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Plug-In Hybrid Electric Vehicles' Potential for Petroleum Use Reduction: Issues Involved in Developing Reliable Estimates

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ABSTRACT

This paper delineates various issues involved in developing reliable estimates of petroleum use reduction by widespread introduction of plug-in hybrid electric vehicles (PHEVs). Travel day data from the 2001 National Household Travel Survey (NHTS) are analyzed to identify vehicle miles of travel (VMT) that can be transferred to electricity from the grid. Various PHEV charge depleting (CD) ranges are evaluated, and 100% CD mode and potential blended modes are analyzed. The NHTS data are also examined to evaluate the potential for multiple PHEV battery pack charges per day. Data from the 2005 American Housing Survey (AHS) are analyzed to evaluate the availability of garages and carports for at-home charging of PHEV battery packs. The AHS data are also reviewed by Census region and household location within or outside metropolitan statistical areas (MSAs). To illustrate the lags involved, the historical new vehicle market share increases by the diesel powertrain in France (a highly successful case) and the emerging hybrid electric powertrain in the United States are examined. A new vehicle technology substitution statistical model is estimated from the French diesel example to illustrate a historically plausible successful new PHEV powertrain market share expansion. Using this share model, the trends in U.S. light-duty sales and light-duty vehicle stock are evaluated to estimate the time required for hypothetical successful new PHEV powertrains to achieve the ultimately attainable share of the existing vehicle stock. Only when such steps have been accomplished will the full oil-savings potential for the nation achieved.

INTRODUCTION

Plug-in hybrid electric vehicles (PHEVs) can use grid electricity to charge their battery packs and use the electricity thus stored to reduce petroleum consumption. In this paper, we assume, as have most studies to date, that a PHEV will have the capability to drive all electrically at moderate and high speeds and when driven fairly aggressively. PHEVs differ from the hybrid electric vehicles (HEVs) currently in the market. The current HEVs do not use grid electricity, use only their internal combustion engines (ICEs) and regenerative braking to charge battery packs, and travel all electrically only at very low speeds. Several of the coming near-term PHEVs will not operate all electrically in many driving conditions. Such PHEVs are said to charge deplete in "blended" mode. For this paper we assume "full" PHEVs, capable of all electric operation in the vast majority of driving conditions when depleting the battery charge. We examine various issues that influence the PHEV's potential to reduce national petroleum use.

We use the 2001 National Household Travel Survey (NHTS) to determine how vehicles are used and how much travel can potentially rely on electricity *(1)*. Put another way, under different sets of working assumptions, we examine the share of vehicle miles of travel (VMT) that can be electrified. We also refer to the 2005 American Housing Survey (AHS) to obtain data on houses with a garage or carport, whose residents are likely to be the buyers of PHEVs *(2)*. Finally, we use a vehicle simulation model, the Powertrain Systems Analysis Toolkit (PSAT), to simulate various PHEV powertrain configurations and analyze the differences in their impacts *(3)*.

The 2001 NHTS covers 69,817 households. Its one-day trip file consists of 642,292 trips made by the residents of these households. Of these 642,292 trips, 387,431 were made by personal vehicles driven by one of the responding drivers. When trips with unreported travel times and travel distances are dropped, 366,084 trips made by 84,916 vehicles are available for further analysis. These trips and vehicles include samples from areas that requested additional sampling. When these add-on samples are removed, 142,111 trips made by 32,022 vehicles are left. The sample without the add-on samples is called the "national sample" by the Federal Highway Administration. We use the national sample in the analysis presented here.

The 2005 AHS consists of 56,650 interviews relating to 124.4 million housing units, of which 108.9 million were occupied. In our analysis, we examine the 108.9 million occupied housing units.

The PSAT model allows vehicle systems analysts to evaluate alternative powertrain configurations through simulations without having to build a vehicle. The model can provide detailed information relating to vehicle performance and energy consumption. Selecting a single passenger car "glider" (vehicle body), we simulated four PHEV powertrain configurations and evaluated battery and ICE energy use under several different driving patterns, varying in average speed and aggressiveness of driving.

A DISCUSSION OF HEV, PHEV, and EV TYPES

Parallel and series powertrain configurations are two primary options for PHEVs. When either of these types of PHEV operates by drawing power from the battery, the PHEV is considered to be operating in the charge depleting (CD) mode. When operating in CD mode without any assistance from the ICE until the battery pack is depleted, the PHEV is operating in 100% CD mode. When operating in CD mode with assistance from the ICE, the PHEV is considered to be operating in blended CD mode. Blended CD operation is possible in both the series and parallel configurations.

HEVs and PHEVs use "electric machines" to provide power to the wheels and to charge battery packs. If an electric machine typically provides power to the wheels, it is usually called a motor. If an electric machine typically is used to generate electricity to charge the battery or to operate a motor, it is called a generator. Electric machines are reversible — they can be used as motors or generators.

HEVs are designed to operate in charge sustaining (CS) mode, in which the battery charge is varied by only several percent. PHEVs can operate either in CD or CS mode. They are designed to first operate in CD mode, then in CS mode. The central location of the CS state-of-charge (SOC) operating window is at a considerably lower SOC for a PHEV than for an HEV. This may stress the PHEV battery considerably more than an HEV battery, representing a greater challenge for PHEV battery packs than for HEV packs.

The parallel configuration uses an ICE, via a traditional mechanical drive and/or an electric motor, to propel the PHEV. A full PHEV's electric motor and battery pack will have capabilities to propel it electrically at nearly all speeds and acceleration rates. In the parallel hybrid, there also is a mechanical linkage from the ICE to the wheels that can assist the electric motor when acceleration is very aggressive or speed is very high. In a parallel blended CD mode PHEV, the motor provides a smaller share of total power than in the full PHEV. In this case, the battery pack and electric motor have capabilities to propel the PHEV fully electrically only at low-to-medium steady speeds. A blended mode PHEV requires ICE assistance for even moderate acceleration, during passing episodes, and at moderate-to-high speeds.

Figure 1 depicts the fuel and electricity flows for a series and simple parallel hybrid, at an acceleration rate for which both the engine and battery pack must simultaneously provide power and energy to accelerate the vehicle. If this condition exists during CD mode, then the vehicle operates in blended mode. If the engine is off during all accelerations when the charge is depleting, without any fuel or energy flow, then the vehicle's CD operation is all electric. The diagrams are illustrative (see endnote)[i]

