Driving Plug-In Hybrid Electric Vehicles: Reports from U.S. Drivers of HEVs converted to PHEVs, circa 2006-07

Dr. Kenneth S. Kurani, Associate Researcher
Dr. Reid R. Heffner, Senior Analyst
Dr. Thomas S. Turrentine Director,
Plug-in Hybrid Electric Vehicle Research Center

Institute of Transportation Studies
University of California, Davis

Funded by
University of California Energy Institute, and
PIER Plug-in Hybrid Electric Vehicle Research Center

Tuesday, October 16, 2007

Abstract

This report examines early users' experiences with plug-in hybrid vehicles (PHEVs). At the time this study was conducted in winter and spring of 2007, PHEVs were not yet commercialized. Still, Americans were becoming aware of PHEVs and 25 to 30 vehicles converted from hybrid electric vehicles (HEVs) to PHEVs were on the road. In interviews with 23 drivers of these vehicles we explored how they used and recharged their vehicles. We also discussed their recommendations for future PHEV designs, and investigated how they think about PHEVs, including the benefits and drawbacks they perceive. While today's PHEV drivers may not represent either mainstream American car buyers now or future buyers of PHEVs, their behavior and viewpoints offer clues about how PHEVs will be received and used by other consumers and may shape both the PHEV technologies offered in the future and the reasons why future consumers value PHEVs.

Keywords

Plug-in Hybrid Vehicles, Consumers, Markets

1. Introduction

This report examines early users' experiences with plug-in hybrid vehicles (PHEVs). At the time this study was conducted in winter and spring of 2007, PHEVs were not yet commercialized, still Americans were becoming aware of the vehicles and 25 to 30 vehicles that had been converted from hybrid electric vehicles (HEVs) to PHEVs were on the road. In interviews with 23 early drivers of these vehicles we explored how they use and recharged their vehicles. We also discussed their recommendations for future PHEV designs, and investigated how they think about PHEVs, including the benefits and drawbacks they perceive in the new vehicles. While today's PHEV drivers may not represent either mainstream American car buyers now or future buyers of PHEVs, their behavior and viewpoints offer clues about how PHEVs will be received and used by other consumers and may shape both the PHEV technologies offered in the future and the reasons why future consumers value PHEVs.

Since so few people have experience with PHEVs, many fundamental questions exist regarding how drivers will use and recharge PHEVs. The goal of this study was to conduct a general exploration of important issues from the perspective of the vehicle drivers. At the time of our interviews, respondents were still evaluating the functionality and interpreting the symbolic meaning of the vehicles. We looked for early indications of what meanings were being associated with PHEVs and the features of PHEVs to which these meanings were being attached. As development of PHEV technology continues and the vehicles are commercialized, the meanings attached to these vehicles will become better defined and more widely held.

This report begins with a short summary of PHEV technology. It then discusses four main findings from the interviews of drivers of Priuses that have been converted to PHEV operation: 1) response to the specific vehicles in this study and specifically all-electric driving, 2) the role of driver instrumentation, 3) recharging behavior, and 4) the perceptions of electricity as a transportation "fuel." To provide additional insight into PHEV drivers we include detailed stories based on three of these interviews. The stories are presented in a more literary style and provide insight into some of the meanings PHEV users attached to their vehicles. These stories present the thoughts, ideas, and beliefs of the storyteller, not necessarily the conclusions of this report.

1.1. Background

Like currently commercialized HEVs, PHEVs use a powertrain that combines an electric motor with an internal combustion engine (ICE). However, conventional HEVs are charge-sustaining: while driving they maintain their batteries at a roughly constant state of charge (SOC: a percentage of the electric capacity of the battery), and recharging occurs only from on-board electricity generation by the heat engine fueled by, in this case, gasoline and the recapture of kinetic energy through regenerative braking. In contrast, PHEVs can operate in either charge-sustaining or charge-depleting mode. As the name suggests, in charge-depleting mode the vehicle depletes the battery's SOC. While PHEV designs can vary considerably, one design is to operate first in charge-depleting mode, then switch to charge sustaining mode once the battery SOC reaches a design minimum. Typically, PHEVs provide greater amounts of on-board energy storage than HEVs by incorporating more onboard electricity storage, e.g., larger batteries. This larger battery size creates the possibility for displacing substantive amounts of fuel for the heat engine with electricity from the electrical power grid. Many PHEV designs also provide all-electric operation for some limited distance, known as the all-electric range (AER). Some authors

have distinguished PHEV designs their AER. A PHEV20, for example, is a PHEV with 20 miles of AER.[1] However, all-electric operation is not essential for PHEVs.

PHEV designs that provide AER contrast to the "blended" operation of currently commercialized HEVs in which power from both the electricity and gasoline systems are more or less continuously combined to provide propulsion. This distance is determined by size of the battery, the SOC threshold between charge-depleting and charge-sustaining modes, the size of the electric motor, power electronics, and energy and power demands resulting from driving conditions, e.g., acceleration, distance, payload, etc. The distance traveled before the design minimum SOC is reached is one measure of all-electric range (AER).

Other definitions have been proposed. For example the California Air Resources Board [1] defined AER as the distance traveled by the PHEV before the first instance of the ICE starting, regardless of battery SOC or operating mode. In essence, CARB—an air quality agency—is primarily interested in whether and how long a PHEV may operate as a "pure electric" or zero-emission vehicle. Alternatively, Gonder and Simpson [2] argue that the distance traveled before the vehicle switches from charge-depleting to charge-sustaining operation—regardless of whether the vehicle can operate in an electric-only mode at all—is a more "appropriate" definition of AER. That is, their definition is related to the size of the "electric storage system" relative to the energy and power demands of any particular vehicle, not the vehicle's repertoire of operating modes, i.e., all-electric, all-ICE, or blending both. They argue that their definition better captures petroleum displacement effects of PHEVs. Such a definition better serves the institutional mission of the US Department of Energy.

The distinction between PHEV designs that facilitate AER and those that operate in a blended mode introduces yet another bit of terminology and affects measurement of an important potential benefit of hybridizing automobility, i.e., "boosted range" and fuel economy. In the US, automotive fuel economy for conventional vehicles is measured according to codified standards and conditions as miles per gallon (MPG)—and implicitly, gallons of gasoline or gasoline equivalent. The question for PHEVs is how to measure fuel economy for a vehicle that uses two distinct "fuels" and may use them in different proportions depending not only on vehicle design, but drivers' driving and refueling/recharging behaviors. The phrase "boosted range" was used by some of our interviewees to describe the distance over which a PHEV operating in blended mode provides substantial increases in fuel economy of the heat engine, i.e., not counting electricity from the grid. Boosted range lasts until the battery reaches its design minimum SOC and the vehicle switches from charge-depleting to charge-sustaining operation. To provide an example, many of the people interviewed for this study reported approximately double the gasoline-only fuel economy of a stock (non-PHEV) Prius during the boosted range of their converted PHEV Prius. At the end of boosted range, the vehicles' gasoline-only fuel economy declines to that of a stock Prius, as the vehicle in effect reverted to operating as a stock Prius. For a given vehicle, maximum boosted range will be a function of driving conditions and driver behavior.

PHEVs are not only a recent development. As reported by Norbye and Dunne [3], prototypes were developed four decades ago. The U.S. Congress first authorized funding for federal research into hybrid electric vehicles in general in 1976. They were the subject of technology

[1] Past studies by EPRI [4] label a plug-in hybrid electric vehicle with a 20-mile AER as an HEV20 rather than a PHEV20. Other studies use the terminology "grid-connected hybrid electric vehicle." This study uses the PHEV acronym and includes all-electric range in miles where applicable, e.g., PHEV20 refers to a PHEV with 20 miles of AER.

research and development and market research in the 1990s and early 2000s, and have been the subject of much recent work by academics, electric utilities, the USDOE's system of national laboratories, environmental and energy NGOs, battery developers, and automobile manufacturers. For examples and reviews of this history of inquiry into PHEVs see the following (the list is intended to be illustrative, not comprehensive): Turrentine and Kurani [5], Plotkin *et al.* [6], EPRI [4, 7, 8], Markel and Simpson [9], Gonder and Simpson [2], Winkel *et al.* [10], Kliesch and Langer [11], Frank [12], Burke [13], Kintner-Meyer *et al.* [14]. In the past few years, pro-PHEV organizations, for-profit HEV-to-PHEV converters, and automaker PHEV research and development programs have been initiated, including DaimlerChrysler's PHEV Sprinter van, GM's Volt design exercise, and Toyota's prototype plug-in Prius. Plug-in Partners (http://www.pluginpartners.org/) is seeking "soft orders" for PHEVs to demonstrate potential demand; as of April 2007, they claim to have registered such pledges from cities, counties, state agencies, electric utilities, and businesses. The 109th Congress passed H.R. 6, The Energy Policy Act of 2005. It calls on the Secretary of Energy to establish a program to "improve technologies for the commercialization of…a plug-in hybrid/flexible fuel vehicle" (Sec. 706(b)(2)), elaborated later in the Act to "include research, development, demonstration, and commercial application of…plug-in hybrid systems (Subtitle A, Sec. 911(a)(2)(A)(ii)). As of March 2007 approximately one dozen bills promoting or funding research on plug-in hybrid vehicles had been introduced in the 110th Congress. Enthusiastic reviews of PHEVs have appeared on the op-ed pages of major newspapers (see for example, Woolsey [15]).

1.2. PHEV Benefits

Charging from the electricity grid allows PHEVs to replace some portion of the gasoline they would otherwise use with electricity. While the reduction in petroleum consumption for a particular PHEV depends on how the vehicle is designed and used, Wang [16] estimates a PHEV may consume nearly 60 percent less gasoline than a conventional vehicle, and almost 30 percent less gasoline than a non-pluggable HEV[2]. Since PHEVs use less gasoline, they also emit lower greenhouse gases (and potentially fewer criteria pollutants) from the tailpipe. In fact, some PHEV designs with robust all-electric driving capability, i.e., the ability to accelerate and cruise all-electrically in real-world driving, would have no tailpipe emissions at all until its onboard electrical energy storage is discharged to its design minimum.

However, tailpipe emissions are not the only consideration. To fully assess the environmental impact of PHEVs, lifecycle emissions (including the emissions that result from upstream electricity generation) must be evaluated. Not surprisingly, the lifecycle emissions benefits of PHEVs are dependent on the fuel sources for the electricity used to recharge them. Recharging PHEVs with renewable electricity dramatically reduces greenhouse gas and criteria pollutant emissions, while using electricity from coal yields less impressive results. Given the complexity of such analyses, a variety of conclusions have been reached; the variation depends on assumptions, inputs, and nomenclature. In general though, results from such studies indicate that PHEVs are likely to reduce greenhouse gas emissions associated with transportation and to reduce exposure to other regulated emissions for most Americans. Wang [16] estimated that a gasoline-powered PHEV using "average" electricity from the U.S. grid would emit 37 percent fewer greenhouse gases than a conventional vehicle, but would increase emissions of nitrogen oxides (NO_X) six percent, particulate matter (PM_{10}) 3.5 percent, and sulfur oxides (SO_X) 62 percent. Kliesch and Langer [11] estimate large regional differences in PHEV emissions benefits.

[2] Wang's [17] model does not assume a specific AER for PHEVs. Instead, it assumes that a PHEV operates exclusively on grid electricity for 30 percent of its total miles.

They estimate a PHEV that recharges from the California grid (in which renewables and nuclear account for 45 percent of generation) will emit about 30 percent less carbon dioxide (CO_2) and SO_X, and 40 percent less NO_X than a non-pluggable HEV[3]. However, if the same PHEV is charged from the coal-intensive power grid in the East Central area of the United States, the same PHEV emits roughly the same amounts of CO_2 and NO_X as a non-pluggable HEV, and over three times the SO_X.[4] EPRI [18, 19] modeled future emissions from conventional gasoline/diesel vehicles, HEVs, and PHEVs based on future projections of automotive emissions and fuel economy as well as electricity generation.[5] The period of analysis, PHEV market penetration levels, and other assumptions differ between the GHG and the air quality analysis. In general, EPRI [18] concludes, "Annual and cumulative GHG emissions are reduced significantly across each of the nine scenario combinations [created by a 3x3 matrix of PHEV market penetration and electric sector CO_2 intensity assumptions]." Further, PHEVs are modeled to create small national reductions in emissions of NO_x, to have small national effects on SO_2 and PM_{10},[6] and reduce the population-weighted exposure to these pollutants (EPRI [19]). Regarding the last, the modeling of air quality impacts indicates in the absence of any air quality policies not already assumed by the analysis, most Americans (61 percent) will benefit from reduced exposure to ground-level ozone, a smaller group will not, and a small group (one percent) will suffer greater exposure [19].

