Estimated Marginal Impact of Workplace Charging on Electricity Demand and Charge Depleting Driving. Scenarios based on Plausible Early Market Commuters' Use of a 5kWh Conversion PHEV

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ABSTRACT

Plug In Hybrid Electric Vehicles, (PHEVs) allow consumers to use gasoline and electricity for their daily travel. However, it is uncertain to what extent PHEV users will operate their vehicles in Charge Depleting (CD) Mode. The uncertainty arises from the relationship between different PHEV designs, and households' travel and recharging behaviors. A PHEV demonstration and market research project at the University of California at Davis is giving 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 charging behaviors. Out of the 67 households who have participated in the demonstration to date, 25 are considered here to be plausible early PHEV buyers who also routinely commute to a workplace. To explore the effects of a variety of PHEV designs as well as the availability of workplace charging infrastructure on time of day electricity use and CD driving, this analysis combines a representative week of each of the 25 household's observed PHEV driving and charging with their own hypothetical PHEV which they designed in an online survey, and analysts' assumptions about plausible workplace charging behavior as informed by observed travel data and interviews of these 25 households. The analyses presented begin to characterize tradeoffs between away from home charging infrastructure, vehicle battery size or CD range, while taking into account consumer interests in different types of PHEV designs, and a diversity of driving and charging behaviors.

INTRODUCTION: PHEV BENEFITS AFFECTED BY DESIGNS, DRIVING, AND CHARGING

Battery electric vehicles (BEVs) have been touted as promising societal and environmental benefits such as reductions in the use of fossil fuels, improved local air quality, decreases in greenhouse gas emissions (GHGs) (1) and possible increases in the overall efficiency of the electrical grid since they potentially serve as sinks for excess off-peak electricity and as mobile power sources to supplement grid electricity in times of peak system demand. (2, 3) Plug-in hybrid electric vehicles (PHEVs), which run on both electricity from the grid and on gasoline, are claimed to provide some of the societal, environmental, and electricity grid benefits of BEVs while offering consumers the option to use gasoline during extended travel and during periods of high top speeds and aggressive accelerations. Thus PHEVs may create a path by which light-duty vehicles can be incrementally electrified. (4) But, it is uncertain as to how directly this path leads to the substitution of electricity for gasoline. The uncertainty arises from the relationship between PHEV designs and households' travel and recharging behaviors. This paper explores the effects of increasing recharging opportunities to those who commute to work in a PHEV on the percentage of miles within a representative week they drive in charge-depleting (CD) mode, i.e., while discharging the storage battery and powering their travel (at least, in part) with electricity from the grid rather than gasoline. This metric, while pertaining to many of the possible societal and environmental benefits of PHEVs, is most pertinent to motivations for substituting electricity for petroleum-derived fuels, e.g., gasoline and diesel.

A PHEV demonstration and market research project at the University of California at Davis is giving 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 charging behaviors. (5) It also reported plausible distributions of time of day electricity demand and grid connectivity, as well as the technical, behavioral, and social factors affecting charging behavior of the particular type of PHEV used and other specific conditions affecting recharging. (6) For example, many participating households lacked a sense of etiquette with regards to plugging in away from home as well as faced a general lack of charging infrastructure. Thus, less charging may have occurred than would be expected in a world with permissive norms and established away from home recharging infrastructure.(6)

Out of the 67 households who have participated in the demonstration to date, 25 are considered here to be plausible early PHEV buyers who also routinely commute to a workplace. To explore the effects that PHEV designs and the availability of workplace charging infrastructure might have on time of day electricity demand and the resulting fraction of CD driving, this analysis combines 1) a representative week of each of the 25 household's observed PHEV driving and charging with 2) their own hypothetical PHEV design elicited during questionnaires and interviews, and 3) analysts' assumptions about plausible workplace charging behavior as informed by observed travel data and interviews of these 25 households.

The analysis is presented in two steps. First, the PHEV design each household created is analytically substituted for the PHEV they drove into the context of an observed week of their driving and charging. As such, these vehicle designs and the resulting analysis represent a baseline for vehicle design preferences and resulting performance. Second, simulated workplace charging is added and the marginal impact of workplace charging on CD driving and electricity demand, given a known battery size and an assumed energy per mile, is estimated. The potential increase in away-from-home charging facilities for household PHEVs provides a complex tradeoff, since it would be expected that increased away from home charging would give some consumers the ability to further downsize their battery (as long as battery size is an option) or increase their fraction of miles in CD mode (either providing benefits readily captured by the households), at the expense of additional grid load and charging infrastructure (costs paid initially by electricity and infrastructure providers that would then presumably be passed on to households).

Assessing time of day grid impacts and CD driving for a fleet of consumer designed PHEVs and combining this with simulated workplace charging is germane to the concerns of engineers, analysts, and policy makers since the marginal economic, societal and environmental benefits of PHEVs (beyond a Full Hybrid drivetrain) depend on the users' driving and charging behaviors just as they depend on the vehicle's technical specifications. (7) The analyses presented begin to characterize tradeoffs between away from home charging infrastructure, vehicle battery size or CD range, while taking into account consumer interests in PHEVs, as well as their driving and charging behaviors.

DATA: PHEV DEMONSTRATION AND MARKET RESEARCH PROJECT

The charging and driving behaviors used in this analysis were recorded in a PHEV demonstration and market research project in which households drove an PHEV conversion for four to six weeks each, choosing when, where and how much to charge the vehicle within the context of their own lives. Participating households drove conversions of Toyota's Prius hybrid vehicle. The conversion adds a 5 kWh lithium ion battery that can be charged from a standard 110-120v/10A household outlet. A fully discharged battery will charge completely within approximately five hours. As PHEVs, the conversions can operate in charge depleting (CD) and charge sustaining (CS) modes. While in CD operation far more electricity is 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. (8) 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 hybrid. (8) On-board data loggers recorded information regarding gasoline consumption, the vehicle's location, driving distance, battery state of charge (SOC), and energy use. Vehicle use and charging data were recorded at one second and one minute intervals respectively.

