

Plug-in hybrid electric vehicle impacts on hourly electricity demand in the United States

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ABSTRACT

In this study we explore the effects of different charging behaviors of PHEVs in the United States on electricity demand profiles and energy use, in terms of time of day and location (at home, the workplace, or public areas). Based on driving behavior statistics on vehicle distance traveled and daily trips (US DOT, 2003) in the US, we develop a simulation algorithm to estimate the PHEV charging profiles of electricity demand with plausible plug-in times and depth of discharge of the PHEVs.

The model enables simulations of the impacts of various grid management strategies on the availability of vehicle charging in public places, the charge power levels and standards, scheduling charging in off-peak periods and policy measures to promote PHEV adoption. PHEV charging imposes a modest pressure on system load on the order of 560–910 W_p per vehicle. We find that enabling charging in places other than home increases the daily electric energy use of PHEV from 24% to 29% (1.5–2 kWh/day). Major findings of the different scenarios are that PHEVs with a 20 mile range (PHEV-20) shift 45–65% of vehicle miles traveled in the United States to electricity, compared with 65–80% for PHEVs with a 40 mile range (PHEV-40).

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1. Introduction

Motivated by energy security and environmental concerns, policy makers in the United States are directing attention to plug-in hybrid electric vehicles (PHEVs) as a partial solution to reducing fossil fuel consumption and carbon emissions. With a target of one million PHEVs on American roads by 2015 (US President Obama, 2008), US energy policy is supporting increasing the use of these vehicles as a transition technology from conventional gasoline to all-electric vehicles (EVs). PHEVs are generally seen as an intermediary technology in the electrification of the transportation sector (IEA, 2008). They have the significant advantage of offering an unlimited driving range since, once the electric battery is discharged, the vehicle can switch to the secondary fuel (gasoline or diesel). PHEVs recharge from the power grid, in contrast with conventional hybrid electric vehicles (HEVs) in which the electric battery is charged by the operation of the gasoline engine.

The electricity fuel mix in given geographic regions is an important factor determining the extent to which PHEV may contribute to emissions reductions. PHEV life-cycle emissions have been found lower than those of conventional vehicles (CVs) in

recent impact studies on electric generation (EPRI, 2007; Samaras and Meisterling, 2008; Jamarillo et al., 2009; Yang, 2009), even in scenarios of high carbon intensity of electricity production. Worst-case scenarios of the electricity fuel mix, assuming electricity is produced at 100% by coal plants emitting 950–1200 g CO₂-eq/kWh still conclude that PHEVs emit less CO₂ per mile (325–356 g CO₂-eq/mile) than a conventional gasoline vehicle (400–450 g CO₂-eq/mile) (EPRI, 2007; Yang, 2009; Yeh, 2009). Jamarillo et al. (2009) find that PHEVs have the potential to reduce emissions by 6–16% compared to conventional gasoline vehicles even if coal electricity without carbon capture and sequestration is used to power transportation.

The environmental benefits of PHEVs relative to hybrid electric vehicles depend on the fuel for electric generation. With a generation mix highly based on coal, PHEVs may lead to 7–21% higher emissions than HEVs (Jamarillo et al., 2009; Samaras and Meisterling, 2008). The assumption that the average US electricity mix emits as much as the worst coal plants (950–1200 g CO₂/kWh), however, is unrealistic given the diversity of generation technologies in different states and the current average US rate of 670 g CO₂/kWh (Samaras and Meisterling, 2008; Jamarillo et al., 2009). With the average US electricity mix in 2009, the well-to-wheels “carbon intensity” of a PHEV is 183–189 g CO₂-eq per mile (EPRI, 2007; Yang, 2009; Yeh, 2009). This does highlight the need for “appropriate policies” (Samaras and Meisterling, 2008) in the electric sector to obtain the maximum climate

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benefits from rechargeable plug-in vehicles. A vehicle fleet fueled with electricity from the grid can contribute to lowering emissions in the light-duty transportation sector, which accounts for around 20% of greenhouse gas emissions in the US (EIA, 2009). With a greater reliance on nuclear, renewable, and less carbon-intensive fuels, CO₂ emissions in the power sector could be cut by 37–78% by 2030 (EIA, 2007).

Previous PHEV load profile analyses in the literature were based on assumptions about charging patterns (EPRI, 2007; Tate and Savagian, 2009; Denholm and Short, 2006; Kintner-Meyer et al., 2007) or on empirical driving data in regional electricity models (Sioshansi et al., 2010b; Sioshansi and Denholm, 2009; Sioshansi et al., 2010a). This analysis is based on data provided by the National Household Travel Survey (US DOT, 2003) on passenger trips, trip distances, start and end times, and start and end locations, developed to test multiple hypotheses about vehicle charging. The algorithm to analyse NHTS data is based on the main premise that observed driving behavior determines charge timing, location, and impact over the day. We use the national NHTS driving database of around 365,000 private vehicle trip records for 91,360 vehicle days to examine the patterns of charging demand and explore “macro”-scale effects: the factors of geographic location (state, urban/rural), vehicle characteristics such as age, activities during different days of the week, and restrictions on charging availability in different locations. The PHEV load profiles can be used as inputs for studies of long-term, US-wide impacts of vehicle charging and be implemented in comprehensive, national dispatch models of the electric power system. Whereas the main focus of these recent studies were the impacts on the supply side of electricity dispatch, power sector emissions, and costs/revenues of electricity and V2G, this paper contributes an analysis of the demand side of PHEV charging.

We show that the model is sufficiently robust in predicting PHEV load when we test for the effects of vehicle age, weekend/weekdays, and urban/rural areas. We find the amount of vehicle miles traveled (VMT) transferred from gasoline fuel to electric fuel by calculating utility factors of PHEVs as a function of charge power rates, battery range, and charging location.

It is clear that the additional increase in long-term electricity demand due to PHEV charging, in the order of 5–8% of total demand in 2030 (EPRI, 2007), will not have a significant impact on security of supply or the grid’s adequacy. The impacts of PHEVs on hourly power demand are, however, a key policy challenge for short-term grid management and operations. Many interesting issues arise around the ability of the existing electricity supply system to satisfy the charging requirements of these vehicles. “Fast-charging” a vehicle battery at 4 kW on a low voltage grid is equivalent to adding three times the average US household’s instantaneous power load (based on EIA (2001) estimates). The effects of peak-demand could be a risk to the grid if all vehicles were to charge at the same time. Distributed over 8 h at night-time, however, the average power load of a vehicle with 20–40 miles of range is reduced to between 0.7 and 1.4 kW – not higher than a large home appliance, such as a dishwasher. The impacts of PHEVs on electricity load will thus depend on managing PHEV charging over the day. This study quantifies the demand profiles of electric and plug-in hybrid electric vehicles in terms of time of day, location, and magnitude of impacts by analyzing consumer driving patterns.

In an uncontrolled charging case we find that the PHEV load peaks in the early evening (6–8 PM) in residential areas, in the morning at the workplace and on weekends (12–2 PM) in commercial areas. PHEV charging imposes a modest pressure on system load in the order of 560–910 Wp per vehicle. We find that enabling charging in places other than the home increases the daily energy charged by 24–29% (1.5–2 kWh/day). The utility

factors we derive from the model show that PHEVs with a 20 mile range (PHEV-20) travel 45–65% of miles on electricity compared with 65–80% for PHEVs with a 40 mile range (PHEV-40). Work and commercial charging can increase the fraction of vehicle miles driven on electricity by 30–35% (PHEV-20).

We discuss the implications of these findings for grid management strategies and charging infrastructure deployment. Results show that the commercial roll-out of PHEVs will not necessarily require complex optimization algorithms or investments in “smart charging” controls but that a delayed charging option could be sufficient to avoid the evening peak load. A second finding is that investments in charging stations and infrastructure should primarily be directed at homes and offices, where PHEVs are likely to be plugged-in for the longest time.

The simple version of the model presented enables simulations of the impacts of various charging strategies on the availability of vehicle charging in public places, the charge power levels and standards, scheduling charging in off-peak periods and policy measures to promote PHEV adoption.

2. PHEV charging profiles

2.1. An idle fleet

On average, 4% of all vehicles driven in the United States are on the road at any one time and 85–90% of vehicles are stationed at home, work and commercial places. Were all vehicles to be charged at the same time without utility control, this idle fleet could potentially represent a concern for grid stability and security of supply.

