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Impact of Observed Travel and Recharging Behavior, Simulated Workplace Charging Infrastructure, and Vehicle Design on PHEV Utility Factors (UF), Total Charge Depleting (CD) Driving and Time of Day (TOD) Grid Demand: Scenarios Based on Consumers' Use of A Plug-in Hybrid Electric Vehicle (PHEV) Conversion

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Scenarios Based on Consumers' Use of A Plug-in Hybrid Electric Vehicle (PHEV) Conversion

By

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ABSTRACT

Plug-in hybrid electric vehicles (PHEVs) can run on gasoline or grid electricity and have been widely touted as promising more future societal and environmental benefits than hybrid electric vehicles (HEVs). However, since the charging of PHEVs will place new loads on the electrical grid, how much and the time of day (TOD) at which users plug in their vehicles will have implications for electricity providers who must meet the additional electrical load required to charge a fleet of PHEVs. PHEV charging could place new burdens on existing electrical infrastructure (substations and transformers) and generating capacity. Information about consumers' recharging behavior can help utilities and interested parties better plan for PHEVS in the marketplace. To date, analysts have made assumptions as to the design of PHEVs that will be purchased, and the travel and recharging behavior of the future users. Furthermore, since PHEVs can run in charge depleting (CD) and charge sustaining (CS) modes there is uncertainty as to how much travel will be completed in each mode due to the variety of possible vehicle designs, access to charging infrastructure, and travel and recharging behavior of PHEV users. Accounting for the amount of travel in each mode is crucial in order to accurately assess the fuel economy (FE) benefits, green house gas (GHG) emissions and costs of PHEVs. In 2001, the Society of Automotive Engineers (SAE) promulgated standard J2841 defining the utility factor (UF) as the percentage of travel that can be completed in CD mode for a PHEV fleet with a given CD range. As such, the SAE standard J2841 has a substantial influence on policies regarding PHEVs and their assumed benefits and costs, and has been used by analysts, industry, and policy makers to calculate PHEV corporate average fuel economy (CAFE), GHG emissions, operating costs and Zero Emission

Vehicle (ZEV) credits. My analysis challenges J2841by calculating the observed UF for a fleet of PHEVs driven by 25 Plausible Early Market (PEM) PHEV buyers in a demonstration and market research project. To estimate the potential effects on the UF of additional charging infrastructure, I model a workplace charging scenario in which each of the 25 households recharges the PHEV at their workplace as well as at home. Lastly, hypothetical consumer designed PHEVs, solicited from each PEM household, are used to create and compare future market scenarios in which consumers are offered a wide variety of makes and body styles of PHEVs—thus simulating a plausible future market in which a variety of PHEVs are offered for sale. The results suggest that promoting "short range" PHEVs and focusing on popular vehicle-types, rather than upon achieving high CD ranges, could lead to greater total benefits from PHEVs in the early market, through more widespread adoption of PHEVs.

Compared to SAE J2841, the observed UFs from the PEM demonstration data are 10 percentage points higher for PHEVs of up to 40 miles of CD range. At 40 miles CD range, J2841 stipulates a UF of 62%; I calculate a UF of 72% from the observed data. The increase in CD driving from adding simulated workplace charging varies by vehicle range, with the largest percentage point increases in CD driving occurring below 20 miles. Workplace charging changes the TOD distribution of power needed to charge a fleet of vehicles, producing a new maximum at 9:30am. The addition of workplace charging under the conditions modeled here does not change the evening peak power demand.

ACKNOWLEDGEMENTS

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INTRODUCTION

Plug-in hybrid electric vehicles (PHEVs) can run on gasoline or grid electricity, and have been widely touted as promising more societal and environmental benefits than hybrid electric vehicles (HEVs) in terms of reductions in fossil fuel use, improved local air quality (Kalhammer et al., 2009; Gonder et al., 2009), and decreases in greenhouse gas emissions (GHGs) depending on the feedstock of the marginal electricity supply used to charge them (McCarthy and Yang, 2009; Benjamin and Hirsh, 2009). In addition since PHEVs have batteries that can be charged from the electrical grid, smart charging and vehicle to grid technologies could potentially increase the overall efficiency of the grid with PHEVs serving as sinks for excess off-peak electricity and power sources to supplement grid electricity in times of peak system demand (Peterson et al., 2010; Quinn et al., 2010). PHEVs can also offer consumers the option to use gasoline to power their vehicle in cases where recharging is not possible, impractical, or not desired by the user.

The following analysis examines the potential impact of a fleet of PHEVs using the observed driving and recharging behaviors of 25 Plausible Early Market (PEM) PHEV buyers observed in a demonstration and market research project in which households drove and charged a PHEV conversion for four weeks. To estimate the potential changes in the Utility Factor (UF), I model a plausible workplace charging scenario in which each of the commuting households plugs in at their workplace. Hypothetical consumer designed PHEVs, solicited from an online survey completed by each PEM household near the end of their vehicle trial, are used to create and compare future market scenarios in which consumers can design their own PHEVs—simulating a market in which a variety of PHEVs are offered for sale. My future market scenarios provide insights into the TOD electricity demand required for a fleet of consumer designed PHEVs with and without workplace charging, as well as the possible tradeoffs between vehicle design, market size and total CD driving. Overall, my analysis advocates the inclusion of better market research and observed vehicle usage patterns into PHEV impact analysis, policy making and PHEV design and points out the shortcomings of current standards (Society of Automotive Engineers (SAE) J2841) based on inadequate travel diary data and assumed recharging behavior, rather than observed PHEV travel and recharging behavior.

Understanding PHEV Technology (CD and CS modes of Operation)

The charge depleting (CD) range of a PHEV denotes the distance in miles that the vehicle can travel on a single full charge of the battery, e.g., PHEV40 represents a PHEV with 40 miles of CD range. Depending on the drive train configuration of the PHEV, CD mode performance, power requirements, and fuel use can vary. In the case of all electric (AE) PHEVs, only electricity is used to power the vehicle during CD mode. In contrast, blended PHEVs use electricity as a primary energy source and a gasoline engine for supplemental power (when battery power alone cannot achieve the performance required) during CD mode, thereby usually significantly reducing gasoline consumption beyond that of a HEV but not providing the electric only CD operation of an AE PHEV. When the CD range is surpassed, all PHEVs revert to charge sustaining (CS) mode, in which liquid fuel (gasoline, ethanol, diesel, etc.) is used to power the vehicle. The transition from CD to CS mode is automatic, and the vehicle can operate in CS mode as long as the liquid fuel is present. Since blended PHEVs require less powerful batteries and power electronics than AE PHEVs, the incremental cost of a blended PHEV drive train is less than that of an AE PHEV (Axsen et al., 2010a). Given the current consumer interest in blended PHEVs with high CD and CS fuel economy, it has been suggested that pursuing blended drive train vehicle designs, and thus giving consumers some electric driving experience, could be a method to increase market demand for electric vehicles and create a path by which light-duty vehicles can be incrementally electrified (Axsen et al., 2010a).

Depending on the vehicle configuration, CD driving can provide significant benefits over CS driving and HEVs. However, the added environmental and social benefits of PHEVs, compared to HEVs, depend on the extent that users operate their vehicles in CD mode (Kurani et al., 2010). Currently, the extent to which PHEV use will lead to the substitution of electricity for gasoline is in doubt. The uncertainty arises from differences in PHEV designs - such as variations in CD range and CD type, (Simpson, 2006; Gonder et al., 2009; Smart et al., 2010) - and, in particular, in households' travel and recharging behaviors (Davies and Kurani, 2010). Daily life provides varying degrees of structure and routine, and any household's use of a PHEV will be incorporated into some established social framework and lifestyle, such as commuting to work, trips to drop off or pick up the children from daycare, or a weekly trip to the grocery store (Kurani et al., 2010). While there may be some degree of predictability in these routines, for most households, the extent to which they will prioritize recharging a PHEV, are able to fit recharging into the context of their established routines, or are willing to create new routines, will vary given differences in lifestyles, understanding of the operating state of the vehicle and technology, access to charging infrastructure, and the perceived benefit and relative importance of plugging in for personal satisfaction or societal benefits (Kurani et al., 2010).

Identifying The Percentage of Travel in CD and CS Modes is Crucial To PHEV Impact Analyses: The Role of The Utility Factor (UF)

Given the two operating states of a PHEV, it is crucial to properly weight the percentage of travel that occurs in CD or CS mode in order to appropriately account for the energy usage, GHG emissions, air pollution, and expected fuel consumption of PHEVs (Gonder et al., 2009; Bradley and Quinn, 2010). To facilitate the testing and evaluation of PHEVs under standardized conditions, SAE established testing procedures for HEVs and PHEVs. According to SAE standard J1711, the fuel consumption of PHEVs (gasoline and electricity) is tested in CD and CS modes independently. In order to produce a single number for the overall expected fleet Fuel Economy (FE) of the vehicle, the CD and CS testing results are then combined using a Utility Factor (UF). Defined in SAE standard J2841, the UF shows the fraction of total daily travel that would be accomplished in CD mode for the entire U.S household fleet (CD miles / total miles) for a PHEV with a given CD range (miles in CD mode with a full charge). For instance, as shown in Figure 1, the SAE J2841 dictates that a PHEV50 would accomplish 70 percent of all daily U.S. household driving in CD mode. The SAE J2841 UF was created using the daily driving distances of 60,000 individuals and 26,000 households recorded in the 2001 National Household Transportation Survey (NHTS). By assumption, each vehicle started the day with a fully charged battery, and was not plugged in for the remainder of the day. As shown in Table 1, (in the following section) Kinter-Meyer et al. (2007) and Duvall (2007) used the same assumptions for recharging frequency.

Figure 1 SAE J2841 Utility Factor (UF) for All U.S. Household Vehicle Travel

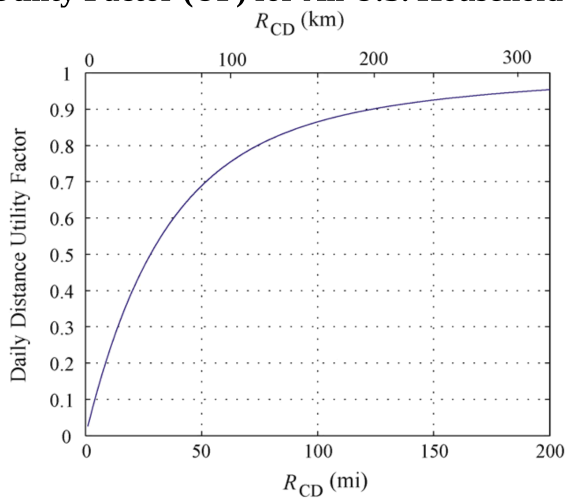


Figure from (Bradley and Quinn, 2010)

Using the UF, the FE of a national PHEV fleet is calculated accordingly:

$$FE_{UFWeighted} = \frac{1}{\left(\frac{UF}{FE_{CD}}\right) + \frac{(1-UF)}{FE_{CS}}} \qquad \text{(Equation 1)}$$

Where FE_{CD} is the FE measured in CD mode on the FTP and HFET test cycles and adjusted for PHEVs according to formulas for EPA's "miles per gallon (MPG)-based approach" shortcut, where the city and highway MPG are calculated accordingly:

$$\text{City MPG} = \frac{1}{0.003259 + \frac{1.1805}{FTP\ FE}} \qquad \text{(Equation 2)}$$

$$\text{Highway MPG} = \frac{1}{0.001376 + \frac{1.3466}{HFET\ FE}} \qquad \text{(Equation 3)}$$

From Equation 1, FE_{CS} is the FE in CS mode as measured by the five cycle testing procedure, in which the fuel use measurements from five drive cycles: FTP, HFET, US06, SC03, and cold FTP are weighted to determine fuel use. The five cycle testing procedure, which has been applied to all 2008 and above model years, was introduced to better reflect real world driving conditions.

The UF and Fleet FE calculations have been used by many analysts to calculate electrical consumption impacts, emissions, fuel costs, and battery lifetime and degradation, such as in Kinter-Meyer et al. (2007) and LeMoine et al. (2008). The SAE J2841 UF is also of particular importance to California state policy, as the state uses the UF to help determine the Zero Emission Vehicle (ZEV) credits and vehicle miles traveled (VMT) allowances for PHEVs as per the following equation (California's Zero Emission Vehicle Program, 2009).

$$\frac{EAER \times (1 - UF_{Rcda})}{11.028} \qquad \text{(Equation 4)}$$

Where the equivalent all electric range (EAER) for blended PHEVs is determined by the test procedure, the UF is the utility factor found in SAE J2841, Rcda is the urban charge depletion range actual, used for AE PHEVs, and 11.028 is a constant.

However, as Davies and Kurani (2010) show, assumptions about PHEV user behavior employed in SAE J2841 may not hold true for actual PHEV usage. Furthermore, it is likely that differences in travel behavior will exist between buyers of new PHEVs and the general automobile owning population of the United States (Bradley and Quinn, 2010). Axsen and Kurani (2010b) suggest that buyers of new PHEVs are more likely to have higher incomes and education levels than those of the general new car buying population. As discussed in a following section, these differences in education and income may produce different lifestyles and, therefore, different activity patterns and driving behaviors. Hence, the use of NHTS travel data may not accurately reflect the usage patterns of typical PHEV buyers.

