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**An Activity-Based Assessment of the Potential Impacts of  
Plug-In Hybrid Electric Vehicles on Energy and Emissions  
Using One-Day Travel Data**

W. W. Recker and J. E. Kang  
University of California, Irvine  
July 2010

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**UNIVERSITY OF CALIFORNIA TRANSPORTATION CENTER  
TECHNICAL REPORT**

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# 1 Background

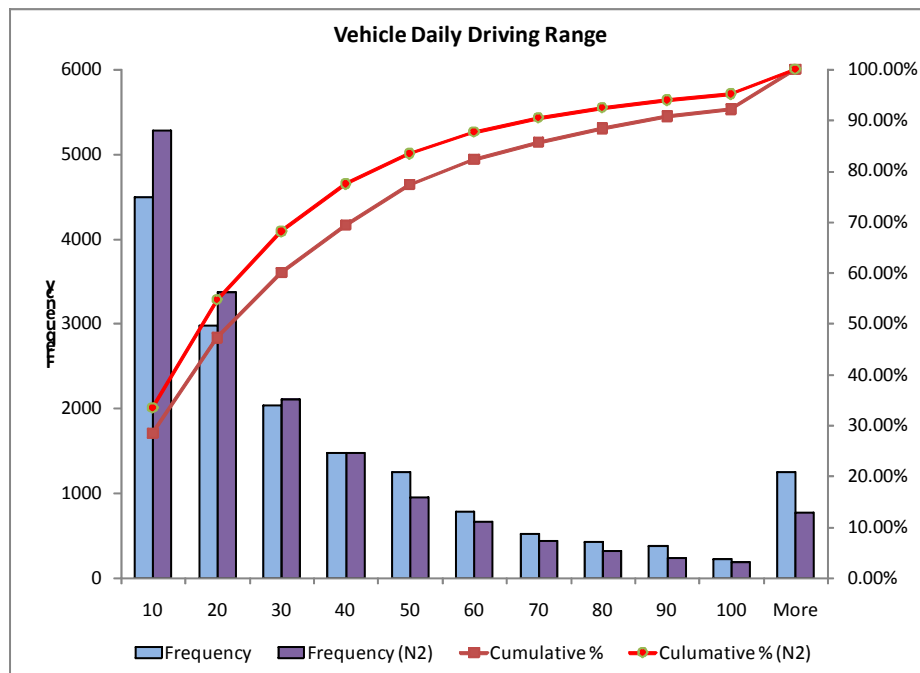
## 1.1 Introduction

With the success of Hybrid Electric Vehicles (HEVs) in the automobile market, Plug-In Hybrid Electric Vehicles (PHEVs) are emerging as the next evolution of this attractive alternative. PHEV market penetration is expected to lead to lower gasoline consumption and less emission. The main objective of this research is to assess PHEVs' energy profile impacts based on simulation of vehicles used in activity and travel patterns drawn from the 2000-2001 California Statewide Household Travel Survey. Simulations replicating reported continuous one day data are used to generate realistic energy impact assessment of PHEV market penetration.

A secondary objective is to estimate the decreased gasoline consumption and increased electricity demand in California. This will involve testing various scenarios involving battery charging to develop policies and strategies to mitigate the recharging demands placed on the grid during periods of peak consumption.

Hybrid Electric Vehicles (HEVs) are a combination of a typical Internal Combustion Engine (ICE) vehicle and a Battery Electric Vehicle (BEV) with an electric motor capable of supplying auxiliary power to the drive train. Plug-in Hybrid Electric Vehicles (PHEVs) take this concept one step further by adding additional batteries to the design, allowing the vehicle to be charged at night and be powered solely from stored electric energy during the day. With the success of hybrid electric vehicles (HEVs) in the market, plug-in hybrid vehicles (PHEVs) are now considered as an “attractive” alternative. The biggest barriers for PHEV market penetration have been limited driving range under electric power and cost. Under current market conditions, PHEVs cost about 10%-20% more than a regular HEV—\$2,000-\$3,000 extra for a sedan, \$5,000 extra for an SUV ([www.calcar.org](http://www.calcar.org)). However, technological

advances and rising fuel prices portend that PHEVs will emerge as being relatively more economical than conventional Internal Combustion Vehicles (ICVs) and HEVs in the long term (Simpson, 2006). Moreover, although the pure electric driving range of PHEVs is quite limited—it varies by type of vehicle and battery technology from between 10 to 60 miles on electricity—survey results indicate that, depending on whether distances between activity locations are calculated using Manhattan or Euclidean metrics, about 47% to 55% of single vehicle usage within one day is less than 20 miles, with 82% to 88% of vehicles traveling less than 60 miles (Figure 1.1), approaching a figure that begins to make possible electric vehicle power without the range limitations common to purely electric vehicles. Because of these factors, the automobile industry increasingly is anticipating a very positive expansion of PHEV penetration into the automobile market—one that will establish PHEVs as the ultimate successor to BEV and HEV technologies.



**Figure 1.1 2001 California Travel Diary Driving Mileage and Distribution under Two Network Assumptions: Manhattan or Euclidean (N2)**

We can expect two major social benefits with respect to energy consumption (reduction of gasoline consumption) and the environment (reduction of emissions). According to the Energy Information Administration, PHEVs with a 20-mile electric range will reduce gasoline consumption annually by over 200 gallons per vehicle for sedans and by over 300 gallons per vehicle for SUVs. That is approximately 100 gallons less than HEV sedans and about 200 gallons less than HEV SUVs per vehicle annually (Sanna, 2005). Considering the energy market's shift in demand to electricity for vehicle charging, several studies show PHEV adoption strategies to handle growing demand at cheaper costs (Kammet, et al., 2007; Electric Power Research Institute, 2007). Previous studies on PHEV emissions provide some optimism regarding significant emission reductions (Electric Power Research Institute, 2007). The California Air Resource Board reports that the transition from gasoline to the current electricity grid for charging will reduce two thirds of greenhouse gases produced by conventional vehicles in equivalent travel, taking an increase in electricity demand into account (Sanna, 2005; Electric Power Research Institute, 2007).

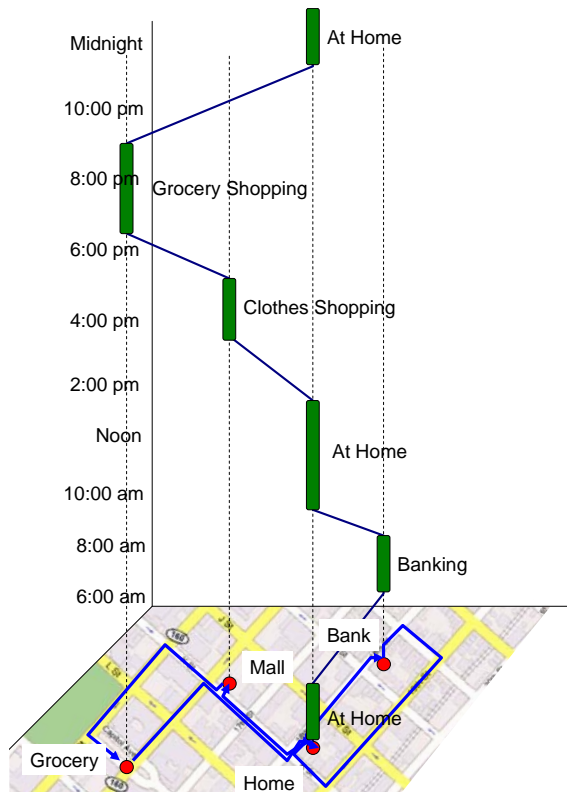
## **1.2 Problem Statement and Motivation**

Previous studies on assessment of PHEV adaptation is that the growing PHEV market is expected to reduce gasoline consumption in United States, and that today's US grid is able to satisfy the increased demands for charging. However, this assessment is based on very limited analysis. Existing studies are almost exclusively either based on macroscopic trend analysis or focused on modeling second-by-second mechanical operations of a single vehicle. And, many of the macroscopic approach assessments are based on aggregated total vehicle-miles-traveled with expected future demand.

Alternatively, it is the actual usage pattern of the PHEVs that will determine the expected balance between their fossil-fuel and electric power consumption, and the

corresponding dynamic (i.e., by time-of-day) demand placed on the grid, as well as their emission profiles (both in terms of mobile sources generated as well as by stationary sources that supply the grid). Vehicle energy use and emissions depend not only on distance and the speed it is driven at, but also on the number of trips, the time between them, and whether the vehicle was warmed up or not when started; i.e., on the spatio-temporal linkages between the collection of activities that individuals and households perform as part of their daily schedules (Figure 1.2). The nature of the interactions among household travel decisions vehicle usage lay at the heart of the limitations of conventional models and data to provide adequate measures of the potential impact of widespread PHEV adoption on petroleum energy consumption, demand on the grid, and corresponding emissions from both mobile and stationary sources.

Recent studies have tried to capture the dynamics of travel demand to approximate charging demand. Gondor et al. (2007) analyzed 277 vehicles' whole day driving data collected by GPS and assessed fuel consumption accordingly to each vehicle type. From these data and the study, Parks et al. (2008) analyzed electricity increases to predict hourly time-of-day PHEV charging demand based on four different scenarios. This research is an extension and expansion of the general approach of taking travel patterns into account in forecasting electricity demand shift, fuel consumption and further inputs for analysis of emissions generated by the transportation sector. In addition, analyzing daily activity patterns can provide temporal energy profiles for each vehicle that enable predicting emission and air quality by time-of-day.



**Figure 1.2 Travel/Activity Pattern**

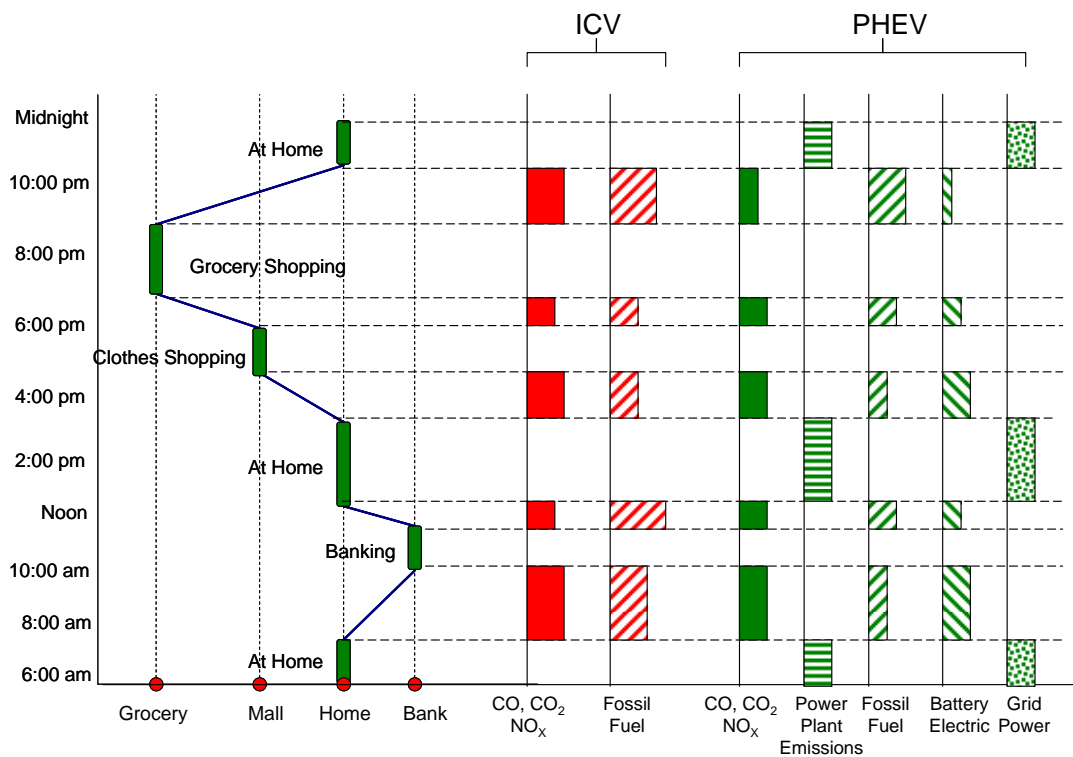
### 1.3 Methodology

This research introduces several methodologies that distinguish it from previous studies of PHEV emission and energy. First, the assessment is applied to a large number of real vehicles and activities performed by households, with travel decisions made at the household level. We base this assessment on geo-coded activity/travel data obtained from the 2000-2001 California Statewide Household Travel Survey that includes 17,172 households and 22,735 vehicles with viable location information. Second, the reported vehicle travel of all members of the households is simulated, using a microscopic approach, both with their recorded vehicles as well as with PHEVs substituted for their current vehicles in order to



assess potential savings in fuel consumption and reduction in emissions that could be achieved by moving to a PHEV fleet. Third, we analyze the potential positive and negative impacts of various electric pricing strategies (e.g., peak and off-peak rates, home only vs. inclusion of workplace/public parking charging stations) on vehicle usage and charging profiles. Using these methodologies, we can assess the bounds of potential impacts of PHEVs on the current transportation system under the assumption that individuals sustain their current patterns of activities and travel.