2.2. A consistent pattern

In the case where charging is not restricted by anything other than the driver’s usage, the single most important factor in charge timing is when people arrive home after the last trip of the day. There is a clear pattern in people’s home arrival times, defined as the time they arrive after the last trip of the day. Over 14% of the population arrives home around 5 PM and about 75% of people are home by 8 PM (Fig. 1). Uncontrolled charging of PHEVs could present a high risk of excessive power demand at these hours. In the model, the vehicles are recharged as soon as people arrive home: the most realistic behavior is that they plug in their car when they park it in their garage. Unless electric charge meters or

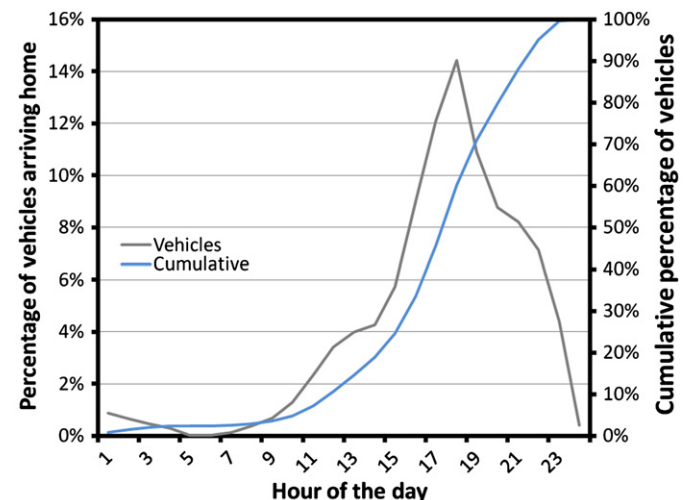


Fig. 1. Home arrival times.

built-in vehicle controls as are available in some early models, offer the possibility to set the charging to begin later, the home arrival time will correspond to peak load time on the grid.

2.3. PHEV profiles in the literature

Recent studies on the daily impacts of plug-in electric vehicles have used assumptions on the daily electricity load pattern of vehicle charging (EPRI, 2007; Denholm and Short, 2006; Hadley, 2006; Kintner-Meyer et al., 2007; Parks et al., 2007; Clement et al., 2009; Tate and Savagian, 2009; Rotering and Ilic, 2009). Rationales for predicting the timing of vehicles' electricity demand fall within the following categories:

- Uncontrolled charging, which occurs whenever PHEV owners are within reach of an outlet. This is the basis for the “uncontrolled” (Parks et al., 2007), the “uncoordinated without delay” (Clement et al., 2009), and the second and third scenarios in Tate and Savagian's study.
- Charging with a time delay in the evening to minimize electricity costs. This assumption is the one behind the “delayed” (Parks et al., 2007), the “uncoordinated with delay” (Clement et al., 2009), the “smart charging without provision of ancillary services” (Rotering and Ilic, 2009) scenarios, as well as the first one in the study by Tate and Savagian (2009) and the profile used in the EPRI-NRDC environmental impact assessment (2007).
- Off-peak charging, optimizing the utilization of the grid during low-load hours as controlled by the system operator. This corresponds to the “off-peak” (Parks et al., 2007), the “valley-filling” (Denholm and Short, 2006; Kintner-Meyer et al., 2007) scenarios.
- Fast charging, which maximizes electric energy charged/use of the electric drive of the vehicle (Rotering and Ilic, 2009).
- Smart charging, which maximizes profit from V2G (“smart charging with provision of ancillary services” in (Rotering and Ilic, 2009)).
- Charging controlled in a way that minimizes power losses in the distribution grid Clement et al. (2009).

A number of studies on the impact of the additional electricity demand caused by PHEV charging assume controlled charging profiles: that PHEV will be charged mainly during the night in off-peak hours, when generation capacity is most available and electricity prices are at their lowest (EPRI, 2007; Denholm and Short, 2006; Hadley, 2006; Kintner-Meyer et al., 2007). They assume the most optimistic case that baseload plants, which are usually underused during off-peak periods, would be called upon more often during off-peak hours due to PHEV charging, resulting in the increased efficiency of power system utilization.

In this model we implement the uncontrolled and delayed charging cases by restrictions on charge timing. The model user can impose additional restrictions on charging availability in certain locations (home, work, commercial centers, schools and churches, etc.) to determine how they affect PHEV grid impacts. Varying the charge power rate mimics the “fast charging” conditions that could allow the vehicle user to increase electric mileage.

The use of NHTS data allows further analysis of factors likely to influence daily load profiles: vehicle age, geographic region, day type (weekend or weekday). These are discussed in the sensitivities section. Thanks to the flexibility provided implementing the analysis in Matlab, the characteristics of the vehicles can be varied to test the effect of different battery sizes and fuel efficiencies (electric mileage). The resulting estimates of daily load profiles of PHEVs indicate load quantities, times and

locations that utilities can expect on average from a plug-in hybrid electric vehicle.

We exclude the potential for vehicles as load servers and regulation service providers and consider only charger-to-vehicle power flows. In theory, an idle vehicle could serve as storage for electricity and provide ancillary services for the grid. Such a use of vehicle batteries can significantly reduce their useful lifetime and is therefore highly unlikely (Peterson et al., 2009). The load profile model also stops short of PHEV load optimization. In this paper we consider realistic driving and charging behaviors derived from NHTS data, which give an estimate of the most likely consequences of vehicle charging without utility control.

3. Model

3.1. Data

The NHTS survey conducted by the US Department of Transportation represents a total of 203 million vehicles in the United States (US DOT, 2003). It reports on hundreds of thousands of vehicle trips made across the United States in 2001. The NHTS 2001 data contains four major files, including a daily trip dataset (“day trip file”) and a vehicle dataset (“vehicle file”). For each trip, the daily trip file contains the data on the distance traveled, the type of vehicle, the time of departure and the time of arrival, the day of the week and the type of departure and destination location. Vehicle-level information, such as the state of the vehicle and the vehicle's age, come from the vehicle file. Since PHEVs were not yet on the market at the time the dataset was taken, we map the 2001 vehicle fleet to a potential PHEV fleet based on the assumption that people's driving behavior would not change were PHEVs to replace the sampled vehicles.

From the full survey, we select only trips taken by private vehicles (the NHTS also contains records for public transportation and walking), with complete records of start time, end time, driver ID and vehicle ID. The parsing code ensures that the same trip is not counted twice if there are multiple persons in the vehicle but includes the trips of a same vehicle with different drivers. The attributes of private vehicle trips from the different NHTS files are joined based on a common ID code that is a concatenation of the household ID and the vehicle ID. For the sensitivity analyses on location, charge power, state, urban/rural, and vehicle age, the Matlab code parses through each of the 365,000 trip records for 91,360 vehicle days to select only certain records based on the values of these parameters.

3.2. Vehicle fleet classifications

The NHTS vehicle types are first mapped according to PHEV types (Table 1) to simulate a PHEV fleet. We deduce the characteristics of the PHEV sample fleet by using the information on vehicle type recorded in the NHTS and, following the classification used in EPRI's (2007) environmental impact assessment. We use ranges of 10, 20 and 40 miles based on expectations of PHEV models likely to be on the market in the next few years (Tate and Savagian, 2009; EPRI, 2004; Shiau et al., 2010). Table 1 shows the vehicle classes used in the model. Cars from the NHTS dataset are classified as light duty gasoline vehicles (LDGV). In the early years of PHEV adoption many different ranges are likely to be available on the market. Most studies use PHEVs with 20–40 miles of all-electric driving range, or 32–64 km (Samaras and Meisterling, 2008; Tate and Savagian, 2009; Kintner-Meyer et al., 2007). Estimates of the market shares of vehicle types are still speculative. The base case for scenarios is 50% of cars are PHEV-40 and 50% are PHEV-20. Vans, SUVs and pickup trucks are aggregated as

Table 1
Attributes of plug-in hybrid electric vehicles per category.

Model classification	NHTS classification	Adjusted DC consumption (Wh/mile)	Range (miles)	Usable battery capacity (kWh)	Fraction of Fleet
LDGV	Car	280.0	40 20	11.20 5.60	29.2% 29.5%
LDGVT1	Van, SUV, pickup truck	346.9	20 10	6.94 3.47	20.6% 20.6%
LDGVT3	Other truck	434.0	10	4.34	0.1%
				Total	100%

light duty gasoline trucks weighing under 6000 lbs (LDGT1) with either a 20-mile or 10-mile range. Vehicles listed in NHTS as “other trucks” would be LDGT3, or trucks weighing between 6001 and 8500 lbs. They are included as PHEV-10. We use this classification as a realistic base case to run the simulations on the effect of charging behavior and driving patterns. The sensitivity analysis to vehicle type presents the effect of different vehicle fleets on the load profiles (Section 5.6.2).

