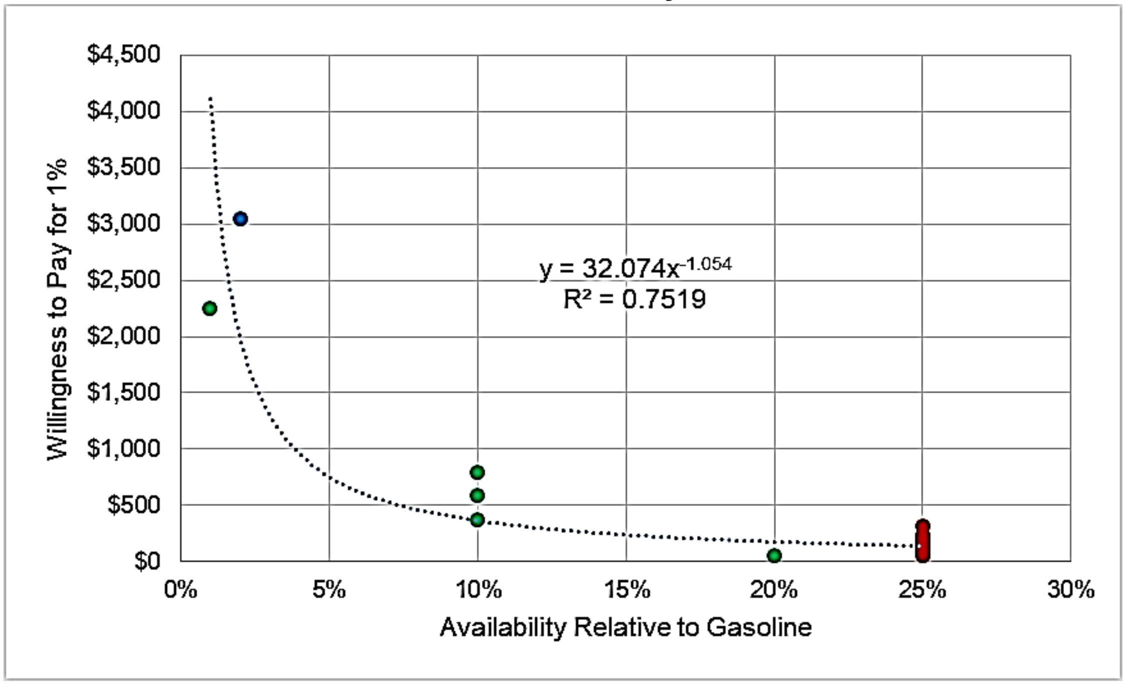
Melaina et al. (2013) appears to be the first and only study to distinguish among willingness to pay for intrametropolitan, medium-distance, and long-distance refueling availability. Based on results of a stated preference survey that included cartographic displays of station coverages, a purchase price penalty of about $3,000 to $4,500 was inferred for urban area availability equivalent to 1 percent of existing gasoline stations, decreasing to $750 to $1,000 for 10 percent coverage. Cost penalties for medium-distance coverage (within 150 miles of the urban center) showed a less consistent trend but ranged from about $1,500 to $2,500 for limited coverage. Intercity, long-distance coverage was highly valued: the cost penalties ranged from $7,000 to $9,000 for no intercity availability, from $4,250 to $6,250 if 70 percent of intercity trips could be accommodated, and from about $750 to $2,500 if 90 percent of trips normally taken could be accommodated.

Long-distance trips are relatively infrequent. Plötz et al. (2017) present data indicating that about 3 percent of trips in the Seattle area are longer than 150 km (93 miles). Tamor et al. (2013) present data from Minneapolis-St. Paul, Atlanta, and the United States National Household Travel Survey that indicate that on the order of 5 percent of trip chains are longer than 100 miles. Using a Web-based map survey tool, Tal and Nicholas (2016) found that the longest trip taken in the past year accounted for more than 5 percent of total annual miles for 20 percent of California households owning at least one PEV. Given the greater distance traveled on longer trips, roughly 20 percent of annual miles would be traveled on trips longer than 100 miles. Assuming total annual miles of 10,000 per year, 2,000 miles would be accounted for by trip chains greater than 100 miles. Assuming a vehicle life of 15 years and discounting at 10 percent per year, trip chains longer than 100 miles represent 15,400 discounted lifetime miles. Dividing the midpoint of Melaina et al.'s (2013) estimate of $8,000 by 15,400 produces a value of about $0.50 per foregone mile of long-distance travel. This number is approximate given the imprecision of the data and differences in definitions of travel. However, it turns out to be roughly consistent with estimates of the value per mile of travel enabled by increased BEV range, derived below.

In principle, the costs of lack of availability of refueling infrastructure for the three distances can be summed to estimate the full cost of limited refueling availability at all scales. The authors note that the willingness to pay estimates from the stated preference survey are much larger than estimates based on theoretical models that estimate only the additional access time costs of limited availability. This implies that lack of refueling or recharging infrastructure is a very large barrier to AFV adoption and indicates a high willingness to pay for refueling and recharging infrastructure.

Greene et al. (2017) estimated willingness to pay for station availability based on U.S. econometric studies published between 1995 and 2015. The estimates are illustrated in Figure 20 as a function of alternative fuel availability measured as a percent of existing gasoline stations. Estimates from a literature review by Greene (2001) and Greene et al. (2004) are shown as green dots. Other estimates are shown as blue and red dots. The red dots are from studies that estimated the value of a 1 percent increase in availability without specifying a reference level of availability. The location of the red dots was determined by maximizing the goodness of fit of the power function shown in Figure 20. The resulting estimated reference level, 25 percent, is like the availability of diesel fuel in the United States. The power function has an exponent very close to -1, suggesting that willingness to pay decreases with the inverse of the number of stations. The power function fit is like Melaina et al.’s (2013) intrametropolitan area values.

Figure 20: Estimates of Willingness to Pay for a Percentage Point Increase in Alternative Fuel Availability



Source: NREL

Using state-level data, Narassimhan and Johnson (2017) estimated equations predicting PEV, PHEV, and BEV sales as a function of recharging infrastructure, monetary incentives, and other factors. To the extent that the incentives represent present value dollars, in the same way vehicle price would, there is an equivalent amount of infrastructure that would have the same effect on PEV sales as a given monetary incentive (e.g., a $1,000 rebate). The study treats all EVSE infrastructure equivalently whether Level 2 or DCFC and regardless of location (e.g., workplace, public garage, curbside, interstate). EVSE availability is measured in units per 1,000 persons of driving age in a state. The analysis found strong and statistically significant relationships between recharging infrastructure and state PEV sales. This finding contradicts the results of Bailey et al.'s (2015) analysis of Canadian new vehicle buyers, which found a strong bivariate correlation that disappeared when other explanatory variables were included in a multivariate analysis.

Fixed effect models were estimated for all PEVs and then separately for PHEVs and BEVs. For PEVs and PHEVs, three alternative formulations are presented, and for BEVs, five are presented. All the models use the log-log functional form, that is, the dependent and independent variables are entered as logarithms. This makes the coefficient estimates elasticities. Models other than fixed effect models are estimated but the fixed effect models are preferred by the authors and the others are estimated primarily to test certain hypotheses.

A Cobb-Douglas functional form, including only EVSE infrastructure, x, and a monetary rebate, p, is shown in Equation 18. PEV sales are represented by Y.

Equation 18

N. $\ln(Y) = a + b\ln(x) + c\ln(p)$

Before taking logs, the function form is the following.

Equation 19

O. $Y = ax^b p^c$

Again, other variables and the fixed effects are omitted to simply the exposition. The effect of a one-unit change in EVSE infrastructure is given by the derivative of Y with respect to x.

Equation 20

P. $\frac{\partial Y}{\partial x} = a(bx^{b-1}p^c) = ax^b p^c \frac{b}{x} = b\frac{Y}{x}$

Similarly, the derivative of Y with respect to p is $c(Y/p)$. Incentives are measured in $1,000s and EVSE in units. The derivatives have units of sales per EVSE or sales per $1,000. Consequently, the ratio of derivatives gives the monetary equivalent of a one-unit change in EVSE, in thousands of dollars. In general, $b > 0$ and $c > 0$ is expected since a positive incentive reduces the price of a PEV.

Equation 21

Q. $\frac{\partial Y/\partial x}{\partial Y/\partial p} = \frac{b\frac{Y}{x}}{c\frac{Y}{p}} = \frac{bp}{cx}$

Equation 21 implies that the marginal value of an additional EVSE unit is inversely proportional to the number of EVSE units already installed, which will vary from state to state. Sales per capita cancel so that willingness to pay for infrastructure does not depend on each state's level of sales per capita. EVSE is measured in units, and population is in units of 1,000 persons. If a state has a population of 10,000,000 persons of driving age, x is units of EVSE/10,000 and a one-unit change in x represents 10,000 EVSE units.

The most appropriate models for calculating equivalent values of EVSE appear to be those that include rebates (measured in $1,000). These are PEV_2, PHEV_2, and BEV_2. Rebates are the closest incentive to purchase price in present value dollars because they are more immediately and dependably available to the customer than a tax credit. However, the coefficient estimates do not imply a large difference between the impacts of a tax credit and a rebate**.**

The equivalent values (willingness to pay) for one unit of EVSE per 1,000 persons of driving age are shown in Table 1 for each of the three models (PEV_2, PHEV_2, and BEV_2). Although there are differences in the estimated willingness to pay across equations the differences are not statistically significant. In general, adding one EVSE unit per 1,000 driving-age persons increases the value of a PEV to a typical car buyer by about $4,000. Because Narassimhan and Johnson (2017) counted all public chargers equally regardless of power level this estimate does not enable inferences about the value of different charging power levels. This may seem like a lot but for a state like Oregon with nearly 4 million residents, one EVSE per thousand residents is 4,000 EVSE units. A single EVSE unit in Oregon would therefore add about $1 to the value of a PEV to a prospective buyer. In California, one EVSE per 1,000 persons translates to 40,000 EVSE units. Since it takes 40,000 EVSE units in California to induce a value of $4,000 per PEV, a single EVSE unit is worth $0.10 to a prospective PEV buyer there. However, as long as the number of car buyers is proportional to the state population, the total induced value per EVSE unit remains the same across all states.

Table 1: Calculation of Equivalent Values of EVSE Infrastructure From Narassimhan and Johnson (2017)

		PEV_2		PHEV_2		BEV_2	
Variable	**Units**	**Value**	**std dev/err**	**Value**	**std dev/err**	**Value**	**std dev/err**
Sales (Y)	Vehicles /1,000 pop.	0.01	0.028	0.0006	0.01	0.006	0.018
EVSE (x)	Units /1,000 pop.	0.02	0.04	0.02	0.04	0.02	0.04
b (EVSE)		3.133	0.973	3.615	1.41	2.458	1.332
Rebate (p)	$1,000	2.476	921.5	2.12	1117	2.832	726
c (price)		0.097	0.022	0.089	0.032	0.096	0.028
dY/dx		1.5665		0.10845		0.7374	
dY/dp		0.000391761		2.5189E-05		0.00020339	
WILLINGNESS TO PAY	$	$3,999		$4,306		$3,626	

Source: NREL (data from Narassimhan and Johnson 2017)

Vehicle Range

By analogy, the willingness to pay for one additional mile of EV travel (eVMT) enabled by an increase in vehicle range should be roughly equal in value to an additional mile of eVMT enabled by recharging infrastructure.[23] In this section, the authors first review estimates of the average value of increased vehicle range and then the effect of income on willingness to pay for range.

