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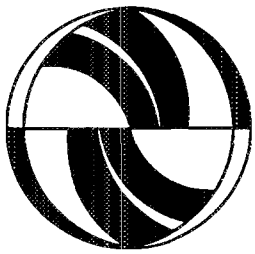

Demand for Electric Vehicles in Hybrid Households: An Exploratory Analysis

Kenneth S. Kurani
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Working Paper
UCTC No. 232

The University of California
Transportation Center

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ABSTRACT

Previous studies of the potential market for battery electric vehicles (BEVs) have reached contradictory conclusions. What they share are untested or implausible assumptions about consumer response to new transportation technology. We frame the BEV purchase decision in terms of a household's entire stock of vehicles, car purchase behavior and travel behavior. Within this framework, households which own both electric vehicles and gasoline vehicles are called "hybrid households". Because nearly all consumers are unfamiliar with the characteristics of BEVs, we designed an interactive interview based on week-long travel diaries, which we call Purchase Intentions and Range Estimation Games (PIREG) to explore hypothetical hybrid household vehicle use. Our primary finding is that consumers' perceived driving range needs are substantially lower than previous hypothetical stated preference studies conclude. We find evidence of a viable market for BEVs with 60 to 100 miles driving range.

Demand for electric vehicles

Key words: electric vehicles; travel behavior; new technologies

INTRODUCTION

Electric vehicles promise large energy and environmental benefits (Sperling; 1994). They are quieter and will likely have lower operating and maintenance costs than internal combustion engine vehicles (ICEVs). Electric vehicles will also be capable of being recharged at home, work and other unconventional, but convenient, locations.

At least initially, electric vehicles are using batteries to store electrical energy. But batteries have low energy density, which results in greatly reduced driving ranges. Also, typical battery recharging times are measured in hours, not minutes. Limited range and long recharge times create uncertainty and skepticism about the possibility of selling battery electric vehicles (BEVs) to consumers habituated to long driving ranges and quick, ubiquitous refueling. Conservative sales estimates in turn lead to high cost estimates because costs are spread over few vehicles. High cost estimates iteratively reinforce estimates of a minimal BEV market.

In a broad sense, the initial target markets for BEVs are commercial, utility and government fleets and the growing number of multi-car households. We focus on the household market in this paper. According to the 1990 Nationwide Personal Transportation Survey, 58 percent of households in the United States (a total of over 54 million) have two or more vehicles (Hu, et al, 1992). BEVs should not be seen as simple one-for-one substitutes for ICEVs. BEVs offer significant limitations as well as new capabilities. BEVs comprise an alternative travel technology which households must learn to integrate with familiar gasoline vehicles. A household which combines BEVs and gasoline vehicles in its stock of vehicles is one example of what we call *a hybrid household.* In contrast to a hybrid vehicle which combines electric and heat engine drive systems in one vehicle, a hybrid household chooses two vehicles with different types of energy systems and then must allocate household travel accordingly.

In many ways, the introduction of BEVs to the car market is analogous to the introduction of microwave ovens to the oven market: a classic example of an appliance with an entirely new set of functional features, what Berkowitz, et al (1992, p.290) call a "high learning product". Sales of microwave ovens were slow but steady. Market penetration increased from 15% of US. households in 1980 to 75-80% by 1992 (ibid). Initially, consumers were concerned whether microwave ovens cooked food as tastefully as did conventional ovens. To convince consumers of the potential uses of microwaves, special "cooking classes" were given to demonstrate the technology. Consumers discovered the comparison to heat ovens was misplaced; the microwave oven did not displace the traditional heat oven. Instead, it became an additional oven, which resulted both in reallocation of previous cooking tasks and new cooking practices. Households which initially rejected microwave ovens because of perceived inferior cooking characteristics, now use microwave ovens everyday for entirely new "cooking" tasks such as defrosting foods, re-heating coffee or cooking any of hundreds of products which have been specifically repackaged for microwave ovens.

As happened with initial microwave oven market research, electric vehicle market research often fails to identify a market for this "radical" new technology. We will show that this inferred lack of a market for BEVs is an artifact of previous research designs. Consumers questioned in previous studies had neither enough information nor experience with the technology to offer informed opinions or to have formed preferences. Consumers' lack of experience with limited ranges, home recharging and other features of BEVs renders conventional survey methods of limited usefulness, both in predicting sales of BEVs and in providing explanations and insights as to which households will consider BEV purchases.

One research design which appears particularly motivated to find households likely to consider BEVs, is in fact too narrowly focused. These studies focus on identifying "green" consumers willing to pay considerably more for a zero emission vehicle. But these studies are often flawed because they allow environmentally motivated consumers to initially respond positively to BEVs without carefully considering the lifestyle implications of limited range.

Conversely, they exclude from the BEV market less environmentally motivated households. But, as we will show, after some reflection on their lifestyle wants and needs, these households which are excluded from the "green" market, may find that short ranges are not a real limitation and that other features of BEVs such as home or workplace recharging make BEVs a superior lifestyle choice compared to gasoline vehicles.

In a mature market, in which households can draw on the experience of other consumers to help evaluate unfamiliar products, these lifestyle choices are readily made. But in the case of electric vehicles, a mature market is years away. Absent the information and product familiarity which characterize mature markets, consumer research must do its best to enhance the information context of survey work, creating learning situations as well as exploring with households the lifestyle implications of new technology. To provide this decision context, we developed PIREG (Purchase Intentions and Range Evaluation Games), an interactive lifestyle-preference interview. PIREG was designed to provide the necessary information context for households to evaluate the strategic impacts of driving range limits and recharging characteristics of BEVs.

We conducted 51 PIREG interviews in three metropolitan areas of California. The households chosen for this study represent potential hybrid households. They own two or more cars, and thus potentially have some flexibility in assigning different vehicles to different drivers and trips. They buy new cars. Most own single-family homes with a garage in which they park at least one vehicle. We included a few renters to explore issues around residential tenure and availability of dedicated parking for recharging a BEV.

The results of this research provide an in-depth view of the decision variables and strategies households consider when evaluating BEVs. Based on these results, we identify three types of households: those who are pre-adapted to BEVs, those who can easily adapt, and those for whom adaptations are difficult or impossible given their routines, lifestyle goals and budgets. We explore the vehicle driving ranges that households are willing to consider and potential impacts of BEVs on their travel behavior. In short, we explore what it might mean to become a hybrid household.