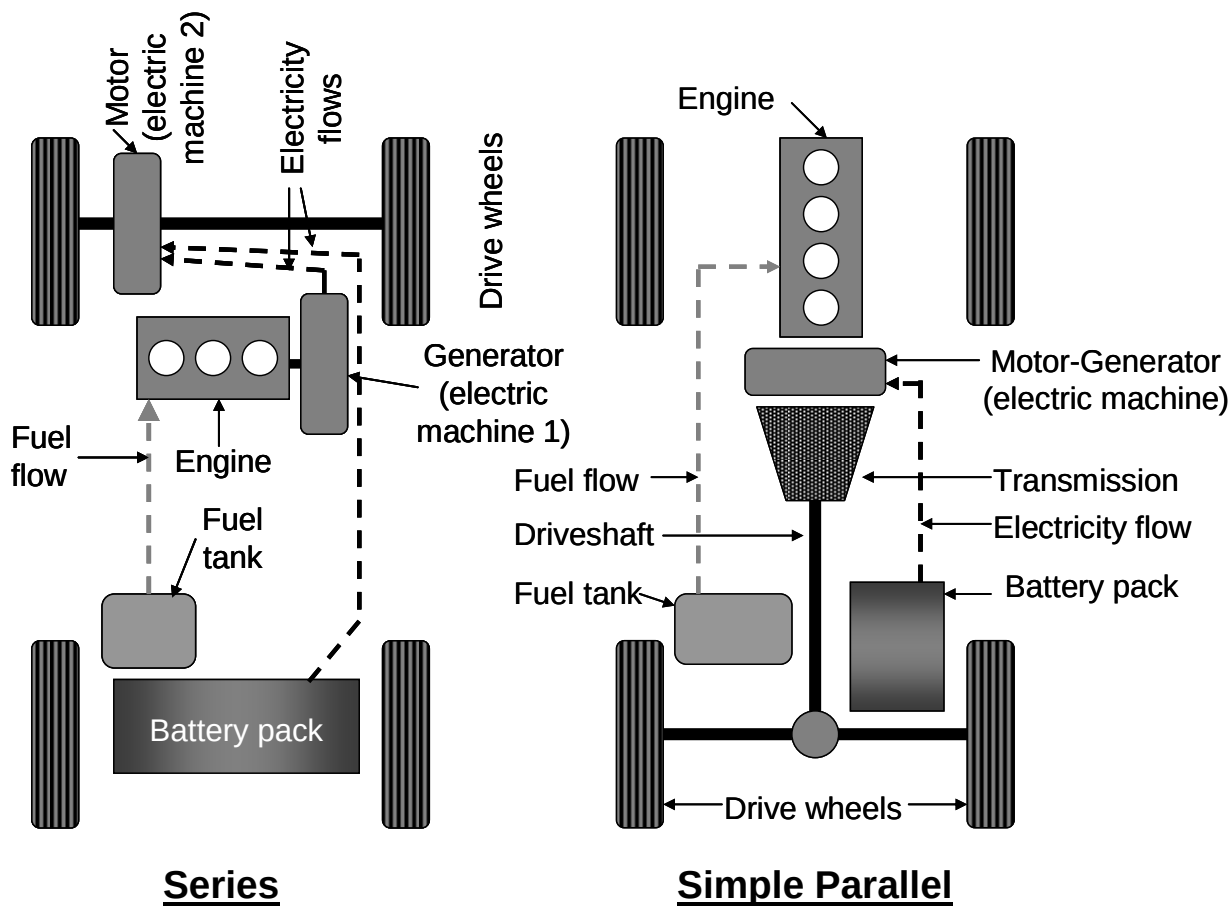

Figure 1 Energy Flows of Simple Parallel and Series PHEV Configurations when Rapidly Accelerating

Several types of hybrid are possible. The only hybrid quantified in this paper is the split hybrid (mostly parallel, partly series), which is most common in the market today. The split hybrid is more complex than the simple parallel or series HEVs/PHEVs described in Figure 1. This configuration, shown in Figure 2, has two electric machines and most commonly is applied with front-wheel drive. The larger of the two electric machines is labeled a motor and the smaller a generator, but both operate either as a motor or a generator. The Toyota Prius and Ford Escape use this type of hybrid powertrain. One other type of parallel hybrid, among several, is the pre-transmission hybrid, in which only one electric machine is used, placed between the engine and transmission, with clutches on both sides of the electric machine. This powertrain is found in the prototype Daimler Sprinter HEV and PHEV, which use rear-wheel drive. Although Figure 1 excludes a symbolic representation of the clutches, it essentially represents the Sprinter configuration.

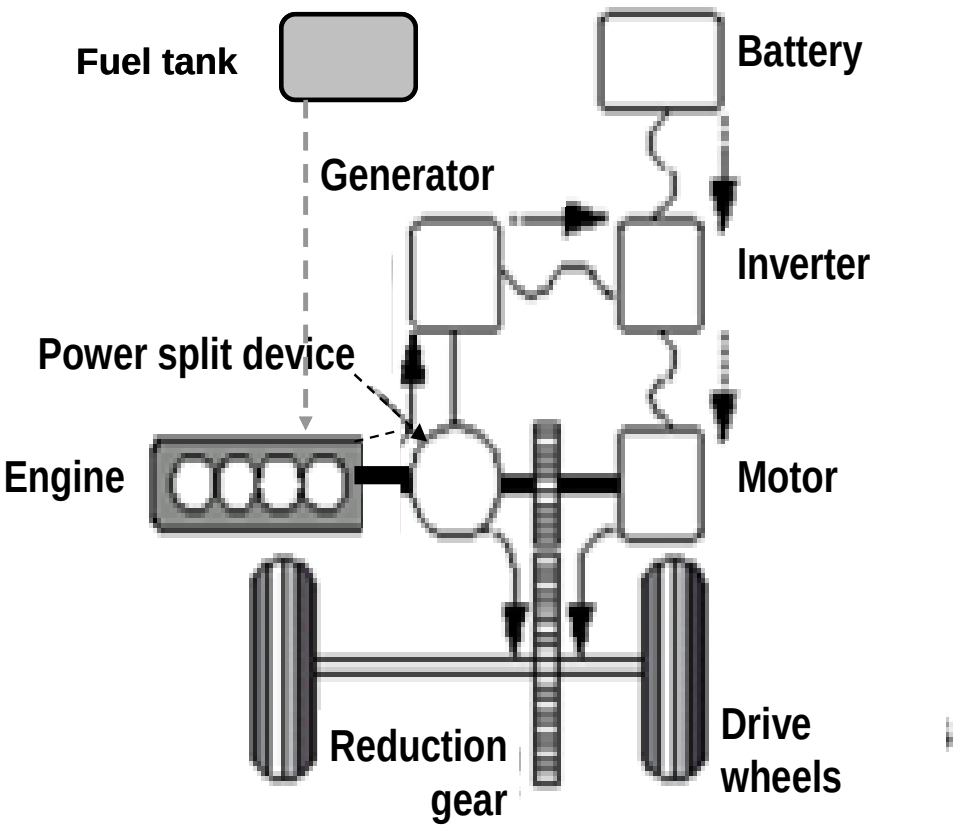

Figure 2 Energy Flows of a Split HEV (or PHEV) Configuration when Rapidly Accelerating

The series configuration uses only the electric motor to propel the PHEV. The series powertrain (or pathway, as in the split hybrid) requires two electric machines. In practice, for the series design, the battery pack will have the capability to propel the PHEV at nearly all speeds and acceleration rates. The key difference between a parallel (or split) and series powertrain is that the series powertrain has no mechanical linkage from the engine to the wheels. The engine operates a generator, which may generate electricity either to charge the battery or to turn the motor (second electric machine) to propel the vehicle.

In a sense, a battery electric vehicle (EV) is like a series HEV, except that the generator of electricity is off-board the vehicle. Electric power is seldom generated by ICEs at an electric power plant. Some types of electric power plants attain significantly greater efficiency than ICEs. Further, few of them use oil-based fuels. Thus, there are significant oil use reduction opportunities available via the introduction of electric drive, which is possible with EVs and PHEVs. However, the disadvantage of EVs is that — for a cost comparable to that of a PHEV — their range is far more limited. We find that the ability of a PHEV to operate over a range comparable to a gasoline vehicle creates a far greater opportunity to "electrify" miles than would a similarly sized vehicle without an ICE to supplement the battery pack (i.e., limited range EVs). This PHEV advantage is addressed in the next section.

FULL PHEV POTENTIAL — VMT TRANSFER FROM GASOLINE TO ELECTRICITY

The NHTS data for one-day travel show that 20% of vehicles were driven 10 miles or less, 42% were driven 20 miles or less, 57% were driven 30 miles or less, 68% were driven 40 miles or less, and 82% were driven 60 miles or less. In terms of VMT, 3% were contributed by vehicles driven 10 miles or less, 11% by those driven 20 miles or less, 20% by those driven 30 miles or less, 30% by those driven 40 miles or less, and 47% by those driven 60 miles or less.