Although comprised of some highly technical aspects, our methodological approach is quite simple. We propose the question: “Assuming travel/activity patterns among households do not appreciably change, what are the bounds of the potential impacts of widespread market penetration of PHEVs on: 1) energy demands and shifts from mobile sources and power generation plants, 2) demand on the grid, and 3) energy profiles of transportation sector?” The steps taken to answer this question are as follows. First, using geo-coded activity/travel data obtained from the 2000-2001 California Statewide Household Travel Survey, we simulate the vehicle (temporal) energy consumption and emissions profiles associated with the recorded activities/travel of the respondents. Next, holding the reported activity/travel patterns constant, we repeat the analysis under the condition that each household’s current stable of vehicles is replaced by an equivalent fleet of PHEVs. In this stage of the analysis, we apply several different scenarios based on: 1) PHEV technology (e.g., PHEV20, PHEV60), 2) PHEV charging options (e.g., home only vs. home and workplace), and 3) PHEV charging infrastructures (e.g., current voltage and amperage vs. upgraded). For each scenario, we produce for each vehicle use pattern the associated temporal profiles of energy consumption (fossil fuel, battery, grid) and emissions generated (both from fossil fuel combustion as well as from recharging demands placed on electric power plants) (Figure 1.3).



**Figure 1.3 Temporal Linkages for Environmental Assessment of PHEVs**

We then aggregate these microscopic results over the household in the survey, and compare these results with those obtained in step 1 of the methodology to obtain estimates of the differential savings/costs for each of the measures considered associated with moving to a PHEV standard. We note that in this procedure, we obtain only upper bounds to the expected impacts since, in our analysis, we have assumed universal demand—recent experience with forecasting demand for conventional HEVs highlights the inadequacy of our abilities to rationally explain (or forecast) public reaction to developments in this volatile area.

The final stage of the analysis involves testing various charging strategies designed to mitigate the recharging demands placed on the grid during periods of peak consumption (ideally designed to relegate PHEV recharging to overnight periods during which grid demand by conventional sources is a minimum). This analysis provides useful information

for decision makers on electricity demand increases and emissions within a time-of-day frame. Depending on their local energy sources, grid capacity or goals of charging policy regarding demand or emission, they can forecast energy or emission bounds of PHEV adaptation.

It is hoped that this assessment of PHEVs will provide a benchmark that will assist in determining the impacts of future PHEV penetration into the automobile market. Specifically, the study provides an upper bound on the potential demand on the existing grid, as well as categorizes expected energy and emissions impacts by time of day and source. Data are drawn exclusively from California drivers, and their travel patterns are simulated at the individual vehicle level; therefore, we can provide more detailed regional results than in previous studies. The study also provides useful data for air quality models and energy supply strategies in California. The results can be associated with future planning projects and policy implementations as well.

## 2 Literature Review

In consecutive working papers, the Electric Power Research Institute (1999, 2001, 2002, and 2004) summarized and refined an extensive amount of information regarding current technologies related to HEVs, and provided assessments of their technical and economical viability, including PHEVs.

Assessment of Current Knowledge of Hybrid Vehicle Characteristics and Impacts (1999) summarized current information and status of general HEV attributes. It covers hybrid technology, vehicle performance, life cycle costs, consumer benefits and expected impacts and issues of HEV penetration. Comparing the Benefits and Impacts of Hybrid Electric Vehicle Options (2001) finds PHEVs more desirable than ICVs in terms of greenhouse gas emissions and petroleum consumption. Relative to the aspect of consumer benefit in terms of monetary cost, it is not certain if HEVs will deliver overall cost savings—HEVs purchase cost is more expensive, but their reduction of fuel costs makes them more economical than ICVs in the long-term. However, considering the possibility that the electric battery has to be replaced after its life cycle of 10 years/ 100,000 miles, there likely is no substantial benefit since battery replacement would increase life-cycle costs significantly. A survey that examines HEV consumer acceptance reported in the study shows market potential, especially for PHEVs, due to their efficiency, environmental and convenience attributes. Regarding charging, participants in the survey preferred charging at home to fueling at gasoline stations.

Comparing the Benefits and Impacts of Hybrid Electric Vehicle Options for Compact Sedan and Sports Utility Vehicles (2002) examined each vehicle type (HEV, PHEV20, PHEV40 etc.) accordingly with current types (compact, mid-size SUV, full-size SUV etc.), and compared emissions and energy usages. HEVs were found to increase fuel efficiency and reduce air pollution. Although HEVs decrease petroleum consumption and produce much less

greenhouse gases, the degree of reduction depends on current vehicle types (sedan, SUV) and HEV engine types (HEV0, PHEV20, and PHEV60 etc.). In addition, relative to economical benefit, results show that HEVs have lower costs associated with both energy as well as vehicle maintenance, and that such cost savings increase as all-electric-range (AER) increases.

Advanced Batteries for Electric-Drive Vehicles (2004) assessed battery technologies and cost-effectiveness for BEV, HEV and PHEV. Major findings related to PHEVs are that latest generation NiMH battery is expected to last for 130,000 to 150,000 miles. Specifically, PHEV20 can reach a total of 150,000 miles—with 33,000-66,000 miles purely on electricity charged from the grid—without having to replace the battery, while PHEV40 can achieve 100,000 miles from the grid. Pollution reduction at no extra cost can be achieved in addition to fuel and maintenance cost savings; for example, PHEV20's life cycle cost is more than \$1000 less than that of a conventional gasoline engine vehicle, while producing zero emissions. .

The EPRI studies mentioned above focus on a single vehicle, rather than on general social expectations, taken as a whole. With proven technical and economical feasibility of PHEVs looming in the near future, more recent studies focused on systemic approaches to assess overall emission and fuel consumption reductions. In their series of two technical reports, EPRI (2007) published Environmental Assessment of Plug-In Hybrid Electric Vehicles to assess nationwide effects of PHEVs in the near future. Based on vehicle market share and charging strategy scenarios, total Vehicle Mile Traveled (VMT) is converted into electricity-powered fraction and conventional gasoline-powered fraction by vehicle types. These papers included increased charging demand in the electricity. The results of emission impacts showed that most of emitted gas types were reduced and air quality was significantly improved while a few certain types of emissions resulting from generating extra electricity demand from grid were increased. Similarly, Kitner-Meyer et al. at (2007) assumed an

average of 33 miles of daily mileage for all vehicles and equivalent electricity needed, and came to a conclusion that existing electricity infrastructure could handle up to 84% of cars in the U.S., while also leading to some greenhouse gas reduction—depending on the local sources for electricity—shifting vehicle emissions in populated areas to power plants in less-populated areas. However, some emissions, such as particulate matter and/or NO<sub>x</sub>, were found to be increased slightly due to grid emissions. Also, the results of Wang (2001) project certain types of emission to be increased, whereas greenhouse gases are expected to decrease significantly. Some studies have gone further into such details as PHEV impact on wind energy market (Short et al., 2006) and regional power generation (Hadley et al., 2008)

From assessments based on fractions of total VMT or averaging, in order to capture the dynamics and time-of-day adjustment of travel, Gonder et al. (2007) collected one-day travel data for 277 vehicles in St. Louis and assessed fuel consumption by time-of-day for CV, HEV, PHEV20 and PHEV40. The one-day travel data include such trip and vehicle profiles as trip duration and times, to integrate the dynamics of activities. From the data, Parks et al. (2001) at the National Renewable Energy Laboratory applied the patterns to 500,000 PHEV cases, equivalent to 30% of light-duty vehicles in Xcel Energy service territory in Colorado. Four different charging scenarios were compared for hourly electricity load, generation sources mix, electricity cost and production cost with each corresponding emission increases for charging and decreases for vehicle operations compared to CV operations: 1) uncontrolled charging (charging starting from the time the vehicle arrived home), 2) delayed charging (charging starts from 10pm), 3) off-peak charging (charging only occurring during overnight, controlled by local agency for minimum electricity generation) and 4) continuous charging (charging available in any parking places).

### **3 Activity-Based Approach, Assumptions and Data**

The key feature of this research in assessing PHEV effects is the use of an activity-based approach with individuals as trip decision makers—trip decision makers choose when and where the trips occur, as well as how long the activities associated with the trips last. That is, all daily activities are analyzed and taken account. This allows us to incorporate the dynamics of travel demand by adding a time dimension and time-space linkage when assessing impacts of HEVs in transportation and energy fields. In addition to spatial location, on which previous emission studies mostly have focused, time-of-day is a significant factor in forecasting emission and energy usages. Time frames play an important role in developing charging scenarios and predicting electricity demand increases, especially for maximum loads for the grid. This can also lead to providing emission profiles both by time-of-day (TOD) as well as by emission sites.

#### **3.1 Data Description**

The analysis is based on data derived from the Travel Diary, California Statewide Household Travel Survey. The Travel Diary contains enumeration of the daily travel activities and their purposes, together with their full location data, for 17,172 California Household members' trips. Each trip has information on the vehicle used, departure and arrival times, trip/activity durations, and geo-coded information on longitude/latitude of the activity locations.

First, from the California Statewide Household Travel Survey a suitable subset of data is selected having complete location information and PHEV substitutable vehicle types (i.e., excludes such vehicles as motorcycles, bicycles etc). Then, person-based trip chains and

activity ordering are converted to those trips that were vehicle-based. Vehicles that were not operated for the survey day are excluded. The final data set used in this analysis includes 11,385 households with 15,823 vehicles in motion for the day.

The data set includes a total of 66,624 trips, with an average of 4.2 trips per vehicle for one day, and 5.85 trips per household. Each trip has an average duration of 18.80 minutes, with standard deviation of 25.09 minutes. The longest trip was 15 hours and 14 minutes and shortest was 1 minute. The average “Euclidean-based” distance per trip is 9.06 miles; the corresponding average “Manhattan-based” distance is 7.16 miles, with standard deviations of 18.82 and 14.46 miles, respectively. This converts to a vehicle traveling 38.14 (Euclidean distance) or 30.14 (Manhattan distance) miles in one day, respectively, on average.

### **3.2 Vehicle Routing and Network Assumptions**

Because an EV’s driving range is limited by distance of travel, it is important to reasonably estimate daily driving mileage for each vehicle in order to find distances that can be covered with electricity from grid. Since only a trip’s origin and destination locations are geocoded, vehicle routing choices and paths are not explicitly determinable from the diary records. Additionally, the study area is the whole state of California; this makes using a detailed transportation network of freeways, arterials, local streets, etc., impractical to derive vehicle routes between any two given locations.