1.3. The current status of the PHEV "Market"

Although automakers have developed PHEV prototypes, currently no mass-produced PHEV is available to consumers. Nonetheless, at the time this study was conducted there were already 25 to 30 light-duty PHEVs on the road in North America. All were modified HEVs (using the Toyota Prius platform) and were built either by a handful of conversion companies or by vehicle owners themselves. These conversions add larger battery packs, either supplementing the existing HEV battery or replacing it entirely and hardware to allow recharging the battery(ies) from the electric grid. The extra energy from these additional battery packs allows the PHEV conversions to drive longer in all-electric mode, under modest power demand. Further, when the gasoline engine is used, Prius-based PHEV conversions also attain higher gasoline-only fuel economy (roughly double that of a conventional Prius) since more electricity can be blended in

[3] Kliesch and Langer [11] assume a PHEV40 with 50 percent higher fuel economy than a comparable HEV.

[4] Emissions of NO_x and SO_x from electricity generating units larger than 25 MW are capped by federal air quality rules and emitters are allowed to bank credits across time. These facts require some subtlety in interpreting reports of increased emissions such as those presented by Wang [16, 17], Kleisch and Langer [11], and others. If PHEVs are recharged from the electrical grid, and if doing so requires more electricity than would otherwise have been produced, and unless all marginal electricity required for PHEVs is generated from sources with no combustion by-products, then more combustion by-products are created. However, those additional combustion by-products cannot be emitted to the environment outside the generating unit if the generating unit is already producing as many such emissions as the cap allows. Any combustion by-products above the cap must be scrubbed, captured, neutralized, or otherwise prevented from being released into the environment. This means additional costs would be incurred to treat the combustion by-products NO_x and SO_x caused by additional electricity generation to recharge PHEVs, not that more emissions would be released to the environment.

[5] EPRI [18, 19] assumed a mix of PHEV10s, PHEV20s, and PHEV40s; that HEVs achieved 35 percent higher fuel economy than gasoline/diesel vehicle; and that PHEVs have fuel consumption equivalent to an HEV—for that portion of the PHEVs driving that is not powered by grid-electricity.

[6] The modeled effects in EPRI [19] for these two pollutants are a slight decrease in SO_2 and a slight increase in PM_{10}.

more frequently than in a standard Prius. [7] Overall, the Prius-based PHEV conversions included in this study appear to be averaging between 65 and 95MPG, with brief periods of driving at well over 100MPG.

These PHEV conversions are expensive: in addition to the purchase price of the original HEV, owners spend another $4,000 to $25,000 for conversion. PHEV conversions also lack some of the assurances that are provided with an OEM vehicle. While some conversions include warranties and support, today's PHEV conversions almost certainly have voided parts of their original manufacturers' warranty and to-date none have been crash-tested in their modified forms. In addition, questions remain about the cycle life of the additional battery packs since PHEVs typically discharge batteries more deeply than existing HEVs. Due to the high costs and uncertainties involved in PHEV conversions, few are currently owned by private citizens—most are in the hands of electric utilities, research institutions, or governments many of which have previous experience with other types of alternative fuel and electric-drive vehicles.

To date, only limited analysis has been conducted on the consumer response to PHEVs. Consumer polling by Synovate [20] claims as many as 49 percent of U.S. consumers become interested in PHEVs once they are made aware of the technology. When consumers are faced with the prospect of paying more for PHEVs than they do for conventional vehicles, interest falls but is still substantial: OPC [21] reported that 26 percent of a sample of U.S. carbuyers in one study said they would pay a $4,000 premium for a PHEV20. An EPRI [4] market research study concluded that among respondents who were characterized as "midsized car buyers," 53 percent preferred a PHEV20 to a conventional vehicle even if the price premium for the PHEV was roughly $3,000. However, as the price difference between a PHEV and a conventional model increased, consumer interest declined: 16 percent of these same respondents were interested in an HEV20 that cost $9,000 more than its conventional counterpart.[8]

However, measures of current consumer interest in PHEVs should be interpreted cautiously. Notably, none of the consumers in the studies cited above were PHEV owners. Further, many of the basic assumptions of past studies are not supported by evidence from HEV buyers. Studies by Kurani *et al.* [22] and Heffner *et al.* [23] of HEV buyers suggest few have compared their HEV to a conventional vehicle during the shopping process, and almost none calculated the price difference between the HEV and an "equivalent" conventional model. If PHEV buyers behave in the same way, data on consumers' willingness-to-pay for PHEV technology derived from the assumption that people are simply comparing powertrains in otherwise identical vehicles may not be useful in predicting demand. Hoeffler [24] notes that asking consumers to predict their interest in a radically new product that does not yet exist in the marketplace can be a challenging process, and the demand forecasts that result are notoriously inaccurate. Since consumers have no

[7] Since PHEVs use two fuels (electricity and gasoline), calculating their fuel economy is different from calculating fuel economy for a conventional gasoline vehicle. Gonder and Simpson [2] note there are different methods for performing this calculation. For PHEVs, they propose using the term "fuel economy" to refer only to gasoline consumption. They also recommend presenting the PHEV fuel economy in conjunction with an electricity consumption figure (for example: 50 MPG, 8.4 Wh/mi). In this report, the term "fuel economy" is used to refer only to gasoline consumption since many drivers talked about and measured their energy use in this way. Since only one respondent also provided electricity consumption data, total energy consumption is not discussed in this report using the method Gonder and Simpson propose. However, the reader should recognize that use of electricity from the electrical grid, not from onboard generation, is implicit in the fuel economy numbers presented here.

[8] Notably, this price sensitivity does not make PHEVs different from any other type of vehicle: in stated preference survey work, respondents are sensitive to price differences for all kinds of vehicles.

experience with PHEVs, it is unlikely that many can predict whether they will buy one until they become more familiar with the new technology and how they might utilize it.

2. Study Design

2.1. Interviews

As PHEVs are not yet widely commercialized, the "PHEVs" in this study are all conversions of Toyota's Prius HEV. In addition, most of these conversions are owned by an organization such as an electric utility, local government, or non-profit group that allows its employees to use the vehicle. Therefore, the interviews focused on respondents' use of a PHEV conversion and their perceptions of its advantages and disadvantages. The goal of these interviews was to conduct a general exploration of important issues from the perspective of the user and to examine a broad set of topics of which the symbolic meaning of PHEVs was a part. Since PHEVs are so new, drivers are still evaluating both the functionality and symbolic meaning of the vehicles. We did not expect to find well-defined meaning attached to PHEVs, but instead looked for early indications of what meanings might be associated with PHEVs and what features of PHEVs might be perceived as symbolic.

The following topics were discussed the interviews:

1. ***Participant Background:*** Information on participant's demographics, occupation, current personal vehicle, and experience with electric-drive vehicles
2. ***PHEV Use:*** Description of where, when, and how participant used a PHEV as well as discussion of these driving experiences
3. ***PHEV Refueling/Recharging:*** Description of when, where, and how participant fuels and charges PHEV, as well as participant's reaction to the recharging process
4. ***PHEV Benefits/Drawbacks:*** Discussion of how participant thinks about PHEV, how he/she thinks others view PHEV, and the benefits and drawbacks he/she associates with the vehicle

In late fall 2006, using information provided by the California Cars Initiative and by PHEV conversion users themselves, we identified a population of 25 PHEV conversions in North America. A request for participation was sent to all vehicle owners; 15 agreed to participate. Data were then collected through semi-structured interviews conducted primarily in winter and spring 2007. Since several of the vehicles had more than one driver, a total of 23 interviews were conducted from the sample of 15 vehicles. The interview participants were located in various cities nationwide. Three-quarters of the interviews were conducted in-person, and the remaining interviews were by telephone. In general, interviews lasted between 30 minutes and 2 hours. Although not all interviews were audio recorded, researchers prepared a summary of each interview that was similar to a transcription.

The objective of analyzing an individual interview was to draw out themes that were important to the respondent, including any symbolic meanings that emerged. We used selective transcription, as described by Strauss and Corbin [25], in which we transcribed only the information from the interviews that we considered most relevant. In our analysis of interview content we applied McCracken's [26] method of analytic category discovery. Researchers first identify a "useful utterance" which McCracken describes as an "entryway…into assumptions and beliefs." These utterances form the basis for observations that are of interest to the researcher. As observations

are examined and linked together, patterns and themes emerge for a particular household. These themes become the basis for establishing important vehicle functions and symbolic meanings.

2.2. Sample Vehicles

A summary of the 15 PHEV conversions owned by the people (or their institutions) interviewed for this study appears below in Table 1. All vehicles were conversions of the Generation II Toyota Prius (model years 2004 or 2005) in one of the following configurations:

1. *EnergyCS*: Professional conversion by California-based EnergyCS/Edrive systems; includes 8.5 kilowatt-hour (kWh) lithium-ion battery pack that replaces stock battery
2. *Hymotion*: Professional conversion by Ontario-based Hymotion; includes five kWh lithium-polymer battery pack installed in addition to stock battery
3. *Independent*: A variety of owner-performed conversions; configurations include six kWh nickel-metal-hydride (Ni-MH) pack added in addition to stock battery, or 2.5 to 3.5 kWh lead-acid (Pb-A) pack added to stock battery using CalCars PRIUS+ or Manzanita Micro PiPrius design

Table 1: PHEVs in the Sample

Vehicle Number	Conversion Date	Converter	Primary Vehicle Use	Location
1	September 2004	Independent	Personal Vehicle	CA
2	March 2005	EnergyCS	Performance Testing	CA
3	March 2005	EnergyCS	Personal Vehicle	CA
4	March 2006	Independent	Performance Testing	CT
5	March 2006	EnergyCS	Fleet Vehicle	CA
6	March 2006	EnergyCS	Personal Vehicle	CA
7	April 2006	EnergyCS	Performance Testing	CA
8	April 2006	Independent	Personal Vehicle	WA
9	May 2006	EnergyCS	Personal Vehicle	CA
10	August 2006	Hymotion	Fleet Vehicle	MN
11	August 2006	EnergyCS	Performance Testing	CA
12	August 2006	EnergyCS	Fleet Vehicle	CA
13	October 2006	Independent	Personal Vehicle	WA
14	November 2006	Independent	Personal Vehicle	IL
15	November 2006	Hymotion	Fleet Vehicle	VA

At the time of this study, 80 percent of the sample vehicles had been operated as PHEVs for less than 12 months. Vehicles were mainly located on the West Coast: 60 percent were based in California. Two vehicles were located in the Midwest, and two others were in the Eastern U.S. Figure 1 classifies the vehicles in the sample by owner type. One interesting aspect of this sample is that three vehicles were owned by private individuals who performed and funded conversions themselves. The remaining 12 PHEV conversions were owned by institutions including city, county, and regional governments, electric utilities, PHEV converters and battery developers, and non-profit groups focused on energy efficiency and PHEV promotion. With a single exception, either EnergyCS or Hymotion converted the institutionally owned vehicles.

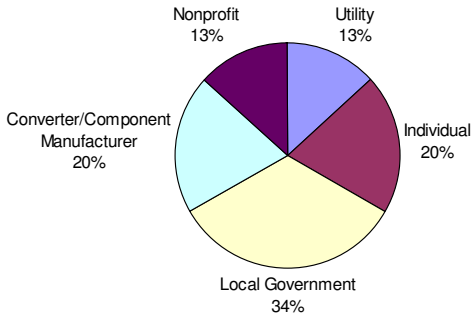

Figure 1: Ownership of PHEV Conversions

PHEV use varied depending upon the owner. Table 1 lists the primary use of each vehicle. Personal vehicles could be owned either by an individual or an institution, but were used mainly by one person for his/her daily driving needs, including personal travel to and from home. With one exception, drivers of personal vehicles had strong knowledge of PHEVs and tended to be PHEV advocates. Fleet vehicles, in contrast, were owned by institutions and were used by a larger number and variety of drivers. A particular driver may have used a fleet-owned PHEV conversion on a daily, weekly, or monthly basis; they may have driven the car once or several times. These vehicles were assigned to employees for temporary use like any other vehicle in the organization fleet. Drivers of fleet vehicle PHEV conversions had various levels of awareness about PHEV technology: some were very knowledgeable while others were new to the technology. In some cases, drivers of fleet vehicle PHEV conversions were not told that they were using a PHEV. Finally, a set of vehicles in this sample was used primarily to collect vehicle and battery performance data. These PHEV conversions were driven primarily on specific test loops according to established procedures. Drivers of these PHEVs were trained before using the vehicles and tended to have high levels of technical expertise.

