# Electricity Demand of PHEVs Operated by Private Households and Commercial Fleets: Effects of Driving and Charging Behavior

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**Abstract** – The U.S. Department of Energy's Advanced Vehicle Testing Activity – conducted by the Idaho National Laboratory for the U.S. Department of Energy's Vehicle Technologies Program – in partnership with the University of California, Davis's Institute for Transportation Studies, has collected data from a fleet of plug-in hybrid electric vehicle (PHEV) conversions, placed into diverse operating environments, to quantify the petroleum displacement potential of early PHEV models. This demonstration also provided an opportunity to assess the impact of PHEVs on the electric grid based on observed, rather than simulated, vehicle driving and charging behavior. This paper presents the electricity demand of PHEVs operating in undirected, real-world conditions.

For personal-use vehicles on weekdays, peak power demand to charge the PHEVs and the period of greatest variability in demand across weekdays occurred during an evening peak that started around 4:00 p.m. and rose until 10:00 p.m. On weekends, peak demand also occurred at 10:00 p.m., but at lower magnitude than on weekdays because fewer vehicles were plugged-in and those that were typically had a higher battery state of charge. For the commercial-use group, peak demand occurred between 2:00 and 7:00 p.m. on weekdays, varying with the day of the week, and around 10:00 p.m. on the weekend. Weekend demand was significantly less than weekday demand. Driving and charging behaviors are examined for both commercial-use and personal-use vehicles. Underlying reasons for charging behavior, based on interviews and survey responses, are also presented.

**Keywords—**"Plug-in Hybrid Electric Vehicle (PHEV) charging," "Electric grid impact"

## 1. Introduction

Through the U.S. Department of Energy's Advanced Vehicle Testing Activity (AVTA), the Idaho National Laboratory (INL) has led an international plug-in hybrid electric vehicle (PHEV) demonstration and data collection project. The AVTA is part of the U.S. Department of Energy's Vehicle Technologies Program. Since 2007, INL has collected data from 294 PHEVs – the majority of them being aftermarket conversions of hybrid electric vehicles – in undirected, real-world operation. From these data, INL has documented the vehicles' gasoline and electricity consumption and the vehicle operators' driving and charging behavior. This demonstration provided the opportunity to quantify the petroleum displacement potential of PHEV conversions and to observe, rather than simulate, the impact of PHEV charging on the electric grid.

PHEVs in this demonstration were driven by commercial fleets and private households. The vehicles operated by private households were part of a PHEV demonstration and research project at the University of California, Davis's

Institute for Transportation Studies (ITS-Davis). ITS-Davis placed Toyota Priuses that were converted to PHEV operation in households in northern California. Households received a PHEV for four to six weeks. They were instructed to substitute the PHEV conversion for one of their existing vehicles. Households were neither encouraged to, nor discouraged from, charging the vehicles. This allowed ITS-Davis to study how people reacted to PHEV technology and how they used their vehicles. INL assisted the University of California Davis with data collection from the vehicles; these data are included in the overall AVTA vehicle data pool.

The purpose of this paper is to document the impact of PHEV charging on the electric grid that was observed in this demonstration, comparing the private household and commercial fleet vehicles. Grid impact is quantified in terms of when the vehicles were plugged into the electric grid and their aggregate electricity demand. Vehicle usage also is described, highlighting the wide variation of driving and charging behavior seen within and across the different vehicle use groups. To date, others have studied PHEV grid impact using computer simulations of PHEVs and the grid that were derived from travel studies of conventional vehicles and assumed charging behavior [1–3]. This paper provides grid impact results based on actual vehicle usage to facilitate further development of vehicle-grid models and energy policies.

## 2. PHEV Fleet Description

The AVTA PHEV fleet was comprised of over 290 aftermarket PHEV conversions from various conversion companies that were based on the Ford Escape Hybrid and Toyota Prius production hybrid electric vehicles. Fleet vehicles were owned by over 90 organizations, operating in 26 U.S. states, three Canadian provinces, and Finland [4]. Vehicle usage across the fleet varied widely, but can be characterized as either commercial or personal use. Each vehicle was equipped with an onboard data logger, which recorded time history data during driving and charging.

