EVS26
Los Angeles, California, May 6-9, 2012

Assessing the potential impact of workplace charging for a group of commuters

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Abstract

A PHEV demonstration project gave 80 consumers within the Northern California counties of Sacramento, Yolo and San Joaquin the opportunity to drive a PHEV-conversion for at least one month each in lieu of one of their existing vehicles. Households decided for themselves when, where, and how much to charge the PHEV, if at all. Out of the 80 households, 25 were characterized as plausible future PHEV owners who also commuted to a workplace. Each of the PHEV-conversions was equipped with loggers which recorded all travel and charging data. To estimate the potential implications of added workplace charging infrastructure across a group of commuting households, each household's vehicle usage is simulated with six hypothetical PHEVs, the design characteristics of which are outlined in Table 2 of this paper. Combining each household's usage data with the hypothetical designs allows their PHEV-conversion experience to be generalized beyond the specific PHEV-conversion to plausible future PHEV designs. Since most households did not have access to charging infrastructure at work, charging events are simulated for each household every time they arrive at their workplace. Comparison between the recorded behavior and the simulated workplace charging case allows for an exploration of the potential impacts of workplace charging on the individual and fleet utility factor, workplace charging infrastructure requirements, and grid load. Workplace charging increases the total fleet average utility factor, however, the benefit varies considerably by household and vehicle charge depleting range. Based on simulation results, up to 75% of commuters would be able to use 1.44 kW charging without experiencing a decrease in electric miles driven, and workplace charging creates a new peak vehicle charging load on the grid in the morning, in the range of 0.8 to 1.4 kW per PHEV.

Keywords: Plug-in Hybrid & Electric Vehicles (PHEV), utility factor, workplace charging, Consumers, Demonstration projects

1 Introduction

Plug-in Hybrid Electric Vehicles (PHEVs) are dual fuel vehicles which allow consumers the option to use grid electricity and/or gasoline for travel. The particular powertrain design and battery capacity dictate how and how long the vehicle performs in Charge Depleting (CD) mode. PHEVs can operate in a high fuel economy CD mode (in which electricity is used for primary propulsion with a liquid fuelled engine providing additional propulsion or power when required by the driving conditions), or an all-electric mode (in which the vehicle only uses electricity for the entire CD range). When the traction battery depletes beyond a pre-determined state, PHEVs, irrespective of the drivetrain design, enter into a Charge Sustaining (CS) mode in which the vehicle operates like a conventional Hybrid-electric Vehicle (HEV), using gasoline as the primary energy source with electricity, which is generated on-board the vehicle through regenerative braking or an ICE tied generator, used to increase fuel economy. As such, PHEVs are seen by certain vehicle manufacturers and transportation analysts as a means to electrify some household travel, while also giving consumers the option to use the gasoline fuelling

infrastructure when charging is not convenient or practical. However, the inherent flexibility of the PHEV drivetrain creates questions as to the benefits and implications of PHEVs since their performance relies on the utility factor (ratio of CD to CS driving) [1,2], which can be heavily influenced by the vehicle design (CD range), consumer purchase decision, travel and charging behaviors, and public charging infrastructure. PHEV user charging behaviors, such as the timing, frequency, power level and location of charging could have short-term implications for electricity providers who may need to upgrade local distribution infrastructure to meet the new Plug-in Electric Vehicle (PEV) charging demand depending on existing capacity, or, in the long term may have to account for PHEV load when determining electricity generation needs [3]. Lastly, understanding actual PHEV impacts can help vehicle manufacturers design and build vehicles which provide consumers with the most value, and can allow regulators to properly credit and account for greenhouse gas emission (GHGe) reductions, decreases in gasoline use and improvement in local air quality emissions. Currently, transportation analysts have relied on single day travel diary data and assumptions about charging behavior to simulate the utility factor and grid impacts of PHEVs [2]. However, while these analyses capture some plausible PHEV usage behaviors they do not capture the variation in behaviors which can be expected in a vehicle owning population over extended periods and cannot reflect patterns or routines in household PHEV usage[4].