A meta-analysis of estimates of consumers' willingness to pay for additional driving range based on 33 international studies was carried out by Dimitropoulos et al. (2013). The estimates were based on 21 stated preference surveys due to repeated use of the same survey data. The estimated mean willingness to pay for a 1-mile increase in driving range was $67 (2005 US dollars), with a median of $42. The range of estimates was large, however, with

[23] Because charging requires additional time, the time cost of charging should be subtracted from the value of e-miles enabled by charging infrastructure.

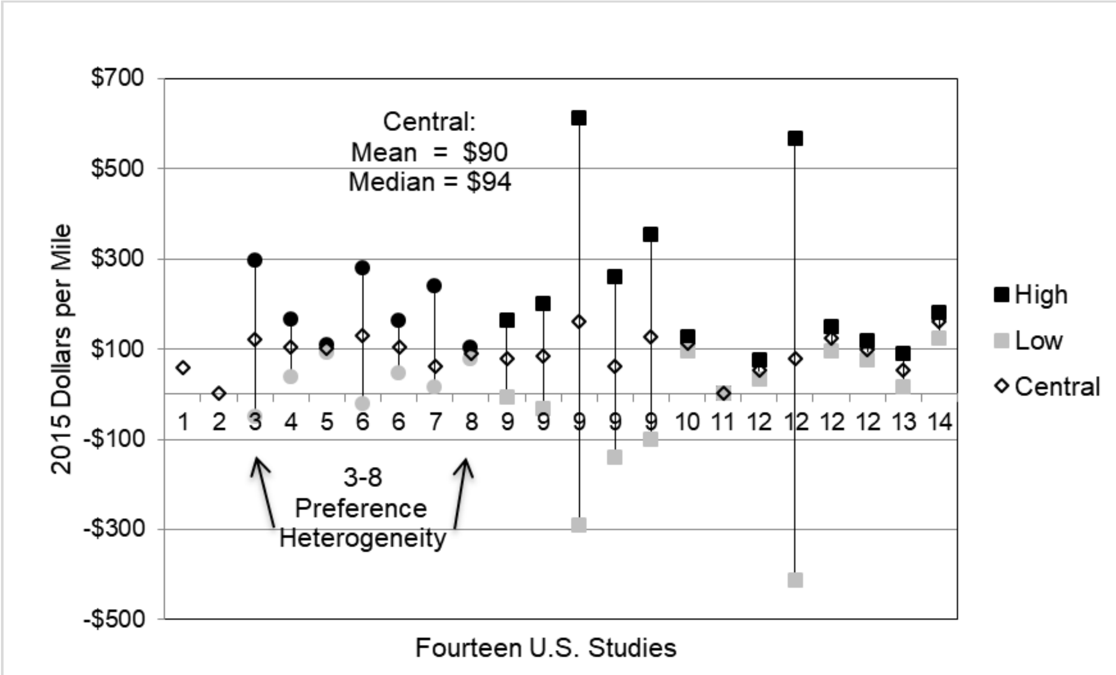
$8/mile being the lowest and $317/mile the highest, reflecting the skewness of the distribution of willingness to pay estimates. Considering only the six studies that focused exclusively on BEV range the mean willingness to pay per mile was $95 with a range of $21 to $195. A key finding of the analysis is that most studies assumed that driving range entered consumers' utility functions linearly, implying that a one-mile increase in range from 100 to 101 miles has the same value as an increase from 500 to 501 miles. The authors infer from a plot of willingness to pay estimates against the reference range used in the survey that willingness to pay for range appears to be linear in the inverse of range. This functional relationship agrees with Greene's (2001) theoretical derivation of the marginal value of range as derived from avoided refueling time. Consistent with this interpretation, Dimitropoulos et al. (2013) note the interrelationship of range, refueling time, and station availability.

"A usually ignored element of consumer valuation of range is that it may well be sensitive to changes in the levels of refuel time and availability of refueling infrastructure considered in the study."

"The practical consideration of the relationship between these three attributes in (sic) consumer's mind would imply a non-linear formulation of the utility function, including interaction terms between driving range, refueling duration and the coverage of refueling infrastructure." (Dimitropoulos et al. 2013, p. 34)

Greene et al. (2017) calculated 22 estimates from 14 U.S. studies that measured the value of range in dollars per mile. Most studies were based on stated preference surveys and addressed the demand for alternative fuel vehicles. The willingness to pay estimates ranged from $2 to $162 per mile, with a mean of $90, a median value of $94, and a standard deviation of $42, all in 2015 dollars (Figure 21). Six of the studies used random coefficients to represent heterogeneity of consumers' preferences. These are studies 3—8 in Figure 21, shown with circular rather than square low and high markers. Ranges for these studies are based on +/- 1 standard deviation while the high and low ranges for the other studies reflect +/- 1 standard error of estimate.

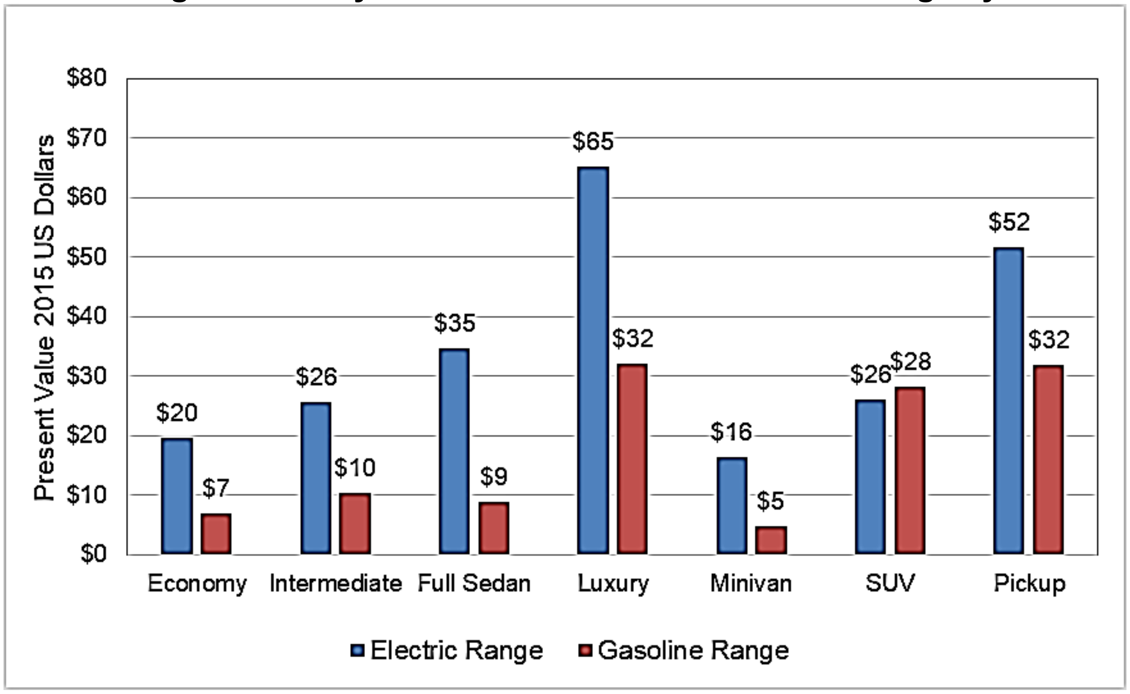
Figure 21: Estimates of Willingness to Pay for Increased Range (+/- 1 standard error or standard deviation)



Source: NREL (data from Greene et al. 2017)

Similar values for increased BEV range were obtained by Higgins et al. (2017) based on a stated preference survey of Canadian vehicle owners (Figure 22). Willingness to pay values were converted from 2015 Canadian to 2015 US dollars by dividing by 1.25. The reference range for a BEV used in the survey was 155 miles (250 km) with alternatives of 93 miles and 218 miles. The range of a gasoline vehicle was given as 435 miles with alternatives of +/- 25 percent. Except for sport utility vehicle buyers (who, along with pickup buyers, were the most averse to purchasing BEVs), the willingness to pay for additional BEV range far exceeds that of gasoline vehicles, reflecting the shorter reference range and longer recharging time of BEVs.

Figure 22: Willingness to Pay for a 1-Mile Increase in Vehicle Range by Vehicle Type



Source: NREL (data from Higgins et al. 2017)

Willingness to pay for range can be used to derive an estimate of the value of additional miles of travel enabled by EVSE. Dimitropoulos et al.'s (2013) meta-analysis concluded that, on average, consumers were willing to pay between $80 and $91 (2015 US dollars).[24] Values such as these can be used to estimate the value per mile enabled by EVSE. Let v be the marginal value of a mile of EV travel, m^* be the additional annual miles enabled by a 1-mile increase in EV range, L be the expected life of an EV, and r be an annual discount rate. The willingness to pay numbers represent the discounted present value of future enabled travel.

Equation 22

R. $$WTP = \sum_{t=1}^{L} \frac{v m_t^*}{(1+r)^t} \rightarrow v = \frac{WTP}{\sum_{t=1}^{L} \frac{m_t^*}{(1+r)^t}}$$

Thus, the value of enabling one additional mile of travel annually is the willingness to pay for a 1-mile increase in EV range divided by the discounted future miles of travel enabled by the increased range.

The willingness to pay for increased vehicle range can be used together with the relationship between range and enabled travel from Wood et al. (2017b, shown in Figure 15) to estimate both the value of any increase in range in terms of value per enabled mile of travel. The annual travel enabled by a 1-mile increase in range for a BEV with a 100-mile range and home recharging only depends on the derivative of the "Home" equation shown in Figure 15.

Equation 23

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[24] Converted from 2005 dollars to 2015 dollars using the Consumer Price Index for all urban consumers: 236.998/195.267 = 1.214.

S. $\frac{d}{dR}22.6ln(100) - 39.91 = \frac{22.6}{100} = 0.226\% = 0.00226$

Assuming the annual miles of the vehicle without range limitation would be 10,300 miles (see Figure 17), the increase in annual miles enabled by a 1-mile increase in range (from 100 to 101) is 10,300 * 0.00226 = 23.3 miles. Using Dimitropoulos et al.'s (2013) mean value of $80 per mile, the value per annual mile of enabled travel is $3.43 (2015 dollars); using the value of $90 from Greene et al. (2017), the willingness to pay per annual mile is $3.86. However, as shown in Equation 22, all miles enabled over the life of the vehicle should be counted, discounted to present value. Discounting future miles at 10 percent per year over a 15-year life results in a multiplier for annual miles of approximately 7.77, making the per-mile willingness to pay based on Dimitropoulos et al. (2013) $0.45 and based on Greene et al. (2017) $0.50 for the mean.

There is no reason to assume that the value of enabled eVMT will decrease with increasing eVMT. The order in which eVMT are enabled depends on the daily travel distance distribution. There is no reason to assume that the per-mile value of travel decreases with increasing trip length. If it is assumed that the willingness to pay per mile of travel is roughly constant over the range 9,310 miles to 10,300 miles, the willingness to pay for range will decrease with increasing range because the miles enabled per unit increase in range decrease as range increases. According to the equations fitted to Wood et al.'s (2015 and 2017b) simulation results (Figure 12 and Figure 18), the marginal willingness to pay decreases with the inverse of range, as predicted by theory.

In a similar way, the value of increased EVSE infrastructure can be estimated based on miles enabled using the relationships from Dong et al. (2014) in Figure 16 (percentage of annual miles enabled as a function of dollar expenditures) or Wood et al. (2015) in Figure 17 (annual miles as a function of DCFC station count). The miles enabled by adding 1 DCFC station when there are 50 stations in place is shown in Equation 24.