3.3. Charge-depleting mode electric consumption

Some values for the charge-depleting mode electric consumption reported in the literature are 0.36 kWh/mile (Parks et al., 2007), 0.35 kWh/mile (Tate and Savagian, 2009), 0.34 AC kWh/mile (Denholm and Short, 2006; EPRI, 2001). The DC Wh/mile consumption we use from the EPRI-NRDC study of EPRI (2007) is the DC energy consumption in the battery after the electricity from the wall outlet has been converted from AC. The analysis does not include a “blended” operation mode where PHEVs would drive on electric and gasoline fuels from departure.

3.4. Algorithm

We analyzed the data in Matlab to produce a daily PHEV load shape. Essential parameters of the simulation model include the charge-depleting electric mileage (e_{CD}), the charger’s power level (P_{max}), the vehicle’s battery size (E_{max}), the charger efficiency (η_c) and any restrictions of where charging takes place. The variations in these parameters constitute the basis for the scenarios and sensitivity analyses.

The state-of-charge and the location of vehicles are tracked over the day. A vehicle starts its first trip of the day with a state of charge of $SOC_{max,usable} = 100\%$ of usable battery capacity. The initial state of charge of subsequent trips depends on whether and on how much the vehicle recharged after its previous trip.

For each trip k an amount of energy $E_d(k)$ is depleted from the battery in proportion to the number of miles driven over the trip $d(k)$ and to the vehicle’s electric fuel mileage $e_{CD}(v)$ in DC kWh/mile. $E_d(k)$ is capped by the maximum capacity of the battery $E_{max}(v)$ and restricted by the $SOC_{i,usable}$ at the beginning of the trip:

$$E_d(k) = \min(d(k) \cdot e_{CD}(v); E_{max}(v) \cdot SOC_{i,usable}(k)), \quad (1)$$

with $0\% < SOC_{i,usable}(k), SOC_{f,usable}(k) \leq SOC_{max,usable} = 100\%$. $SOC_{i,usable}(k)$ indicates the charge level of the battery at the beginning of each trip k and $SOC_{f,usable}(k)$ is the state of charge at the end of each trip k in terms of usable battery capacity. At the end of each trip we calculate the state of charge of the battery.

$$SOC_{f,usable}(k) = SOC_{i,usable}(k) - \frac{E_d(k)}{E_{max}(v)} \cdot 100\%. \quad (2)$$

The total energy to be charged from the grid is then, in kWh:

$$E_c(k) = \frac{1}{\eta_c} \cdot \frac{SOC_{max,usable} - SOC_{usable,f}(k)}{SOC_{max,usable}} \cdot E_{max}(v), \quad (3)$$

where η_c represents the efficiency of the PHEV charging system. Vehicles charge from the grid as soon as they arrive in a plug-in-enabled location. Each vehicle can only charge if it is at a location where charging is enabled, something which depends on the scenario. Five types of locations are considered: home, work, commercial, school and church, and other. The battery at the start of the vehicle’s next trip of the day is then increased by the amount of energy it has just recharged from the grid. The charge time Δt is limited either by the battery being fully charged or by the start of the vehicle’s next trip:

$$SOC_{i,usable}(k+1) = \min\left(SOC_{max,usable}; SOC_{f,usable}(k) + \frac{\Delta t \cdot P_{max}}{E_{max}(v)} \cdot 100\%\right). \quad (4)$$

When a vehicle is not in a suitable location for charging, the load is 0 and the vehicle starts its next trip with a battery in the same state of charge as when it ended its previous trip. When the vehicle does not have enough time to recharge in between two trips it leaves for its next trip with a battery that is not fully charged. In these cases, the vehicle starts its next trip with a lower state of charge than it had for its previous trip. Because of these cases, the resulting load profile must be lower than the maximum potential grid impact of driving all miles on electricity.

NHTS sample weights are used in the calculation of total PHEV load on the grid and for the average load profiles. Each vehicle driven from the sample is weighted with the weights in the NHTS vehicle file, NHTS variable *wthhfin*. Variables from the daily trip file are weighted with their corresponding weights, *wtrdfin*.

The algorithm adds the load of all vehicles plugged in at every minute of the day. To obtain a representative individual PHEV load profile the total electric load is averaged over the total count of vehicles driven during the day, weighted with the vehicle trip weights. The PHEV load profile considers all vehicles that were driven out, i.e. with miles traveled > 0 , while the NHTS includes any private vehicle of the households surveyed whether they were driven out on the sample day or not (i.e., trips of 0 miles). The resulting load profile is lower than if we averaged it using only the vehicles plugged-in and actually charging at a given time, but it takes into account that most vehicles do not have a load impact during most of the day.

3.5. Charge efficiency

The charge efficiency accounts for losses from the charger, battery losses and transmission losses. A vehicle draws more electric power from the grid to recharge it after a certain level of consumption by a factor of $1/\eta_c$ where η_c is the charge efficiency. In this analysis we assume the charge efficiency to be 90% (EPRI, 2009).

3.6. Battery assumptions

The battery sizes in the model (Table 1) are expressed in terms of usable battery capacity in kWh, which accounts for the fact that batteries are never used to their full nominal storage capacity. The usable battery energy corresponds to the 20–95% range of nominal capacity. The lower limit means that PHEVs operate in all-electric, or charge-depleting, mode until the battery is depleted to 20% of its total capacity. Once this state of charge is reached, the vehicle switches to gasoline mode (Shiau et al., 2010; Bradley and Quinn, 2010). The maximum usable capacity corresponds to 95% of full capacity as higher charge levels damage batteries (Nelson et al., 2009).

3.7. Charging scenarios

3.7.1. Location

The model is set up to test the effect of different charging behaviors. In the first scenario, vehicle owners only plug in their vehicle at home. This may be at the end of the day, when they arrive home after their final trip, or during the day whenever they are at home in between trips. The second scenario looks at the charge load when vehicles charge at home and at work. Many people spend a significant time of the day at their place of work (Tate and Savagian, 2009; US DOT, 2003) and therefore, the impact of charging at work is expected to be significant. This scenario allows users to quantify the amount of power drawn from workplace charging during peak periods of the day, as well as the additional amount of energy used by the vehicle when driving on electricity. In the third scenario, PHEV drivers can charge at home, at work, and in shopping centers, like strip malls and restaurants. This scenario assesses the amount of energy that can be supplied by public charging, determined by whether people remain in these places long enough to charge any significant amount of energy into the PHEV battery.

3.7.2. Power

The charge power scenarios test the sensitivity of the model to charging at 1.44, 3.88, and 7.68 kW. These rates are standard power levels derated by 20%. The first is a common household circuit level (120 V/15 A), the second that of 240 V/20 A circuits and the 7.68 kW charge rate corresponds to a common household circuit used for heavy-duty appliances (240 V/40 A) (Parks et al., 2007). We compare the different power levels with particular focus on how much more electric energy a car will use if it can charge at higher power levels, and on how much higher the average power load is at different locations given higher power charging.

3.8. Utility factors

The utility factor measures the fraction of miles driven in charge-depleting mode or powered by electricity over the miles traveled using gasoline, or in charge-sustaining mode. We modify the definition of the Society of Automotive Engineers (Bradley and Quinn, 2010; Kromer and Heywood, 2007) and the one that we use here is the ratio of miles driven on electricity to total miles driven in a vehicle day:

$$UF = \frac{\sum_k VMT_{el}(k) \cdot wttrdfrn(k)}{\sum_k VMT_{tot}(k) \cdot wttrdfrn(k)} \quad (5)$$

The amount of gasoline displaced by vehicle electrification can be directly derived from the utility factor, the fuel economy in gallons per mile F , and the distance driven annually D in miles per

year, as:

$$\Delta F = (UF) \cdot F \cdot D. \quad (6)$$

The algorithm allows users to calculate the daily electric VMT with or without recharging between trips by enabling/disabling the availability of charging stations in certain locations. Rather than estimating a probability distribution of distances driven as in Kromer and Heywood (2007), the utility factor calculated from the model incorporates actual driving usage. The utility factors are computed at the society level using national totals for miles driven. A different “vehicle-level” utility factor could be calculated as an average of the utility factor for each vehicle. The society UF which we use is representative of the amount of gasoline displaced in the country by PHEVs.

