Public Charging Infrastructure for Plug-in Electric Vehicles: What is it worth?

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Abstract

Lack of charging infrastructure is an important barrier to the growth of the plug-in electric vehicle (PEV) market. Public charging infrastructure has tangible and intangible value, such as reducing range anxiety or building confidence in the future of the PEV market. Quantifying the value of public charging infrastructure can inform analysis of investment decisions and can help predict the impact of charging infrastructure on future PEV sales. Estimates of willingness to pay (WTP) based on stated preference surveys are limited by consumers' lack of familiarity with PEVs. As an alternative, we focus on quantifying the tangible value of public PEV chargers in terms of their ability to displace gasoline use for PHEVs and to enable additional electric (e-) vehicle miles for BEVs, thereby mitigating the limitations of shorter range and longer recharging time. Simulation studies provide data that can be used to quantify e-miles enabled by public chargers and the value of additional e-miles can be inferred from econometric estimates of WTP for increased vehicle range. Functions are synthesized that estimate the WTP for public charging infrastructure by plug-in hybrid and battery electric vehicles, conditional on vehicle range, annual vehicle travel, pre-existing charging infrastructure, energy prices, vehicle efficiency, and household income. A case study based on California's public charging network in 2017 indicates that, to the purchaser of a new BEV with a 100-mile range and home recharging, existing public fast chargers are worth about $1,500 for intraregional travel, and fast chargers along intercity routes are valued at over $6,500.

I. Introduction

The adoption of alternative fuels and vehicles is hindered by the "chicken or egg" problem: consumers are reluctant to 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 to make it profitable (Sperling 1988; McNutt and Rodgers 2004; NRC, 2015; Gnann and Plötz 2015; Melaina *et al.*, 2017). In the early stages of market development alternative refueling infrastructure tends to be underutilized (e.g., EV Project, 2014, 2015) and the development of sufficient demand can take decades (NRC, 2013, 2015). As a consequence, unless the private benefits of AFVs are compelling, public policy intervention is

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necessary to initiate markets for AFVs and related infrastructure and sustain them during the early phases of development (NRC, 2013). This is especially true when there are important public benefits, such as reduced greenhouse gas emissions, improved local air quality, and energy security.

Quantifying 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, and predicting its impact on future PEV sales.[4] In this paper, we focus on the value of the existence of public charging infrastructure to the consumer, apart from any charge for using it. In this sense, our estimates correspond to the economic concept of willingness to pay (WTP), as explained in section II. At this stage of the market, utilization rates of public charging are low, their business model is uncertain, public and private roles are not well defined, chargers are subsidized in many instances, and cost of charging varies widely geographically and temporally (e.g., Klass, 2018; Lee and Clark, 2018; Muratori et al. 2019). The cost of using public charging is obviously important but it is not included in our WTP estimates.

Estimating WTP via stated preference experiments can produce valuable insights but also has limitations. Given the novelty of PEVs, their small market shares, and motorists' lack of familiarity with recharging a vehicle, it is difficult for respondents to provide valid answers to survey questions (Lee and Clark, 2018, p. 46). In this paper we develop an alternative framework for estimating the tangible value of public PEV recharging infrastructure that has its own limitations but may still provide useful insights. The method focuses on estimating the ability of public charging stations to enable additional electric miles (e-miles) of travel. Infrastructure also enhances the visibility of electric vehicles and creates confidence in their viability and

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[4] A **plug-in electric vehicle** is a **vehicle** with an on-board battery that can be recharged from an external source.

permanence, which can also influence adoption (Bailey et al., 2015). Public chargers can potentially make it possible for those without home/workplace charging capabilities to own such a technology. However, such benefits are not included in this analysis.

Simulation analyses making use of geographically and temporally detailed vehicle travel data have quantified the ability of charging stations to enable additional e-miles. Econometric analyses of the value of infrastructure and especially the value of PEV range allow us to infer the value of enabled e-miles. By combining insights from existing simulation modeling and econometric analyses, we develop functions that estimate WTP for charging infrastructure by type of PEV, as a function of its electric range, drivers' annual vehicle travel, pre-existing charging infrastructure, energy prices and efficiency, and household income.

The value of public charging infrastructure is defined in terms of WTP in section II. We distinguish between two types of PEVs and three types of infrastructure because they affect WTP in different ways. The tangible sources of value for plug-in hybrid electric vehicles (PHEVs) and all-electric or battery electric vehicles (BEVs) are described in section III, and the costs of access and charging time are considered. Our method of estimating WTP is presented in section IV along with supporting empirical evidence. Section V presents the functions relating WTP for public charging stations for PHEVs, and BEVs in intra- and inter-regional travel. Section VI presents a case study, estimating illustrative WTP for charging infrastructure, leveraging data representative of California's PEV market and charging station availability.

II. The value of public charging infrastructure

The value of a good to a consumer can be measured by the consumer's WTP for it, defined as the maximum amount of money an individual would agree to give up to obtain a good or avoid a bad (Varian, 1992). Let $U(\boldsymbol{x}, \boldsymbol{y}, \boldsymbol{z})$ be the indirect utility function of a representative consumer, where $\boldsymbol{x}$ is a vector of vehicle attributes including price, $\boldsymbol{y}$ is a vector of consumer attributes, and $\boldsymbol{z}$ contains variables describing the context of the choice, one of which is the availability of public charging stations denoted as I while another would be the cost of charging. The total derivative of U with respect to charging infrastructure, I, and vehicle price, x_p, with all other factors constant, is presented in Equation 1.[5]

$$dU = \frac{\partial U}{\partial I} dI + \frac{\partial U}{\partial x_p} dx_p \tag{1}$$

Setting Equation 1 equal to zero and solving for the negative of the change in price that is exactly offset by a change in infrastructure availability gives the quantity of present value dollars (i.e., income) that would keep consumer utility constant given a change in infrastructure availability.

$$\frac{dx_p}{dI} = -\frac{\partial U / \partial I}{\partial U / \partial x_p} \tag{2}$$

This quantity, known as the compensating variation, represents the maximum amount a consumer would be willing to pay for an increase in infrastructure availability. A consumer's WTP function is equivalent to a demand function.

At any given time, the economic benefit of public charging depends on the number of people who own and drive PEVs. A multinomial logit discrete choice model can help illustrate this point. The probability, P_{1j}, that consumer j will choose a BEV *(vehicle type* $i=1$*)* is given by Equation 3, in which $U_i(x,y,z)$ are the utilities of all types of vehicles, indexed $i \in \{1,.., N\}$.

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[5] The derivation is an adaptation of that presented in Gatta et al. (2015). WTP values derived in this paper are like those that can be inferred from random utility models of vehicle choice.

$$P_{1j} = \frac{e^{U_1(x_1, y_j, z)}}{\sum_{i=1}^{N} e^{U_i(x_i, y_j, z)}} \qquad (3)$$

For the multinomial logit model, the change in consumers surplus for increasing the availability of chargers from I_0 to I_1, is given by Equation 4 (Small and Rosen,1981).

$$CS_j = -\frac{1}{\beta}\left(ln\left(\sum_{i=1}^{N} e^{U_i(x, y_j, I_1)}\right) - ln\left(\sum_{i=1}^{N} e^{U_i(x, y_j, I_0)}\right)\right) \qquad (4)$$

In Equation 4, the consumers' surplus effect of public charges is weighted by the probability of choosing to own a BEV. Even for those who do not choose a BEV, public chargers reduce the cost of limited range and longer refueling time. In the future, if BEV costs decrease or consumer awareness increases, the availability of public charging would increase BEV sales.

WTP will vary for a number of reasons. The marginal utility of income ($-\partial U/\partial x_p$) decreases with increasing income (Layard et al., 2008), leading to an increasing willingness to pay for attributes as income increases, all else equal. In addition, the value of time varies with income (e.g., Brownstone and Small, 2005) and so the time cost of charging will also. WTP will also vary with PEV range and the consumer's demand for vehicle travel. WTP will vary by type of PEV and type of charger.

Three types of chargers are generally recognized based on nominal power that determines recharging time (AFDC, 2018b):

- Level 1 (L1), which uses a standard 120 V source and can supply 2–5 miles of range per hour of charging at about 1.4–1.92 kW
- Level 2 (L2), which requires a 240 V source and can supply 10–60 miles of range per hour at 7.2–19.2 kW
- 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.[6]

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[6] Extreme fast charging technology is being developed that can deliver electricity at 350 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.

In general, L1 and L2 chargers are used for "convenience charging", that is, charging where and when a vehicle would normally be parked for an extended period of time. DCFCs, on the other hand, can be used en route to extend a BEVs range without incurring a major delay.

The location of chargers is also important. The literature distinguishes between home, workplace, and public charging. The latter is the focus of this paper. The great majority (75%–80%) of PHEV and BEV charging is done at home with workplace charging a distant second (INL 2015; CEC, 2017) (Figure 1).[7].