This paper addresses the results of Hymotion Prius conversion PHEVs that were equipped with data loggers from Gridpoint (formerly V2Green). Conclusions are made based on electronic data collected by data loggers and interviews of household and commercial fleet drivers.

The Hymotion Prius has a 5–kWh, lithium-ion supplemental battery pack that is charged by plugging into the electric grid. All charging of these vehicles was “uncontrolled,” meaning charging was not purposefully delayed or otherwise directed from the grid side. Also, all charging was done at the Level 1 charge rate (up to 120 V AC/12 A).

The Hymotion Prius data set was separated into commercial-use and personal-use groups (the latter being the ITS-Davis vehicles). For this paper, all analyses of the personal-use group were performed on data that came from the last week of vehicle operation by 67 households through March 2010. For the commercial-use group, charging and driving behavior was analyzed using a data set that included all commercial-use vehicle operation that occurred from January through December 2009. Results of these analyses are given in Section 5. To increase computational efficiency, a smaller data set was used for commercial-use vehicle grid impact analysis, which is shown in Section 4. This smaller data set included charging events that were performed during six randomly sampled weeks between January and December, 2009 by 67 random vehicles in each week.

Table 1 summarizes the number of vehicles (for the personal-use group this number is synonymous with households), number of trips, charging events, and driving distance accumulated by both vehicle groups.

Table 1: PHEV vehicle groups.

| Use Group | Personal[1] | Commercial[2] |
|---|---|---|
| Number of Vehicles | 67 | 153 |
| Number of Trips | 2,245 | 66,443 |
| Distance Driven (mi) | 19,168 | 634,784 |
| Number Charging Events | 531 | 14,363 |

1. Count of personal "vehicles" is the number of distinct households. Counts of personal trips, distance, and charging events are based on one week each from each household.
2. Counts of commercial trips, distance, and charging events are based on each commercial vehicles' total time in service during 2009.

## 3. Vehicle Energy Consumption and Charge Depleting Operation

As a dual-fuel vehicle, the Hymotion Prius consumes energy for propulsion from both gasoline and electricity. When the supplemental plug-in battery pack is charged, the vehicle operates in charge depleting (CD) operation, typically drawing a higher proportion of propulsion energy from electricity. When the plug-in pack reaches its minimum state of charge, the vehicle operates in charge sustaining (CS) mode. Tables 2 and 3 show the gasoline consumption, electricity consumption, and proportion of operation in CD and CS modes for the personal-use and commercial-use groups, respectively.

Table 2: Personal-use group (one week) energy consumption and operating mode.

| Operating Mode | CD | CS | Com-bined |
|---|---|---|---|
| Gasoline Consumption (mpg) | 66 | 44 | 53 |
| Electricity Consumption (Wh/mi) | 176 | 0 | 86 |
| Percent of Distance Driven (%) | 49 | 51 | 100 |

Table 3: Commercial-use group (total 2009) energy consumption and operating mode.

| Operating Mode | CD | CS | Com-bined |
|---|---|---|---|
| Gasoline Consumption (mpg) | 63 | 43 | 48 |
| Electricity Consumption (Wh/mi) | 183 | 0 | 56 |
| Percent of Distance Driven (%) | 31 | 69 | 100 |

Other publications have elaborated on operation of the Hymotion and the factors that influence its fuel consumption [5, 6]. However, this paper focuses on the effect of vehicle charging on the electric grid.

## 4. Grid Impact

The impact of PHEV charging on the electric grid that was observed in this demonstration is quantified in terms of the percent of vehicles plugged into the electric grid and their aggregate electricity demand versus time of day and day of the week.