Equation 24

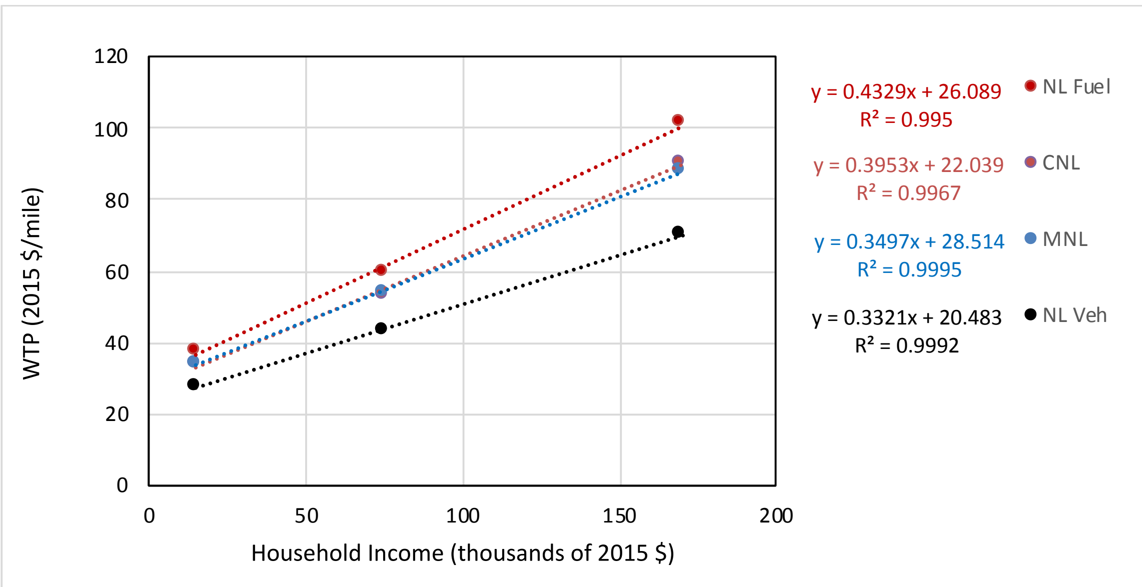
T. $\frac{d}{dR}(330ln(50) + 8741) = \frac{330}{50} = 6.6$

Lifetime discounted miles enabled would be about 7.77 * 6.6 = 51, which, valued at $0.50/mile, would be about $25. The implication is that adding one more DCFC station would be worth $25 present value (on average) per BEV.

As noted above, economic theory implies that the willingness to pay for range should be an increasing function of income. Of the 23 studies that the authors reviewed estimating the value of range, only 4 allowed willingness to pay for increased BEV range to vary with income (Brownstone and Train 1999; Brownstone, Bunch, and Train 2000; McFadden and Train 2000; Hess et al. 2012). Three studies used the same data set, a 1993 California stated preference survey, and were similar in model formulation, constraining willingness to pay to increase with the logarithm of income (Brownstone and Train 1999; Brownstone, Bunch, and Train 2000; McFadden and Train 2000). The fourth interacted categorical income variables with income, thereby allowing for a flexible functional relationship (Hess et al. 2012). Based on a 2008–2009 California Vehicle Survey, Hess et al. (2012) report willingness to pay for range for households with annual incomes of less than $20,000, $60,000 to $80,000, and greater than

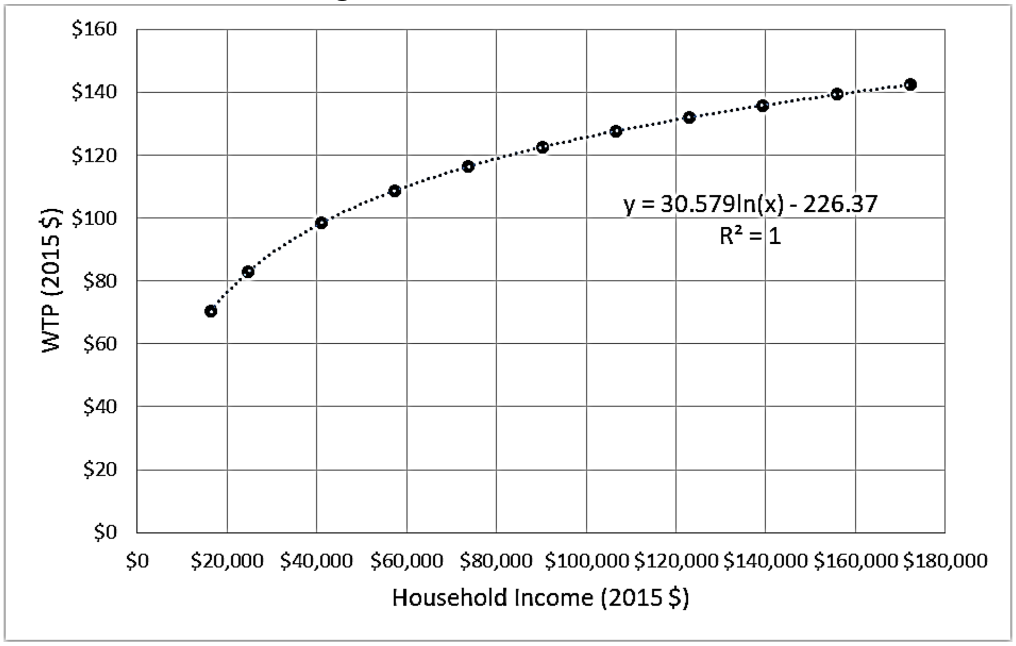
$120,000. In 2008, 80 percent of U.S. households earned less than $123,000 (2015 U.S. dollars) (U.S. Census Bureau 2017). In 2015 U.S. dollars, income at the midpoint of the highest income quintile in 2008 was $170,000. The lowest quintile households' incomes were less than $26,000 with a midpoint of $15,000. For the purpose of approximately graphing Hess et al.'s willingness to pay estimates, the authors locate the 2008–2009 >$120,000 value at $170,000, the <$20,000 value at $15,000, and the $60,000 to $80,000 value at $75,000. The four models estimated by Hess et al. imply a linear relationship between willingness to pay and income, with willingness to pay increasing by $0.33 to $0.43 per $1,000 of income (Figure 23). McFadden and Train's (2000) mixed logit model estimates increase with the log of income because vehicle price enters as price divided by the natural log of income (Figure 24). The average rate of increase per $1,000 from about $15,000 to $17,000 is $0.42. Very approximately, the two studies indicate that willingness to pay for a 1-mile increase in range increases about $0.40 (2015 U.S. dollars) for each $1,000 increase in household income.

Figure 23: Willingness to Pay for a 1-Mile Increase in BEV Range Over a 134-Mile Base as a Function of Income



Source: NREL (data from Hess et al. 2012). Note: The legend acronyms refer to different types of discrete choice models. NL = Nested Logit, CNL = Cross Nested Logit, MNL = Mixed Nested Logit. Nesting is by fuel type except the model labeled NL Veh, in w hich the nesting is by vehicle type.

Figure 24: Willingness to Pay for a 1-Mile Increase in Compressed Natural Gas or BEV Range as a Function of Income



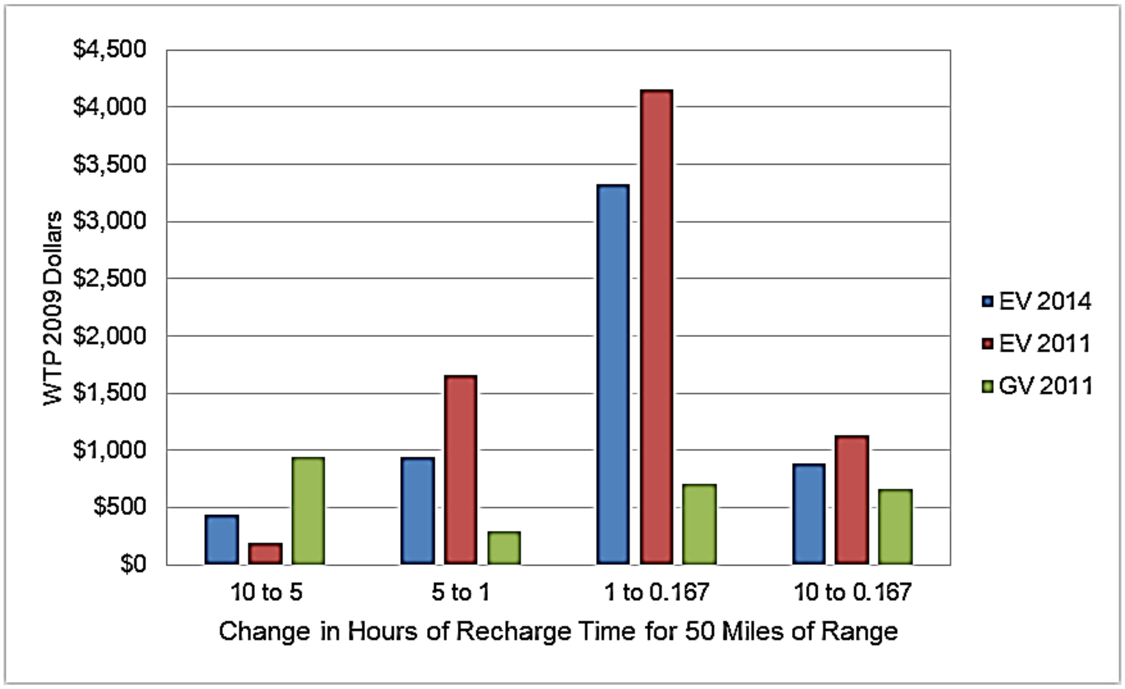
Source: NREL (data from McFadden and Train 2000)

Using the same relationship as above between willingness to pay per 1 mile of range for a new vehicle and willingness to pay per mile of enabled eVMT per year, a $0.40 increase in willingness to pay translates into about $0.002 per mile per thousand dollars of income. Assuming a median willingness-to-pay value of $0.25 per mile corresponds to the median U.S. household income in 2015 of $57,000, a household with an income of $100,000 would be willing to pay about $0.34 per enabled eVMT per year, while a household with an income of $160,000 would be willing to pay about $0.46 per mile (0.25 + (160-57)*0.002).

Recharging Time

Willingness To Pay for faster recharging time was estimated by Hidrue et al. (2011) based on a 2009 U.S. national stated preference survey and re-estimated by Parsons et al. (2014) using the same data. Relative to a reference point of a 10-hour charge for a BEV with a 75-mile range, willingness-to-pay values were inferred for 5 h, 1 h, and 10-minute (0.167 h) charge times for 50 miles of driving range. A latent class model was used to identify "EV-oriented" and "GV-oriented" (gasoline vehicle) respondents. In contrast to GV-oriented respondents, EV-oriented respondents possessed attributes and attitudes that increased their likelihood of selecting an EV. For EV-oriented respondents, the inferred willingness to pay per hour of charging time increased strongly and consistently as charging time decreased (Figure 25). The pattern and levels are similar for EV-oriented respondents in both studies. The pattern for GV-oriented respondents is inconsistent due to statistically insignificant parameter estimates for the GV-oriented group. It seems reasonable to infer that the GV-oriented group lacked enough knowledge of EVs and EV charging to make informed judgments about recharging time (Bailey et al. 2015; Krause et al. 2013; Axsen et al. 2015).