While Table 1 lists a primary purpose for each vehicle, most vehicles served additional functions. For example, PHEVs that were used primarily for performance testing also served as fleet vehicles; in some cases, employees even took these vehicles home to test them during their commutes. Most personal vehicles and fleet vehicles were also subjected to some performance testing. Since PHEV technology is so new, virtually all PHEV owners were interested in collecting basic metrics such as fuel economy. However, the differing primary purposes of the vehicles illustrate the wide variety of drivers that are using today's PHEV conversions. Some of these individuals have deep technical knowledge and such strong belief in PHEVs that they paid for conversions with their own money. Others have little knowledge of PHEVs, and their first exposure to these vehicles came when climbing into the driver's seat.

This study is not a technical examination of existing PHEVs. Instead, it focuses on the drivers of these vehicles and their reaction to the technology. The intention of this report is not to critique the technical aspects of the three PHEV conversion configurations. However, it may be helpful for the reader to be aware of some basic differences in vehicle functionality.

All PHEV conversions in this study are based on the Toyota Prius. They can be divided into two groups: 1) EnergyCS and Hymotion conversions using Li-ion batteries and those independent conversions which used Ni-MH batteries, and 2) independent conversions that used Pb-A batteries. Vehicles in the first group store larger amounts of energy on-board than those in the

second. As a result, those in the first group provide larger amounts of all-electric range (AER), though they are still subject to the speed and acceleration constraints of their base Prius platform. PHEV conversions in both groups provide periods of higher fuel economy (called "enhanced boost mode" or "boosted range" by users in this sample) than the stock Prius. Again, those in the first group provide more than those in the second. For example, if driven conservatively at speeds below 34 MPH, EnergyCS vehicles can provide between 20 and 25 miles of AER. In contrast, conversions using batteries that store less energy, such as the less energy-dense Pb-A batteries, generally attain between 8 and 12 miles of AER.

Another difference between configurations is in driver instrumentation. Hymotion vehicles provided the driver no additional data on the status of the supplemental battery pack. Independent conversions tended to use CAN-view hardware to provide the driver with more information on electricity use and fuel consumption. Finally, the EnergyCS PHEVs included a separate display that provided the driver with detailed feedback on his/her energy demands.

3. Findings

This section outlines four main findings from interviews with PHEV users. It discusses users' feedback on PHEV design and AER, experience with on-board instrumentation, recharging behavior, and general expectations regarding PHEV technology. For each finding, implications and recommendations for future PHEVs also are included.

3.1. Blended or All-Electric?

A key question regarding PHEVs is how much all-electric range they should provide? However, there is any even more basic question: is AER even necessary? Some analysts view AER as a critical advantage of PHEVs. Yet Winkel *et al.* [10] note that a PHEV without AER would still deliver fuel economy benefits and could offer faster acceleration and higher top speed. They go on to suggest these would improve the marketability of such PHEVs over those with all-electric driving capability. This is because delivering quick acceleration and operation over a wide range of speeds in all-electric mode requires a larger electric motor as well as a battery with high power output. A PHEV that only operates in "blended" mode, in contrast, is constantly providing some propulsion power from its internal combustion engine, allowing the use of a smaller electric motor and decreasing the peak power requirements for the battery. As a result, a PHEV0 is likely to be less expensive than a PHEV offering AER and thus, for those consumers who place less value on AER, a more desirable option.

Today's PHEV conversions provide AER, but subject to the control strategy of their underlying Prius platform. Accelerating to speeds above 34 MPH, rapid acceleration, or use of the vehicle's climate controls can activate the Prius ICE; vehicle startup also requires the ICE in order to raise some emissions control equipment to proper operating temperature. In other words, today's PHEV conversions are limited in all-electric range (AER) and all-electric performance (AEP). Winkel *et al.* [10] observe that limiting all-electric acceleration and speed could be one strategy to achieve higher AER without adding more expensive components to PHEVs. However, consumers would have to be willing to accept slower acceleration times and reduced speeds in order to drive such a vehicle in all-electric mode.

3.1.1. Early Users' Thoughts on AER

In fact, that is precisely what many of the people interviewed for this study are doing. Most run their PHEVs on electricity as much as possible when driving conditions permit. One driver—who used his PHEV conversion primarily on city streets—proudly acknowledged driving all-

electrically for the majority of his trips, attaining an average gasoline-only fuel economy of over 800MPG. Many users were aware of the basic criteria needed to keep their vehicles in all-electric mode, and at least two-thirds of users had access to an electronic "EV button" that would manually place the vehicle in all-electric mode (assuming certain operating conditions were met). One driver even went as far as to pull over to the side of the road and shut his vehicle off when the ICE came on since this "reset" the vehicle and placed it back into electric mode.

Many drivers expressed a desire to have all-electric operation under a wider set of conditions than their PHEV conversions allowed: the most common request was for higher top speeds. One set of users envisioned PHEVs as a "surface-street-EV" that traveled on only electric power up to speeds of 45 to 50 MPH, thus allowing electric operation on all roads except highways and freeways. Another group of users wanted a PHEV capable of still higher electric speeds (60 to 65 MPH)—they wanted a freeway-EV that permitted all-electric highway cruising. Top all-electric speed is clearly an important characteristic for today's PHEV conversion drivers. Few commented on other related performance metrics such as acceleration times or passing power. It is likely they do have some underlying assumptions about these parameters that were not revealed in the course of these interviews.

Many also shared what they believed their ideal AER might be; responses ranged from 20 to 40 miles. Since most users in this study were not faced with a personal vehicle purchase decision, their AER demands were hypothetical—but informed by their experience driving the converted vehicles. The method they used to determine their desired AER offers some insight into how future buyers may determine their AER needs. Participants generally used a simple, easily accessible figure—their one-way commute distance—and most (if not all) assumed they would recharge both at home and at work. However, even among drivers with short commutes that could be accommodated by less AER, 20 miles of AER seemed to be the minimal acceptable amount. One user, who drove six miles to work and had recharging available at his office, nonetheless dismissed a PHEV with less than 20 miles of AER as a "joke." A few users did acknowledge interest in PHEVs with lower AER, but they explained AER below 20 miles was acceptable only in initial vehicles as manufacturers improved PHEV technology. For example, one driver characterized 10 miles of AER as an acceptable starting point for PHEVs, but not necessarily an ideal configuration as the technology matured, or the right amount of AER for his driving needs.

The value of AER is in its meanings as well as in its aesthetics and financial value. Heffner *et al.* [23] and Heffner, [27] found even brief all-electric operation was an important symbolic feature for those HEV owners whose vehicles offered this feature. The ICE shut-off at a stop, starting all-electrically from a stop, and regenerative braking—signaled to HEV owners their vehicles used advanced technology, consumed less fuel, and generated less pollution. While HEV owners did not calculate fuel cost savings or emissions reductions, each time their vehicles operated all-electrically, they were reminded of these ideas.

Similar symbolic meanings may be assigned to PHEVs and amplified because of their AER. The further they can drive a PHEV all-electrically, the more some drivers may associate their vehicles with high technology, environmental preservation, economic sensibility, and freedom from petroleum fuels—the same meanings that HEV owners attach to their vehicles. For example, one the people interviewed for this study explained how disappointed he was each time the ICE came on in his PHEV conversion during urban driving. For him, it was a signal that he had returned to using old "brute force" technology instead of clean electric drive.

Given participants' past experience with EVs, it is not surprising that they found AER an attractive feature. Three-quarters of the 23 participants had prior driving experience in an electric-drive vehicle and four still drove an electric-drive vehicle on a regular basis.[9] Past experience with battery electric vehicles (BEVs) in particular also explains why this group tended to characterize future PHEV designs as BEVs (either as a freeway BEV or as a surface street BEV). For many respondents, PHEVs represent progress away from conventional, internal-combustion powered cars toward a robust BEV. As one participant explained, PHEVs were "the missing link" between conventional vehicles and BEVs. While the HEV was really just "a regular old gas car with a few electric tricks," he saw a PHEV as a real electric vehicle. He was skeptical of blended-mode PHEV designs. Limited AER and AEP were necessary in the short run, he explained, but for him the eventual goal was for PHEVs to evolve into capable, robust BEVs.

3.1.2. The Blended Option

In fact, no participant envisioned future PHEVs as blended-mode PHEV0s, however, many did emphasize high MPG, a feature that can be delivered effectively by such designs. Today's Prius-based PHEV conversions deliver roughly twice the gasoline-only fuel economy of a conventional Prius. In side-by-side road testing of an unmodified Prius and an EnergyCS PHEV conversion, the Sacramento Municipal Utility District [25] reported average fuel economy of 48MPG and 98MPG, respectively. Like all vehicles, PHEV fuel economy depends on how the vehicles are driven. In addition, PHEV fuel economy is heavily influenced by how far the vehicle travels between charges. The vehicles driven by people in this study achieve higher fuel economy than a stock Prius only as long as the battery SOC is above the design minimum—at which point the vehicle reverts to its base Prius personality—a charge-sustaining HEV. Depending on configuration, today's PHEV conversions attain "boosted ranges" of between 20 and 60 miles. A driver who consistently makes trips within his/her boosted range and then recharges the battery from the electrical grid achieves much higher (gasoline-only) fuel economy than a driver who regularly exhausts the boosted range but continues driving before recharging. This makes sense: when a PHEV can blend in more electricity, it displaces more gasoline. But this feature of charge-depleting PHEVs makes predicting average gasoline-only fuel economy of PHEVs challenging. In the absence of adequate consumer data, assumptions are made not only about how a PHEV is used, but also about both the frequency and timing of recharging events.

Nearly all drivers in this study knew the fuel economy of their PHEVs: average reported MPG for the 15 vehicles ranged from 55 to 98 MPG. However, only one user offered an overall measure of energy use that included both gasoline and electricity. As noted earlier, the PHEV uses two energy sources and a total "energy economy" number must account for both. Yet all drivers but this one omitted their grid-based electricity use when discussing fuel economy. This was even the case among drivers of EnergyCS vehicles, which are capable of displaying both electricity and gasoline consumption (see the following section on driver instrumentation). These early users of PHEVs may think about their vehicles' fuel use in the same way that they think about the fuel use of a conventional vehicle. While users know they are using electricity when they drive, they are accustomed to measuring vehicle fuel economy using a metric (MPG) that captures only part of the PHEV's total energy consumption.

Many drivers cited a fuel economy number of 100+ MPG, and in some cases advertised this on their vehicles. One driver explained that while 100MPG was higher than he achieved in his

[9] Three participants regularly drove BEVs, and a fourth drove a fuel-cell electric vehicle (FCV).

Box 1: Emily Williams, Electric Utility Employee
2005 Prius, converted 2006 (EnergyCS)

Emily Williams had her first experience driving a PHEV conversion in the spring of 2006. At that time, her employer had just taken delivery of a converted Prius that it planned to use as part of a PHEV technology performance testing program. When the vehicle wasn't being tested, it was made available to employees for business use. Emily, who was scheduled to attend an out-of-town conference was selected to use the PHEV for her trip. While Emily was not an expert in advanced vehicles, she had driven BEVs in the past, and was curious about what it would be like to drive a PHEV.

As she began her trip to the conference site, Emily initially was overwhelmed by the PHEV's instrumentation. She had never driven a Toyota Prius before, and she had difficulty even locating the speedometer at first. But as she drove, Emily became more comfortable and began watching the fuel economy displays. Her EnergyCS conversion had an additional display mounted on the dashboard, but Emily focused mainly on the Prius multi-function display (MFD). She tracked her fuel economy and the amount of regenerated energy. Gradually, Emily tailored her driving using feedback from the MFD and enjoyed pushing her fuel economy higher as she drove. On downhill portions of the trip, Emily shifted the PHEV into regeneration mode and was excited to see the graph bars grow on the MFD's energy consumption screen. When driving uphill, she tried to accelerate carefully, and was disappointed when the internal combustion engine came back on. When she reached the conference site, she plugged in the PHEV outside of her hotel. Unlike the EVs she had driven in the past that required special recharging infrastructure, Emily characterized the PHEV as a "little miracle" since it could recharge using any conventional outlet.

After several days and a few hundred miles of driving, Emily attained what seemed to her to be "astronomical" fuel economy: 98 MPG. She was sold. She figured she wouldn't purchase too many more cars in her life, and confidently declared, "my last car is going to be a plug-in hybrid." For Emily, the PHEV represented "the complete solution:" it could cut emissions, reduce the country's dependence on foreign oil, and save its owner money, plus it could be driven just like a conventional vehicle, including on long trips. As Emily thought about owning a PHEV in the future, she imagined a vehicle that provided higher AER and AEP than the Prius conversion she had driven. Emily really wanted a PHEV that would operate all-electrically at faster speeds, perhaps as high as 60 MPH. Emily also thought that the PHEV should have 40 miles of all-electric range, which she guessed would allow most people to commute all-electrically. With that type of vehicle, she estimated that all of her own travel—except for long trips—could be handled in electric mode. Even a full day of shopping, during which she might drive to several area stores or malls, seemed likely to her to involve less than 40 miles of travel.