EVs cannot travel beyond their CD range, while PHEVs can. Accordingly, the maximum electrified VMT of EVs will be limited to VMT up to and including travel distances equivalent to their range. We estimate the maximum miles electrifiable by EVs as if all vehicles driven up to the range capability of the EV were EVs. The PHEVs that travel further than a specified CD range can also electrify the first miles of their daily travel, up to that range. Fortuitously, because PHEVs can drive well beyond their CD range, they can increase the maximum electrified VMT by transferring all post-charge VMT up to their CD range to electricity, then continue in CS mode using gasoline. This is illustrated in Table 1, where five PHEVs with different ranges are shown. PHEVs with a 10-mile CD range and operating in 100% CD mode can electrify the same VMT as EVs up to that CD range (3.1%). However, far more importantly, they can electrify the first 10 miles for all vehicles traveling beyond 10 miles, thereby electrifying an additional 19.4% of all VMT on a typical day.

TABLE 1 Estimation of Maximum Electrifiable VMT at Various CD Ranges of PHEV

Daily Travel Range of Vehicles (Miles)	VMT Share (%) in NHTS 2001	One Charge/Day, Maximum Electric VMT % by PHEV[§]				
		CD Miles = 10	CD Miles = 20	CD Miles = 30	CD Miles = 40	CD Miles = 60
Up to 10	3.1	3.1	3.1	3.1	3.1	3.1
10.1 to 20	7.5	4.8	7.5	7.5	7.5	7.5
20.1 to 30	9.6	3.8	7.5	9.6	9.6	9.6
30.1 to 40	10.0	2.8	5.6	8.4	10.0	10.0
40.1 to 60	17.0	3.4	6.8	10.2	13.6	17.0
More than 60	52.8	4.6	9.1	13.7	18.2	27.3
Total all vehicles	100.0	22.5	39.6	52.5	62.0	74.4
Unable to use all range		**3.1**	**10.6**	**20.2**	**30.2**	**47.2**
Heart of the market		19.4	29.0	32.2	31.8	27.2

§ Column total assumes 100% market share by specified PHEV, one charge per day, and PHEV operation in 100% CD mode until the battery is depleted. The solid line and "unable to use all range" segment divides the upper limit of the proportion of VMT in each column that could be served by EVs. The entire column can theoretically be served by PHEVs, although the "unable to use all range" segment is for improbable purchasers.

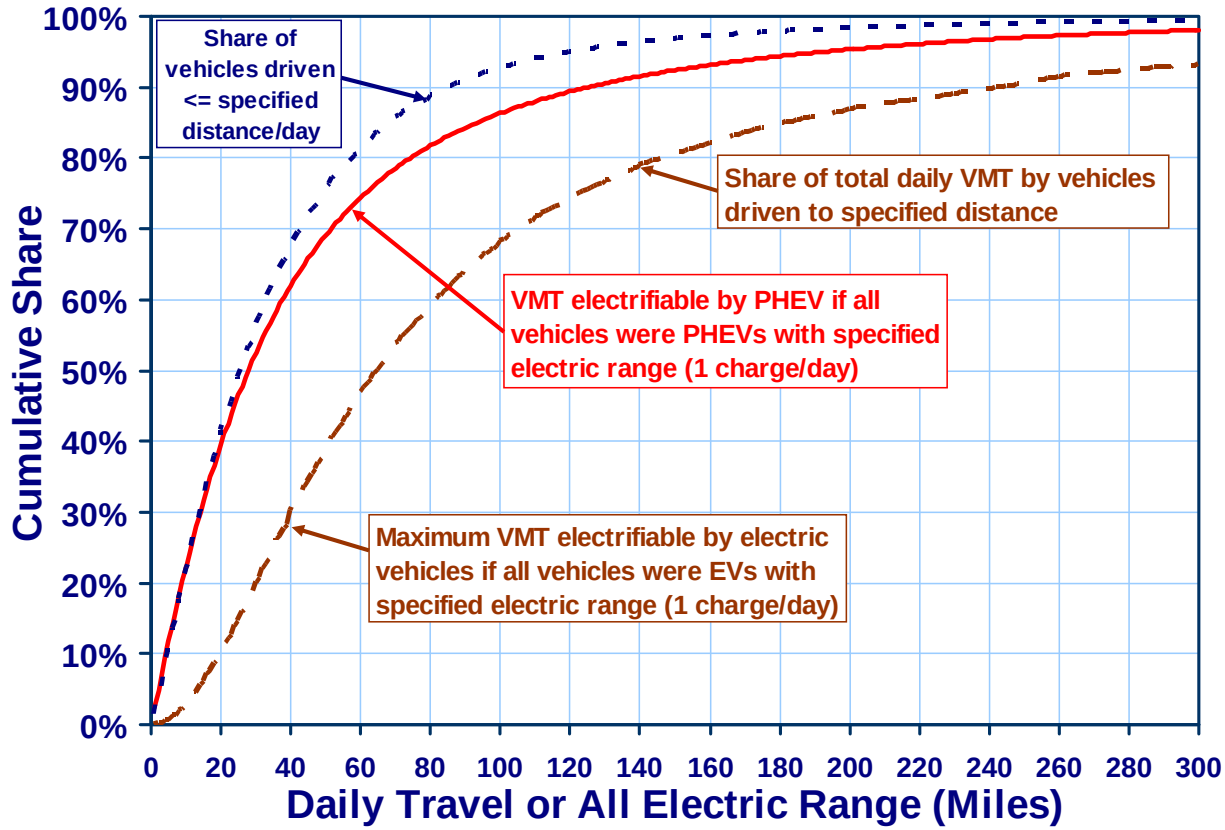

Figure 3 NHTS One-Day Travel Data and Maximum Potential Electrified VMT by PHEV

The NHTS data in terms of vehicle and VMT shares and maximum potential electrifiable VMT at various EV and PHEV ranges are shown graphically in Figure 3. The solid line in Figure 3 shows the maximum potential electrified VMT, if one assumes that all PHEVs have the specified range on one charge per day and the vehicle fleet is entirely served by such PHEVs (100% fleet market share). We term this curve as the maximum distance-weighted probability of VMT electrification, assuming that only one range option has been provided to vehicle owners.

Data in Table 1 and Figure 3 show the maximum potential transfer of VMT to electricity when all vehicles in the nation are full PHEVs with the single specified theoretical range capability, charged once, and completely charge depleted once per day. In reality, market penetration will be affected by the PHEV cost and perceived return. In light of the expense of batteries, sales of PHEVs to those who cannot fully utilize the battery pack is far less probable than for those who can effectively utilize the pack each day. Thus, we separate out the proportion of the daily miles of travel that are less than the specified CD range, treating these customers as unlikely purchasers of PHEVs. The "heart of the market" for PHEVs is the set of customers driving further than the CD range (i.e., those who can get maximum value from their battery packs).

A drawback of an EV is that one must purchase a very costly reserve range if the vehicle is to be a reasonable substitute for a gasoline vehicle. In effect, since range in an EV is so expensive, the cost of the vehicle becomes prohibitive. While our theoretical attainable shares for EVs at 20 miles of range would be 11.6%, Kurani, Congleton, and Turrentine estimated that a City EV that exhibited a 20 mile range limitation when driven on interstate highways (much less than the advertised range) might be capable of a market share of 2-4% *(4)*. Thus, these shares of miles electrifiable by EVs should be regarded

as upper bound estimates. Since the battery is such an expensive storage device, the less of it purchased, the better. We have constructed a "heart of the market" approximation in Table 1, assuming that consumers who do not normally drive as far as the allowable CD range for a PHEV will not purchase the vehicle due to its high cost for the service obtained. In effect, for those who drive very few miles per day, we argue that the conventional powertrain will be preferred. This is consistent with our 2007 calculations of the net present value of battery packs as a function of utilization rate *(5)*.