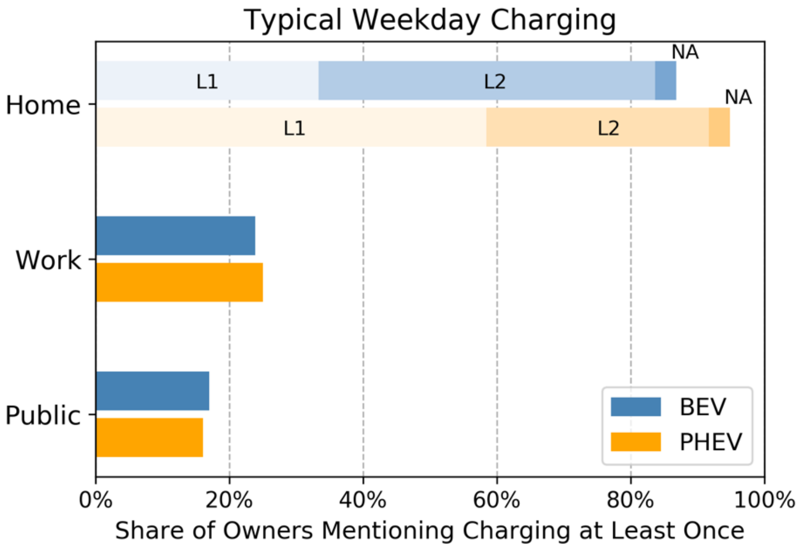

Figure 1. Typical weekday charging locations for PEVs in California (CEC, 2017).

III. Tangible benefits of public charging infrastructure

Public charging infrastructure increases the value of PEVs to their owners and potential purchasers by increasing the number of miles that can be traveled powered by electricity (e.g., Peterson and Michalek, 2013; Lin and Greene, 2011). Because PHEVs are capable of continued

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[7] With 12% of the population of the United States, California has 24% of the public PEV charging stations and 30% of the outlets for charging PEVs (AFDC, 2018a).

operation when their batteries are depleted, the tangible benefit of more e-miles lies in cost reduction by substituting electric miles for gasoline-powered miles.[8] The source of value is fundamentally different for BEVs: the tangible benefit is the ability to accomplish more travel with the BEV. For both, there are also intangible benefits we do not quantify, such as altruistic satisfaction from reducing environmental pollution (e.g., Degirmenci and Breitner, 2017) or reduced range anxiety or increased confidence the future of PEVs.

Tangible benefits of public charging for PHEVs

The cost savings from plugging in a PHEV depend on its battery storage capacity, *C*, the price of gasoline, p_G, the price of electricity, p_E, the energy consumption rates when using gasoline, e_g(gallon per mile), and when using electricity, e_E (kWh/mile), the probability that charging is available at the end of the i^{th} trip, P_i, the rate at which electricity can be delivered 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 vehicle's battery at the end of trip i.[9] The value of public charging infrastructure is the sum of savings over all trips, appropriately discounted over time.[10]

$$WTP = \sum_{i-1}^{N} P_i \min(d_i A_i, C - c_i)(p_G e_G - p_E e_E) f_i \qquad (5)$$

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[8] Survey data on the use of public chargers by PHEV owners supports this premise. Nicholas et al. (2017) found that the frequency of PHEV charging by drivers in a California survey was positively related to the PHEV's electric range. In addition, when gasoline prices decreased, PHEV owners plugged in less frequently.

[9] For simplicity, the possibility of stopping to recharge during a trip is omitted, thereby limiting the analysis to what is called "opportunity charging".

[10] 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 p_e to be the cost per mile (including both gasoline and electricity) in charge-depleting mode corrects the simplification.

Equation 5 requires knowing each individual's trip schedule over time and the probability of each type of charger being available each time the vehicle is parked. To estimate the value of public charging to PHEVs drivers, we make use of studies that have simulated these factors using geographically and temporally detailed data that tracks individual vehicles over an extended period of time.

Tangible benefits of public charging for BEVs

The tangible benefits of public charging infrastructure to BEV drivers arise from increasing the amount of daily travel that can be accomplished by the BEV. [11] Annual miles enabled by charging infrastructure that extends daily e-miles can be estimated from daily travel distributions. Lin and Greene (2011) formulated the value of chargers to BEV owners in terms of reducing the number of days on which desired travel exceeded the vehicle's range. Each limited travel day was assigned a "range anxiety" cost ($15) and charging infrastructure availability was specified as the probability the range anxiety cost would be incurred. Instead, we estimate the number of vehicle miles enabled by charging infrastructure derived from simulations based on geographically and temporally detailed vehicle travel data or from daily vehicle travel distributions.

Let $\Delta(I)$ be the increase in the fraction of vehicle miles that would have been traveled using a conventional gasoline vehicle, that are enabled by deploying I public chargers. The I public chargers increase the BEV's effective daily range from R_0 to R. For inter-regional travel,

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[11] Omitting the benefit of reduced "range anxiety", the fear of being unable to complete a trip due to a depleted battery. Although the additional e-miles will come at a lower cost per mile than a comparable internal combustion engine vehicle, our method of valuing the incremental miles based on WTP for increased range should take that into account.

Greene et al. (2018a) show that the effective increase in vehicle range enabled by charging infrastructure can be approximated by a linear function of the number of chargers. Assuming a Weibull cumulative distribution function of annual mileage (Plötz *et al.*, 2017), $\Delta(I) = \Delta(R,R_0)$ is given by Equation 6, where λ is a scale parameter and k the shape parameter. [12]

$$\Delta(R,R_0) = \left(1 - e^{-\left({R}/{\lambda}\right)^k}\right) - \left(1 - e^{-\left({R_0}/{\lambda}\right)^k}\right) = e^{-\left({R_0}/{\lambda}\right)^k} - e^{-\left({R}/{\lambda}\right)^k} \qquad (6)$$

The resulting fraction of conventional vehicle miles can be closely approximated by an empirical cubic function of the increase in range over an assumed range of 75 miles (which has been calibrated with 2017 National Household Survey data), as shown in Figure 2.

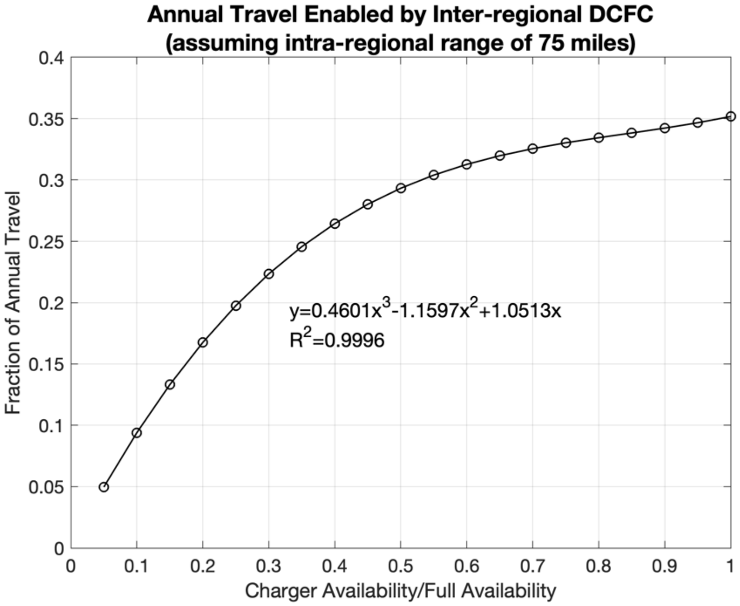

Figure 2. Fraction of Annual Miles of Travel Enabled Beyond a 75-mile Range Assuming a Weibull Distribution of Daily Travel Distances (Greene et al., 2018a)

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[12] 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.

The time required to access public charging infrastructure can reduce its value. Access time will depend on the number and location of chargers. Several studies have estimated the time required to access an alternative fuel station as a function of station availability, although none is specifically focused on access to PEV chargers. Nicholas *et al.* (2004) showed that the time required to access fuel in a metropolitan area decreased at a decreasing rate as the number of stations was increased and that a simple power function of the ratio (ϕ) of the number of alternative fuel stations (n) to the total number of gasoline stations (N) fit the decrease in access time well. Multiplying access time ($K\phi^a$) by the value of time (w) results in a power function for the access cost of limited fuel availability within a metropolitan region (C_{f}), as shown in Equation 7.

$$C_\phi = wK\left(\frac{n}{N}\right)^a = wK\phi^a \qquad (7)$$

Translating this to a present value cost per vehicle requires estimating the number of refueling events over a vehicle's lifetime and discounting to present value. Let access and refueling time for a gasoline station be t_g and recharging time t_{rc}. A decreasing exponential function of age provides a reasonable approximation to annual miles over a vehicle's lifetime (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's lifetime and r the annual discount rate. The present value additional time cost of recharging is given by Equation 8, in which m corresponds to discounted lifetime miles of travel.