Here, we use two cases to bound the daily driving mileage by vehicles. First, we assume that the beginning and end points of any two activities (geocoded locations) fall at respective intersections on a grid network; we then compute the travel distance between the two locations as the sum of longitude and latitude differences (i.e., use a “city block” or “Manhattan” distance metric. If the transportation network is assumed to be a fairly dense grid-network, which is not unreasonable for networks in California, this is the longest



distance a vehicle can take (except for cases requiring detouring). Second, for each pair of locations defining the beginning and end points of a trip, we compute the Euclidean distance between the two locations; this is the shortest length two points can be connected. Given these two cases regarding the distance measure, the distance covered by the actual vehicle routes will be between the two estimated values (Figure 3.1).

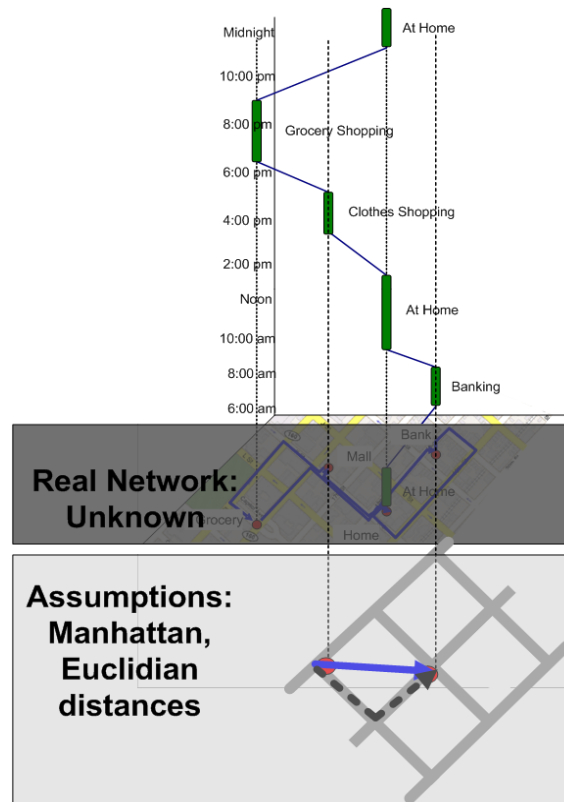


Figure 3.1 Manhattan and Euclidian Network Assumptions

### 3.3 HEV Types and Vehicle Operation Assumptions

HEVs are categorized into two types. The first are vehicles with zero electric range capability—HEV 0; battery is charged by gasoline engine when it is turned on. The Toyota Prius, Honda Insight and Honda Civic Hybrid are examples of this type, which are currently available in the market; they do not have plug-in capability, and therefore are not chargeable through electricity grid. The second type comprises vehicles with All-Electric-Ranges

(AER)—also called PHEV (Plug-in Hybrid Vehicle) because they are rechargeable from the electricity grid with plug-in capability. In contrast to HEV 0 in which the battery is charged while the gasoline engine is running during vehicle operation, this type does not require that the gasoline engine charge the battery. For this type of vehicles, the AER is represented by a number, as in PHEV x, which shows x miles of AER.

PHEVs are generally more efficient and have greater fuel-savings compared to HEV 0; however they require a larger electric battery than do HEV 0s to store energy from the grid. Also depending on the specific value of AER, vehicles have different battery sizes—higher AER vehicles generally require larger batteries with correspondingly greater electricity capacity, and take longer to charge.

In this study, PHEV20 and PHEV60 are considered as potential substitutes for current vehicles. From the daily mileage distribution, fully-charged PHEV 20 market penetration will be able to handle about 50% of vehicles without charging during the day (Figure 1.1). PHEV60 will cover 80% of the vehicle operations for this day; basically, PHEV 60 substitution potentially will approach a pure-electricity-run case.

There are two basic driving modes for PHEV vehicles—blended and binary driving modes. Blended mode operation uses the electric motor to run during low-speed/power operation, while an Internal Combustion Engine (ICE) supplies additional power for high-speed/power operation. Although some studies capture emission and energy profiles of blended mode operations for PHEV (see, e.g., Carlson, 2007), the two engines' usage pattern is not easily separated; investigation of blended operation is beyond the scope of the current study and is not considered herein. In this study of PHEVs, we restrict our analysis to only the binary mode of operation. Thus, since PHEV does not need ICE to be turned on to charge battery, the implication is that a fully-charged PHEV x can be run on the electric motor only for the first x miles; after x miles of driving, the electric motor turns off and the internal

combustion engine starts to operate. While the internal combustion engine is working, it reasonably can be assumed to have similar emission and energy usage as current ICV operation. Thus, for this study in which only the binary mode is considered, the first 20/60 miles of a fully-charged PHEV are assumed to be powered by electricity and then the ICE takes over with a consumption/emissions profile similar to ICV vehicles currently in use. Statistics in Section 5 are based on this binary mode of operation only.

## **4 Charging Scenarios and Electricity Demand Increases**

### **4.1 Charging Parameters**

Charging time depends not only on battery size, but also on circuit voltages and amperage levels. Three cases are considered. First, we consider the case in which charging complies with the existing charging infrastructure with no extra upgrades; this case is used to predict PHEV charging status during an initial adoption stage. Current charging capability is 120 V and 15 amp and corresponding charging hours are applied. For faster charging, circuit upgrades are assumed to be incorporated; their corresponding costs are estimated by the Hybrid Electric Vehicle Working Group. Circuit upgrades are more likely to be installed in public parking areas where customers (drivers) can plug in their vehicles and purchase based on charging hours or amounts in the future. The two remaining cases involve charging scenarios with upgraded circuits—one with 120 V and 20amp, and a second based on 240 V and 40 amp. Table 4.1 shows charging times for each of these circuit specifications for various vehicle types. In the following sections, these parameters are applied to assess charging profiles and peak loads for PHEVs under the assumption that people maintain their same activities as accomplished with ICVs.

Charging Circuit	Charger Size <sup>1</sup>	Charging Rate <sup>2</sup>	Infrastructure Costs	Charging Time (To Charge Empty Pack <sup>3</sup> )	
				PHEV 20	PHEV 60
<b>Compact Car</b> Pack Size Rated Pack Size <sup>4</sup> 120 V 15 amp 120 V 20 amp 240 V 40 amp	1.4 kWh 1.9 kWh 7.7 kWh	1.0 kWh/hr 1.3 kWh/hr 5.7 kWh/hr	\$ 0 \$ 200 \$ 1,000	5.1 kWh	15.5 kWh
				4.1 kWh	12.4 kWh
				4.0 hrs	12.3 hrs
				3.0 hrs	9.2 hrs
<b>Mid-size SUV</b> Pack Size Rated Pack Size 120 V 15 amp 120 V 20 amp 240 V 40 amp	1.4 kWh 1.9 kWh 7.7 kWh	1.0 kWh/hr 1.3 kWh/hr 5.7 kWh/hr	\$ 0 \$ 200 \$ 1,000	7.9 kWh	23.4 kWh
				6.3 kWh	18.7 kWh
				6.3 hrs	18.6 hrs
				4.7 hrs	14.0 hrs
<b>Full-size SUV</b> Pack Size Rated Pack Size 120 V 15 amp 120 V 20 amp 240 V 40 amp	1.4 kWh 1.9 kWh 7.7 kWh	1.0 kWh/hr 1.3 kWh/hr 5.7 kWh/hr	\$ 0 \$ 200 \$ 1,000	9.3 kWh	27.7 kWh
				7.4 kWh	22.1 kWh
				7.4 hrs	22.1 hrs
				5.6 hrs	16.5 hrs
				1.3 hrs	3.9 hrs

**Table 4.1 Charging Times for Various Circuit Voltage and Amperage Levels**

Source: Comparing the benefits and impacts of hybrid electric vehicle options for compact sedan and sport utility vehicles (EPRI, 2002)

<sup>1</sup> An 80% required safety factor for continuous charging is used.

<sup>2</sup> Charger efficiency assumed to be 82% for 120V chargers and 87% for 240 V chargers.

<sup>3</sup> Battery efficiency assumed to be 85%.

<sup>4</sup> Rated pack size assumed to be 80% of nominal pack size.

## **4.2 Electricity Demand Increases**

Assuming that the 15,823 vehicle operations in the survey data are ‘representative’, charging profiles of these vehicles can present useful guidelines to forecast future charging demand on the grid. From an electricity supply point of view, these data also provide projected maximum load increases on the current grid on an hourly basis. Based on some boundary values, we can provide guidance for adoption of specific charging policies designed to meet goals of local agencies or for grid upgrades that may be required in the event that the current grids cannot meet the increased demand in the region.

Here, four different charging behavior options are analyzed. Based on these scenarios, additional demands due to PHEVs are derived. To approximate charging electricity per vehicle or per household to predict future demand, the results in this section can be divided respectively by the number of vehicles (15,823 vehicles) or by the number of households (11,385 households).

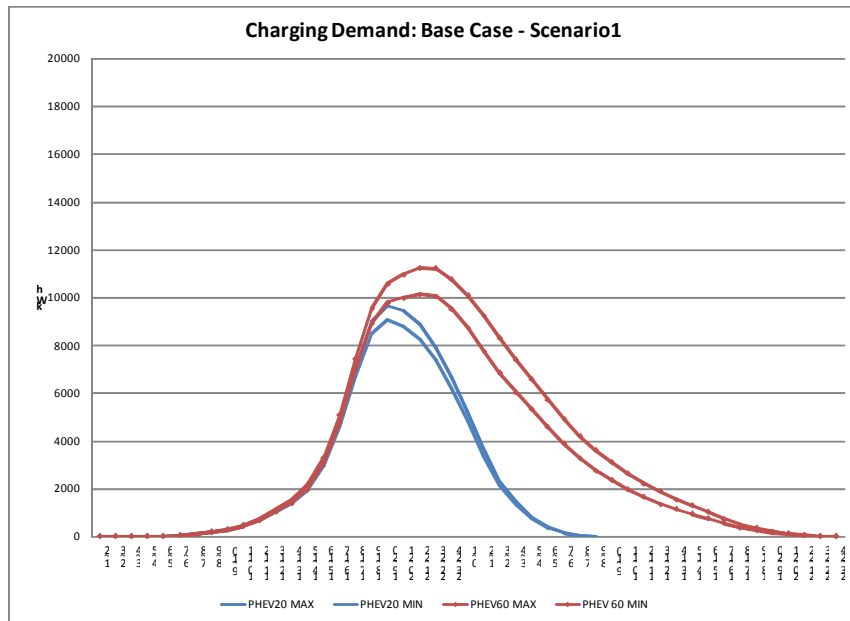
In the following, Scenarios 1, 2 and 3 assumes the home—or private garage—as the only place for PHEV charging. Scenario 4 assumes that the basic infrastructure to support PHEV charging in all public/private parking spaces is installed and charging electricity from the grid is purchasable based on charging times in the parking lots.

### **4.2.1 Scenario 1: End-of-travel-day Recharging**

Scenario 1 assumes that drivers charge their vehicles following the last trip of the day; i.e., when they reach their final destination, which is home for the vast majority of cases considered. Charging times depend on their battery capacity (20/60 miles) and cumulated mileages throughout the day. Drivers are assumed to plug their vehicles into the grid as soon as they park their vehicles from their last trip of the day. Charging is assumed to start immediately and stop when the batteries are fully charged to their equivalent 20 mile/60 mile

capacity.