In total, 25 households are classified as the "plausible early market PHEV buyers" who also regularly commute to work—and thus are considered here. The "plausible early market PHEV buyers" are those who were new car buyers (they had purchased a new vehicle within the five years prior to their participation in the demonstration) and designed a PHEV sedan or truck in the medium and high cost survey design games, respectively. (9)

Households were asked to completely substitute the PHEV-conversion for one of their existing vehicles and were required to have access to a standard electrical outlet (110-120V/10A) at their home where they could charge the vehicle—if they chose to. Geographically, the participants lived in the cities and towns along Interstate 80 in Northern California, including Solano, Yolo, Sacramento, and Placer counties. The total 67 participating households from which the 25 discussed here are chosen 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, education and income. (5) On these measures, the demonstration participants are distributed similarly as a sample of new car buying households in the U.S.—though not all demonstration participants were new car buyers. However, no claims are made to represent larger populations as neither the original sample of 67 nor the sub-sample of 25 plausible early PHEV buyers who commute to work is a random sample of the relevant populations; the analyses presented here explore a range of effects.

Representative Week of Driving and Charging

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 left to experiment with the vehicle, charging behavior changed over time, as did the households' understanding of how they would use this vehicle if they actually owned it, and according to which household member chiefly drove it. The selection of a single week for each household was based on the premise that within any household many weeks have much in common, but the household may undertake infrequent (compared to say, a daily commute) extended trips. Within the context of this study then, a week of travel and recharging is chosen from the actual data that is meant to look like, or represent, most weeks of these households' lives. The use of a representative week of travel and recharging also provides a common number of days and days of the week to analyze. Although the households took part in the demonstration between August 2008 and April 2010, the results are interpreted here as though all 25 households' representative weeks occurred during the same calendar week.

PHEV Design Game

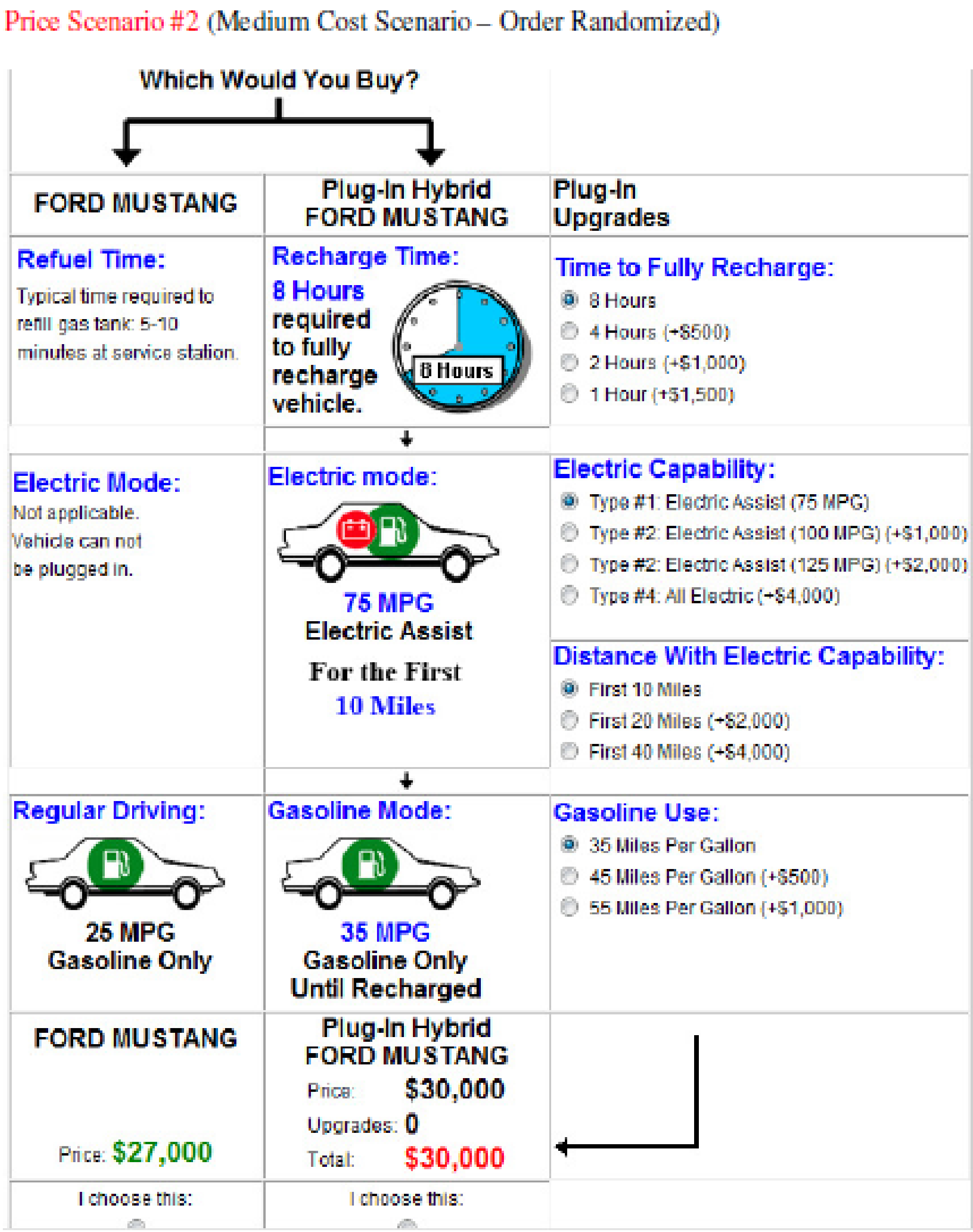
The design games allow the households' to explore and express their interest in buying a PHEV within the context of their next vehicle purchase. The first step was for them to specify a vehicle they would be interested to buy next. Then they were presented the options of a base plug-in version of the same vehicle or the opportunity to redesign the PHEV with greater electric capabilities, e.g., blended or all-electric CD operation, CD range, the time to charge the PHEV battery and the CS fuel economy. Participants were presented with these options in three separate, randomized, price scenarios. Figure 1 shows a screenshot from the medium price design game for cars. Households who chose to purchase a truck, SUV, or minivan faced higher upgrade costs, commensurate with the increased battery costs. (9)

RESULTS

What PHEVs Did Households Design?