The percent of vehicles plugged into the electric grid is a measure of when vehicles were physically plugged into an electrical outlet, regardless of how much power the vehicles were drawing from the grid. The vehicles could be at any state of charge or even finished charging. Electricity demand refers to the aggregate load shape that would be seen by a single hypothetical electric utility serving all these PHEVs. Figures 1 through 4 contain these distributions for the personal-use and commercial-use groups.

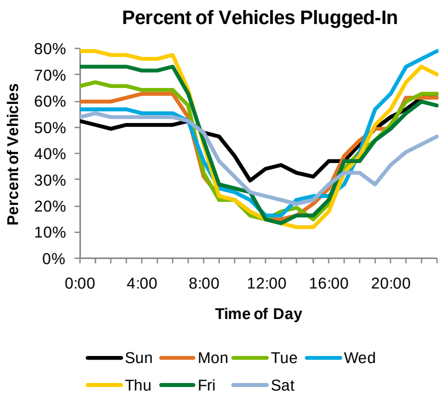


Figure 1: Percent of personal-use vehicles plugged-in.

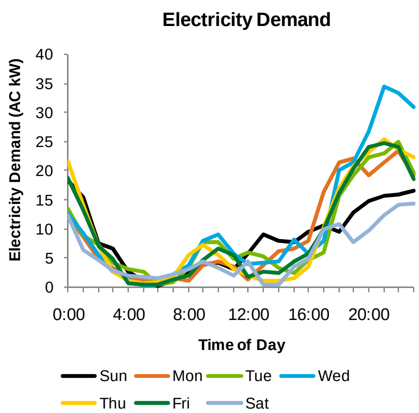


Figure 2: Electricity demand of personal-use vehicles.

For the personal-use group (Figures 1 and 2), all charging events recorded during each household's last week of PHEV use were included in the distributions. Charging from all 67 households was assumed to take place within a single calendar week. Electricity demand for both use groups is shown as the sum of power demand from all vehicles in each data set.

Most personal-use drivers commuted to and from work on weekdays. Therefore, the percent of vehicles plugged-in steadily decreased and electricity demand dropped between 6:00 and 9:00 a.m. as drivers unplugged to drive to work. Daytime electricity demand among personal-use PHEVs can be attributed to a small number of vehicle drivers who plugged in at work and the retired individuals, homemakers, and telecommuters who were usually at home during the day. As commuters returned from work, the percent of vehicles plugged-in steadily increased throughout the evening and peaked from midnight to 6:00 a.m. Electricity demand peak saw a similarly steady rise, but peaked between 9:00 and 10:00 p.m.

Peak power to charge a Hymotion Prius typcially varied between 1.0 to 1.4 AC kW. However, in aggregate, peak demand per vehicle was considerably less. For example, the percent of possible power drawn per vehicle on Wednesday at 9:00 p.m. – the period of absolute peak aggregate demand – was 37% (assuming a 1.4-kW maximum power demand per vehicle). This was due to the variation in starting times of individual charging events throughout the day and night. At any given time, some vehicles drew full power, while others were plugged-in but had completed charging and consumed little power.

Figures 1 and 2 show variation in charging behavior between the days of the week. The most noticeable differences are seen between weekdays and weekend days. The percent of vehicles plugged-in on the weekend was lower at night and higher during the day than on weekdays. The exception is Sunday evening, which aligns with weekday nights. This was because fewer vehicles were driven on the weekend; therefore, they were left plugged-in more often. Total electricity demand was lower on the weekend for this same reason. Section 5.2 quantifies weekday and weekend driving behavior.

The trends in Figures 1 and 2 also reflect weekend travel routines of some of the households (i.e., often taking overnight trips and not plugging in the vehicles until returning home later in the day on Sunday [7]). Also, note the reduced charging demand and percent of vehicles plugged-in during Monday morning. This may mean that drivers perceived less of a need to charge the vehicle, perhaps knowing that the vehicle was fully charged to start the week.

Figures 3 and 4 show the grid impact of the commercial-use vehicles.