THREE TYPES OF PREVIOUS BEV MARKET RESEARCH: INADEQUATE APPROACHES AND A CONTRADICTION

Previous research on BEVs has focused on predicting the size of the market at the expense of understanding market dynamics for a fundamentally new consumer product. Many of these studies have relied upon convenient rather than appropriate data samples. Others have used data from hypothetical choice exercises. Almost all, we believe, rely on an implausible set of assumptions regarding consumer behavior. Such shortcomings exist precisely because there are no sales data for BEVs. In the absence of sales data, researchers have tried three methods to develop estimates of BEV market potential -- attitude studies, travel behavior analyses, and stated preference surveys.

These three research streams present an apparent paradox. Attitude studies and travel behavior analyses tend to show BEVs to be a practical and desired technology, but stated preference studies typically conclude consumers are unwilling to consider BEVs at anything but "fire sale" prices. This paradox calls for close scrutiny of the methods and findings in these studies.

Attitude Surveys

A number of attitude surveys and some focus group studies by auto manufacturers, electric utilities and auto market analysts have found, rather universally, a sizable percentage of consumers who are interested in, and favor, electric vehicles and other alternatives to gasoline (Buist, 1993; PG&E, 1993; Fairbanks, Maulin and Associates, 1993;). It appears that electric vehicles in particular have a special fascination over other propulsion systems because they have the most progressive image technically and environmentally (Turrentine, et al, 1992).

However, these attitudes are far removed from vehicle purchase and use; they represent the ideals of consumers and not their full decision process. Additionally, these studies often report conflicting attitudes. They report that on the one hand consumers strongly favor electric cars, but on the other, want similar driving range as their gasoline vehicles. Such conflicts often lead to simple dismissal of consumer attitudes as merely "feel good" answers.

Another flaw is that attitude studies which set out to find a "green" market are unduly constraining their search for a BEV market. Ford Motor Co. (Buist, 1993) has reported using this approach; first, finding the environmental consumer, and then culling those willing to pay the purchase price premium Ford projects for BEVs. This approach may be interesting to manufacturers for several reasons. It captures those with certain strong convictions about BEVs; it may identify some consumers who are willing to pay more for an BEV than a gasoline vehicle; and it may even identify consumers who have not previously purchased a new vehicle, but might buy a BEV. But many of those with strong environmental convictions have neither appropriate vehicle use nor purchase behavior. By focusing on the green aspect as an initial filter of the market, studies such as Ford's eliminate a wide set of consumers for whom BEVs offer practical advantages as part of a hybrid household fleet. We have found in previous studies (Turrentine, et al, 1992) and in this work that broader lifestyle issues are better primary filters for the BEV market than environmental convictions.

Travel Behavior Studies

In studies based on travel behavior or constraints analyses, researchers have largely focused on the issue of limited range. Typically such studies attempt to count households which have two or more vehicles and travel habits which can accommodate a limited range BEV. The primary assumption in these studies is that potential BEV-owning households must have at least two vehicles. The other common assumption is that there can be no pattern of daily vehicle use in which both vehicles travel beyond the range of the BEV. The data used in these studies often come from the Nationwide Personal Transportation Survey (NPTS) or the American Housing Survey (AHS). The NPTS contains a one day travel diary. The AHS asks only about typical travel and commute travel. For examples of these constraints analyses, see Deshpande (1982), Kiselewich and Hamilton (1982) and Nesbitt, et al (1992).

The primary finding of most of these studies is that more than 90 percent of two car households could use one vehicle with 100 miles of daily range and that most "second" cars are used more than 100 miles on only a few days per year. In general, such studies conclude that 55 to 60 million households could accommodate a 100 mile range vehicle. Studies of this type in other countries return equally impressive potential market estimates. A study conducted in the former Federal Republic of Germany concluded 7 million households could accommodate BEVs (Hautzinger, et al, 1991).

One of the more recent of these studies adds a further constraint on top of vehicle ownership and use -- the household must have a logical place to recharge the BEV. They find about 28% of American households (28 million households) could accommodate a BEV (Nesbitt, et al, 1992). Greene (1985) uses the travel behavior approach but distinct data; he analyzes multi-day refueling diaries, and infers underlying distributions of travel. He concludes that with 95% probability, half of all household vehicles travel less than 105 miles per day on 95% of all days. There was no substantive difference between vehicles in single- and multi-car households.

A recent study by General Motors, aimed at understanding the market for electric vehicles, concurs that the majority of any household's travel requires minimal range or passenger payloads (Dables, 1992). Potential BEV owners kept three-week driving logs in that study. GM reported 84% of their sample drove less than 75 miles a day and in only 5% of trips were more than two persons in the car.

All these studies present reassuringly large market potentials. But the limitation of the travel behavior approach is that it doesn't measure consumer preferences. While measuring a "potential market", these studies don't examine attitudes or social processes which will shape consumer lifestyle choices. Additionally, they analyze vehicle stocks rather than new car sales.

Skeptics of the potential market for BEVs have criticized constraints analyses, arguing that regardless of how people actually use their vehicles, consumers probably won't give up unlimited range or fast refueling of ICEVs. Hamilton complained that such studies were merely wishful thinking (Hamilton, 1983); the third approach to BEV market studies, stated preference techniques, appear to support this argument quite forcefully.

Stated Preferences

Stated preference surveys present consumers with options, in written or telephone survey form and ask them which they would be willing to buy. Each option is described by attributes common to all the possible choices. The attribute levels are varied over several trials to elicit different choices of vehicle options. Econometric models based on such data assign partial utility values to consumer preferences for vehicle attributes. The partial utilities for driving range are often then used to estimate a purchase price penalty for limited range vehicles.