Table 1 shows the distribution of vehicle designs for sedans (medium cost scenario) and trucks (high cost scenario), the resulting battery size estimate, (4) the charging level, and the number of households that created that design. Most of the 25 households designed PHEVs with performance capabilities that are modest compared to those assumed by prior analyses (10-12); none designed a PHEV with a 40-mile all-electric range and one designed a PHEV with all-electric CD operation. Most households favored the base PHEV with blended CD operation achieving gasoline-only fuel economy of 75 mpg over 10 miles of CD range. As such, the median battery size for all of the households' PHEV designs was 1.7 kWh. Of the 25 households, 22 designed a vehicle with 10 or 20 miles CD range, and only 3 designed a vehicle with 40 miles CD range.

FIGURE 1 Survey Design Game, Medium Cost Scenario.



The estimates used for battery size and energy per mile consumption (4) are based on a single vehicle modeled on the US06 drive cycle, with an 80% depth of discharge. While US06 is the most aggressive of the drive cycles, our battery energy figures do not take into account the unique driving styles of the households, thus, there is no variation in the observed CD range for a given vehicle design, either with regard to more or less aggressive, or vehicle mass.

TABLE 1 Households' PHEV Designs

Vehicle Type	Electric Assist	CD Range	Battery Size kWh[i]	Charging Level[ii]	Number of Households
Sedan	75 MPG	10 Miles	1.45	Level 1	9
Sedan	100 MPG	10 Miles	1.7	Level 1	3
Sedan	100 MPG	10 Miles	1.7	Level 2	1
Sedan	100 MPG	20 miles	3.4	Level 1	3
Sedan	100 MPG	40 Miles	6.8	Level 1	2
Sedan	100 MPG	40 Miles	6.8	Level 2	1
Sedan	125 MPG	20 Miles	4.6	Level 2	1
Sedan	All Electric	20 Miles	7.5	Level 1	1
Truck	75 MPG	10 Miles	1.9	Level 1	2
Truck	75 MPG	20 Miles	3.7	Level 1	1
Truck	125 MPG	10 Miles	2.9	Level 1	1

i. See (4)
ii. Charging level determines the rate at which the vehicle's battery charges from the grid. Level 1 and level 2 charging are modeled as creating an instantaneous grid load of 1.0 kW and 4.4 kW respectively.

Characterizing Representative Driving and Charging Behaviors

Table 2 characterizes the driving and charging behaviors of all 25 households during their respective week of representative driving and charging, summarizing the distribution of the total, weekday and weekend miles traveled by each household and the average weekday charging frequency with (simulated) and without (observed) workplace charging, as well as the CD range of the PHEV that the household designed.

During the observed representative week of driving and charging, households traveled anywhere from 109 to 449 miles, with a median and average distance of 205 and 239 miles respectively. In estimating what each household's week of driving would have looked in their design PHEV, and again with workplace charging, no changes are made to the households' observed driving record.

Daily life provides varying degrees of structure and routine: households' use of the PHEV conversion had to be incorporated into some established social framework and lifestyle, such as commuting to work, trips to drop off or pick up the kids from daycare, or a weekly trip to the grocery store. While there may be some degree of predictability of these routines for most households, the extent to which our households prioritized charging the PHEV conversion, or were able to fit charging into the context of their established routines varied given differences in lifestyles, understanding of the operating state of the vehicle and technology, access to charging infrastructure, perceived benefit and relative importance of plugging-in for personal satisfaction or societal benefits. As such, the 25 households differed in their recharging behavior; on average households were observed to plug in the PHEV conversion from 0.4 to 3.0 times per weekday.

Table 2 Summary of Representative Week of Driving and Charging Behavior

Household	Total Weekday Miles	Total Weekend Miles	Total Miles Driven[ii]	CD Range	Observed Weekday Charging Frequency	Weekday Simulated Workplace Charging Frequency
1	96	13	109	20 Miles	0.4	1.6
2	122	36	159	10 Miles	0.6	2.0
3	73	73	146	10 Miles	0.8	1.8
4	360	72	431	10 Miles	1.2	1.8
5[i]	321	38	359	20 Miles	3.0	3.0
6	180	90	270	40 Miles	1.0	3.0
7	245	3	248	10 Miles	0.8	1.8
8	178	22	200	10 Miles	1.0	2.6
9	114	38	152	10 Miles	1.4	2.2
10	126	17	143	20 Miles	1.2	2.6
11	227	191	418	10 Miles	1.0	2.6
12[i]	196	54	250	10 Miles	1.8	1.8
13	153	5	158	20 Miles	1.0	2.4
14	120	35	155	20 Miles	0.4	2.0
15	161	45	206	10 Miles	0.6	2.0
16[i]	223	107	330	40 Miles	2.0	2.0
17	135	14	148	10 Miles	0.8	2.2
18	121	94	215	20 Miles	0.6	1.2
19	367	81	448	10 Miles	1.0	2.0
20	166	39	205	10 Miles	1.4	3.0
21	185	203	388	10 Miles	0.8	1.6
22	111	41	152	10 Miles	1.6	2.4
23	139	44	182	40 Miles	1.0	2.6
24	328	28	355	10 Miles	0.8	2.2
25	93	56	149	10 Miles	1.0	2.0

i. Indicates household charged at their workplace during representative week
ii. Total miles may not match the sum of total weekday and weekend miles due to rounding

The combination of the observed charging behavior with simulated workplace charging changes the range of average daily plug in frequency to 1.2 to 3.0 plug-in events, with households plugging-in on average 0.6 to 2 more times per day. Variation in the increase in the average number of times households could have plugged-in is primarily due to differences in work schedules and routines such as leaving the workplace for lunch.

Plug in events vary in the amount of energy taken from the grid. Given the distribution in the battery sizes of the designed vehicles, the energy required to fully charge the battery ranges from 1.45 to 7.5 kWh. The frequency distribution of energy per plug-in event is disproportionately weighted towards lower energy-in, since most households designed vehicles with smaller batteries. Allowing workplace charging decreases the energy in per charging event: 80% of charging events require 2.5 kWh or less compared to the 3.5 kWh without workplace charging. For a given battery size, as the distance between charging events decreases, vehicles will require less energy to fully charge their battery per charging event, although total daily energy demand may increase depending on whether or not workplace charging allows households to increase their daily CD driving.