$$C_A = w\big(K\phi^a - t_g + t_{rc}\big)\int_{t=0}^{L}\frac{1}{R}M_0e^{-(\delta+r)t}dt = w\big(K\phi^a - t_g + t_{rc}\big)\frac{M_0}{R}\frac{1}{\delta+r}\left[1 - e^{-(\delta+r)L}\right] =$$

$$w\big(K\phi^a - t_g + t_{rc}\big)\frac{m}{R} \qquad (8)$$

Combining the effects of range, recharging time, and range-enabling infrastructure leads to a formula which is a product of, (1) the effect of z chargers on enabled electric annual vehicle miles traveled (eVMT) as a fraction of conventional vehicle travel, $h(z)$; (2) the effect of range on diminishing the impact of adding infrastructure, $k(R)$; (3) the annual miles of a comparable conventional gasoline vehicle, M; [13] and (4) a factor, D_j, reflecting the discounted value of future travel to convert annual WTP to lifetime WTP. Equation 8 provides estimated WTP for a total level of infrastructure of z with respect to a reference level of coverage z_0 in present value dollars. In Equation 9, v_j is the value per mile of enabled travel and $t_r{}^*$ is charging time.[14] The term $K(\phi^a - 1)$ is the increase in access time versus gasoline. [15]

$$WTP = h(z_j)k(R_i)M_j\left(v_j + w_j\left(K(\phi_j^a - 1) - t_g + t_r^*\right)\frac{1}{R_i}\right)D_j \qquad (9)$$

IV. Quantifying WTP: Combining theory, simulation, and econometrics

In this section we synthesize functions describing WTP for charging infrastructure as a function of vehicle range, charger availability, income and annual miles of travel, first for BEVs and then PHEVs. For BEVs we rely on simulation studies to estimate functions relating the availability of public charging infrastructure to additional enabled vehicle miles of travel. We turn to econometric analyses to estimate the value of enabled miles. Simulation studies provide estimates of the ability of public chargers to enable PHEVs to substitute electricity for gasoline. For PHEVs, public chargers' tangible value is estimated in terms of fuel cost savings.

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[13] After reviewing evidence from simulation studies (e.g., Dong and Lin 2012), it becomes clear why the appropriate definition of annual miles is the annual mileage of a comparable conventional gasoline vehicle rather than the actual annual miles of the PEV.

[14] For opportunity charging, t_r could equal zero or the value of time applied to t_r could be set to zero.

[15] Public charging infrastructure also has value to potential future owners of PEVs which can be estimated by using vehicle choice models to estimate the effect on consumer's surplus.

Reliance on existing simulation studies has strengths and weaknesses. The fact that such studies are based on geographically and temporally detailed data that describe activity patterns of vehicles in normal operation over an extended period of time enables highly realistic simulation modeling of the effects of limited range and recharging availability on the use of PEVs, taking into consideration trip distances, timing, locations, and time spent parked (e.g., Neubauer and Wood 2014). Such data should provide more realistic estimates of enabled e-miles than single-day trip records for a large number of vehicle. On the other hand, simulation studies make a number of simplifying assumptions that carry over to our estimates: (1) PEVs are driven like conventional vehicles; (2) BEV owners have access to residential charging; (3) public charging infrastructure is optimally deployed and drivers know where it is located (there is no searching for chargers); (4) queuing at charging stations does not occur; and 5) vehicle operators have foreknowledge of their daily trips. The first assumption implies that the simulations do not allow changes to 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).

Finally, the way that infrastructure availability is measured is generally idiosyncratic to a study. Not only do different studies use different measures but relative availability depends on the number of vehicles in the study, the network on which they are traveling and the details of their trip making. Nearly all studies provide results as a function of the number of chargers deployed. To minimize the impact of study-specific factors, we transform number of chargers into relative availability by dividing by the maximum number of chargers assumed in the study. As a consequence, applying our methods to different locations requires a reasonable estimate of the minimum number of chargers required for "full availability".[16] Some studies include such availability numbers for both L2 and DCFCs. For BEVs we rely on studies based on deploying only DCFCs for estimating the WTP for public charging infrastructure because any service that can be provided by an L2 charger can be provided as well or better by a DCFC.[17] For long-distance travel along intercity highways, DCFCs are certain to predominate, except for locations where vehicles may spend the night. Nie and Ghamami (2013) 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.

Enabled e-miles for BEVs

Simulation analyses show a substantial potential for public charging to enable additional travel by BEVs for both intra-regional and inter-regional travel. Dong and Lin (2014) analyzed travel patterns of 382 vehicles in the Seattle area with more than half a year of GPS-tracked travel data and found that adding just one opportunity for public recharging increased the fraction of drivers for whom a 75-mile-range BEV could accommodate at least 95% of trips from about 35% to 75%.[18] Analyzing the same data, Neubauer and Wood (2014) estimated that the percentage of original trips taken that could be accomplished by a 75-mile-range BEV could be increased by 11% to 15% via widespread availability of L2 chargers.[19]

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[16] Conceptually, full availability of chargers is the point beyond which additional chargers provide little or no increase in e-miles. Practically, it is usually the maximum number of chargers included in a simulation analysis.

[17] Public L2 chargers can provide equivalent service to DCFC when and where vehicles would normally be parked for an extended period of time away from their home base or work location.

[18] The calculations assumed what is now a relatively modest nominal range of 76 miles and that drivers would use only 80% of that. A charger is assumed to be available during the longest time the vehicle is parked away from home, wherever that may be. Thus, even one recharge per day implies a widespread charger availability.

[19] Drivers were assumed to require 15 miles of range at the end of any trip as a safety margin.

Using a GPS database of trips by 275 Seattle households operating 445 vehicles over periods as long as 18 months, Dong *et al.* (2014) calculated optimal locations for L1, L2, and DCFC chargers by minimizing the number of missed trips subject to a budget constraint on expenditures on chargers. An expenditure of only $500 per vehicle resulted in fewer than 5% of trips being missed. The benefit of additional chargers decreased rapidly with increasing investments: approximately 70% of the vehicle miles enabled by a $5,000 per vehicle investment in chargers were enabled by the first $500 invested.[20]

The benefits of enabling additional intra-regional BEV travel by deploying 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.[21] The results show that a logarithmic function describes reasonably well the total VMT enabled as a function of the DCFC station count, as shown in Figure 3.

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[20] At $500 per vehicle more than 95% of the budget would be spent on level 1 charging stations. At $1,000 per vehicle more than 70% would be spent on level 1 chargers with the rest for level 2 chargers. At $1,500 per vehicle the majority of expenditures would be on level 2 chargers. Nothing would be spent on DCFCs until expenditures exceeded $2,500 per vehicle.

[21] The assumption that conventional vehicle trip-making behavior strictly applies to BEVs, will seriously underestimate the importance of DCFC in inter-regional travel. In long-distance travel, BEVs will undoubtedly make additional stops to take advantage of the opportunity to use a DCFC.

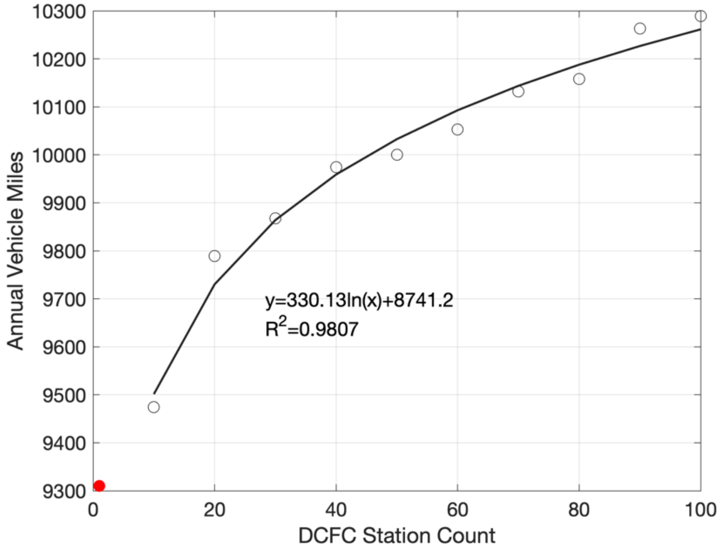

Figure 3. Effect of DCFC Station Count on BEV VMT (Greene et al., 2018a)

The marginal benefits of public chargers diminish with increasing vehicle range. Wood *et al.* (2015) found that enabled e-miles decreased with the inverse of approximately the square root of range. Figure 4 shows the effect of range for three percentiles, the 25th percentile having the lowest annual mileage and the 75th percentile having the highest.