Virtually every stated preference study estimates huge average penalties for limited range vehicles. For example consider the estimated average purchase price penalty (adjusted to 1991$) assigned to a 50 mile range vehicle when compared to a 200 mile vehicle for the following three studies: Morton, et al (1978), $10,000; Beggs and Cardell (1981), $16,250; and more recently, Bunch, et al (1993), $15,000. In a slightly different study, Calfee (1985) calculates individual-specific price penalties. The range of estimated penalties is large, but many are close to the average penalties reported in the other studies -- even for consumers who claimed they preferred BEVs. [1]. Considering that the average price of a new automobile in 1991 was $16,700 (MVMA, 1992), these studies suggest that on average consumers would be indifferent to the choice between two cars which were identical, except one was free and had a 50 mile range, and the other, for which they must pay full price, had a 200 mile range. Using these large average penalties for limited range, projected BEV sales are very low. Market penetration estimates in these studies range from 2% down to 0%.

We are skeptical regarding this conclusion for two reasons. First, the average utility is irrelevant to the dynamics of market development. The average penalty for limited range makes an apparently compelling argument for those opposed to the introduction of BEVs. But "average" consumers are not, by definition, the first buyers of something new. It is the distribution of disutilities which matters. The appropriate objective is to determine how many consumers have positive, or relatively small negative, utilities for BEVs, not the magnitude of the average utility. Our second reason for skepticism is the underlying assumptions regarding consumer behavior in stated preference studies and the contradictions to these assumptions we find in our work. We address these issues next.

Volatility in stated preferences for range

The underlying assumptions about consumer behavior contained in econometric models based on stated preference experiments seem untenable to us. A complete critique is provided elsewhere (Turrentine and Sperling, 1991). Here we focus briefly on the characteristics of preferences. In order to make inferences about the value placed on driving range, it must be assumed that respondents have well formed preferences for range. Preferences have specific properties, e.g. transitivity and communativity. Most importantly for purposes of forecasting future market shares, preferences must be stable or there must be enough longitudinal data and an adequate theoretical understanding to also forecast the rate of change of preferences. These are highly speculative assumptions for attributes with which consumers have no experience. As we will show, consumer "preferences" for driving range shift dramatically based upon small increments of information. Such shifts are evidence of instability and may result in non-transitivity of "preferences" for different attributes.

Not only do stated preference studies find very high penalties for limited range, but so too do other less rigorous, studies such as those of Ford (Buist, 1993) and J.D. Powers (1993). Focus group studies (Morton et al 1978; J. D. Powers 1991) report that consumers state their desired driving range to be essentially that of their gasoline vehicle.

Such responses are grounded in consumers' past experience with familiar vehicles. The contrast between these responses and the actual daily distance provide the motivation for this PIREG interviews. We began to explore this problem in a previous study in which 11 focus groups were conducted with participants of a drive test clinic of electric, compressed natural gas and methanol fueled vehicles in 1990 in Pasadena, California (Turrentine, et al, 1992). In the focus groups, we elicited initial estimates of needed driving range from each participant at the start of the session. Then we discussed range needs in a number of ways, first asking participants to estimate their actually daily driving, and then to make trade-offs between range, fuel prices and vehicle prices to explore the stability of their initial range need estimates. The primary finding was that participants' stated preferences for range were extremely volatile and changed dramatically under the influences of new information, attitudes expressed by other group members, and attempts of the moderator to influence responses by suggesting range related problems. Some respondents' stated needs increased, but overall, there was a pattern of drastic reductions in stated daily range needs.

This finding suggested there was a learning curve for driving range. While our sample was small and the setting informal, we found nothing to support the extreme average penalties reported in stated preference work. We concluded that innovative survey and interview methods were needed to provide both consumers and researchers an adequate context to understand and measure potential consumer demand for range.

A NEW APPROACH

Previous studies of potential BEV demand come to very different conclusions: travel behavior studies find that households could easily use a limited range vehicle, while stated preference studies find limited range to be an overwhelming drawback. Some consumer attitude studies show people view BEVs very favorably. Yet these studies have also been used to show that those consumers who should view BEVs most favorably, so called "green" consumers, are unwilling to buy BEVs. We suggest the need for a new approach, one which provides consumers with more information about BEV range and recharging characteristics and allows them to reflect on their own driving and vehicle use patterns. To understand potential BEV markets, we investigate in detail the travel and vehicle purchase decision behavior of households, as well as their lifestyle plans. In order for both we and our study participants to gain adequate information, we employ *interactive stated lifestyle-preference* techniques.

Interactive stated lifestyle-preference techniques differ from stated preference techniques in that the researcher and participants engage in *simulated decision making contexts* designed from actual behavior of the household. The process creates hypothetical choice situations constructed from the real material of a household's activities. This process increases the validity of responses and allows the researchers to observe the lifestyle decisions of the household. Previous examples of this type of work include the Household Activity Transportation Studies (HATS) developed by Peter Jones (1979) for studies of transportation mode choice, and the Car Use Patterns Interview Games (CUPIG) developed by Martin Lee-Gosselin (1990) to study household responses to motor fuel rationing.

PIREG (Purchase Intentions and Range Estimation Games)

With the participation of Martin Lee-Gosselin, we developed an interactive stated lifestyle-preference interview, PIREG, to explore household responses to limited-range, home-rechargeable BEVs. In PIREG, like other interactive lifestyle-preference transportation studies, participants keep one week diaries of all household motor vehicle travel. These diaries are transferred to a time-line which contains complete trip-by-trip information on trip purposes, origins, destinations, distances, start and end times. This chart is used to construct "what if" situations in a two hour interview with participants in their home. The chart and other travel information about the household are used to see if they understand the problems and questions posed in the interview.

A PIREG interview has five parts:

1. CALIBRATION: The household is questioned about the typicality of the week on the chart and about daily, weekly, monthly or annual travel not found on the chart (including travel by other modes).

2. MINIMUM RANGE ESTIMATION: One of the household vehicles is "replaced" by an exact copy, except the copy has a limited range and is recharged at home. The interviewers choose a "challenging" range - a range which will cause some problems in completing the week of actual travel. The household members review the week and discuss how to solve the problems presented. If they successfully solve these problems, a lower range is proposed. The process is repeated until the household arrives at the lowest range vehicle it is willing to accommodate.

3. ADAPTATION: Using the minimum range vehicle, the interviewer presents the household with further problems not contained in the diary, such as a medical emergency or other real situations which might demand more range or further behavioral change. The household continues the process of problem solving.

4. OPTIMIZATION: The household is asked to optimize the use of their hybrid fleet of vehicles under the condition of higher operating costs for their gasoline vehicle, using the disincentive of a very high gasoline price.