To Emily, the PHEV seemed so much better than other vehicles. Hydrogen fuel cell vehicles were interesting to her, but she was concerned that large amounts of energy were needed to make hydrogen. BEVs just didn't seem practical: they were fine for local travel, but required that their owners keep a conventional vehicle—a "backup car"—to be used on long trips. Even HEVs didn't appeal to Emily. After driving the PHEV, HEVs like the Toyota Prius and Honda Civic Hybrid seemed to barely be an improvement over conventional vehicles: "They don't really do what they are supposed to do," Emily complained. To her, HEVs did not make much of a contribution toward cleaner air or reduced petroleum consumption. For Emily, exposure to the PHEV made other vehicle technologies obsolete, and she determined to continue driving a conventional vehicle until PHEVs became available.

PHEV conversion, it seemed to resonate with people in a way that lower numbers (including 99.9) did not. Indeed, the 100+ MPG claim is true to some extent. Today's PHEV conversions regularly attain gasoline-only fuel economy of over 100 MPG under the right conditions. Drivers of the EnergyCS vehicles (which are equipped with displays that show MPG with three digits to the left of the decimal point instead of two as in the stock Toyota MFD) reported often seeing triple-digit fuel economy readings. These drivers described the excitement they felt when they saw such high fuel economy, especially when they saw it while cruising at freeway speeds. Drivers' descriptions of this experience as "astronomical," "amazing," and "very cool" hint that there is more at work than simply using less gasoline. For more detail on one PHEV driver's reaction to her vehicle's high fuel economy, see Box 1.

High fuel economy, particularly numbers over 100 MPG may be valued more for there symbolism than for their marginal financial value. Seeing 100+ MPG on the fuel economy display, even if briefly, may signal to drivers that the vehicle has important qualities: it is unique, environmentally-friendly, and financially-sensible. High MPG is also important since it provides a basis for comparison with conventional vehicles. The typical American carbuyer has never owned a BEV or HEV, and thus is unfamiliar with all-electric driving. MPG, in contrast, is a relatively familiar measure. For owners of conventional vehicles, high MPG may be the single most important way to understand PHEVs—a key symbol for those with no BEV background.

However, there is a symbolic meaning that blended-mode PHEV0s cannot access as effectively as PHEVs with AER: freedom from gasoline. Numerous drivers in this study discussed this meaning: they envisioned driving a PHEV all-electrically for local travel and using the gasoline engine only for longer, out-of-town trips. As one driver explained, "you can drive electrically most of the time, and put in gas when you're going to take a [long] trip." Another expressed a similar PHEV vision, noting that with such a vehicle she would "not go to the gas station at all." The association of PHEVs with the meaning of freedom from gasoline has not only been made by these PHEV drivers. Articles in the press (for example, see EV World [29]) describe PHEVs as gasoline-optional hybrid vehicles (GO-HEVs) that allow drivers to skip gasoline refueling under most travel conditions. For numerous respondents in this study, independence from gasoline was a powerful meaning that fueled their excitement about PHEVs. To attain this meaning, PHEVs must be designed to operate as freeway-EVs during charge-depleting operation, adding both expense and complexity to their design. However, a PHEV that requires no gasoline for local travel has much clearer and stronger association with independence from petroleum than existing HEVs, and this meaning may be important for consumers in differentiating the two types of vehicles.

3.1.3. Offering Blended and All-Electric Options

The people interviewed for this study are clear: they want larger amounts of AER and greater AEP than offered by the converted vehicles they drove. While these requests come from a group with extensive electric vehicle experience, they should not necessarily be ignored since other early buyers of PHEVs may share these views and past experience. However, manufacturers and policymakers should be careful to not yet limit the designs and ideas about PHEVs to those that appeal to this group. At one extreme, some people may see greater value in a PHEV0 that has a lower purchase price and attains very high fuel economy but offers no AER. At the other, some people may be strongly motivated by the symbolic meanings of PHEVs and prefer a one with higher AER than any technical analysis would ever conclude is cost effective. Additional research is needed in this area to understand how consumers will respond to various PHEV

designs and capabilities, including a blended-mode PHEV0.[10] Such research must also include a deeper examination of symbolic meanings associated with particular PHEV designs, and an assessment of how these meanings relate to consumers' identities. Ultimately, the solution may be to offer PHEVs in a variety of configurations. Just as today's vehicles are available with a choice of engines, a future PHEV might offer a variety of AERs at different price points, each appealing to a different segment of car buyers.

3.2. Driver Instrumentation

Many of today's PHEV conversions present detailed information to the driver about how energy is used. Unmodified HEVs typically display instant fuel economy information to the driver (in MPG for U.S. vehicles). Some, like the Toyota Prius, provide more detailed information about fuel economy and energy use. The Prius multi-function display (MFD) is shown in Figure 2. The stock MFD includes two screens that include fuel economy information: an Energy Monitor that shows current MPG and diagrams the flow of mechanical and electrical energy in the hybrid powertrain, and a Consumption Summary that shows current MPG, average MPG over a specific distance, and recent regenerated energy. Drivers who are not interested in this information can switch off the MFD or use it to display information related to other vehicle functions, such as climate control. Nearly all the Prius PHEV conversions in this study had instrumentation in addition to the stock MFD. The exceptions were the two Hymotion vehicles, which retain the unmodified MFD. Most independent conversions incorporated the CAN-view display from Hybrid Interfaces, a multi-screen unit that can be displayed by the existing MFD or shown on an additional LCD display. Figure 3 shows one screen from such a unit. In addition to providing information on numerous parameters related to battery and engine performance, this display also includes fuel economy data, including historical and current MPG. Unlike the stock MFD which can display fuel economy between 0 and 99.9 MPG, the CAN-view is capable of displaying fuel economy numbers over 100 MPG. It also shows users when their vehicles are operating in all-electric mode and, for some vehicles, provides an "EV button" that the driver can use to request all-electric operation.

The most comprehensive energy and fuel economy data is provided in the EnergyCS conversions. These PHEV conversions include an additional dashboard-mounted display unit that showing a variety of performance parameters, including customized data about the PHEV battery pack. The EnergyCS display provides multiple screens: one is shown in Figure 4. Like the CAN-view unit, the EnergyCS display is capable of showing MPG over 99.9 MPG, tells users when they are operating in all-electric mode, and allows users to request all-electric operation. In addition, the EnergyCS unit provides a graphical display of the driver's power requests and their effect on the vehicle's use of electricity and gasoline. For example, while in all-electric mode drivers can use the display to moderate throttle inputs to keep the vehicle in all-electric operation.

3.2.1. Instrumentation and PHEV Drivers

The instrumentation in today's PHEV conversions serves as both a tool and symbol. One of its roles is to remind users that they are driving a new type of vehicle. To a skilled observer, it may seem obvious that a PHEV is distinct from an HEV. However, for the typical driver today's PHEV conversions offer few clues to differentiate themselves from unmodified Priuses. Most PHEV conversions in this study have some type of exterior signage identifying themselves as

[10] Winkel *et al.* [10] note that previous consumer studies such as those by EPRI [4] did not include a blended-mode option.

Figure 2: Toyota MFD Energy Monitor Screen

Source: Toyota Motor Sales [30]

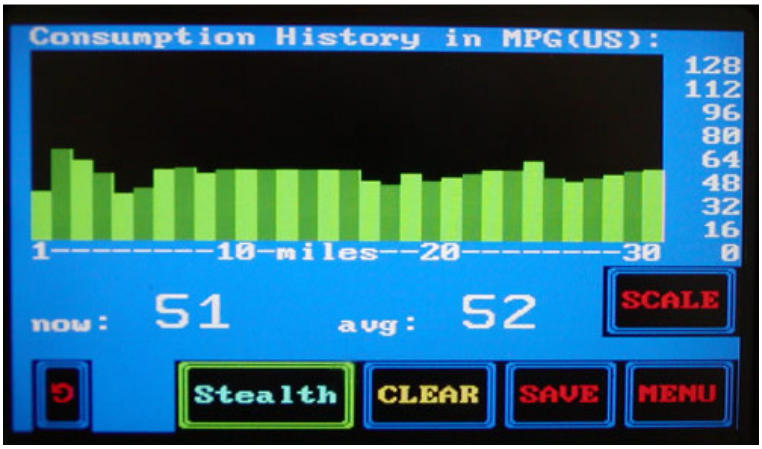

Figure 3: CAN-view Source: Hybrid Interfaces, [31]

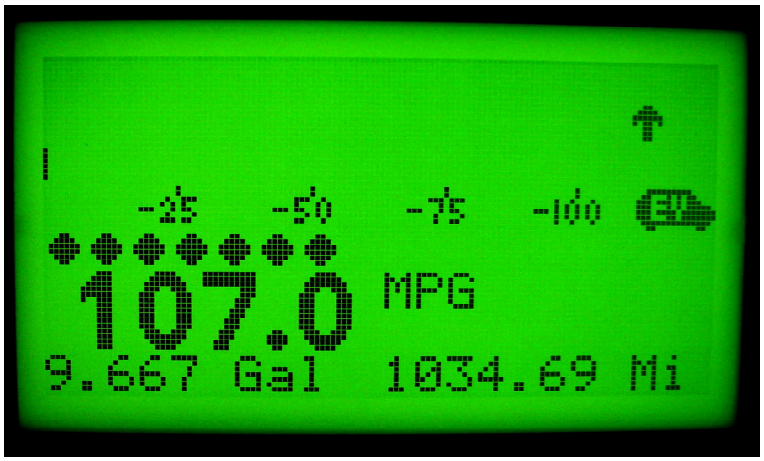

Figure 4: EnergyCS Display

Source: California Cars [32]

PHEVs, but otherwise the only unique exterior features are a small charging receptacle on the rear bumper and, in some vehicles, additional vents for battery cooling. Inside the vehicles, drivers have no indication that they are driving a PHEV except in those cars that included additional displays or modifications to the MFD. In one Hymotion vehicle that served as a fleet vehicle, the only distinction drivers had from a conventional Prius was a note affixed to the dashboard reminding them to unplug the vehicle before leaving the parking lot. Even the driving experience was not different enough for many drivers to tell the difference between the PHEV conversion and an unmodified Prius. As one user of an EnergyCS conversion explained, "if no one told you, you would never know it was a plug-in hybrid." Installing instrumentation that includes feedback on gasoline and electricity use is one way to differentiate PHEVs and to alert and remind drivers that they are in a new type of vehicle.

Instrumentation can also provide PHEV drivers with feedback that allows them to maximize their fuel economy. Most drivers in this study monitored their fuel economy as they drove, a skill they developed in past experience with conventional HEVs. One driver characterized his CAN-view as a "great training tool" that was constantly instructing him how to extract the most fuel economy from his PHEV. Another confessed to watching his vehicle's instrumentation closely and "playing the fuel economy game" as he drove. Like these drivers, consumers who buy PHEVs in the future are likely to care about higher fuel economy, so it makes sense to provide tools that will help them attain it.

Drivers in this study emphasize that instrumentation design is important. Several were concerned the displays in these conversions were too complex. A few acknowledged making mistakes using the displays/interfaces. Drivers of two vehicles inadvertently shut off the battery packs pushing the wrong button on the display (which also acted as an interface to PHEV functions); another driver reported unintentionally adjusting the emissions mode of his PHEV in a similar way. The EnergyCS and CAN-view displays are designed for a technically competent user; future instrumentation will have to be accessible to all drivers.

In addition to serving as a tool for drivers who wanted to maximize their fuel economy, the instrumentation in this study's PHEVs also had a different significance for numerous drivers. Many drivers were excited when their vehicles attained 100 MPG and higher, even if this lasted only briefly. For many, 100+ MPG signals performance they never thought was possible in an ICE-powered vehicle. "It's just amazing to drive at freeway speeds and get 100 MPG," explained one participant. For others, seeing 100 MPG on the fuel economy display serves as a tangible reminder of their vehicles' reduced greenhouse gas emissions or low consumption of imported petroleum. The excitement drivers feel when experiencing such high fuel economy cannot be explained simply by the marginal value of fuel cost savings. Instrumentation affirms the connection between PHEVs and other significant ideas. Many of these ideas are the same denotations found to be associated with HEVs: preserving this environment, providing less support to oil companies and overseas oil producers, and accessing new technology (Heffner *et al.* [21]; Heffner [24]).