Using a continuous week of high resolution, in vehicle, recorded travel and charging behavior of 25 plausible Northern California PHEV buyers and a PHEV market scenario, this paper estimates the utility factor, charging infrastructure requirements and charging profiles for a fleet of PHEVs. Varying assumptions for charging location also allow for the creation of a hypothetical workplace charging scenario in which charging events are simulated based on the GPS data of each household. Comparison between the two scenarios allows for the evaluation of the impact of workplace charging. Hence this paper is meant as a step towards the incorporation of actual consumer PHEV travel and charging behaviors into PHEV impact analyses.

2 Methodology and Data Sources

The Plug-in Hybrid and Electric Vehicle Research Center, with support from the California Public Utilities Commission and Air Resources Board conducted a PHEV demonstration and market research project in which data logger equipped PHEV-conversion vehicles were placed into Northern California households for up to six weeks each [4]. The project provided one of the first observations of non-early adopters use of PHEVs. While participants drove a specific PHEV-conversion, the travel and charging data obtained are unique to each household and can be generalized to a variety of different PHEV drivetrains by varying vehicle energy use, charging power attributes and charging locations. As such, each household's unique PHEV use profile informs how changes in PHEV benefits occur given changes in CD range, charging power, and charging locations.

2.1 Travel and charging data

During the households' trial, the conversion vehicles' CANBUS, GPS location, and Hymotion battery status were logged at one second intervals. Households were not coached on when, where, or how often to charge the conversion. Based on household interviews and a consumer survey design game, a subset of the users were identified as plausible PHEV consumers based on their interest in purchasing a PHEV in the next five years. With the help and input of each household, a representative week of travel and charging behavior was selected, and destinations and charging locations were coded based on a simple home, work or other location designation. The selection of a week of travel allows for comparison between households across the same number of weekdays and weekend days. The 25 households used in this analysis completed a total of 175 travel days (125 weekdays and 50 weekend days). Figure 1 plots the cumulative distribution of all daily driving for weekdays and weekend days alongside the 2009 NHTS distribution as a means of comparison and discussion. Over the period, the households under analysis travelled between zero to 190 miles in a day, with approximately 90 per cent of daily driving being less than 70 miles. As was expected from the constraints of the study, extended daily driving for the period analysed in this sample was not captured. Therefore, application of these results to total fuel usage predictions may be limited, but the data can be used to form comparisons between various

scenarios to provide relative differences or changes.

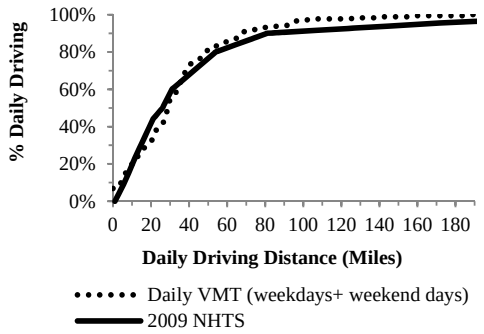

Figure 1: PHEV-conversion daily driving distribution

Daily PHEV-conversion charging behavior varied across the observational period. As would be expected, some households developed a charging routine which revolved around existing vehicle usage patterns, such as bringing the vehicle into the garage at the end of the day. Some households adapted charging behavior to their expected and actual usage, making decisions about plugging-in when necessary to maintain CD driving, or not plugging-in in anticipation of not using the vehicle the next day. Other households developed new routines and experiences and actively sought out charging opportunities to help maximize their CD driving.

The daily charging frequency varied over the observed usage period, as illustrated by Figure 2. On any given weekday, eight to 32 per cent of households did not plug in at all and 55 to 68 per cent of households plugged in once a day. On weekend days, between 12 to 44 per cent of households did not plug in at all and 44 to 58 per cent of households plugged in once a day. Figure 2 illustrates that there was no one daily charging frequency that accurately described the observed behavior of all users, and that the daily routine charging frequencies of a likely group of PHEV owners varied by up to 24 and 32 percentage points across weekdays and weekend days respectively.

