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Abstract

To explore the potential energy impacts of widespread PHEV use, an innovative, three-part survey instrument collected data from 877 new vehicle buyers in California. This analysis combines all the available information from each respondent—driving, recharge potential, and PHEV design priorities—to estimate the energy impacts of the respondents' existing travel and understandings of PHEVs under a variety of recharging scenarios. Results suggest that the use of PHEV vehicles could halve gasoline use relative to conventional vehicles—the majority of this reduction being due to increases in charge sustaining (CS) fuel economy. Using three scenarios to represent potential boundary conditions on PHEV driver recharge patterns (unconstrained, universal workplace recharging, and off-peak only charging), we estimate tradeoffs between the magnitude and timing of PHEV electricity use. In the unconstrained "Plug and Play" recharge scenario, recharging peaks at 6:15pm, following a far more dispersed pattern throughout the earlier part of the day than anticipated by previous research. PHEV electricity use could be increased through policies increasing non-home recharge opportunities (e.g., the "Enhanced Workplace Access" scenario), but most of this increase occurs during daytime hours and could contribute to peak electricity demand (depending on a given region's definition of "peak"). We also demonstrate how deferring all recharging to off-peak hours (8pm to 6am) could eliminate all additions to daytime electricity demand from PHEVs. However, in such a scenario less electricity is used due to the elimination of daytime recharge opportunities and less gasoline is displaced. Overall, policy, technology, and energy providers may use this information to understand whether their plans, designs, and goals align with these present empirically-informed understandings.

Keywords: PHEV, energy consumption, market, charging, environment

1 Introduction

As hybrid-electric vehicles (HEVs) continue to achieve significant commercial success in the U.S. market, plug-in hybrid vehicles (PHEVs) are touted as the next step in electric drive development [1]. PHEVs are one step closer to the pure electric vehicle (EV) initially envisioned by California's zero emissions vehicle mandate; users can charge the battery from the electrical grid and drive limited distances in charge-depleting (CD) mode. During this mode, the vehicle is powered either by electricity only (all-electric operation) or by electricity and gasoline (blended operation). Once the battery is depleted to a minimum state of charge, the PHEV uses only gasoline in charge sustaining (CS) mode, achieving gasoline-only fuel efficiency typical of today's HEV. Battery size, degree of hybridization, and drivetrain design all influence the overall operation of a given PHEV [2].

PHEVs' use of gasoline and electricity depends on the interaction between vehicle design and recharging and travel behaviours, creating inherent uncertainty for policymakers, automakers, electric utilities, researchers, and other interest groups. Due to lack of direct data on these interactions and behaviors, previous impact and market analyses have assumed them [1,3-9], often drawing by proxy from data on aggregate travel and housing stocks. The choice of assumptions seriously affects results; Lemoine et al. [1] illustrate how varying time of day recharge assumptions can substantially influence predictions of electricity grid impacts. In all, there is a demonstrated lack of data on consumer behavior and demand pertinent to PHEV markets and subsequent environmental and energy impacts.

We focus this paper on one question: what energy impacts (gasoline and electricity) can we anticipate with significant PHEV adoption? To empirically answer this question, we construct recharge scenarios based on data collected by a web-based survey of new vehicle buying households. Results from this survey were recently reported at the U.S. level [10], but this paper focuses on respondents from California—a sub-region that was purposely oversampled for the purpose of conducting a representative analysis. Three types of data were collected: (1) time of day driving patterns, (2) recharge potential, and (3) new-car buyers' PHEV design priorities, collected via design games. Taken together, the collected information regarding driving patterns, recharge potential and design priorities allow the creation of realistic recharge scenarios. We simulate grid impacts under three scenarios to investigate potential tradeoffs between overall gasoline and electricity use and the timing of electricity use.

2 Methods

2.1 Survey design

Data was collected using a multi-part online survey. Driving patterns and recharge potential were elicited using a *Plug-in Potential* diary of driving and parking for a vehicle purchased new (model year 2002 or later) that is driven several times per week by the respondent's household. Respondents were assigned a day of the week and instructed to record information for a 24 hour period starting with their first trip of that day. Information included the timing and distance of each trip, parking locations, and the proximity of those locations to an electrical outlet. Respondents recorded data in a diary printed from a PDF document and then input their data online. The respondent's diary day was immediately depicted to them as a graph, using a technique similar to that used by Kurani et al. [13,14] to help respondents better understand their own driving behaviour and how an electric-drive vehicle could fit into their lifestyle.