Thus, a 10-mile CD range PHEV will be cost effective to those traveling longer than 10 miles. This assumption would reduce the extent of VMT that can be electrified from 22.5% to 19.4% for a 10-mile CD range, from 39.6% to 29% for a 20-mile CD range, from 52.5% to 32.2% for a 30-mile CD range, from 62.0% to 31.8% for a 40-mile CD range, and from 74.4% to 27.2% for a 60-mile CD range.

The "heart of the market" concept is illustrated in Figure 4. The solid line in Figure 3 that represents distance-weighted probabilities is shown by dotted lines in Figure 4, and the "heart of the market" curve is shown by solid lines. The "heart of the market" curve shows that if a single range were to be selected, that range would likely be best somewhere between 20 and 30 miles. No more "heart of the market" benefit is obtained by designing for a longer range. Since additional CD ranges have cost penalties associated with them for many consumers (too much battery pack for their needs), a longer PHEV CD range would not be attractive to buyers without cost subsidies. With regard to incremental effectiveness, the first 10 miles increases the nominal PHEV share from 0 to 19.4%. The next 10 miles increases the attainable share by only 9.6%, while the 10 miles from 20 to 30 miles increases the share by only 3.2%. Since many cost and design factors beyond those discussed here occur as more and more battery pack is stuffed into a given vehicle glider, considerations of risk would tilt the optimum single range goal to a value from 10 to 20 miles, rather than 20 to 30 miles.

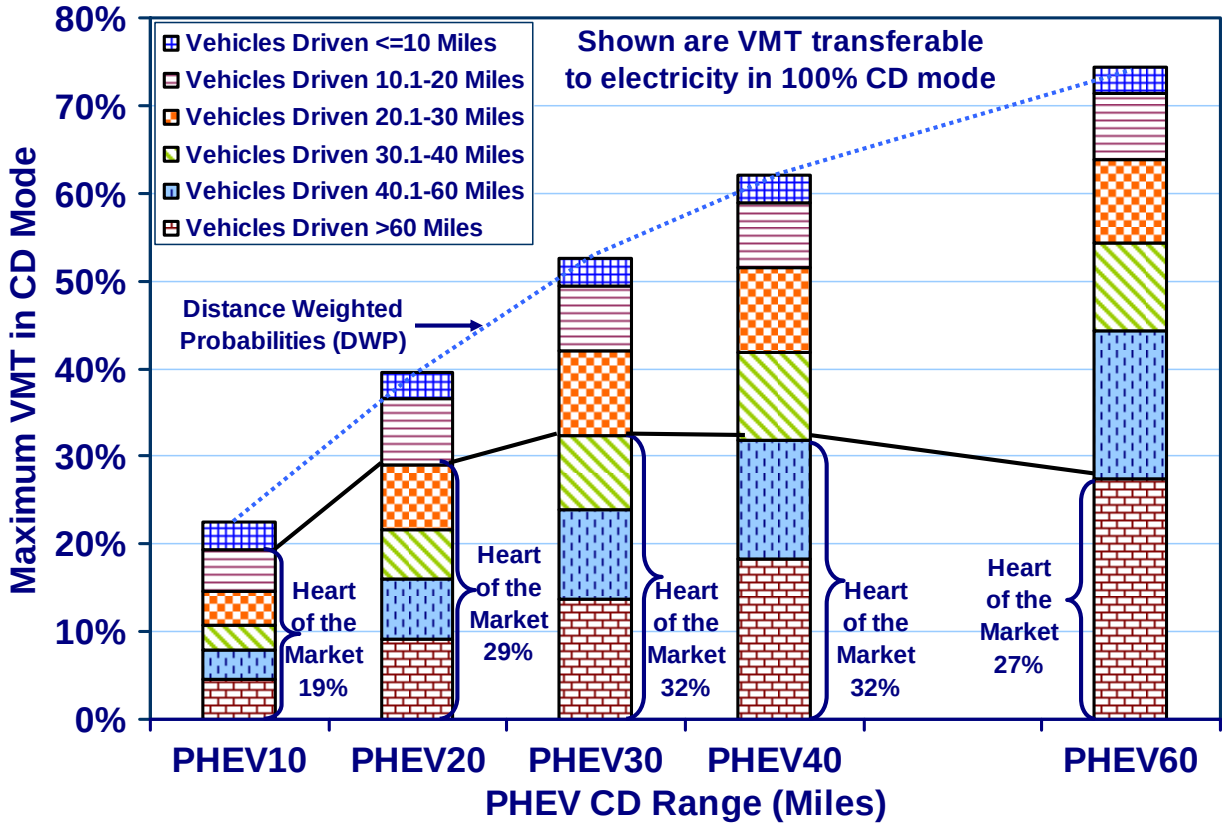

Figure 4 VMT Transfer to Electricity under the Cost-Effective "Heart of the Market" Concept

Complications — Considering Blended Mode Operation

So far we have assumed that PHEVs can operate in 100% CD mode until their battery packs are depleted. In order to make them cost effective, many of the early PHEVs are likely to have smaller, less powerful electric drives and battery packs. Such PHEVs would require ICE assistance during episodes involving power or energy demands higher than the battery pack and electric drive can provide. Behavior during such episodes is illustrated in Figures 1 and 2. Thus, these PHEVs are likely to operate in blended CD mode. Some of our PSAT simulations have indicated that some battery pack and electric drive combinations could require a PHEV to operate in 50% blended CD mode. In reality, the percent of blended mode will depend on driving pattern. Two different drivers are likely to have different percentages of blended CD mode on the same vehicle.

In order to develop a lower bound, we estimated VMT that can be electrified under 50% blended mode for 10-mile through 60-mile PHEV CD ranges. We assumed that a PHEV with a 10-mile CD range would deplete its battery pack at 20 miles. The resulting electrified VMT for all vehicles were: 19.8% for the 10-mile CD range, 31% for the 20-mile CD range, 37.2% for the 30-mile CD range, 40.9% for the 40-mile CD range, and 44.7% for the 60-mile CD range. When compared with the VMT percentages in Table 1, we observe that as CD distance increases, the gap between VMT electrifiable at 100% CD mode and 50% blended CD mode increases. For the 10-mile CD range, the gap is only 2.7%; for the 20-mile CD range, the gap is 8.6%, increasing to 29.7% for the 60-mile CD range.

Potential for More Than One Charge per Day

A shorter CD range would result from use of a smaller battery pack. According to recent estimates by Kromer and Heywood *(6)*, this increases PHEV cost effectiveness. They estimated decreasing cost effectiveness as the PHEV CD range increased. However, with a shorter PHEV CD range, the potential VMT electrifiable, under our one charge per day assumption, would be much lower. However, more VMT can be electrified if a PHEV's battery pack is charged more than once per day.

In order to examine the possibility of second charges per day by location, we analyzed NHTS data and identified the trip purpose associated with the longest dwell time for each vehicle between 6 a.m. and 6 p.m. We ignored the dwell time following the last trip recorded in NHTS for two reasons: (1) such vehicles can be charged overnight, and (2) we would have to assume a start time for the next day's first trip, thereby introducing a bias.

Residents in detached single housing units within metropolitan statistical areas (MSAs) are most likely to buy PHEVs. We limited this initial analysis to that segment. The results of our analysis are tabulated in Table 2. Some 3% of the vehicles driven by detached single-unit residents living in MSAs made only one trip during the travel day. We eliminated these vehicles. Of the remaining vehicles, 36.4% had their longest dwell time at work, 22.6% at home, and 8.5% while shopping. The remaining 32.5% had various purposes.