4. Results and sensitivity analyses

Load values are given at the electric outlet, i.e. they do not take account of transmission and distribution losses. Here only the electricity use between the plug and the vehicle are considered in this study whereas T & D losses would be included in a model of the power system to the vehicle. We focus on the following variables of interest: daily energy consumption, daily peak load, daily load shape, and compare the results at different locations and at different charge power levels.

4.1. Total electric energy charged from the grid for driving

Depending on the scenario, average daily energy demand ranges from 6 to 8.5 kWh/day per vehicle (see Table 2). Allowing users to charge everywhere, at any time during the day increases the total electric drive by 24–29.4% depending on the charge power which means that the battery capacity is used more. The availability of charging in stations at the workplace, in addition to home, will increase the use of the charge-depleting mode of PHEVs. The availability of charging stations at strip malls, restaurants and other commercial public places, where people stay for shorter times, also increases the use of the electric drive, but only in high charge power cases.

4.2. Peak vehicle load

The maximum amplitude of additional load power indicates that there is no immediate need for utilities to increase their reliability margins because of PHEVs. Vehicle charging will not impose a higher load on an outlet than other home appliances and is, on average, a relatively low load on the grid. Of the locations considered, the highest power demand due to PHEV charging occurs at home and is in the order of 450–910 W, depending on the availability of other charging locations (Table 2) and the charge power.

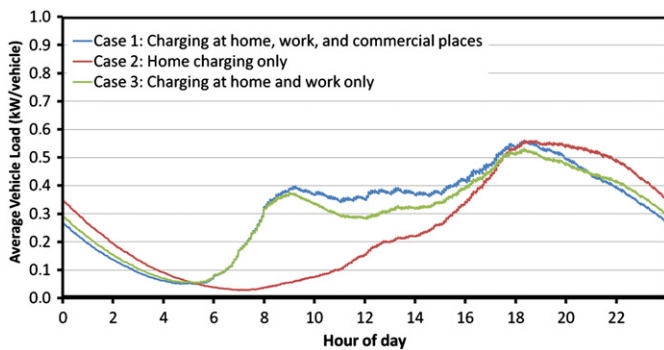
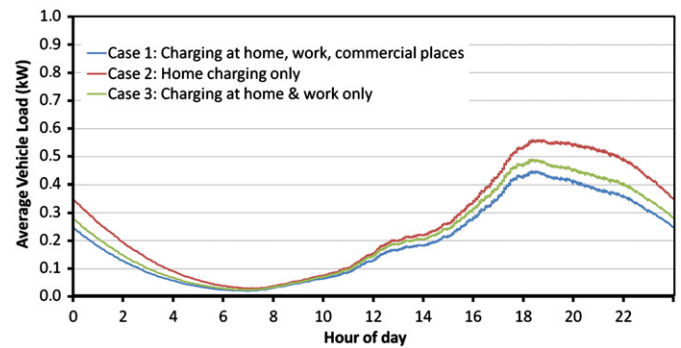
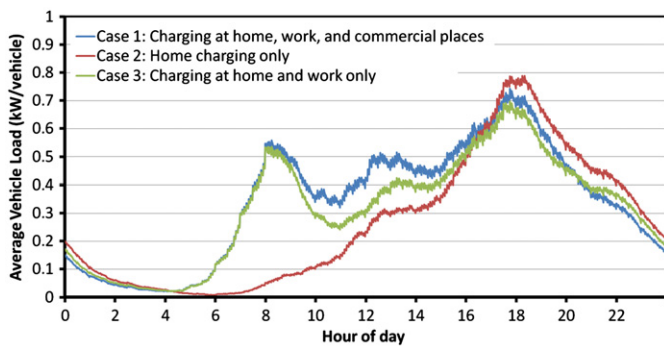
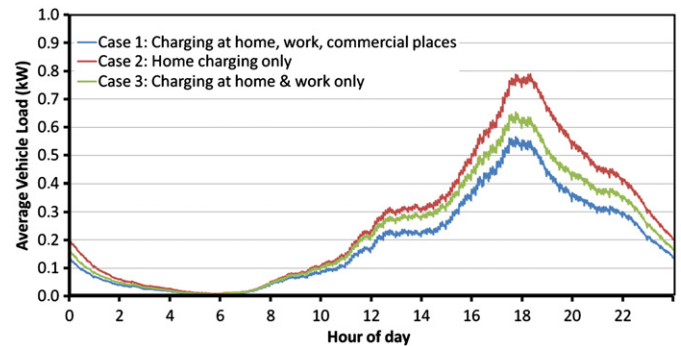
4.3. Load shape over the day

The distribution of electric load over the different times of the day is critical for utility planning purposes. Charging anywhere, at any time, increases the load at peak hours (9 AM–9 PM), and, in particular, at the morning peak, which corresponds to the time of arrival at work, and late afternoon peak, which corresponds to the time most people return home. Charging at home only strongly affects the afternoon peak load and shifts a great deal of the charging energy use to later hours in the off-peak period (Figs. 2 and 3).

Table 2

Summary of results for the load profile model.

		Case 1: charging anywhere (home, work, & commercial)				CASE 2: Charging at HOME & WORK			Case 3: charging at home only	
		Home	Work	Shopping	Total	Home	Work	Total	Home	Total
Daily energy (kWh)	1.44 kW	4.67	1.93	0.98	7.58	5.22	2.02	7.24	6.12	6.12
	3.88 kW	4.54	2.05	1.60	8.20	5.42	2.18	7.60	6.40	6.40
	7.68 kW	4.44	2.08	1.93	8.46	5.51	2.22	7.74	6.53	6.53
Peak load (W)	1.44 kW	449	315	109	561	491	324	531	560	560
	3.88 kW	566	470	205	743	654	484	697	789	789
	7.68 kW	643	589	283	848	747	607	794	911	911
Average daytime load (W) ^a	1.44 kW	247	108	72	427	274	113	387	308	308
	3.88 kW	289	88	121	498	346	95	441	406	406
	7.68 kW	293	79	147	518	366	87	453	435	435
Average nighttime load (W) ^a	1.44 kW	142	53	10	206	162	55	217	202	202
	3.88 kW	89	84	12	185	106	86	193	127	127
	7.68 kW	78	95	14	187	93	99	192	109	109
Average daytime load (Percentile +) ^b	1.44 kW	65%	71%	74%	78%	64%	70%	72%	63%	63%
	3.88 kW	72%	69%	74%	76%	71%	69%	74%	72%	72%
	7.68 kW	76%	63%	73%	74%	75%	63%	74%	77%	77%
25% percentile (W)	1.44 kW	63	13	6	185	69	14	322	82	217
	3.88 kW	41	12	6	133	48	12	139	55	55
	7.68 kW	36	10	6	130	41	10	138	48	48
75% percentile (W)	1.44 kW	326	115	72	408	366	122	405	426	426
	3.88 kW	307	98	123	493	370	112	447	437	437
	7.68 kW	291	99	150	521	363	114	460	418	418

^a Daytime is defined as 9 AM–9 PM, nighttime as 9 PM–9 AM.^b Percentile + is the percentage of hours the load is higher than the mean peak-period value.**Fig. 2.** Average vehicle load for different charging scenarios (charge power: 1.44 kW).**Fig. 4.** Load at home: average vehicle load for different charging scenarios (charge power: 1.44 kW).**Fig. 3.** Average vehicle load (3.88 kW charging).**Fig. 5.** Load at home: average vehicle load (3.88 kW charging).

4.4. Load at specific locations

The clear patterns in private transportation are reflected in PHEV load profiles: the morning charging peak occurs at work

and the evening peak occurs mainly as drivers arrive home. The charging load at home is significantly higher when people do not charge anywhere else (Table 2), especially at high charge powers. During the peak hours of the day, home energy demand, when

people only charge at home, is 24–29.4% higher than when they can charge anywhere and 4.7–9.3% higher than when charging is possible only at work (in addition to home) (see also Figs. 4 and 5). This suggests that a significant portion of PHEV charging will take place in stations at work and in commercial places. The predicted load profiles are upper bound estimates of the load at commercial centers since they assume immediate and systematic charging upon arrival of the vehicle. They assume the ubiquitous availability of charging stations, no queuing, and sufficient convenience and pricing incentives that customers will charge at every stop.