The PHEV design priority data used in this analysis were collected with a priority-evaluator game. Commonly, researchers will infer preferences for attributes of alternative fuelled vehicles by presenting respondents with a description of one or several new technologies, followed with a set of hypothetical choice scenarios in which respondents make several choices from sets of vehicles of different attributes, e.g. [15-18]. However, Heffner et al. [19] demonstrate that more in-depth research, such as household interviews, can reveal important information that choice experiments cannot. To improve the quality of data gathered through a nationwide survey, prior to the PHEV design exercises, respondents were provided two types of preparatory information: (1) the 24-hour diary exercise described above served the additional role of reflecting to respondents aspects of their travel patterns and potential access to recharge spots, and (2) a PHEV buyers' guide describing basic design options for PHEVs. Respondents then completed a *Purchase Design* game with design possibilities priced in dollars; respondents could reject buying a PHEV, retaining a conventional vehicle. This type of in-depth research has previously been described as reflexive design [14].

Table1: Price of upgrades for Purchase Deign game (prices incremental to conventional vehicle)

		"Higher" price		"Lower" price	
Attributes	Attribute level	Car	Truck	Car	Truck
Base premium over conventional		$3,000	$4,000	$2,000	$3,000
Added premiums:					
Recharge time	8 hours	0	0	0	0
	4 hours	+$500	+$1,000	+$250	+$500
	2 hours	+$1,000	+$2,000	+$500	+$1,000
	1 hour	+$1,500	+$3,000	+$750	+$1,500
CD mpg and type	Blended				
	75 mpg	0	0	0	0
	100 mpg	+$1,000	+$2,000	+$500	+$1,000
	125 mpg	+$2,000	+$4,000	+$1,000	+$2,000
	All-electric	+$4,000	+$8,000	+$2,000	+$4,000
CD range	10 miles	0	0	0	0
	20 miles	+$2,000	+$4,000	+$1,000	+$2,000
	40 miles	+$4,000	+$8,000	+$2,000	+$4,000
CS mpg	Conventional mpg +10	0	0	0	0
	Conventional mpg +20	+$500	+$1,000	+$250	+$500
	Conventional mpg +30	+$1,000	+$2,000	+$500	+$1,000

Potential PHEV designs offered to respondents were informed by previous analysis of early PHEV drivers [20]. There were four PHEV design attributes: (1) hours required for complete recharge of a depleted battery, (2) gasoline use in charge-depleting (CD) mode, (3) miles of range in CD mode, and (4) gasoline use in charge-sustaining (CS) mode.[1] In each game, a base PHEV design was offered with capabilities easily achievable by current technology [2]: a PHEV that requires up to 8 hours to completely recharge, that can be driven for the first 10 miles in CD mode using blended operation that increases gasoline-only fuel economy to 75 mpg, and that can improve fuel economy by 10 mpg when operating in CS mode over a conventional, i.e., gasoline-ICE, version of the same vehicle.[2]

[1] To ease comparison with other literature, we report distances in miles, where 1 mile = 1.61 km.

[2] These PHEV design games are meant to represent designs that are technologically feasible, but not necessarily with exact specifications. For instance, the battery required for our base PHEV design would likely require only 2 to 3 hours to fully recharge with a 110 to 120 volt circuit. However, with careful pre-testing, we consciously chose to simplify attribute levels and ignore potential interactions among attributes to create exercises that are more likely to be understood by our respondents than to adhere to experts' knowledge.

Respondents were given opportunities to improve each attribute under the different price conditions depicted in Table 1. The PHEV design exercise was framed in the context of the household's next new vehicle purchase. The questionnaire first elicited information about the anticipated price, make and model of the next new vehicle the respondent's household would buy. The respondent then completed two PHEV purchase exercises, each comparing their anticipated conventional vehicle with a PHEV version of the same. Respondents were presented with a "higher" price and "lower" price PHEV purchase conditions, where prices in both conditions also depended on whether the vehicle was a car or truck. Each exercise started with the same base PHEV model, with additional upgrades available for added price. In each exercise, the respondent could choose to purchase their anticipated conventional vehicle, the offered (base) PHEV version, or an upgraded PHEV version. The costs in Table 1 are largely hypothetical, although they are comparable to previous estimates [21-23].

2.2 Data collection

Our target population is new vehicle buying households in California. To qualify, respondents had to own a new gasoline vehicle that they purchased in 2002 or later, which they personally drove at least 3 times per week. The respondent also must have played a significant role in the household's decision to purchase this vehicle. In limiting our study to this population, we imply that the early market for PHEVs is limited to households that tend to buy new vehicles in general. In total, 877 California respondents completed the entire survey in December of 2007 (Fig.1).