Overnight excess electricity generating capacity is consistently available for charging PHEV battery packs. However, important regional and seasonal differences do exist for the electricity-generating capacity available for daytime charging of PHEV battery packs. An examination of Illinois electric utility loads showed that, excepting summer months, PHEV battery packs could be charged during the day without reaching peak summer capacity *(7)*. During the summer, sharp afternoon peaks were evident due to air conditioning. For summer months, if charging were to occur during the day, it would have to be completed before the early afternoon. A presentation by the Northern California utility, Pacific Gas and Electric Company (PG&E), indicated that their summer residential peak load pricing pattern included partial peak rates that would apply for battery pack charging before noon *(8)*. For the Illinois loads, we noticed much lower levels on the weekend than during the workweek for all three seasons. For the PG&E summer rates, we noticed that the weekend rates were considerably lower than the workweek rates, with

off-peak rates extending deep into the weekend days. If this is an indication of a general phenomenon of lower electric loads on weekends, then weekend days should offer greater opportunity for multiple charges per day.

In our tabulations, which did not break out workweek and weekend days, the results were as follows:

- Of the 36.4% of vehicles that had the longest dwell time at work, the majority (67.6%) arrived between 6 a.m. and 9 a.m. Almost all (97%) had a dwell time exceeding 3 hours, thus making charging at the work place possible from morning through noon, especially if 220-V charging is provided at work. This would allow for more rapid charging at work than the anticipated 110-V charging available in most garages.
- In contrast, among the 22.6% of vehicles that had longest dwell time at home (between 6 a.m. and 6 p.m.), only 11.7% began the dwell time before 9 a.m., with 67.5% having a dwell time longer than 3 hours. Taking into account that fewer trips return home than go to work, and considering the late return of vehicles to the home, we estimate that a much smaller fraction (<2%) of vehicles returned to the home could have multiple summertime workweek charging per day without interfering with the typical utility's afternoon workweek summer peak.
- Only a small minority, 5.3% of the 8.5% total, of shopping-related dwell times took place before 9 a.m. Also, 84.2% of such instances involved a dwell time of less than 2 hours. Thus, multiple charging at shopping places is much less advantageous than at work locations.

While charging rapidly may provide greater technical opportunities for multiple location charges per day, such capability will come at a cost, both in dollars *(9)* and charging efficiency *(10)*. Battery pack energy storage for PHEVs is likely to vary from about 4-16 kWh. This paper, in effect, argues that the lower end of this range is the more economic. In any case, in 2001, Graham et al. *(9)* estimated that the infrastructure upgrade cost of garage charging, at a rate of 1.0 kWh/h, would be negligible using existing standard 120-V, 15-amp circuits. For 1.3 kWh/h upgrading to a 120-V, 20-amp circuit, the cost was estimated to be $200. For a rate of 5.7 kWh/h with a 240-V, 40-amp upgraded circuit, the infrastructure cost estimate rose to $1,000. This did not include meter costs. For a household meter to allow the utility and customer to have variable costs, with reduced overnight rates, the cost was estimated at $235. The added charger costs for a 240-V capability instead of a 120-V capability were estimated to be $70. These estimates are several years old, but they illustrate that rapid charging capability can drive up charging costs considerably. It is true that the high rate charger theoretically allows many more vehicles to be charged per day, but the logistics of matching charger location to vehicle location will make this hypothetical benefit difficult to fully utilize. At work, vehicles often remain in the same spot during the entire work day. In shopping locations, the intended dwell time at a parking spot also may not match up with the time to charge, so the spot may be filled after charging is complete.

It appears that multiple charging could most cost effectively be made possible by installing low-rate charging infrastructure at work, where long dwell times are common. If other charging locations are to be considered, the battery cycle life effect of multiple charges per day at high rates is also a factor that should be examined.

TABLE 2 Pattern of Longest Dwell Time by Time of Day within Purpose for Vehicles Driven by Detached Single Unit Residents of MSA

	Percent of Vehicles Parked within Purpose by Time of Day (in Military Time) When the Longest Dwell Time Began												
Longest Dwell Time (Hours)	**6:01-7:00**	**7:01-8:00**	**8:01-9:00**	**9:01-10:00**	**10:01-11:00**	**11:01-12:00**	**12:01-13:00**	**13:01-14:00**	**14:01-15:00**	**15:01-16:00**	**16:01-17:00**	**17:01-18:00**	**Total**
Parked at Work (36.4% of All Vehicles Used)													
<=1	0.3	0.2	0.1	0.1	0.1	0.0	0.1	0.1	0.0	0.0	0.0	0.1	1.0
1-2	0.2	0.3	0.3	0.2	0.2	0.1	0.1	0.2	0.1	0.1	0.1	0.0	1.8
2-3	0.3	0.6	0.7	0.6	0.3	0.2	0.3	0.5	0.3	0.2	0.1	0.1	4.2
3-4	0.3	1.7	**2.5**	0.7	0.3	0.5	1.1	1.2	0.2	0.1	0.1	0.1	8.8
4-5	1.2	**4.4**	**2.1**	0.8	0.3	0.7	**2.8**	1.3	0.2	0.2	0.3	0.2	**14.8**
5-6	1.4	1.8	1.4	0.7	0.5	0.9	0.9	0.4	0.2	0.2	0.2	0.2	9.0
>6	**14.8**	**21.2**	**11.8**	**3.8**	1.6	1.2	1.0	1.2	1.8	1.3	0.6	0.2	**60.4**
Total	**18.5**	**30.2**	**19.0**	7.0	3.3	3.6	6.2	4.8	2.9	2.2	1.4	0.8	100.0
Can be charged by noon	18.0	29.7	18.6										66.3
Parked at Home (22.6% of All Vehicles Used)													
<=1	0.1	0.2	0.4	0.6	0.4	0.5	0.4	0.4	0.8	0.6	0.7	0.8	5.8
1-2	0.1	0.4	1.0	1.3	1.7	1.8	**2.0**	1.7	1.6	2.0	1.9	1.1	**16.6**
2-3	0.2	0.6	0.8	1.2	**2.0**	**2.8**	**2.8**	**2.1**	**2.5**	**2.4**	1.9	0.8	**20.0**
3-4	0.1	0.4	0.9	1.2	**2.4**	**2.2**	**2.5**	**2.1**	**2.8**	**2.1**	0.8	0.3	**17.6**
4-5	0.1	0.5	1.0	1.2	1.4	1.7	**2.8**	**2.4**	1.8	0.9	0.4	0.2	**14.3**
5-6	0.1	0.3	1.0	1.0	0.9	1.9	**2.1**	1.4	0.6	0.4	0.2	0.1	10.1
>6	0.4	1.4	1.9	**2.3**	**2.4**	**3.0**	1.8	1.0	0.6	0.3	0.1	0.1	**15.5**
Total	1.1	3.6	7.0	8.8	11.3	**13.9**	**14.4**	11.1	10.8	8.8	6.0	3.3	100.0
Can be charged by noon	0.9	3.0	5.6										9.5
Parked while Shopping (8.5% of All Vehicles Used)													
<=1	0.3	0.9	**2.3**	**5.2**	**8.9**	**6.6**	**5.4**	**8.5**	**7.2**	**6.4**	**5.1**	**3.9**	**60.7**
1-2	0.1	0.1	0.5	**2.2**	**3.8**	**3.2**	**2.6**	**3.4**	**2.8**	**2.3**	1.4	1.1	**23.5**
2-3	0.1	0.0	0.3	0.9	1.1	1.7	1.5	1.6	0.6	0.6	0.4	0.2	8.8
3-4	0.0	0.1	0.1	0.3	0.9	0.8	0.7	0.4	0.4	0.1	0.2	0.1	4.3
4-5	0.0	0.0	0.2	0.0	0.3	0.2	0.3	0.1	0.1	0.1	0.1	0.0	1.6
5-6	0.0	0.0	0.0	0.0	0.1	0.1	0.0	0.0	0.0	0.0	0.0	0.0	0.4
>6	0.0	0.0	0.0	0.2	0.2	0.1	0.0	0.0	0.0	0.0	0.0	0.0	0.7
Total	0.6	1.2	3.5	8.9	**15.4**	12.7	10.6	**13.9**	11.2	9.5	7.3	5.3	100.0
Can be charged by noon	0.2	0.2	0.7										1.1

Source: 2001 NHTS Day Trip File *(1)*. Assumes all vehicles are PHEV. Each row represents the dwell time duration, and each column shows the time of day between 6 a.m. and 6 p.m. when the dwell time began. If a duration interval for the hour of day has 2% or more of vehicles, and if the total share of vehicles by hour of day or parking duration is a rounded 14% or more, the cell and percentage are highlighted in bold.