5. COMFORTABLE RANGE ESTIMATION: Finally the household is presented with a priority evaluator (PE) table of driving range and recharge times. Each option has an associated price. Households choose to "buy" a new range/ recharging package or to retain the one they arrived at in the adaptation phase.

PIREG Sample

Rather than survey the general population, for PIREG we sampled from households who are buying new motor vehicles in California. We selected households whose past vehicle purchase and lifestyle patterns make them probable candidates for BEVs. These households own two or more vehicles, all of which were reliable and suitable for long distance travel, and the last new vehicle they purchased was a four cylinder sub-compact, compact, minivan or small pickup truck -- the body styles most likely to first be offered as BEVs. This allows us to easily review the lifestyle decisions which led to the purchase of that particular vehicle. The households are predominately owners of their own single-family residence and most have household incomes greater than $50,000. Public studies on the annual new car buying market do not exist; however estimates based upon a Newsweek study of new car buyers indicate there may be 200-350 thousand California households per annum in the population defined by our PIREG sample (Newsweek 1990). This estimate is substantiated by Rutherford et al (1994) who find 30% of the annual car market fit the same criteria as the population from which we drew our PIREG sample.

From this population we recruited a variety of household types to explore distinct lifestyles, including the following: households with various numbers and ages of children, including teenage drivers; households with one and two wage earners; and households of retired persons. We conducted PIREG interviews in three areas of California -- Sacramento, Santa Clara (southern San Francisco Bay area) and Orange (southern Los Angeles area) counties -- to uncover any important contrasts in infrastructure, urban form and consumer information related to BEVs, limited range and lifestyles. All three of these counties are largely suburban, reflecting the dominant lifestyle choice of Californians.

RESULTS FROM THE PIREG STUDY

This is not primarily a quantitative assessment of anticipated market shares for BEVs, but rather a detailed examination of the potential pivotal variables in the BEV market and of the lifestyle planning that households are likely to employ in evaluating BEVs for their own use. We report frequencies and some means and deviations, but we caution against generalizing these numbers, even to the population from which PIREG interviews are sampled. The results presented here are themselves hypotheses to be tested on a larger scale in the next phase of our research. These results do suggest, however, that previous BEV market studies may have serious validity problems.

Second car or hybrid household?

Previous BEV research has improperly framed the decision context for electric vehicles in terms of first, second and even third cars. Properly framed, the purchase of BEVs is a choice between a homogeneously-fueled fleet or a hybrid fleet. This is a new concept for households and requires interaction between the researchers, who have technical knowledge of the vehicles, and households, who ultimately know what such vehicles mean for their lifestyle.

Travel behavior studies have often conceptualized BEVs as a "second" car, using one or more of the following criteria: order of purchase; ranking of value; amount of use; or priority of use compared to the other vehicles in the household. In fact, the use of the term "second car" is a cultural-historical concept, related to the perceived purchase patterns of the nuclear family in the post-world war period, in which young families first acquired a car which the father used for work and a second car was purchased for mom to do shopping. One can still read this anachronistic cultural interpretation in many discussions of the role of electric vehicles (e.g. DeLorenzo, 1993), despite radical shifts in vehicle buying habits of households which include the specialization of vehicles and the increased role of women in automotive purchases.

Some argue that the newest car in most households would normally be the preferred long range vehicle, and that this vintage and use pattern defines the "first" vehicle. But in our sample of households, the issue of which vehicle would be the long range vehicle was determined by vehicle body style, not order of purchase or vehicle age. Universally, households in the PIREG sample use their larger vehicles, such as minivans or larger sedans, for long range travel because of their comfort and payload capacities. The smaller vehicles, which in the PIREG sample are also the newest vehicles, are used primarily for local driving, yet travel nearly as far as the larger vehicle in the household -- an average of 34 miles per day for the smaller, newer vehicle versus 37 miles per day for the larger, older vehicle. Thus in these households the "second car" label does not accurately describe any vehicle in the household. We find the terms "first" car, "second" car, etc. to be bereft of analytical content. Therefore, we do not assign the BEV a "second" car role in the household, but allow the household to explore the ways in which the BEV changes their assignment of vehicles to drivers and tasks.

Drivers are often, buy not always, assigned to a specific household vehicle. The exclusivity of this assignment varies greatly between households. Some households have very exclusive his-hers vehicle purchase and use patterns while others have a pattern of daily or even trip-by-trip allocation of vehicles to tasks and drivers. Therefore, at least one decision step for households when considering a BEV is to first estimate the routine trip allocations expected for the vehicle being purchased, as well as special, occasional demands on the vehicle. This decision involves weighing the adaptations required for those occasional trips against the benefits of BEVs, such as home recharging or low fuel cost.

In the PIREG interview, we first ask households to imagine replacing one of their vehicles with a BEV (note that this is not a purchase intention, but a use intention). Since we originally recruited households based upon their having recently purchased a car of the likely body styles of BEVs, we call this newly purchased vehicle the **target car** -- the vehicle we hypothesize will be replaced by an electric. However, not all households select the target vehicle to be a BEV: 7 choose another vehicle in the household. Additionally, 3 households,

with the income and car purchase habits to back it up, stated they would likely add an electric vehicle to their household stock of vehicles and 4 households felt incapable of using a limited range vehicle in place of any of their vehicles. Thus, 37 households chose the target vehicle.

Once the household chooses which vehicle will be electric, we proceed with the interview on the premise that the electric vehicle is exactly like the gasoline vehicle it replaces, except for its driving range and recharge characteristics. Households must next discover the minimum range to which they could imagine adjusting.

Minimum range

After examining their travel activity recorded in their 7-day trip diaries, households were asked to decide upon a minimum range to which they could adapt without undue (in their view) sacrifice of their lifestyle goals (which they define). The household is asked to explain how they arrived at such a range, and asked to relive the previously-recorded week using their hypothetical hybrid fleet of vehicles. The interviewer interjects with problems based on the known car use patterns of the household and potential emergencies in order to challenge the selected minimum range. The point is to explore how the household adapts to these unplanned activities -- whether they adjust their minimum range requirement, reassign the household's vehicles, or make other travel adjustments. The first column of Table 1 reports the minimum range selected by households.