Data were collected with a web-based survey. Relative to mail and telephone methods, this mode improves the degree of design flexibility, response interaction [24], response accuracy for travel diaries [25], and data administration time and cost [26]. In recent years, web-based surveys were susceptible to non-coverage error, where a significant portion of the target population, in this case new car buyers, could be excluded if they don't have internet access. This concern is declining in the U.S. as internet usage rates have grown from 44% in 2000 to over 70% in 2007 [27]. Also, we suspect there is a positive correlation between internet access and likeliness to buy new vehicles, implying an even higher usage rate among our target population. However, non-response bias is still an important concern because those without internet access tend to be disproportionally older, with lower incomes and less education [24, 28].

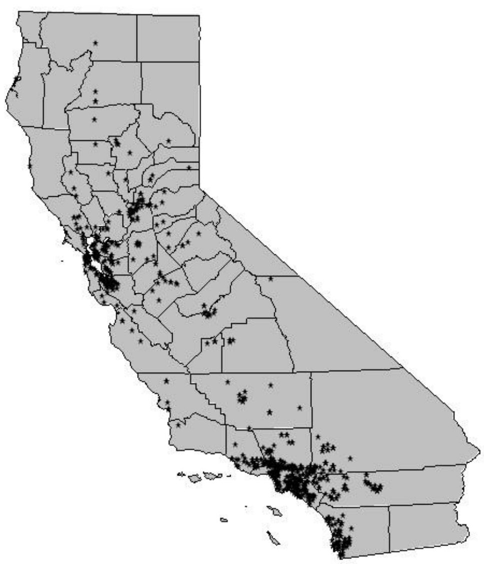


Figure1: Geographic distribution of California sample

Respondents for this survey were recruited by Harris Interactive from their internet panel. To counteract concerns of non-coverage and non-response error, Harris estimates weights to better match the realized sample to the target population. Weights are based on geographic, demographic and attitudinal data, and matched to existing databases collected through multiple survey modes (including mail and telephone). All results presented in this study use these weights to match our sample to the California population of new vehicle buyers.

To assess the external validity of our sample, we compare our sample distributions with a sub-sample of 389 California households owning new vehicles drawn from the 2001 National Household Travel Survey (NHTS). We find that the income levels of both samples are about 40 percent higher than general population estimates from similar years. Also, gender and age follow similar distributions between the two samples of new vehicle buying households. Our sample does have fewer households without any college level education (8.8 percent) relative to the NHTS sample (22.1 percent), and fewer households living in detached homes (68.1 percent) than the NHTS sample (79.4 percent). Overall, we feel these differences are not likely to be problematic. We conclude that our sample matches well with one other sample of new car owners on these socio-demographic measures, strengthening claims that our results can be extended to the California population of new-car owning (and therefore, new car-buying) households.

3 Results

3.1 Recharge access

Results from the *Plug-in Potential* vehicle diary indicate that more new vehicle buyers may be pre-adapted for vehicle recharging than estimated in previous constraints analyses. Following Graham et al. [15], we consider a parking spot to be viable for recharging if located within 25 feet of an electrical outlet. Of the 877 respondents, 52.1 percent found at least one viable recharge location during their 24-hour diary day, and 45.3 percent identified one at their home. Only 4.4 percent of respondents found outlets at work, and 9.1 percent found outlets at other non-home locations (e.g. friend's home, school, commercial site, etc.).

In Fig.2, we represent driving and recharge potential over a 24-hour cycle (in 15 minute intervals); the sample was proportionally assigned a weekday or weekend-day to complete their diary. On weekdays, the proportion of respondents' driving follows an expected daily pattern (the black line in Fig.2), peaking during common commute hours at 7:30am and 5:00pm. In any given 15-minute interval, total recharge potential ranges from over 45 percent of respondents from 9:00pm to 6:00am, to under 20 percent from 10:00am to 3:00pm. Throughout the day, home is by far the most frequent location of recharge opportunities within respondents' existing travel and recharge potential. Neither work nor other non-home locations have recharge potential that surpass 4 percent of respondents for any 15 minute interval during the day. The general pattern in Fig.2 is consistent with driving patterns; recharge potential drops when many respondents are driving or parked at work or other locations, and rises when vehicles are parked at home. Driving patterns on weekend days (not shown) do not show morning and afternoon peaks, but rather a single broad mid-day rise to a peak at around 4:00pm (with a lesser peak in the later evening). Weekend recharge potential during any given 15 minute interval ranges from a high of 55.1 percent to a low of 19.5 percent of all respondents; home also dominates the potential recharge locations for weekends.