The charge load at the workplace represents around 40–48% of total peak power demand and 24.6–28.7% of energy in kWh/day. With PHEVs at the workplace, charging shows a clear pattern, with a peak in the morning (500 W at 3.88 kW), a decline until noon and a second much lower peak at 1 PM (100 W at 3.88 kW charging). Between 2 PM and 6 AM, vehicle load at work is, on average, lower than 100 W (Figs. 6 and 7). The slight differences in the two curves in Fig. 6 show that charging at work can displace a very small amount of commercial center load in the middle of the day, if commercial charging is not possible. The time and extent of peak PHEV demand at the workplace varies a great deal, depending on the charge power rate (Fig. 7). Charging at 1.44 kW leads to a 9 AM peak at 300 W while charging at 7.68 kW leads to a slightly earlier peak of 600 W at around 8 AM.

Load for vehicles parked in commercial areas represents between 12.9% and 22.8% of daily energy in kWh and 12.4–18.7%

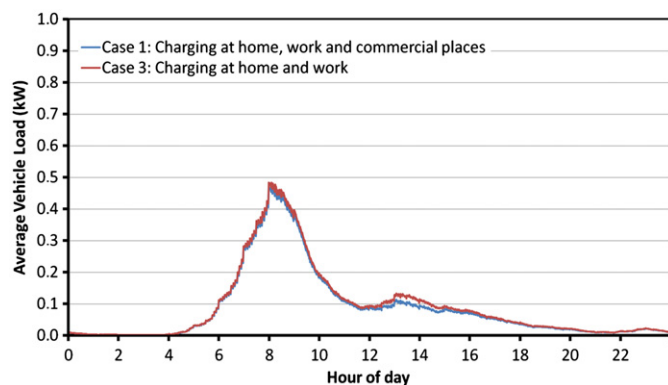


Fig. 6. Workplace charge load (charge power: 3.88 kW).

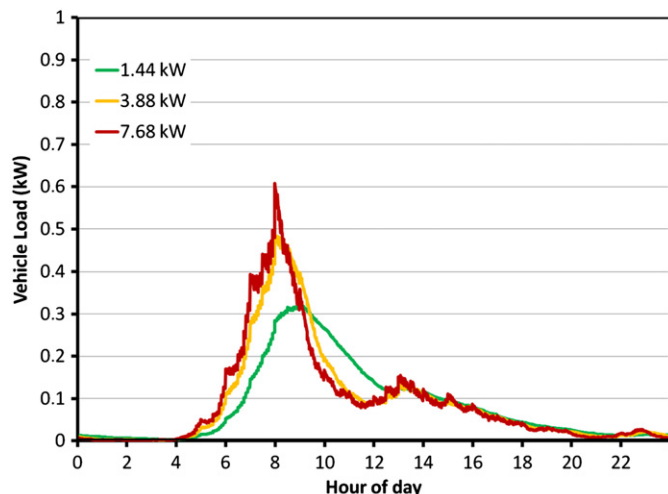


Fig. 7. Workplace charge load (Case 3: charging at home and work).

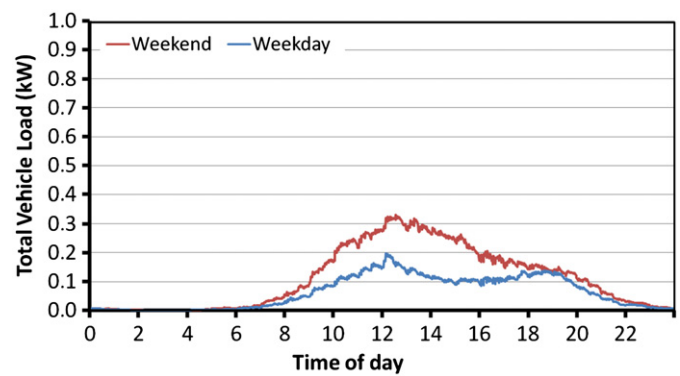


Fig. 8. Commercial charge load (3.88 kW).

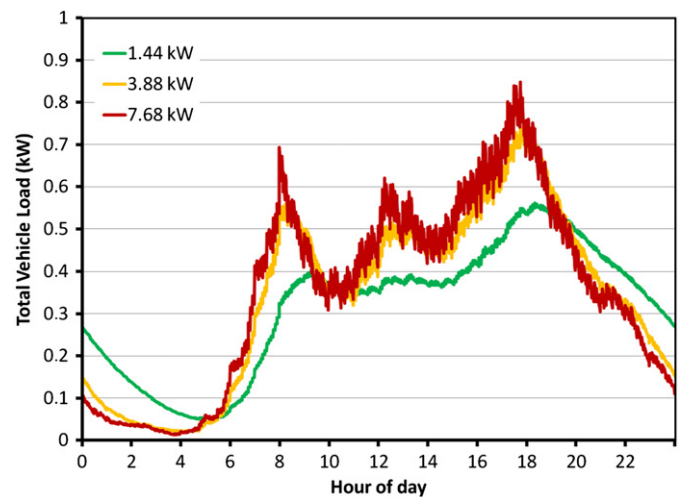


Fig. 9. Sensitivity: charge power (Case 1: home, work and commercial charging).

of peak power load in watts (Table 2). At the intermediate charge power level of 3.88 kW, power demand at commercial charging stations does not exceed an average 300 W on weekends and 200 W on weekdays. Due to increased shopping on weekends during peak hours of the day (between 9 AM and 9 PM) the weekend commercial load consistently exceeds the weekday commercial load (Fig. 8).

4.5. Charge power comparisons

High power charging increases peak power demand for charging by about 50% (cases 2 and 3, when charging at home and when charging at home and work) to 62% (charging anywhere). By reducing the time a vehicle needs to refill its battery, high power charging should contribute to improving the all-electric VMT and increase the total amount of daily energy drawn from the grid. We find that high charge powers contribute to increasing daily electric energy demand by 6.6–11% (Table 2). Charging at level 1 (1.44 kW) power is likely to be most widely available in households and contributes to distributing the evening load for people coming home more evenly into the off-peak hours of the night. In scenarios 2 and 3, where only home and home and work charging are permitted, charging at 1.44 kW nearly doubles the average load at home during nighttime hours compared to higher power scenarios (Table 2). The 3.88 and 7.68 kW charging create much greater variability in the load and increase power demand at peak times (early morning, early evening) (Fig. 9).

4.6. Sensitivities

4.6.1. Vehicle age

On average, people drive newer cars more than old ones: the average American vehicle is driven 14,000 miles in its first year and less than 6000 miles per year after 20 years. The first consequence expected for the load profile analysis is that younger vehicles will have higher energy and power demands than older vehicles. The second is that younger vehicles will be over-represented in the model since they tend to be driven more often. Furthermore, the projected PHEV fleet will be a fleet of vehicles less than 10 years old until 2020 and will be driven accordingly. For short term modeling of PHEV grid integration, it is relevant to look at the sample of vehicles that are less than 7–10 years old in calculating the average PHEV demand. We first make the hypothesis that people not only drive their newer vehicles for greater distances than their old ones, but also that

- Fewer vehicles are driven on any given day as they get older, i.e., that older vehicles are left in the garage more often than newer ones.
- Older vehicles might be used for different trip purposes than newer vehicles. The daily pattern of use can also change and influence the modeled load impact.

We run the model on the vehicle age categories of 1–5, 6–10, 11–15, 16–20, and 20+ years of age. Fig. 10 only shows the average vehicle load in each age group for vehicles that were actually driven. The similarities in the load curves suggest that people do not alter their driving behavior with their older cars. The load profiles display a similar pattern over the day across vehicle age groups, which suggests that people do not use their older cars for different trip purposes than for their new ones. The weighted load profiles show comparable magnitudes and shapes for different age categories of driven vehicles.

4.6.2. Vehicle type

We test the effect of using different PHEV battery sizes in the fleet. Fig. 11 shows the load profiles for fleets of PHEV-10, PHEV-20, and PHEV-40s for the case where charging is enabled at home, work and in commercial locations at the intermediate power level of 3.88 kW. Total daily energy is increased by 75% between the

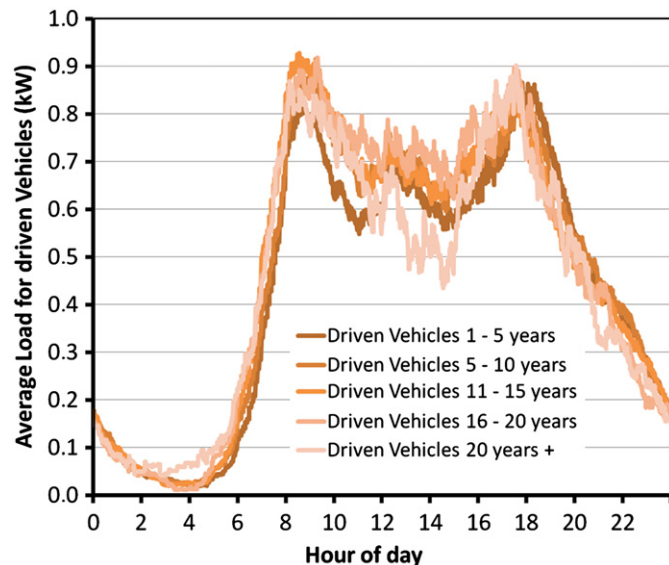


Fig. 10. Sensitivity to vehicle age (driven vehicles): average PHEV load at 3.88 kW charging.