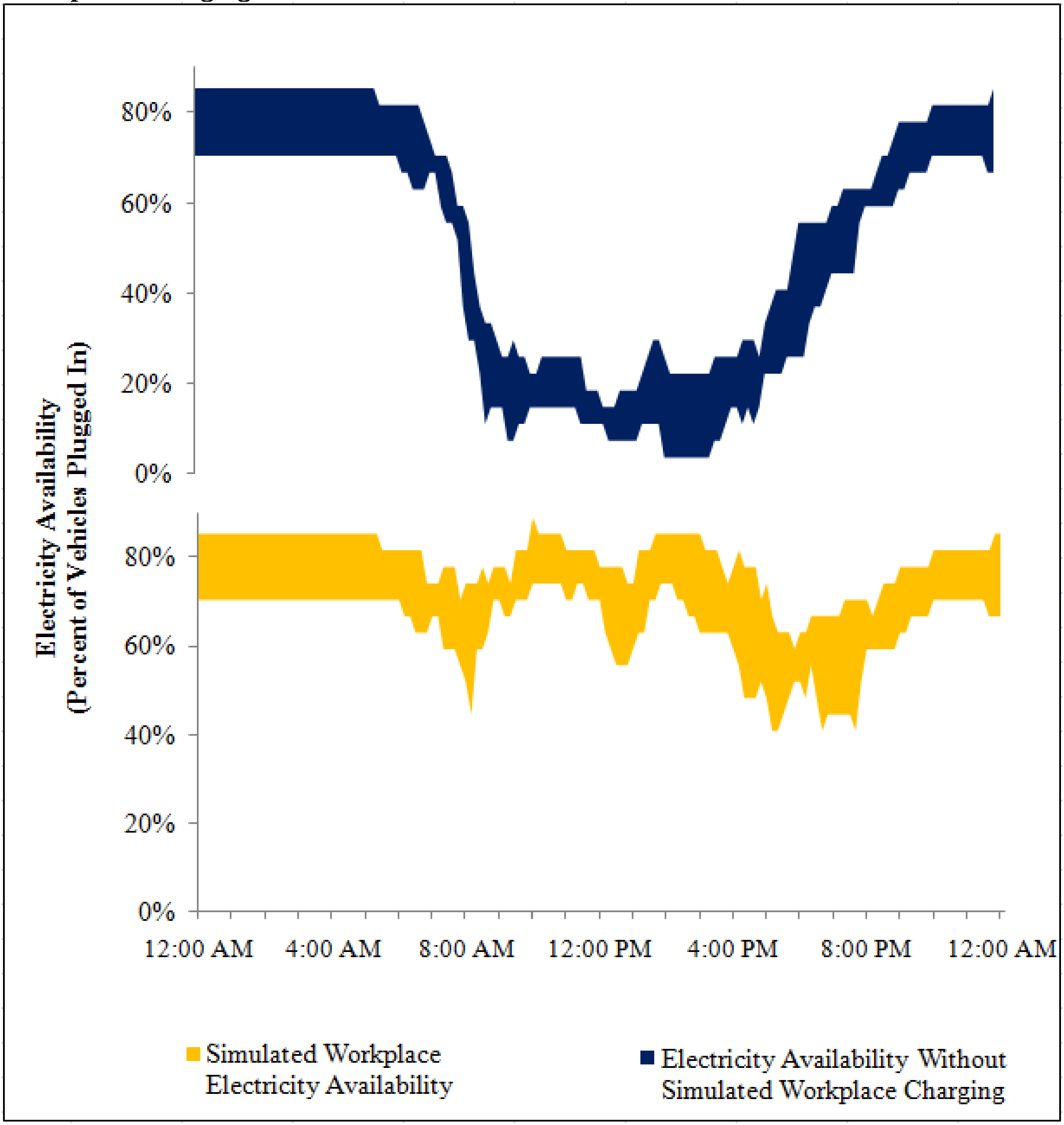
Estimating the Effects of Adding Workplace Charging on Time of Day Electricity Availability, Power Demand and CD driving

In order to model the marginal differences in electricity availability, power demand, and CD driving as a result of additional workplace charging, the following additional assumptions are made. First, the frequency and start time of households' at home charging behavior does not change. The analysis assumes that all workplace charging is supplemental to the observed at home charging done by the households. As such, these results are most plausible in a system where away from home charging is not cheaper or more convenient than the home. Second, the PHEV is assumed to be plugged-in every time it arrives at work, even if this happens more than once per day. As such, the analysis is meant to show the maximum potential and impact of workplace charging. As one could imagine, in reality, additional charging infrastructure may not be used at every given opportunity, especially for those households who do not exceed their daily CD range. Given that most households designed vehicles with 10 and 20 mile CD range, it is expected they would take advantage of additional charging opportunities. For the three households who actually charged at work, they were plugged in 99% of the time their vehicles were parked at their work location, but it should be noted that each of those households' daily driving exceeded the CD range of the vehicle. Third, the charging rate for the simulated workplace charging is based on the recharging rate of each household's PHEV design. While most households designed PHEVs that recharge at level 1 (110v/10amps), those two households who designed vehicles with level 2 recharging (220v/20amps) were assumed to charge at that rate at home and at work. Lastly, as mentioned previously our battery energy and per mile electricity consumption do not take into account the unique driving styles of the households.