A substantial number of households can adapt to even very short ranges. Fourteen of the 51 households adapted to a 40 mile range vehicle and 12 more to a range of 50 miles. A total of forty-seven households adapted to a range of 120 miles or less. Only four households simply could not accept a range limit without also having fast charging capability; the vehicles either were not parked during the day where they could be recharged at a slow or "normal" rate or they were always on the move.

What do you do when you need to go farther?

The interactive-problem solving quickly reveals it is too simplistic to assume that the BEV simply substitutes for one of the household's gasoline vehicles. Substitution is only the starting point for the household's learning. Households quickly recognize the possibilities for reallocating travel between vehicles and drivers as well as other strategies for incorporating the BEV into the household fleet.

Below we describe each of the strategies used by households in incorporating the hypothetical BEV into their fleet of vehicles. We also report the number of households who suggested they would employ each strategy.

1. *Work recharging:* We allowed persons who worked at locations with 100 or more employees to assume their employers would offer recharging facilities. Cars which are parked for several hours at work are capable of effectively doubling daily range. This is the second most frequently chosen adaptation to specific hypothetical range problems (22 households).[2]

2. *Swapping:* When the driver who normally uses the BEV needs greater range on a given day, he or she swaps vehicles with another driver whose range needs are less on that day. This was the most frequently chosen adaptation (25 households) in the face of a range problem. This behavior is already in the repertoire of many households in the sample. They currently swap vehicles for several reasons, e.g. increased passenger or cargo capacity for a day. Conversely, a few households never swap. These include households in which drivers identify strongly with their vehicles, or in which one driver does not like driving other vehicles because of standard transmissions, vehicle size differences, passenger load needs, or special cargo requirements such as child seats or business supplies which are inconvenient to transfer between vehicles.

3. *Switching:* When the driver of the electric vehicle needs more range, and there is another, unused vehicle in the household, that driver either switches to the unused vehicle at

the beginning of the day in anticipation of a need for additional range or returns home to switch vehicles later. This is the third most frequently chosen adaptive strategy, used by 21 households to solve a range problem. This strategy is most commonly employed on weekends when both drivers traveled together and one car was idle.

4. *Daytime charging:* A BEV user may recharge during the day at home between trips in order to extend daily range. This strategy is employed by 10 households to solve a specific problem, but additionally is expected as a routine practice by 16 households, often on weekends. If home serves as the hub of daily activity, as in the case of retired persons and home-workers, daytime charging at home is more likely to be an important strategy.

5. *Fast Charging:* We defined fast charging as being available at a special fast charging station which offers up to 80% of full charge in 20 minutes. Only 4 households expected to use this strategy to solve any range problem. Fast charging was widely rejected as a solution because of two issues: the long in-station time of twenty minutes and households' desire to use the gasoline vehicle for any travel extending beyond their routine activity space. Drivers who indicated they would like to fast charge have no time during the day to park their car at a possible slow charging location.

6. *Carpooling/van pooling:* A household overcomes a range problem by either traveling together in a household gasoline vehicle, or traveling in a gasoline vehicle not owned by the household. Note this definition extends well beyond trips to work. For example, two couples traveling together to a social activity constitutes a carpool under our definition. The 4 households using this solution live in Orange County where recent legislation has created employer-provided carpool incentives and heightened household awareness of this option.

7. *Renting:* A household or individual driver rents a gasoline vehicle to overcome a range problem. Only one household suggested renting to solve a specific problem. Households often describe vehicle renting as too expensive and too inconvenient.

8. *Borrowing:* A household borrows a gasoline vehicle from another household to solve a range problem. In 4 households, borrowing the car of a friend or family member was suggested as a reasonable adaptation, especially in emergencies. Borrowing was a normal practice of these households.

9. *Bike, walk, transit:* A household uses a bike, walks or uses transit to solve a range problem. Two households suggested biking and 4 suggested transit to solve specific problems.

10. *Chauffeur:* Gasoline vehicle driver in a household chauffeurs the BEV user to a destination which would have strained the limits of the BEV's range. Used by 2 households, in both cases the household was made up of retired persons.

11. *Reschedule trips:* Household or BEV user reschedules trips from a "long range" day to a day on which fewer or shorter trips are made. Rescheduling is used to solve range problems by only 2 households in the minimum range and adaptation phases of the interview, but is used by 5 households to optimize BEV use during the final interview phase.

12. *Cancel/reduce trips:* The household or the BEV driver cancels or shortens a trip to solve a range problem. Trips were only canceled or reduced in 4 households and then only in the last part of the interview as an optimizing action.

Transition from minimal to comfortable driving range

After determining minimum acceptable ranges, exploring adaptive strategies, and determining how much of the households travel could be shifted to a hypothetical BEV (which

has the minimum acceptable range), households were given the opportunity to "buy" a BEV with a different driving range and recharging time. The goals of this section were: to see whether households would choose to buy longer driving range than their minimum range; to observe trade-offs between range and recharge time; and to explore responses to different electric vehicle technologies (e.g. fast recharging and fuel cells) which offered more "gasoline"-like performance (i.e. longer range and faster refueling at fuel stations).

Driving range and recharging times were bundled together in "option" packages and presented in a priority evaluator (PE) table in which each range/recharging option was assigned a relative price -- that price being the difference between each range-recharge option and their minimum adapted range (their "base" option). Thus, these relative prices were customized for each household. In general, households could chose to pay a higher price than the base option by buying longer range or faster recharging, or to pay a lower price by buying shorter range or slower recharging. Some of the range-recharge options have a zero price difference from the base option bundle so that certain levels of range and recharge rates can be chosen with no hypothetical dollar cost (or savings). We do not report the prices used because they are not indicative of either willingness-to-pay for range and recharging time or the cost of actually providing specific range and recharge times. Consistent with the goals for this phase of the interview, the prices simply serve to stimulate further household exploration of range and recharging. We report on recharging rate choices later in the paper. The second column of Table 1 reports the ranges chosen by households in this phase as "comfortable range" and Table 2 shows the transition matrix for changes from the minimum range to this comfortable range.