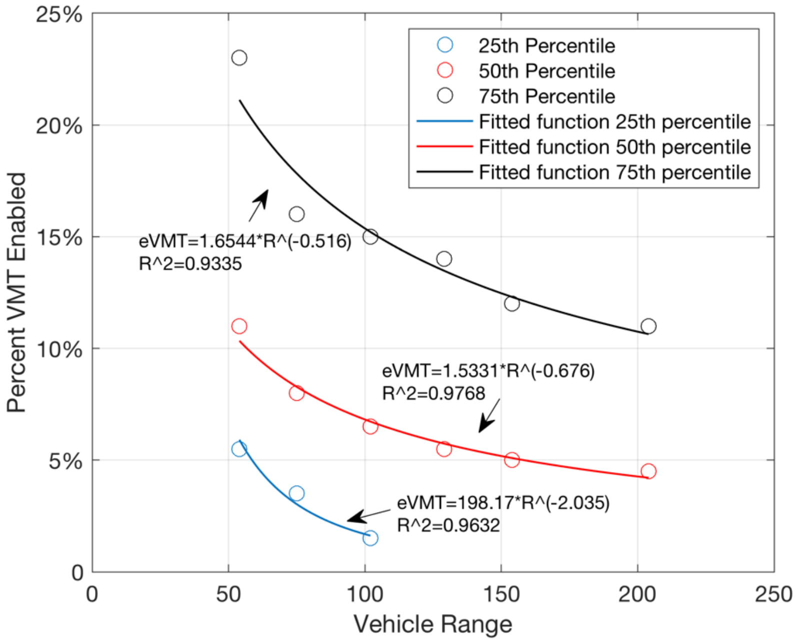

Figure 4. VMT enabled by DCFC stations by vehicle range (based on Wood *et al.* 2015)

The effects of home, work, and public charging on the fraction of CV travel that could be accomplished by BEVs with ranges of 100, 200, and 300 miles were estimated by Wood *et al.* (2017b) for 20,177 vehicles in the 2011 Massachusetts Travel Survey, as shown in Figure 5. Adding public charging to home and work locations enabled an additional 12% of annual miles for BEVs with a 100-mile range but only 6% for 200-mile range BEVs and 4% for BEV300s, indicating that the benefit is decreasing with the inverse of vehicle range.

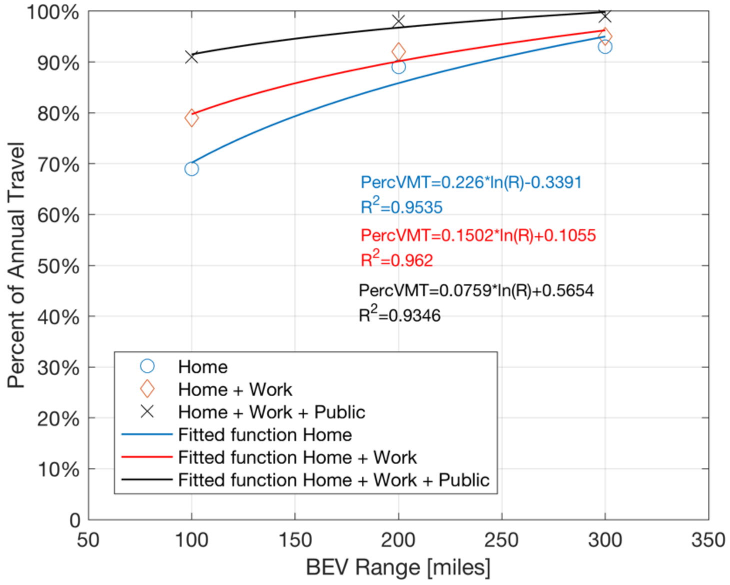

Figure 5. Effect of Range on percent of CV annual miles achievable with a BEV (Wood et al., 2017b)

Valuing enabled e-miles: Econometric evidence

The econometric literature provides two kinds of evidence of consumers' willingness to pay for additional e-miles: (1) direct estimates of the value of charging infrastructure in vehicle choice models, and (2) estimates of WTP for increased vehicle range.

WTP for charging stations[22]

Researchers have represented infrastructure availability by density of charging stations per area, distance from home to the closest station, and charging availability at home, work, or public places (e.g., Kontou et al. 2019; Liao et al., 2017). Most econometric studies show a significant, positive effect of charging infrastructure on the probability of adopting a PEV, with one study finding a more appropriate diminishing marginal utility of charger availability (Achtnicht et al. 2012). To date, no study has distinguished between DCFC and slower charging levels.

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[22] Detailed descriptions of the WTP estimates discussed in this section can be found in Greene et al., 2018a.

Using quarterly data for the period 2011 to 2013 from 353 U.S. Metropolitan Statistical Areas (MSA), Li et al. (2017) estimated a model in which PEV sales and the number of chargers were simultaneously determined. Results indicated that a 10% increase in the number of charging stations would result in an 8.4% increase in PEV sales, on average. At the MSA average of 22.6 stations for the 2011–2013 period, the price-equivalent value per vehicle of one additional station was $961 per PEV. The value decreased to $795 at 27.3 stations (the 2013 average).

Using state-level data, Narassimhan and Johnson (2018) estimated equations predicting PHEV, and BEV sales as a function of recharging infrastructure, monetary incentives, and other factors. All charger infrastructure was treated equivalently whether level 2 or DCFC, and regardless of location (*e.g.,* workplace, public garage, curbside, interstate) and was measured in units per 100,000 persons.[23] Models were estimated separately for PHEVs and BEVs. Increasing the number of charging stations by 1 per 100,000 persons was estimated to increase BEV sales by 7.2% and PHEV sales by 2.6%. In the BEV model, increasing a rebate by $1,000 increased sales by 7.7%, implying an equivalent value of $935 per charging station per 100,000 residents. In California, one charger per 100,000 persons translates to roughly 400 chargers, making a single charger worth about $2.00-$2.50 to an average prospective BEV buyer in California.

WTP for Increased Range

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[23] This 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.

Because increased range also enables additional e-miles, WTP for increased range can be used to infer WTP for public charging.[24] A meta-analysis of consumers' WTP estimates for additional driving range based on 33 international studies was carried out by Dimitropoulos *et al.* (2013). The estimated mean WTP for a 1-mile increase in driving range was \$81 2015 USD, with a median of \$51. The range of estimates was large: from \$10 to \$317 per mile. Considering only the six studies that focused exclusively on BEV range, the mean WTP per mile was \$115 with a range of \$25 to \$236.

Greene *et al.* (2017) calculated 22 estimates from 14 U.S. studies that measured the value of electric range in dollars per mile, most of which were derived from stated preference surveys. The WTP 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 USD. Similar values for increased driving range were obtained by Higgins *et al.* (2017) based on a stated preference survey of Canadian vehicle owners for both BEV and gasoline vehicles (\$20 to \$65).

WTP for a 1-mile increase in range can be used to derive an estimate of WTP for e-miles enabled by public charging. WTP for increased range represents the discounted present value of future travel enabled by increased range for a new vehicle. In Equation 10, v is the value of an e-mile of travel, M^* is the additional annual miles enabled by a 1-mile increase in EV range, L is the expected life of a PEV, and r is an annual discount rate.

$$WTP = \sum_{t=1}^{L} \frac{vM_t^*}{(1+r)^t} \quad \rightarrow \quad v = \frac{WTP}{\sum_{t=1}^{L} \frac{M_t^*}{(1+r)^t}} \qquad (10)$$

Using the relationship between range and enabled travel from Wood *et al.* (2017b, shown in Figure 6), the annual travel enabled by a 1-mile increase in range for a BEV with a 100-mile

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[24] Studies reviewed by Liao et al. (2017) found that consumers' preferences for range are correlated with annual miles traveled.

range and home recharging only depends on the derivative with respect to range of the "Home" equation shown in Figure 6 [25]:

$$\frac{d}{dR}(22.6ln(100) - 33.91) = 0.00226 \qquad (11)$$

Using the average annual mileage of conventional vehicles in Wood et al. (2017) (10,300 miles), the increase in annual miles enabled by a 1-mile increase in range (from 100 to 101) is 10,300 * $0.0023 \approx$ 24 miles. Using Dimitropoulos *et al.*'s (2013) mean value of $67 per mile of range, the value per annual mile of enabled travel is $3.37 in 2015USD (median of $2.09); using the value of $90 (2015 $) from Greene *et al.* (2017) the WTP per annual mile is $3.75 2015USD. Dividing by the discounted lifetime miles enabled by 1 additional mile per year (7.7)[26] produces estimated per-mile WTP values based on Dimitropoulos *et al.* (2013) of $0.44 for the mean and $0.27 at the median, and based on Greene *et al.* (2018a) of $0.49 for the mean.[27]

The enabled miles function derived from Wood et al. (2015) (Figure 4) is:

$$VMT = 330ln(I) + 8741 \qquad (12)$$

Adding one DCFC station when there are 50 stations in place enables 6.6 e-miles annually, as follows:

$$\frac{d}{dR}(330ln(50) + 8741) = \frac{330}{50} = 6.6 \qquad (13)$$

Lifetime discounted miles enabled are approximately 7.7 * 6.6 = 51, which, valued at $0.47/mile, would be about $24 and at $0.27 about $14 per BEV.[28]

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[25] The "Home" equation describes the amount of annual travel a BEV with only home recharging could accomplish as a function of its range.

[26] Discounting future miles at 10% per year (Bento et al. 2018)[26] over a 15-year life (NHTSA, 2006) results in a multiplier for annual miles of approximately 7.7.

[27] It is not necessarily true 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 miles on longer trips are worth less than those on shorter trips.

[28] Enabled miles increase at a decreasing rate as the number of chargers increases. The marginal increase in annual miles with 100 stations in place would be not 6.6 but 3.3 miles.