Time of Day Electricity Availability

Figure 2 compares the electricity availability, as the range in percent of vehicles plugged in at any given time of day across all five weekdays, without (in blue) and with (in gold) simulated workplace charging for all 25 households. The time of day charging behavior without simulated workplace charging is based on households observed driving and time of day plug-in behavior. Across weekdays 70 to 85 percent of all vehicles were plugged in between midnight and 4:00am. As households unplug to drive their vehicles to work, electricity availability begins to decrease around 6:00am to about 10 to 20 percent of vehicles during the day. Daytime electricity availability is predominantly due to those three households who plugged in at their workplace, and those few households with work schedules that allowed them to work from home on some days, as well those with modified work schedules who did not commute to work on some days of the week. As drivers return home from their workplaces, electricity availability steadily increases from 5:00 to 10:00pm. Variation in the time at which households plug in when they return from work is due to differences in charging behavior across households. As observed through the demonstration and in-depth household interviews there appear to be several patterns which describe when households plug-in; those households who plug-in at almost every opportunity, those who plug in only when they need to, and those who typically don't plug in until they have finished using the vehicle for the day, or until the PHEV is brought into the garage at night.

Figure 2 Weekday Time of Day Electricity Availability, With and Without Simulate Workplace Charging.



The increased plugging in from assumed additional workplace recharging dramatically changes the time of day distribution. The peak percentage of plugging in increases dramatically throughout daytime hours as the commuters beginning to plug in their PHEVs when they arrive at work, sometimes unplugging during the noon hour, and plugging in again if they return to work and then unplugging as they leave for the day. Variation in daytime charging occurs as a result of differences in when commuters arrive at the workplace, and differences in work schedules—including 4/10 workweeks, state employee furloughs, and vacation days. The time of day with the greatest variation in plugging in occurs in the evening at approximately 7:30pm, when between 40 to 70 percent of vehicles are plugged in.

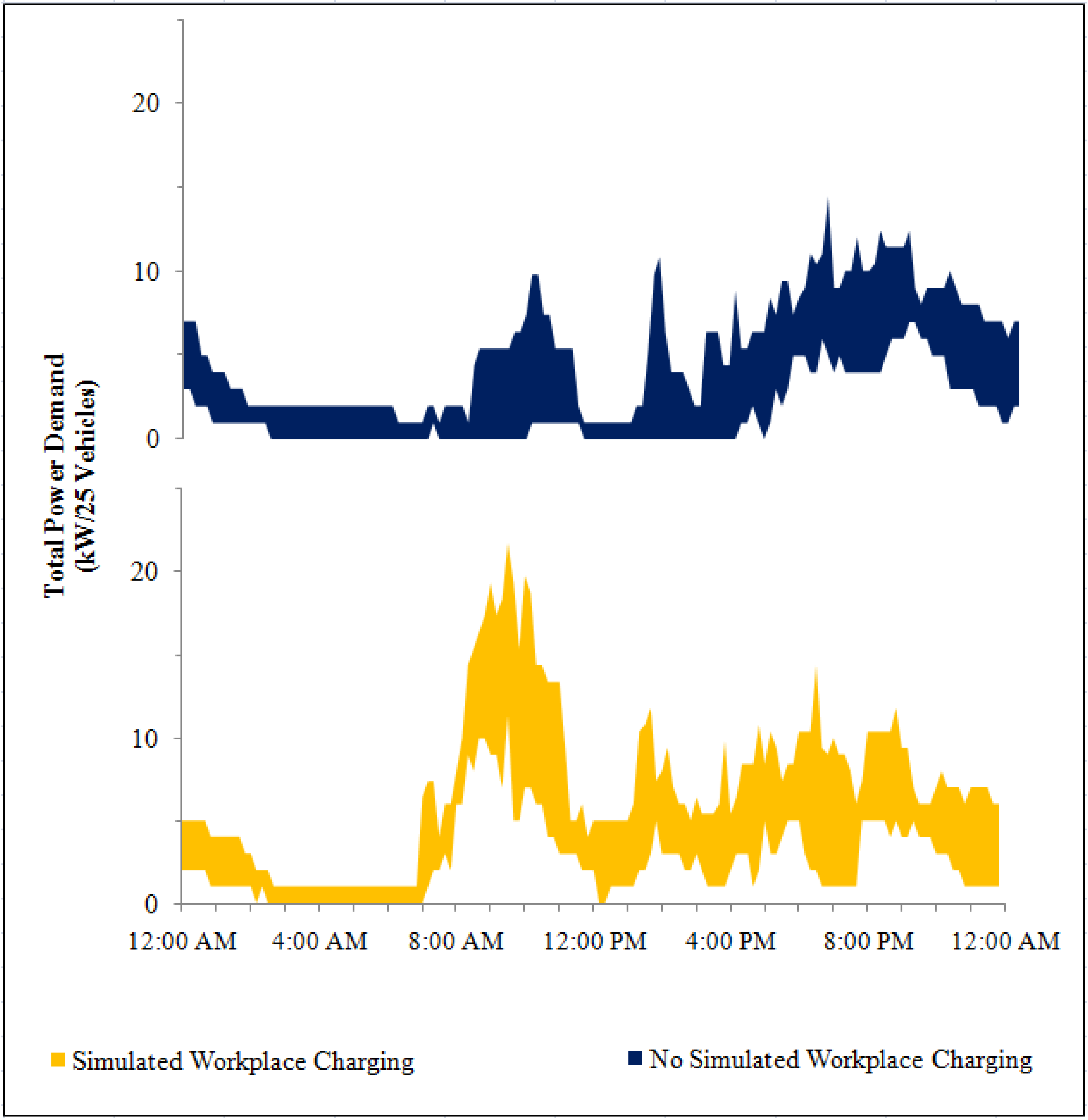
Time of Day Electricity Demand

Electricity demand establishes the time of day total power (sum of power demand for 25 vehicles) and variation in power required at a given time of day to charge the vehicles. Figure 3 shows the modeled electricity demand for all 25 vehicles with and without simulated workplace charging. Electricity demand is calculated by combining each household's driving and charging record with the battery size, per mile energy use, and charging level characteristics of the vehicle they designed in their survey. In the case of simulated workplace charging, additional charging events are inserted within the driving and charging record every time the car is parked at work

The total power demand to charge all 25 PHEVs is determined by the distribution of the battery sizes, the batteries' state of charge when plugged in, and the charging rate chosen by the households for their design vehicle. As seen in Figure 3, total power demand without simulated workplace charging (in blue) increases sharply at 11:00am, 2:00pm and reaches a peak of 15 kW around 6:30pm. Power demand throughout the early morning is minimal between 2am and 8am. Power demand increases in the morning as three of the households were able to, and chose to recharge at their workplace. At 11:00 am and 2:00pm, electricity demand spikes. These spikes, mostly short in duration, are caused by a household who was able to plug-in at work, and designed a survey vehicle with level 2 charging. While vehicles using level 2 charging take less time to charge, they cause comparatively more rapid rises in electricity demand than do most other vehicles charging at 110v/10 amps since they use approximately four times as much instantaneous power.