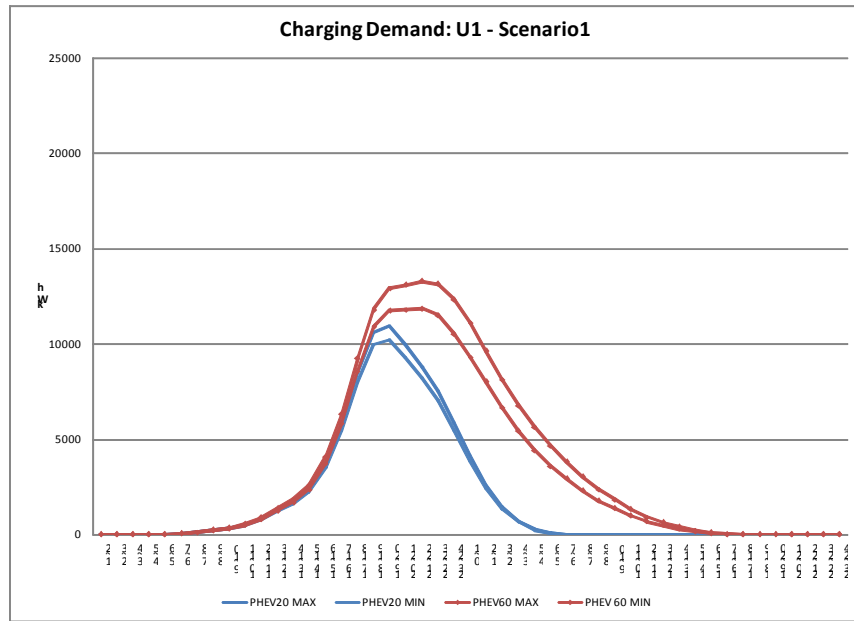
Figure 4.1 presents the results for the Scenario1 base case (120V and 15amp). Charging is seen to increase rapidly starting late afternoon and has a peak at 7-8pm for PHEV20, and 9-10pm for PHEV60. It can be inferred from the charging patterns that, as expected, PHEV 60s cover more trips (and, correspondingly, greater distances) run on electricity. However, their greater charging capacity results in base case (current circuit, no upgrades) charging hours up to 22 hours for large-sized PHEV60 SUVs, with some vehicles still being charged later than 9 am on the next day; this may hinder the completion of activities on the following day, or the vehicle may not operate with a fully-charged battery on the next day.



**Figure 4.1 Hourly PHEV Charging Demand: Scenario 1 Base Case (120V, 15amp)**

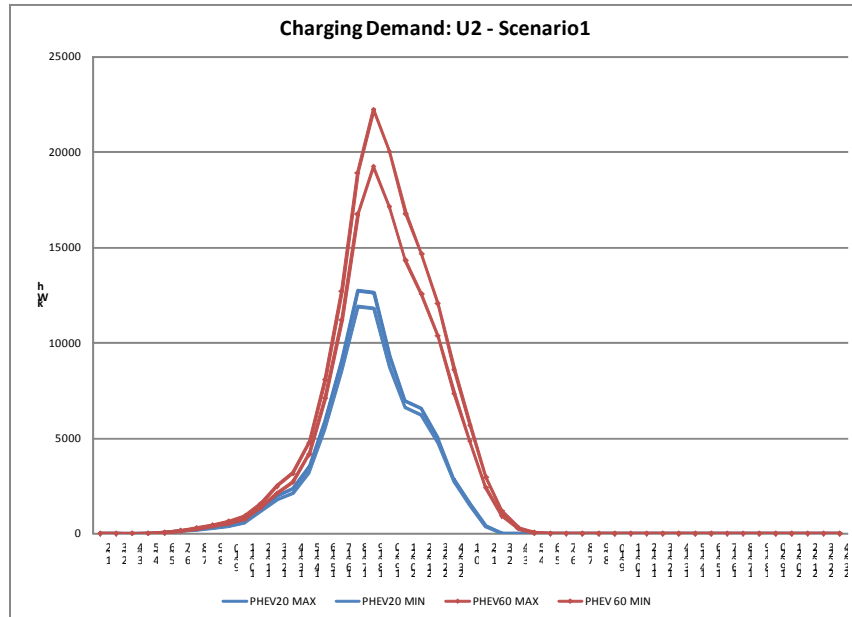
As seen in Figures 4.2a and 4.2b, upgrading the charging infrastructure at individual homes reduces charging times significantly, presenting a solution to the problem of excessive

length of time for charging PHEV 60—with upgrades delivering faster charging, many fewer vehicles need to be charged through the next day. While the difference in charging time between PHEV20 and PHEV 60 cases gets smaller with upgrades, the peak gets bigger, and with the second upgrade the peak reaches over 20,000 kWh (Figure 4.2b).



**Figure 4.2a Hourly PHEV Charging Demand: Scenario 1 with Circuit Upgrade 1 (120V, 20amp)**



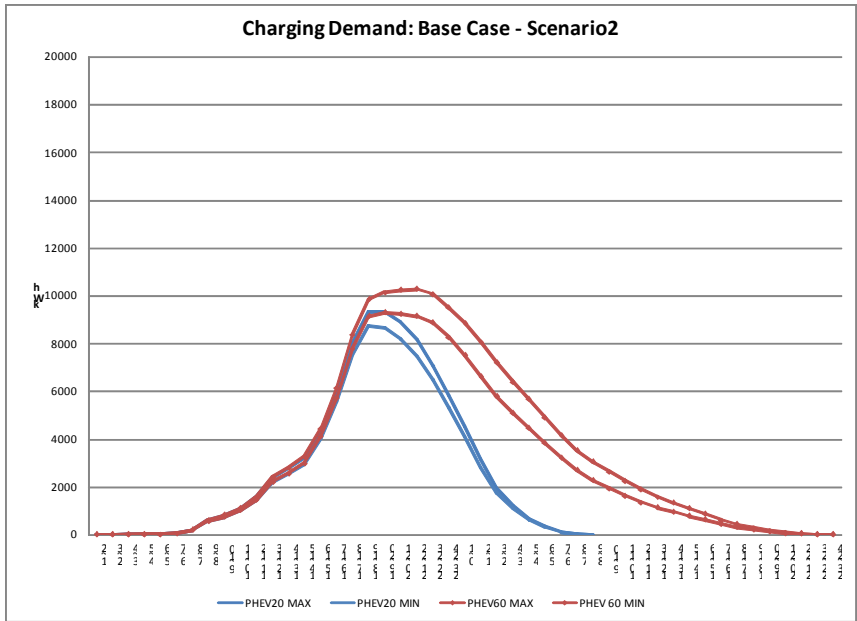


**Figure 4.2b Hourly PHEV Charging Demand: Scenario 1 with Circuit Upgrade 2 (240V, 40amp)**

### 4.2.2 Scenario 2: Uncontrolled home charging

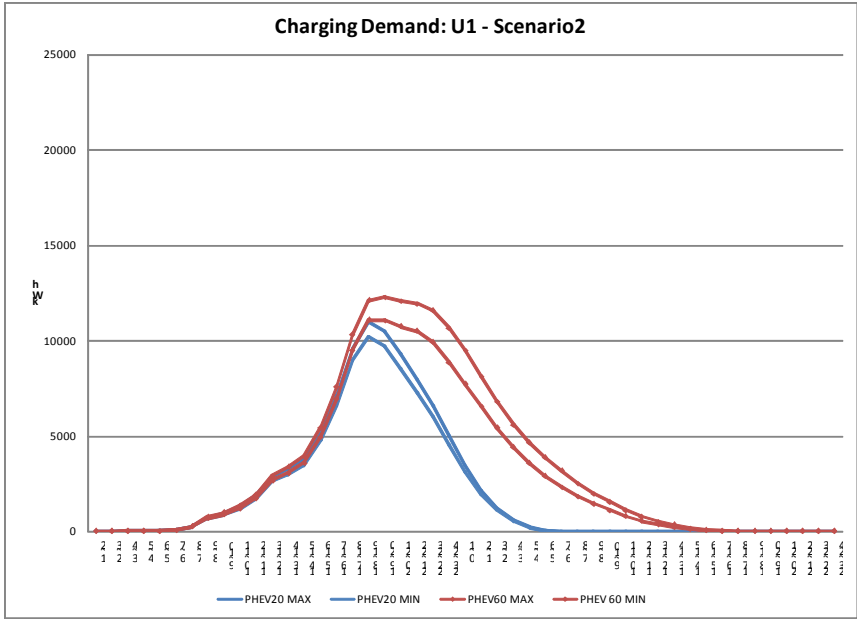
Scenario 2 assumes different behavior rules from Scenario 1. For this scenario, drivers are assumed to charge their vehicles each time the vehicle stops (i.e., every time the vehicle is parked) at home. In this scenario, it is assumed that drivers routinely connect the vehicle to the electricity outlet in their home garage.

As seen in Figure 4.3, this has the effect of dispersing the charging demand to earlier hours than in Scenario 1. Both PHEV20 and PHEV60 peaks have decreased slightly compared to peaks in Scenario 1. The number of vehicles being charged after 9 am the next day decrease somewhat in this scenario and charging demand has been reallocated to some extent due to the demand shift to earlier home charging. But, overall, this behavioral change did not significantly change the results observed with Scenario 1.

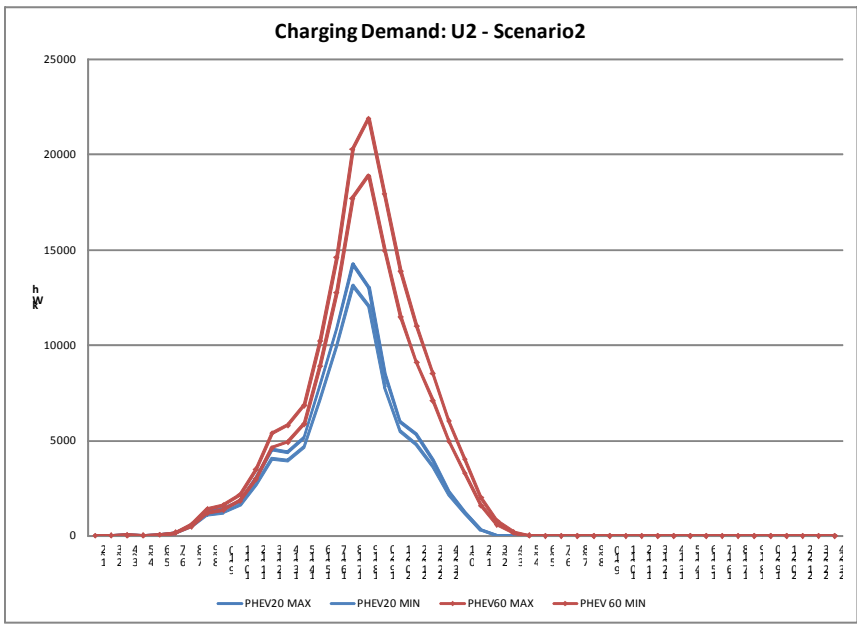


**Figure 4.3 Hourly PHEV Charging Demand: Scenario 2 Base Case  
(120V, 15amp)**

Even with the faster charging times obtainable with equipment upgrades, this behavioral assumption did not lead to significant reallocation of charging demand (Figures 4.4a and 4.4b). Charging patterns stay similar to those observed with Scenario 1. As in the previous scenario, upgraded grid capacity results in higher peaks than with the base circuits; the difference in the number of charging hours between PHEV 20 and PHEV 60 decreases with higher voltage and amperages.