Table 2 indicates that no households chose to "buy" a range shorter than their minimum range. While 34 households could adapt to a minimum range of 60 miles or less, only 8 households chose those short ranges when offered the range-recharge bundles in the PE table. Twelve households chose a 100 mile range. One hundred appears to be a "magic" number -- a round number which perhaps represents a perceived threshold required to accomplish lifestyle objectives. Four households who already had high minimum ranges of 100 to 120 miles moved to an even higher range of 150 miles.

These range choices are labeled "comfortable" because it allowed them to either eliminate all adaptive behaviors previously necessary to adapt to their minimum acceptable range, or to reduce the frequency of such adaptations to only a few occasions per year. In the end, three-fourths of our households discovered that replacing one of their vehicles with a BEV with 100 miles or less driving range made virtually no difference in their ability to accomplish their chosen activities.

We observed tremendous instability in households' choices of range when presented with incremental information and new problems. Reflection on their own travel and the introduction of information on BEV range and recharging elicited various range and recharge rate selections at different points in the interview. Households often discussed their selections at length and it was not uncommon for households to make three different range choices during the minimal range, adaptation and comfortable range stages of the interview.

New household decision variables related to driving range

We observed three critical new decision variables in households' decision making regarding limited range. These variables have not previously appeared in survey work on the BEV market. The first is driving-range safety buffers, the second is routine activity space, and the third we call the critical destination.

The *safety buffer* was the range to be left on the electric vehicle at all times. (As a feature of the BEV we posited instrumentation which precisely estimated the remaining driving range at all times.) Most households in this study responded that they wanted twenty miles of range always left on the vehicle. Households arrived at this 20 mile buffer almost irrespective of the types of hypothetical emergency situations created by the interviewers or the location of the household with respect to emergency services and activity locations. Fourteen households were able to adapt to a 40 mile range vehicle while maintaining this safety buffer -- that is, they

regularly accomplished their daily activities while traveling less than 20 miles in one of their vehicles.

Routine activity space contains the locations of activities that the household accesses on a routine basis, including work, schools, doctors, banks, favorite shopping locations, grocery stores, local family and friends. Households are quite aware of this set of destinations and most are familiar with the distances to these activities. These routine activities form the basis for the initial judgment of driving range needs and the value of home recharging. For households with geographically small routine activity spaces, home recharging provides virtually all recharging needs and is therefore quite attractive.

The *critical destination* is the furthest destination which the household member using the BEV feels they must be able to reach, perhaps for an emergency or for activities important to their lifestyle. They must be able to reach this destination even when the gasoline vehicle is not available. Common critical destinations are a friend or family member who is visited frequently or a favorite recreational location. Not all family members choose the same critical destination. In some cases, one member identifies a destination which is already part of the household's activity space, either within the routine activity space or otherwise frequented. Another member may argue for an *imaginary critical destination*, a destination which is not actually in the travel history of the household, but which the person nevertheless wants available.

Sometimes singly, sometimes in combination, these three decision variables act to determine the driving range choices of households in our study. What is clear to us is that households have widely varying degrees of self-awareness of these elements prior to actually documenting their travel in their travel diaries. Faced suddenly with a distance budget (in the form of a BEV purchase decision), it appears most households will require a period of learning to determine their range choices.

It is true that in some households, one member did express discomfort with buying a vehicle with any range limits. Their objections were not based upon calculation of demonstrated needs, but rather upon desires for the open-ended possibilities of long range and fast refueling. However, in the midst of lifestyle planning with their partner during the interview, they agreed that the household was not greatly inconvenienced by having one limited range vehicle. Only in households in which each driver made highly autonomous auto purchase and use decisions did desires for unlimited range prevail over the practical reality of how and where the household actually travels.

Response to long recharge times

Faced with "refueling" times measured in hours, households were far more sensitive to changes in driving range than recharging time. The base range-recharge option in the PE table for each household had a recharge time of either 4 or 6 hours, depending on the range. Most households then chose 6 or 8 hour recharging. That is, households almost universally preferred to solve any problems by increasing the BEVs driving range, rather than decreasing charging time. The single most common choice pattern in the PE table was for households to find a longer range, but slower charging, vehicle which "cost" the same as, or only slightly more than, the base option vehicle. Only 3 households chose the fast charging option (at any range). We described fast charging as taking twenty minutes from arrival at the station to departure to get 80 percent of a full charge. Most participants could not imagine spending more time in stations than about ten minutes -- twenty minutes simply was not "fast". The few households interested in fast charging also wanted longer ranges either because they intended to use BEVs for long distance driving or their vehicle is not parked at work or at home for any substantial time during the day and thus cannot be conventionally charged during the day.

Recharging of BEVs is an unfamiliar concept, and much of the interview is spent discussing how recharging works. Many surveys and reports on BEVs tell readers that a BEV with 100 miles of range takes, for example, six to eight hours to recharge. That technical fact explains a certain limit on BEVs, but does little to help potential BEV users imagine what they would do on a daily basis or what sort of problems they might encounter. Our PIREG

households discovered there are only a few days per year they would actually drain the batteries low enough in their comfortable-range vehicle to require a full six or eight hour recharge. We find in our interviews that most daily recharging would entail only 2-3 hours recharging at home at night to recover 20-50 miles of daily use, plus occasional daytime recharging at work and other daytime parking locations. This daytime charging may be especially valued for lead-acid batteries, which perform better and last longer if not deeply discharged.

The sheer quantity and complexity of information regarding recharging characteristics is a barrier in the BEV market. Recharging rates for many battery types are not constant -- e.g. for lead-acid batteries, energy is recovered more quickly in the first portion of the recharge period. There may be many types of batteries in different BEVs and many types of recharging outlets with distinct costs depending on location, time-of-day and size of electrical service. All this makes BEV recharging sound difficult, complicated and inconvenient. But in households whose lifestyles fit within the distance budgets of BEVs, recharging may not be an inconvenience; just the opposite, home recharging and work recharging can eliminate gasoline station visits. Depending on trip patterns and time demands on drivers, as well as attitudes towards gasoline stations, home recharging is a substantial perceived benefit for many households. Many women who are the primary caregivers to the family's children stated they did not like to go to the gas station with the children in the car. This necessitated scheduling gas station visits between trips in which they were chauffeuring children, or requiring their spouse to refuel the vehicle. Short, home-based trips whose sole purpose is to buy gasoline were not uncommon in our sample.