Figure 3 also shows the modeled weekday time of day electricity demand for all 25 household's survey designed vehicles with workplace charging. Under the modeled conditions, the peak power demand to charge all 25 vehicles moves from the evening to the morning, at approximately 9:30am. The addition of workplace charging for 22 commuter vehicles increased the daytime power demand peak from 12 to almost 22kW, and results in a relatively stable electricity demand from 5:00pm to 10:00pm. However, the power demand shown here for workplace charging does not include any mechanism, such as timers, to help level peak demand. Given that the median vehicle design has a 1.7 kWh battery, and that vehicles are routinely parked from 6 to 9 hours a day at the workplace there may be the possibility to limit morning peak by further decreasing the charging rate or controlling how many when vehicles charge at any given time. However, the merits and necessity of such systems vary depending on the total time of day system load experienced by each utility.

FIGURE 3 Weekday Time of Day Electricity Demand, With and Without Simulated Workplace Charging.



Effects of Simulated Workplace Charging on CD Driving

The degree to which households complete travel in CD mode is the result of a combination of the CD range of their designed vehicle, the number of miles between charging events, and the amount of electricity transferred to the car's battery during each charging event. The fraction of total driving distance a household can complete in CD mode, percent of miles in CD mode, can provide some idea as to the ability of households to make use of the CD range of their PHEV. Table 3 shows the distribution of the miles traveled by each household during their representative week of driving and the resulting percentage of CD driving that the household would have accomplished if they were driving the PHEV they designed in the survey, with and without simulated workplace charging. For the 22 households who commuted to work and were unable to charge there during their PHEV trial, driving their designed PHEV would have resulted in 15 to 100 percent of miles in CD mode, with an overall mean of 35%. Simulated workplace charging raised the average percent of miles in CD mode from 35 percent to 52 percent, with some households increasing their percent of miles in CD mode by as much as 42 percentage points. In general, households who drove more miles during their representative week appear to have driven a lower percentage of them in CD mode than households who drove fewer miles.

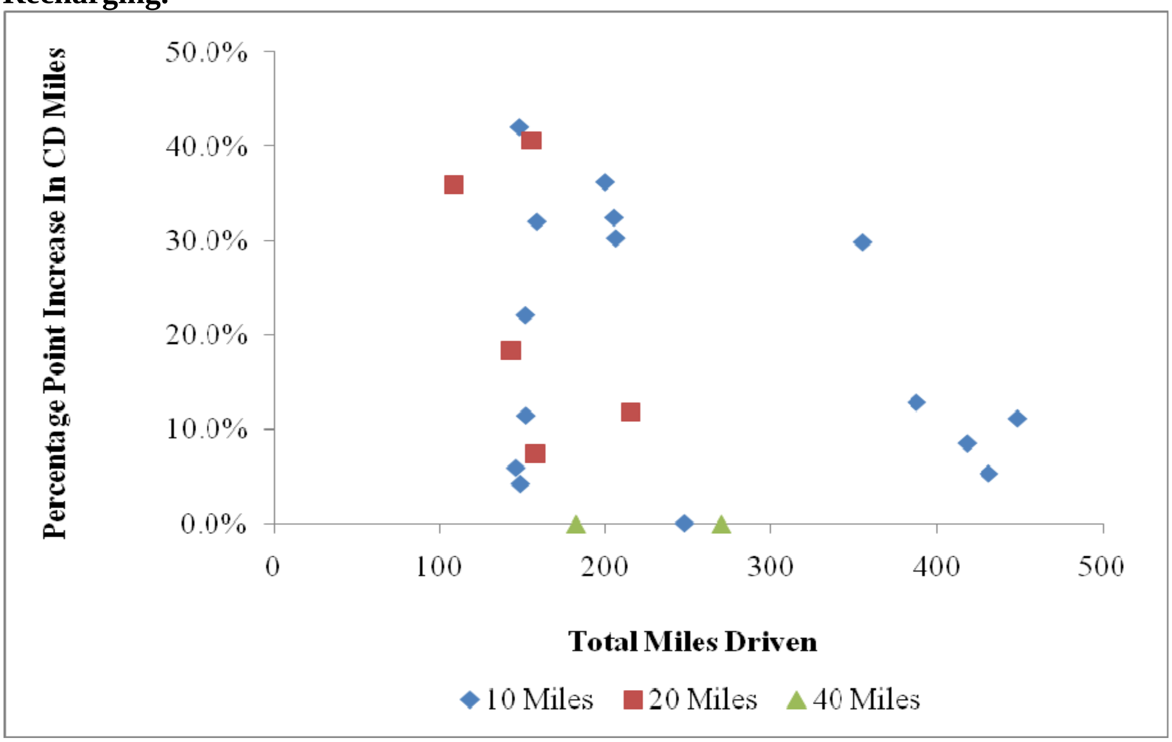
Table 3 Summarizing CD driving with and without simulated workplace charging

Household	Total Miles Traveled	CD range	Percent CD miles Without Simulated Workplace Charging	Percent CD miles With Simulated Workplace Charging	Percentage point increase in CD miles
1	109	20 Miles	64.1	100.0	35.9
2	159	10 Miles	19.2	51.2	32.0
3	146	10 Miles	41.3	47.2	6.0
4	431	10 Miles	14.9	20.2	5.3
5[i]	359	20 Miles	51.4	NA	NA
6	270	40 Miles	83.6	83.6	0.0
7	248	10 Miles	27.6	27.6	0.1
8	200	10 Miles	24.4	60.5	36.2
9	152	10 Miles	52.6	64.1	11.5
10	143	20 Miles	81.6	100.0	18.4
11	418	10 Miles	18.4	26.9	8.6
12[i]	250	10 Miles	35.3	NA	NA
13	158	20 Miles	54.7	62.1	7.4
14	155	20 Miles	51.5	92.0	40.5
15	206	10 Miles	24.3	54.5	30.2
16[i]	330	40 Miles	91.8	NA	NA
17	148	10 Miles	33.7	75.7	42.0
18	215	20 Miles	46.4	58.3	11.9
19	448	10 Miles	15.6	26.8	11.1
20	205	10 Miles	35.8	68.2	32.4
21	388	10 Miles	15.5	28.4	12.9
22	152	10 Miles	31.3	53.4	22.1
23	182	40 Miles	100.0	100.0	0.0
24	355	10 Miles	25.7	55.5	29.8
25	149	10 Miles	52.4	56.6	4.2

i. Indicates household charged at their workplace during representative week. As such their %CD operation does not change between the without/with conditions modeled here.