**Figure 4.4a Hourly PHEV Charging Demand: Scenario 2 with Circuit Upgrade 1 (120V, 20amp)**

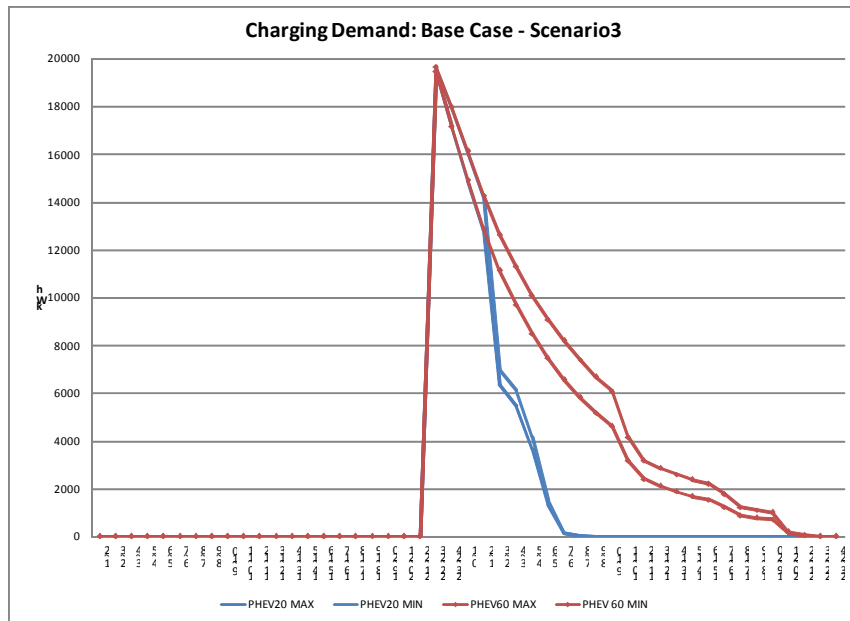


**Figure 4.4b Hourly PHEV Charging Demand: Scenario 2 with Circuit Upgrade 2 (240V, 40amp)**

### 4.2.3 Scenario 3: Controlled charging (10pm)

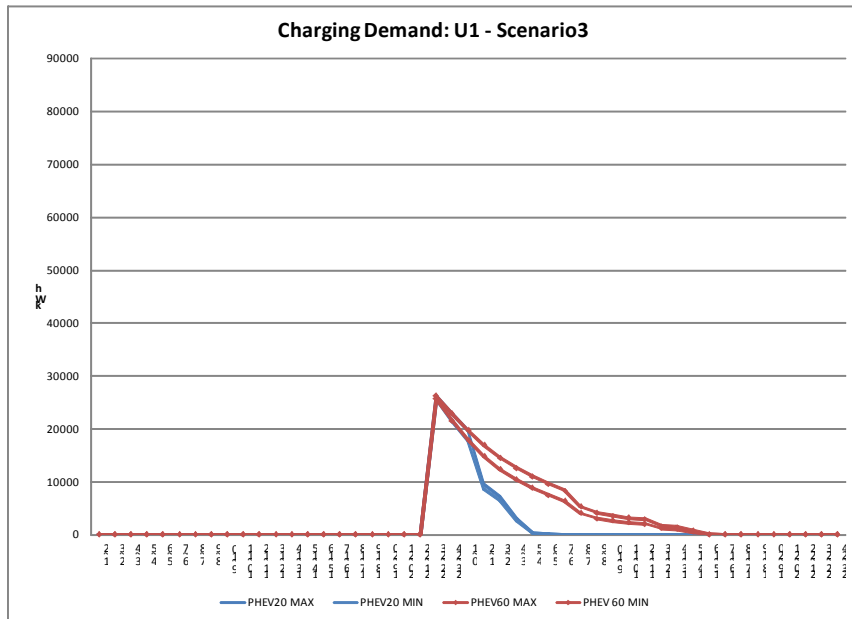
Scenario 3 assumes controlled charging. To avoid additional increases in daytime high-demand hours of current electricity usage, this scenario assumes that the charging of vehicles is allowed only from 10 pm at night through the next morning. The intent is to evaluate whether or not charging can be accommodated using existing off-peak grid capacity with no extra infrastructure improvement. In addition, off-peak electricity cost is generally cheaper for both consumers and generation. This also assumes that a driver plugs in his/her car after the last trip of the day, should that last trip end after 10:00 pm, as in Scenario 1.

The Base Case Scenario 3 charging profile is shown in the following Figure 4.5. Although this case has off-peak charging for most of the cases, the shifting of PHEV 60 charging to later hours causes more vehicles to be charged throughout the next day. Expectedly, this also results the highest peak among all scenarios, with the peak occurring at 10 pm, the starting time of the permitted time window for PHEV charging.

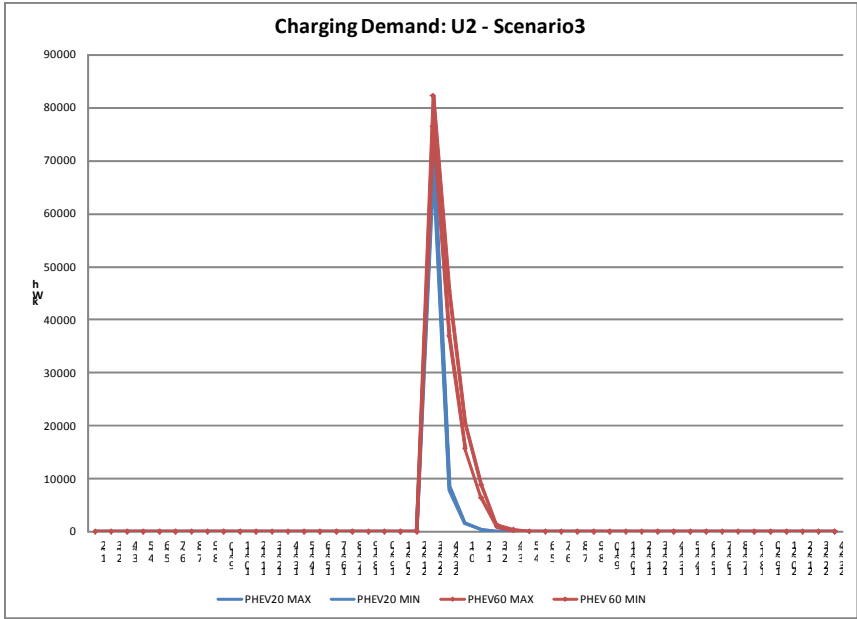


**Figure 4.5 Hourly PHEV Charging Demand: Scenario 3 Base Case (120V, 15amp)**

With upgraded circuits, peaks become more pronounced. Upgrade 1 reaches over 25,000 kWh and upgrade 2 reaches over 80,000 kWh during the peak hour. An option, should the resulting peaks cause problems for electricity generation or grid capacity in the region, would be to alter this policy by allowing different charging time windows in the region; this may yield better results than specifying a common charging time window.



**Figure 4.6a Hourly PHEV Charging Demand: Scenario 3 with Circuit Upgrade 1 (120V, 20amp)**

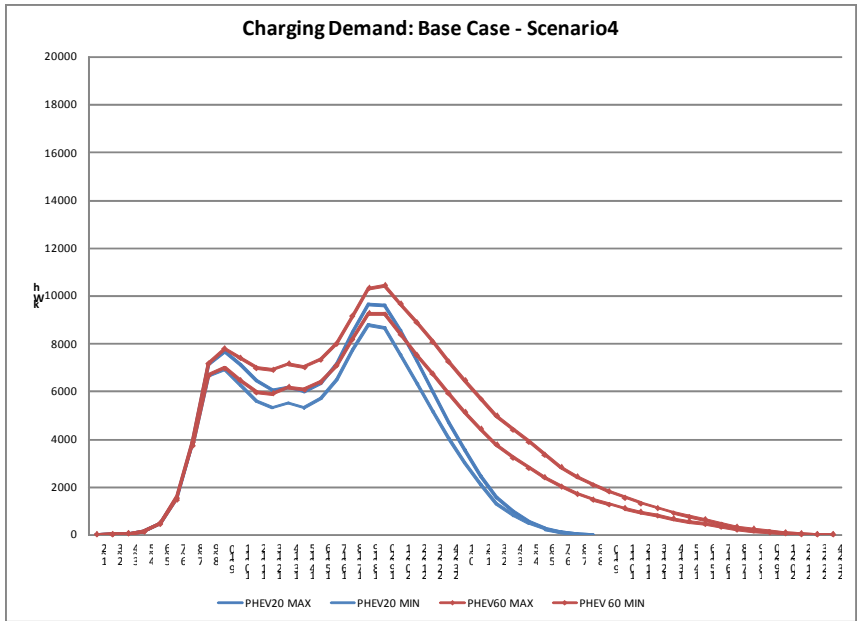


**Figure 4.6b Hourly PHEV Charging Demand: Scenario 3 with Circuit Upgrade 2 (240V, 40amp)**

#### **4.2.4. Scenario 4: Purchasable electricity charging**

Scenario 4 assumes that the basic infrastructure to support PHEV charging in all public/private parking spaces is installed and charging electricity from the grid is purchasable based on charging times at these parking spaces. Although the costs of electricity may be manipulated to encourage drivers to charge their vehicles during off-peak periods, this scenario assumes that drivers charge vehicles during any activity in which the vehicle is stationary and at a public (vs. private) location with duration of more than one hour, regardless of cost. In simple terms, this means that while vehicles are parked over one hour, the driver connects his/her car to the grid and purchases charging electricity, and that all parking spaces are equipped to accommodate such charging. Charging ends either when the battery is fully charged or when the next trip starts.

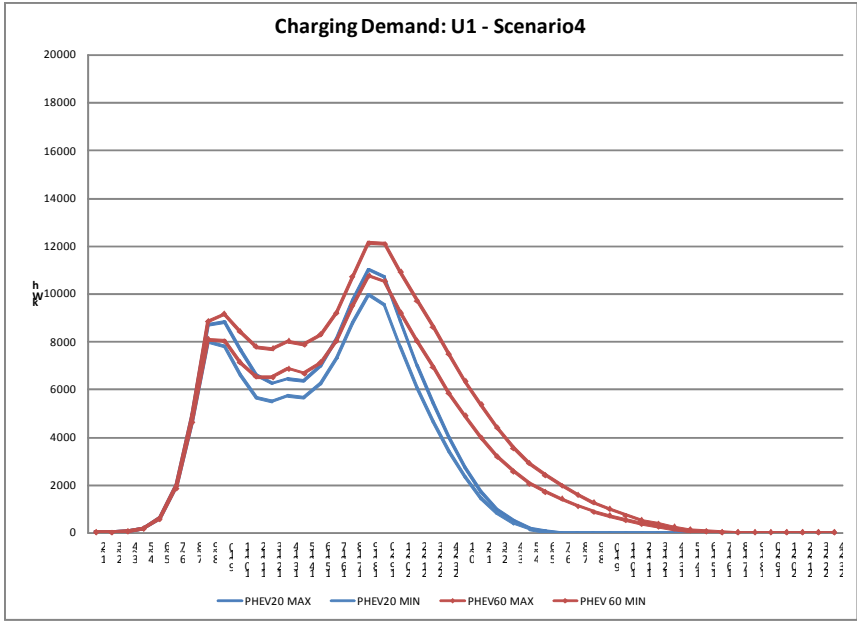
Results for this scenario are presented in Figure 4.7 for the base case. The charging profile has two peaks, ostensibly following two traffic peaks—morning and evening work-related trips. Expectedly, the peaks are not as pronounced when compared to other scenarios, with the demand more temporally dispersed. However, in this scenario, the charging times are clustered around daytime hours when electricity demand is highest. In the PHEV 60 case, fewer numbers of vehicles require charging during the next morning due to the availability of earlier daytime charging.



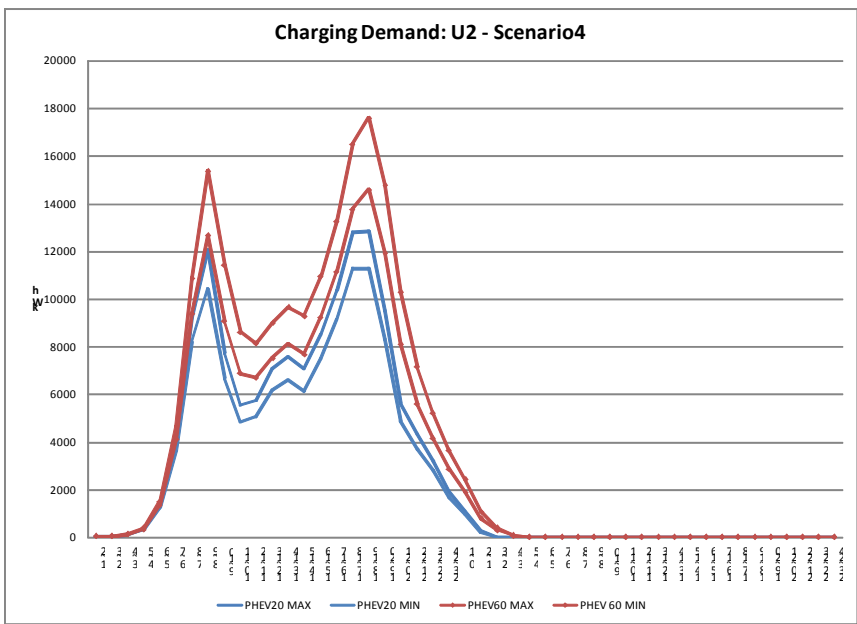
**Figure 4.7 Hourly PHEV Charging Demand: Scenario 4 Base Case  
(120V, 15amp)**

With upgrades, the charging time difference between PHEV20 and PHEV60 is observed to decrease, while the peaks are higher than in the base case. These results are similar to previous scenarios.