DWELLING UNIT, GEOGRAPHIC LOCATION, AND POTENTIAL PHEV MARKET

Residents of single unit houses with a garage or carport constitute the most likely buyers of PHEVs. We used the 2005 AHS to analyze this. Of the 108.9 million occupied housing units, 64.3% are detached single units, 5.7% are attached single units, 23.7% are two or more apartments, and 6.4% are mobile homes.

The regional distribution of occupied housing units is detailed in Figure 5. As shown in the figure, the South region, stretching from Delaware to Texas, has the highest share of all types of housing units, accounting for 36.5% of the total. Of the 64.3% of housing units represented by detached single units, 24.1% are in the South region, 16.3% are in the Midwest, 13.8% are in the West, and 10.2% are in the Northeast.

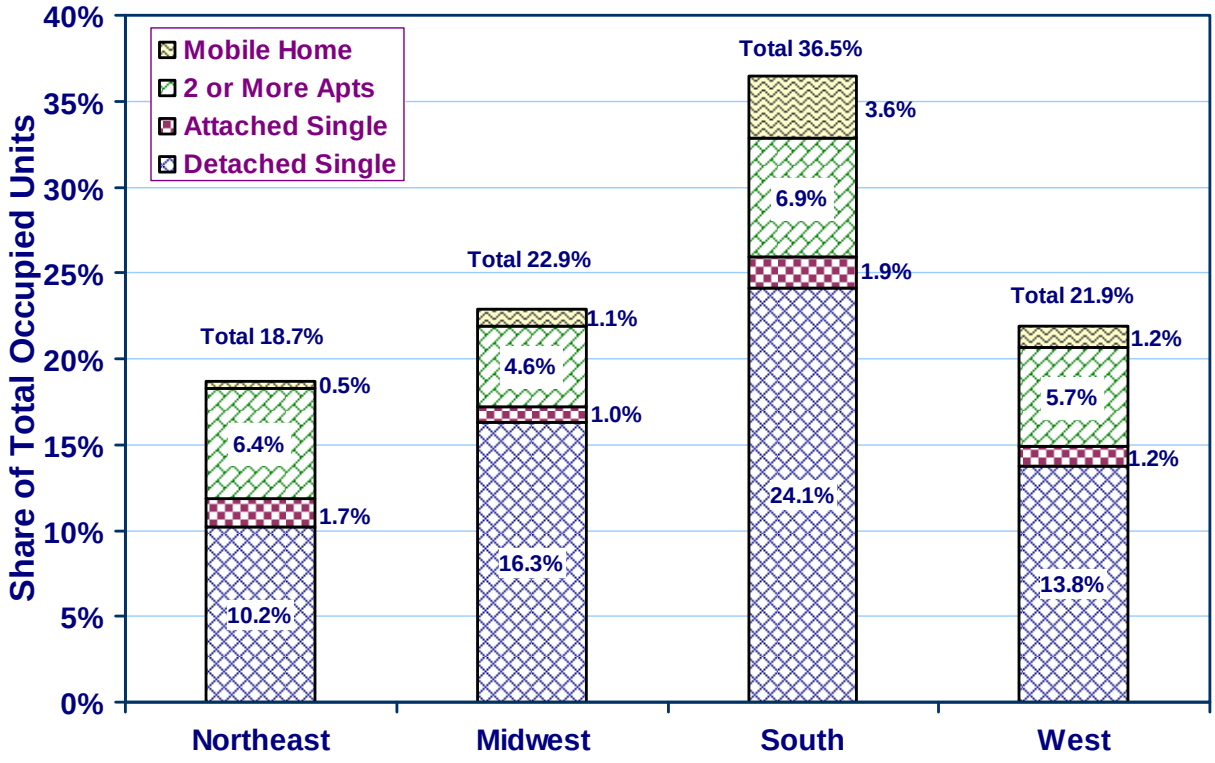

Figure 5 Occupied Housing Units by Type and Region

We analyzed detached single units in terms of availability of a garage or carport and vehicle ownership. The shares of detached single units by MSA central city, MSA outside central city, and other areas and Census regions are shown in Table 3. Some 73.7% of the detached single units are in MSAs, and 60.3% have a garage or carport. In terms of the share of total housing units, 47.4% are detached single units located in MSAs, and 38.7% have a garage or carport.

Table 3 also shows detached single unit shares by vehicle ownership and Census region. Some 73.5% of detached single unit households own two or more vehicles, with 54.3% located in MSAs. In terms of the share of total housing units, 47.3% are detached single units that own two or more vehicles, with 34.8% located in MSAs. The analysis of 2005 AHS shows that if PHEVs require garages or carports

to charge their battery packs, they may not replace all household vehicles. Detached single units with a garage or carport constitute only 51.5% of total housing units. However, the 2005 AHS data also show that 92.4% of the detached single units built during 2000-2005 have garages or carports. This indicates that as the housing stock expands and old units are replaced, more detached single units will have a garage or a carport.

TABLE 3 Detached Single Housing Units by Census Region and MSA Status in AHS 2005

Census Region	Location	Total	With Garage/ Carport	Off-Street Parking Only	No Special Parking	No Vehicle	1 Vehicle	2 or More Vehicles
Northeast	MSA: Central City	1.9%	1.1%	0.6%	0.2%	0.2%	0.6%	1.1%
	MSA: Not C. City	11.1%	8.6%	2.2%	0.3%	0.3%	2.3%	8.5%
	Other	2.8%	1.9%	0.8%	0.1%	0.1%	0.7%	2.0%
	All	15.8%	11.7%	3.6%	0.6%	0.6%	3.6%	11.6%
Midwest	MSA: Central City	5.6%	4.6%	0.7%	0.3%	0.3%	1.8%	3.4%
	MSA: Not C. City	11.5%	10.4%	1.0%	0.1%	0.2%	2.4%	8.9%
	Other	8.2%	7.0%	1.1%	0.1%	0.2%	1.8%	6.3%
	All	25.3%	22.0%	2.8%	0.5%	0.8%	5.9%	18.6%
South	MSA: Central City	8.7%	6.1%	2.3%	0.3%	0.4%	2.6%	5.7%
	MSA: Not C. City	17.8%	13.8%	3.7%	0.3%	0.4%	4.0%	13.4%
	Other	11.0%	7.5%	3.2%	0.3%	0.5%	2.7%	7.8%
	All	37.5%	27.4%	9.2%	0.9%	1.3%	9.3%	26.9%
West	MSA: Central City	6.3%	5.7%	0.5%	0.1%	0.2%	1.5%	4.6%
	MSA: Not C. City	10.9%	10.0%	0.8%	0.1%	0.2%	2.0%	8.6%
	Other	4.2%	3.4%	0.7%	0.1%	0.1%	0.9%	3.2%
	All	21.4%	19.0%	2.1%	0.3%	0.5%	4.5%	16.5%
All	MSA: Central City	22.5%	17.5%	4.1%	0.9%	1.1%	6.5%	14.8%
	MSA: Not C. City	51.2%	42.8%	7.7%	0.8%	1.1%	10.7%	39.4%
	Other	26.3%	19.9%	5.8%	0.6%	0.9%	6.1%	19.3%
	All	100.0%	80.1%	17.6%	2.3%	3.2%	23.3%	73.5%

Source: 2005 American Housing Survey *(2)*.