Economic theory implies that the willingness to pay for range should be an increasing function of income. Out of 23 studies estimating the value of range, only 4 allowed WTP 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). Based on a 2008-9 California Vehicle Survey, Hess et al. (2012) reports WTP for several households' annual incomes showing a linear relationship between WTP and income, with WTP increasing by $0.33 to $0.43 per $1,000 of income, as shown in Figure 6a. In McFadden and Train's (2000) mixed logit model, WTP increase with the logarithm of income because vehicle price enters as price divided by the natural logarithm of income, as shown in Figure 6b. 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 WTP for a 1-mile increase in range increases about $0.40 (2015 USD) for each $1,000 increase in household income.

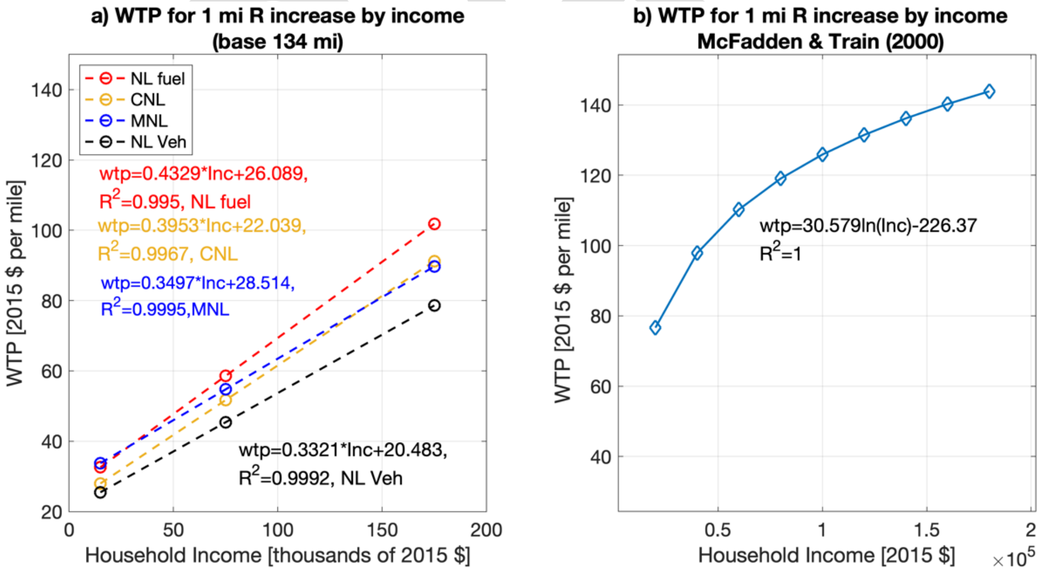

Figure 6. a) Willingness to pay for a 1-mile increase in BEV range over a 134-mile base as a function of income (data from Hess et al., 2012). For the purpose of very approximately graphing Hess et al.'s WTP estimates, we locate the 2008-9 >$120,000 value at $170,000, the <$20,000 value at $15,000 and the $60,000 to $80,000 value at $75,000. b) Willingness to

pay for a 1-mile increase in CNG or BEV range as a function of income (data from McFadden and Train, 2000).

Assuming as above that a 1-mile increase in range translates into 24*7.7 = 185 discounted lifetime miles, \$0.40 translates into about \$0.002 per mile per thousand dollars of income. Assuming a median WTP 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 enabled e-mile 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).

Enabled e-miles for PHEVs

A simulation analysis of the daily driving of 229 conventional vehicles in Austin, Texas, by Dong and Lin (2012), found that an extensive public recharging network could reduce PHEV gasoline use by more than 30% and energy costs by more than 10% without changing the usage patterns of the vehicles. The marginal reduction of PHEV gasoline consumption per mile relative to reference gasoline consumption based on Dong and Lin (2012) decreases exponentially with increasing coverage, defined as the probability that a charger will be available when and where the vehicle parks.

The effect of charging network coverage on miles traveled in charge-depleting mode $F(I)$ can be calculated from its 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% coverage (f_0), and (3) the ratio of gasoline use at coverage level I to gasoline consumption at 0% 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.

$$F(I) = \frac{(1-f(I))Me_s + f(I)Me_d}{(1-f_o)Me_s + f_oMe_d} \tag{14}$$

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

$$f(I) = \frac{F(I)\left[\frac{1-f_o}{e_d/e_s} + f_o\right] - \frac{e_s}{e_d}}{1 - \frac{e_s}{e_d}} \tag{15}$$

The relationships in Figure 7 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 Bradley and Davis (2011).[29] The data points are well approximated by quadratic functions over the range 0 to 1. It may seem counter-intuitive that the value of additional public chargers is reduced by increased range. However, home charging is assumed, and it reduces the usefulness of public charging as PHEV range increases.

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[29] 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.

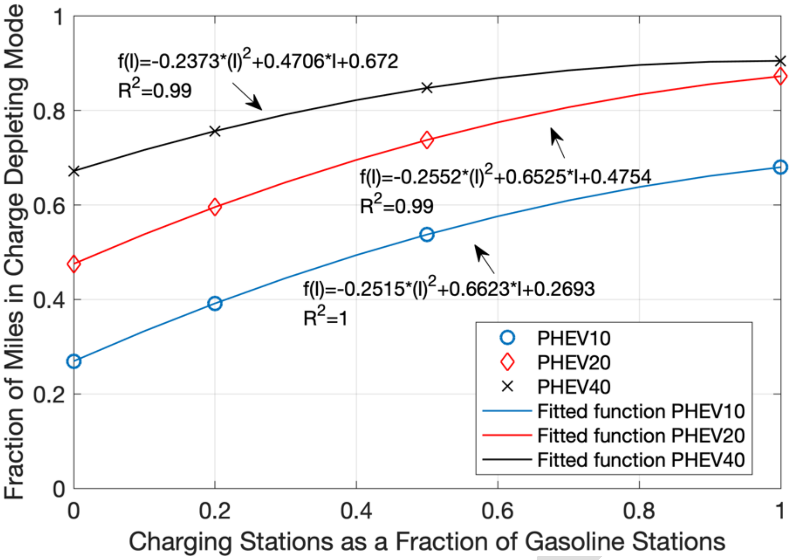

Figure 7. Effect of charging infrastructure on PHEV miles in charge-depleting mode

Wood *et al.* (2017b, fig. 16) estimated that adding workplace charging to home-based charging increased average electric miles by about 13% for PHEVs with a 20-mile charge-depleting range. Adding ubiquitous public charging opportunities enabled another 11% for the PHEV20 vehicle for a total benefit for both type of charging opportunities of about 24%. In all cases benefits declined with approximately the inverse of the square root of charge-depleting range, indicating that increasing PHEV battery capacity reduces the benefits of public charging to PHEV owners.

Estimates of the value of public chargers to PHEV owners are scarce. Sierzchula et al. (2014) found that infrastructure encourages PEV sales but did not provide a specific value. According to Hidrue et al. (2011), public charging can be worth thousands of dollars per vehicle. Analyzing US state-level data, Narassimham and Johnson (2018, Appendix 4) found that an increase of 1 charging station per 100,000 persons increased PHEV sales by 2.6% but their results did not allow them to derive a WTP estimate.

IV. Synthesis: WTP for charging infrastructure

In this section we combine the functional relationships from simulation modeling with the value functions for increased e-miles, inferred from econometric studies, to produce functions associating the capitalized present value of WTP for charging infrastructure to a change in infrastructure availability. The WTP functions presented below estimate total WTP as a function of availability of public chargers. The marginal WTP for an increase in availability is therefore the derivative of these functions. The WTP functions are illustrated by surfaces in the space defined by WTP, charger availability (I), and range (R), and vary with household income. The estimates are based on the following:

- Home-base charging is assumed to be available for all PEVs.
- Charger locations are known and there is no queuing to charge.
- Desired annual travel is what would be accomplished by a conventional vehicle.
- All public chargers for BEVs are DCFC.
- Charger availability (I) is measured as a fraction of "full availability".

"Full availability" will vary with geography, travel demand and the number of BEVs and PHEVs, and is therefore specific to time and place. Our illustrations are based on Wood et al. (2015) as shown in Figure 4, assuming that the 100 DCFC represents 100% availability.

BEVs Intra-Regional Travel

WTP for public chargers for a BEV's intra-regional travel is a function of enabled e-miles, which depend on public charging availability, I. Enabled e-miles decrease with increased range, R_i, relative to the base range, R_0, for which the enabled miles function was estimated. WTP also depends on the value of an enabled mile, v_j, the value or time in \$ per hr, w, and the additional time to access a charger (in minutes), $K(\phi^a - 1)$, all of which vary with income.[30] Assuming individual consumer data is not available, i and j correspond to vehicles and geographical areas respectively. M_j denotes the annual miles that would be traveled assuming ubiquitous charging infrastructure and D_j expands the annual benefit of charging infrastructure to a lifetime discounted benefit.[31] BEVs intra-regional drivers value the existing charging infrastructure based on Equation 16:

$$WTP_{ij} = \left[a_0 + a_1 ln\left(\frac{I_j}{X_j}\right)\frac{b_0}{R_i^{b_1}} M_j \left(v_j - \left(w_j K\left(\phi_j^a - 1\right)\frac{1}{CR_i}\right)\right)\right] D_j \quad (16)$$

The illustration of Equation 16 in Figure 8a assumes a value of $0.36 per enabled mile for a household income of $115,000, roughly the mean household income of new BEV buyers in the 2016 California Vehicle Survey. The effect of chargers on enabled e-miles is based on Wood *et al.'s* (2015) simulation analysis with the range of 0 to 100 percent representing no public chargers to full availability.[32] WTP increases at a decreasing rate, as charging availability increases. The value of chargers for intra-regional BEV travel decreases by about half as vehicle range increases from 75 miles to 325 miles. The effect of income on WTP is illustrated in Figure 8b.