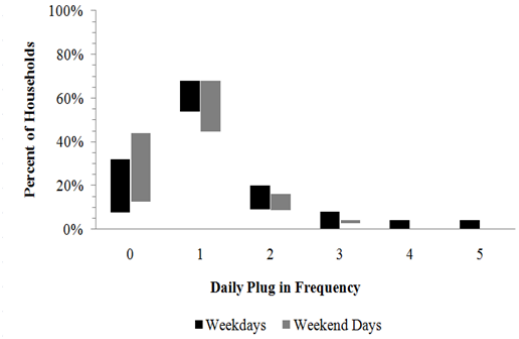

Figure 2: Daily plug-in frequency distribution

To better visualize the day to day changes and adaptations in charging behavior, Figure 3 shows the number of plug-in events as per the day of the week. It should be noted that this figure is meant to illustrate the possible day to day differences in usage, and should not be interpreted as a projection of charging frequency by day of the week for the entire PHEV population.

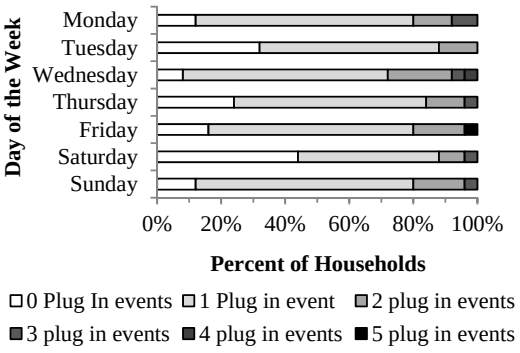

Figure 3: Plug-in frequency by the day of the week

2.2 Hypothetical PHEV market

The load profiles shown in this paper are influenced by vehicle design and user charging behaviors. The hypothetical PHEV market presented here is an estimate of the distribution of PHEVs by CD range (10, 20 or 40 miles) and by general body style (sedan or truck). The ratios are taken from **[5],** a general population market research survey of a sample of San Diego residents which asked participants to design their next new vehicle. Respondents were then given the option of upgrading their next new vehicle to a PEV, or hybrid based on costs associated with battery size and vehicle performance. Table 1 shows the design preferences by per cent of total market for those households who upgraded their hypothetical next vehicle to a PHEV. Since participants could

upgrade any vehicle to a PHEV, the survey is most representative of a mid to long term scenario.

Table 1: Hypothetical PHEV market

CD Range	Sedan	Truck
PHEV10	18.5%	12.5%
PHEV20	16.6%	13.3%
PHEV40	23.6%	15.5%

2.3 Simulation

Each household's travel and charging PHEV-conversion data is modelled for each of the six vehicle designs from Table 1, using the per mile energy consumption and total battery capacity estimates in Table 2. The per mile energy use in CD mode remains constant and does not change with the specific drive cycle.

Table 2: Hypothetical PHEV design attributes

CD Range	Usable battery Capacity (kWh)		Per mile energy Use (kWh)	
	Sedan	Truck	Sedan	Truck
PHEV10	3	3.8	0.3	0.38
PHEV20	6	7.2		
PHEV40	12	14.4		

To assess the difference that increased charging power has on the utility factor, the model is run using charging power values of 1.44 kW and 3.84 kW. This is also intended as a method of estimating what the home charging requirements of PHEV users may be under a variety of charging behaviors and vehicle designs. The two AC power levels, 1.44 kW and 3.84 kW represent standard 120V/15 amp and 240V/20 amp circuit breakers de-rated by 20%. The vehicle charging power is also modelled as a constant load, and does not include pre cooling or pre heating of the cabin, or thermal management of the battery pack. To account for the losses from the charger to the vehicle's battery the charging process is assumed to incur a loss of 15 per cent from wall to battery.