Among the factors determining the additional CD driving that resulted from workplace charging was the households design vehicle's CD range. Figure 4 summarizes the additional CD driving that would have been achieved by all 22 households (who did not already recharge at work) in the simulated workplace charging scenario based on each household's designed vehicle. Though the sample is small, the results are suggestive. Across the diverse travel days of these commuters and across the CD ranges of their PHEV designs, the consistent addition of workplace recharging increases the percentage of CD miles by zero to 42 perecnt of the CD miles modeled to be driven in a PHEV of their design.

FIGURE 4 Percentage Point Increase in CD Miles Per Household from Adding Workplace Recharging.



Given that the effect of workplace charging on amount of CD driving varies according to the modeled CD range, Figures 5 and 6 illustrate the effect of CD range without and with simulated workplace charging. To simplify the graphic, each "band" in the figures represents a quartile of households, i.e., about six households are represented by an area rather than by their own line. Note, an all-electric PHEV is used as it represents an extreme case where the impact of charging would have the smallest increase in CD range given the high per mile electricity consumption. It is expected that vehicles with lower per mile electricity consumption, i.e., the blended PHEVs most of the households designed, would yield greater increases in CD driving.

Figure 5 combines the observed driving and charging for each of the 25 households with the energy consumption characteristics of an all-electric PHEV for CD ranges from 1 to 40 miles. The percent of miles in CD mode by CD range is plotted. Without workplace recharging, as the simulated CD range increases the marginal increase in CD miles slowly decreases. Given the current driving and charging behaviors observed across the 25 plausible early market commuters, a PHEV with 20 miles of CD range would have provided between 20 and 80 percent of miles in CD mode. At 40 miles of CD range, the percent of miles driven in CD operation varies between 40 and 100 percent.

FIGURE 5 Effect of CD Range on Percent of Miles Driven in CD Mode.

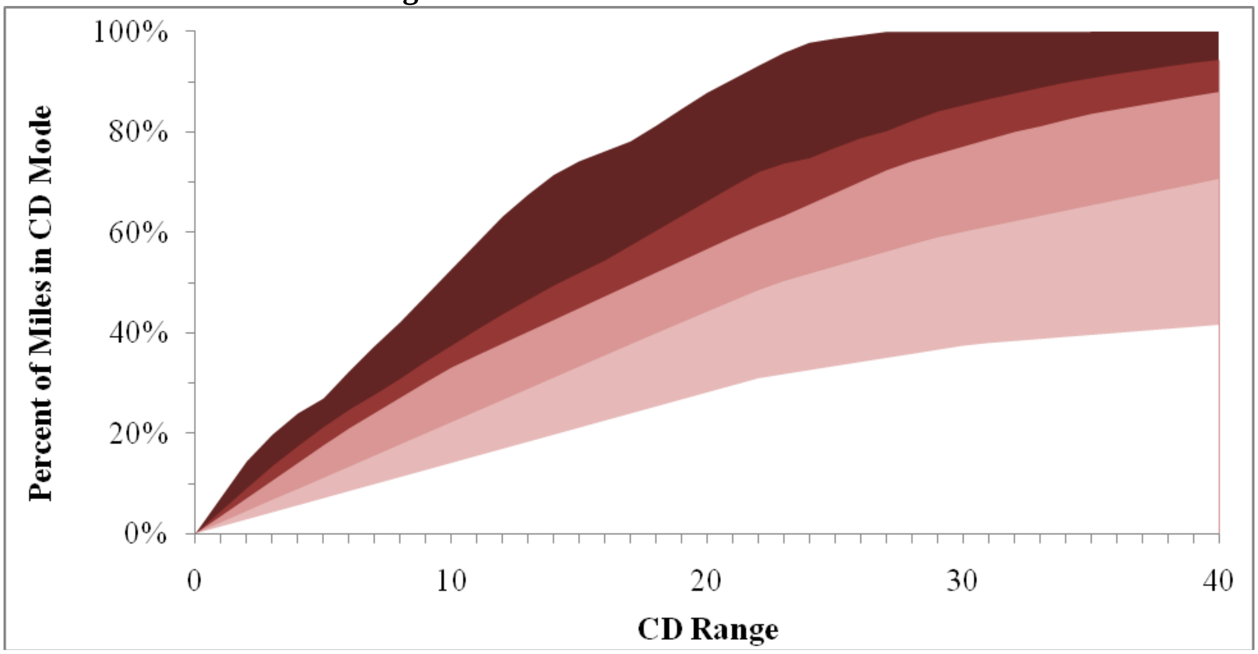
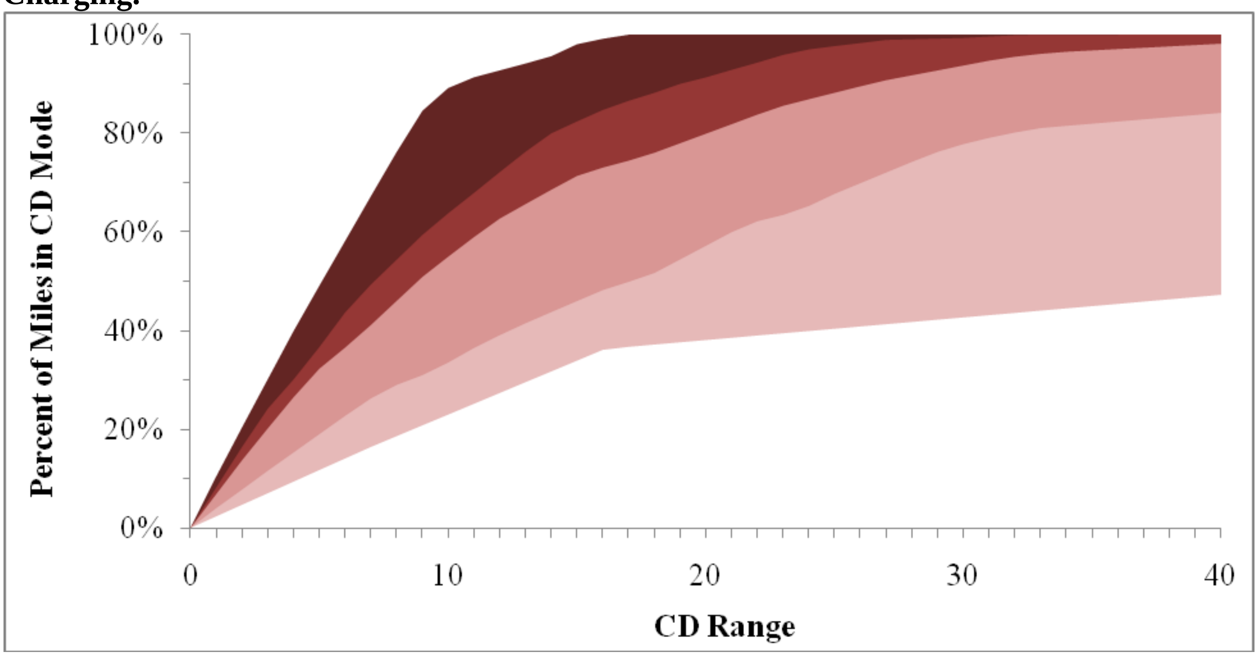