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[30] The time cost of access is converted to a cost per mile (the same units as v_j) by dividing by the fraction of the vehicle's range enabled by the charge, *C*, times vehicle range, *R*.

[31] In Equation 16 all intra-regional charging is assumed to be either opportunity charging or DCFC charging and so recharging time, t_r, is omitted.

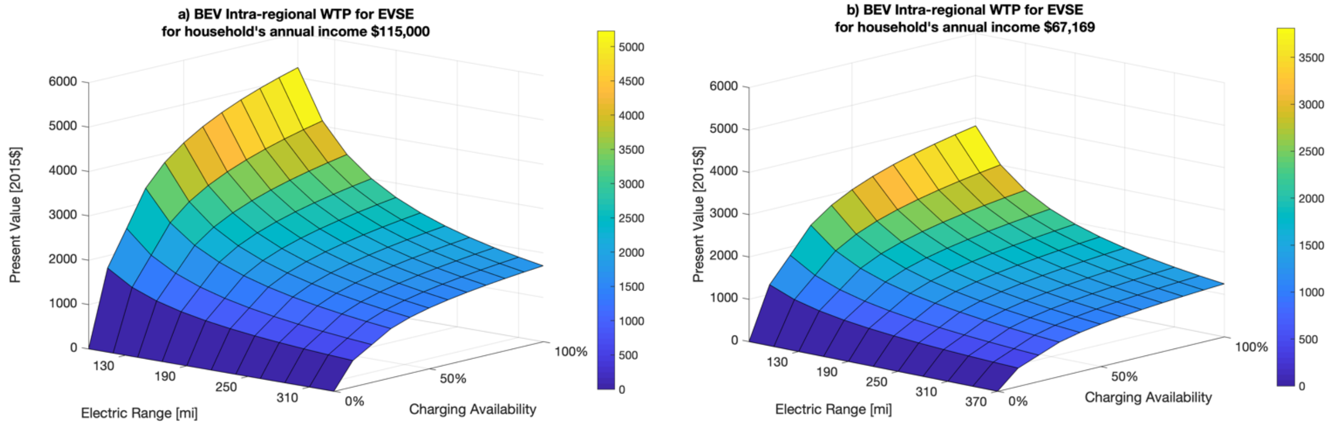

Figure 8. Illustration of BEV WTP for charging infrastructure as a function of range for a household with an annual income of a) $115,000 and b) $67,169.

BEV Inter-Regional Value of DCFC

Inter-regional travel is defined as travel that leaves a metropolitan region. The two logarithmic functions in Figure 9 are based on a Weibull distribution of daily travel (Equation 4) and assume that trips of 100 miles (upper curve) or 150 miles (lower curve) can be accommodated within the region. The parameter values shown correspond to the $\alpha_0 + \alpha_1 ln(I_j)$ portion of Equation 17.

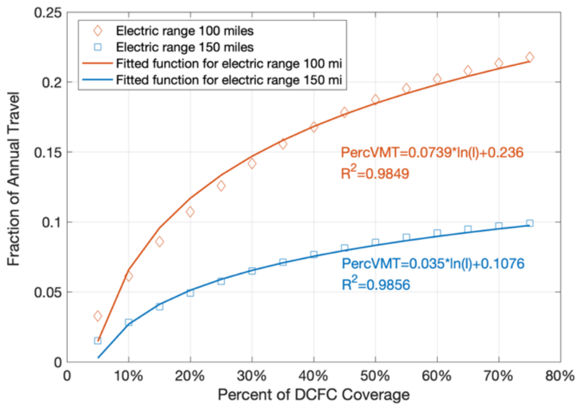

Figure 9. Fraction of annual travel enabled by inter-regional DCFC for intra-regional ranges of 100 and 150 miles.

The first term in round brackets in Equation 17 gives enabled e-miles as a fraction of inter-regional 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 17 and are converted to cost per mile by dividing by practical range, θR. In Equation 17, m is not total miles but only the inter-regional miles that would be traveled in a conventional vehicle.

$$WTP = \left[\left(\alpha_0 + \alpha_1 ln\left(I_j\right)\right)\left(e^{-b(R-R_0)}\right)m_j\left(v_j - \frac{w_j}{\theta R_i}\left(K(\phi^a - 1) + \frac{\theta R_i e_i}{d}\right)\right)\right]D_j \qquad (17)$$

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 (θ100)%.[33]

The estimated value of inter-regional travel enabled by installing DCFC along inter-regional routes is illustrated in Figure 10. A value of $0.36 per enabled mile is used, corresponding to a household income of $115,000. Infrastructure is measured as availability relative to gasoline refueling stations (assumed to represent full availability). Despite the infrequent nature of inter-regional travel, WTP for full availability amounts to thousands of dollars for BEVs with ranges under 150 miles.

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[33] To the extent that the charging for inter-regional travel is convenience charging (e.g., a rest stop) charging time may be omitted.

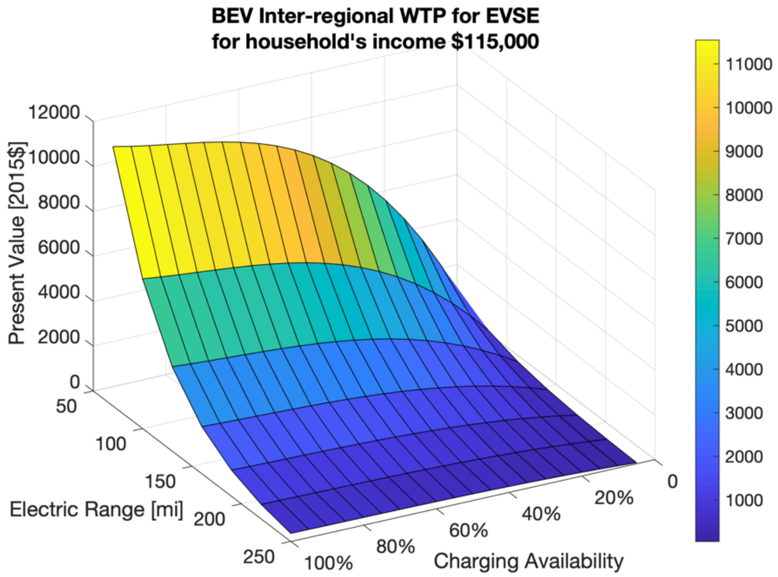


Figure 10. Illustration of value of inter-regional DCFC infrastructure

PHEVs

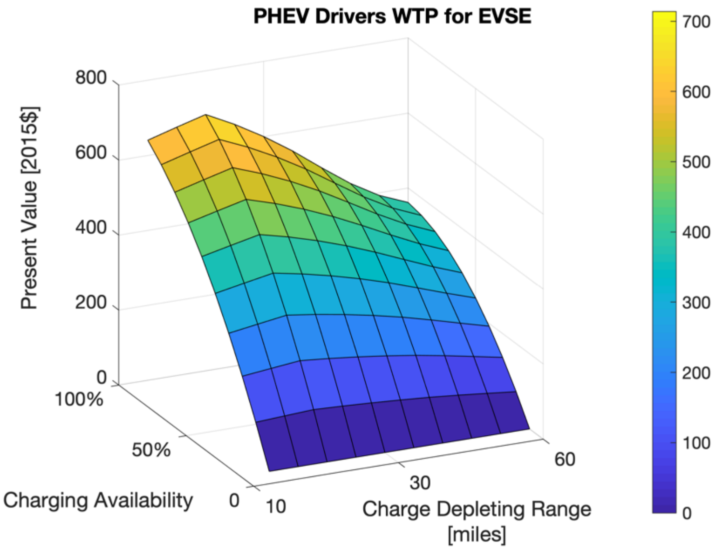
WTP for charging infrastructure for a PHEV is the present value of energy savings from additional miles operated in charge-depleting mode which allow electricity to be substituted for gasoline. It is the product of the following:

- Charge-depleting miles enabled as a fraction of total annual miles, $f(I,R)$, depending on charge-depleting range, R, infrastructure availability, I,
- Annual vehicle mileage, M, where *D* expands annual mileage to lifetime discounted traveled miles,
- Fuel savings per mile operating in charge-depleting, *d*, versus charge-sustaining, *s*, 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,
- i and j index vehicles and geographical locations, respectively.

$$WTP_{ij} = \left[f\left(I_j, R_i\right) - f(0, R_i)\right] M_{ij} \left(p_{jG} e_{iGs} - \left(p_{jG} e_{iGd} + p_{jE} e_{iEd}\right)\right) D_{ij} \quad (18)$$

For PHEVs, public charging infrastructure includes level 2 charging stations, due to the smaller battery capacities of PHEVs and the prevalence of convenience charging.