For each household and vehicle design, a single home and work charging power is determined based on the trade-off between CD driving and charging power. 3.84 kW charging is modelled only for those household and vehicle combinations that receive a CD driving benefit over 1.44 kW charging. Given differences in battery size between sedans and trucks, the infrastructure requirements for a given household may change depending on vehicle class and CD range. Table 3 provides an example of the decision process of how power is determined for each household and vehicle design type.

Table 3: Charging power assignment

	Sedan (CD miles driven)					
	PHEV10		PHEV20		PHEV40	
ID	**1.44**[a]	3.84	**1.44**[a]	3.84	1.44	**3.84**[b]
XY	**45**[a]	45	**78**[a]	78	95	**134**[b]

[a] Household achieves the same CD driving with 1.44 kW charging power and 3.84 kW charging power. 1.44 kW charging is modelled for this condition.

[b] Household achieves more CD driving with 3.84 kW charging power compared to CD driving with 1.44 kW. Household is modelled to charge with 240V charging.

When each household's charging power has been determined as per the scenario and vehicle design, the TOD load profiles can be created for each household. All 25 households' load profiles are summed for each of the six vehicle types, creating 24 hour TOD profiles for PHEV10s, PHEV20s and PHEV40s sedans and trucks. To create a single TOD load profile for the entire hypothetical market, the TOD profiles for each vehicle type are then weighted to the proportions shown in Table 1 for a vehicle market of 100 vehicles. As such, it should be emphasized that differences in the PHEV market will change the TOD profiles shown here. Using an assumption for workplace charging, the simulation is repeated and charging events are simulated for the duration of each parking event at the household's workplace. Using a similar process to that described in Table 3, charging power for workplace charging is determined, and the utility factor and charging load is established for the workplace charging simulation.

3 Results

The numerical results of the analysis are shown based on the two broad categories of utility factors and TOD load profiles. Given the commuter sample and regional nature of the analysis, care should be taken when interpreting the specific numerical results.

3.1 PHEV utility factors and CD driving derived from PHEV-conversion usage

The utility factors shown in Figure 4 are derived from a continuous week of travel and charging behavior from each household and are designed to show the average fleet-wide electric driving fraction (total CD driving divided by all driving) as a function of CD range based on existing travel and charging (solid black line), and with simulated workplace charging (dashed black line). Overall, increases in CD range increase the fleet average utility factor, however the increase in the utility factor is not linear with respect to CD range. Workplace charging increases the average fleet utility factor considerably for some PHEVs, but differences depend on the CD range.

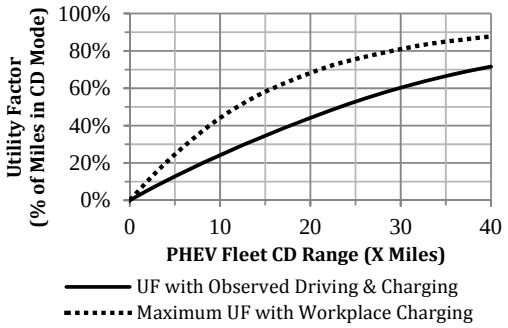

Figure 4: Fleet-wide utility factor

To provide a fleet-wide utility factor Figure 4 aggregates all households' unique driving profiles into a single representation. However, such an approach does not take into account the diverse driving and charging behaviors which will shape each consumer's experience and individual PHEV utility factor. An average utility factor may also be skewed downwards by the relatively few households who drive long distances between charging events. A single average also implies that each household benefits equally from increases in CD range, an assumption that, in the light of observed varying travel and charging patterns, will likely not hold true. To capture each household's likely utility factor experience with a given CD range, Figures 5 and 6 plot each household's unique utility factor (UF) under the two charging scenarios explored in this paper.