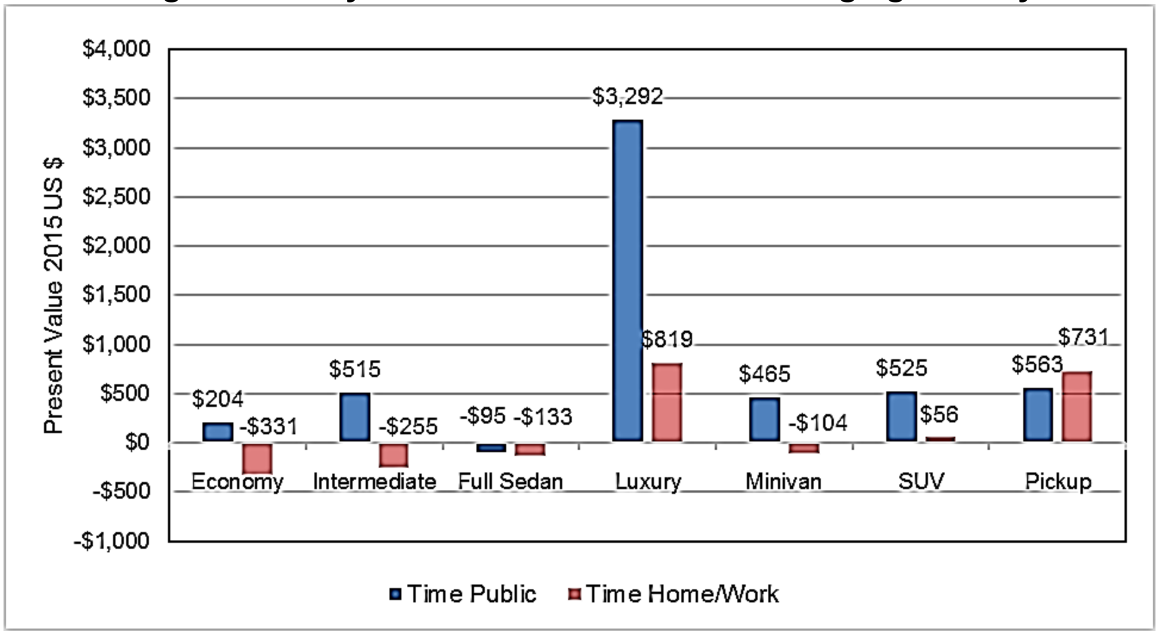
Figure 25: Average Willingness to Pay for a 1-Hour Reduction in EV Recharging Time Over the Indicated Interval



Source: NREL (data from Hidrue et al. 2001; Parsons et al. 2014)

Higgins et al. (2017) provide additional evidence of the context-dependence of the value of reducing charging time. Their analysis of a Canadian stated preference survey showed that willingness to pay for reduced charging time was greater for public charging than for home or workplace charging (Figure 26). The reference time for public charging of a BEV was 2 hours and 56 minutes, while that of home charging was specified as 5.25 hours. For a PHEV, the reference public charging time was 2 hours and 45 minutes, and the reference time for home or work charging was 2 hours. Alternative charging times used to infer consumers' willingness to pay were +/-80 percent of the base value for public charging and +50 and +100 percent of the base value for home charging. Willingness to pay varied across vehicle types, with luxury vehicle owners valuing public charging time almost an order of magnitude more than owners of nonluxury vehicles. None of the negative values shown in Figure 26 are statistically significant.

Figure 26: Willingness to Pay for a 1-Hour Reduction in Charging Time by Vehicle Type



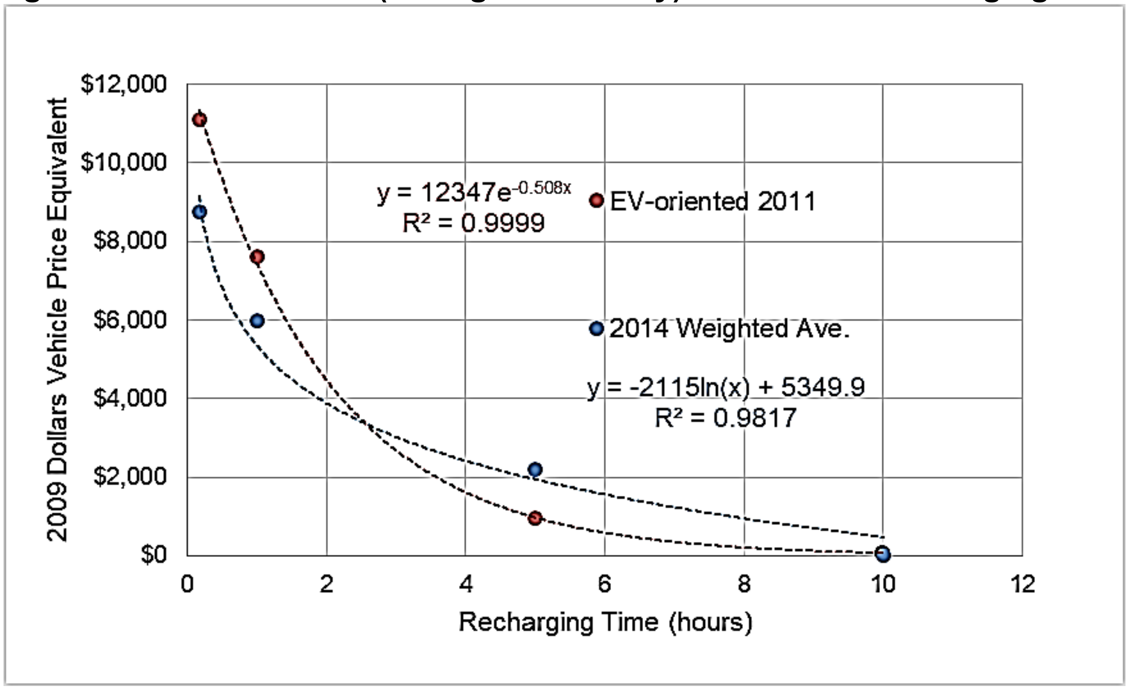
Source: NREL (data from Higgins et al. 2017, converted from kilometers to miles and Canadian to US dollars)

These results suggest that DCFCs provide additional value versus Level 2 or Level 1 EVSE. A reasonable interpretation is that respondents assumed that long charging times of 5 to 10 hours would be accomplished when it was convenient, either overnight or while the vehicle would normally be parked for a long period. In such circumstances, reduced recharging time is of little value because there is little likelihood that the vehicle would be needed during those times. As recharging times approach one hour or less, reduction of recharging time begins to enable additional vehicle use and thereby acquires substantial value. Under this interpretation, the value of reduced charging time in the vicinity of one hour is derived from the value of enabled longer trips. This result supports the finding of Melaina et al. (2013) that long-distance (interregional) travel is highly valued by consumers despite the infrequent occurrence.

Based on a stated preference survey in Japan, Ito et al. (2013) estimated that the average Japanese motorist would be willing to pay about $670 present value 2010 U.S. dollars additional for a BEV if the battery could always be fully replenished in 5 minutes via battery exchange versus a reference 8-hour recharge time. Different EVs were presented to survey respondents with ranges between 50 km and 200 km, but the willingness to pay for quick recharge was assumed to be independent of the vehicle range. A confidence interval for willingness to pay is shown graphically in the paper and appears to be roughly +/- $500. While this amount is lower than the estimates of Hidrue et al. (2011) and Parsons et al. (2014), it likely reflects differences in trip length distributions between Japan and the United States.

Exponential functions fitted to the Hidrue et al. (2011) and Parsons et al. (2014) estimates are shown in Figure 27. The exponential function from Hidrue et al. (2011) for the EV-oriented respondents seems most appropriate for representing the values of EV owners and buyers in the early market. It is less likely that the weighted average of EV-oriented and GV-oriented respondents adequately represents the EV market since the GV-oriented respondents do not appear to have had well-formed preferences in 2009. Given the time elapsed since 2009, it seems more appropriate to use the EV-oriented function for the full market, but the two functions produce similar results.

Figure 27: Present Value (Willingness to Pay) of Reduced Recharging Time



Source: NREL (data from Hidrue et al. 2011; Parsons et al. 2014)

Calculation of the value of reduced recharging time per charge is illustrated in Table 2. Vehicles are assumed to last for 15 years and travel 10,000 miles per year when new, decreasing at an average rate of 3 percent per year. The discount rate for money is assumed to be 7 percent per year. This produces a multiplier for annual costs or benefits of about 7.8. In both studies, consumers were told that a base EV had a range of 75 miles, but they were asked to compare the base EV to EVs with ranges of 150, 200, and 300 miles. The value of charging time was not related to vehicle range in the survey. The authors assume a range of 175 miles and that recharging is typically done when the remaining range is 50 miles. This assumption implies 80 recharges in the first year and 622 discounted lifetime recharges. Dividing the benefit of reducing recharge time from 5 hours (approximating level 2) to 0.5 hours (approximating DCFC) by the discounted lifetime recharges gives an average value of reduced time per charge of $7.84 for the weighted average parameters and $13.83 per charge for the EV-oriented group. The calculated value of Level 2 versus Level 1 is much smaller: $2.36 and $1.44. These estimates are assumed to be in 2009 dollars, the year of the survey. They can be converted to 2015 or 2017 dollars by multiplying by 1.105 or 1.142, respectively.

Table 2: Value of Reduced Recharging Time per Recharge

	Weighted Ave.	EV-Oriented
	Parsons et al. 2014	Hidrue et al. 2011
First year annual VMT (miles/year)	10,000	10,000
VMT decrease/year	3%	3%
Vehicle life (years)	15	15
Annual discount rate	7%	7%
D (conversion from annual to discounted lifetime $)	7.77	7.77
Range (miles)	175	175
Remaining range at recharge (miles)	50	50
Recharges per year	80	80
Discounted lifetime recharges	621.5	621.5
Value at 5 h	$1,946	$973
Value at 0.5 h	$6,816	$9,570
Value of reduced recharge time from 5 h to 0.5 h	$7.84	$13.83
Value at 10 h	$480	$77
Value of reduced recharge time from 10 h to 5 h	$2.36	$1.44

Source: NREL (data from Parsons et al. 2014 and Hidrue et al. 2011)

CHAPTER 6: Quantifying the Willingness to Pay for Public Charging

Willingness to pay for recharging infrastructure reflecting the interdependence of range, recharging time, and public EVSE availability can be used in benefit-cost analyses of public investment in charging infrastructure, as well as incorporated in random utility models of vehicle choice. As explained in Chapter 5, random utility models represent the utility of a vehicle as a function of the associated attributes (**x**), those of the decision maker (**y**), and the context of the decision (**z**). The willingness to pay for EVSE is a function of all three types of variables. The equations for willingness to pay for EVSE given below can be inserted into the utility function of a random utility vehicle choice model. Because the equations provide the value of EVSE to a vehicle purchaser in terms of the related present value in dollars, the coefficient of willingness to pay for EVSE should be the same as the coefficient of vehicle price, with the opposite (positive) sign because EVSE represents a benefit rather than a cost. However, adding new variables for EVSE will likely require recalibrating the vehicle choice model since other variables, especially any alternative specific constants, may have been affected by the omission of the value of EVSE.

The equations for calculating the present value of EVSE for PHEVs and for BEVs in intraregional and interregional travel are summarized below along with graphs illustrating willingness to pay as a function of vehicle range and EVSE deployment. The graphs are based on several important assumptions that mainly reflect the premises of the simulation models reviewed in Chapter 4.