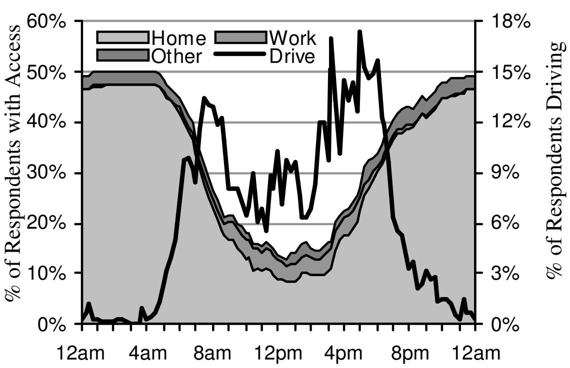


Figure2: Time of day driving and recharge potential (weekdays only, n = 644)

3.2 PHEV design and value

Because recharge opportunities are relatively sparse at work and other non-home locations, we focus on home recharging as the key criteria to characterize a potential early PHEV market in this analysis. This constraint is substantiated by the experience of early drivers of PHEV-conversions [20]. Thus, for the remainder of this study, we limit our consideration to the 45.3 percent of our sample that identified an electrical outlet within 25 feet of their vehicle parking spot at their home location at some time during their 24-hour diary. Among respondents with home recharge potential, 73.3 percent designed a PHEV for their next new vehicle in the "higher" price condition, and 84.0 percent did so in the "lower" price condition. We further constrain this segment based on PHEV interest as indicated by purchase intentions in the design games. Thus, we select the respondents that demonstrate both access to sufficient recharge infrastructure and PHEV interest as a group best representing the early PHEV market in California—33.2 percent using the "higher" price scenarios, and 38.1 percent using the "lower" price scenarios. We will refer to these subsets as the *plausible early market* respondents.

Focusing on the interests of these *plausible early market* respondents, results of the PHEV design games are summarized in Fig.3. PHEV performance priorities varied substantially; no majority PHEV design emerged. A substantial portion of *plausible early market* respondents chose the base PHEV models with no upgrades—31.5 percent in the higher price condition and 23.2 percent in the lower price condition. Among those that chose to pay extra for upgrades, CS fuel economy upgrades were chosen more often than other upgrades, and there is no evidence of the strong interest in all-electric CD operation observed among some PHEV pioneers [20]. All-electric upgrades were chosen by only 2.7 and 3.9 percent of respondents in the higher and lower cost conditions, respectively. CD operation and range improvements were chosen relatively less often than CS upgrades.

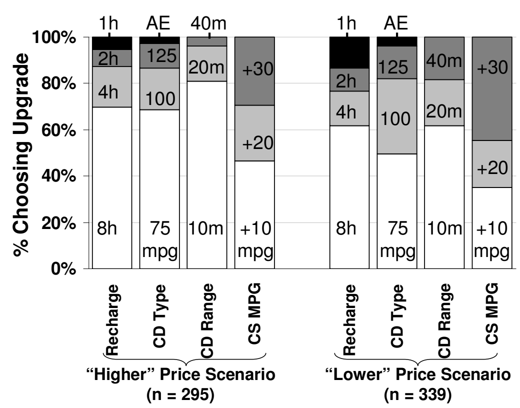


Figure3: Distribution of selected PHEV upgrades (all *plausible early market* respondents)

3.3 PHEV energy use scenarios

To create scenarios of gasoline and electricity use among early PHEV buyers, we integrate the information presented thus far from respondents in the *plausible early market* segment: driving behaviour and recharge potential as recorded by their 24-hour diary, and PHEV design choices as demonstrated in the *Purchase Design* game. In other words, we create scenarios of gasoline use and recharge patterns for each *plausible early market* respondent as if they had driven their PHEV design on their 24-hour vehicle diary day. These scenarios rely on the following assumptions:

- Gasoline use is modelled using the estimated miles per gallon (MPG) of the vehicle, without accounting for potential variation in driving patterns. In other words, if the vehicle is rated at 20 MPG, we assume this constant rate for each mile driven (neglecting potential for different drive patterns over a given trip or across drivers).
- For charge depleting (CD) operation, electricity use (kWh/mile) and available battery energy capacity (kWh) is estimated as in Table 2, based on previous estimates [23, 28, 29]