TIME TO REACH THE ULTIMATE MARKET SHARE

A new powertrain technology takes considerable time to reach the ultimate market share. We analyzed diesel powertrain penetration in France *(11, 12)* and hybrid electric powertrain penetration in the United States *(13)*. The diesel powertrain share of cars sold in France has increased from 2% in 1973 to 73.6% in 2007. The hybrid electric powertrain was introduced in the United States in December 1999, and its share of the U.S. car market has been increasing slowly. Marketing professionals often use models for projecting the rate of technology substitution. In this case, we used a logit model formulation previously used by Santini *(14)* in historical investigations of powertrain and fuel technology shifts to project the length of time it may take for these two powertrain technologies to reach their ultimate market share. Our choice of plausible illustrative PHEV scenario here is informed in part by the historical fits by Santini for various complexity levels involved with past powertrain, vehicle, and/or fuel switching.

Figure 6 shows the results of this analysis. According to the logit model fit, the diesel powertrain may reach its ultimate market share in France after 50 years. Very limited data on U.S. HEV sales, using the logit model fit, provided us with an estimate of 25 years before it would reach its ultimate share in the

United States, which was estimated to be well below 100%. Given these two illustrations, PHEVs may take considerable time to capture their ultimate share of the market.

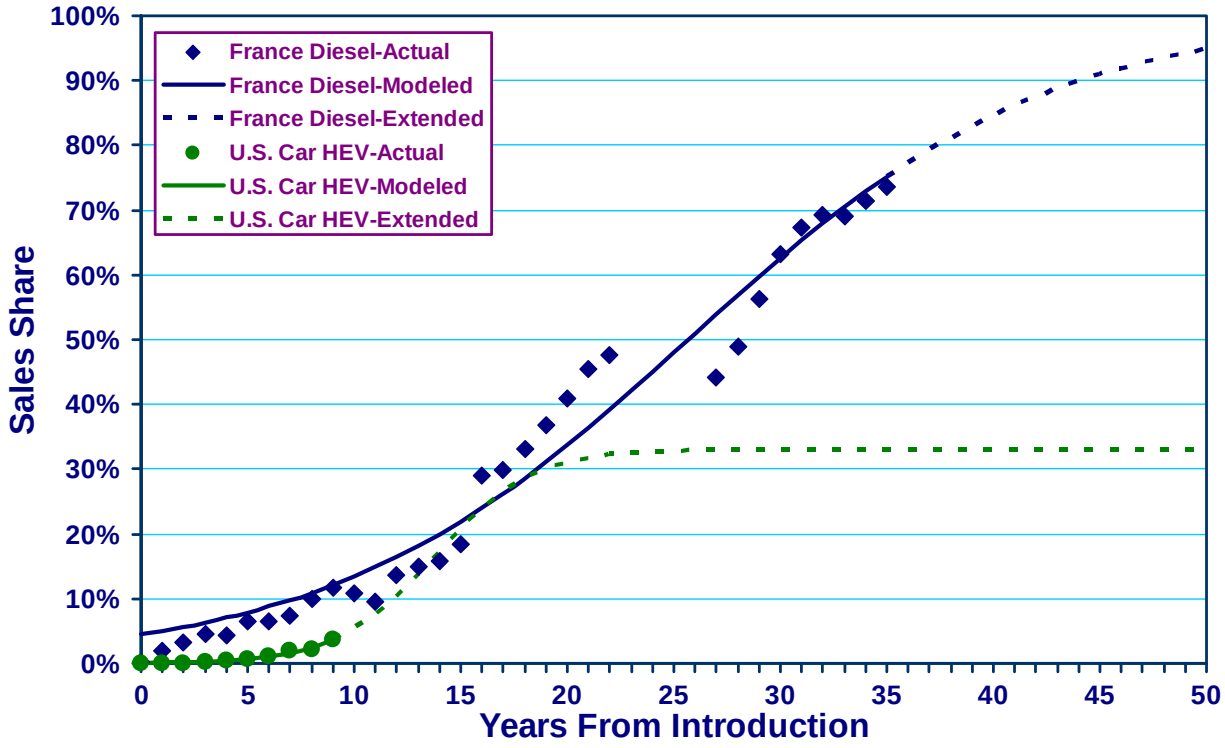

Figure 6 Application of a Logit Model to New Vehicle Technology Market Penetration

Also, new vehicle sales constitute only 7-8% of vehicle stock. The 1999-2006 new light-duty vehicles sales, in millions, were 16.93, 17.36, 17.15, 16.83, 16.65, 16.87, 16.95, and 16.52 *(15)*. The corresponding registrations of cars and two-axle-four-tire trucks, in millions, were 207.79, 212.71, 221.82, 220.93, 222.86, 228.28, 231.90, and 234.52 *(16)*. The new vehicle sales represented 7.0-8.2% of the vehicle registrations. Thus, even if a new technology were to replace all other technology at some point in time, we estimate that it would take a minimum of nearly 12 years of such consistent sales before it would replace all vehicles on the road.

SPEED, ACCELERATION, AND FUEL USE OF THE FIRST MILES FROM THE HOUSE — POWERTRAIN SIMULATION MODELING

Our analysis, as shown in Figures 3 and 4 and in Table 1, is heavily influenced by thinking that existed prior to our research. In particular, the notion of electrification of miles has existed for years, starting with assessments of the potential of EVs. The assumption that has been made presumes that if a certain percentage of miles can be electrified, then a similar proportion of fuel savings will be possible. Unfortunately, this is probably not precisely correct.

In this section we describe emerging procedures we are using to investigate this question. We broke down the speed of travel as a function of the distance the vehicle had traveled from the morning starting point (i.e., garage, carport, driveway, etc). We examined the first 20 miles of travel, the next 20,

and the remaining travel beyond 40 miles. What we find is that the average speed of travel increases for each of these increments (Table 4). Further, within each of the categories, we found that the average speed of those whose daily travel ended within the category was slower than for those who drove further. Thus, for the first 20 miles of travel one can separate the category into two groups: first, those who travel up to 20 miles, but no further; and second, the speed in the first 20 miles of travel among those vehicles that travel more than 20 miles per day. A similar breakout is possible in the 20-40 mile category. Note that it is the second group that we assert to be members of the "heart of the market" for PHEVs. Thus, when we estimate the fuel use patterns vs. distance of daily travel for likely PHEV owners, we do so for this group. Also, note that the difference in speed for the two portions of the market within the first 20 miles is fairly significant — 17 mph for those traveling less than 20 miles, and 29 mph for those traveling beyond. This has implications for the "best" PHEV design for this customer base, as it does for "city" EVs that might serve those traveling less than 20 miles.

TABLE 4 Speed, Share of Time, Miles, and Fuel Use, by Distance Traveled from Day's Start

Distance from day's starting point (miles)	First 0–20[§]	Next 20–40[#]	Remainder >40	All
Mph of portion traveling up to the distance	17.2	25.7	Not applicable	19.7
Mph of portion traveling beyond the distance	29.4	30.9	41.3	34.7
Mph total (average) for category	24.8	28.2	41.3	30.4
Share of VMT for category	39.6%	22.4%	38.0%	100.0%
Share of time for category	49.7%	21.7%	28.6%	100.0%
Share of trips for category	64.4%	19.4%	16.2%	100.0%
Estimated car share of fuel use for the portion traveling beyond the distance (heart of market)	44.0%	20.1%	35.8%	100.0%
Estimated car share of fuel use within category	41.4%	20.0%	38.6%	100.0%
Miles per trip for category	5.6	10.4	21.2	9.1
Minutes per trip for category	13.5	19.6	30.8	17.5

[§] Includes travel up to 20 miles and the first 20 miles of travel of vehicles traveling >20 miles.