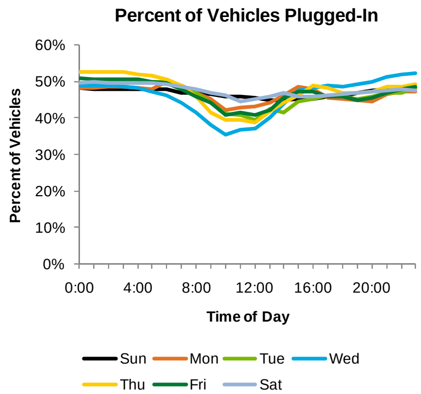


Figure 3: Percent of commercial-use vehicles plugged-in.

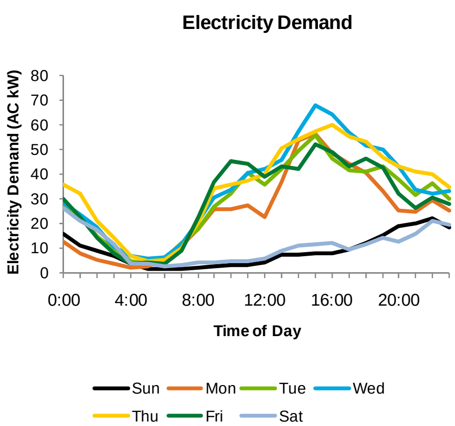


Figure 4: Commercial-use vehicle electricity demand.

The distribution of vehicles plugged-in (Figure 3) is much more uniform throughout the day and night for commercial-use vehicles than personal-use vehicles. There were two main reasons for this. First, while the average distance driven per day on days when the vehicle was driven was higher for the commercial-use group than the personal-use group, the weekly distance driven per commercial-use vehicle was much lower (see Section 5.2). This means that the commercial-use vehicles much less likely to be driven every day, in which case, they were usually left plugged-in the entire day. Secondly, on days when commercial-use vehicles were driven, they were able to plug in more often during the day. Charging during the day was possible because many commercial-use vehicles returned to their primary charging locations, such as a company motor pool, between trips during the day. They also plugged in at other locations during the day, such as a field office with an outlet designated for charging the company-owned vehicle. Charging behavior is explained further in Section 5.1.

Figure 4 shows that daily weekday peaks occurred between 2:00 and 7:00 p.m. becasue most vehicles that were driven returned to their primary charging locations at the end of the work day. Comparing days of the week, peak demand was lower and earlier in the day at the beginning and end of the work week and it peaked on Wednesday. Weekend peak demand occurred around 10:00 p.m. and was very low compared to weekdays because more vehicles remained plugged-in at their primary charging location over the weekend and less driving was done over the weekend. A small number of vehicles were taken home by employees or driven to special events on the weekend, such as promotions or fairs. Electricity demand on Saturday and Sunday increased gradually as those vehicles driven on the weekend returned to their home location (either personal residences or company fleet parking area) and plugged in at the end of the day.

## 5. Factors that Influence Electricity Demand

It important to characterize vehicle usage in order to understand the underlying causes of the observed electricity demand. Electricity energy and power demand from PHEV charging is determined by three factors:

1. Charging behavior (e.g., where, when, and for how long drivers choose to charge)
2. Driving behavior (e.g., distances driven between charging events)
3. Vehicle and charging infrastructure

characteristics (battery energy capacity, per-mile electricity consumption, and charge rate).

These three groups of factors are interrelated. Driving and charging behavior vary significantly across both use groups, along with vehicle per-mile electricity consumption.

### 5.1 Charging Behavior

#### 5.1.1 Charging Time of Day

To further understand vehicle operator behavior, individual charging events were examined. First, charging events were categorized as weekday (WD) or weekend (WE) and as end-of-day or during-the-day. End-of-day charging events are those that occurred after the last trip of the calendar day, regardless of what time the last trip ended. During-the-day charging events are those that took place between trips in a calendar day. Tables 4 and 5 give the proportion of charging events and charging energy that fell into these categories.