FIGURE 6 Effect of CD Range on Percent of Miles Driven in CD Mode, With Workplace Charging.



Adding workplace recharging in Figure 6, below about 15 miles CD range, each additional mile of range contributes more to the percent of miles driven in CD operation than above 20 miles. With workplace charging, at 20 miles CD range the households are achieving between 40 and 100 percent of their driving in CD mode and the median percentage of approximately 80 percent of miles is the same as the maximum percent of CD miles at 20 miles CD range without workplace recharging.

Comparing Figure 6 to Figure 5 shows the effect of CD range on the percent of CD driving given the addition of simulated workplace charging. As shown by Figure 5, with current driving and charging behaviors observed in the demonstration, 25 percent of all demonstration participants could achieve between 60 to 80% of their routine driving in CD mode with a 20 mile PHEV. The addition of a single charging spot at each household's workplace dramatically increases the percent of miles in CD modeof, with 25 percent of households achieving 60 to 90 percent of their miles in CD mode with an all electric 10 mile PHEV, and 50% of all households achieving 80 to 100 percent of their miles in CD mode with and all electric 20 mile PHEV. The addition of a single, frequently and regularly used charging location would allow those who used their PHEVs to commute to work to complete a significant portion of their commute day driving in CD mode with a "short range" PHEV.

CONCLUSION

A PHEV demonstration and market research project provided a group of 25 plausible early market PHEV buyers the opportunity to drive and charge a PHEV conversion within the context of their own lives, choosing when, where and how much to drive and charge the vehicle. Combining each household's observed driving and charging behaviors with assumptions about per mile energy use for a PHEV of each households' design allows us to estimate the grid impact and resulting CD driving that would have occurred. While the proportion of CD driving is pertinent to clean air and climate goals, the relationships are confounded by regional differences in electricity power generation. The specific goal of increasing the proportion of miles that PHEVs are driven in CD mode is more clearly connected to motivations for substituting electricity for petroleum *per se*, e.g., energy security.

Participants' PHEV designs provide measures of consumers' present expectations and perceived requirements. At present, the 25 commuters studied here mirror the results of the larger sample of 67 households from which they are drawn: their PHEV designs emphasize blended CD operation and modest CD ranges. (And these 67 mirror the designs created by a far larger U.S. national sample of new car buyers (13)). In a world where CD range is a consumer option, it could be expected that consumer designed PHEVs would achieve between 15% to 100% of their miles in CD mode during representative weeks of travel; the percentages of all actual miles of travel in the PHEV would be somewhat lower as "representative weeks" as applied here tend to exclude infrequent long travel days. Given that most households designed vehicles that require batteries smaller than 4kWh, electricity demand to recharge these PHEVs peaks before 8:00pm at approximately 15 kW as compared to a potential maximum of 25kWh if all the vehicles were plugged in and charging at the same time.

Assumed workplace charging allows estimates of the impact on CD driving and the resulting tradeoff with daytime electricity demand. Overall, the impact of workplace charging on CD driving depends on a number of factors, including CD range, at home charging behavior, driving distances between charging events, the frequency with which households drive to work, and the amount of time the vehicle remains parked there. Workplace charging allowed most of the plausible early PHEV market commuters to increase their total percentage of miles in CD mode between 0 and 35 percentage points. The additional CD driving comes at the expense of increased daytime electricity demand. The new resulting morning peak starts to build as soon as vehicles start to arrive at workplaces in the morning and does not subside to levels for the non-workplace recharging case until just before noon.

The assumptions used in the analysis highlight important guidelines for away from home charging. While additional charging opportunities can increase CD driving, thus extending the personal and societal benefits of PHEVs, policy 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, households might completely shift charging away from their home to the workplace, thus helping to exacerbate daytime electricity demand. Lastly, as households begin to explore electric transportation options it would appear that diversity in vehicle CD range might help some households enter the vehicle market without purchasing "too much battery." Furthermore workplace charging may provide additional value to some PHEV users, especially those with 10 to 20 miles of CD range, by allowing them to increase their overall CD driving, or by allowing households to meet their daily driving needs with smaller batteries, potentially allowing more widespread introduction of PHEVs in a world where battery capacity andrange are expensive.

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