**Figure 4.8a Hourly PHEV Charging Demand: Scenario 4 with Circuit Upgrade 1 (120V, 20amp)**

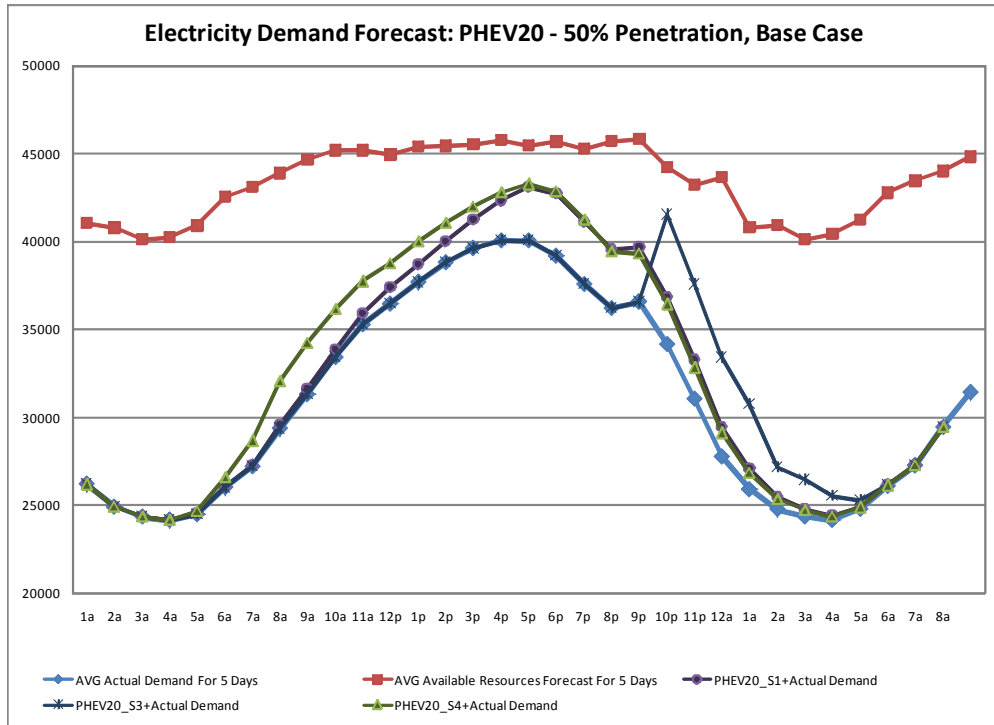


**Figure 4.8b Hourly PHEV Charging Demand: Scenario 4 with Circuit Upgrade 2 (240V, 40amp)**

### **4.3 California Electricity Supply with Future PHEV Charging Demand Increases**

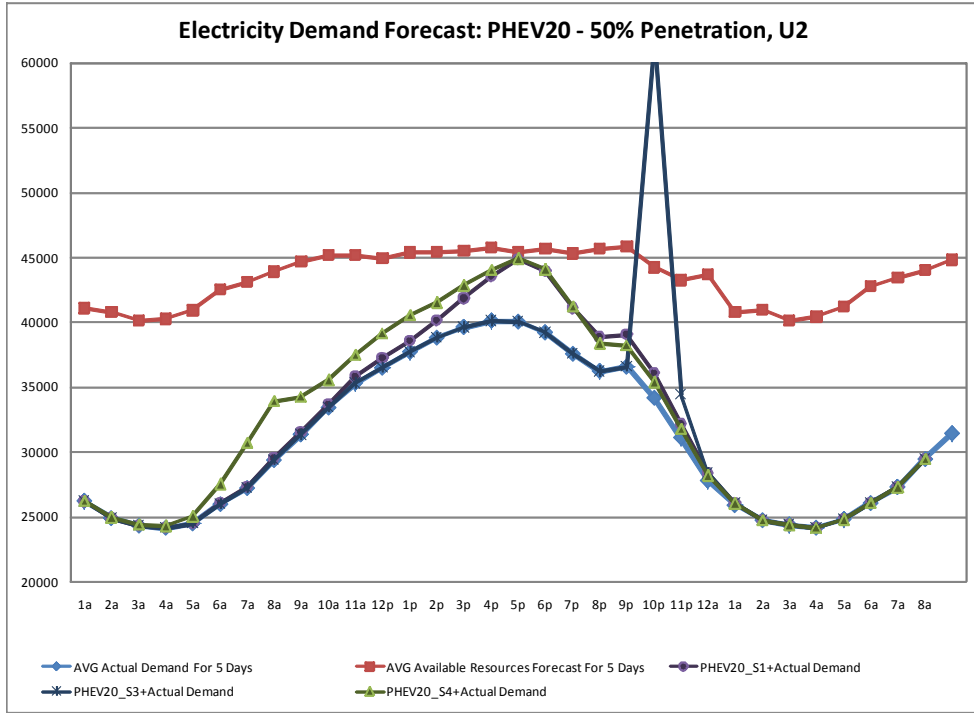
In order to maximize energy efficiency with increased PHEV charging demand, the previous results can be used to forecast future electricity demand. For example, assume that PHEV20 penetration rate is 50%. That means that half of total households in California, 11,502,870 (<http://www.census.gov>), consume extra electricity for charging their PHEVs in direct proportion to the results in previous figures for the sample of 11,385 households in California. This same process can be used to generate consumption patterns by vehicle statistics as well.

Hourly electricity generation data is provided by California ISO, CAISO (<http://www.caiso.com>), who supplies about 75% of electricity in California. Assuming that this same rate of 75% holds for charging demand, we can forecast the future electricity load on an hourly basis (Figure 4.9 and 4.10). In these figures, Manhattan network cases are presented to produce upper bounds of each scenario. Also, the hourly demands are based on five weekday's average (excluding weekends).



**Figure 4.9 Electricity Demand Forecast (MWh) for PHEV20, 50% Penetration with Base Case (120V, 15amp)**

At 50% penetration of PHEV20, all base case scenarios' estimates do not require any systemic changes to the grid. Electricity demands stay within the available resources forecast that CAISO has set for current usage (Figure 4.9). However, the maximum demand increase is produced by the upgrade 2 (240V, 40amp) case, which consumes over five times more electricity per unit time than does the base case. When circuit upgrades are in place, all scenarios approach the available resources forecast limits (Figure 4.10) under the 50% penetration scenario. In particular, for Scenario 4, the peak is extremely high and far exceeds grid capacity. The implication drawn from this sort of hypothetical forecast is that having Scenario 4 and Circuit Upgrade 2 at the same time should be strongly discouraged.



**Figure 4.10 Electricity Demand Forecast (MWh) for PHEV20, 50% Penetration with Circuit Upgrade 2 (240V, 40amp)**

## 5 Results and Outcomes

In this section, aggregated statistics on mileage, number of trips and temporal trip distribution by different energy sources are presented. The trip/activity chains of each vehicle in the sample are replicated, and results on energy and emission profiles based on different charging scenarios are presented. Figure 5.1 presents an example of such a replication for an actual vehicle from California Travel Survey. This vehicle has total of 6 trips and of 37 miles (Manhattan distance) of travel on this particular day. Based on charging Scenario 1 or Scenario 3 behavioral assumption, this vehicle is run on 20 miles by electricity—with the remaining 17 miles by ICE—but, with home-charging (Scenario 2) between the trips, it can purely run on electricity. Associated emissions can be also derived as the figure shows. The statistics in the Section 5 are aggregated from this process for all 15,823 vehicles in the survey.

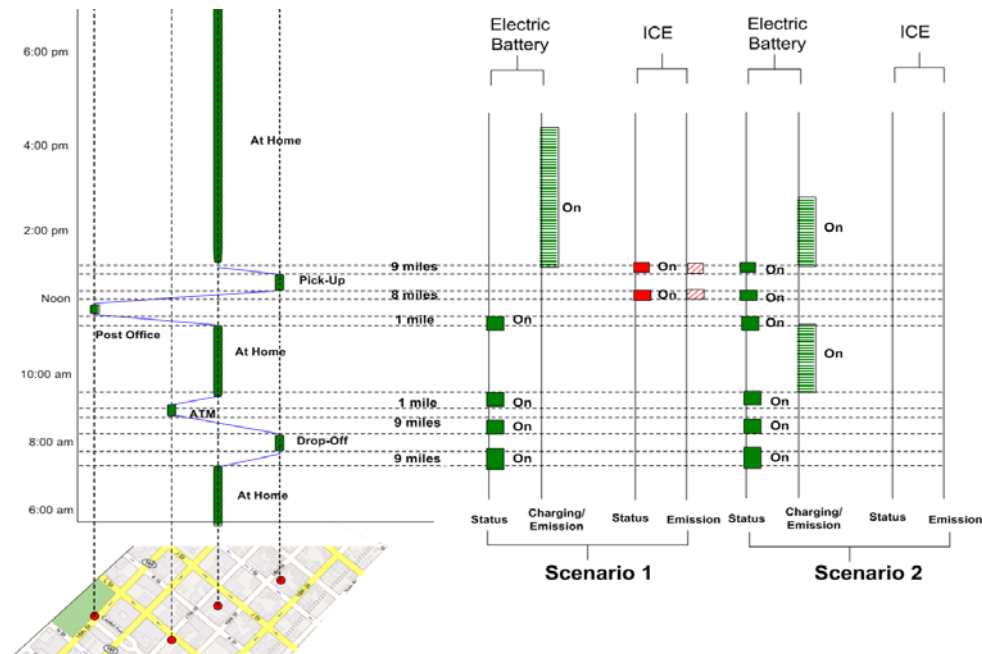


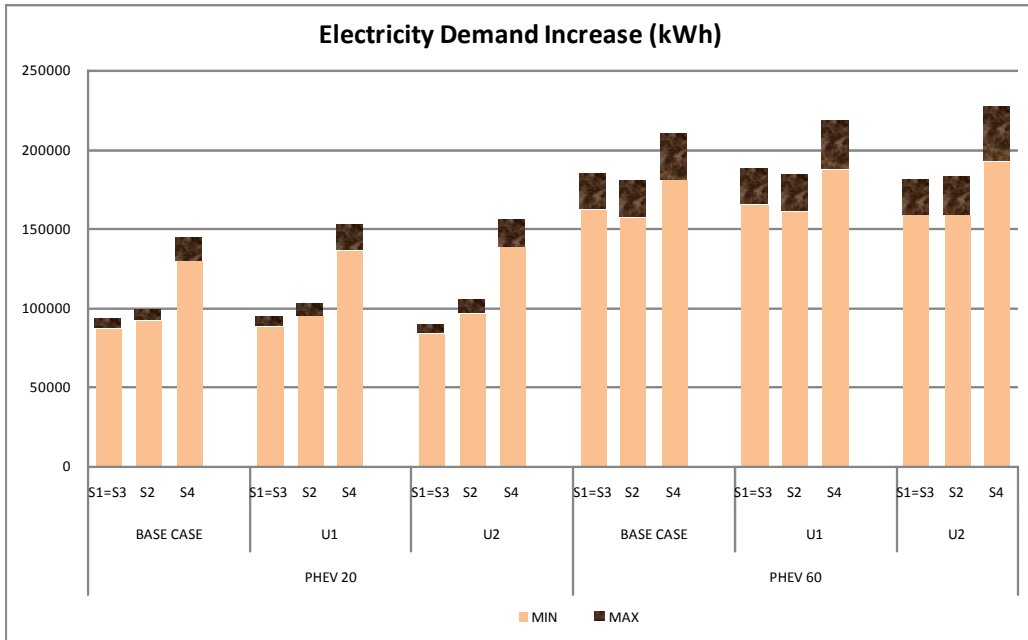
Figure 5.1 Replication of a Single Vehicle

## 5.1 Electricity Demand Increase

Figure 5.2 presents a summary of the total electricity charging demand increase by households in the sample for all scenarios (both with PHEV20 and PHEV60) that would be required to hold to current activities and trips using PHEVs. The two different network assumptions provide boundary values; real values are expected to be between the minimum and maximum bounds. PHEV 20 cases have a peak demand of 100,000 kWh for private (in home) charging only, and 150,000 kWh for circumstances allowing public parking charging, i.e., Scenario 4. PHEV 60 penetration results in around 200,000 kWh electricity sector demand increase daily.