- Level 1 or 2 charging is available at home for a PEV's and is used as needed to accomplish the maximum amount of daily travel.
- At the beginning of each day, drivers have foreknowledge of the trips they will take.
- Vehicles leave home each day either fully charged or with enough charge to accomplish the day's travel if that is less than the practical range of the vehicle.
- PEV range is a constant fraction (e.g., 80 percent) of the rated range of the vehicle that includes a minimum charge level but does not reflect the effects of temperature, traffic conditions, battery degradation, or other factors known to affect PEV range in actual use.
- BEV owners make optimal use of EVSE, subject to the assumption that they do not change their travel behavior. (In general, simulation models have not considered adding or changing stops to make most efficient use of charging infrastructure.)
- PHEV drivers' use of EVSE is limited to only convenience charging because the simulation analyses from which estimates of enabled eVMT have been derived typically assume no deviation from the travel and parking times and locations of the respective conventional vehicle.

- EVSE deployment is optimally located to be available when and where vehicles stop during travel, and usually no queuing is considered.
- The perceived value of BEV range derived from stated preference surveys provides reasonable estimates of consumers' actual willingness to pay.

Some of these assumptions. such as the availability and use of home-base charging, are well supported by data on *current* PEV owners but are less applicable to other potential adopters, for example, those living in multiunit dwellings or using street parking. Others will tend to understate the value of charging infrastructure to PEV owners, such as the assumption of optimal EVSE location or constant range. Others reflect the limitations of existing knowledge, such as the assumption that willingness to pay for enabled e-miles can be derived from willingness to pay for added vehicle range based on stated preference surveys.

PHEV Value of EVSE

The contribution of EVSE to the value (utility) of a PHEV is represented as the value of energy savings from additional miles operated in charge-depleting mode and is the product of the following:

1. Charge-depleting miles enabled as a fraction of total annual miles, $f(I,R)$, a function of installed infrastructure, I, and charge-depleting range, R, in the absence of public charging
2. Annual vehicle miles, M
3. Fuel savings per mile when operating in charge-depleting versus charge-sustaining mode: $p_G e_{Gs} - (p_G e_{Gd} + p_E e_{Ed})$ where p and e are energy prices and energy use per mile, G and E indicate gasoline and electricity, and s and d indicate charge-sustaining and charge-depleting modes of operation
4. A factor to expand annual value to discounted lifetime value, D.

Equation 25[25]

U. $$WTP_{ij} = [f(I_j R_i) - f(0,R_i)] M_{ij} \left(p_{jG} e_{iGs} - (p_{jG} e_{iGd} + p_{jE} e_{iEd})\right) D_{ij}$$

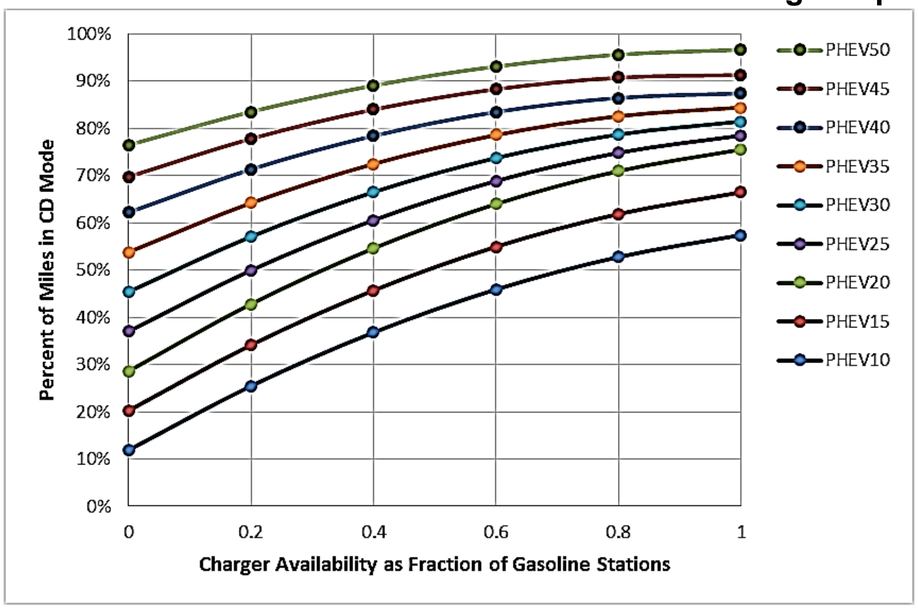
In Equation 25 i indexes vehicles and j indexes geographical locations.

The quadratic equations derived from Dong and Lin (2012) are used in equation 25 to estimate the effects of infrastructure on enabled e-miles. Because $f(0,R_i)$ is subtracted from $f(I_j,R_i)$, the constant terms of the quadratic equations cancel. The three levels of PHEV range provide by Dong and Lin (2012) – PHEV10, PHEV20, and PHEV40 – are used to calculate functions for intermediate ranges by linearly interpolating the coefficients of x and x^2 in Figure 11. The variable I is equivalent to x in Figure 11 and is the number of charging stations as a fraction of the number of gasoline stations. Ranges up to PHEV50 are extrapolated from the

[25] A complete list of variable definitions for Equations 25, 26 and 28 is provided as an appendix.

PHEV40 coefficients with the following adjustments to ensure that the fraction of charge-depleting miles never exceeds 1.0 and that the increase in e-miles increases at a decreasing rate with increasing range. The reduction in the coefficient of I^2 per mile of range from PHEV20 to PHEV40 is multiplied by 2 for the increase from PHEV40 to PHEV45 and by 4 from PHEV45 to PHEV50. The rate of change in the coefficient of I is multiplied by 0.9 for both. Finally, the increase in the intercept of the quadratic equation is reduced by multiplying by 0.9 from PHEV40 to PHEV45 and by 0.8 from PHEV45 to PHEV50. While these changes are strictly judgmental, they produce a pattern that satisfies the conditions stated above, as shown in Figure 28. Available battery capacity is implicitly accounted for in Equation 25 because the simulation models used to estimate enabled miles $[f(I, R)]$ account for the state of charge and battery capacity of PHEVs at each charging opportunity.

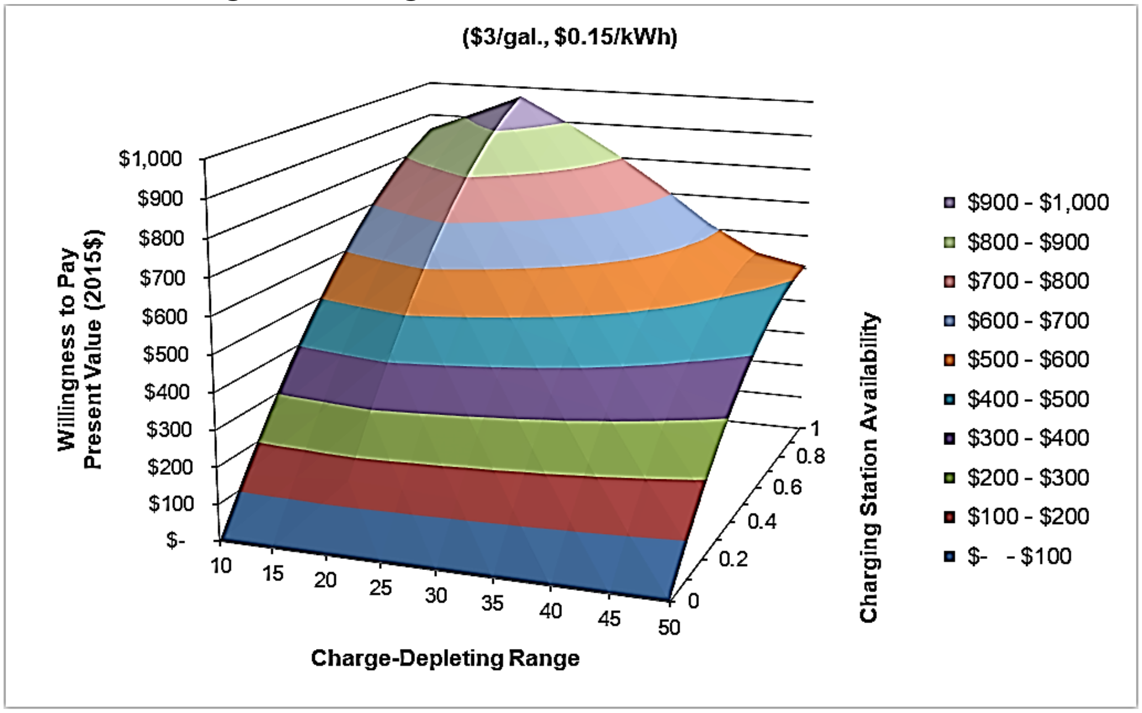
Figure 28: Interpolated and Extrapolated Functions to Predict the Effect of Charging Infrastructure on the Fraction of PHEV Miles Traveled in Charge-Depleting Mode



Source: NREL

PHEV willingness to pay for recharging infrastructure increases at a decreasing rate with increased charging infrastructure, exceeding $500 present value per PHEV20 vehicle when the number of charging stations approaches the number of gasoline stations. In general, PHEV willingness to pay for charging infrastructure decreases with increasing nominal charge-depleting range. The maximum at PHEV20 in Figure 29 is a consequence of the particular energy consumption rates taken from Dong and Lin (2012, table 2) and is likely an artifact of the specific makes and models of PHEV10s and PHEV20s available at the time the paper was written.

Figure 29: Illustration of PHEV Willingness to Pay for Public Charging Stations as a Function of Range Assuming $3/Gal for Gasoline and $0.15/kWh for Electricity



Source: NREL

BEV Intraregional Value of EVSE

The contribution of EVSE to the value (utility) of a BEV is represented as the value of added miles, as shown in Equation 13. The BEV willingness to pay for EVSE depends on the same factors as the PHEV willingness to pay for EVSE except for fuel costs,[26] and additionally it depends on the value of an enabled mile, v, and the value, w, of reduced time to access a charger, $K(\left(\frac{I_0}{X_0}\right)^{\alpha} - \left(\frac{I_j}{X_j}\right)^{\alpha})$, where I_0/X_0 is the initial relative availability of EVSE. K is the constant term of the Nicholas et al. (2004) station access time model (see Equation 11). I is the existing number of charging stations and X is the number required for full availability. In Equation 26 recharging time, t_r, is estimated by the effective range (ϕR_i) multiplied by the vehicle efficiency divided by the charging rate (e_i/d). The value of time spent in DCFC charging and how much is convenience charging is not well understood. The U.S. Department of Transportation recommends estimating the value of travel time by multiplying hourly earnings by 50 percent (Belenky 2011). We use the U.S. Department of Transportation method to estimate the value of time spent charging and convert income to an hourly earnings rate (w_j) by dividing by 2,080.[27]

[26] Because the value of eVMT enabled by public charging infrastructure is based on estimated willingness to pay for increased BEV range, fuel cost savings are assumed to be included in the willingness-to-pay estimate.

[27] Because the authors use household income and vehicle occupancy rates are low, they probably overestimate the value of time by this method.