Flexibility of vehicle assignments to household trips

The distance traveled in the vehicle replaced by a hypothetical BEV changes very little in the search for the minimum range to which the household can adapt. In essence, the households find the minimum range BEV they can use to accomplish the same activities in their diary week. Only six households substantially reduce (>10% reduction) the proportion of the household travel assigned to the vehicle selected to be replaced by the hypothetical BEV. Thirty-two households make no changes in the use of the selected vehicle.

In the last phase of PIREG interviews, households optimized the use of their hypothetical hybrid fleet under the premise that gasoline prices had risen to $5 per gallon. The hybrid fleet consists of a BEV of the minimum-adapted range and all the household's other ICEVs. The intent of this exercise was not to test their response to expensive gasoline per se, but rather to test their ability to reallocate driving between vehicles under conditions which greatly favored the use of one fuel (electricity) over the other (gasoline). When pressed by high gasoline prices to increase the use of their BEV, virtually all the households shifted additional travel to it. Three households that did not are poor candidates for BEVs because they had greatly reduced the miles assigned to the BEV in their earlier search for a minimum adapted range and were unable to shift travel back to the BEV in the optimizing scenario. After optimizing vehicle use, the BEVs in the 48 other households traveled an average of 17 percent more miles than the gasoline vehicle it replaced had traveled during the diary week. Half the households shifted at least12 percent more travel to the BEV, and one-fourth of the households shifted at least 25 percent more.

These results further support the idea that analyses which assume simple substitution of a BEV for one household vehicle are too simplistic. Under a variety of conditions, households are able to shift travel between household vehicles. Our interview uses a "shock" technique to force households to use fuel prices to make these adjustments. But the results suggests a dynamic in which new hybrid households may shift increasing amounts of their travel to a BEV, if they realize the promise of lower operation and maintenance costs or are offered vehicle use incentives such as preferred parking and use of high-occupancy-vehicle (HOV) lanes.

Market Segments: Household's Adaptability to BEVs

Based on the preceding results, we classify households into one of three categories with respect to their ability to incorporate a BEV into their household fleet. We find 29 of the 51 households are *pre-adapted* to BEVs. To use a truly limited-range BEV, these households require no change in their travel behavior, no away-from-home recharging location (with the possible exception of work place recharging in 13 cases), and no change in the body styles of vehicles they buy. Their routine activity space is small in geographical extent and their critical destination is easily reached in a BEV. The "comfortable" range selected by all these households is less than 100 miles -- sometimes much less.

We classify another group of 15 households as *easily adapted.* These households infrequently switch vehicles or swap vehicles between drivers to accommodate a limited range vehicle. These behaviors are already part of these households' repertoire of travel behaviors. They are more likely than pre-adapted households to want to recharge at work during the day. Their routine activity spaces are larger in size and their critical destinations are farther away. These households choose "comfortable" driving ranges between 80 and 100 miles.

Lastly, 7 households are *non-adapted.* These households exhibit one or more behaviors which make it difficult or impossible for them to include a BEV in their household stock of vehicles: they have large routine activity spaces resulting from long or uncertain daily trips for work (as opposed to trips to work), a critical destination beyond 150 miles from home, or inflexibility in the assignment of household vehicles. Absent large changes in their routines, lifestyle goals or budgets, these households would not purchase a BEV.

WHY DO PREVIOUS STUDIES ESTIMATE HIGH PENALTIES FOR LIMITED RANGE?

One inescapable conclusion of the PIREG interviews is that many multi-car households easily adapt to driving range limits on one household vehicle. How then do we interpret previous research which estimates extremely high disutilities for limited driving range? One of our hypotheses is that households do not understand, or not aware of, the distances of either their individual trips or daily travel. To understand how well households know their travel distances, we asked PIREG participants to estimate each day's travel at the start of the day and each trip's distance at the start of the trip. They also recorded odometer readings, which allowed us to calculate the actual distance traveled each day and each trip.

As expected, participants were much better at estimating travel distances for regular trips than irregular trips. Commute trips are the most common type of regular trips. Commute trip length in our sample ranged from 1 to 45 miles, with a mean of 12.6. The distance of the first recorded commute trip was generally estimated accurately, with an average absolute error of 1.1 miles, or 8.7% of the mean estimate. Greater absolute and percent errors were made in estimating the distance of the longest (non-commute) trip made during the week, which is typically a trip to an irregular destination. No matter how the data are analyzed to distinguish between errors due to irregularity of the trip and errors due to the length of the trip, we find average errors around the mean estimate that are 3 times larger than the commute trip errors. Analyzing only those longest non-commute trips that are less than 45 miles in length to remove the possibility that people are simply less able to estimate longer distances than shorter distances, yields a mean trip length of 22.5 miles and a mean error of 5.0 miles (24%). We also selected the worst estimate for each driver, regardless of the trip type or length. The average worst error was 34% of the actual trip distance. Since initial commute distance estimates have an average error of only 8.7%, drivers are clearly estimating other trip distances with much less accuracy.

Drivers showed improvement during the diary week in estimating trip lengths. The average error in estimated trip distance between the first and third recorded commute trip dropped from 8.7% to 1.2%. The act of estimating and measuring trip distances was itself a

learning process for many households. Several households indicated the diary had increased their awareness of both the number of trips they made and how far they traveled.

On the issue of total daily distance estimates, we examined the most poorly estimated day for each driver. Drivers had more difficulty estimating long travel days, just as they had difficulty with irregular trips. The average absolute worst error in estimating how far an individual driver would travel on a given day was 17 miles or 34% of the average actual distance for that day. Households which underestimated their longest day tended to do so by a larger amount than households which overestimated their longest day; the mean underestimate was 28 miles and the mean overestimate was 18.6 miles.

Despite the magnitude of these errors, we cannot attribute the high disutility of limited range inferred from stated preference to these errors. We created worst case scenarios by adding a households worst absolute error to its longest travel day (regardless of whether they actually occurred on the same day). The sum is still much less than the driving range of gasoline vehicles and well within the range of the BEVs considered in this study for all but a few households. In only four households does the sum of the longest day and the worst error exceed 150 miles. Note we have added the absolute value of the worst error, thus inflating the apparent range requirement.