Public parking charging (Scenario 4) enables daytime charging and therefore increased total electricity for the PHEV 20 case which will lead to less oil consumption for vehicle operations. However, for the PHEV 60 case, provision of public charging stations (Scenario 4) yields only minor improvements over the three scenarios that involve private charging only. This can be explained by the fact that an energy equivalent to 60-miles stored in the battery (which typically can be achieved with overnight charging) covers most of the trip chains for one-day activities (Figure 1.1).

Regarding different types of charging circuit infrastructure, as indicated in Section 4, while upgrades deliver shorter charging times, they do not considerably increase the total amount of electricity substitute for ICE fuel (Figure 5.2).



**Figure 5.2 Total PHEV Charging Demand (kWh)**

In general, higher charging demand indicates that a larger fraction of mileage is run by electricity with less gasoline consumed. However, depending on local sources of electricity generation, this does not guarantee an improvement relative to such environmental perspectives as emissions; to make claims regarding efficiency of energy usage or reduction in total emissions, these results need to be further tested and analyzed. However, in terms of gasoline-dependency, converting fuel to electricity will undoubtedly lower the need for petroleum imports since electricity generation depends on a variety of energy sources.

## 5.2 Mileage Substitution by Electricity

In this section, vehicle-based activity chains are analyzed with the first 20/60 miles run on electricity motor (assuming binary operation for PHEVs), and the remaining miles (if any) on ICEs. Alternate network assumptions (i.e., Manhattan vs. Euclidean distance metrics) provide maximum and minimum values, and represent ranges for estimated values of future energy usage.

Based on the results of the previous analysis, there are several remarks associated with electricity coverage on mileage. First, circuit upgrades do not generally make a big difference in mileage substitution (by electricity). Scenario 4 has the biggest increase in mileage substitution with circuit upgrades; when charging is available at public parking facilities, it is estimated to result in as much as a 5% point increase. The public parking case can lead to 70% coverage; however, PHEV 20 adoption covers a maximum of 50% of current driving distances just with daytime charging at home and upgrades on circuits (Figure 5.3a).

For PHEV 60, the base case with night home charging can convert a minimum of 70% of trip distances to being electric-powered (Figure 5.3b). Daytime public parking charging with upgraded circuits can deliver up to 90% of total mileage; however Scenario 4 adds more demand during high-peak hours—this may become another problem to the grid and power generation. With circuit upgrades, PHEV60 delivers a much bigger shift from fuel to electricity in terms of mileage than does PHEV20. In addition, both Scenarios 1 and 3 of PHEV20 and PHEV60 cases, that assume end-of-travel charging behavior, delivered mileage substitution slightly less than vehicle daily driving range distribution (Figure 1.1) for the PHEV20 case (47% to 55%), and 82% to 88% for the PHEV60 case.



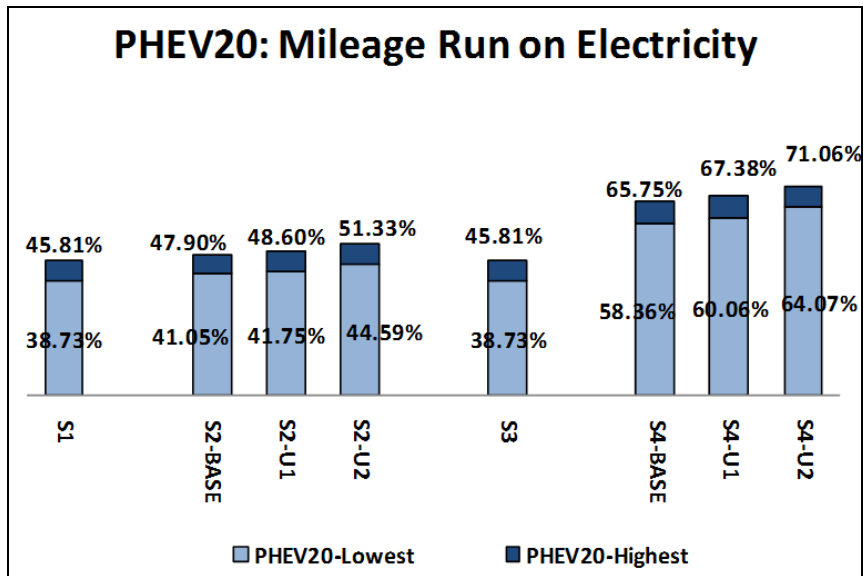


Figure 5.3a Total Mileage Run by Electricity for PHEV 20

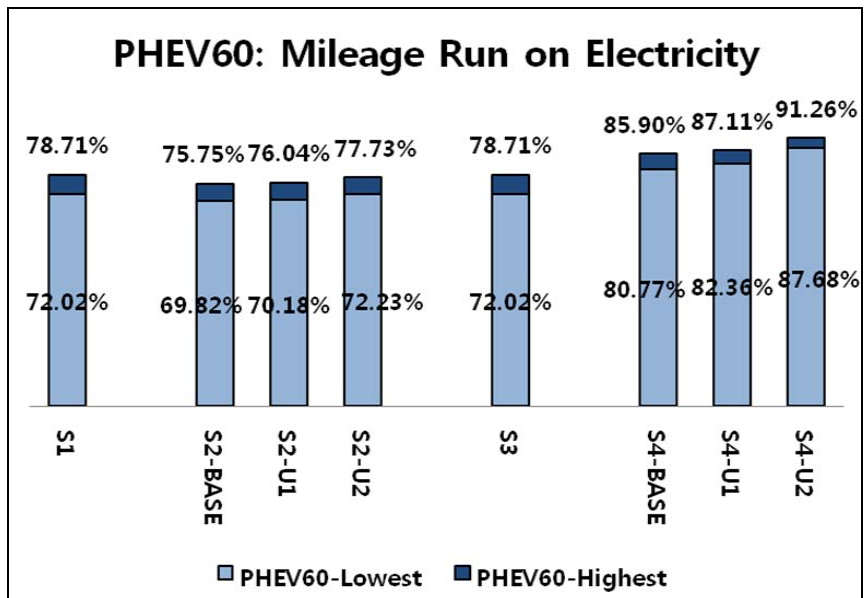


Figure 5.3b Total Mileage Run by Electricity for PHEV 60

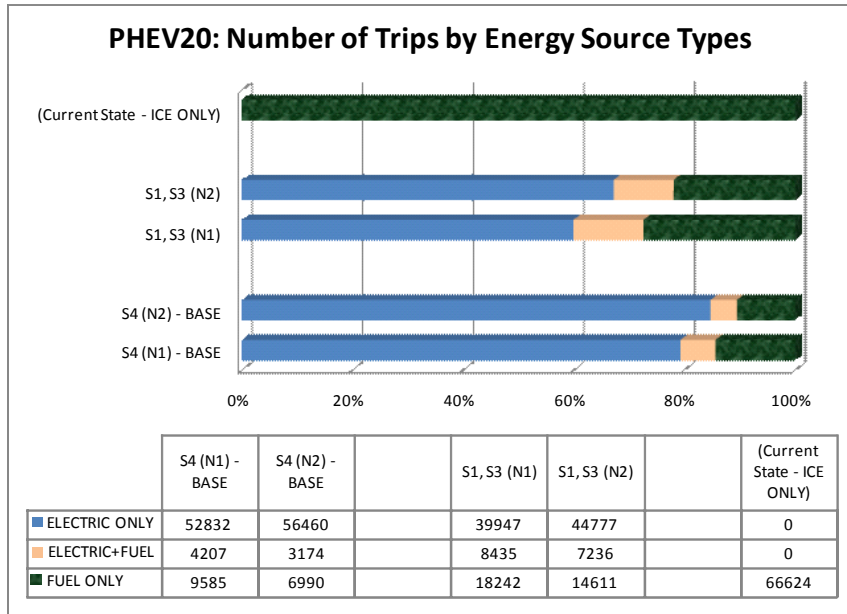
### 5.3 Number of Trips by Energy Types

Because Internal Combustion Vehicles' (ICVs) emissions depend not only on mileage but also on the condition of the engine upon starting, the ranges of mileage coverage that PHEV adoption may achieve are not sufficient to derive emission reduction effects. For ICVs, engine starts determine a significant portion of total emissions produced by trips. Here, the number of trips by energy sources is analyzed to derive ranges for emission reduction effects more precisely vis-à-vis mileage coverage. In the following figures, the numbers of trips, which are equivalent to the numbers of engine starts, are presented for each PHEV type for several of the base case (no circuit upgrades) charging scenarios.

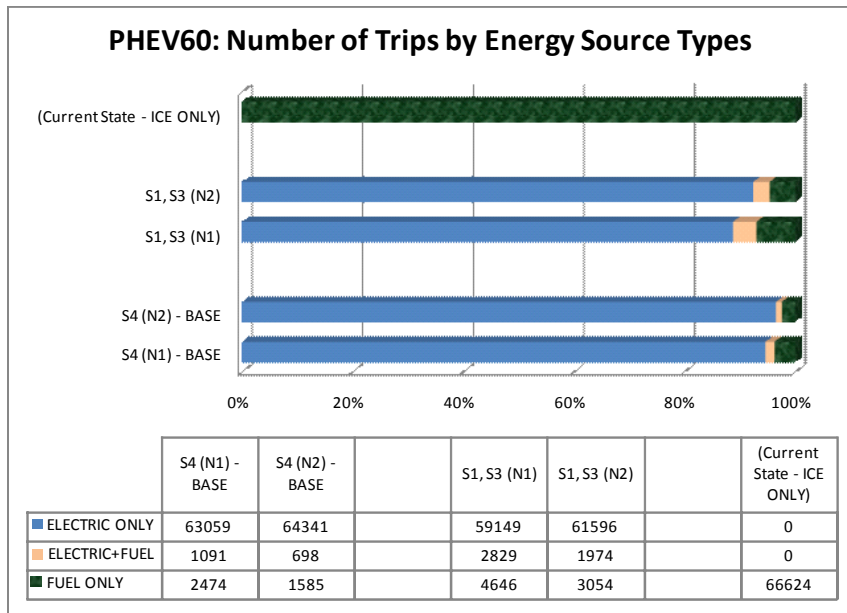
In the figures, the 'electricity only' portion represents trips run purely on electricity; a similar notation is used for the fuel portion. The category 'Electricity and fuel' represents trips started with power provided by the electric motor, and then at some point in the trip the battery was discharged completely and the ICE turned on. Although the figures do not specifically identify what portions of mileage were run on certain types of energy, they nonetheless provide an idea of the number of (or percentage of) trips in which the electric battery was depleted. The exact number of trips is also available from the figures—the total number of trips is 66,624.