While many drivers reported driving to maximize fuel economy, there were a few drivers who ignored the fuel economy displays. One of these drivers explained that while he believed in the promise of PHEVs, he was skeptical that the average carbuyer would change his driving habits to get better fuel economy. Rather than carefully watching the fuel economy display, he simply "drove the PHEV like a normal vehicle" at freeway speeds. His resulting fuel economy was not much better than a more careful driver would get in a conventional HEV, but he felt he had

conducted an important test. “Plug-in hybrids have to function like normal cars, or they won’t be widely accepted,” he claimed.

This driver’s behavior illustrates an important point: the efficiency of PHEVs varies significantly depending on how the vehicles are driven. Driver behavior therefore, is an important component that must be better understood when assessing the environmental and energy use impacts of PHEVs. This driver also demonstrates that instrumentation is not a panacea. Regardless of how much information they are given about fuel economy or energy consumption, some drivers will maintain their old driving habits.

However, instrumentation can play an important role in making efficiency “real” for some drivers, and can cause them to drive more carefully than they otherwise would. One participant explained that he paid greater attention to efficiency when driving his PHEV conversion than when driving his BEV. Maximizing energy efficiency might seem to be more important in a limited range BEV, however, he explained that he drove the PHEV conversion more carefully because it gave him direct feedback about his energy use while his BEV did not.

3.3. Recharging Behavior

A key issue in predicting the environmental benefits and fuel savings from PHEVs is the frequency and timing of recharging. With no data available on consumers’ PHEV recharging behavior, previous analyses have relied on assumptions. For example, the Society of Automotive Engineers Recommended Practice (SAE J1711) covering HEV and PHEV fuel economy assumes that PHEV owners have a 50 percent chance of charging their vehicles on a given day. In their analysis of SAE J1711, Gonder and Simpson [2] argue once-per-day charging is more likely. Gonder and Simpson’s reasoning is based on economic incentives: per-mile fuel costs for the PHEV will be lower if operated on electricity. PHEV owners, therefore, will have an incentive to drive on electricity and recharge often, even multiple times per day if possible.

3.3.1. Drivers’ Willingness to Plug In

Among PHEV drivers in this study, frequent recharging is common: 12 of the 15 vehicles were regularly plugged in multiple times per day. In fact, owners of nine vehicles reported plugging them in whenever possible; some organizations required their fleet vehicles to be plugged in anytime they were not being driven.[11] Many participants explained that since they were driving a PHEV, they wanted take advantage of recharging. Since all of the PHEV conversions in this study could recharge using a common, 110-volt (110V) 20-amp household outlet, the number of potential recharging locations was large. The majority of vehicles (80 percent) were recharged in multiple locations that drivers visited regularly such as their workplaces and homes. A smaller number of vehicles were also opportunity charged at other locations, including friends’ homes, hotels, and offices visited during the workday. Owners of independent conversions tended to conduct the most ambitious opportunity charging since their Pb-A batteries provided the shortest boosted range. One participant had learned the importance of regular recharging with his previous vehicle, a BEV conversion. He carried a 50-foot extension cord with him in his PHEV and plugged in at home, at work, at friends’ houses, and even on the street where outlets were available.

[11] Of these vehicles, six were EnergyCS conversions. Owners of EnergyCS vehicles were advised to keep the vehicles plugged in as much as possible to maintain the condition of the battery pack. The charging behavior of these vehicles’ owners may have been different if they had not received this advice from their conversion provider.

Numerous drivers mentioned the ability of PHEVs to reduce gasoline costs, that in general running their vehicles on electricity was less expensive than fueling them with gasoline, and associated PHEVs with the idea of saving money. One participant explained that recharging regularly maximizes the "extra efficiency that you paid for." Another predicted, "anyone who would pay for a PHEV is going to plug it in, it just makes economic sense." Many also felt that cost savings would be the most appealing aspect for the average carbuyer. One driver explained that he did not believe everyone was interested in the PHEV's environmental benefits, but the "pain in the wallet" caused by rising gas prices seemed to be a universal concern PHEVs could reduce. Another agreed with this idea, saying that he emphasized cost savings when talking to the public about PHEVs. Rather than discussing details about the PHEV's battery, he explained the benefits of having "a second fuel tank that can run the car for [a few] cents per mile."

However, it is not clear that today's PHEV owners recharge everyday because, as Gonder and Simpson [2] suggest, it saves the most money. Most drivers did not calculate the cost savings from operating their PHEV conversions electrically, nor did they compare lower operating costs with initial purchase and conversion prices to determine a payback period. Those drivers who did analyze their operating expenses discovered that their PHEVs delivered only modest cost savings. For example, one owner of an independent conversion estimated that he had saved $8.00 in 3,000 miles of driving. Some drivers did mention the potential for greater fuel cost savings in the future. For example, one participant predicted that continued rising gasoline prices would make electricity an increasingly attractive fuel for PHEVs, eventually allowing her to "save big bucks at the gas station." She and other drivers who talked about future savings were thinking beyond today's Prius-based PHEVs to new configurations with greater AER and AEP. These participants envisioned PHEVs that covered 80 percent or more of their miles in all-electric mode. But even these drivers did not have specific cost savings in mind, and none had calculated an estimate of future fuel cost savings.

In this way, PHEV drivers are similar to many HEV owners who associated their vehicles with saving money even though they had not performed the financial analysis to confirm this belief (Heffner *et al.* [23], Heffner [27]). PHEV users know the vehicles can be operated for less money using electricity rather than gasoline, and the *idea* of saving money is what matters to them. Quantifying savings is less important, as is comparing ongoing fuel cost savings to other costs such as purchase price, maintenance, insurance, or other household expenditures. Like HEV owners, PHEV drivers also associated driving all-electrically with other symbolic meanings, including reducing air pollution, emitting fewer greenhouse gases, consuming less imported petroleum, and using a high-technology product. Since plugging in enables driving electrically, it also enables access to these important meanings. The same applies to PHEV conversion owners' purchase decisions. Only a handful of these drivers actually owned their PHEV, but those who did pay for their own conversions were not interesting in saving money. (For the story of one independent PHEV owner's reasons for converting his vehicle, see Box 2).

Past studies often assume that consumers will pay more for technologies that increase fuel economy only if the initial cost of these technologies is offset by fuel cost savings during a specified period of time, known as the "payback period" (for example, see National Research Council [33]). Kurani and Turrentine [34] find that few consumers of conventional vehicles actually perform payback computations when purchasing any type of vehicle. There is no question that widening the gap between electricity prices and gasoline prices will make PHEVs more financially attractive. But policymakers and marketers should be careful not to overemphasize the importance of the payback period. U.S. sales of HEVs climbed to 250,000

units in 2006 despite continued insistence by some analysts and automakers that the vehicles do not make financial sense for consumers (for example, see Edmunds.com [35] and White [36]). For drivers in this study, PHEVs were more than just a way to save money, and it is likely that other carbuyers will see additional value in PHEVs beyond their financial effects.

3.3.2. Drivers' Skepticism About Plugging Out

Another indication that PHEV drivers were not primarily interested in financial payback was that few raised the possibility of generating revenue by selling electricity back to the electricity grid. Vehicle-to-grid (V2G), in which electric-drive vehicles provide power to the electricity grid, have been proposed as one method to offset the additional costs of PHEVs (for example, see Kempton and Tomic [37]). Participants were not prompted to discuss V2G. The drivers who did raise the topic were mostly employees of electric utilities, and viewed V2G as impractical.

One driver who did express interest in connecting his PHEV to the grid was not interested in selling electricity. Instead, he was excited by the possibility of providing electricity to his home during electricity outages. He felt that the ability to provide such backup power could be an important selling point for PHEVs.

3.3.3. Recharging Problems

While most drivers charged their vehicles frequently, two drivers in this study had difficulty plugging in on a regular basis. Each of these drivers used a PHEV conversion as a personal vehicle. Because they could not regularly recharge, their PHEV conversions performed as unconverted Priuses. While most vehicles in this study were plugged in at night, nighttime charging was not feasible for these two drivers. One frequently had his PHEV conversion on overnight trips away from home; the other was home each evening, but parked her vehicle on a public street without access to an electrical outlet. Daytime charging was also challenging for these drivers since both typically traveled to various destinations throughout the business day. One was able to recharge at her office for an hour or two each day, but this was not enough to fully recharge the battery.

The experiences of these two drivers suggest that recharging is more complicated for people who lack a "home base" for recharging their PHEVs. In this study, the vehicles that were plugged in most often were those that made short trips (less than 40 miles) and regularly returned to a single location where recharging was available. The further a vehicle's use patterns deviates from this model, the more challenging it may become to recharge it.

Operating a PHEV as an HEV for extended periods raises of few other potential problems. The two users confirmed that some of today's PHEV conversions' battery packs could experience failures when they remain undercharged for long periods of time. This is another technical issue that must be addressed before PHEVs can meet users expectations of them as fuel-flexible vehicles.

Infrastructure improvements may be one solution to the problems experienced by the two drivers described above. It is unclear whether these two drivers were unable to opportunity charge at other locations where they parked their vehicles, including hotels and offices. It is also possible these drivers were wary of opportunity charging. As other drivers explained, opportunity charging was not always easy. Asking hotel clerks, parking attendants, or property managers for permission to plug-in often resulted in confusion and skepticism. Plugging in without permission

Box 2: Alan Young, Private PHEV Owner
2005 Prius, converted 2006 (PiPrius)

In the fall of 2005, Alan Young bought a Toyota Prius. He already owned a BEV, a conventional vehicle that he had converted with help from local BEV enthusiasts. Alan loved his BEV, but it wasn't always the most practical vehicle. Its limited range meant that he was often "stranded" away from home while it recharged, and careful planning was required to successfully handle his 40-mile round-trip work commute. Alan's Prius offered more reliable transportation, and at the time of his purchase Alan was already imagining a way to make it even better. Months earlier, he had read an article about PHEVs and was intrigued by the concept. To Alan, the PHEV seemed like the "best of both worlds." Much of his driving (perhaps 50 to 80 percent) could be done electrically, but he also would never be stranded as he often was in his BEV. A year after buying his Prius, Alan decided to convert it to a PHEV.

For a private individual, the cost of a PHEV conversion is considerable, and Alan found he had to sell his BEV to afford the PiPrius conversion kit. But for Alan, the expense was worth it. He was thrilled with his new PHEV, describing it as "infinitely better than an EV." Like his BEV, the Prius PHEV could operate all-electrically—under the right conditions—and Alan tried to keep his PHEV in electric mode as much as possible. He also drove to maximize fuel economy, using a CAN-View unit to provide him with fuel use information and feedback on his driving style. Even with the majority of his driving on the freeway, Alan was averaging 60 MPG, roughly a 20 percent improvement over his previous mileage in the Prius. Part of Alan's strategy to maximize mileage was to recharge his vehicle as often as possible, plugging in wherever and whenever he could. Typically, he charged at home in the evening and at work during the day. In addition, Alan charged opportunistically, carrying an extension cord in his trunk to connect his PHEV with outlets wherever he parked, including at friends' houses. Alan recalled one occasion when plugging in at a friends' condominium had caused a confrontation with the property manager, who accused Alan of "stealing energy." Alan was amused and calmly explained to his accuser that, at current rates, it cost just fifty cents to fully charge his PHEV's 5 kWh battery pack.

For Alan, the PHEV was mainly about the environment. He explained that he "feel[s] pride in leaving a better carbon footprint" and in doing his part to reduce fuel use. The denotation of advanced technology also played a role. Alan explained how his BEV had made him feel like a "maverick," as his PHEV also linked to the idea of personal uniqueness. In addition, Alan indicated that his PHEV was a statement to automakers. To Alan, automakers seemed intent on selling inefficient trucks that most buyers didn't really want. Recently, he had watched the Superbowl on television and recalled that many of the advertisements were for large pickup trucks and SUVs. But Alan hoped that at some point in the future, automakers would embrace PHEVs, and television advertisements would showcase PHEVs rather than pickups. Yet Alan was realistic about the future of PHEVs. He recognized that many people would not buy a PHEV simply because it was better for the environment. While saving money was not a factor in his own purchase, he guessed that finances would figure more prominently in the purchase decision of the average carbuyer. Unless gas prices rose and PHEV prices dropped, Alan was unsure if many households would really be interested in buying PHEVs.

sometimes drew the angry attention of property owners. See Box 3 for a story of one PHEV conversion driver's adaptation to recharging only at work.