PHEVs and Their Potential Impact on the Electricity Grid

Since the charging of PHEVs will place new loads on the electrical grid, the time of day (TOD) at which users plug in their vehicles will have implications for electricity providers who must meet the additional electrical load required to charge a fleet of PHEVs with existing distribution (substations, transformers) infrastructure (Stanton and Tsvetkova, 2008). Therefore, additional information about the load shape or the TOD power requirements for early PHEV users will help those policy and decision makers who seek to better understand these energy needs and to target what infrastructure improvements may be needed to support a large scale transition to PHEVs. Prior analyses have assumed pertinent driving and recharging behaviors, e.g., the day-to-day frequency and time of day of charging, combined with various data sources of personal household travel. Table1 summarizes some recent PHEV analyses and their battery size and recharging assumptions. Kinter-Meyer et al. (2007) and Duvall (2007) assume uniform recharging behavior; all PHEVs are fully charged at the start of everyday, but not charged throughout the day. However, as reported by Axsen and Kurani (2010b) and Parks et al. (2007), differences in assumptions as to TOD charging produce very different estimates of electricity grid impacts.

Axsen and Kurani (2010b) and Parks et al. (2007), do not assume TOD and daily frequency, but use daily travel data (though each very differently) to determine the actual arrival times of vehicles at charging locations assumed in each of their scenarios. However, these analyses do assume where PHEV drivers will charge and whether or not they will charge their vehicles at any particular location (and time). To explore the implications of their assumptions, these studies posit recharging scenarios in which all PHEV users are assumed to exhibit the same specific behaviors, e.g., everyone charges at work, or users can only charge at home and do so every time the vehicle stops there, and/or users only charge during off peak periods of electricity demand, etc.

Table 1 Summary of Prior PHEV Recharging Analysis Assumptions

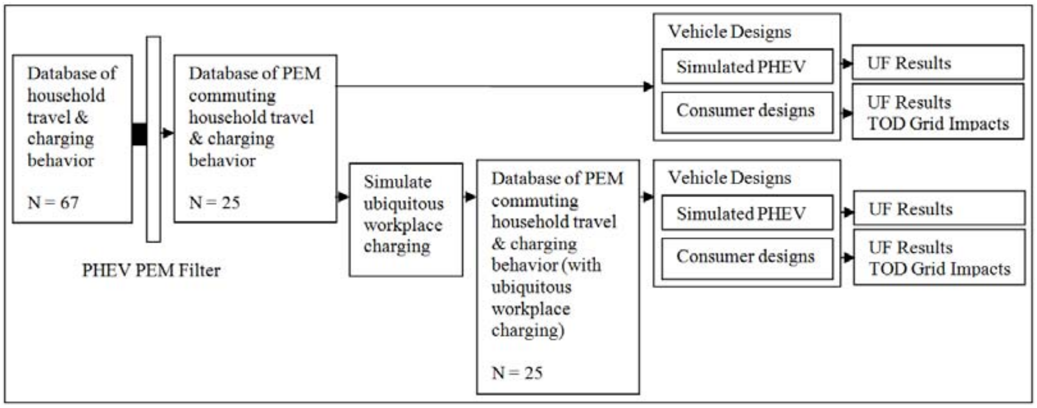
Report	Battery Capacity	Recharge Profile	Charging Frequency
(Kinter-Meyer et al., 2007)	13kWh	100% of PHEV battery capacity, all between 10pm and 6am	Every vehicle, once a day.
(Duvall, 2007)	5.8 kWh &17.9 kWh	76% of PHEV battery capacity recharged between 10pm and 6am 24% of PHEV battery capacity recharged between 6am to 10pm	Every vehicle, once a day.
(Parks et al., 2007)	7.2 kWh	Based on GPS travel data from conventional vehicles. Used multiple scenarios to create an array of recharging profiles including plug-in frequencies	**Uncontrolled Charging:** Charge only at home; plugged-in immediately after the vehicle arrives home until it is fully charged or driven again. **Delayed Charging:** All charging occurs at home, but only after 10 p.m. **Off-peak Charging**: All charging occurs at home overnight, but utility matches vehicle charging precisely to periods of minimum demand. **Continuous Charging:** The vehicle charges whenever it is parked, limited by the battery capacity.
(Axsen & Kurani, 2010b)	1.5 kWh to 15 kWh	Start and stop charging times based on travel diary data from passenger vehicles. Used multiple scenarios to create an array of recharging profiles including plug-in frequency	**Plug and Play (P&P):** The vehicle is recharged every time it is parked within 25ft of an outlet. **Off-peak only:** Vehicle is recharged every time it is parked within 25ft of an outlet, between 10 p.m. and 6a.m. **Enhanced worker access**: P&P plus, recharging occurs while vehicle is parked at work (even if the vehicle is not now parked within 25 ft of an outlet at work.

While assumptions such as these about recharging behavior have been applied to estimate the impacts of a PHEV fleet, there has been little data on how actual PHEV users recharge their vehicles when faced with the recharging options and opportunities available to them. The observations of actual PHEV travel and recharging behavior used in this analysis allow for comparison to prior assumptions, and the exploration of factors that influence recharging behavior and, subsequently, PHEV impacts, such as differences in weekend vs. weekday travel, lifestyle, habits, and access to places to recharge. This study also suggests the extent to which the commuters among the new car buying public may be prepared to consider and accept a PHEV, and to adapt or incorporate PHEV recharging into their individual daily lives.

DESCRIPTION OF METHODOLOGY AND ANALYTICAL PROCESS

My analysis uses a combination of market research, vehicle design assumptions, and a rich data set of observed driving and recharging behaviors to provide impacts of various PHEV designs for a PEM. Changes in vehicle designs, criteria for determining which households belong in the PEM, and additional simulated recharging allow for the comparison of the impact of different infrastructure, market size, and vehicle designs. By these means, I assess the incremental benefit that some changes in any one of these categories could make to the UF or TOD grid impacts of PHEVs. Interviews with PEM participants provide validation of some assumptions. Figure 2 summarizes this analytical process. Additional details about each of the specific parts of Figure 2 are described in greater detail in the following sections.

Figure 2 Analytical Modeling Process



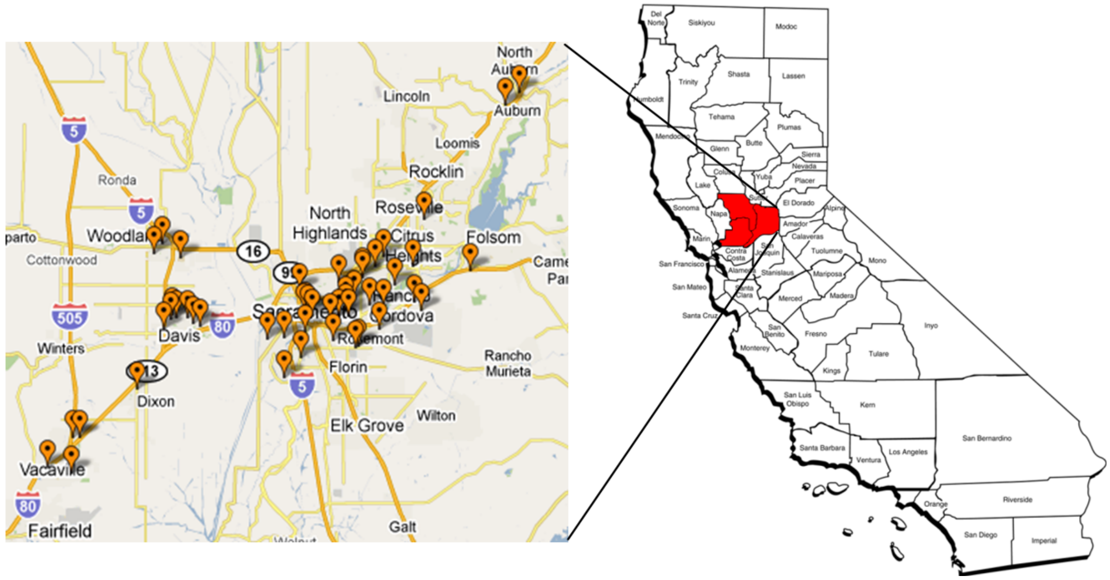
Household PHEV Usage and Market Data Obtained from a PHEV Demonstration Project

A PHEV demonstration and market research project at the University of California at Davis gave 67 households the opportunity to drive a PHEV conversion for four to six weeks each. The project provided one of the first opportunities to observe undirected, real world, consumer PHEV driving and recharging behaviors as well as the technical, behavioral, and social factors affecting recharging behavior (Kurani et al., 2010). Participants were not coached on when, where, or how much to plug in the vehicle, but, upon a household's specific inquiry, they were told that plugging in was something they could do that might reduce fuel consumption, at the expense of added electricity costs.

Participating households substituted an existing vehicle with a Toyota Prius hybrid that was converted to a PHEV using A123 Systems' conversion package. The conversion adds a 5 kWh lithium ion battery that can be charged from a standard 110v/10A household outlet. A fully discharged battery will charge completely within approximately five hours. During CD operation far more electricity is used and substituted for gasoline than in a stock Prius, but the converted car still uses gasoline and electricity more or less continuously under real-world driving conditions. Electric only operation is limited to modest accelerations and speeds less than ~35 mph. The CD range (starting with a fully charged battery) that participants achieved varied from 25 to 35 miles. Once the supplemental battery is discharged, the vehicle switches to CS mode and operates as a normal Prius. (See Lu and Smart (2010) for an in depth description of the Hymotion conversion vehicle.)

The Department of Energy (DOE) Idaho National Laboratory provided Gridpoint, Inc. data loggers. These recorded information regarding gasoline consumption, the vehicle's location, driving distance, battery state of charge (SOC), and energy use. Vehicle driving and charging data were recorded at one second and one minute intervals respectively. Participating households were required to have access to a standard electrical outlet (110V/10A) at their home where they could charge the vehicle, if they chose to do so. They were also responsible for paying all gasoline and electricity costs. Geographically, the participants lived in the cities and towns along Interstate 80 in Northern California, including Solano, Yolo, Sacramento, and Placer counties, as shown in Figure 3 below. The participants varied in their prior understanding of electric drive vehicles, beliefs about political and environmental issues, vehicle ownership, employment status, presence or absence of children in the household, levels of education and income (Kurani et al., 2010). The participants are distributed similarly to the sample of new car buying Northern California households in Axsen & Kurani (2010b).

Figure 3 Geographic Distribution of All PHEV Demonstration Participants



Plausible Early Market (PEM) Derived from Surveys and Interviews of PHEV Demonstration Participants

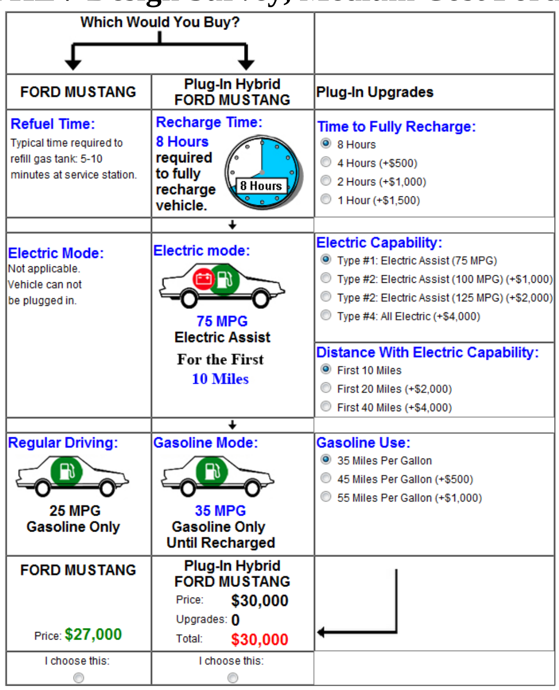
Based on survey responses and in depth interviews, out of those 67 households who took part in the PHEV demonstration and market research project, a subset of 25 have been classified as plausible early market (PEM) consumers. For the purpose of this study the PEM is defined as those demonstration participants who purchased a new vehicle within the last five years, designed a PHEV sedan or truck in the medium and high cost scenarios respectively of the PHEV design game (described in greater detail below) and who also routinely commuted to a workplace in the PHEV. These criteria create a filter by which the subset of 25 PEM households were selected from the 67 households who participated in the UC Davis PHEV demonstration and market research project.

Near the end of their four weeks' driving experience with the PHEV conversion, each of the 67 participants took part in a multi-stage online survey, similar to that used by Axsen and Kurani (2010b). In the first step of the survey each household was asked to specify if they were considering purchasing a new vehicle within the next five years, and, if so, which vehicle they were currently interested in buying. Households were allowed to choose any vehicle in the new car fleet as their “base” vehicle. They were then presented with the option of upgrading the drive train of the vehicle they selected from the standard internal combustion or hybrid to a plug-in hybrid. Participants were next given the ability to customize their PHEV by choosing among options for CD range, CD type (AE or Blended), and the maximum time required to fully charge the battery.

Participants were also presented with purchase scenarios distinguished by low, medium, and high prices; the order in which price levels were presented was randomized across respondents. Households who chose to purchase a truck, SUV, or minivan faced higher upgrade costs, commensurate with the increased battery costs for a larger and heavier vehicle. Figure 4 shows a screen shot of the medium cost PHEV design section of the survey. In this example, a Ford Mustang is selected as the likely next new vehicle with a purchase price of $27,000 specified by the respondent. The option is to upgrade the vehicle to a base PHEV with the following performance: 10 mile CD range; CD FE of 75 mpg, i.e., a blended CD PHEV; CS FE of 35 mpg (the conventional Mustang’s FE of 25 mpg as specified by the respondent plus 10 mpg); and 8 hour recharging time. The price premium in the mid-price game is $3,000, for a total price of $30,000 for the “Ford Mustang PHEV.” Further upgrades can also be made to each of the PHEV characteristics as shown in Figure 4.