Equation 26[28]

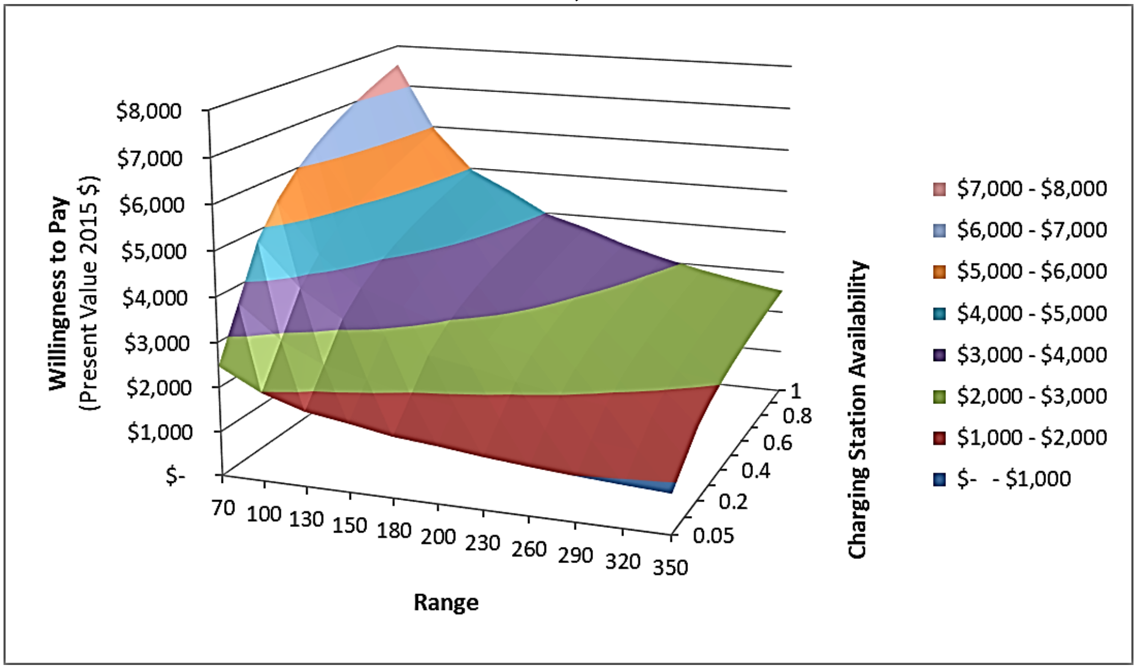
$$\text{V. } WTP_{ij} = \left[\left(a_0 + a_1 ln\left(\frac{I_j}{X_j}\right)\right)\left(\frac{b_0}{R_i^{b_1}}\right) M_j \left(v_j - \frac{w_j}{\phi R_i}\left(K\left(\left(\frac{I_j}{X_j}\right)^{\alpha} - \left(\frac{I_j}{X_j}\right)^{\alpha}\right) + \frac{\phi R_i e_i}{d}\right)\right)\right] D_j$$

The willingness-to-pay function is a surface in the space defined by willingness to pay, EVSE (I), and range (R). An illustration is shown in Figure 30 that assumes a value of $0.50 per enabled mile. That WILLINGNESS TO PAY is based on an annual household income of $115,000, roughly the median household income of BEV owners in the 2016 California Vehicle Survey. The number of chargers is based on Wood et al.'s (2015) simulation analysis, as illustrated in Figure 17. The DCFCs in that study were serving only the Seattle metropolitan area, and only 317 vehicles were included in the study. By almost any relevant measure, California is an order of magnitude larger than the Seattle metropolitan region and so the number of chargers has been scaled up by a factor of 10. There are approximately 500 public DCFCs in California today that are not restricted to Tesla owners. willingness to pay increases rapidly as the first hundred stations are added but then grows at a decreasing rate with further expansion of EVSE (Figure 30). The value of EVSE for intraregional BEV travel decreases by about half as vehicle range increases from 75 miles to 325 miles.

The average household income of U.S. new car buyers is about $80,000 (Wernle 2015). Applying the equations for willingness to pay for enabled e-VMT as a function of income (see the "Vehicle Range" section of Chapter 5) results in the function illustrated in Figure 3131. With half the annual income of California's BEV owners, the average United States new car buyer would pay only $0.43 per enabled e-VMT.

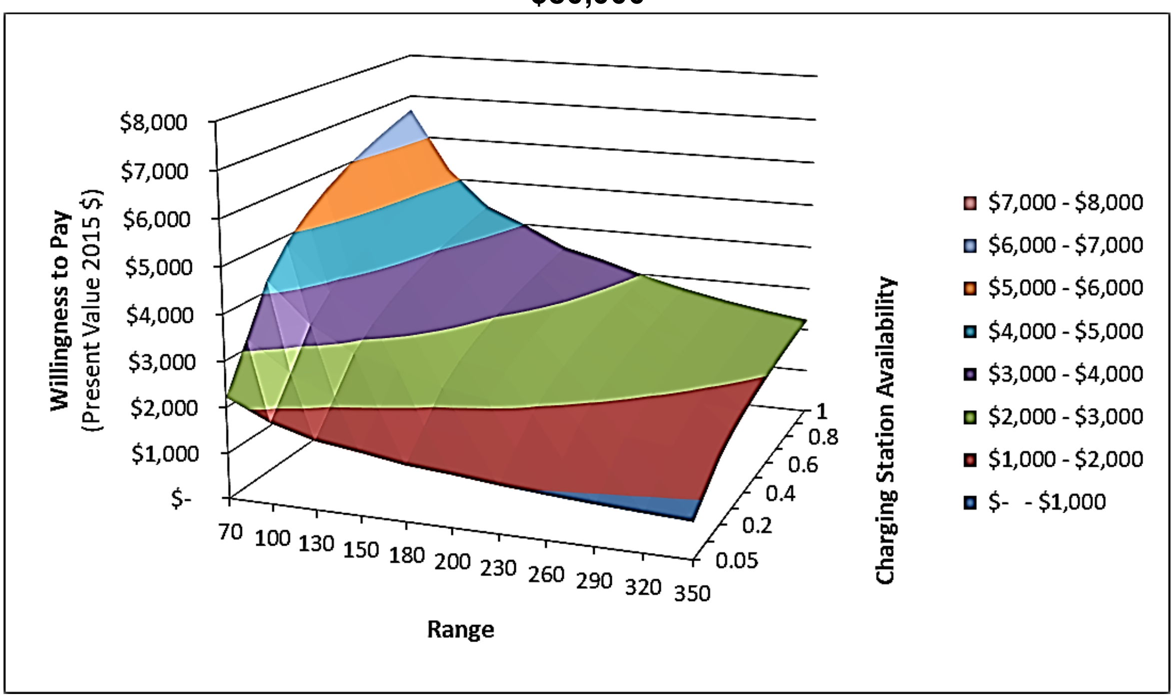
[28] A complete list of variable definitions for Equations 25, 26, and 28 is provided as an appendix.

Figure 30: Illustration of BEV Willingness to Pay for Public Charging Stations for Intraregional Travel as a Function of Range for a Household With an Annual Income of $115,000



Source: NREL

Figure 31: Illustration of BEV Willingness to Pay for Public Charging Stations for Intraregional Travel as a Function of Range for a Household With an Annual Income of $80,000



Source: NREL

BEV Interregional Value of EVSE (DCFC)

Interregional travel involves only long-distance trips that extend beyond the boundary of a metropolitan region. Long trips that make up the tail of the trip distribution function account for a surprisingly large fraction of annual VMT. Trips over 100 miles account for about 20 percent of annual VMT according to one estimate (Tal and Nicholas 2015). Based on a Web-based survey of 5,000 new PEV buyers in California in 2015, Tal and Nicholas (2015) found that for 20 percent of the households the longest trip of the year accounted for more than 5 percent of annual VMT.

To get a sense of the size of regions and the length of trips that would leave the region, a synthetic "radius" can be calculated for each United States metropolitan area by assuming that the area has the shape of a circle. By this measure, only two U.S. metropolitan areas have radii larger than 100 miles: Los Angeles-Anaheim-Riverside (167 miles) and Riverside-San Bernardino (150 miles), both in California. No other U.S. metropolitan area has a synthetic radius larger than 85 miles. The median synthetic radius is 51 miles. For illustrating willingness to pay for interregional travel, daily vehicle travel greater than 75 miles is assumed to be interregional.

All interregional charging infrastructure is assumed to be DCFC. The effect of DCFC infrastructure on enabled miles of interregional travel by BEVs is estimated in two steps. The first is to estimate the effect of DCFC on the daily trip distance the BEV can accomplish. The second step is to estimate how much additional travel is enabled by the increased radius using the daily trip distribution function illustrated in Figure 8. Because no simulation analysis has yet estimated the amount of interregional travel enabled by DCFC infrastructure, the authors rely on Wood et al.'s (2015) simulations of the effects of DCFC and BEV range on annual miles of travel to calibrate two functions:

1. Enabled e-miles as a function of the availability of DCFCs as a fraction of full availability, *M(I)*
2. Enabled e-miles as a function of vehicle range, *M(R)*.

By inverting *M(R)* we get $R(M) = M^{-1}(R)$, range as a function of enabled miles. Although this is not the same as daily trip distance as a function of enabled miles it is the best proxy available. Substituting *M(I)* for *M* gives *R(M(I))*, a plausible though not ideal relationship between infrastructure availability and enabled daily trip distance. Logarithmic approximations are used for the enabled miles functions instead of the somewhat better fitting cubic polynomials because the logarithmic functions produce a much simpler yet almost as closely fitted functional form for *R(M(I))*.

Equation 27

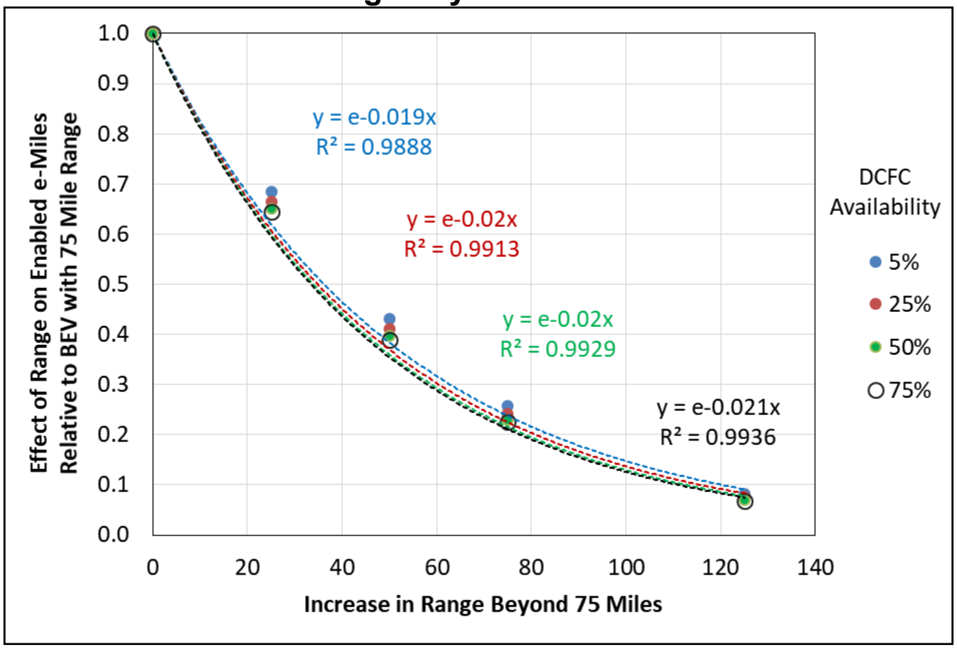
$$M(R) = 1498.5\ln(R) - 2589\ ; M(I) = 0.109\ln(I) + 0.3642$$

$$R\big(M(I)\big) = R(I) = e^{0.9653\ln(I)+4.953}\ ; R\left(\frac{I}{100}\right) = 1.42X^{0.97}$$

Equation 27 implies that trip distance increases almost linearly with DCFC availability, expressed as a fraction of full availability, at the rate of 1.42 miles per 0.01 increase in availability. This result is by no means definitive, however, since it is based on a rough analogy between vehicle range and enabled daily trip distances. Additional research is needed to establish the relationship between enabled inter-regional travel and charging infrastructure along intercity routes.