Part of what makes developing PHEV charging infrastructure easy is that today's vehicles recharge using widely available 110V circuits. However, some of today's PHEVs also permit rapid recharging on higher-voltage circuits. Several owners reported occasionally "fast charging" their vehicles, usually on a 220V household circuit.[12] The ability to recharge in less time would have solved the problem of one of the PHEV drivers who had recharging issues since her vehicle was parked at her office for a couple hours each day (assuming her employer was willing to install a higher voltage outlet for her vehicle). Rapid charging was not a priority for most drivers in this study; most were satisfied with 110V recharging. However, this example illustrates that for some PHEV drivers, rapid charging is important. In addition to providing 110V charging, future PHEVs may want to offer higher-voltage rapid charging as an optional feature.

3.3.4. Timing of Day of Recharging

Studies assessing the impact of PHEVs on the U.S. electric grid generally assume these vehicles will charge only during periods of off-peak power demand (for example, Kintner-Meyer *et al.* [14]). In this study's sample, nearly all vehicles were regularly charged during daytime business hours. Since owners of the eight EnergyCS vehicles were encouraged by the converter to keep their vehicles plugged in when they were not being driven, their daytime charging habits were likely influenced by guidance from their converter and may or may not represent future PHEV recharging behavior. However, among the remaining seven PHEVs, six were also plugged in as often as possible during the day. This result is not surprising given that many owners were not subject to time-of-day electricity rates, and therefore did not incur higher costs when recharging during peak electricity demand periods. Several drivers did acknowledge concern about exacerbating peak electricity demand. At least one driver intentionally delayed recharging his vehicle until late in the evening. But generally, participants did not voice strong concerns about the ability of the electrical grid to handle the additional load of PHEVs. This small sample of drivers of PHEV conversions shows that when drivers have the capability to refuel from the electricity grid and (as for many of these people) do not personally face the different costs of doing so, they recharge most any time. Various methods have been proposed, including time-of-use rate schedules, timers, and smart meters to discourage vehicle recharging during peak times.

3.4. Evaluating Electricity as a Fuel

As mentioned earlier, the environmental benefits of PHEVs vary depending on their source of electricity. Numerous participants were aware of this issue and talked about how their electricity was generated. In particular, drivers of PHEV conversions in the Northeast and Midwest noted that much of their electricity came from coal-fired plants. These drivers regularly claimed to members of the public that PHEVs using electricity from coal were cleaner than conventional vehicles, since large plants could generate energy more efficiently and offered a single point where pollution control technology could be applied. Nonetheless, some PHEV drivers were uncomfortable with connection between their clean vehicles and coal-generated electricity. For example, one Midwestern PHEV owner purchased renewable electricity from its local utility and

[12] Although drivers in this study referred to it as "fast charging," 220V/50A charging was referred to as normal charging during the development and deployment of recharging infrastructure for battery electric vehicles during the 1990s.

Box 3: Steve Anderson, County Employee
2005 Prius, converted 2006 (PiPrius)

Steve Anderson first heard about PHEVs at a solar energy conference in late 2004. At the time, he didn't have any first-hand experience with hybrids or electric vehicles, but he was immediately interested in the PHEV concept. Steve, who led his county's economic development efforts, began researching PHEVs and searching for ways to acquire one. Two years later, Steve was granted approval by his county to purchase a used Toyota Prius. With help from engineers at a local college, he converted it to a PHEV using a PiPrius conversion. The vehicle was one of the first PHEVs owned by a government agency, and Steve was proud to be an early PHEV user.

Steve and his assistant used the PHEV mainly for work-related trips during the business day, although Steve also commuted to and from home in the vehicle occasionally. Whenever the PHEV was parked at Steve's office, it was plugged in to recharge its 3.5 kWh lead-acid battery pack. Generally, Steve recharged the car only during the business day. At night, he disconnected the vehicle since he was concerned that charging problems might occur while the office was closed and the vehicle was unattended.

While driving the PHEV, Steve did his best to keep the vehicle in all-electric mode as much as possible. Nominally, his PHEV had 10 to 12 miles of AER, but Steve had found that he generally could drive 4 to 5miles electrically before the internal combustion engine started. For Steve, driving all-electrically meant that his fuel economy numbers would increase. As he drove, he watched the fuel economy reading on his CAN-view unit. Steve confessed that when he first had his PHEV, his numbers hadn't been so impressive. But the CAN-View had proved to be a "great training tool," and as Steve changed his driving habits, his in-town mileage rose to between 85 and 100 MPG. Like many PHEV drivers, Steve was captivated by the idea of attaining 100 MPG or more. "Our transportation fuel is in jeopardy," Steve explained, and vehicles with dramatically higher fuel economy seemed to be an important step toward a more sustainable and reliable transportation system. Steve felt the 100 MPG idea resonated with others too, and stickers on the outside of his PHEV told onlookers that the vehicle was capable of "100+ MPG."

For Steve, part of the PHEV's appeal was its high technology image. Steve's county was in a rural area that was trying to broaden its economic base beyond agriculture. High-technology firms were beginning to show interest in relocating to the area, and part of Steve's strategy to attract them was to demonstrate that the county's leaders had technology vision. The companies Steve was courting were not automotive component manufacturers, but he figured that by purchasing a PHEV, the county defined itself as technology-savvy in general, "a place where new technology can be embraced." Steve also thought that the PHEV appealed to many of the county's residents who (he believed) saw the vehicle as it was being driven around the area. Steve imagined that, to them, the PHEV signified saving money and addressed the "pain in the wallet" that he imagined they felt each time gas prices rose. Steve also explained that many residents were political conservatives who were likely to be motivated by concerns about energy security. Steve guessed that for these residents, the PHEV represented an end to the situation in which we "hold ourselves hostage" through over-reliance on overseas petroleum.

It was these meanings that made the PHEV exciting for Steve. Most of his economic development work was so specialized that friends and family rarely asked about the details. But the PHEV was different. Members of the general public (especially young people) were interested in the car, and seemed to easily understand the bigger implications PHEV technology could have on transportation. "PHEVs are hot," Steve explained, and it felt good to be part of something that had so much appeal among residents in his community.

proudly displayed an image of a wind turbine on the side of its PHEV. Even among PHEV drivers who recharged their vehicles with relatively clean electricity, the appeal of renewable electricity was strong. Two owners were planning to add solar panels to their homes' roofs to recharge their PHEVs, and several others responded enthusiastically to this idea.

Financial benefits from PHEVs also depend on using electricity as a fuel—so long as electricity remains a less expensive option than gasoline. Respondents appeared near universal in their belief that gasoline prices would continue to increase, thus increasing the future fuel cost savings of driving on electricity. Though seldom explicitly discussed, respondents appeared to assume that electricity would remain either constant in price, or would increase in price more slowly than gasoline.

Access to important symbolic meanings, and thus important sources of value, of PHEVs appears to be through electricity as transportation "fuel" and the aesthetics of electric-drive vehicles. "Substituting for," "reducing," and "getting off" gasoline and similar phrases are repeated throughout the interviews. Gasoline is viewed as "old technology," "dirty" and "polluting," while "quiet," "smooth," "silent," were offered to describe the sensation of driving in all-electric mode. Even conventional HEVs come off poorly in this comparison for some respondents. The location of PHEVs between a gasoline past and an electric future strongly indicates and illustrates people who are accessing their view of a more desirable future. According to McCracken [38], people may locate their ideals to an "…almost infinite number of locations on the continua of time and place…" if they are not attainable in their current reality. The future is a popular choice: individuals often look forward to a time in the future when their ideals will be realized. That future can be described in terms of how the world will be and who the respondent will be. Thus not only is the world imagined to cleaner, less dependent on oil, and safer, but the person may see them self as a pioneer, a progressive, an involved community member, and as a smart consumer.

4. Discussion

4.1. Where are we with PHEVs?

In the past few years, numerous organizations have begun to lobby policymakers, automobile manufacturers, and the public about PHEVs. Their efforts, combined with coverage of PHEVs in the popular press, have made many Americans aware of the new technology. Wall [39] claims that over 75 percent of the U.S. public now has heard of PHEVs. Several of this study's drivers commented on the "buzz" that surrounds PHEVs and a few acknowledged actively promoting the PHEV concept. In general, today's PHEV drivers are enthusiastic about the technology and believe it has significant potential. However, many are pragmatic when discussing the future market for PHEVs. The most common view was that the financial argument for PHEVs needed to improve considerably before widespread purchases would occur. Currently, aftermarket PHEV conversions can nearly double the base price of the original vehicle. Clearly OEM manufacturing can reduce this cost. But participants also felt that fuel prices would play a major role in affecting the public's interest in PHEVs. "$6/gallon gas would change a lot of minds," opined one participant. Even among private owners of PHEVs, this view was common, although these owners acknowledged that their own decisions to acquire a PHEV were not motivated by any potential for cost savings.

4.2. Long-Term Reliability of PHEVs

PHEV drivers in this study discussed the reliability of their PHEV conversions. While the majority of respondents expressed interest in driving a PHEV as their personal vehicle, at least one voiced caution about the state of the technology, saying that he would likely delay his purchase of even a mass-marketed OEM PHEV until the second or third production year to avoid buying a vehicle that might have unresolved or unknown problems. In fact, numerous vehicles in this study experienced technical problems; four vehicles had severe issues including failures of battery modules, on-board chargers, and electrical connectors. Some of these issues often persisted for weeks and prevented the use of the vehicles as PHEVs. At the time these interviews were conducted, two owners were operating their PHEV conversions as HEVs due to failures in the PHEV systems, and a third owner declined to participate because his PHEV was not functioning.

Another important consideration is that nearly all of the PHEV conversions in this study have been on the road for less than one year. In that time, they have generated valuable real-world data on battery and component performance. However, these vehicles don't yet tell us about what may happen in the long-term. In particular, key questions remain about the expected life of PHEV batteries that cannot be answered simply by looking at past experience with HEVs. Part of the uncertainty is due to the use of a battery chemistry that has not previously been employed in motor vehicles. Today's HEVs use Ni-MH batteries, but the most appealing battery chemistry for future HEVs (including PHEVs) is currently Li-ion. In this study's sample, two-thirds of the vehicles used Li-ion batteries. In the long term, Li-ion promises higher gravimetric and volumetric energy densities at lower cost than existing technologies. But technical issues (including thermal management) remain, and additional testing of Li-ion batteries in motor vehicles is needed to determine the actual performance potential of the technology.

A second source of uncertainty is rooted in the higher demands PHEVs place on their batteries than do HEVs. Today's HEVs maintain their batteries within a relatively narrow SOC window to maintain battery life. This has allowed manufacturers like Toyota to ease customer concerns about HEV technology by warranting batteries for 100,000 miles of use. PHEVs require deeper discharging of their batteries than do HEVs. All else being equal, deeper charge-discharge cycles will reduce battery life. The question arises, what will not be held equal? Clearly battery chemistry is likely to change; even HEV batteries are likely to shift to lithium rather than nickel-based chemistries and there are more than one candidate lithium-based batteries. Because this study's sample vehicles have been on the road a short time, they tell us little about the long-term performance of Li-ion batteries in PHEVs. One PHEV did require replacement of its battery pack, but it used lead-acid rather than Li-ion technology. Will warranties be held equal? Have HEVs set the standard by which PHEV battery life and reliability will be judged by consumers? By modifying their HEVs, owners in this study accepted potential loss of manufacturer warranty coverage for their vehicles, far more risk than the average consumer is likely to take when purchasing a new vehicle.

4.3. Managing Consumer Expectations

Given the questions that remain about PHEV performance, some care should be taken to properly set consumer expectations. Educating the public about PHEVs makes sense as long as the technology is not oversold. Wind and Mahajan [40] note that the "marketing hype" around a new technology product can substantially enhance consumer acceptance, but warn that timing is important. Getting consumers interested in PHEVs too long before the vehicles are available risks frustrating potential buyers. Much of this frustration will be directed at automakers, and

some is already evident. In January 2007, General Motors unveiled a series-hybrid PHEV concept vehicle, the Chevrolet Volt, at the North American International Auto Show. As a result, General Motors received substantial positive press coverage and over 400,000 consumer requests for the company to build the vehicle; however, two months later the company acknowledged that consumers' and policymakers' expectations regarding the Volt were far too optimistic, and labored to explain that major technical hurdles remain before the PHEVs like the Volt can be mass-produced (Terlep [41]).

Among PHEV drivers in this sample, frustration with automakers was apparent. Several felt that automakers had a poor understanding of consumer needs, particularly regarding environmentally friendly vehicles. Participants also accused automakers of ignoring PHEVs in favor of vehicles with older, less efficient technology (including ICE-powered trucks) that could be manufactured more cheaply and sold more profitably. Participants who were interviewed after GM's Volt announcement strongly favored the design, but many questioned whether the vehicle would be mass-produced. Certainly some of this skepticism is justified: until recently, most automakers showed little interest in PHEVs. Even Toyota, the leader in HEV sales, deemed PHEVs too impractical (Hakim [42]) until just recently announcing they had made eight PHEV8s for on-road testing (Toyota [43]). However, automakers do have a point that additional research and development on PHEVs is needed, and this effort takes time.