More details on upgrade costs and survey design can be found in Axsen and Kurani (2010b). The vehicle design exercises gave households the opportunity to explore and express their interest in buying a PHEV, as well as identifying the PHEV attributes they currently found most attractive. While the actual distribution of PHEVs offered to consumers, i.e., brand, size and models, as well as societal values, vehicle and energy prices will affect the ultimate size and composition of the PEM commuter market, the set of households that represent this "market" here is useful for illustrating the potential effect of driving and recharging behaviors, infrastructure, and vehicle designs on the UF and TOD grid impacts.

Figure 4 PHEV Design Survey, Medium Cost Ford Mustang



Screenshot from Vehicle Design Survey (Axsen and Kurani, 2010b)

The homes of the 25 PEM commuting households, on which the remainder of this analysis is based, were distributed along the I-80 and CA-50 corridors in the Davis and

Sacramento regions. While most households worked in the greater Sacramento area, some commuted to Vacaville, Auburn, Woodland and Folsom.

Figure 5 Location of PEM Homes (yellow symbol) and Workplaces (blue & grey

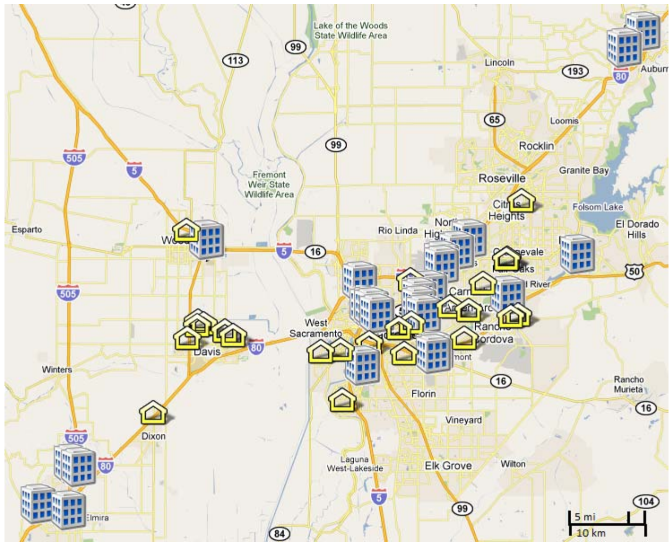


Table 2 summarizes the PEM's demographic information and makes a comparison to the 67 households in the Demonstration and Market Research project, a northern California sample of new car buyers obtained in 2007, and to the 2001 NHTS. In comparison to the 2001 NHTS, the PEM commuter group used in this analysis tends to be older, with a greater level of education, and with a much higher proportion of the sample earning over $100K a year. Differences in vehicle ownership are also observed, with approximately 25 percent of the PEM households owning a hybrid vehicle. Given that the actual demographics of the PHEV market are currently unknown, it cannot be judged if the households shown in the PEM are representative of a future PHEV buying population. However, the demographic differences observed between the general car owning population and the subset of the PEM households (see Table 2) suggest that the two groups lead different lifestyles, and thus, could have much different travel patterns. Therefore, using NHTS data as representative of the driving of PHEV owners may be incorrect.

Table 2 Comparison of PHEV Demonstration Participant's Demographic Information to General Samples

Group		PHEV Demonstration		New vehicle buyers			General population	
Year		2008 – 10	2008-10	2007	2007	2001	2005-7 ACS [f] (Cal.)	2000 Census [g] (Cal.)
Data source		PHEV Demo PEM Commuters	PHEV Demo All Participants	PHEV Survey (Nor. Cal.)[a]	PHEV Survey (Cal.)[a]	NHTS[b] (Cal.)		
Sample size		25	67	216	851	389		
Hybrid owner?	Yes	24%	16.4%	8.9%	10.6%	-	-	-
Gender[c]	Male	43.5%	47.5%	59.7%	48.5%	44.5%	50.0%	49.7%
	Female	56.5%	52.5%	40.3%	51.5%	55.5%	50.0%	50.3%
Education[d]	High school or lower	4%	4.6%	2.6%	8.8%	22.1%	43.0%	43.3%
	Some college	20%	23.0%	34.9%	33.9%	22.1%	20.4%	22.9%
	College degree	36%	37%	32.8%	39.5%	39.9%	26.3%	24.2%
	Graduate degree	40%	35.4%	29.7%	17.8%	15.9%	10.4%	9.5%
Age[c]	15 to 24	8.7%	4.2%	4.6%	3.3%	6.5%	19.0%	18.3%
	25 to 34	6.5%	8.3%	21.1%	20.5%	18.0%	18.3%	19.8%
	35 to 44	26.1%	28.3%	27.3%	29.0%	23.5%	19.3%	21.6%
	45 to 54	26.1%	28.3%	29.4%	23.7%	24.8%	17.6%	16.5%
	55 to 64	30.4%	26.7%	10.8%	15.1%	13.3%	12.1%	9.9%
	>64	2.2%	6.4%	6.7%	8.3%	13.8%	13.8%	13.8%
Household income[d]	< 30 k	0%	1.6%	1.8%	2.0%	6.3%	25.3%	31.2%
	30 k to 60 k	8.3%	14.0%	11.9%	17.6%	3.4%	25.8%	9.5%
	> 60k to 100k	16.7%	28.1%	35.1%	27.7%	32.3%	23.0%	22.1%
	> 100k	75%	56.3%	51.2%	52.7%	38.0%	25.8%	17.3%
	Mean income[e]	$118,208	$112,031	$106,949	$104,814	$84,416	$73,944	$61,441
Housing type[e]	Detached house	96.0%	91.0%	71.3%	68.1%	79.4%	58.0%	
	Attached house	4%	7.5%	10.3%	11.9%	4.4%	7.0%	
	Apartment	0%	0%	17.9%	16.7%	13.6%	30.7%	
	Mobile home	0%	1.5%	0.5%	3.4%	2.6%	4.2%	

Table adapted from Kurani et Al. (2010)

a weights provided by Harris Interactive.
b NHTS sample limited to responding California households that had purchased a vehicle of model year 2001 or 2002.
c For PHEV Project: data reported for all participants; for PHEV survey: data only reported for responding member of household.
d Incomes are in constant dollars.
for PHEV Project and PHEV survey: data only reported for responding member of household.
e Mean approximated from the product of middle values assigned to each income category and the proportion of the sample in that category.
f 2005-2007 American Community Survey 3-year estimates, California
g 2000 Census by the U.S. Census Bureau

Vehicle Battery and Charging Specifications of PEM-designed PHEVs

Households designed hypothetical PHEVs by stipulating a make and model of vehicle they thought they might buy next, then, if they chose to do so, designing a PHEV version of the vehicle by specifying CD range, CD FE, CS FE, and charging time. In order to estimate the impacts of these PHEV designs, each of the possible design permutations were matched to battery and charging specifications, shown in Tables 3 and 4.

The estimates for battery specifications are those used in Axsen et al. (2010a), for peak power, peak power density, total energy capacity and total energy density. The estimates for battery size and energy per mile are based on vehicles that are modeled on the US06 drive cycle. While the US06 is the most aggressive of the drive cycles used to estimate the fuel and emission use of light duty vehicles, the battery energy figures do not take into account the particular driving styles of our households, and thus there is no variation in the observed CD range, either as a result of more aggressive or more efficient driving.

The charging specifications are based on the DC power required to fully charge the PHEV shown in a given amount of time. However, the minimum charging power for vehicles was assumed to be 1.0 kW, which is within the capabilities of a standard household outlet.

Table 3 Battery Specifications for Survey Design Vehicles

CD Type	Units	CD Range in Miles					
		Car			Truck[a]		
		10	20	40	10	20	40
B *(75 mpg)*							
Peak power[b]	kW	27[c]	27[c]	27[c]	39	39	39
Peak power density	W/kg	453	340	227	653	490	326
Total energy capacity[d]	kWh	1.5	2.9	5.8	1.9	3.7	7.4
Total Energy density	Wh/kg	24	36	48	31	46	62
B *(100 mpg)*							
Peak power[b]	kW	37[c]	37[c]	37[c]	53	53	53
Peak power density	W/kg	613	460	307	883	662	442
Total energy capacity[d]	kWh	1.7	3.4	6.8	2.2	4.4	8.7
Total energy density	Wh/kg	28	43	57	36	55	73
B *(125 mpg)*							
Peak power[b]	kW	43[c]	43[c]	43[c]	62	62	62
Peak power density	W/kg	720	540	360	1037	778	518
Total energy capacity[d]	kWh	2.3[e]	4.6[e]	9.1[e]	2.9	5.8	11.6
Total energy density	Wh/kg	38	57	76	49	73	97
AE							
Peak power[b]	kW	96[f]	96[f]	96[f]	138	138	138
Peak power density	W/kg	1600	1200	800	2304	1728	1152
Total energy capacity[d]	kWh	3.8[g]	7.5[g]	15[g]	4.8	9.6	19.2
Total energy density	Wh/kg	63	94	125	80	120	160

Figure from Axsen and Kurani (2010a and 2010b)

[a] A "truck" is assumed to require 28 percent higher electricity use and 44 percent higher Peak power relative to a "car," as approximated from Graham et al.'s (2001) and Duvall et al.'s (2002) estimates for mid-sized car and mid-size SUV PHEV20s.

[b]Assuming motor efficiency of 85 percent.

[c] Peak power approximated from Burke and Van Gelder (2008) simulations for Toyota Prius with US06 drive cycle- multiplied by 1.36 to scale from ~1300 to ~ 1600 kg car.

[d]Assuming DOD of 80 percent.

[e] Energy use approximated from Burke and Van Gelder (2008) simulations for Toyota Prius with US06 drive cycle – multiplied by 1.16 to scale from ~ 1300 to ~1600 kg car.

[f] Peak power approximated from Kromer and Heywood (2007) simulations of optimized Toyota Camry with US06 drive cycle, assuming 85 percent motor efficiency- multiplied By 1.36 to scale from ~1300 to ~ 1600 kg car.

[g] Energy use approximated from Kromer and Heywood (2007) simulations of optimized Toyota Camry with US06 drive cycle, assuming 85 percent motor efficiency- multiplied By 1.16 to scale from ~1300 to ~ 1600 kg car.

Table 4 DC Charging Power Estimates for Designed Vehicles, in kW

CD Type	Charging Time	CD Range in Miles					
		Car			Truck		
		10	20	40	10	20	40
B *(75 mpg)*							
	8 Hours	1.0	1.0	1.0	1.0	1.0	1.0
	4 Hours	1.0	1.0	1.5	1.0	1.0	1.9
	2 Hours	1.0	1.5	3.0	1.0	1.9	3.7
	1 Hour	1.5	2.9	5.8	1.9	3.7	7.4
B *(100 mpg)*							
	8 Hours	1.0	1.0	1.0	1.0	1.0	1.0
	4 Hours	1.0	1.0	1.7	1.0	1.1	2.2
	2 Hours	1.0	1.7	3.4	1.1	2.2	4.4
	1 Hour	1.7	3.4	6.8	2.2	4.4	8.7
B *(125 mpg)*							
	8 Hours	1.0	1.0	1.2	1.0	1.0	1.5
	4 Hours	1.0	1.2	2.3	1.0	1.5	2.9
	2 Hours	1.2	2.3	4.6	1.5	2.9	5.8
	1 Hour	2.3	4.6	9.1	2.9	5.8	11.6
AE							
	8 Hours	1.0	1.0	1.9	1.0	1.2	2.4
	4 Hours	1.0	1.9	3.8	1.2	2.4	4.8
	2 Hours	1.9	3.8	7.5	2.4	4.8	9.6
	1 Hour	3.8	7.5	15.0	4.8	9.6	19.2

Common Week of Driving and Recharging

The PHEV driving and recharging behaviors used in this analysis are taken from one week of each household's experience with the PHEV conversion. Since households were allowed to experiment with the vehicle, recharging behavior changed over time, as did the households' understanding of how they would use this vehicle if they actually owned it, and which household member would chiefly drive it. The week of driving and recharging used in this analysis was selected with the help of the households, and represents a week from each of these households' lives. Infrequent, extended away from home travel was not sampled. However, since the PHEV was a new vehicle introduced into the household, and had a CS FE higher than or equal to the household's own vehicles, the PHEV became the vehicle of choice in many households and often replaced more than one of the household's existing vehicles. From the household interviews, it is judged that such behavior would likely continue if the household actually owned the PHEV.

Given these complexities of vehicle substitution within households, I submit that actual PHEV travel data, such as used in this analysis, is more likely to be a better representation of actual PHEV usage than NHTS or similar travel diary surveys which routinely follow a specific family member, instead of a vehicle, and thus do not capture usage of specific vehicles within a household.

The selection of a week of travel and recharging provides a common number of days and days of the week to analyze across households. Although each household took part in the demonstration for four to six consecutive weeks within the study period of August 2008 to April 2010, the data from all PEM households are aggregated into a single week, i.e., the data are treated as if they all are drawn from the same calendar week.

Compared to the 2001 NHTS data used in SAE J2841, my small PEM sample size limits the application of the specific results. However, the depth and continuity of a single travel week for each household, compared to the single day snapshot of the NHTS, is at least conceptually capable of providing insights into “life-is-lived-over-time” reality. The use of the NHTS data to establish UF standards is conceptually wrong precisely because it is based on, and limited to a single day of travel data. As postulated by Lin and Greene (2011), the use of a single day of travel data skews the distribution of daily vehicle miles traveled (VMT) to the right, increasing VMT and thus overestimating CS driving and underestimating PHEV benefits.