It is not the travel estimation errors per se which are the source of the apparent disutilities of limited range vehicles, rather it is consumers choice of a familiar anchor when faced with the unfamiliar prospect of a distance budget. Although it was not a formal part of the study[3], many PIREG participants stated at the end of the interview that prior to completing their travel diary, they would have offered much higher estimates of their daily minimum range needs. But after reviewing their actual driving needs and lifestyle goals, they found that they could adapt to a limited ranged vehicle. Households deal daily with money and time budgets, but have no *daily distance budgets,* and currently do no accounting of distances (unless they do so for business purposes or to gauge fuel consumption rates). When consumers, unfamiliar with a distance budget, are asked to respond to limited ranges, they typically respond with a range they are familiar with -- that of their current gasoline vehicles. But those vehicles have refueling characteristics and range instrumentation optimized for open road, long distance travel. We have observed this anchoring to the familiar gasoline vehicle range in focus groups (Turrentine, et al; 1992) and believe this behavior is largely responsible for the high apparent disutilities estimated by previous stated preference studies.

CONCLUSIONS

Our investigation of hybrid household behavior, motivated by discrepancies between travel behavior and stated preference studies and by the conflicting results of attitude surveys, suggests the following. First, travel behavior studies are flawed methodologically. Their results are biased not only by their use of one day travel diaries and questions regarding "typical" rather than actual travel, but more importantly by the assumption that the BEV is a substitute for <u>one</u> particular household vehicle.

Second, stated preference studies, which result in high disutilities for short driving ranges, are incorrect. We find that hybrid households are willing to engage in a wide range of adaptive behaviors and that, given the opportunity to reflect on their own travel, most discover that a range limit on one household vehicle is simply not a problem. Stated preference studies are likely measuring uncertainty and unfamiliarity, not utility. The large apparent "utility" of long range may simply be an artifact of consumer conservatism when faced with an unfamiliar technology.

Third, surveys of "green" attitudes fail to provide useful insights into who may buy BEVs. If we accept the definition of a "green" market as a contingent of consumers who are willing to pay several thousand dollars extra for a zero emissions vehicle, then we do not find strong evidence for such a market.

However, we do find evidence for a viable BEV market. We believe that a large portion of multi-car households are "pre-adapted", or can easily adapt, to the BEV range and recharge characteristics attainable with technology likely to be available in 1998, the first year "zero emission vehicles" must be sold in California. What these households lack to make a BEV purchase decision is information and experience.

We are not, however, arguing that all the pre-adapted and easily adapted households in this study will purchase a BEV. We see significant barriers in the market. In fact we find little evidence in this study that most consumers are willing to pay significantly more for BEVs. We do find that most of the households in our sample can easily adapt to vehicles of far shorter range than previous research suggests and most PIREG households see a few simple adaptations as a reasonable commitment in the context of an historical shift to clean cars. In pre-adapted and easily adapted households, BEVs with driving ranges of 60 to 100 miles will compete with gasoline vehicles at roughly comparable prices, but only after the requisite education and reflection which consumers will require to estimate the value of hybridizing their vehicle holdings. Our findings suggest that the market for electric vehicles will require substantial educational efforts, assisted by government and industry.

The problem is that previous market research and thinking about the BEV market has neither explored complex range and recharging issues with consumers nor provided an adequate context for consumers to estimate the impact of BEVs on their lives. Nor has any previous study adequately addressed the positive utility which may be assigned to home refueling. For this reason, we expect that previous survey work based on hypothetical choices has systematically underestimated the BEV market because consumers are unfamiliar with the potential ways of combining gasoline and battery electric vehicles in their households. Future survey work could be improved if it incorporates information on the adaptive behaviors and critical decision variables used by our PIREG households: vehicle switching and swapping, home and workplace recharging, range buffers, routine activity space and critical destinations.

Additionally, it is premature to focus on consumer preferences for BEVs. Our work demonstrates that preferences for driving range and recharging are as yet unformed. In a complex and rapidly changing information milieu such as that around electric vehicles, we are well advised to create experimental and experiential contexts. Given all this, market research must focus less on providing questionable market penetration estimates and instead work to identify potential market segments for BEVs and to understand the nature of market barriers. Our social goals of energy flexibility and clean air and our private goal of accessibility to desired activities will be better served by an understanding of market dynamics and information on how to build viable markets for electric transportation options than by contentious and unreliable estimates of some future end-state.

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Table 1: Minimum Acceptable and Comfortable Driving Range

Driving Range	Number of households for whom this was the minimum acceptable range	Number of households for whom this was the comfortable range
40 miles	14	1
50 miles	12	3
60 miles	8	5
70 miles	3	3
80 miles	6	10
90 miles	0	3
100 miles	2	12
120 miles	2	6
150 miles	0	4
Unlimited miles	4	4
Total	51	51

Table 2: Transition Matrix from Minimum to Comfortable Range

	Comfortable range								
Minimum Range	40 miles	50 miles	60 miles	70 miles	80 miles	90 miles	100 miles	120 miles	150 miles
40 miles	1	1	1	1	3	1	4	2	
50 miles		2	3	1	2		3	1	
60 miles			1		4		1	2	
70 miles				1	1		1		
80 miles						2	3	1	
90 miles									
100 miles									2
120 miles									2

Note: This table does not include the 4 households who could not/would not accept any limits.

FOOTNOTES

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[1]The variable of range is separated from other refueling\recharging attributes such as type of fuel, speed of recharging or refueling. We selected from the data in these studies the 50 mile range to fit the bottom end capabilities of BEVs and the 200 mile range to represent the most extreme possibilities for BEVs, although such a battery system is not yet demonstrated for conventional payloads and driving cycles.

[2]In PIREG we did not discuss potential differences in on-off peak electricity rates for recharging, although such behavioral issues are important for utility load management. We were most interested in consumer behavior outside such rates, and it is unlikely consumers could easily assess their valuation of daytime opportunity charging given different electricity prices, even in the PIREG interview context. Our results cannot be used to measure potential daytime use assuming differential rates, rather they demonstrate how much daytime charging BEV drivers might do if such charging is easy and inexpensive.

[3]We do not discuss household's "preferred" range prior to the PIREG interview. We wished to avoid both anchoring to a pre-concieved number which we had observed in previous work over-dramatization of the magnitude of any possible changes in their daily range choices.