Table2: Assumed PHEV energy requirements

CD mpg/type	Car	Truck
75 MPG		
CD kWh/mile	0.12	0.15
kWh for 10 miles	1.2	1.5
kWh for 20 miles	2.3	3.0
kWh for 40 miles	4.6	5.9
100 MPG		
CD kWh/mile	0.14	0.17
kWh for 10 miles	1.4	1.7
kWh for 20 miles	2.7	3.5
kWh for 40 miles	8.0	7.0
125 MPG		
CD kWh/mile	0.18	0.23
kWh for 10 miles	1.8	2.3
kWh for 20 miles	3.6	4.7
kWh for 40 miles	7.3	9.3
All electric		
CD kWh/mile	0.30	0.38
kWh for 10 miles	3.0	3.8
kWh for 20 miles	6.0	7.7
kWh for 40 miles	12.0	15.4

- Each vehicle's assumed battery state of charge at the beginning of the day is a function of the distance driven the previous day (assumed to be the same as the diary day due to lack of multi-day data) and the respondent's estimated hours of recharge potential from the previous day (elicited elsewhere on the survey).
- Following Lemoine et al.'s [1] assumptions, the minimum recharge rate for a PHEV battery using a regular 110-120 V outlet is 1 kWh per hour. If the respondent's chosen PHEV design has a recharge rate faster than that required for their battery size, we apply the shorter of the two recharge times. For example, if the respondent chose a PHEV requiring 8 hours for complete recharge, yet their battery size is only 1.2 kWh (requiring a maximum of 1.2 hours for full recharge), we apply the 1.2 hour time. In contrast, if the same respondent selected a recharge time of one hour, we apply the one hour time.
- Following Lemoine et al.'s [1] assumptions, vehicle recharging is approximately 83 percent efficient—increasing the battery's state of charge by 1 kWh requires 1.2 kWh from the electrical outlet.
- Each scenario is scaled up to represent 1 million vehicles. This value is not selected in anticipation of a particular sales volume for a particular year, but instead is a relatively feasible market size that serves to normalize energy use to allow comparisons across scenarios (with different sample sizes).[3]
- Vehicles are recharged on a daily basis as detailed in the scenario descriptions below.
- The PHEVs are used precisely as were their non-PHEV variants; the scenarios are based on replicating the travel-days as recorded in the diaries and do not allow for households to change the assignment of vehicles within the household or otherwise change vehicle use in response to the PHEV.
- We assume for this analysis that one-day cross-sectional data are adequate to characterize travel and therefore energy impacts. One-day diaries systematically under-represent longer trips unless the sampling is conducted according to the frequency distribution of travel-day or trip distances across people and days. By sampling across all seven days of the week we attempt to reduce

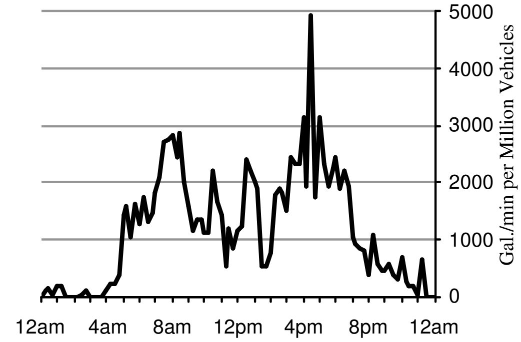
[3] An alternative approach would be to estimate the effect of each recharge scenario on the size of the potential PHEV market, such as the addition of potential PHEV buyers resulting from the expansion of public vehicle recharge infrastructure, e.g. at the workplace. However, we leave such analyses to future research, and instead focus on "what-if" scenarios using a set market size.

the effect on our analysis, but do not represent that it is immune. It seems plausible that we, and anyone using one-day travel data, will underestimate total energy use and gasoline use in particular. We leave the estimation of the size of this potential problem to future research.

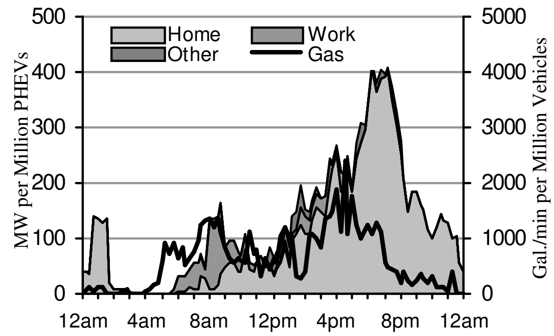
Following these assumptions, we created four scenarios using data from the *plausible early market* respondents:

- **No PHEVs** (Fig.4a): In this scenario, we estimate and aggregate the gasoline used by the respondents on their actual diary days.
- **Plug and play** (Fig.4b): We simulate the gasoline used for driving *and* the electricity used for recharging, allowing that the conventional vehicles are displaced by a vehicle with the PHEV upgrades chosen in the *Purchase Design* game. Drivers are assumed to recharge whenever they are parked within 25 feet of an electrical outlet. In other words, there are no pricing mechanisms, e.g., time of use electricity tariffs, or technologies, e.g., smart charging mechanisms, to divert recharging to off-peak.
- **Enhanced workplace access** (Fig.4c): This scenario starts with the conditions in *Plug and Play*, but further supposes that all workers can and do recharge at work.
- **Off-peak only** (Fig.4d): Finally, using the same recharge potential and PHEV designs as *Plug and Play*, in this scenario no PHEV recharging is allowed during daytime peak hours (6am to 8pm). Smart charging technology is used to optimize the timing of electricity use over this period, represented as a flat line (the actual shape of this line would likely vary according to the needs of a particular electric utility).