Simulated Vehicle Recharging by Location

The onboard data loggers regularly recorded each vehicle’s longitude and latitude at approximately one second intervals. From these, a complete travel record of trip start and end points and dwell times between trips is constructed for each vehicle. Knowing the location of the vehicle at all times allows for the simulation of unobserved charging at specific vehicle locations. This provides insights as to the potential of additional away from home charging infrastructure to change the UF of a PHEV of a given CD range, as well as changing the TOD impact on the electrical grid.

The potential for away from home charging infrastructure to increase the UF has yet to be examined in any significant detail. The potential ability of additional infrastructure to increase CD driving is related to a number of factors. The “recharge potential” of any given away from home charging station depends on circumstances such as the frequency with which vehicles use the location, daily driving distance, at home recharging behavior, the state of charge of the vehicle when it arrives at the charging spot, the length of time the vehicle is plugged in, and the charging rate.

My analysis is designed to show the maximum potential and impact of workplace recharging on the UF and TOD grid demand. In order to model electricity availability, power demand, and CD driving as a result of additional workplace recharging, the following assumptions are made. First, it is assumed the frequency and start time of households' at home recharging behavior does not change and that all workplace recharging is supplemental to the observed at home recharging. Secondly, the PHEV is assumed to be plugged in every time it arrives at work, even if this happens more than once per day. Workplace charging infrastructure may not be used at every given opportunity, especially in the case of those households who do not exceed their daily CD range. However, the three households who actually charged at work plugged in their vehicles for 99 percent of the time that they were parked at their workplace, although each of those households' daily driving exceeded the CD range of the PHEV conversion. Thirdly, for the market scenarios, the charging rate is based on each household's hypothetical PHEV design. While most households designed PHEVs that could recharge at level 1 (110v/10amps), those two households who designed vehicles that required level 2 charging (220v/20amps) were assumed to charge at that rate at home and at work.

Excel Spreadsheet Model Used To Track Battery Energy Flow

An excel spreadsheet model was developed to track the flow of energy to (charging) and from (driving) the battery based on each household's unique travel and charging data. Based on the battery capacity at the beginning of each trip, the proportion of the total CD miles for each trip and in total is calculated. The model interface allows all specifications regarding charging time, CD range, and per mile energy use to be customized; default values based on those from Tables 3 and 4 can be also be selected. Workplace charging events are simulated by inserting a charging event each time a trip ends at the GPS coordinates of the household's workplace. As such, changes in the UF for each household are estimated given changes in any of the above parameters.

RESULTS

Observed PHEV Conversion Usage

The following section describes the observed usage of the PHEV conversions by the 25 PEM commuting households. This section provides a baseline of PHEV driving and recharging, as well as a demonstration of the methods used to document and analyze the impacts of PHEV user behaviors. Households were each asked to substitute a PHEV conversion for one of their existing vehicles for four to six weeks. Researchers were careful not to influence households' use of the vehicle, allowing participants to figure out how to use the vehicle in the context of their own lives. As such, the following analysis provides a measure of households' undirected real-world use of a PHEV.

The context for interpreting the observed PHEV recharging behavior is as follows. Firstly, all of the participants were able to recharge a PHEV at their home. Secondly, since households reported that they lacked a sense of the etiquette or rules of behavior that would shape recharging at away-from-home locations, less away-from-home recharging was observed than may otherwise occur in a world where the rules and conventions are known. Households who noticed "Electric Vehicle (EV) parking" and charging spaces often asked us whether they were allowed to park and charge their

PHEVs in such spaces. The few bolder individuals who attempted this discovered that such spaces lacked 110-volt outlets suitable to recharge the PHEVs they were driving. Many households also said they were uncertain of the propriety of asking friends, acquaintances, employers, and business-owners if they could plug in. In one household, plugging in at work would have required a participant to take her boss's reserved parking space. Thirdly, no household paid for electricity based on TOD electricity tariffs which might have encouraged, or discouraged, recharging at different times of day (and, therefore, possibly at different locations). Fourthly, participants had to find recharging opportunities within the existing network of electrical infrastructure, meaning that they were restricted to existing electrical outlets and the electrical extension cord (50 feet; 15.24 meters in length) provided with the vehicle. In practice, we found participants were very conscious of the cord as a tripping hazard, and were also reluctant to use it away from the home for fear it would be stolen.

Observed Driving and Recharging Behaviors

Table 5 shows summaries of the observed driving and recharging behaviors of all 25 PEM households: the total travel and average number of times each household plugged in during the selected consecutive five weekdays and two weekend days. Households drove anywhere from 109 to 449 miles over the seven days: the median and average weekly driving distances were 205 and 239 miles, respectively. The average daily charging frequency for each household was calculated by dividing the total number of recorded charging events by the number of days. Charging events were registered by the onboard loggers each time the household plugged in the vehicle; thus, not all charging events were full charges of the battery.

Figure 5 also distinguishes between those households who were able to plug-in at work during their PHEV trial (three) and all of the other households (22) who commuted to work but were unable to, or did not plug in, once they arrived.

Table 5 Summary of All Households' Week of Driving and Recharging

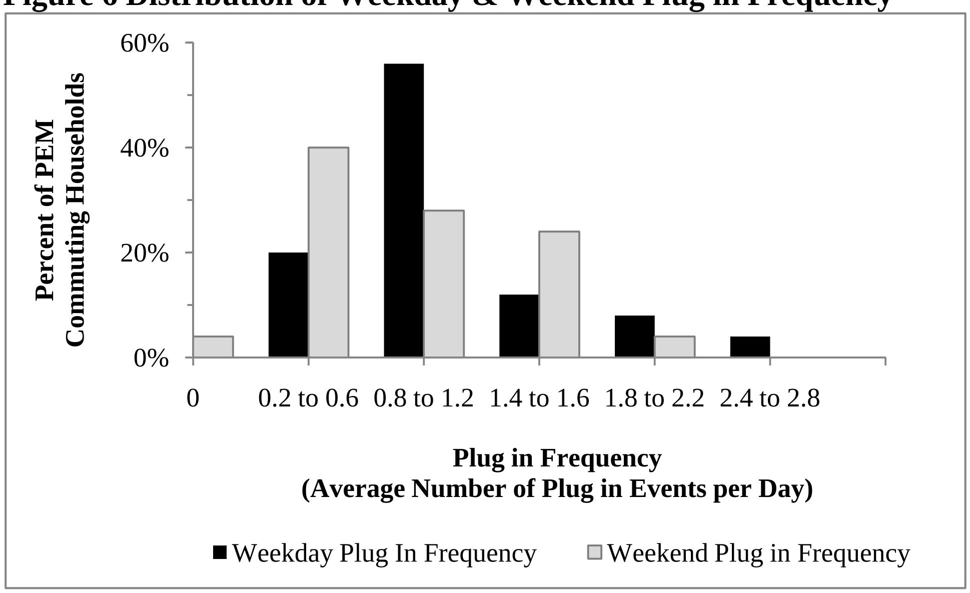
Household	Weekday Driving (Miles)	Weekend Driving (Miles)	Total Driving (Miles)	Weekday Charging Frequency (Plug in events/day)	Weekend Charging Frequency (Plug in events/day)
1	96	13	109	0.4	1.0
2	122	36	159	0.6	0.5
3	73	73	146	0.8	1.5
4	360	72	431	1.2	1.5
5 [a]	321	38	359	2.8	0.5
6	180	90	270	1.0	1.0
7	245	3	248	0.8	0.5
8	178	22	200	1.0	0
9	114	38	152	1.4	0.5
10	126	17	143	1.2	1
11	227	191	418	1.0	2
12 [a]	196	54	250	1.8	1.5
13	153	5	158	1.0	0.5
14	120	35	155	0.4	0.5
15	161	45	206	0.6	0.5
16 [a]	223	107	330	2.0	1.0
17	135	13	148	0.8	0.5
18	121	94	215	0.6	0.5
19	367	81	448	1.0	1.0
20	166	39	205	1.4	1.5
21	185	203	388	0.8	1.0
22	111	41	152	1.6	1.5
23	138	44	182	1.0	1.0
24	327	28	355	0.8	0.5
25	93	56	149	1.0	1.5
Total	**4,538**	**1,438**	**5,976**	**1.08**	**0.92**

[a]Indicates households recharged at work during the week of driving and recharging shown here.

Users differed in the average number of times they plugged in the PHEV conversion per day, with weekday and weekend charging frequency ranging from 0.4 to 2.8 and 0 to 2.0, respectively. Figure 6 presents the observed charging frequencies for weekdays and weekend days as a histogram. Since there are a different number of weekdays and weekend days used in the analysis (five weekdays and two weekend days), Figure 6 clusters the observed charging frequencies into ranges so the two data sets can be compared.

Overall, on weekdays about 55 percent of the 25 PEM households plugged in the PHEV once a day on average, 20 percent did so every other day, and 25 percent did so more than once per day. The average weekday plug in frequency was observed to be 1.08, but the distribution has a longer tail toward higher daily frequency. On weekends, most PEM households plugged in at least once, and most only plugged in once during the two weekend days. They rarely plugged in more than 1.5 times a day on weekends. The figure reveals the possible differences between weekday and weekend vehicle usage and the implications for charging frequency.

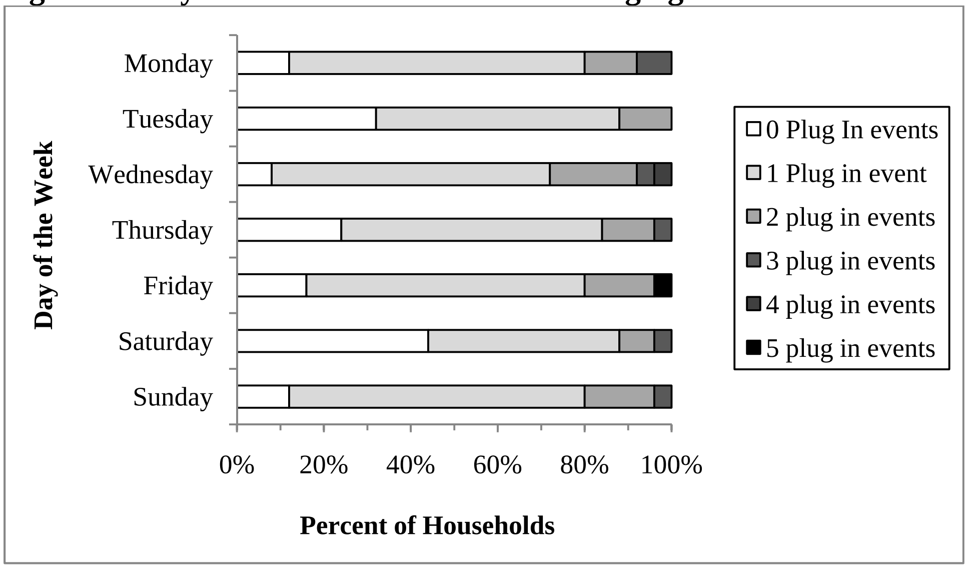
Figure 6 Distribution of Weekday & Weekend Plug in Frequency



The three households that recharged at their workplace during their PHEV trial tended to plug in as soon as they arrived at work, and, if they used the car to leave during the day, they tended to plug in again after returning to work. They typically would recharge again at home in the evening. Three other households who did not have access to workplace charging still plugged in the car more than once a day on average, and reported making conscientious use of opportunities, such as plugging in as soon as the vehicle arrived at home in order to receive a partial charge before going out again later in the evening. They also consciously delayed trips until the vehicle had had a chance to recharge.

Looking at individual days of the week in Figure 7, households plugged in between zero to five times a day. On any given day, between eight and 44 percent of households did not plug in at all. Comparing weekdays, I observed a low of 0.74 plug in events per vehicle on Tuesday and a high of 1.22 plug in events per vehicle on Wednesday. Comparing weekdays, I observed a low of 0.74 plug in events per vehicle on Tuesday and a high of 1.22 plug in events per vehicle on Wednesday. Comparing weekend days, charging frequency differed, averaging 0.67 on Saturday and 1.04 on Sunday. Such differences in charging frequency are indicative of possible variations in routine, and consequently in vehicle usage. The high proportion of households not plugging in on Saturday indicated away from home travel (and consequent absence from the primary charging infrastructure), lack of routine, or simply that the vehicle wasn’t driven.

Figure 7 Daily Distribution of Observed Charging Events



Observed CD Driving and Energy Consumption

Table 6 shows the CD driving accomplished by each household for weekdays and weekend days respectively, with the accompanying plug in frequency, and total AC energy. Overall, households achieved between 41 to 100 percent of their week's miles in CD mode at the expense of 15 to 38 kWh of electricity.