The effect of vehicle range on e-miles enabled by infrastructure was estimated by recalculating the function shown in Figure 9 for BEVs with ranges of 75, 100, 125, 150, and 200 miles for DCFC availability levels of 5, 25, 50, and 75 percent. The results are illustrated in Figure 32 relative to the enabled e-miles of a 75-mile-range BEV. At zero increase in range, the enabled e-miles are always those of a 75-mile-range BEV so that the relative value is 1.0. Enabled e-miles decrease exponentially with the increase in vehicle range beyond the base 75 miles. Exponential functions fitted assuming an intercept of 1.0 indicate a decrease in enabled e-miles of about 2 percent per mile of range almost regardless of the availability of DCFCs.

Figure 32: Effect on Annual Travel Enabled by Interregional DCFC by Increasing BEV Range Beyond 75 Miles



Source: NREL

In Figure 33, it is assumed that all EVSE will be DCFC. The first term in round brackets in Equation 28 gives enabled e-miles as a fraction of total annual miles, *M*. The second term in round brackets adjusts for the effect of range on enabled e-miles. The third term includes the value of an enabled mile, *v*, minus the cost of access time and charging time. Both time costs are included in Equation 28 and are converted to cost per mile by dividing by practical range, ϕR. The coefficients of the enabled eVMT equation and the effect of range will also differ, in general. As discussed above, the value of enabled eVMT may be greater for interregional travel. Some charging for inter-regional travel may be convenience charging (e.g., a rest stop) and so the value of time is also likely to differ from that used in the intra-regional equation.

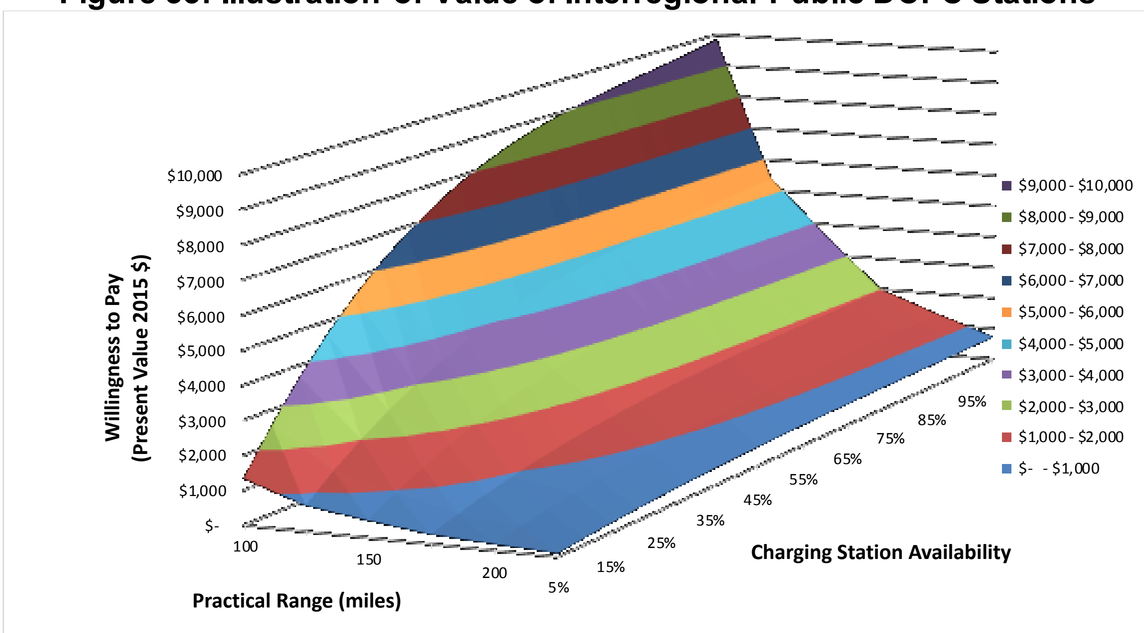
Equation 28[29]

$$\text{W. } WTP_{ij} = \left[\left(a_1\left(\frac{I_j}{X_j}\right) + a_2\left(\frac{I_j}{X_j}\right)^2 + a_3\left(\frac{I_j}{X_j}\right)^3\right)\left(e^{-b(R-R_0)}\right)M_j\left(v_j - \frac{w_j}{\phi R_i}\left(K\left(\left(\frac{I_j}{X_j}\right)^{\alpha} - \left(\frac{I_j}{X_j}\right)^{\alpha}\right) + \frac{\phi R_i e_i}{d}\right)\right)\right]D_j$$

The final term in the square brackets of Equation 28 is the time cost of recharging, including access, for a BEV with range of R_i miles, energy consumption of e_i kWh/mile, and chargers with an electricity delivery rate of d up to a maximum charge of (ϕ100)%.

The estimated value of interregional travel enabled by installing DCFC along interregional routes is illustrated in Figure 33. A value of $0.50 per enabled mile is used, corresponding to a household income of $115,000. Infrastructure is measured as availability relative to gasoline refueling stations. Despite the infrequent nature of interregional travel, willingness to pay amounts to thousands of dollars.

Figure 33: Illustration of Value of Interregional Public DCFC Stations



Source: NREL

Equations 25, 26, and 28 calculate the total willingness to pay for charging infrastructure for PHEVs and BEVs for intra- and interregional vehicle travel. They estimate the present value to current and potential PEV owners of additional recharging infrastructure over the life of a PEV. Suitably calibrated, they could be incorporated into the utility functions of discrete choice models of household vehicle or fleet vehicle choice and used to project the effects of public charging investments on the sales of PEVs. The change in consumers' surplus resulting from

[29] A complete list of variable definitions for Equations 25, 26, and 28 is provided as an appendix.

the provision of additional public charging could also be calculated, providing a critical measure for assessing the costs and benefits of public investments in EVSE.

Illustration of Willingness to Pay Methodology:

Public DCFC in the Sacramento Area

The methodology presented in this report for estimating the tangible value of public PEV charging infrastructure is illustrated below by example calculations for a BEV with a range of 100 miles located in the Sacramento Area Council of Governments (SACOG) region. Although the estimates are not definitive, they indicate that the value of the existing public DCFC infrastructure to the purchaser of a new BEV in California amounts to thousands of dollars and is similar in magnitude to the value of existing federal and state incentives for BEV purchasers. Public charging infrastructure not only provides substantial value to current BEV owners by extending the utility of their vehicles but also constitutes an important tangible incentive for increased BEV sales.

The estimates below are not definitive because both the methodology and critical metrics, especially the infrastructure availability metric, need further refinement. Nevertheless, they illustrate how the methodology can be applied and provide insights on the order of magnitude of the value of public charging. The availability metric used is intended to represent "A basic level of geographic coverage…to guarantee nationwide charging opportunities and enable long-distance travel for BEVs." (Wood et al. 2017a, p. 3) For coverage of intra-regional travel, the NREL study assumed a density of 56 stations per thousand square miles would be required. For intercity travel it considered station spacing along intercity routes ranging from 40 to 100 miles. The NREL (2017) study notes that, "Over time, a larger network of stations will be required to satisfy growing charging demand." Coverage as defined in the NREL study is intended to be a minimal measure of full charger availability and is relevant only during the early stages of market transition.

The calculations presented here are based on area-wide averages; more precise estimates would consider the actual geography of development, the topography of the road network, and traffic volumes. Only DCFCs are considered in order to be consistent with the simulation studies used to calibrate the WILLINGNESS TO PAY model (i.e., Wood et al. 2015). Key assumptions are listed in the table below, and WILLINGNESS TO PAY values are in present value 2015 dollars for a new BEV.

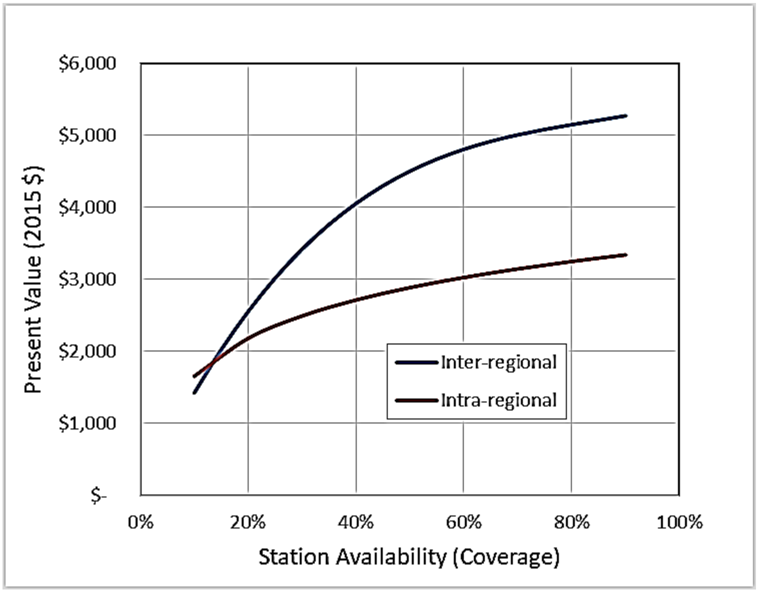
In 2017, there were 6,768 BEVs registered in the 6,128 square mile SACOG region (1,551 were newly registered during the year), and there were 193 publicly available DCFC stations (IHS 2017). Using the NREL (2017) intra-regional coverage metric, the existing stations provide 193/343 = 56% coverage. The median annual household income of a BEV owner in California is approximately $115,000 (California Energy Commission 2017). Using that income, **the value of the existing intra-regional public DCFC infrastructure is estimated to be about $3,500 per vehicle** for BEVs with a 100-mile range. Even for vehicles with a 300-mile range, the existing infrastructure is estimated to be worth $1,500—$2,000 to a new BEV purchaser in terms of increased e-miles of travel enabled within the SACOG region over the life of the BEV. The average household income in the SACOG region is $85,000 (ACS 2017). Using that income level, the value for 100-mile BEVs is $2,500—$3,000.

The 548 DCFCs located in California's urban areas are assumed to be enough to support inter-regional BEV travel passing through urbanized areas. The value of inter-regional charging infrastructure is estimated based on coverage of the 3,128 miles of rural highways connecting different urban areas included in the California National Highway System, according to NREL analysis of Caltrans (2016) data. There are 53 non-Tesla DCFCs located no more than 1.0 miles from rural highways. Assuming a 40-mile spacing of chargers, the existing chargers provide about 67% coverage. The **value of the existing public charging infrastructure to a new 100-mile-range BEV in the SACOG region is estimated to be about $6,000**, assuming an income of $115,000, and about $5,000 for a household income of $85,000.