[#] Includes the 20+ mile portion of days of travel > 20 miles, but < 40 miles; for days of travel > 40 miles, includes the 20-40 mile portion.

To develop our first illustration, we simulated the fuel consumption of one particular passenger car glider with several different powertrains. We simulated the fuel consumption for several "on-road" driving cycles for the United States and Europe, ranging from 7 to 62 mph. For this discussion, we include a plot with the conventional gasoline ICE, the diesel, the split HEV, the split PHEV with medium range (~ 20 miles at low speed), and a series PHEV with long range (~ 40 miles at low speed). While details are important for precise comparisons, our point here is straightforward and generic (Figure 7). Fuel consumption *per hour* for each powertrain increases as average speed increases. Our observation with the NHTS data was that the average hours spent in the vehicle across the United States were roughly constant, regardless of population density. We do note that a considerably higher share of time is spent in low speed miles than at a higher speed (Table 4). However, based on a rough estimate for this single vehicle simulation case, given the rate of decline of fuel consumption per hour as a function of decline in speed, shown in Figure 7, our initial approximation is that the share of fuel saved by PHEVs electrifying miles within the "heart of the market" could actually be greater than the miles electrified. In contrast, EVs operating at the lower speeds applicable in their best market may save a smaller share of fuel than miles electrified. Since this is the first example we have generated, the result should be regarded as an illustration of the process and its potential value, rather than an estimate to rely on. Minivans, SUVs, and pickup trucks, which have greater frontal area and higher coefficients of drag than the passenger car we

have simulated here, can be expected to have larger shares of fuel use at high speeds due to the effects of aerodynamic drag.

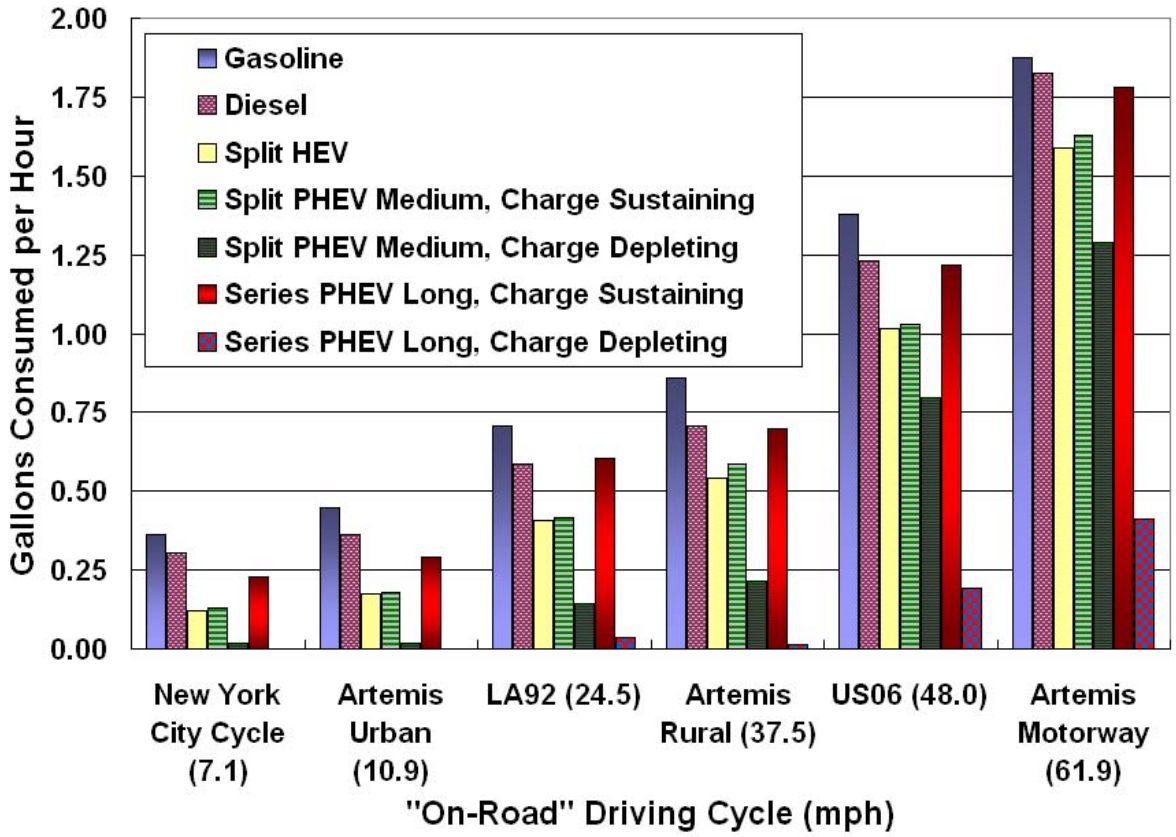

Figure 7 Fuel Consumption per Hour for Multiple Powertrains in a Passenger Car — On-Road Driving vs. Speed

CONCLUSIONS

We have analyzed available data to highlight issues involved in estimating the petroleum reduction potential of PHEVs. The following conclusions can be reached:

- If a single electric CD range goal were to be chosen for PHEV R&D, a range between 10 and 20 miles would be superior to a range between 30 and 40 miles.
- It is probably more desirable to try to develop a diverse portfolio of PHEV CD capabilities. If future PHEVs have multiple CD range values and capabilities, their potential to meet varying customer needs, thereby electrifying more miles, will be enhanced.
- A simple distance-weighted probability curve for estimating the share of miles electrifiable can be developed, but its usefulness for estimating national oil-savings potential is limited.
- PHEVs are likely to be expensive. More benefits would accrue to those who utilize their CD range to the fullest. The need for a customer to consistently exceed the CD range will limit the ultimate market to a share less than predicted by a simple distance-weighted probability curve.

- Multiple charging may be feasible for a subset of PHEVs. Work places appear to be the best location to set up charging infrastructure away from the house. This would increase PHEV petroleum use reduction potential, but its effect on battery life is unknown.
- Availability of garages and carports for PHEV charging is likely to limit their ultimate market share until and unless a ubiquitous charging infrastructure is built. Nevertheless, the market with garages and carports is large and is increasing as a fraction of the housing stock.
- Even with technical success, the time involved in increasing production capacity and consumer acceptance will cause a substantial time lag before the ultimate market share is captured.
- Light-duty vehicle fleet turnover is slow and will cause substantial delay before full benefits are realized.
- Since the miles electrifiable by PHEVs will be operated at lower speeds than those not electrifiable, an assessment of the rate of fuel use specific to projected speed and aggressiveness of driving is desirable to obtain a more accurate estimate of the oil-savings potential of PHEVs in actual use. Blended mode PHEV CD operation complicates estimation difficulties.

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[i] Endnote: In order for these vehicles to become "plug-in" hybrids, at the level of detail of the diagrams, addition of a charger and plug would be sufficient. For either case, if the electric machine operating as a motor and battery pack have enough power, it would be possible to adopt a control strategy disallowing use of the engine during charge depletion. Such a control strategy decision would require all electric operation until the battery was depleted. In effect, the powertrain would operate as an electric vehicle during charge depletion. The same powertrain would operate as a hybrid once the battery charge was depleted. The Chevrolet Volt, using a series design, might adopt this type of control strategy.