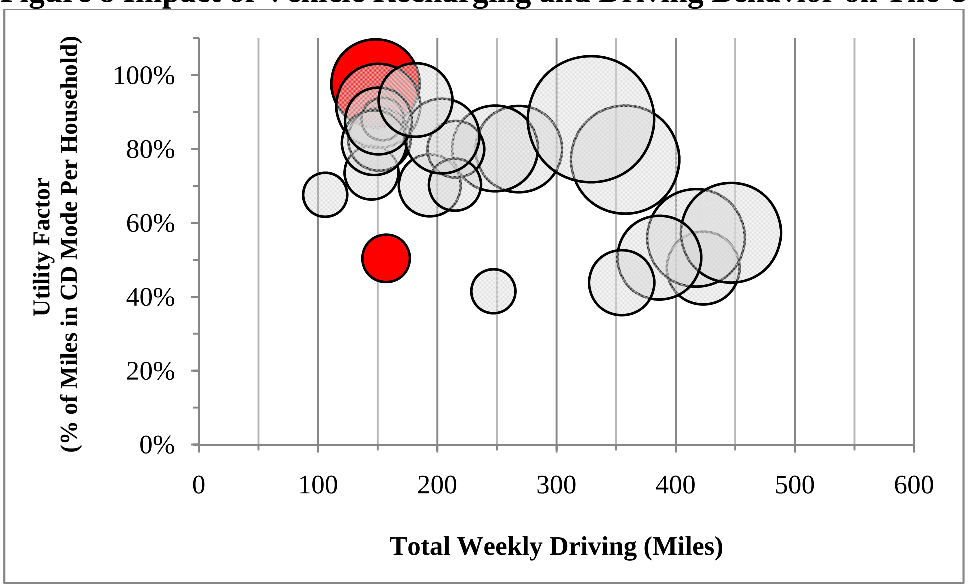
Table 6 Summary of All Households' Week of Driving and Recharging

ID	Total Driving (Miles)	UF (%CD Miles for the week)	Total DC Energy Consumption (kWh)	Mean Weekday Charging Frequency (Plug in events/day)	Mean Weekend Charging Frequency (Plug in events/day)
1	109	64	15.4	0.4	1.0
2	159	47	16.5	0.6	0.5
3	146	82	18.8	0.8	1.5
4	431	53	25.4	1.2	1.5
5 [a]	359	77	37.7	2.8	0.5
6	270	98	30.1	1.0	1.0
7	248	41	15.4	0.8	0.5
8	200	67	21.5	1.0	0
9	152	97	29.3	1.4	0.5
10	143	100	25.2	1.2	1
11	418	67	34	1.0	2
12 [a]	250	75	29.9	1.8	1.5
13	158	83	21.8	1.0	0.5
14	155	99	14.8	0.4	0.5
15	206	82	19.8	0.6	0.5
16 [a]	330	98	44.0	2.0	1.0
17	148	80	22.6	0.8	0.5
18	215	87	18.2	0.6	0.5
19	448	53	34.9	1.0	1.0
20	205	80	26.1	1.4	1.5
21	388	73	29.2	0.8	1.0
22	152	89	23.3	1.6	1.5
23	182	96	25.7	1.0	1.0
24	355	46	22.7	0.8	0.5
25	149	99	30.8	1.0	1.5
Total	**5976**	**74**	**633.1**	**1.08**	**0.92**

[a] Household recharged at work during the week of driving and recharging summarized here.

Differences in PHEV drivers' recharging behavior and in the vehicle's per mile electricity consumption affects the UF. To depict and compare the impact of driving and charging on the UF, Figure 8 plots each household as a circle, with regards to weekly driving distance (x-axis), the UF achieved (y-axis), and the total AC energy consumed (represented by the width of the circle). At any given distance driven, as the UF increases, so does total electricity consumption. The effect of additional charging is moderated by driving behaviors. Driving behaviors which lead to high per mile electricity consumption, such as stop and go driving, heavy traffic, high speeds, and aggressive accelerations will decrease the UF, while driving behaviors and conditions which lead to lower electricity per mile consumption can increase the UF. Overall, differences in driving and recharging behaviors between households driving approximately the same distance impacted the UF as much as 50 percentage points, as illustrated by the two sets of household data that are presented in red in Figure 8 below. Both households drove similar total weekly distances, between 143 and 159 miles, but achieved very different UFs of 100 and 47 respectively.

Figure 8 Impact of Vehicle Recharging and Driving Behavior on The UF

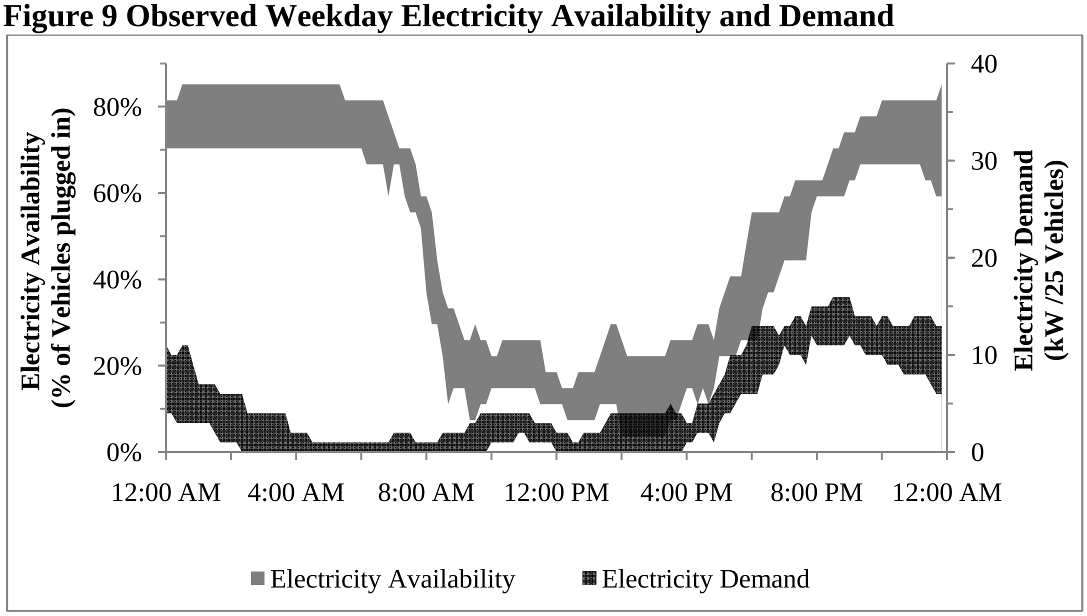


Observed Time of Day (TOD) Charging and Grid Impacts

To describe the TOD at which drivers plug in the PHEV and the total TOD impacts of the observed recharging behavior, two measures are summarized and reported: electricity availability and power demand. Electricity is said to be available to the vehicles whenever the vehicles were physically plugged into an electrical outlet. Power demand represents the total electrical power (kW) drawn from the grid to recharge all 25 PHEVs at any given time. The individual charging rates for a single PHEV conversion were generally observed to be between 900 and 1,200 Watts. To compare and summarize across households, the power required to charge a single vehicle is standardized (by assumption) to be 1.0 kW. For the purpose of clarity, I have ignored the minor additional loads for the battery cooling system (in the range of 1 to 50 Watts), brief periods of higher demand during the initial phases of battery charging, and longer periods of lower demand at end of the charging cycle.

Figure 9 shows variability in electricity availability across weekdays as the percentage of the 25 vehicles plugged in at a given time for weekdays (in grey, and on the left axis) and the range in the total (sum) power demand to recharge all 25 vehicles across weekdays at a given time of day (in black, and on the right axis). The bottom edge of the grey and black areas represent the lowest values observed at each point in time on any weekday, and the top edges represent the highest values.

Figure 9 Observed Weekday Electricity Availability and Demand



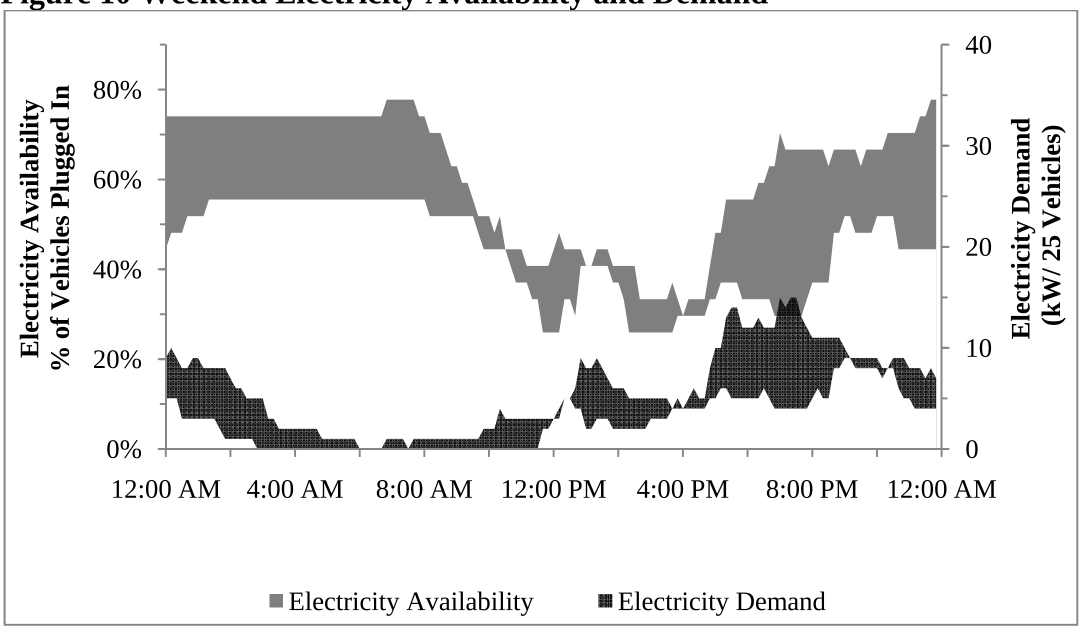
Across the 135 weekdays represented in Figure 9 (25 households times 5 weekdays each), 70 to 85 percent of PHEVs were plugged in between 10:00 pm and 6:00 am. By 9:00 am only 10 to 30 percent of the 25 PHEVs were connected to the grid. This decrease in the number of vehicles plugged in or drawing power during midday reflects the households in this sample who all commuted to full time jobs in the PHEV. Three of these households plugged in the PHEV during the day while at work. Additional daytime recharging was due to households who had the day off work, or who had alternative work schedules, such as the opportunity to telecommute, or flex their work hours. At 4:00 pm, when households started to arrive home, vehicles began to be plugged in, until 10:00 pm, by which time the percentage of households connected to the grid stabilized again between 70 to 80 percent. The greatest variation in the percentage of vehicles plugged in, some 30 percentage points difference across weekdays, occurs during the early evening (6:00pm), and reflects the variability both across households in the time of day when they plug in the vehicle and the variation in plug in behavior across different days of the week. The lower boundary of the electricity availability during the evening is largely defined by Friday night when more people tended to plug in the PHEV later in the evening than they did on other weekdays. For the time period between midnight and 6:00am, the low value was predominantly due to the recharging behavior observed on Monday nights. The maximum values for electricity availability and power demand were predominantly due to recharging behavior observed on Wednesdays, with over 92 percent of the households plugging in at least once during the day.

The black area in Figure 9 shows electricity demand in kW to recharge all 25 of the vehicles at any given time of day. Given the households' PHEV driving and recharging behaviors, electricity demand to recharge their PHEVs increased rapidly at 5:00pm and peaked just after 9:00pm. It then declined steadily through the night and approached zero by 4:00am. The households that plugged in at work typically did so immediately after arriving there, usually between 8:00am and 9:00am. On the days the cars were driven during lunch, the drivers typically plugged the vehicles in again upon returning to work. The most day-to-day variability in power demand occurred in the evening between 6:00pm and midnight. The lower boundary of the power demand between 4:00pm and 8:00pm is primarily a result of the increased probability of households plugging in the PHEV later in the evening on Fridays. The upper boundary is shaped by a higher percentage of people recharging on Wednesday nights. Regardless of the absolute power level at 5:00pm, there is a rapid increase (up to a tripling) in the power demanded between 5:00pm and 6:00pm.

By comparing electricity availability and power demand in Figure 9, a picture of aggregate recharging behavior and corresponding electricity grid impacts emerges. While the prospect of increases in electricity demand to recharge PHEVs (or any EV) during peak hours might be alarming to electricity providers, as well as to energy and environmental analysts, it is clear from a comparison of the grey and black areas in Figure 9 that there is potential to shift electricity demand for these particular PHEVs in these households from early evening until after 10:00pm, since electricity demand to recharge these vehicles declines rapidly after 10:00pm and all charging is completed by 4:00am the following morning.

Figure 10 shows weekend electricity availability (in grey, on the left axis) and power demand (in black, on the right).

Figure 10 Weekend Electricity Availability and Demand



Compared to weekdays, the maximum percentage of vehicles plugged in is less, with a high of 75 percent of vehicles plugged in between 11:00pm and 6:00am on weekends compared to a maximum of 85 percent between 11:00pm and 6:00am on weekdays. While electricity availability decreases towards and into the morning, it does so gradually and does not decline below 30 percent. The incidence of households plugging in their vehicles between 2:00pm and midnight increases less rapidly than on weekdays. Some individuals left their PHEV plugged in longer on the weekend than on weekdays. Overall, there is less variability in the percentage of vehicles plugged in between 8:00am and

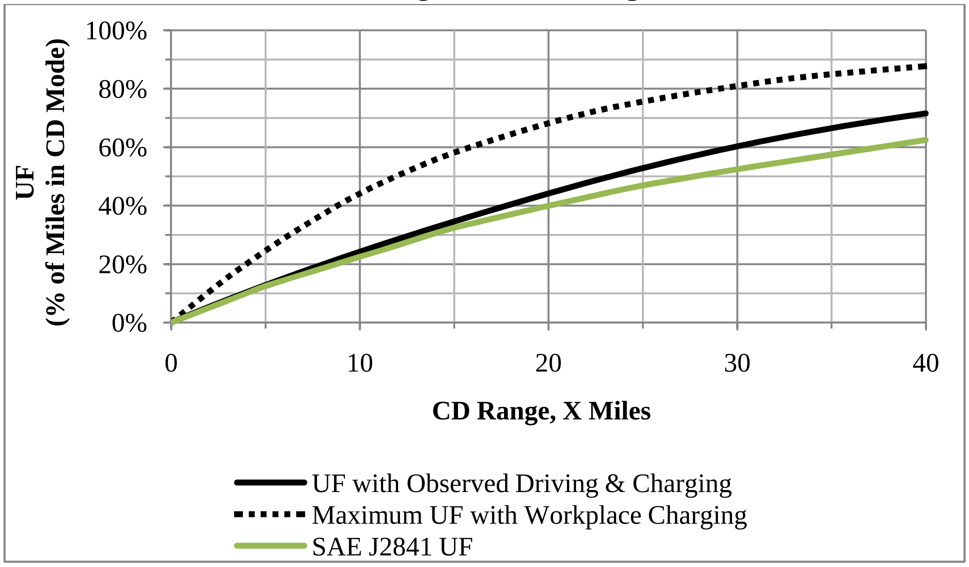
4:00pm on weekends than between 7:00pm and 12:00am. The lower boundary during this latter period is defined by Saturday, with people tending to plug in later in the evening. Sunday defines the upper boundary of the evening in the figure, i.e., more of the vehicles were plugged in on Sunday evening than on Saturday evening.