Table 3: Assumptions Used in Calculating WILLINGNESS TO PAY for Public Charging Infrastructure

VARIABLE	VALUE	SOURCE
ANNUAL MILES PER VEHICLE	13,273	2017 NHTS, California passenger cars
VEHICLE LIFETIME	13	NHTSA/EPA 2018
DISCOUNT RATE	7%	FRED 48-month new car loan average 2000—2017
DECREASE IN MILES WITH AGE	3.5%	2017 NHTS, California passenger cars
AVERAGE SACOG HOUSEHOLD INCOME	$85,000	2017 American Community Survey
MEDIAN CA BEV OWNER HOUSEHOLD INCOME	$115,000	2016 California Vehicle Survey
BEVS ON ROAD	6,768	IHS 2017
DCFCS ALONG RURAL CA HIGHWAYS	50	AFDC 2018, NREL analysis 2018
DCFCS IN SACOG REGION	193	AFDC 2018, NREL analysis 2018

Figure 34: Estimated Tangible Value of Public DCFC Infrastructure to a Purchaser of a New BEV-100 in the SACOG Region (Annual Household Income of $85,000)



CHAPTER 7: Concluding Observations

Public charging infrastructure creates value for owners and potential owners of PEVs. From a consumer perspective, for PHEVs, EVSE increases the miles in which the vehicle can be operated in charge-depleting mode, thereby saving money by substituting electricity for gasoline. For BEV owners, EVSE adds value to their vehicles by increasing the distance the vehicle can travel in one day, thereby expanding its ability to provide mobility and access.[30] The tangible value created by EVSE induces a willingness to pay on the part of PEV owners. For new vehicle purchasers, EVSE adds value to the choice of a PEV, thereby increasing the likelihood of purchase. The value of public charging infrastructure appears to be able to offset a large fraction of the perceived cost of the limited range and long recharging time of the BEV. Furthermore, to this tangible consumer value, there exist several personal intangible benefits and societal benefits of charging infrastructure in supporting PEV adoption and decarbonizing the transportation sector that have not been considered in this report such as improvements in air quality and other environmental benefits.

How best to measure charging infrastructure for estimating willingness to pay remains a challenge. In the example calculations presented in this report, the authors have used availability of recharging stations relative to gasoline stations and the number of chargers per metropolitan region. These measures were chosen mainly because they could be related to existing simulation studies that projected the associated effect on the utility of PEVs. The 2016 California Energy Commission survey measured charger availability in terms of the time required to access a charger (California Energy Commission 2017). Melaina and Bremson (2008) measured station availability in terms of spatial density: stations per square mile. Dong et al. (2014) measured charging infrastructure by the ratio of dollar expenditures per PEV. Wood et al. (2015) measured deployment of DCFCs by the number of units, while Wood et al. (2017a) used chargers per PEV. Nie et al. (2016) measured charging availability by the ratio of the number of stations to a calculated optimum number of stations. Others have measured charger availability by the ratio of the number of chargers to the number of gasoline stations (Greene and Duleep 2004; Achtnicht et al. 2012; Melaina et al. 2013). The analogy to gasoline stations is intuitively appealing yet imprecise because it does not consider the rate of delivery of energy; home, workplace, and other opportunity charging; or ways that BEV owners may adapt their travel behavior to maximize the utility of their vehicle. Narassimhan and Johnson (2017) measured charging infrastructure by the number of EVSE units per 1,000 persons of driving age. Bedir et al. (2018) provided insights on infrastructure requirements to achieve California's zero-emission vehicle deployment goals, including destination chargers at workplaces and public locations and home charging solutions at multifamily dwellings.

[30] These tangible values can also create intangible values, such as a greater sense of confidence in the future of PEVs, reduced concern about being stranded by a depleted battery, or an increased sense of community approval.

Most studies measure availability relative to some measure of actual or potential demand for charging. Because in a vehicle choice model EVSE availability affects the probabilities of PEV choice for all vehicle purchasers, measures that represent the value to both owners and potential owners of PEVs seem preferable. Perhaps because the PEV market is still in the early stages of development and EVSE usage relative to capacity has been low (INL 2014), only one study concerning the provision of EVSE for taxis in Seoul included queuing for charger use (Jung et al. 2014).

Melaina et al.'s (2013) findings concerning the importance of long-distance travel suggest that measures of recharging infrastructure should distinguish between chargers for inter-regional versus intra-regional travel. For this reason, two measures of charging infrastructure seem most relevant: (1) units of EVSE per mile of roadway for intra-regional travel and (2) DCFCs per mile of interstate (plus other freeways and expressways) for interregional travel. These suggested measures make the strong assumption that chargers have been appropriately, if not optimally, located so that the degree of optimality of charger locations need not be measured. In addition, they assume that charger availability, or density, is best measured relative to the space in which vehicles move: roadways. Wood et al. (2017a) and Bedit et al. (2018) have estimated number of EVSE required to support a certain number of PEVs without focusing on long-distance travel. At some point in the future it may be necessary to add a measure of congestion, and perhaps vehicle charging queuing, to refine estimates of EVSE requirements per miles of roadway or number of PEVs.

Because it is likely that, to date, chargers have not been optimally located, the number of existing chargers in a region is not directly comparable to the optimally located chargers of simulation studies. This makes calibrating willingness-to-pay functions to specific geographical locations challenging. Suboptimal charger location is partly due to uncertainty about how the PEV market will evolve and partly to an incomplete but growing understanding of how, where, and why PEVs and supporting EVSE are used. Future charger locations are likely to be closer to optimal because researchers are making impressive progress toward understanding the PEV-EVSE nexus, as illustrated by the studies cited in this report. Still, much remains to be done and research is needed on many fronts. Understanding how public charging infrastructure encourages the growth of PEV ownership and how PEV ownership and use enhance the economics of charging infrastructure operations are among the most important unanswered questions.

Additional unanswered questions remain that could be addressed by future simulation modeling and econometric analysis.

1. Today, home-based charging is available to almost all PEV owners. However, residential charging might not be available to all future consumers as the PEV market expands (e.g., multiunit dwellings, renters, on-street parking), requiring investment to provide a reliable changing option to all, including more extensive workplace or public charging.
2. Simulation analyses have generally assumed that EVSE is available when and where it is needed. Econometric studies have used measures such as EVSE per capita or per land area. How best to measure EVSE availability, considering travel patterns and the number and types of PEVs in the existing vehicle stock, remains an unanswered question. The Energy Commission and NREL are continuing to develop the Electric

Vehicle Infrastructure Projection Tool (EVI-Pro) to help address the issue of adequate EVSE availability. EVI-Pro conducts bottom-up simulations of PEV charging behavior to generate geographically specific metrics such as plugs per 1,000 PEVs that are indexed based on PEV and EVSE types, residential charging access, and PEV fleet size (Wood et al. 2017a, Bedir et al. 2018).

3. Additional simulation modeling focused on interregional trips could produce improved estimates of the increase in interregional miles enabled by DCFC infrastructure along interregional routes. To complicate the issue, interregional EVSE, even if located only along intercity routes, will serve some intraregional traffic and vice-versa. The Energy Commission and NREL are developing a simulation framework to anticipate future DCFC needs along highway corridors for enabling long distance travel. This simulation framework will enable intraregional demands from EVI-Pro to be overlaid with intercity demands to estimate aggregate demand along highway corridors.
4. Almost all the econometric literature on the value of range and recharging time is based on stated preference studies from a time when respondents had very little first-hand knowledge of PEVs. Moreover, there is a lack of empirical data for the value of time spent at fast chargers. Updating these studies with recent findings based on revealed preference data may provide different insights.
5. As EVSE infrastructure expands and the stock of PEVs increases, econometric studies may be able to discriminate among the benefits of different types of EVSE in different contexts.
6. The need for a high level of reliability and availability of EVSE infrastructure to ensure an appropriately low level of unavailability due to mechanical failure or waiting time is another topic in need of additional research, and networking to enable remote monitoring has been proposed as a possible solution (Bedir et al. 2018). Simulation modeling is an appropriate method for quantifying the relationship between redundancy and reliability.
7. Congestion, or waiting time, for use of EVSE infrastructure could become an important issue as the number of PEVs on the road increases. It seems likely that simulation modeling and observed data (e.g., annual peak charging during holidays) could provide valuable insights.
8. Finally, while this report has focused on the straightforward and tangible benefits of charging infrastructure from a consumer perspective, charging infrastructure also has more difficult to measure benefits in the form of insurance against becoming stranded, confidence in the future of the PEV market, positive reinforcement of the values and decisions of PEV owners, and larger societal benefits related to displacing petroleum use and related emissions. Understanding the roles of such factors in the evolution of the PEV market and, if possible, quantifying their value to public and private investors at large is also an important area for further research.

Given the complexity of the question of the value of recharging infrastructure, it is appropriate to conclude with a caveat. Awareness of public charging infrastructure may differ from actual availability, especially during the early phases of PEV adoption. Likewise, consumers unfamiliar with PEVs may not correctly perceive the value of charging infrastructure. Consumer expectations about the permanence and future expansion of charging infrastructure have not been considered in this report, nor has the value of public charging infrastructure as insurance against forgetfulness or unanticipated travel requirements. Redundancy to ensure the continuity of availability also has value but has not been considered in the above analysis. Nevertheless, the measures of willingness to pay for EVSE derived in this report are based on measurable relationships between charging infrastructure and the utility of PEVs. They are intended to serve as a useful starting point for fully quantifying the value of investments in public charging infrastructure and for introducing infrastructure as a key variable in models that project consumers' likelihood of purchasing PEVs.

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List of Acronyms

ADOPT	NREL's Automotive Deployment Options Projection Tool
AFV	alternative fuel vehicle
BEV	battery electric vehicle
DCFC	direct current fast charging
EV	electric vehicle
eVMT	electric annual vehicle miles traveled
EVSE	electric vehicle supply equipment
GPS	Global Positioning System
GV	gasoline vehicle
PEV	plug-in electric vehicle
PHEV	plug-in hybrid electric vehicle
VMT	annual vehicle miles traveled
WTP	willingness to pay

APPENDIX: Equations 25, 26, and 28 and Definitions of Variables

Equation 25

$$WTP_{ij} = \left[f\left(\frac{I_j}{X_j}, R_i\right) - f(0, R_i)\right] M_{ij} \left(p_{jG} e_{iGs} - \left(p_{jG} e_{iGd} + p_{jE} e_{iEd}\right)\right) D_{ij}$$

Equation 26

$$WTP_{ij} = \left[\left(a_0 + a_1 ln\left(\frac{I_j}{X_j}\right)\right)\left(\frac{b_0}{R_i^{b_1}}\right) M_j \left(v_j - \frac{w_j}{\phi R_i}\left(K\left(\left(\frac{I_j}{X_j}\right)^{\alpha} - \left(\frac{I_j}{X_j}\right)^{\alpha}\right) + \frac{\phi R_i e_i}{d}\right)\right)\right] D_j$$

Equation 28

$$WTP_{ij} = \left[\left(a_1\left(\frac{I_j}{X_j}\right) + a_2\left(\frac{I_j}{X_j}\right)^2 + a_3\left(\frac{I_j}{X_j}\right)^3\right)\left(e^{-b(R-R_0)}\right) M_j \left(v_j - \frac{w_j}{\phi R_i}\left(K\left(\left(\frac{I_j}{X_j}\right)^{\alpha} - \left(\frac{I_j}{X_j}\right)^{\alpha}\right) + \frac{\phi R_i e_i}{d}\right)\right)\right] D_j$$

WTP	Willingness to pay in discounted present value dollars per new vehicle
f	Enabled miles as a fraction of miles of a comparable conventional vehicle
I	Number of charging stations
X	Number of charging stations needed for full availability
R	Rated range in miles
M	Annual miles of a comparable conventional vehicle
p_{jg}	Price of gasoline in $/gal.
p_{jE}	Price of electricity in $/kWh
e_{iGs}	Gasoline use per mile of PHEV in charge sustaining (s) mode
e_{iGd}	Gasoline use per mile of PHEV in charge depleting (d) mode
e_{iEd}	Electricity use per mile of PHEV in charge depleting (d) mode
D	Factor converting annual to discounted vehicle lifetime costs
w	Value of time in $/minute
v	Value of one mile of enabled electric vehicle travel
ϕ	Minimum remaining range at which a driver would normally recharge
d	Charging rate in kW
i	Indexes vehicles
j	Indexes regions

The following parameters' values are calibrated and differ in the three equations:

a_0, a_1, a_2, a_3, b, b_0, b_1, K, α