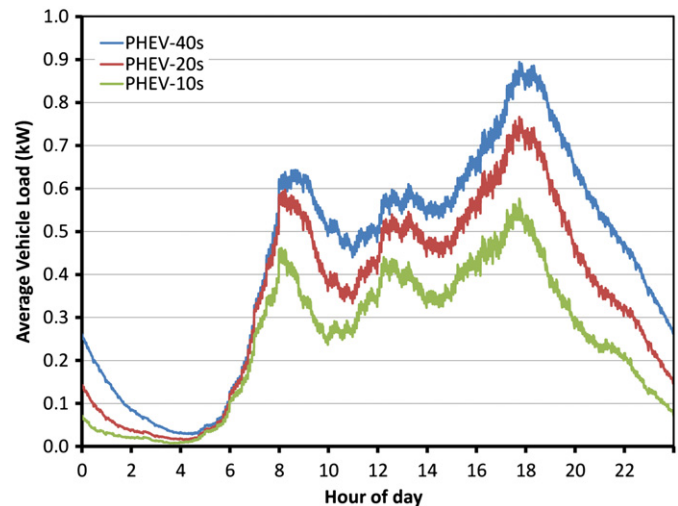


Fig. 11. Vehicle types (charge power: 3.88 kW, case 1: home, work and commercial charging).

case with only PHEV-10s and the case with all PHEV-40s (Table 3) and by 29% relative to the mixed vehicle fleet in the same scenario (Table 1). The distribution of the load over the day shows similar patterns in all cases of vehicle types: a morning peak due to arrivals at work, a mid-day peak and a high peak at around 6 PM when drivers return home (Fig. 11). Peak power demand varies between 576 (PHEV-10s) and 894 W (PHEV-40s), compared with 743 W (Table 1) for a mixed fleet charging at 3.88 kW. The impacts of large PHEV batteries are comparable increases in energy and power demand to increasing the charge power rate from 1.44 to 7.68 kW (Table 1).

4.6.3. Weekend vs. weekday load

Because of people's different patterns of activities on the weekends, PHEV electric load is distributed differently than during weekdays. Figs. 12 and 13 show two resulting load profiles, with charging possible at home, work and commercial places at intermediate-level power. Interestingly, although weekends are off-peak periods, the peak power from PHEV charging is higher on weekends than on weekdays when charging is enabled anywhere. PHEV load is distributed very differently over the day, with a single peak occurring around 1 PM, in contrast to weekdays that have morning and evening peaks.

The mid-day peak on weekend days would occur mainly in commercial areas (strip malls, restaurants, shopping centers), as shown by the difference in 12–3 PM load between cases 1 and 2 in Fig. 14. A small portion of the load in the morning is due to charging at the workplace. Power demand in commercial centers has a much higher peak on weekends than on weekdays (peak load increase of 100%, see Fig. 8).

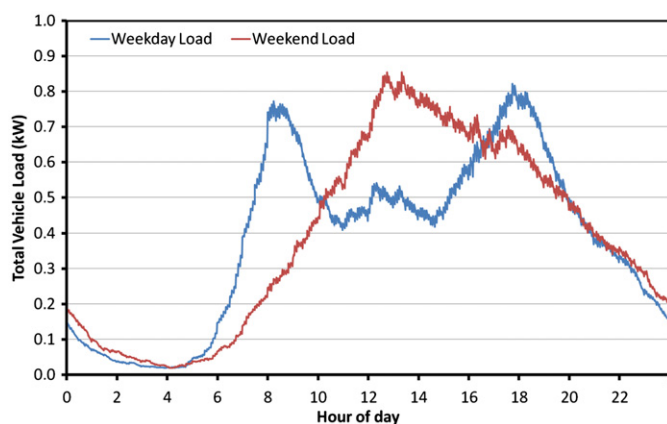
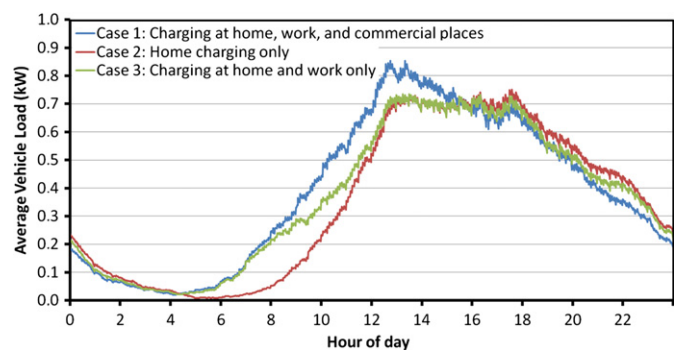
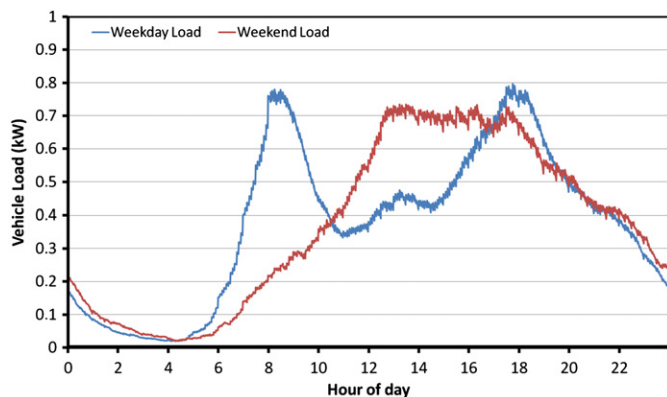
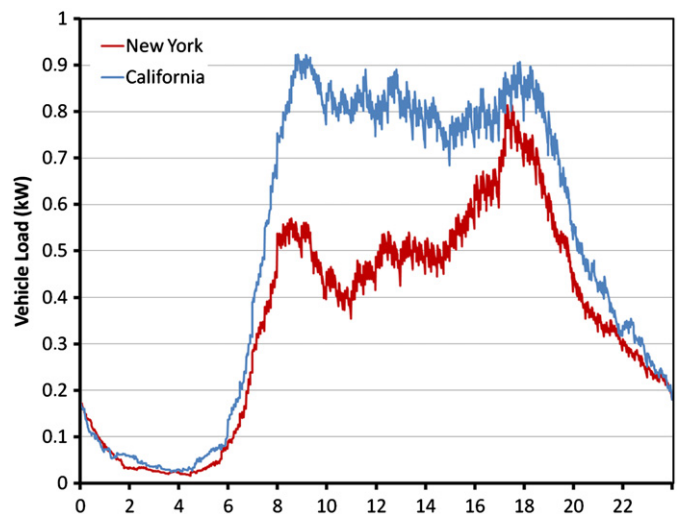
4.6.4. State and urban vs. rural

Fig. 15 compares average PHEV loads in the states of California and New York, the first being a South-Western state, with a high rate of vehicle ownership and commuter distances, and the second a dense and highly urbanized North-Eastern state. There is a significant difference in PHEV load shapes and magnitudes. The load in California is more evenly distributed throughout the day, while the load in New York clearly peaks in the evening around 7 PM. The total load is about 65% higher between 8 AM and 2 PM in California than in New York. These differences suggest that a nationwide, aggregate PHEV load profile is not very representative of the potential grid impacts of PHEVs in

Table 3

Sensitivity analysis for different PHEV types (3.88 kW, Case 1: home, work and commercial charging).