As with weekdays, most weekend electricity demand to recharge the vehicles occurred between 5:00pm and 2:00am. However, much less total energy and lower peak power are required on weekend days than on weekdays. Overall, weekend electricity demand increased more slowly over the course of the early evening than on weekdays. This occurred because, during weekends, the PHEVs were plugged in at a higher starting SOC than on weekdays. Essentially, as those vehicles were plugged in, their impact on total power demand (all 25 households) was less than on weekdays because vehicles that were plugged in earlier had already finished charging. As with the case of weekday power demand, it appears as though there is an opportunity to shift charging of these PHEV conversions to off-peak electricity demand periods.

Utility Factors (UFs) Derived from Consumer Usage Patterns

The PHEV demonstration gave households the opportunity to use a specific PHEV conversion in the context of their own lives, deciding when, where and how much to charge the vehicle. Combining each household's observed driving and recharging behaviors with the constant per mile electricity consumption and battery capacity referenced in Table 3 for an AE PHEV for CD ranges from 1 to 40 miles allows us to construct a UF for the simulated PHEV based on observed PEM households' PHEV usage patterns. It should be noted that while SAE J2841 is defined for vehicles with CD ranges up to 200 miles, the UFs based on observed travel and recharging and with workplace charging in Figure 11 only extend to CD ranges up to 40 miles to correspond with the provided survey design space. All workplace charging is in addition to each household's observed charging. An AE PHEV was used in the UF simulations because it represents the highest per mile energy usage case. It is expected that vehicles with lower per mile electricity consumption, i.e., blended PHEVs, would yield a higher UF but lower displacement of gasoline by electricity. Using the UF based on observed driving and recharging patterns as a baseline, the second UF then shows the particular impact of simulating the addition of workplace charging. Figure 11 shows UFs for the simulated PHEV AE-Xs based on 1) observed driving and recharging of all 25 PEM commuting households, 2) estimated UF assuming all PEM households also recharged their PHEVs every time they park at their workplace, and 3) UF prescribed by SAE J2841.

Figure 11 UF based on Observed Usage Patterns & Simulated Workplace Charging, for PHEVs with AE-X CD range where X ranges from 0 to 40 miles



Increasing vehicle range leads to increases in the observed UF. Increases are non-linear; a doubling in CD range did not lead to a doubling of the UF. Given the variety of driving and recharging observed in the PHEV demonstration, these PEM commuters could have achieved about 72 percent of all their weekly travel in CD mode with a PHEV 40, or 44 percent of travel with a PHEV 20. Workplace charging provides larger percentage benefits for shorter CD ranges. Compared to the UF based on observed driving and recharging at 10, 20 and 40 miles of vehicle CD range, ubiquitous workplace charging would have increased the aggregate weekly UF for these households by 83, 55 and 23 percent respectively. Compared to the SAE J2841, providing workplace charging for PHEV20s creates a higher aggregated UF, than if all participants were driving PHEV40s under the conditions assumed in J2841.

The simulation results displayed in Figure 11 address several key criticisms of SAE J2841 by implementing a variety of PHEV recharging behaviors. Whereas SAE used one-day data from drivers of conventional vehicles, the PEM households are observed to drive and recharge a PHEV for one-week. Overall, the differences between the UF based on observed PEM behaviors and SAE J2841increase with vehicle CD range, with almost no difference between the two UFs at 10 miles increasing to a difference of 10 percentage points at 40 miles. Conceptually, the differences between the assumed charging frequency used in J2841 and the observed recharging behaviors in the PHEV demonstration produce little difference in total CD driving at short vehicle ranges. However, as vehicle CD range increases, each additional charging event results in more CD driving, and thus a larger percentage difference between the two UFs.

Impact of Added CD Range Varies By Household: Creating Individual UFs for Each Household

While estimating the UF of a given vehicle design is important, the UFs presented above can be misleading. By presenting the total CD driving for all households, the analysis implies that every household benefits equally from increases in CD range. In reality, given differences in driving and recharging behaviors between households, the benefit of additional CD range will vary. For instance, it is possible that a household using a PHEV with a shorter CD range will have a higher UF than another household using a PHEV with a longer CD range. Furthermore, within households depending on driving and recharging behaviors, increasing CD range may not increase a household's total CD driving at all. As such, SAE J2841 does not give any indication of an individual household's ability to increase CD driving relative to their total miles driven. The discrepancies could be further compounded if we consider the case where, given a variety of different vehicle types, households select vehicles with CD ranges which complement their driving and recharging behaviors, or, conversely, even modify their vehicle usage to complement the vehicle's specifications. (The potential exists for consumer education about personal driving habits, especially given the penetration of web enabled devices and applications which can monitor an individual's driving and charging opportunities, based on location and dwell time, and make recommendations as to appropriate vehicle specifications.) In which case, we could expect the resulting UF to be higher for vehicles with short CD ranges. To further examine these ideas, Figure 12 plots each household's unique UF, based on their observed driving and recharging behavior, the SAE J2841 UF and the PEM households' UF based on observed driving and recharging from Figure 11.

Figure 12 Individual Household UFs

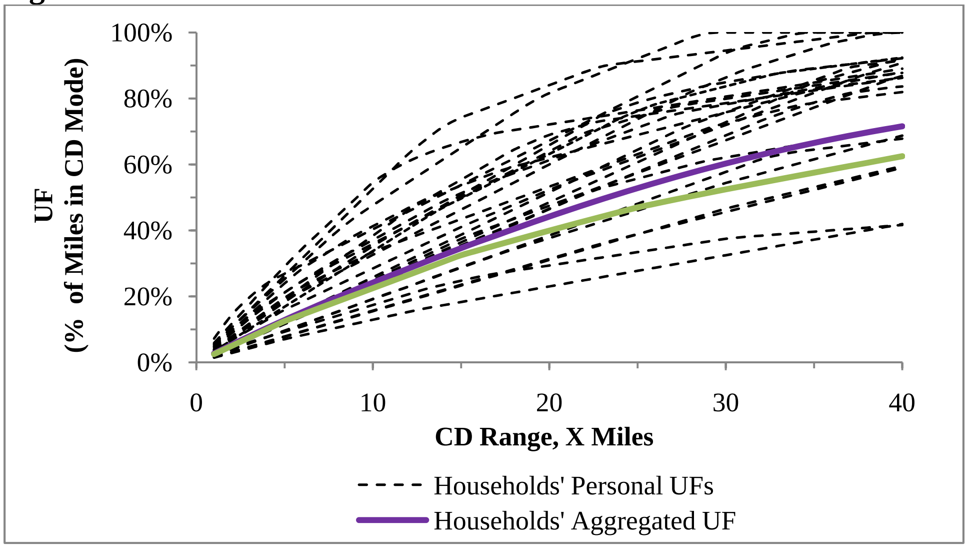
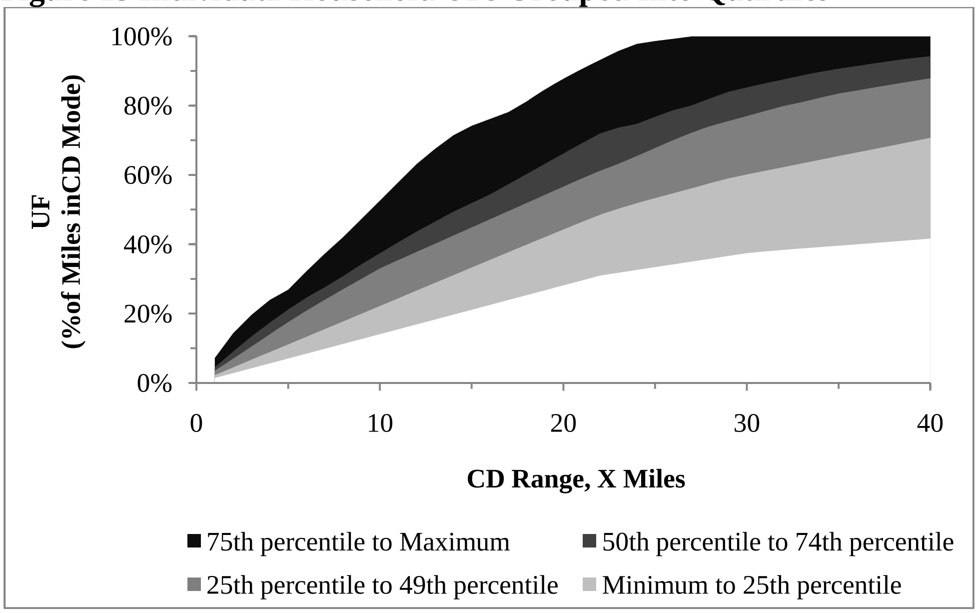


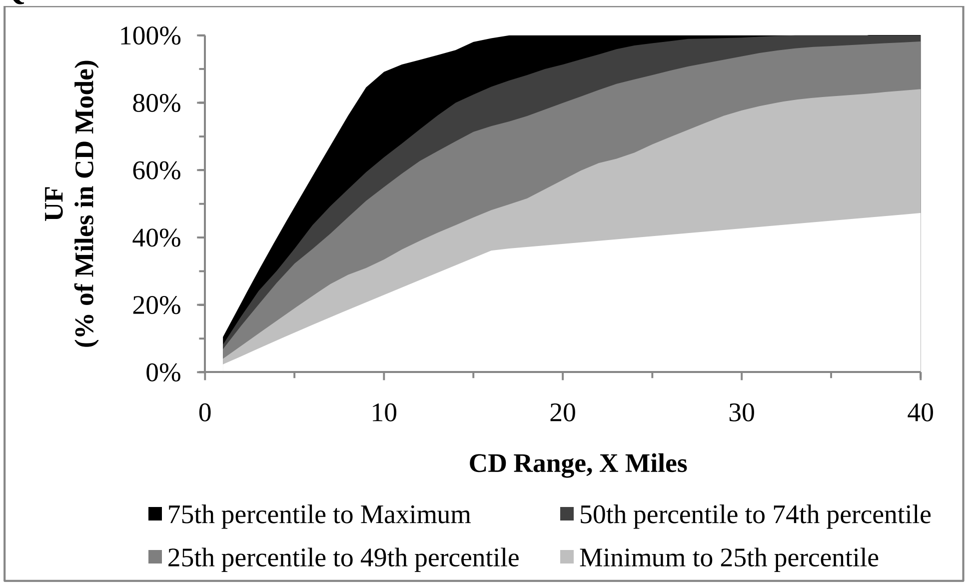
Figure 12 shows the change in the UF of each of the 25 PEM commuting households as by CD range. With a PHEV 40, a minimum UF of 30 percent is achieved and a maximum of 100 percent. While the shape of each household's UF appears to be unique, they are distributed in varying densities. As can be seen from Figure 12, neither aggregate UFs accurately represent most users' individual UFs, with 84% and 72% of household individual UFs distributed above the SAE J2841 UF (shown in green) and the households' aggregate UF (shown in purple), respectively. Conceptually, the aggregate household UF is biased downwards by those few households who drove farther, and achieved lower individual UFs. To help visualize this distribution, Figure 13 arranges each of the 25 household weekly UFs into quartiles. Given the driving and recharging behaviors observed across the 25 PEM commuters, a PHEV20 would provide a UF between 20 and 80 percent, with the top 50 percent of households achieving a UF over 50 percent. A PHEV40 would provide a UF between 40 and 100 percent, with top 50 percent of households achieving a UF over 80 percent. This compares to a UF of 40 (for a PHEV20) and 62 (for a PHEV40) for the SAE standard.

Figure 13 Individual Household UFs Grouped Into Quartiles



The addition of a single, frequently and regularly used charging location can increase the UF of the PEM households (Figure 14), thus further substituting more CD driving, and the environmental, economic, and societal changes which are associated with it. With workplace charging, a PHEV20 affords the PEM households a UF between 40 and 100 percent; 50 percent of all households would achieve a UF over 80 percent.

Figure 14 Individual Household UFs With Workplace Charging Grouped Into Quartiles



PEM Consumer Vehicle Designs and Impacts

Nearing the end of each PEM household's PHEV trial, participants completed an online questionnaire. The questionnaire included PHEV design games in which households were given the option to design their own PHEV within the context of their next vehicle purchase. I now create two more scenarios using these PHEV designs. First, I combine them with the PEM households' observed driving and recharging behaviors. Second, I add ubiquitous workplace recharging. Through this analysis I explore the projected impact of PHEV market segment size, vehicle availability, and charging infrastructure on the total CD driving and TOD grid impact of consumer designed PHEVs. In this instance, I am defining PHEV market segments by the four attributes of PHEV performance that households were asked to manipulate; not body style, size, or the other commonly used attributes of automobiles.