Compared to the statistics based on mileage coverage ranges, the same scenarios generally produce about 20% point more in terms of the number of trips only by electricity. For example, the base case home charging scenario 1 for PHEV 20 (Figure 5.4a) has mileage coverage range of 38% to 46% but has almost 60% to 70% in terms of the number of trips on electricity only; the range is even larger with 'electricity and fuel' trips included. For the PHEV 60 case (Figure 5.4b) with same scenario, more than 90% of trips are covered while a maximum 78% of mileage is covered from grid source. This difference can be explained by

the presence of long-distance trips. Since the maximum distance a PHEV covers is only 20/60 miles, long-distance trips might be categorized into a single 'Fuel' trip or 'Electricity and Fuel' trip, while the mileage on gasoline could be a much larger percentage of the total miles traveled. However, in terms of reducing ICE starts, these results are expected to contribute more emission reduction than those based on mileage results alone.



**Figure 5.4a Number of Trips by Energy Source Types for PHEV 20**

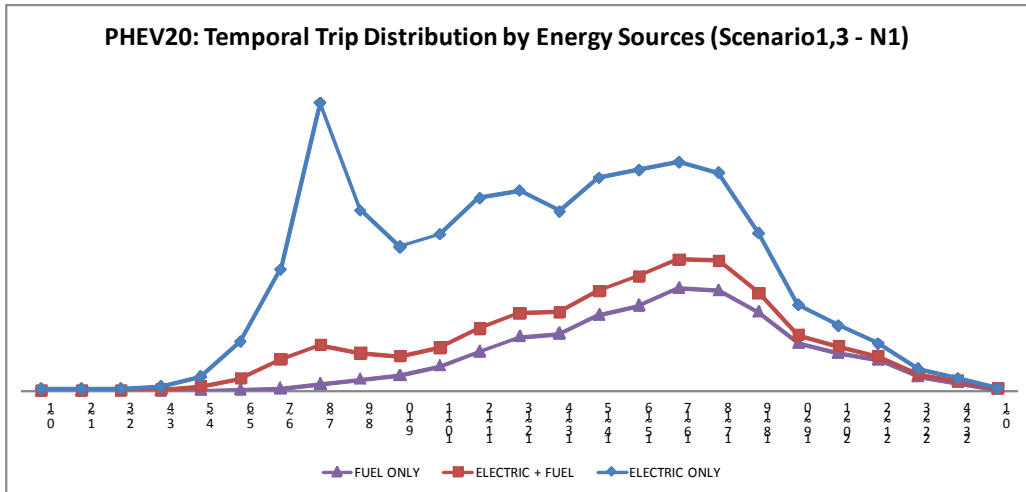


**Figure 5.4b Number of Trips by Energy Source Types for PHEV 60**

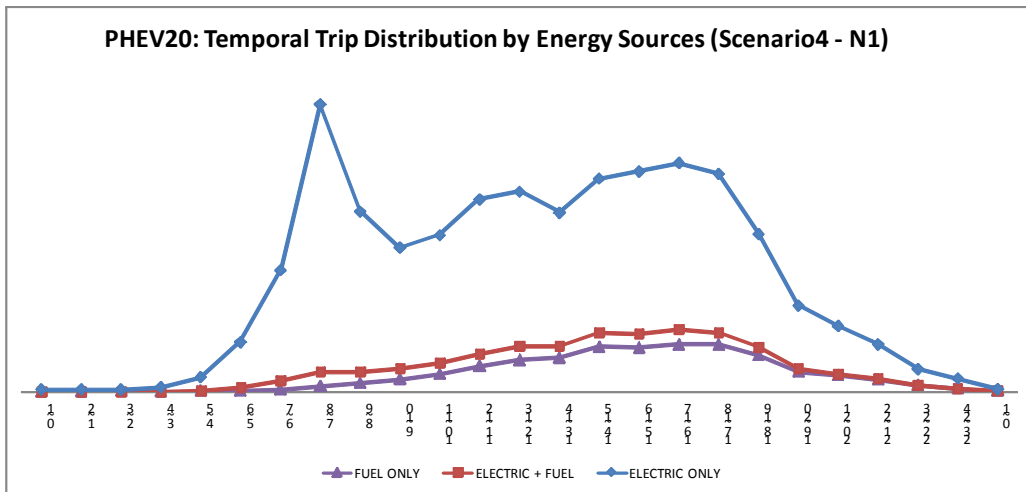
## 5.4 Temporal Trip Distribution by Energy Types

The activity-based approach employed herein specifically incorporates the temporal linkages between travel and activities and therefore enables the creation of hourly energy profiles of vehicle usage. Aggregated energy profiles for 15,823 vehicles are shown in the Figures 5.5a, 5.5b and 5.5c. These results can provide some measurements for emission studies incorporating time-of-day adjustments relative to time-sensitive characteristics of air quality. Also, based on air circulation patterns, dynamic emission and energy profiles (within a time frame) may be used to estimate how long pollutants stay, how they travel and what impacts they would cause.

As expected with the binary mode assumption that vehicles will drive with electric motors first and the ICE turning on only when batteries are depleted, more vehicles are run on fuel in the afternoon (after 20/60 miles) trip chains that day. For the PHEV 20 base case charging Scenario 1, roughly more than 50% of trips after 2pm in the afternoon are run either on fuel or on a combination of fuel and electricity. Consequently, afternoons are subject to greater exposure to emissions from the transportation sector than are mornings, ostensibly concentrated more in such locations as major corridor and arterial roads in urban areas. As seen in Figure 5.5b, with public parking charging plus daytime charging (Scenario 4), fuel usage drops dramatically. Under the assumption that all of the current vehicles are substituted with PHEVs with battery size PHEV 60, the reduction in afternoon emissions is much greater (Figure 5.5c).



**Figure 5.5a Temporal Trip Distribution Source Energy Profiles**



**Figure 5.5b Temporal Trip Distribution Source Energy Profiles**

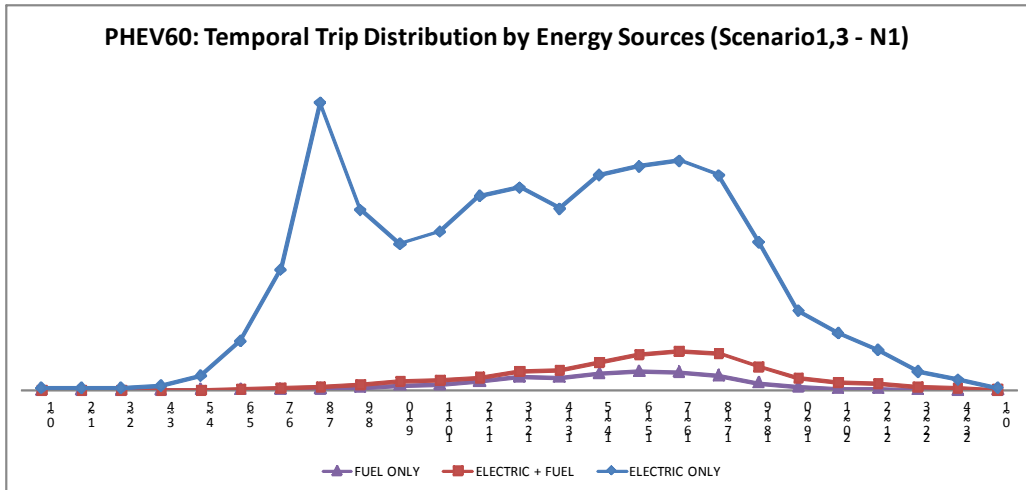


Figure 5.5c Temporal Trip Distribution Source Energy Profiles

## 6 Conclusions and Future Research

Commercial PHEV release in the automobile market in the near future will certainly bring positive impacts on emission and foreign oil dependency as well as consumers' financial benefits with rising fuel costs. To optimize energy usage and to minimize additional energy costs and emissions regarding grid charging, this research presents estimates of PHEVs impacts and provides inputs for policy makers to assess the current states of electricity generation and infrastructure as they pertain to increased adoption of PHEVs.

Charging demand shifts on an hourly basis are presented for four different scenarios with different circuits. Circuit upgrades bring faster charging times, and reduce charging time differences between PHEV20 and PHEV60.

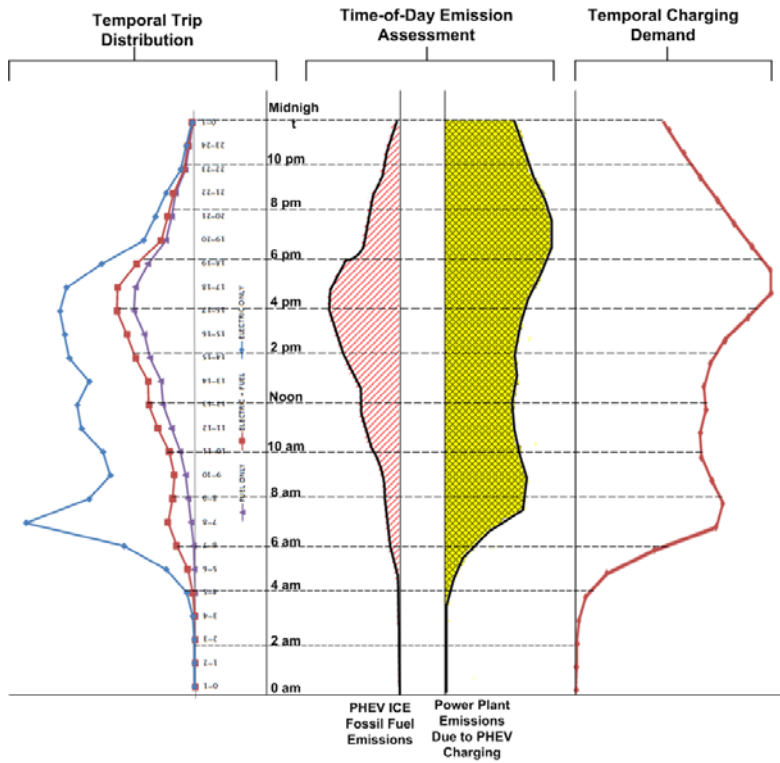
Home charging will replace 40-50% of total distances currently travel using ICEs with electric power for PHEV 20 and 70-80% for PHEV60. If charging facilities are available in public parking facilities, which will lead to more daytime charging, PHEV20 can convert 60-70% of total mileage from fuel to electricity, and 80-90% for PHEV60. Emission reductions will be higher than those percentages since PHEVs will cover a greater fraction when measured by the number of trips, which emphasizes the equivalent number of ICE starts.

It is not certain that diverting charging demands to off-peak periods will maximize energy efficiency. As we document, daytime charging will allow more trips by electricity, but will result correspondingly in higher peaks for high-demand-periods. Charging policies need to be determined with consideration of regional situations regarding energy profiles and associated infrastructure. This result draws attention to such issues and may better enable decision makers to predict future impacts under different scenarios.

There are limitations to the assessments provided in this research. This research does not fully provide environmental impacts from PHEV penetration. Increased emissions and other types of energy usage regarding extra grid electricity demand are not assessed. Chemicals associated with electric batteries are not taken account. Life cycle analysis on environmental impacts regarding different mechanical parts of CVs and PHEVs are not analyzed. In further studies, more far-reaching environmental assessments are needed.

In future studies, more comprehensive and detailed analyses would shed greater light on the impacts of projected demand increases when compared to current emissions along temporal and spatial dimensions. Emissions and air quality are location-sensitive. Areas near power generation facilities likely will not benefit from PHEV adoption from an environmental perspective. The potential impacts are also time-sensitive. Afternoons were found to emit more pollutants than mornings. Figure 6.1 shows one example of how such factors might be incorporated into further emissions studies. Using such an approach, we will be able to get a more complete assessment of the time and space linkages of PHEV impacts under a similar set of activities and trips conducted with the current state of ICVs.





**Figure 6.1 Incorporating Trip Distribution by Energy Sources, Charging Demand for Further Emission Studies**

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- “US Census Bureau” online <http://www.census.gov/>