	Vehicle types in model fleet	Home	Work	Shopping	Total
Daily energy (kWh)	100% PHEV-10	3.16	1.49	1.39	6.04
	100% PHEV-20	4.63	2.15	1.65	8.44
	100% PHEV-40	6.08	2.67	1.81	10.56
Peak load (W)	100% PHEV-10	431	385	190	576
	100% PHEV-20	588	505	212	767
	100% PHEV-40	696	540	219	894
Average daytime load (W) ^a	100% PHEV-10	211	57	106	375
	100% PHEV-20	300	91	126	516
	100% PHEV-40	368	126	136	630
Average nighttime load (W) ^a	100% PHEV-10	52	67	10	129
	100% PHEV-20	86	89	12	186
	100% PHEV-40	373	19	29	420
Average daytime load (Percentile +) ^b	100% PHEV-10	79%	64%	74%	73%
	100% PHEV-20	74%	70%	74%	75%
	100% PHEV-40	69%	74%	73%	80%
25% percentile (W)	100% PHEV-10	22	7	4	81
	100% PHEV-20	38	12	5	130
	100% PHEV-40	63	17	9	193
75% percentile (W)	100% PHEV-10	199	73	107	386
	100% PHEV-20	304	98	126	517
	100% PHEV-40	427	129	138	611

^a Daytime is defined as 9 AM–9 PM, nighttime as 9 PM–9 AM.^b Percentile + is the percentage of hours the load is higher than the mean peak-period value.**Fig. 12.** Weekend vs. weekday (charge power: 3.88 kW, case 1: home, work and commercial charging).**Fig. 14.** Total vehicle load on weekends for different charging scenarios (3.88 kW).**Fig. 13.** Weekend vs. weekday (charge power: 3.88 kW, case 3: home and work charging).**Fig. 15.** New York State vs. California (charge power: 3.88 kW, case 1: home, work and commercial charging).

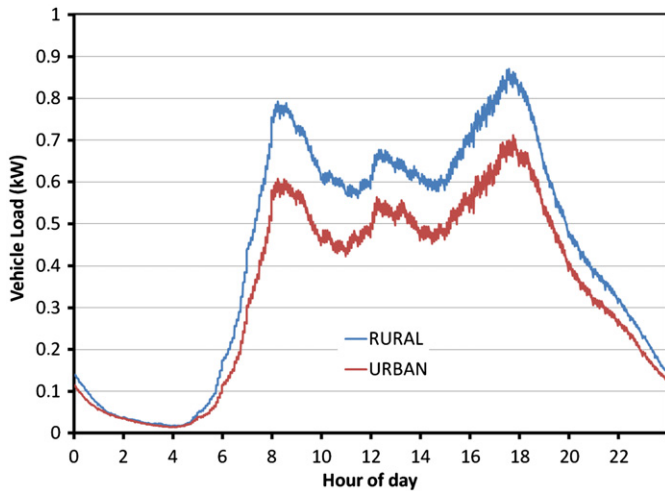


Fig. 16. Urban vs. rural (charge power: 3.88 kW, case 1: home, work and commercial charging).

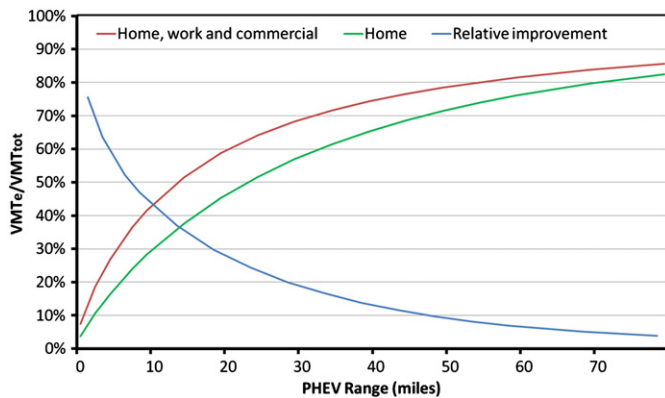


Fig. 17. Utility factors (1.44 kW).

different states and regional electricity markets. The national average power profiles underestimate the peak demand locally as they assume that peak power in one region can be offset by a lower peak demand in another region. The averaging effect spreads the peak demand out in a way that does not reflect the physical limits of power transmission between interconnected areas. The average load profiles in this paper, based on national data, are indicative estimates rather than conducive to direct implications for local grid planners.

The load profiles for urban and rural household vehicles display similar shapes, with morning, mid-day and evening peaks. Rural load is consistently higher than urban load, especially during the peak period of the day (8 AM–7 PM) when it is between 25% and 33% higher (Fig. 16). This is not surprising since urban drivers typically cover fewer miles per day and public transportation takes on a share of the transportation dominated by private vehicles in rural areas.

4.7. Utility factor results

The utility factor plotted against the range of vehicle shows the benefit of increasing battery size as regards the number of all-electric miles a user can get from a vehicle. Figs. 17 and 18 show the resulting utility factor of driven vehicles for different charging scenarios and charge power levels. The results confirm the hypothesis that low-range PHEVs (20 miles or less) benefit more from the implementation of multiple charging locations than

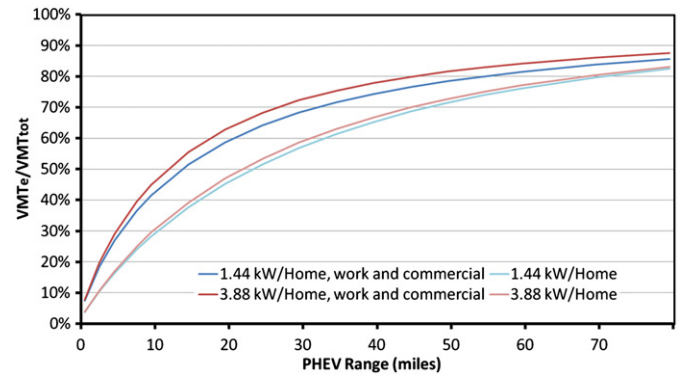


Fig. 18. Utility factors at different charge power levels for different charging location scenarios.

those with larger batteries. The utility factor of a PHEV-20 increases from 45.3% to 47.8% of VMT, with charging at home only, to 58.7–64.5% of miles driven with charging enabled at work and commercial locations (1.44–7.68 kW charge rate, respectively). This is equivalent to a 30–35% increase. As the battery sizes increase, less recharging is needed between trips over the day to use the electric drive of PHEV. In terms of the utility factor, the added benefits of having charging available in multiple locations decrease as a function of vehicle range (Fig. 17). With a range of 40 miles, charging at home only leads drivers to use their vehicle for about 65% of miles driven, as opposed to 77% with work and commercial charging at 1.44 kW. The resulting utility factor improvement is thus around 15% for a PHEV-40, or half the improvement for a PHEV-20. Higher charge power levels also contribute slightly to increasing utility factors, since faster recharge will increase the miles driven on electricity.

5. Discussion

5.1. Maximizing electric drive or minimizing on-peak load

There is a tradeoff between allocating load to “off-peak” hours in the evening and at night and maximizing the amount of driving fueled by electricity by recharging during the day, when vehicles are parked at work or in other public places. Enabling charging at places other than home will require investment in infrastructure, more detailed modeling of the power system to ensure the security of its operations, especially at the distribution level, and potentially, additional capacity investment in the long term. These are standard responsibilities for utilities as power suppliers. PHEV adoption is likely to occur in clusters in neighborhoods and further assessments of impacts on local infrastructure are needed. PHEV impacts will be experienced most critically in distribution systems that are already overstressed.

The goal of using plug-in hybrid electric vehicles is to ease the shift to electricity as a transportation fuel and to replace as much gasoline as possible with lower emitting fuels. Though on-peak electricity is generally produced by the least efficient and most highly emitting technology, older generation capacity will be replaced over time by more efficient and less polluting technologies, such as combined cycle gas or coal turbines. The greater the electric demand, the faster improvements are likely to occur.

5.2. Enabling charging in commercial areas

The availability of charging stations in shopping centers, strip malls, food courts and the like does not significantly impact the electric system, in terms of average energy use and charge power

loading. Charging in shopping areas is however the cause for the peak load observed on weekends, as shown in Fig. 14. The result highlights that charging in shopping centers could cause a high power demand in an otherwise off-peak period, thus increasing the utilization efficiency of the power system, and that it could significantly increase the use of a vehicle's electric mode when people drive on weekends. Another important justification for having charging stations in malls and shopping centers is public reassurance and marketing. "Range anxiety" is a term that comes up frequently in public concerns about PHEVs and placing public charging stations in as many places as possible will help to reduce the fear of "running out", especially in the case of EVs (PHEVs can continue driving in gasoline mode). Shopping centers equipped with charging stations in their parking lots would potentially gain a "green" marketing edge and be able to advertise their environmental and social ethics. PHEV/EV charging may lead to the development of new business models in electricity supply. An interesting question is that of who will invest for the energy and the infrastructure. Electric utilities might bear the costs for most of the infrastructure for charging, just as they do for regular electricity supply. The incentives may be high for related industries in the automobile sector to invest in charging infrastructure and subsidize electricity for consumers. Subsidized charging, fixed-price "all-you-can-use" contracts, and preferential or free parking spaces will encourage early adopters in the plug-in vehicle market.