In the end, PHEV advocates (including many drivers in this study) face a balancing act. Many want to spread the word about PHEVs in order to influence automakers to produce these vehicles. But the risk is that promises will be made that cannot be kept. The claim of one PHEV advocate that "plug-in hybrids are totally available and ready to be manufactured" (Motavelli [44]) is a good example: while the message may excite consumers, it does not fairly represent the state of battery technology, manufacturer readiness, or experience of many of the drivers interviewed for this study.

5. Conclusions

5.1. All-Electric Range

The people interviewed for this study drove PHEV conversions that did not in general provide all-electric operation across the wide variety of conditions drivers face every day. In all cases, AER was limited to low-power driving conditions, i.e., low speeds, modest accelerations, or coasting at higher speeds. Within these limits, the maximum achievable AERs by vehicles in this study appear to range from a few miles to perhaps 20 to 25 miles. As such, these vehicles do not conform to the idealized distinction between PHEVs that provide AER and those that operate only by continuously blending power from electricity and gasoline.

And yet, these drivers have opinions and thoughts about AER that sound strongly held. Many stated their desired AER to be equal to the distance of their one-way commutes, arriving at AERs between 20 and 40 miles. For most drivers these estimates appeared to be tied to their imagining recharging a PHEV at home and at work, so their PHEVs could be fully replenished for the evening commute home.

There are two points to be made about these estimated desired AERs. First, these same drivers position PHEVs as transitional between conventional vehicles and BEVs. If one already sees the BEV as the desired goal, then a PHEV that provides AER is important, and increasing the AER capability of PHEVs over time is important. Second, though the stated basis for estimated desired

AERs is often one-way commute distances, these drivers immediately move to a conversation about PHEVs accomplishing all but the longest of trips.

The AER desires of non-commuters—none of which were interviewed—cannot be determined by this same one-way commute distance rule. Nor can we assume that the vast majority of people—who have no past experience with BEVs—are prepared to see PHEVs as transitional to BEVs and therefore as requiring AER. We would contextualize the results of this study as saying that BEVs are an important source of meanings and functionality goals for PHEVs for many of the people who have experience with the currently available PHEV conversions. Generalization to a larger population can be achieved by providing a wider cross-section of people with information and experience with a variety of PHEVs.[13]

5.2. Fuel Economy and Fuel Costs

Overall, drivers of the Prius-based PHEV conversions in this study report "boosted range" fuel economy values from 65 to well over 100MPG. Several drivers claim that gasoline-only MPG values, i.e., not accounting for the electricity from the grid being substituted for gasoline, are "twice whatever you get in a conventional Prius." A driver who consistently makes trips within his/her boosted range and then fully recharges the PHEV achieves much higher gasoline-only fuel economy than a driver who regularly drives distances greater than boosted range before recharging. Such differences in driving and recharging behavior make predicting or modeling average fuel economy of PHEVs difficult: data is needed on how a vehicle is driven and on both the frequency and timing of recharging from the grid.

High fuel economy, particularly numbers over 100 MPG that have not been attained before in production automobiles, have both symbolic and financial value. Episodes of 100+ MPG, even if brief, signal to drivers that the vehicle has valued qualities: that it is technologically exceptional, environmentally friendly, or financially sensible. Heffner *et al.* [23] reported these types of meanings were important for buyers in the early market for HEVs. High fuel economy is also important since it provides a basis for comparison with conventional vehicles. The typical American car buyer has never owned a BEV or HEV, and thus is unfamiliar with all-electric driving. MPG, in contrast, is a familiar measure to many more people. For owners of conventional vehicles, high MPG may be the single most important way to access highly valued meanings and capabilities of PHEVs.

Combined with results from prior studies of a more general population of vehicle buyers (Turrentine and Kurani [34]) and HEV buyers (Heffner *et al.* [23]), no consumers, including these PHEV drivers, apply financial analyses such a payback calculations or a net present value framework to personal vehicle choices. The choices by institutions and businesses are not, at this early point, about private financial calculations either. Despite their lack of interest in the

[13] For these and other reasons, the use of cross-sectional data on commute distances to estimate market demand for AER remains speculative at best. This practice has been repeated in numerous prior PHEV market estimates. Data on commute distance from the National Household Travel Survey (NHTS) in particular has been used to make claims about the potential market for PHEVs with different AERs. The problem with these cross-sectional data from the NHTS is they are drawn from one-day travel surveys. Households do not buy vehicles based on how far they travel (or where they travel) on a single day; nor do they buy vehicles based on how far other people travel on a single day. Yet these are the implicit assumptions made by those who use cross-sectional, one day commute distance data to estimate market demand for AER.

immediate financial payoff of PHEVs, most respondents in this study believe "other," "later," "mainstream" people will be most interested in cost savings.

There is no question that widening the gap between electricity prices and gasoline prices will make PHEVs more attractive. But policymakers and marketers risk missing the very market they hope to foster if they over-emphasize the importance of payback periods.[14] PHEVs are more than just a way to save money, and it is likely that other automobile buyers will see additional value in PHEVs beyond any private financial benefits.

Though mentioned by few respondents, the connection between PHEVs and home electricity systems should be explored further in future consumer research. In particular, the idea of bundling PHEVs with home systems that generate renewable electricity should be discussed with consumers to understand whether it increases the appeal of PHEVs. Also, the idea of PHEVs as providing mobile electric services such as home emergency power may be highly valued by some consumers. And V2G should not be dismissed solely on the basis of these interviews, but should wait fuller evaluation in settings that allow people to experiment with such services.

5.3. PHEVs and Instruments

Drivers derive value, meaning, and reinforcement, and they learn through vehicle instrumentation. As we saw in previous studies of HEVs, the instrumentation of some of these PHEV conversions was important to most of their drivers. With PHEVs it is likely that instrumentation of the energy systems will be even more important to develop the value of the vehicle to buyers by monitoring the performance of the electric system *vis-à-vis* the gasoline system. Commercial PHEVs will have to provide accessible, as well as informative and even motivating, feedback to drivers with less understanding of PHEV technology. Further, the vehicle may become a necessary location of information on both gasoline and electricity expenditures by households, as there is currently no other system to track and present both cost and use streams to drivers.

5.4. Recharging PHEVs

Not facing time of day tariffs and on the advice of one vehicle converter, the vehicles in this study are recharged throughout the day. This sample shows that when drivers have unconstrained (in time, if not location) capability to recharge from the electricity grid, they use it in an unconstrained manner. Various methods have been proposed, including time-of-use rate schedules, timers, and smart chargers, to encourage or constrain PHEV owners or otherwise manage time-of-day of PHEV recharging—echoes of early discussions about managing recharging of BEVs. Whether or not constraining recharging makes PHEVs less or more attractive to potential buyers is an open question. On its face, any constraint might be assumed to limit the appeal. However, if the public understands that PHEVs' personal and societal benefits are maximized if recharging is done off-peak, then time-of-day "constraints" might be repositioned as "guidelines for maximizing benefits."

[14] It is possible that some consumers are swayed by such financial arguments. But this is not the same as saying they make such calculations for themselves. The car shopper who has dismissed an HEV because Consumer Reports or some other trusted source says such vehicles don't payback is not conducting such an analysis, but is engaged in constructing symbolic meaning: "I'm a smart consumer who uses research such as Consumer Reports to help me make decisions."

Unconstrained access to free or under priced electricity may seem like a useful and powerful incentive—again with echoes of BEVs. However if such access where to produce habitual travel and recharging behaviors and especially recharging during existing peak electricity usage, those behaviors may prove difficult to undo should they prove contrary to the social goals for PHEVs. Research on behavior change uniformly concludes that behaviors that have passed from conscious consideration to habit can be difficult to change. For example, Jackson [45] writes, "…many of our ordinary, everyday behaviours are carried out with very little conscious deliberation at all…the process of 'routinization' of everyday behaviours makes them less visible to rational deliberation, less obvious to understand, and less accessible to policy intervention….Habit is one of the key challenges for behavioural change policy since many environmentally significant behaviours have this routine character."

Thus what might seem like a nice incentive to early buyers may develop into habitual behavior contrary to the goals of marketing PHEVs in the first place. Further, linking personal purchases of alternative vehicles or fuels to private financial cost savings through cheap fuels—such as would be accomplished by shielding consumers from the financial costs of recharging PHEVs during peak periods in an effort to provide some early market boost—has proven fragile in every instance. Even the perception that a fuel price advantage might disappear (never mind whether it actually disappeared) helped to doom diesel in the light-duty vehicle market in California (and probably the US) (Kurani and Sperling [46]), natural gas in Canada and New Zealand (Kurani [47]), and would likely have doomed ethanol in Brazil if they had not stuck to it for decades as a matter of national development. The point being that if we give electricity away for cheap or free, we may never be able to charge full price lest we risk the sort of AFV market crashes seen before.

Restricting PHEV charging to off-peak periods may also affect the PHEV configurations that appeal to buyers. If the option of daytime charging is constrained—by availability or pricing—drivers may lose the option to recharge at their workplace during business hours. As a result, they may want greater on-board energy storage to satisfy their round-trip commute distances. All else being equal, PHEVs with additional AER will cost more than PHEVs with less AER. The EPRI [4] market research study suggests that many survey respondents lose interest in PHEVs as hypothetical prices increase: seven percent of respondents said they would pay $15,000 more than a conventional vehicle to buy a PHEV60. It remains to be seen whether such measures will be substantiated by continuing research as more people gain real-world experience with a variety of PHEVs.

5.5. Driving with electricity

Drivers of the PHEV conversions in this study say they want larger amounts of AER and greater AEP than provided by these vehicles. As a group they have far more extensive experience with electric-drive vehicles than does the vast majority of American automobile buyers. Locating value to the future, PHEV drivers imagine a better future that has BEVs, based on development of PHEVs today.

Other future buyers of PHEVs may share these views, and early buyers are often the source of information, images, values, and symbols used by later buyers. BEVs are only one potential source of meanings for PHEVs; the previously commercialized HEVs are another likely source. Additional research is needed in this area to understand how consumers will respond to various PHEV designs, including a blended-mode PHEV0. Ultimately, the optimal solution may be to

offer PHEVs in a variety of configurations. Just as today's vehicles are available with a choice of engines, a future PHEV might offer various AERs at different price points.

Respondents' idealized AER varied from 20 to 40 miles. The method they used to determine these values may offer insight into how they and other future commuters may assess AER: participants generally used their one-way commute distance between home and work assuming home and workplace recharging.[15] However, even among drivers with shorter commutes, 20 miles of AER seemed to be the minimal acceptable amount. One of the few users who acknowledged interest in a PHEV10 characterized 10 miles of AER as an acceptable starting point for PHEVs, but not an ideal that matched his view of a successful long-term market.

Parking affects recharging, and thus recharging is a problem for some households. Not being able to park and recharge at home makes recharging difficult (except in those cases where an employer or institutional-vehicle owner provides recharging at the work place). Past studies by Nesbitt *et al*. [48] and Williams and Kurani [49]) of household's ability to refuel battery electric, natural gas (and by extension some hydrogen fuel cell vehicles) at home conclude that this ability may be far more limited than many realize. Such studies have relied on several proxy variables to estimate whether or not households have adequate parking and electrical service at their homes. New studies targeting these aspects of American consumers and their housing stock can refine the estimates of the proportion of households who can recharge at home.

6. References

[1] California Air Resources Board (2003) *California Exhaust Emission Standards and Test Procedures for 2005 and Subsequent Model Zero-Emission Vehicle, and 2002 and Subsequent Model Hybrid Electric Vehicles, in the Passenger Car, Light-Duty Truck and Medium-Duty Vehicle Classes*. California Environmental Protection Agency.

[2] Gonder, J. and A. Simpson (2006) "Measuring and Reporting Fuel Economy of Plug-in Hybrid Electric Vehicles." 22nd International Battery, Hybrid and Fuel Cell Electric Vehicle Symposium and Exhibition (EVS-22), Yokohama, Japan, October 23-28. Available from: http://www.nrel.gov/vehiclesandfuels/vsa/pdfs/40377.pdf

[3] Norbye, J. and Dunne, J. (1969) "…and a Commuter Car with Hybrid Drive." Popular Science. July.