Table 4: Personal-use group (one week) charging statistics.

| End-of-day | WD | WE | All |
|---|---|---|---|
| Number of charging events | 292 | 101 | 393 |
| Percent of all charging events | 55% | 19% | 74% |
| Charging energy consumed (AC kWh) | 1,078 | 315 | 1,393 |
| Percent of all energy consumed | 65% | 19% | 84% |
| **During-the-day** | **WD** | **WE** | **All** |
| Number of charging events | 109 | 29 | 138 |
| Percent of all charging events | 21% | 5% | 26% |
| Charging energy consumed (AC kWh) | 207 | 59 | 266 |
| Percent of all energy consumed | 12% | 4% | 16% |

Table 5: Commercial-use (total 2009) charging statistics.

| End-of-day | WD | WE | All |
|---|---|---|---|
| Number of charging events | 8,387 | 1,138 | 9,525 |
| Percent of all charging events | 58% | 8% | 66% |
| Charging energy consumed (AC kWh) | 23,554 | 2,913 | 26,466 |
| Percent of all energy consumed | 66% | 8% | 74% |
| **During-the-day** | **WD** | **WE** | **All** |
| Number of charging events | 4,503 | 321 | 4,824 |
| Percent of all charging events | 31% | 2% | 34% |
| Charging energy consumed (AC kWh) | 8,688 | 5,63 | 9,251 |
| Percent of all energy consumed | 24% | 2% | 26% |

Table 4 shows that for the personal-use group, 26% of charging events were during-the-day events. These consumed only 16% of the personal-use group's total charging energy. Table 5 shows that for the commercial-use group, 34% of the charging events were conducted during the day and consumed 24% of the charging energy. This is consistent with the time-of-day grid impact trends discussed earlier, which indicated that the commercial-use PHEVs were plugged-in more often throughout the day. For both groups, during-the-day charging events were shorter and consumed less energy per charging event than end-of-day charging. This was due to shorter charging events and higher battery state of charge at the start of charging. Data in the tables also show that much less charging was done on the weekend for both groups.

#### 5.1.2 Charging Location

One of the reasons for differences between the commercial-use and personal-use charging behavoir was access to charging locations away from the primary charging location. Few of the households in the personal-use group plugged into outlets at locations away from home. Figure 6 quantifies the distinct number of charging locations used per personal-use vehicle/household. It shows that the vast majority of vehicles plugged in exclusively at one location (their residence).

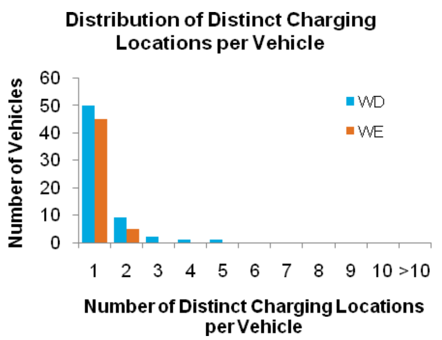


Figure 6: Personal-use group distinct charging locations per vehicle.

Households that did not plug in away from home reported two factors that limited away-from-home charging: (1) perceived lack of access to an electrical outlet and (2) unknown etiquette about plugging into an outlet that did not belong to them. Some households might have had access to an outlet away from home (within the reach of the extension cord) that did not belong to them, but felt uncomfortable asking permission to plug in. For instance, one household driver could have plugged in at work if she could have parked in her boss's parking space; however, she did not feel it would be appropriate to ask for such a privilege [7].

Interestingly, while the group as a whole did not charge away from home very often, those individuals who had access to and were willing to use away-from-home charging locations were plugged in 99% of the time while they were parked in those locations [8].

On the other hand, the commercial-use group had greater access to multiple charging locations, especially on weekdays when the vehicles were more likely to be driven (Figure 7).

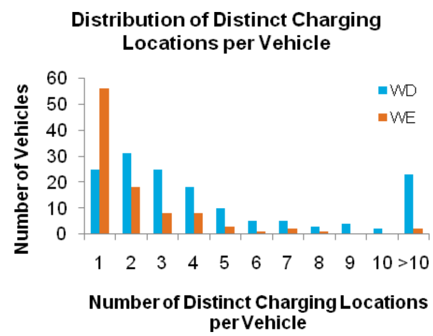


Figure 7: Commercial-use distinct charging locations per vehicle.