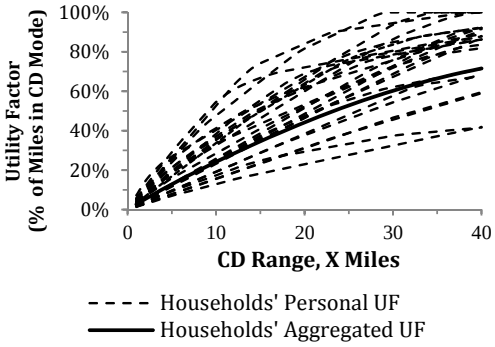

Figure 5: Households' unique UF

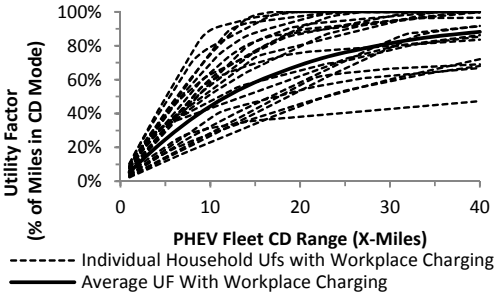

Figure 6: Households' unique UF with ubiquitous workplace charging

Figures 5 and 6 show the individual utility factors (dashed lines) and average utility factors (solid black line) for the PHEV-conversion travel and charging behavior and with simulated workplace charging, respectively. In both cases there is a considerable range in the utility factors which would have been experienced by households using a PHEV, and, therefore, the households' benefit from increased CD range also varies. Further, it is important to note that, in both scenarios, the unique, individual utility factor of most households is greater than the average fleet wide utility factor, with approximately 70 per cent of households demonstrating a utility factor greater than the average. Thus, in using a fleet-wide utility factor to plan households' CD driving needs it is likely that analysts will overestimate CD range requirements for households, since the fleet-wide average utility factor is skewed downwards by households with long travel distances, infrequent charging routines, or both. However, while workplace charging does increase total CD driving for the fleet, the individual benefit of providing workplace charging depends on vehicle CD range and the at home charging behavior of PHEV drivers. Therefore, given the differences in travel and charging patterns observed in the demonstration, the

additional impact (measured in added CD driving from workplace charging per household) is not distributed evenly among the population. To demonstrate this point, Figure 7 shows the increase in total CD charging with workplace charging for all CD ranges between 0 to 40 miles. Instead of presenting each household as a line, Figure 7 arranges households into quartiles to show broader trends and ranges. Based on the simulated workplace charging scenario used in this analysis, workplace charging provides anywhere from 0 to 180 miles more CD driving per household per week for a PHEV25.

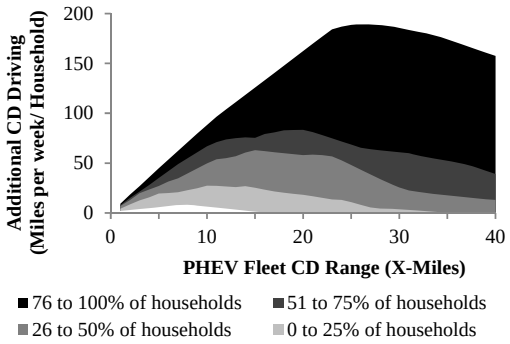

Figure 7: Distribution of additional CD driving from ubiquitous workplace charging

Given the tremendous variability in the impact of workplace charging infrastructure on CD driving across the population, it appears that even if workplace charging cannot be provided ubiquitously to all PHEV commuters, providing it to a significant portion of the population would be sufficient to account for most of the added increase in CD driving. For instance, in the case modelled here, the provision of workplace charging to the top 25 per cent of PHEV40 users (in black) accounts for 90 per cent of the total possible CD driving benefit derived from providing workplace charging to all PHEV40 users. Similar patterns can be seen for other CD ranges. However, as CD range decreases, the additional CD driving benefit becomes more uniform between households. However, it should be noted that, while these distributions remain true for the population in total, the spatial distribution of the charger resources, or determining where to place workplace charging infrastructure are not accounted for in this analysis.