[4] EPRI (2001) *Comparing the Benefits and Impacts of Hybrid Electric Vehicle Options.* EPRI: Palo Alto, CA. Report 1000349

[5] Turrentine T. and K. Kurani (1998) *Consumer Benefits of EVs and Plug-in HEVs* Report , Electric Power Research Institute, EPRI TR-110780. Palo Alto, CA, June.

[15] A little driver education could have large effects on desired AER. Kurani, Turrentine, and Sperling [50] found that fewer than half of regular commuters in a small sample knew their one-way commute distance accurately (within one-half mile). Only under conditions in which they were able to learn their driving distances through keeping a week-long travel diary did most drivers learn to accurately enter travel distances in their diaries *prior to* making the trip. Across the sub-sample of commuters, on the first day they commuted to work 19 percent underestimated their commute distance (and thus would underestimate their AER based on the one-way commute distance rule), 41 percent knew their commute distance, and 40 percent overestimated their commute distance (and thus would overestimate their AER). The overestimates would vary from one to ten miles. If recharging is not available at both work and home, and if the PHEV driver wanted to start both the home and work-end commute trips with a battery at 100 percent SOC, then the overestimates span twice this range.

[6] Plotkin. S., F. An, J. Anderson, D. Bharathan, D. Santini, A. Vyas and M. Wang (1999) "Argonne's HEV Energy and Cost Analyses: Scoping Out the Potential Energy Cycle Impacts and Monetary Costs." Presented at: Transportation Research Board, 78th Annual Meeting, January 11. Washington, DC

[7] EPRI (2002) *Comparing the Benefits and Impacts of Hybrid Electric Vehicle Options for Compact Sedan and Sport Utility Vehicles*. EPRI: Palo Alto, CA. Report 1006892

[8] EPRI (2004) *Advanced Batteries for Electric-Drive Vehicles: A Technology and Cost-Effectiveness Assessment for Battery Electric Vehicles, Power Assist Hybrid Electric Vehicles, and Plug-in Hybrid Electric Vehicles*. EPRI: Palo Alto, CA. Report1009299.

[9] Markel, T. and A. Simpson (2006) "Plug-in Hybrid Electric Vehicle Energy Storage System Design." Conference Paper NREL/CP-540-39614. National Renewable Energy Laboratory: Golden, CO. Presented at Advanced Automotive Battery Conference, Baltimore, MD. May 17-19.

[10] Winkel, R., van Mieghem, R., Santini, D., Duvall, M., Conte, V., Alakula, M., Badin, F., Bleis, R., Brouwer, A., and Debal, P. (2006) "Global Prospects of Plug-in Hybrids." Paper Presented at the 22nd International Battery, Hybrid, and Fuel Cell Electric Vehicle Symposium and Exhibition. Yokohama, Japan. 23-28 October

[11] Kliesch, J. and Langer, T. (2006) *Plug-in Hybrids: An Environmental and Economic Performance Outlook.* American Council for an Energy-Efficient Economy. Report T061. Washington, DC

[12] Frank, A.A. (2007) "Plug-in Hybrid Vehicles for a Sustainable Future." American Scientist. v. 95 pp. 156-63.

[13] Burke, A.F. (2007) "Batteries and Ultracapacitors for Electric, Hybrid, and Fuel Cell Vehicles." Proceedings of the IEEE. v. 95, n. 4.

[14] Kintner-Meyer, M., K. Schneider, and R. Pratt (2007) *Impacts Assessment of Plug-in Hybrid Vehicles on Electric Utilities and Regional US Power Grids, Part 1: Technical Analysis*. Pacific Northwest National Laboratory. Available at: http:// www.pnl.gov/energy/eed/etd/pdfs/phev_feasibility_analysis_combined.pdf

[15] Woolsey, J. (2006) "Gentlemen, Start Your Plug-Ins." Wall Street Journal (Eastern edition). New York,: 30 Dec 30 p. A 10

[16] Wang, M. (2001) *Development and Use of GREET 1.6 Fuel-Cycle Model for Transportation Fuels and Vehicle Technologies*. Center for Transportation Research, Argonne National Laboratory, Argonne, IL.

[17] Wang, M. (1999) *GREET 1.5 Transportation Fuel Cycle Model*. Center for Transportation Research, Argonne National Laboratory: Argonne, IL. Report ANL/ESD-39.

[18] EPRI (2007a) *Environmental Assessment of Plug-In Hybrid Electric Vehicles, Volume 1: Nationwide Greenhouse Gas Emissions*. Final Report 1015325. Palo Alto, California. June. http://www.epri-reports.org/Volume1R2.pdf

[19] EPRI (2007b) *Environmental Assessment of Plug-In Hybrid Electric Vehicles, Volume 2: United States Air Quality Analysis Based on AEO-2006 Assumptions for 2030*. Final Report 1015326. Palo Alto, California. June. http://www.epri-reports.org/Volume2Part1R2.pdf and http://www.epri-reports.org/Volume2Part2.pdf

[20] Synovate Motoresearch. (2006) "Study Shows Strong Consumer Consideration for Flex-Fuel Vehicles Including E85, Plug-in Hybrids Peak Interest." Press release. http://www.synovate.com/current/news/article/2006/08/study-shows-strong-consumer-consideration-for-flex-fuel-vehicles-including-e85-plug-in-hybrids-peak-interest.html 16 August.

[21] Opinion Research Corporation International. (2006) Would You Buy a Hybrid Vehicle? Study #715238, conducted for National Renewable Energy Laboratory. 8 June.

[22] Kurani, K.S., R.R. Heffner, and T.S. Turrentine (2006) "Narrative Self-Identity and Societal Goals: Automotive fuel economy and global warming policy." In Sperling, D.S. and J. Cannon (eds.) *Driving Climate Policy*. New York: Elsevier Academic Press.

[23] Heffner, R.R., K.S. Kurani, and T.S. Turrentine (in press) “Symbolism in the Early Market for Hybrid Electric Vehicles.” Transportation Research D. http://dx.doi.org/10.1016/j.trd.2007.04.003

[24] Hoeffler, S. (2003) “Measuring Preferences for Really New Products.” Journal of Marketing Research v. 40, November. p. 406-420.

[25] Strauss, A. and Corbin, J. (1990) *Basics of Qualitative Research: Grounded Theory Procedures and Techniques*. Sage, Newbury Park.

[26] McCracken, G. (1988) *The Long Interview*. Sage, Newbury Park.

[27] Heffner, R.R. (2007) *Semiotics and Advanced Vehicles: What Hybrid Electric Vehicles (HEVs) Mean and Why it Matters to Consumers*. Institute of Transportation Studies, University of California, Davis. Ph.D. Dissertation. http://hydrogen.its.ucdavis.edu/people/rrheffner/ploneexfile.2007-09-06.0704768549/attachment_download/file

[28] Sacramento Municipal Utility District (2006) “PHEV Prius Test Program by Sacramento Municipal Utility District.” Presentation to the CARB 2006 ZEV Technology Review. Sacramento, CA. September 27. http://www.arb.ca.gov/msprog/zevprog/symposium/presentations/maccurdy.pdf

[29] *EV World.* (2005) What's In A Name? 7 April. Available from: http://www.evworld.com/news.cfm?newsid=8142

[30] Toyota Motor Sales (2006) Photo: Toyota Prius Interior, Electronic Multifunction Display. http://www.toyota.com/prius/interior.html Accessed 2 April 2007.

[31] Hybrid Interfaces, Inc. (2007) Photo: V4 Using Add-on Touch Screen. Available from: http://hybridinterfaces.ca/ Accessed 2 April 2007.

[32] California Cars Initiative (2007) Photo: Technical Photos of Plug-In Hybrids and Components. Available from: http://www.calcars.org/photos-tech.html Accessed 2 April 2007.

[33] National Research Council (2002) Effectiveness and Impact of Corporate Average Fuel Economy (CAFE) Standards. Washington, D.C.: National Academy Press.

[34] Turrentine, T.S. and K.S. Kurani (2007) “Car Buyers and Fuel Economy?” Energy Policy v.35, pp. 1213-23.

[35] Edmunds.com (2005) “Most Hybrid Vehicles not as Cost-Effective as they Seem, Reports Edmunds.com.” Press Release, June 1.

[36] White, J.B. (2005) “Doing the Hybrid Math: Rising Gas Prices Have Consumers, Auto Maker Calculating the Difference.” Wall Street Journal, 26 Sept.

[37] Kempton, W. and J. Tomic (2005), "Vehicle-to-grid power fundamentals: Calculating capacity and net revenue," *Journal of Power Sources*, vol. 144, pp. 268-279.

[38] McCracken, Grant (1988a). *Culture and Consumption.* Indiana University Press, Bloomington.

[39] Wall, E. (2006) “Consumer Perspectives are Changing: Initial Results from ORC Survey on PHEVs.” Presentation at Office of FreedomCAR and Vehicle Technologies, Discussion on Plug-in Hybrid Electric Vehicle (PHEV) Technology, Washington, D.C., 4-5 May

[40] Wind, J. and Mahajan, V. (1987) “Marketing Hype: A New Perspective for New Product Research and Introduction.” Journal of Product Innovation Management 4 (1), 43–49.

[41] Terlep, S. (2007) “GM Tries to Unplug Volt Hype.” The Detroit News. 23 March.

[42] Hakim, D. (2005) “Hybrid-Car Tinkerers Scoff at No-Plug-In Rule.” New York Times. New York: 2 Apr. p. C 1

[43] Toyota Motor Corporation (2007) “Japan Certifies Toyota Plug-in Hybrid for Public-road Tests.” News Release. http://www.toyota.co.jp/en/news/07/0725.html July 25.

[44] Motavalli, J. (2006) “The Quest for a Plugged-In Prius.” New York Times. New York: 2 Apr. p. 12.1

[45] Jackson, T. (2005) *Motivating Sustainable Consumption: A review of evidence on consumer behavior and behavioral change.* Report to the Sustainable Development Research Network. http://portal.surrey.ac.uk/pls/portal/docs/PAGE/ENG/STAFF/STAFFAC/JACKSONT/PUBLICATIONS/JACKSONSDRN-REVIEW.PDF

[46] Kurani, K.S and D. Sperling (1988) "The Rise and Fall of Diesel Cars in the USA: A Consumer Choice Analysis." *Transportation Research Record 1175*. Transportation Research Board: Washington, D.C.

[47] Kurani, K.S. (1992) *Application of a Behavioral Market Segmentation Theory to New Transportation Fuels in New Zealand*. Ph.D. Dissertation. Report UCD-ITS-92-5. University of California, Davis.

[48] Nesbitt, K. A., K.S Kurani and M. A. DeLuchi (1992) "Home Recharging and the Household Electric Vehicle Market: A Near-Term Constraints Analysis." *Transportation Research Record 1366*. pp. 11-19.

[49] Williams, B.D. and K.S. Kurani (2007) "Commercializing light-duty plug-in/plug-out hydrogen-fuel-cell vehicles: 'Mobile electricity' technologies and opportunities." Journal of Power Sources. v. 166 pp.549-66.

[50] Kurani, K.S., T. Turrentine, and D. Sperling (1994) "Demand for electric vehicles in hybrid households: an exploratory analysis." Transport Policy v.1 n.4 pp. 244-56.

7. Authors

Dr. Ken Kurani is an Associate Researcher at the University of California, Davis' Institute of Transportation Studies. He has spent much of the past 22 years examining consumer response to alternative fuel, electric-drive, and other innovative vehicles. His research explores how citizen/consumers use new technologies to shape their own lives and support efforts to achieve collective benefits such as improved energy efficiency, air quality, fuel flexibility, and peace. His ongoing research includes consumer response to electric, hybrid, plug-in hybrid, and fuel cell vehicles, consumer/citizen valuation of automotive fuel economy and efficiency, and the process of motorization in China.

Dr. Tom Turrentine is Director of the new CEC PIER Plug-in Hybrid Electric Vehicle Research Center and Research Anthropologist at the Institute of Transportation Studies, University of California, Davis. For the past 20 years, Tom has been applying methods and theory from anthropology to guide research on potential consumer response to alternative fuels, vehicle technologies, road systems, and policies with environmental benefits. His most recent projects have been studies of consumers response to fuel economy and hybrid electric vehicles. He is beginning new projects on consumer response to Plug-in Hybrid vehicles, and new types of energy use instrumentation in vehicles.

Dr. Reid Heffner is a researcher at the University of California, Davis' Institute of Transportation Studies. His work focuses on the consumer response to advanced-technology vehicles, including hybrid, plug-in hybrid, and fuel-cell vehicles. Dr. Heffner also has seven years of experience designing, building, and marketing high-technology products and has worked with companies including General Motors, Harley-Davidson, Ford, Nissan, and Mitsubishi. Dr. Heffner holds an MBA from Georgetown University and a PhD from UC Davis.