The households were specifically asked to customize values for CD range, CD FE and type, recharge time and CS FE. Across households a variety of PHEV designs were created. Most pertinent to the discussion of UFs, the CD performance characteristics of most households' designs were blended operations for 10 or 20 miles. Table 7 lists the vehicles the households designed, as well as the estimated vehicle specifications necessary to achieve the level of performance desired by the survey respondent as evaluated by Axsen et Al. (2010). Charging power was divided into two categories to reflect the distinction between level 1 (1.0 kW: 110v, 10A), and level 2 (4.4 kW: 220v, 20A) charging. As such, the minimum charging power was 1.0kW. The recharge times shown in Table 7 may not reflect the actual time necessary to recharge the designed PHEV, but rather, the length of recharge time that the household deemed acceptable. The charging power shown in Table 7 was used to calculate the TOD electricity demand in Figure 16 and does not exceed the maximum recharge time designed by each household.

Table 7 Households' PHEV Designs and Associated Vehicle Specifications

Household Designed Vehicles				**Designed Vehicle Specs.**		
Vehicle Type	Electric Assist	CD Range (Miles)	Recharge Time	Battery Size (kWh)	Charging Power (kW)	Number of Households that Selected Design
Sedan	B *(75 mpg)*	10	8 Hours	1.45	1.0	8
Sedan	B *(75 mpg)*	10	4 Hours	1.45	1.0	1
Sedan	B *(100 mpg)*	10	8 Hours	1.7	1.0	3
Sedan	B *(100 mpg)*	10	1 Hour	1.7	4.4	1
Sedan	B *(100 mpg)*	20	8 Hours	3.4	1.0	3
Sedan	B *(100 mpg)*	40	8 Hours	6.8	1.0	2
Sedan	B *(100 mpg)*	40	2 Hours	6.8	4.4	1
Sedan	B *(125 mpg)*	20	2 Hours	4.6	4.4	1
Sedan	AE	20	8 Hours	7.5	1.0	1
Truck	B *(75 mpg)*	10	8 Hours	1.9	1.0	2
Truck	B *(75 mpg)*	20	4 Hours	3.7	1.0	1
Truck	B *(125 mpg)*	10	8 Hours	2.9	1.0	1

Applying the vehicle designs in Table 7 to each household’s observed driving and recharging behavior, and then, again, to a scenario in which workplace charging is simulated produces the estimated UFs for each household shown in Table 8. Compared to the PHEV conversion, 92 percent of households designed hypothetical PHEVs that result in a lower UF than what was observed in the study. The implication here may well be that, to consumers newly entering the PHEV market, the prospect of completing some portion of their driving in CD mode may be exciting and meet their personal goals, expectations, or budgetary constraints. In a world where batteries are expensive and experience with PHEVs is limited, CD range and blended CD type as specific design options could give new car buyers the opportunity to enter the market, while providing some additional societal or environmental benefits. As a means of increasing CD driving, additional workplace charging infrastructure could be installed. Workplace charging would most certainly provide some users with additional CD driving, although the increases would vary by households given existing usage and behavior patterns. Table 8 summarizes each household’s total driving and UF with the vehicle they drove during their demonstration, what their UF would have been if they had used the vehicle they designed and the percentage point increase in the UF resulting from ubiquitous workplace recharging.

Table 8 Summary of All Households' Week of Driving and Charging

ID	Total Driving (Miles)	UF (% CD Miles)			
		Demo Vehicle	Household Designed Vehicle	Household Designed Vehicle with Workplace Charging	Percentage Point Increase from Workplace Charging
1	109	64	64	100	36
2	159	47	19	51	32
3	146	82	41	47	6
4	431	53	15	20	5
5 [a]	359	77	51	51	0
6	270	98	84	84	0
7	248	41	17	28	11
8	200	67	24	61	37
9	152	97	53	64	11
10	143	100	82	100	18
11	418	67	18	27	9
12 [a]	250	75	35	35	0
13	158	83	55	62	7
14	155	99	51	92	41
15	206	82	24	55	31
16 [a]	330	98	92	92	0
17	148	80	34	76	42
18	215	87	46	58	12
19	448	53	16	27	11
20	205	80	36	68	32
21	388	73	15	28	13
22	152	89	31	53	22
23	182	96	100	100	0
24	355	46	26	56	30
25	149	99	52	57	5

[a]Indicates households recharged at work during the week of driving and charging shown here.

Implications of Households' PHEV Designs for Total CD Driving

Households were free to design a PHEV based on any existing new car or truck, and could also choose among options for CD range and CD type. This variety of makes and models of PHEVs may be offered to consumers in the future, but greatly exceeds the variety of present and near-term announced PHEV models. Therefore, it would be expected that limiting the variety of PHEV makes, models, and types such as those shown in Table 7 available to consumers would change the composition of the early on-road fleet of PHEVs; different possible fleets may produce differences in total CD driving. To begin to explore the impact that limitations on PHEV vehicle design and availability could have, Table 9 summarizes the total CD driving and UF that would be produced by the 25 PEM households' PHEV designs by broad body style categories, i.e., sedan or truck, and by CD ranges.

Table 9 Summary of UF and CD miles driven of the PEM households' PHEV designs by vehicle type and CD range

		Total CD Miles		UF	
	Total Driving (Miles)	As Observed	With Workplace Charging	As Observed	With Workplace Charging
All Designed Vehicles (n= 25)	5976	2360	3188	40%	53%
Sedans (n = 21/25)	5015	1976	2656	41%	54.7
PHEV 10 (n=13/25)	3309	814	1366	25 %	41%
PHEV 20 (n=5/25)	923	451	579	49%	63%
PHEV 40 (n=3/25)	782	711	711	91%	91%
Trucks (n= 4/25)	961	220	357.77	23%	37%
PHEV 10 (n=3/25)	746	120	232	16%	31%
PHEV 20 (n=1/25)	215	100	126	47%	59%
PHEV 40 (n=0/25)	n/a	n/a	n/a	n/a	n/a

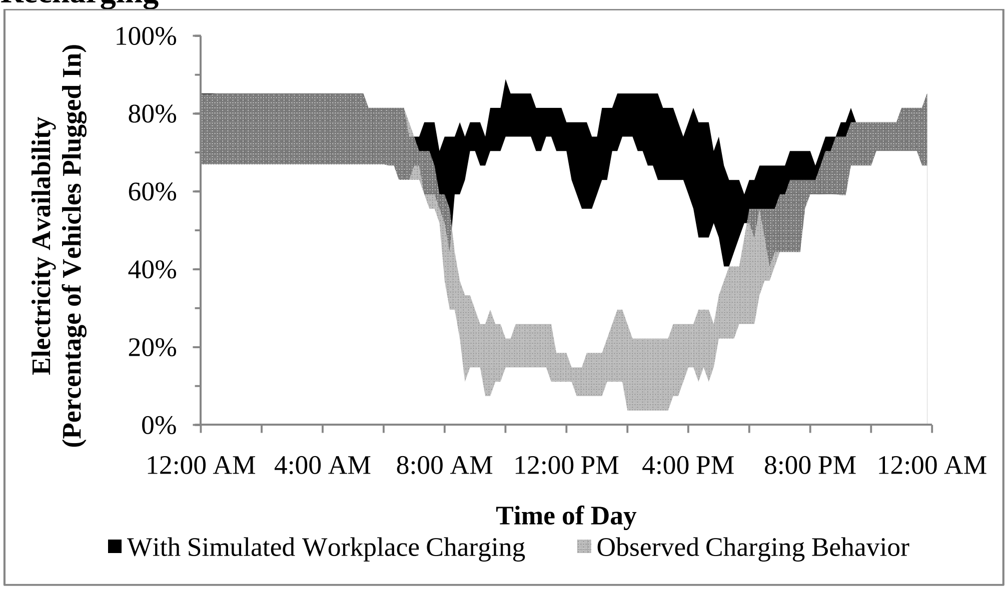
Based on their observed driving and recharging behavior, the three households who designed a PHEV40 sedan (no household designed a PHEV40 truck) would have completed the majority of their observed week of driving in CD mode, achieving an aggregate UF of 91 percent. The 13 households who designed a PHEV10 sedan would have achieved an aggregate UF of only 25 percent. However, because there were so many more households who designed a PHEV10 than there were people who designed a PHEV40, the PHEV10s would have been driven more CD miles than would the PHEV40s: 814 miles in PHEV10s compared to 711 in PHEV40s. Regarding gasoline use, assuming these PHEV10s and PHEV40s had the same CD type (blended or all-electric) as well as the same CD and CS FE, the PHEV10s would collectively achieve greater CD driving and reductions in tank to wheels (TTW) fuel use. In the workplace charging scenario, the PHEV10 market segment would substantially increase their CD driving, producing in total almost twice as much CD travel as the far fewer PHEV40s. In these terms, Table 9 illustrates that market segment size, differentiated by choice of vehicle type (sedan or truck), CD range, and price, influences calculations and estimations of the total CD driving that would be accomplished by PHEVs in a market. As such, it would seem that promoting “short range” PHEVs and focusing on market size and popular vehicle-types rather than individual vehicle performance, could lead to greater total benefits from PHEVs in the early market.

Impact of Workplace Charging on TOD Grid Demand

With regard to ubiquitous and regularly used workplace charging there is a tradeoff between increases in CD driving and the additional electricity demand to charge PHEVs in the morning and early afternoon. The TOD grid impacts imply different things to different electric utilities depending on their existing grid distribution system, generating capacity, the geographic distribution of PHEVs within their service territory, and ability to develop or import new electricity supply.

Under the conditions modeled, simulated workplace recharging produces a significant change in the TOD electricity availability and power demand. Figure 15 compares the electricity availability that would have resulted if the PEM households' PHEV designs were used for the driving recorded during each household's week, with workplace recharging (shown in black) and without workplace recharging (shown in grey and replicating the same TOD electricity availability values shown in Figure 9).

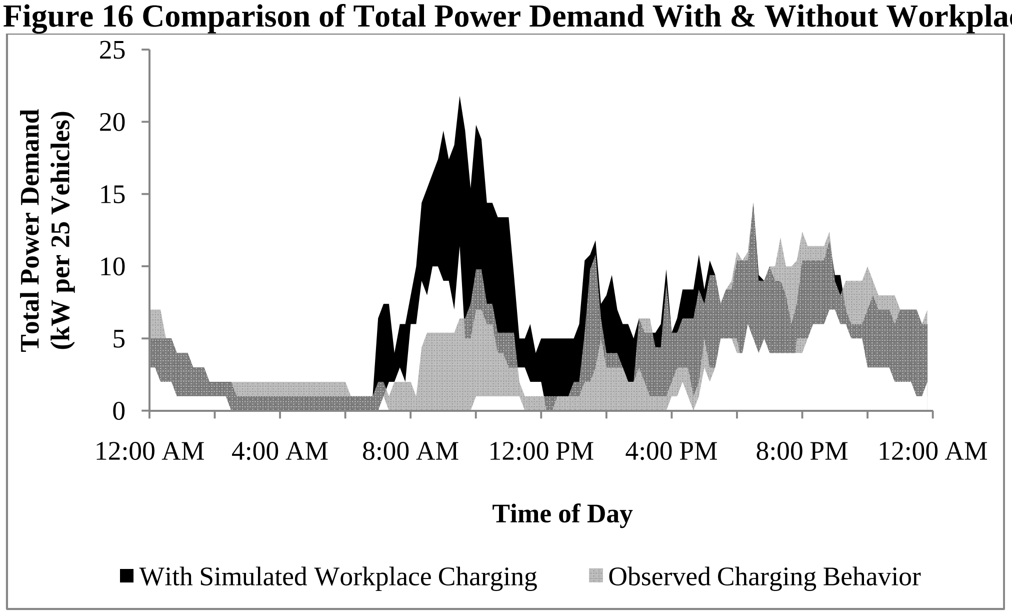
Figure 15 Comparison of Electricity Availability With & Without Workplace Recharging



With simulated workplace charging, electricity availability would have increased during the late morning as commuters arrived at their workplaces and plugged in their PHEVs. Electricity availability would have decreased at noon, as some participants would have left work during the noon hour. It would have reached a 24-hour minimum of about 40 percent at 5:00pm. It then increases steadily as households begin to plug in at home, and stabilizes around midnight.