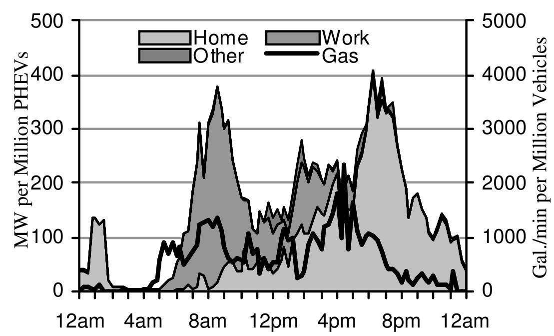
Taken together, these scenarios are meant to represent potential boundary conditions, that is, where the entire market adheres to a selected condition, i.e., no recharge regulation, enhanced workplace access, or off-peak charging. Of course, the early PHEV market may include elements of more than one of these scenarios, as well as other potential conditions we do not consider here, all of which are likely to change over time. However, the purpose of this exercise is to present these boundary conditions to frame discussions of the potential benefits and drawbacks of different recharge strategies and policies.



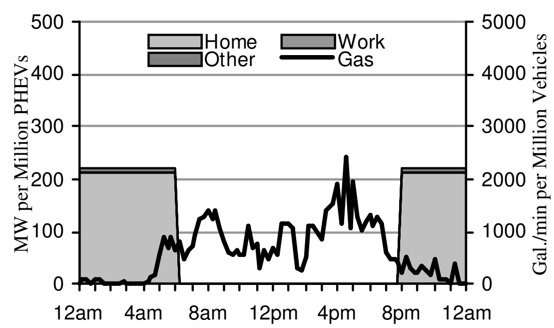
(a) No PHEVs



(b) Plug and play



(c) Enhanced workplace access



(d) Off-peak only

Figure 4: Recharge profiles using "higher" price scenario (weekdays only, n = 231)

Table3: Summary of recharge scenarios, scaled to one million PHEVs

Scenario		PHEV Design Game: "Higher" price		PHEV Design Game: "Lower" price	
		Weekday (n = 231)	Weekend (n =52)	Weekday (n = 265)	Weekend (n =58)
No PHEVs	Gasoline (Gal.)	1,658,895	1,353,784	1,627,466	1,347,016
CS Upgrade Only	Gasoline (Gal.)	1,024,708	820,077	952,423	804,611
	% Gas reduced	38.2%	39.4%	41.5%	40.3%
Plug and Play	Gasoline (Gal.)	870,444	690,669	778,571	678,475
	% Gas reduced	47.5%	49.0%	52.2%	49.6%
	Electricity (MWh)	3,007	2,516	3,679	2,663
	Peak (MW)	416	300	513	327
	Peak Time	6:15pm	5:15pm	6:30pm	6:30pm
Enhanced Workplace Access	Gasoline (Gal.)	826,251	686,557	737,325	672,658
	% Gas reduced	50.2%	49.3%	54.7%	50.1%
	Electricity (MWh)	3,843	2,655	4,481	2,843
	Peak (MW)	410	300	486	365
	Peak Time	5:45pm	5:15pm	6:15pm	6:15pm
Off Peak Only	Gasoline (Gal.)	909,208	717,625	815,810	700,178
	% Gas reduced	45.2%	47.0%	49.9%	48.0%
	Electricity (MWh)	2,199	1,917	2,873	2,217
	Peak (MW)	220	192	287	222
	Peak Time	8pm-6am	8pm-6am	8pm-6am	8pm-6am

Figures 4a-d portray each scenario for respondents who completed weekday diaries given the PHEV designs they selected in the "higher" price conditions. Table 3 includes these as well as results from respondents with weekend day diaries, as well as "lower" price conditions PHEV designs. Figures 4a-d depict the time of day gasoline use (gallons per minute) and electricity use (MW) per million vehicles over a 24-hour period. The areas under the curves represents the total gallons of gasoline, or MWh of electricity, used over the day. In the Plug and Play scenario, most recharging occurs at home, peaking at 6:15pm at 416 MW (513 MW in the "lower" vehicle price condition)—significantly lower than the 1,200 MW peak anticipated by Lemoine et al. [1] for 1 million PHEVs. Their higher peak electricity demand estimate is due to their assumptions about a uniform PHEV design across the market (20 miles of all-electric CD range) and relatively uniform recharging patterns of PHEV drivers.[4] In contrast, the present study allows for substantial variation in PHEV designs and daily driving.