The quadratic functions shown in Figure 7, linearly interpolated for intermediate PHEV ranges, are used as the function $f(I, R)$ in Equation 18 to estimate the increase in charge-depleting miles as a function of charging availability (here relative to gasoline station availability).[34] PHEV WTP for recharging infrastructure, presented in Figure 11, increases at a decreasing rate with increased charging infrastructure and decreases with increasing nominal charge-depleting range.[35] Given the gasoline and electricity prices noted on the figure's caption, total WTP exceeds $700 present value per PHEV20 vehicle when the number of charging stations approaches maximum charging availability.



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[34] Available battery capacity is implicitly accounted for in Equation 15 because the simulation models accounted for the state of charge, charging rate and battery capacity at each charging opportunity.

[35] The maximum at PHEV20 is a consequence of the particular energy consumption rates taken from Dong and Lin (2012, table 2) and may be an artifact of the specific makes and models of PHEV10 and PHEV20s available at the time the paper was written.

Figure 11. Illustration of PHEV WTP for charging infrastructure as a function of range assuming a gasoline price of $3/gal and an electricity price of $0.15/kWh.

Equations 16-18 estimate the total WTP for charging infrastructure for PHEVs and BEVs for intra- and inter-regional vehicle travel. After suitable calibration for the population of interest, such WTP equations could be incorporated into utility functions of discrete choice models of household vehicle ownership and used to project the impacts of public charging investments on the sales of PEVs sales. Consumers' surplus changes resulting from the provision of additional public charging could also be calculated, providing a critical measure for assessing the costs and benefits of investments in public chargers.

V. California Case Study

The State of California (CA) is leading the way in adoption of PEVs nationally, accounting for 47.38% of the U.S. market in 2016 (IHS Markit, 2017). State and local agencies support light-duty vehicle electrification though various policies, including the Zero Emission Vehicle mandate (CARB 2017), tax credits, rebates, high occupancy vehicle lanes access, and more (AFDC 2018c). Significant investments have been made to support publicly accessible chargers. As of April 2018, 3,939 L2 and 584 DCFC public charging stations (40,699 L2 plugs and 1,762 DCFC plugs) were available throughout the State (AFDC 2018c)[36]. To reach the state's ZEV goals of 1.5 million zero emission vehicles on the road by 2025 between 229,000 and 279,000 publicly accessible plugs will be required (9,000 to 25,000 DCFC) (CEC, 2018a).

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[36] The California Energy Commission's (CEC) Alternative and Renewable Fuels and Vehicles Technology Program spent $80 million deploying 7,695 charging stations of various levels (private and publicly accessible) statewide as of April 2018, of which 3,352 were publicly accessible (CEC, 2018b, Table 12).

In this section, we use CA-specific data (Table 1) to evaluate Equations 16, 17, and 18 and estimate the tangible value of existing public charging infrastructure for PHEVs' and BEVs' intra- and inter-regional travel. The WTP estimates show that the existing public L2 and DCFC infrastructure value to the purchaser of a new BEV in California amounts to thousands of dollars. The outcome 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 PEV owners by extending the utility of their vehicles, but also constitutes an important incentive for increased PEV sales.

The results of the California case study should be considered illustrative rather than definitive. First, although key data are CA representative (e.g., CEC 2018a), the transferability of functions calibrated to other areas is an open question (e.g., Seattle data for Neubauer and Wood, 2014 and Wood et al, 2015). Second, as noted above, it is not clear how best to measure charging availability and, although the metrics we use are reasonable and commonly applied, they are almost certainly not optimal.

We adopt Wood et al.'s (2017a) measure of full public charging availability. They estimate that a density of 56 stations per thousand square miles is sufficient coverage in the early stages of market development. For inter-regional travel, we use CEC's (2018a) estimate that a spacing of 40 miles between charging stations represents full availability on intercity routes.

Table 1. California-specific data for charging infrastructure WTP estimation

Data	Notation	PHEVs	BEVs intra-regional	BEVs inter-regional	Sources
# of L2 stations	-	3,939	-	-	AFDC 2018a
# of DCFC stations	-	-	584		AFDC 2018a
# of DCFC stations along rural highways	-	-	53		AFDC 2018a, Wood et al. 2017a
Annual average VMT [miles]	M_{CA}	14,500			CHTS 2017 – See Figure A1 in Appendix
VMT decrease in miles with vehicle's age	-	3.5% per year			NHTS Household CA, 2017. Automobile/Car/Station Wagon
Annual average inter-regional VMT [miles]	$\widehat{M}_{CA}$	-	-	633	Goulias et al. 2017 – Tables 4.3 and 7.1b
Price of electricity (commercial) [$/kWh]	p_{CA_E}	0.15	-	-	EIAb 2018
Price of gasoline [$/gal]	p_{CA_G}	3.08			EIAa 2018 – all grades avg.
PHEV range [mi]	R_{PHEV}	30	-	-	assumption
BEV range [mi]	R_{BEV}	-	100, 150, and 200		assumption
Gasoline fuel economy [mpg]	e_{CAGs}	27.5	-	-	CHTS 2017
Electricity fuel economy [kwh/mile]	e_{CAEd}	0.32			CHTS 2017
Value of travel time [$/hr]	w_{CA}	13.6		19.04	DOT 2016 – personal travel assumption
Value of e-mile [$/mi]	v_{CA}	0.25			2017 ACS median income for CA [$ 67,169]; US Census Bureau
Battery capacity [kWh]	-	14.33	30	30	assumption: 80% SOC
Charging power [kW]	d	-	-	125	assumption
Discount factor	D_{CA}	7.35			7% discount rate, 13 years of vehicle lifetime; NHTSA & EPA 2018
Median household income [$2017]	-	$67,169			Median income & mean income [$96,104]; US Census Bureau 2017

Based on IHS Markit 2017 data, there were 123,760 PHEVs registered in California and 3,939 public L2 stations to support their daily operations. The majority of currently available PHEVs models can only use L2 plugs so those are only considered for PHEVs drivers. The existing station numbers correspond to an infrastructure availability of 45.15% relative to our measure of full coverage for the State of California. At this level of public charging availability, the total value of the infrastructure is about $400 per vehicle for a 30-mile range PHEV (as shown in Figure 12).

In 2017, there were 133,446 BEVs registered (IHS Markit, 2017) in the 155,779 square miles California region (USGS, 2010) and there were 584 publicly available DCFC stations. Using the Wood et al. 2017 intra-regional coverage metric, the existing stations provide 9,786/155,779=6.70% coverage. The median annual household income of a BEV owner in California is approximately $115,000 (CEC, 2017). Using that income level, the value of the existing intra-regional public DCFC infrastructure is estimated at $1,528, $1,233, and $1,045 per vehicle for BEV drivers with a 100-, 150-, and 200-mile range respectively. The existing charging station infrastructure is estimated to be worth $817 to a new 300-mile driving range BEV purchaser with average household income of $115,000. Using the average household income in the California region, $96,104 (US Census Bureau, 2017), the WTP values for 100-, 150- and 200-mile BEVs intra-regional charging infrastructure are $1,330, $1,083, and $921, respectively. L2 charging infrastructure could also support intra-regional travel in California via workplace or convenience charging. By omitting these stations from the BEV charging infrastructure value analysis, we underestimate the value of existing public charging infrastructure for intra-regional travel.

The inter-regional charging infrastructure value is estimated based on coverage of the 3,128 miles of California's rural highways connecting different urban areas included in the California National Highway System, according to Caltrans (2016) data analysis. There are 53 non-Tesla DCFCs (those can be used by a variety of BEVs makes and models) located no more than 1.0 mile away from rural highways. Assuming a 40-mile optimal spacing of chargers, the existing number of charging stations provide about 67.7% coverage. The value of the existing public charging infrastructure to a new 100-, 150-, and 200-mile range BEV in the California region is estimated at $6,745, $2,581, and $968 respectively, assuming an income of $115,000. However, for income levels comparable to the 2017 median household income in CA ($67,169), the value of existing infrastructure levels is reduced to $4,653 for 100-mile range BEV and to $1,812 and $685 for 150- and 200-mile BEV drivers, respectively.

Sensitivity analysis is conducted to capture the effect of different ranges of PHEVs and BEVs on WTP for a) different electric driving ranges and b) charging station availability (coverage), as shown in Figures 12 and 13, respectively.