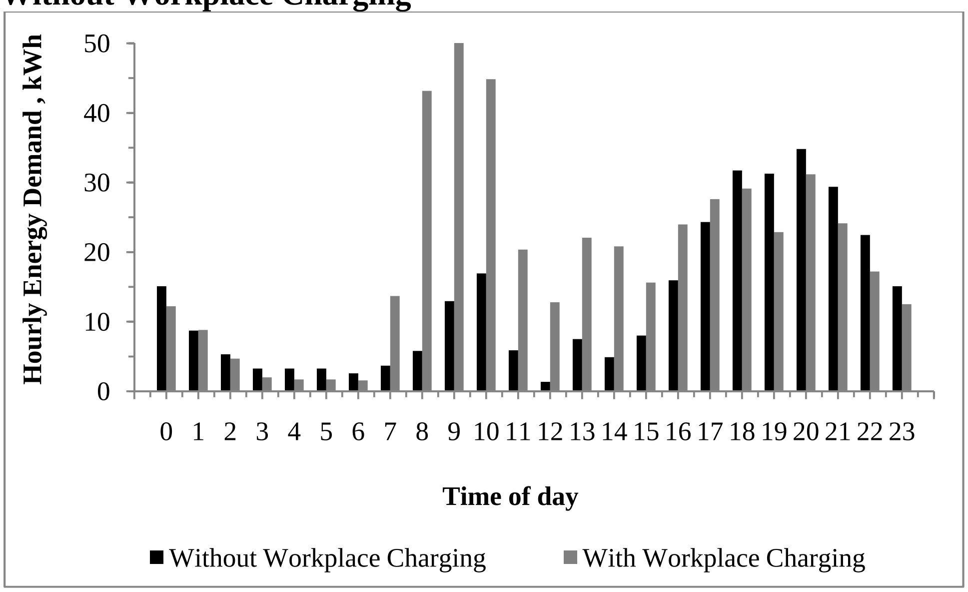
The total electricity demand, in kW, of all 25 household designed vehicles is shown in Figure 16: with workplace charging shown in black, and without workplace charging shown in grey. Simulated workplace charging significantly increases the peak power needed during the morning. As vehicles arrived at work and plugged in, the power required to charge all 25 vehicles would have increased, from 10 to 22 kW at 9:30am, ie., more than double the demand for this time in the without workplace condition. Furthermore, in the case modeled here, simulated workplace charging does not decrease the evening peak power requirements of 15 kW at 6:30pm. Conceptually, since most vehicles have relatively short CD ranges, workplace charging occurs in addition to evening charging and does not displace the evening peak.

Figure 16 Comparison of Total Power Demand With & Without Workplace Charging



To compare the changes in the time of day distribution of energy as a result of simulated workplace charging, Figure 16 plots the percent of total energy consumed during each hour, summed for all 5 weekdays. In a world where away from home charging infrastructure is almost non-existent, 70 percent of the energy used to charge the PHEVs was consumed between 4:00pm and midnight. Simulated workplace charging not only leads to a significant overall increase in electricity availability, but also changes the TOD distribution of energy consumed to charge the vehicles, with 40 per cent of the total energy consumed in the workplace charging scenario used from 4:00pm to midnight and another 40 percent of the total energy consumed between 7:00am and noon.

Figure 16 TOD Distribution of Hourly Energy Demand to Recharge PHEVs, With and Without Workplace Charging



CONCLUSION

I use data from a PHEV demonstration and market research project to measure the utility factor (UF) of PHEVs, the resulting number of CD miles for a hypothetical PHEV market, and the time of day (TOD) distribution of demand to recharge PHEVs. The data are from a subset of 25 households who drove and charged a PHEV-conversion: these 25 were identified as plausible early market (PEM) buyers who also commuted to a workplace. The observed driving and recharging behavior, along with the scenarios based on households driving the PHEV they designed in the survey design game - both with and without workplace charging - allow the impact and tradeoffs of vehicle market size, vehicle design type, and workplace vehicle charging infrastructure to be explored across a PEM with a diversity of observed household driving and recharging behaviors. While the TOD impacts of PHEVs on the grid (Kinter-Meyer et al., 2007 ; Duvall, 2007 ; Parks et al., 2007; Axsen & Kurani, 2010b) and their ability to enable CD driving had been previously explored (SAE J2841; Bradley and Quinn, 2010), none of these incorporated the observed behaviors of households driving, charging, and refueling a PHEV. Similarly, while some experts have qualitatively defined a hierarchy of charging infrastructure (home, work, and then public) no one has quantitatively assessed the potential impact of additional infrastructure on electricity demand and CD driving across an entire market based on a variety of observed driving and recharging behaviors and vehicle types.

UFs Created from Observed Travel and Recharging Data

Based on observed travel and recharging data from the PEM demonstration, I calculated a UF of 72% for a PHEV40. This is 10 percentage points higher than the figure of 62% stipulated by SAE J2841. Using the observed UF as a baseline, the added impact of ubiquitous workplace charging for a PHEV between 1 and 40 miles CD range was examined. The impact of workplace charging on CD miles driven can vary depending on distance driven until the next plug in event, the completeness of charging and the vehicle CD range. In total, my modeling of ubiquitous workplace charging increases the UF and CD driving in the PEM for all CD ranges from 1 to 40 miles. As CD range increases, the percentage difference in the UF without and with workplace charging decreases. Across all 25 vehicles in the PEM, providing workplace charging for PHEV40s increases the UF and aggregate CD miles driven (by a fleet of 25 PHEV40s driven as the PEM drove their demonstration PHEV) by 16 percentage points. In contrast, workplace charging increases aggregate CD miles driven by 90 percent for PHEV10s and 50 percent for PHEV20s under the same conditions.

Looking at the effect of CD range on the UF for each household, we see that the added benefit of CD range varies. Without workplace charging, 50 percent of households in the PEM would have reached a UF of at least 30 percent with a PHEV10. Depending on driving and recharging behavior, doubling CD range does not necessarily result in twice as much CD driving. With workplace charging, 50 percent of households complete at least 50 percent of their driving in CD mode with a PHEV10, and more than 20 miles of range gives little percentage benefit in CD travel. Given ubiquitous workplace charging, it would seem that the largest percentage increase is seen for vehicles with 1 to 20 miles of range.

Potential Impact of PHEV Designs and Market on Total CD Driving

The participants' PHEV designs, though hypothetical, provide measures of actual consumers' present expectations and perceived performance requirements with regard to PHEVs in the real world of daily commuter and family driving. Moreover, since these participants were driving and recharging an actual PHEV conversion for some weeks, they also represent a measure of how readily, and to what extent, a population can or will adapt to the concept of PHEVs, and learn new routines and behaviors that owning and driving a PHEV will involve. Ultimately, for PHEVs to capture or create a market share, consumers must recognize not only the perceived benefits of the vehicles (for example, in terms of the effects on the environment), but also acknowledge the economic benefit to themselves (for example, avoidance or reduction of costly fill-ups at the gas station) and are persuaded that the introduction into their lifestyle of modified driving behaviors and new recharging routines (with an evolving, socially acceptable charging etiquette) are worth the effort. In this respect, the PEM households have opened themselves up to the possibility of buying a PHEV as their next new car and of driving it on a permanent basis, providing that other design criteria are met. Moreover, the burden that they are placing on PHEV performance is not ambitious in terms of CD driving distance requirements or CD FE when compared to the vehicle designs envisaged by Axsen and Kurani (2008). Given such freedom of hypothetical choice, it is remarkable that our participants generally designed PHEVs with technically modest battery specifications, with about 90 percent of households designing a blended PHEV and 50 percent of households designing a vehicle that required batteries with capacities of less than 2.0kWhs each. It might have been expected that given the option to "design" their own PHEVs, participants would build vehicles with long AE ranges, as envisaged by some PHEV pioneers and industry experts who viewed PHEVs as a stepping stone to EVs (Axsen and Kurani, 2008).

The 25 households' vehicle designs studied here mirror the PHEV design results of the larger sample of 67 households from which they are drawn, and those designs created by a far larger U.S. national sample of new car buyers in Axsen and Kurani (2008). Based on observed travel and recharging behavior and the vehicles designed by each household, in a world where PHEV CD ranges of 10, 20 and 40 are offered as options, it could be expected that consumer designed PHEVs would achieve a UF between 15 and 100 percent, with a median UF of 36 percent, during a week of travel.

An individual PHEV40 will achieve a higher UF than a PHEV10, yet under the driving and recharging behaviors observed among the PEM households and given the distribution of PHEV designs that those households created, PHEV10s in aggregate could produce more CD miles than the PHEV40s in aggregate, because so many more of the PEM households designed PHEV10s than designed PHEV40s. Based on the simulations here, this would hold true even without the addition of workplace PHEV charging infrastructure. Hence, increasing the PHEV market may lead to larger total benefits than simply focusing on increasing vehicle performance.

Impact of Workplace Charging on TOD Electricity Availability and Demand

My study suggests that the existence of ubiquitous workplace charging could shift the TOD distributions of electricity availability, energy, and power required to charge a fleet of PHEVs. With regard to the TOD power demand, my simulation of workplace charging events produces an additional peak and new 24 hour maximum in the power required to charge all 25 PHEVs at 9:30am. Under the conditions simulated, workplace charging more than doubles the electricity demand required to charge all 25 vehicles compared to the case based on observed driving and recharging. The 9:30am workplace charging peak is greater in magnitude than the evening peak without workplace charging, since most households arrive at their workplace and plug in within a narrow window of time. Evening plug in times are more widely distributed across the evening hours because of differences in home arrival times and recharging behaviors, i.e., whether the driver plugs in the PHEV right away or later in the evening. Simulated workplace charging increases total energy consumed subject to my assumption that PHEVs are plugged into the grid every time they arrive at work, though it does not change the magnitude of evening peak electricity demand.

Given the relatively small size of the batteries for the vehicles designed by households, and since most households remained plugged in from midnight to 6:00am, my analysis suggests that an opportunity may exist to shift the energy required to charge this fleet of PHEVs from the evening peak to after midnight through the use of timers or smart charging infrastructure.

Context to Interpret Results

The analysis presented here does make certain assumptions; one being that households would choose to drive and charge a PHEV with a different CD range in the same way that they used the PHEV conversion vehicle, where they usually achieved 25 to 35 miles of CD range. In the absence of observations of households driving PHEVs with shorter ranges, the assumption is necessary to expand the results past the very specific conversion PHEV. Based on observed behavior, it can be anticipated that given the opportunity to drive a PHEV with a shorter CD range, some households might choose to drive the vehicle differently, in terms of charging more frequently, or possibly delaying trips until the vehicle has charged enough to provide sufficient CD range, hence, it is possible that some households might achieve a similar UF in a shorter CD range PHEV by charging more and modifying trip times.

My analysis presented here describes the grid impacts and CD driving benefits for a PEM of commuters under a variety of conditions, however, it does not take into account any costs, such as those associated with charging infrastructure and the possibility of reduced battery lifetime from increased recharging. Furthermore, the analysis does not quantify the perceptual role that increased visibility of charging stations could play in growing the plug in electric vehicle market.

Although this analysis was undertaken using vehicles with small batteries and modest per mile electricity consumption compared to an AE PHEV, it is expected that vehicles with larger batteries and higher per mile energy consumption would show similar conclusions, but that larger capacity batteries would increase the magnitude (power) and duration (energy) of the TOD peak electricity demand for charging.

Implications of This Analysis for Industry Analysts and Policy Makers

While the specific numerical results may vary with a number of factors, such as sample size, changes in the pro-societal values of new car buying commuters, energy costs, consumer vehicle preferences, and public awareness of the "cost of gasoline", my results are indicative of broader possibilities and plausible ranges of impacts and benefits for all stakeholders (including car buyers, car makers, energy utilities, policy makers), and for society and the nation at large.

My analysis has particular implications regarding the implementation and validity of the SAE J2841 as an industry and policy standard. While a UF is a means to produce FE estimates for CAFE, and can be a useful tool for policy makers and vehicle designers, in its current form the SAE J2841 standard is inadequate. Given the complexities of travel and recharging behavior that I observed among my PEM households, a single "daily" snapshot of aggregated usage—no matter how large the sample—cannot accurately describe the day-to-day variation across PHEV drivers. Furthermore, given the potential for added recharging opportunities and increasing vehicle availability (and consumer choice and self selection for a vehicle design that most suits their needs) to modify the UF, there exists a strong likelihood that the standard will become even less relevant in the future. The inherent danger is that the promulgation of a biased standard may place regulators and vehicle manufacturers in a position, similar to the Corporate Average Fuel Economy (CAFE) experience, where it was known that on-road vehicle FE differed significantly from the FE results obtained during testing, yet the procedures could not be updated. Given the many factors that affect the real world UF, care should be taken to observe and describe the actual travel and recharging behavior of PHEV users. Additionally, tracking how use changes with different levels of infrastructure, energy prices, market penetration and vehicle design options, among other variables, would provide a much clearer starting point for a UF standard that could be updated to provide policy makers and vehicle designers with relevant and meaningful, real world feedback. My analysis also illustrates the potential impact of market segment size, differentiated by choice of vehicle type (sedan or truck), CD range, and price, on the total CD driving that would be accomplished in a PHEV market. Given that few households designed vehicles with CD ranges of more than 20 miles, it would seem that an industry emphasis upon "short range" PHEVs, and focusing on market size and popular vehicle-types rather than upon individual vehicle performance, could lead to greater total benefits from PHEVs in the early market. In simplistic terms, a PHEV version of a popular vehicle platform that can offer some CD driving today, for a broader constituency, would have more immediate impact than waiting for more expensive PHEVs with longer CD ranges. The promotion of "popular" PHEVs as defined by our observed consumer PHEV designs would also introduce a wider segment of the population to the concept of CD driving, and would also help to develop a much more broadly based sense of CD driving and charging etiquette, culture and accepted routines – something that our interviews found was noticeably lacking.

The assumptions used in the analysis and results highlight important guidelines for away from home charging for PHEVs and potential TOD grid impacts. While additional recharging opportunities can increase the UF and CD driving, thus possibly extending the personal and societal benefits of PHEVs, decision makers should be cautious with regard to providing undue incentives for away from home charging. In a situation where it is easier and cheaper to plug in at work than at home, it could be imagined that households might completely shift charging away from their home to the workplace, thus helping to exacerbate daytime electricity demand and providing little or no additional CD travel. Incorporating information about demonstrated driving and recharging behavior, market size, real consumer preferences for vehicle type, and a consumer willingness to approach and adopt a PHEV mindset and culture, if the vehicles seem practical and appropriate to their needs, can provide useful guidelines that will help policy makers and industry to promote more relevant standards, valuable solutions, and better targeted incentives. The analysis undertaken here is offered as a small step towards these goals.

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