Time of day gasoline use corresponds with the rush hour periods observed in Fig.2. These simulations indicate that in the Plug and Play scenario overall gasoline use is estimated to cut gasoline use by half relative to the No PHEV scenario (Table 3). Notice that gasoline use is reduced by a larger degree in the morning due to the higher proportion of miles driven in CD mode earlier in the day. Table 3 also shows that a large portion of this gasoline reduction (75 to 85 percent) is due to upgrades to CS fuel economy with CD capabilities eliminated.[5] For this reason, overall gasoline savings varies little across the three charging scenarios or the vehicle price levels in the design game; in all instances, gasoline use is cut in about half compared to the No PHEV scenario.

However, the peak magnitude and timing of recharging varies significantly across the scenarios. Fig.5 plots all three recharge scenarios. The Enhanced Workplace Access scenario increases overall electricity use by 28 percent relative to Plug and Play, with much of the

[4] In each recharge scenario presented by Lemoine et al. [1], PHEV drivers are assumed to begin recharging at approximately the same time of day for the same duration.

[5] However, simulating only CS fuel economy upgrades may be inappropriate—respondents might not have chosen the vehicle upgrades without plug-in and CD capabilities.

addition occurring in the morning as drivers arrive at work. In contrast, the Off Peak Only scenario reduces electricity use by 27 percent, largely due to the elimination of work and other non-home recharge opportunities that occur during peak hours. Of course, this scenario has the benefit of eliminating all electricity use during peak hours, with nightly demand balanced at 220 MW. As noted, the specific balancing strategy used in this scenario would likely vary by electric utilities to flatten out overall off-peak demand, as seen in Lemoine et al.'s [1] "optimal charging" scenario. Our scenario merely demonstrates the potential for shifting and minimizing peak demand.

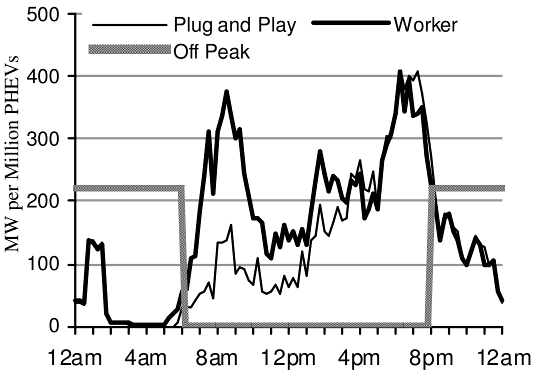


Figure4: Comparing PHEV recharge scenarios ("higher" price scenario, weekdays only, n=231)

4 Discussion and Conclusions

Results from this analysis offer initial answers to our research question: anticipating the energy impacts of the early PHEV market. Our simulated world contains far more variety of PHEV designs than any prior study. This is an intentional difference, allowing respondents to design the PHEV they would most desire given their current understanding and valuation of four PHEV performance parameters. We believe this is a more realistic representation of a plausible near future than the imposition of one or a few PHEV designs on the entire population of vehicle drivers. Certainly as we analyze "one-million PHEV" scenarios—suggesting that we are attempting to analyze a world existing a few years after the introduction of PHEVs—a world of greater variety is more plausible than a world of one or a few PHEV designs.[6] Our scenario analyses remain susceptible to other threats endemic to such efforts. Radically changing travel behaviour—in response to fuel prices, competition from other alternatives, or in response to PHEVs themselves—could invalidate our use of data on existing real travel. Rapid technology development and cost reductions—or their delay—may render our design games under-, or over-optimistic. And as discussed in the description of our recharging scenarios, none of them likely capture precisely what will happen with workplace recharging, efforts to control time of day of recharging, or efforts to provide home recharging to the over one-half of new car-buying households in California who do not now find access to electricity where they park their cars.

The present analysis is useful in providing a plausible baseline for the early PHEV market; but a baseline from which consumers, infrastructure and vehicle providers, and policy makers can create change. Research suggests that with the right incentives, consumers might locate more recharge locations, modify existing recharge locations, e.g. clean up the home garage, and adjust driving patterns and adapt vehicle use among the household fleet to maximize electricity use [14, 20]. Still much adaptation by consumers may not occur until after they purchase a PHEV, and their perceived recharge potential that may lead to PHEV purchase may be based on existing driving patterns, i.e., current perceptions of recharge locations.