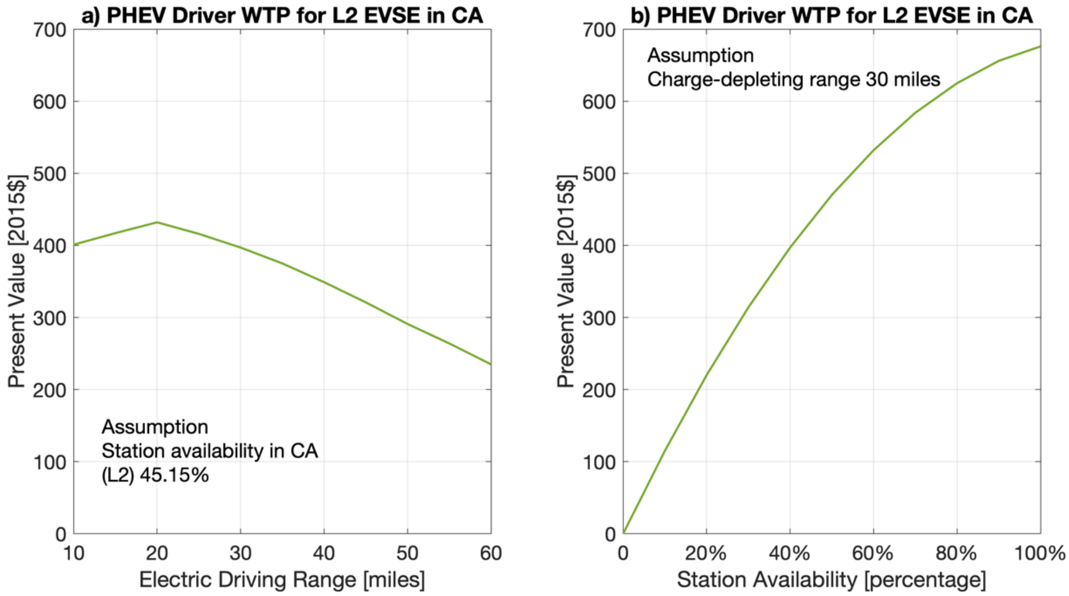

Figure 12. WTP sensitivity for L2 charging infrastructure for California PHEV drivers.

PHEVs' WTP for infrastructure decreases as range increases (when charge-depleting range is greater than 20 miles for 45.15% California-specific L2 charging station coverage. As the charging station coverage increases, WTP for L2 charging increases with diminishing returns, reaching approximately $680 for 100% L2 charging station coverage when the charge-depleting range of the PHEV of the CA driver is 30 miles. Results are based on the mean California household income for 2017, $96,104. Assuming a household income close to the CA median income (as presented in Table 1), the current level of L2 infrastructure is valued close to $400 by a 30-mile charge-depleting range PHEV driver.

CA BEV drivers' WTP for DCFC is greater for inter-regional travel compared to intra-regional travel when their all-electric driving range is less that 200 miles, as shown in Figure 13a, for charging station availability 67.7% and 6.7% respectively. When charging availability is low, corresponding to coverage less than 20% in Figure 13b, WTP for 150-mile and above BEV inter- and intra-regional travel falls below $2,000. The tangible value of DCFC increases as charging availability increases with diminishing returns, for both intra- and inter-regional travel. The magnitude of the value of existing infrastructure for inter-regional travel is above $6,000 when the BEV all-electric driving range is below 100 miles. DCFC value, as compared for 150- and 200-mile BEV electric range in Figure 13b, decreases at a greater rate for inter-regional travel as the all-electric range of the BEV increases. DCFC stations can contribute to greatly enhancing the utility of BEVs to drivers, which can potentially lead to increasing BEV sales and curbing drivers' range-anxiety.

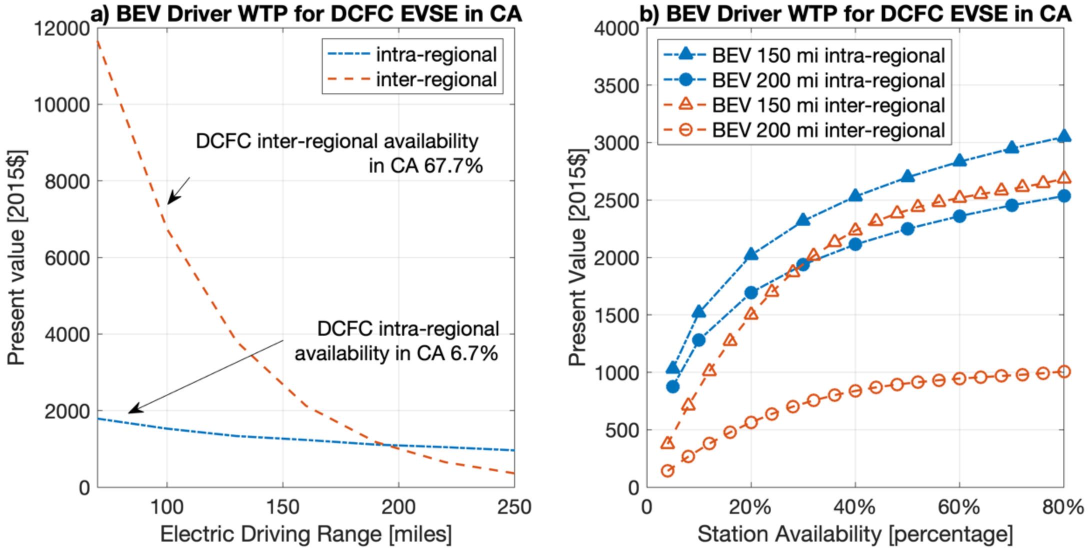

Figure 13. WTP sensitivity for DCFC charging infrastructure for California BEV drivers.

VI. Conclusions, Limitations and Recommendation for Future Research

We have presented a methodology for estimating the value of plug-in electric vehicle public charging infrastructure based on the tangible benefits of enabling additional miles of travel by BEVs and the substitution of electricity for gasoline by PHEVs. The willingness-to-pay (WTP) functions derived here from detailed simulation modeling and econometric estimates of the value of enabled miles of vehicle travel could be incorporated into utility functions of vehicle choice models and used to help project the impacts of public charging investments on future PEV sales. Consumers' surplus changes resulting from the provision of additional public charging can also be calculated, providing a critical measure for assessing the costs and benefits of investments in public chargers. Our methods also incorporate some important sources of heterogeneity in consumers' preferences, including income, annual miles of travel and daily travel distributions.

Our estimates indicate that public charging infrastructure creates substantial value for current and potential future owners of BEVs by increasing their ability to provide mobility and access.[37] Public charging infrastructure appears can offset a substantial fraction of the perceived cost penalty due to BEVs' limited range and long recharging time. Its value appears to be similar in magnitude to the current $7,500 U.S. tax credit for BEVs. The potential benefits for PHEV owners, derived from substituting electricity for gasoline, appear to be substantial although an order of magnitude smaller.

Our methods also have limitations that suggest areas for future research:

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[37] These tangible values can also create intangible values, such as a greater sense of confidence in the future of PEVs, reduced range anxiety, or concern of remained stranded with a depleted battery, or an increased sense of better transportation.

- We assume that public charger availability can be measured by the number of chargers relative to “full availability”. There is no consensus method for estimating full availability for a specific region. How to weigh L1, L2 and DCFCs in calculating availability is also unresolved. Additional research on how PEV owners use public chargers to enable e-miles of travel could provide useful empirical data.
- There is a lack of consensus about how best to measure public charging availability. The literature includes a variety metrics from the ratio of recharging stations to gasoline stations to the number of chargers per mile of intercity highway. It seems likely that additional geographically and temporally detailed simulation and optimization studies for inter- and intra-regional travel, and for different regions and levels of PEV market penetration could lead to the development of appropriate availability metrics.
- The geographic transferability of functions relating enabled e-miles to charger availability has not been investigated. Again, additional simulation and optimization studies using detailed vehicle travel data for different regions could provide insights or possibly functional relationships that could enable calibration of region-specific functions.
- To date, simulation analyses have assumed that the travel behavior of BEV owners will be the same as that of current owners of internal combustion engine vehicles. Future simulations could also be enhanced to allow adaptation of trip making behavior to maximize the benefits of PEVs, for example, by allowing additional stops to recharge.
- The intangible benefits of charging infrastructure are also likely to confer substantial value on PEVs, especially during early market development. Consumer expectations about the permanence and future expansion of charging infrastructure can affect vehicle

choices, and so can the value of public charging infrastructure as insurance against forgetfulness or unanticipated travel requirements. Additional survey research directed at PEV owners and non-owners is needed to quantify such intangible values.

- Redundancy to ensure availability and resiliency also has value but has not been considered in this analysis and is another promising area for research.
- We do not consider the business models or institutional relationships and public policies under which public chargers might be deployed and made available to the public. These are obviously critical to the deployment of charging infrastructure and its viability and could influence their value to consumers if they affect consumers' access.

While our method has limitations, so also do estimates derived from stated choice experiments and discrete choice modeling which, to date, rely on the hypothetical choices of consumers, most of whom are unfamiliar with PEVs and their use. We do not claim that our method will produce the right answer but rather that it provides an alternative perspective based on measurable relationships between charging infrastructure and the utility of PEVs. Quantifying the tangible value of public charging infrastructure in this way provides an alternative perspective on the value of such investments to a heterogeneous population of motorists.

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