As mentioned earlier, many companies operating these vehicles had more than one office or work site between which the vehicles were driven. Many companies designated charging outlets for PHEV charging at multiple sites. Also, vehicles were often made available to multiple drivers for business or personal use. This means that, over time, a single vehicle may have spent time plugged-in at multiple business facilities or employees' homes.

### 5.2 Driving Behavior

Charging behavior and the impact of charging on the electric grid are inseparably connected to driving behavior. Clearly, a vehicle cannot be plugged in while it is being driven and the amount of electricity demanded from the electric grid is proportional to the amount of electricity consumed by the vehicle during driving.

Figures 8 and 9 show distributions of daily distance driven by the personal-use and commercial-use groups, respectively.

On average, the personal-use group drove 45 miles per day on days when the vehicle was driven and 286 miles per vehicle per week. The commercial-use group drove 48 miles per day when driven and 174 miles per vehicle per week.

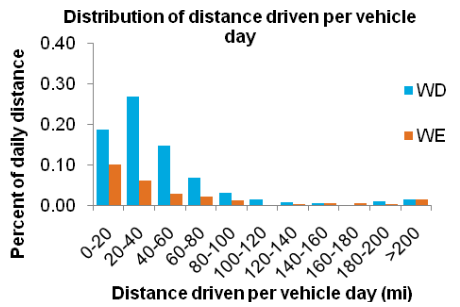


Figure 8: Personal-use daily driving distance.

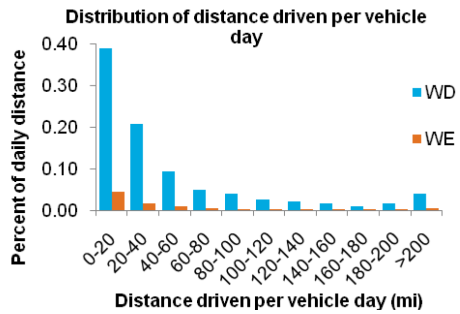


Figure 9: Commercial-use daily driving distance.

## 6. Discussion of Behavior

### 6.1. Variation within Use Groups

Thus far, discussion has emphasized behavioral differences between the two use groups. It is important to note that there also was tremendous variation within each group. For example, charging frequency and distance driven between charging events (or per day) varied from one household, commercial-use fleet, and vehicle to another. For the personal-use group, these differences were attributable to differences between, and even within, specific households. Within the final week of each household's data, weekly driving distances varied from 60 to 947 miles, plug-in events per day varied from 0.4 to 3.0, and percent of miles driven in CD mode varied from 13 to 100%. Commercial-use vehicles exhibited similarly wide.

### 6.2. Underlying Charging Motivations

Most households in the personal-use group had some degree of routine, such as commuting to work, trips to drop off or pick up kids from daycare, or a weekly trip to the grocery store. Similarly, most commercial-use vehicles were used for specific business purposes (such as making customer calls) rather than simply being demonstration vehicles. Therefore, both groups had to incorporate charging their PHEVs into their exisiting routines. The extent to which vehicle drivers prioritized vehicle charging or were able to fit charging into their routines varied. These differences in priority depended upon many factors, including the following:

- Lifestyle or work pace
- Vehicle mission
- Understanding of the vehicle, including ability to determine the battery's state of charge
- Access to charging infrastructure away from the home or fleet location
- Actual and perceived benefit of plugging in, including private and social benefits
- Perceived social acceptability (or lack thereof) of plugging into an outlet that did not belong to them.

Some vehicle drivers typically plugged in their vehicles whenever parked for a significant amount of time at a known charging location. For example, one personal-use vehicle was plugged-in approximately 94% of the time when it was parked at home. That household reported they made charging the vehicle a priority, citing the time they would save at the gas station and the relative ease of plugging in [7].