Table 4: Workplace charging infrastructure requirements

Vehicle	Percent of PHEV commuters needing workplace chargers to achieve 90%[1] of total possible fleet CD driving
PHEV10	75
PHEV20	50
PHEV40	25

[1] 90% measure was picked arbitrarily for demonstration purposes

3.2 TOD PHEV load profiles

To estimate the potential changes in grid demand to charge a fleet of PHEVs at the workplace, estimates for charging infrastructure power were made according to the iterative modelling process described in Section 2.3 of this paper and the results of that charging power assessment are shown in Table 5 for the home and workplace locations.

Table 5: Charging power assessment results

	Workplace		Home	
CD Range	**120v**	**240v**	**120v**	**240v**
PHEV10	79%	21%	72%	28%
PHEV20	64%	36%	64%	36%
PHEV40	80%	20%	52%	48%
Market	**75%**	**25%**	**62%**	**38%**

Based on the simulation of PHEV charging power requirements, approximately 60 per cent of PHEV households in this analysis could have used 120v charging without noticing a decrease in their overall Charge Depleting driving. For workplace charging, based on the observed travel and charging behaviors of the households in the demonstration and the PHEV market explored here, 120v charging could be sufficient for up to 75 per cent of PHEV users.

Given the differences in travel and charging behaviors the TOD power required to charge a fleet of PHEVs varied considerably across days. To display this variation, Figure 8 shows the range in the power demand per vehicle for the hypothetical market condition in Table 1 and the charging specifications in Table 5 across the observed 5 weekdays. The addition of workplace charging creates an increase in the TOD power demand per commuting vehicle from a maximum of 0.3 kW without ubiquitous workplace charging infrastructure to 0.8 to 1.4 kW. While workplace charging is shown to create a new 24 hour peak in

power demand for PHEVs at 9:30 am, the addition of PHEV users who do not need to plug-in at work, or users who do not commute to a workplace, would change the relative magnitude for total PHEV demand between the morning and evening high demand periods. In aggregate, ubiquitous workplace charging decreases the evening peak power demand of commuters by approximately 17 per cent to a maximum of 1.0kW /vehicle

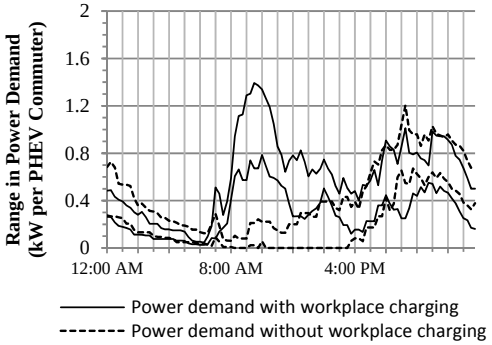

Figure 8: TOD PHEV load profile with and without workplace charging

4 Discussion

For commuting households, the added benefit of workplace charging can vary significantly. The analysis presented here estimates the range of benefits from workplace charging for CD driving and highlights the potentially large variation which occurs due to differences in travel, charging behavior and vehicle design. The utility factor analysis underscores the importance of showing the distribution of housholds' individual and unique utility factors to better understand potential consumer experiences and to build a full product line of vehicles which matches consumers' needs as households' experiences may not correspond to the fleet average.

Providing workplace charging creates a trade-off between increased CD driving and increases in daytime power consumption. In the scenario used in this analysis, the addition of workplace charging does increase the vehicle daytime electricity demand to a maximum of 1.4 kW per vehicle across the entire market, compared to 0.2 kW per vehicle in the base scenario. However, the specific impact of workplace charging on the grid will depend on the existing utility load, generating capacity, and the electrical infrastructure in or around the site where charging is taking place. The aggregate figures presented here illustrate that loads from PHEV charging can be variable, but may not be as large as previous expectations or assumptions may dictate. Lastly, the simulation results point to the opportunity of using level 1, 120V charging as a way of effectively providing infrastructure to PHEV consumers, and extending the benefits of PHEVs with less impact on the grid. While networked electric vehicle supply equipment (EVSE) providers do not provide a level 1 charging solution with the built in J1772 chord set, it would seem that such a product would provide a practical alternative to a level one convenience charger.

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