5.3. Charging availability

Increasing the availability of charging at more locations can have the effect of shifting some of the load from home to other locations. It is interesting to note that the work charge load is completely unaffected by the availability of charging in commercial areas (Fig. 6). The home charge power load decreases significantly from scenario to scenario: home peak load is reduced by 20% if workplace charging is available and by 35% when both work and commercial charging are possible (Table 2, Fig. 5). The availability of charging is assumed to be exogenous in the analysis. Contrary to EVs, since PHEVs do not need to be recharged to be driven, the only reason drivers would modify their original route in anticipation of charging needs would be to minimize fuel costs. The effect of such behavior on driving patterns and on the load profiles is expected to be minor. The assumption that vehicles start charging whenever they are parked is realistic in most cases because it is cheaper for the driver to use electricity than gasoline as fuel. Plugging-in upon arrival at work, supposing parking spaces will have individual charging stations, will be convenient and easy for drivers who prefer to leave on their next trip with a fully charged battery. This assumption is least realistic for short stops in public spaces (commercial areas). Technical reasons and cost factors may limit charging availability in some locations (Morrow et al., 2008).

5.4. Optimal charge power

Lower charge powers may not seem optimal for PHEV drivers who want to charge their vehicles as quickly as possible to increase electric driving usage. In fact, contrary to this expectation, fast charging does not significantly increase the electric energy used by a vehicle over the day and has much less of an impact than making charging possible in multiple places (Table 2). This interesting result suggests that the amount of driving that people get out of their PHEV's electric mode is not limited by charging time, but more by charging locations. Perhaps this can be explained by the fact that the longest trips of the day follow the longest non-driving times, e.g. after the vehicle has been parked all night at home or all day at work, or on weekends at a shopping center. For places where people

stay for relatively short times, in public places like commercial areas, charging stations would be most useful at high charge power (e.g. 7.68 kW, level 3). A lower charge power is an advantage for utilities wanting to minimize on-peak PHEV impact in order to minimize costs. From an infrastructure perspective, most garages are already equipped either with 120 or 240 V/20 A outlets and the cost of upgrading to a higher voltage (\$500–\$1500 per panel, (Morrow et al., 2008)) would have to be evaluated against the value of having additional electric drive energy. We suggest that lower charge powers are sufficient for domestic stations for most PHEVs. However, if larger PHEVs with 40 or 60 mile range become more prevalent, level 1 charge power rates may be insufficient to allow vehicles to recharge over the night and leave with a full charge on their first trip of the day. This study assumed vehicles were fully charged at the start of the day. This may not always be the case due to charge power rates, unavailability of charging and battery discharge level (Tate and Savagian, 2009). Higher charge powers at home may be necessary to complement charging availability in different locations to avoid the cases where vehicles do not have time to recharge over the night if they returned home at 0% SOC. The charge power level does influence the load on the system, the load power variability and total electric energy. The electric power load will be distributed over a longer period and have a flatter shape at lower charge powers, as seen in the graphs of total, work, and home vehicle load (Figs. 2–7).

5.5. Comparison with other studies

Load impact results are of the same order of magnitude as those found by Tate and Savagian (2009) and Parks et al. (2007), on the order of 500–800 W per vehicle reaching up to 1.2 kW or more in certain circumstances (e.g. on weekends at high power). EPRI (2009) analyses also agree with the amounts of the findings for the load profile analysis. It would require further analysis in an optimal dispatch model to compare load impacts with other studies that have presented PHEV grid impact as a fraction of pre-PHEV peak load (MW) or pre-PHEV energy demand (MWh).

5.6. V2G and "smart charging"

If optimally managed, PHEVs could generate revenues as distributed storage means that uptake electricity to charge, store and release energy to the grid as appropriate to the instantaneous demand and supply balance of the power system. Research groups and utilities are enthusiastic about the profitability of idle PHEV fleets as vehicle-to-grid and ancillary service providers (Kempton and Tomic, 2005a, 2005b; Andersson et al., 2010) even though the technology necessary to make them possible is not yet available. The technology for V2G, including two-way transmission in the chargers, smart metering and information controls in the vehicles, will not be on the market for years. The value of storing electricity in a PHEV's battery pack for later discharge is limited by the non-stationarity and unavailability when a vehicle is being driven. The primary purpose of private vehicles is transportation and this will be the main constraint or factor in PHEV charging. The profitability of intra-day arbitrage of PHEV charging is secondary to driving requirements. Peterson et al. (2009) conclude that "it appears unlikely that these profits alone will provide sufficient incentive to the vehicle owner to use the battery pack for electricity storage and later off-vehicle use".

6. Conclusion

The load profiles derived from the NHTS data can be used as additional hourly or intra-hourly load in any electricity dispatch

model. The algorithm elaborated in Matlab can be reapplied to the NHTS survey data published in 2010 to recalculate the load profiles from more recent statistics. It can also be applied to other national transportation survey data. In a further step, if the algorithm is compiled into a software package, it can be a useful tool for utilities to do preliminary tests of the effect of different PHEV load management strategies.

Driving patterns and electricity supply systems vary greatly between different NERC regions and between different states. California and New York state had two of the most different load profiles in the dataset (Fig. 15). This paper provides a national-level basis for policy discussion of the relationship between transportation patterns and PHEV electricity impacts. The load profiles are appropriate to simulate different factors of PHEV demand for system-wide conclusions for policy-making. Future work is needed to examine local differences and to assess how optimistic the national estimates are for specific cities and regions.

As a next step, the load profile algorithm could be extended to include vehicle-to-grid capabilities for ancillary services and storage and to determine a smart charging algorithm based on endogenous market signals. The behavioral load profile model could be developed further to include electricity prices (average hourly and intra-day wholesale prices). We could then devise a smart-charging algorithm based on the optimization of driving needs and economic incentives simultaneously. Price endogeneity could lead to delayed evening PHEV charging as is the case for other appliances. A more sophisticated analysis could show whether mid-afternoon, early morning, or other off-peak charging would be initiated by time-of-use pricing in a price and driving behavior optimization model (Peterson et al., 2011).

This analysis presents many new findings of interest for power utilities in the US, automobile companies, and potential PHEV drivers. The electrification of passenger vehicles has implications for both carbon emissions and demand for oil and will play a role in reducing both. PHEVs with all-electric ranges as low as 10, 20 and 40 miles allow drivers in the US to cut their gasoline consumption by more than half by shifting 45–77% of miles traveled from gasoline to electricity. Clearly, PHEVs come as a cost-effective solution for fuel economy since electricity costs about \$0.03 per mile (at \$0.13/kWh) whereas gasoline costs \$0.12/mile (at \$3/gallon) (Yeh, 2009). As regards environmental benefits, emissions from PHEVs are lower than conventional gasoline vehicles even though their extent depends on the electricity production mix in given geographic regions (Peterson et al., 2011). As mentioned earlier in Introduction, PHEVs at the average US mix would cut marginal emissions (g CO₂-eq/mile) by 53–58% (183 g CO₂-eq per mile vs. 400–450 g CO₂-eq/mile) compared with a conventional gasoline vehicle. With electricity produced from a non-emitting source such as wind power, well-to-wheels PHEV emissions could become closer to 120 g CO₂-eq/mile (EPRI, 2007). In charge-depleting electric mode, direct PHEV tailpipe emissions would be reduced to 0 g CO₂-eq (Yang, 2009).

Environmental and transportation policy in support of electric vehicles will ultimately determine how much impact PHEVs will have on the power system in the future. Economic incentives, including subsidies and tax breaks for PHEV buyers, as well as taxes on carbon emissions and gasoline, will influence the number of vehicles sold by creating a favorable environment for PHEV markets. Time-of-use electricity pricing and similar market signals, and eventually smart charging infrastructure and technology, will encourage users to schedule PHEV charging in the off-peak periods or whenever grid and market impacts are minimized. Other general policy measures may support the availability of vehicle charging in public places and facilitate their use by standardizing plug-in station infrastructure and charge power levels. By emphasizing a few pivotal variables, the simple modeling framework established

in this paper provides a better understanding of the impacts of such economic and policy measures.

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