Still, it may be possible to lead PHEV purchases by changing perceptions of the availability of vehicle recharging, by actually increasing the availability of recharging for those households who do not now find it, and by improving the visibility and viability of existing electrical infrastructure for vehicle recharging. Recharge infrastructure could expand to a higher percentage of households with changes in building codes, as well as increased employer and publicly installed vehicle recharge outlets.

[6] Our simulated world may be too plastic, too molded to the individual vehicle selections of our respondents. We caution against strict adherence to analogies to HEV markets to judge how quickly makes and models of PHEVs will be introduced. PHEVs are, as a set of design possibilities, more plastic than HEVs, and certainly one of the viable interpretations of the launch of HEVs is that a dearth of makes and models slowed the market entry of hybrid technology.

Among the respondents with at-home vehicle recharging, most constructed more expensive vehicle designs that added plug-in capability to their next vehicle purchase than did those without access to recharging. Given access to recharging and the distribution of PHEV designs from the games, we estimate that about one-third of new vehicle buying households in California have both the required infrastructure and interest to purchase a vehicle with plug-in capabilities. The variety of PHEV designs created by respondents suggests there is still ample opportunity for automakers to explore and develop different PHEV designs.

We observed a wide diversity of consumer interests in PHEV design options. Starting with a base PHEV design offering long recharge times, short CD range, blended rather than all-electric operation, but non-trivial increases in both CD and CS gasoline fuel economy, the most popular upgrade category was to further improve CS fuel economy. Respondents also exhibited interest in increasing vehicle range in CD mode, and improving CD fuel economy. Fewer respondents were willing to devote resources to reduce recharge time; most *plausible early market* respondents have access to periods of home-based charging long enough to fully recharge each day even at the slowest offered rate. Given their present vehicle purchase and travel behaviour, and their present understandings of PHEVs (as enhanced by the tutorial in their questionnaire), almost no new car-buying households in California design a PHEV with all-electric CD operation.

The final analysis in this report combined all the available information from each respondent—driving, recharge potential, and PHEV design priorities—to estimate the energy impacts of the respondents' existing travel and understandings of PHEVs under a variety of recharging scenarios. Results suggest that the use of PHEVs could halve gasoline use relative to conventional vehicles—the majority of this reduction being due to increases in CS fuel economy. Using three scenarios to represent potential boundary conditions on PHEV driver recharge patterns (unconstrained, universal workplace recharging, and off-peak only charging), we estimate tradeoffs between the magnitude and timing of PHEV electricity use. In the unconstrained Plug and Play recharge scenario, recharging peaks at 6:15pm, following a far more dispersed pattern throughout the earlier part of the day than anticipated by previous studies [1,7]. The more dispersed time-of-day recharging pattern in our work is due to our ability to realistically account for heterogeneity in driving and parking behaviour and to allow for heterogeneity of PHEV designs. PHEV electricity use could be increased through policies increasing non-home recharge opportunities (e.g., the Enhanced Workplace Access scenario), but most of this increase occurs during daytime hours and could contribute to peak demand (depending on a given region's definition of "peak"). We also demonstrate how deferring all recharging to off-peak hours (8pm-6am) could eliminate all additions to daytime electricity demand from PHEVs, similar to what Lemoine et al. [1] call "optimal charging." However, as also found by Kurani et al. [30] for EVs, in this scenario less electricity is used due to the elimination of daytime recharge opportunities and thus less gasoline is displaced.

This analysis provides one measure of potential threat and opportunity for electric utilities. The threat is that without control, the majority of recharging may occur during peak hours (6am-8pm), with a peak at 6:15pm during weekdays. This spike coincides with seasonal peak electricity demand periods in some California regions and with a large enough PHEV market, overall electricity generation requirements may be increased [1]. However, the observed 12am-6am recharge potential in late evening and early morning presents an opportunity for "smart charging" strategies in which PHEV recharging (as well as any other electrical load) can be shifted to off-peak periods subject to varying levels of control by electricity users and suppliers.

Our scenarios are limited in that we do not represent recharge scenarios specific to the various regions and electric utilities across California. Instead we produce an aggregated state-wide pattern without explicitly representing current electricity demand patterns, i.e., without PHEVs. Our intention is to represent energy use according to general trends rather than to provide a specific energy analysis for a given region.

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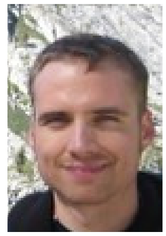

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