Other households plugged in the vehicle when they were done driving for the day or when the vehicle was parked in the garage for nightly storage. In some cases, even though the vehicle was parked at a charging location with an empty battery, vehicle operators waited to plug in until later. This behavior was seen most in the personal-use group and in the commercial-use group where one or a small number of people drove the vehicle.

Finally, a small group of households were among the most advanced PHEV users. They were often cognizant of the state of charge of the vehicle's battery and their upcoming travel. These households tended to plug in the vehicle only when they felt it was necessary to maintain charge depleting operation for their anticipated travel.

## 7. Context for Interpreting Charging Behaviors

The behavior presented in this paper is specific to driving and charging of a blended PHEV conversion with a 5-kWh plug-in battery, Level 1 charging using a standard 110-V NEMA 5 plug, in an environment with the following:

- Minimal designated public vehicle charging infrastructure;
- Unknown etiquette for plugging into outlets owned by others;
- Minimal real-time feedback from the vehicle informing the driver of the battery state of charge or operating mode (CD vs. CS);
- No time-of-day use electricity tariffs or incentives in most areas and limited awareness among vehicle drivers or fleet operators of incentives in areas where they were present; and
- No grid-side charge control.

Analysts should exercise caution when translating results from this demonstration to studies where conditions differ.

## 8. Conclusion

This paper describes the effects of driving and charging on electricity demand to charge 5-kWh, blended-operation PHEVs observed in undirected, real-world conditions. The vehicles were from samples of two fleets, neither of which can be said to be representative of the population from which they were drawn, but varied enough to exhibit a broad range of driving and charging behaviors. One is drawn from households in northern California and the other is drawn from commercial fleets in the U.S., Canada, and Finland.

The time of day when the PHEVs were plugged in by households looks, generally, as has been widely imagined: the highest percent of vehicles were plugged-in from midnight to 6 a.m. The percentages decline in a wide trough, reaching a minimum in early afternoon before rising as PHEV drivers arrive home throughout the evening. There are substantial differences in the details across weekdays. Most notably, no more than two-thirds to three-fourths of vehicles were plugged-in on at any time on weekdays and less than 60% on weekend days.

The distribution of commercial-use fleet vehicles plugged into the grid versus time of day is more nearly uniform throughout the day, at between 40 and 70%. However, this masks two distinct patterns. First, many commercial-use vehicles went undriven for days at a time and were plugged-in this whole time. Second, other commercial-use vehicles were driven frequently and caused a drop in percentage of vehicles plugged-in during the day-time hours.

For personal-use vehicles on weekdays, peak power demand to charge the PHEVs and the period of greatest variability in demand between days of the week occurred during an evening peak that started around 4:00 p.m. and rose until 10:00 p.m. Another small peak occurred between 8:00 and 11:00 a.m. due to those few household commuters who found a place to charge at work. Because of the relatively small battery size in the vehicles in this study, batteries were nearly always fully charged during the night. Therefore, charging power demand declined to near zero every morning by 5:00 to 6:00 a.m. However, power demand rarely actually dropped to zero throughout any day because of the incidence of during-the-day charging between the households multiple stops and returns to home throughout a day. On weekends, peak demand also occurred at 10:00 p.m., but at lower magnitude than on weekdays because fewer vehicles were plugged-in and those that were typically had a higher state of charge.

For the commercial-use group, peak demand occurred between 2:00 and 7:00 p.m. on weekdays, varying with the day of the week, and around 10:00 p.m. on the weekend. Weekend demand was significantly less than weekday demand.

Reasons for the differences in demand between the two use groups include differences in access to charging infrastructure during the day and at multiple locations, the total distances driven, and charging energy consumed. While much of the driving, charging, and power data are presented in summary forms that eases description and comparison, it should be reiterated that wide variation in charging and driving behavior was observed within each use group and within each behavioral unit (i.e., household or fleet) within each group.

## 9. Acknowledgments

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