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Using GPS Travel Data to Assess the Real World Driving Energy Use of Plug-In Hybrid Electric Vehicles (PHEVs)

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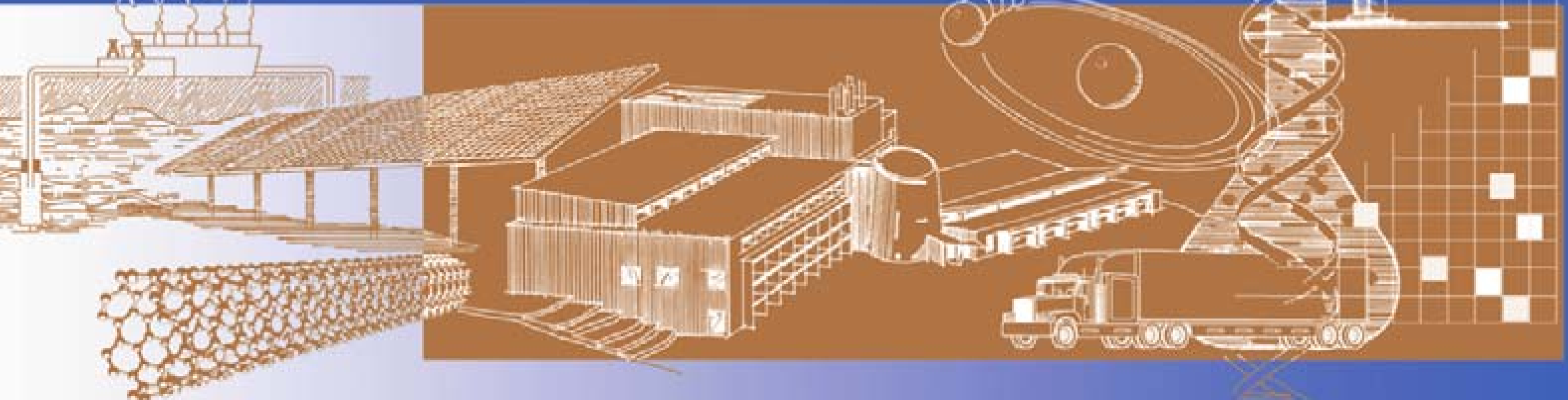

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Using GPS Travel Data to Assess the Real-World Driving Energy Use of Plug-In Hybrid Electric Vehicles (PHEVs)*

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ABSTRACT

Plug-in hybrid electric vehicles (PHEVs) have received considerable recent attention for their potential to significantly and quickly reduce petroleum consumption in the transportation sector. Analysis to aid the design of such vehicles and prediction of their real-world performance and fuel displacement must consider the driving patterns the vehicles will typically encounter. This paper goes beyond consideration of standardized certification cycles, leveraging state-of-the-art travel survey techniques that use global positioning system (GPS) technology in order to obtain a large set of real-world drive cycles from the surveyed vehicle "fleet." This study specifically extracts 24-hour, second-by-second driving profiles from a set of 227 GPS-instrumented vehicles in the St. Louis metropolitan area. The performance of midsize conventional, hybrid electric and PHEV models is then simulated over the 227 full-day driving profiles in order to assess the fuel consumption and operating characteristics of these vehicle technologies over a set of "real-world" usage patterns. In comparison to standard cycles used for certification procedures, the travel survey duty cycles include significantly more aggressive acceleration and deceleration events across the velocity spectrum, which impacts vehicle operation and efficiency. Even under these more aggressive operating conditions, a PHEV using a blended charge-depleting energy management strategy consumes less than 50% of the petroleum used by a similar conventional vehicle. Although true prediction of the widespread, real-world use of these vehicles requires expansion of the vehicle sample size and a refined accounting for the possible interaction of several variables with the sampled driving profiles, this study demonstrates a cutting-edge use of available GPS travel survey data to analyze the (highly drive-cycle dependant) performance of advanced technology PHEVs. This demonstration highlights new opportunities for using innovative GPS travel survey techniques and sophisticated vehicle systems simulation tools to guide vehicle design improvements and maximize the benefits offered by energy efficiency technologies.

INTRODUCTION

The United States faces a transportation energy problem. The transportation sector depends almost entirely on a single fuel—petroleum. The future of petroleum supply and its use as the primary transportation fuel threatens both personal mobility and economic stability. The United States currently imports nearly 60% of the petroleum it consumes and dedicates over 60% of its petroleum consumption to transportation (*1*). With ever-climbing U.S. petroleum consumption despite steadily declining domestic production, the petroleum import percentage will keep growing. International pressures also continue to increase as the growing economies of China and India consume petroleum at rapidly increasing rates. Many experts now predict that world petroleum production will peak within the next 5-10 years, greatly straining the petroleum supply and demand balance in the international market (*2*).

Hybrid electric vehicle (HEV) technology presents an excellent way to reduce petroleum consumption through efficiency improvements. HEVs use energy storage systems (ESS) combined with electric motors to improve vehicle efficiency by enabling engine downsizing and by recapturing energy normally lost during braking events. A typical HEV can reduce gasoline consumption by about 30% over

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a comparable conventional vehicle. This number could approach 45% with additional improvements in aerodynamics and engine technology (*3*). Since their introduction in the United States, HEV sales have grown at an average rate of more than 80% per year. However, after 5 years of availability, they represent only 0.1% of the total U.S. vehicle fleet. There are 237 million vehicles on the road today and more than 16 million new vehicles sold each year (*4*). Each new vehicle (the vast majority of which are not hybrids) will likely be in use for more than 15 years (*5*). With continued growth in the vehicle fleet and in average vehicle miles traveled even aggressive introduction rates of efficient HEVs to the market will only slow the increase in petroleum demand. Reducing U.S. petroleum dependence below present levels requires vehicle innovations beyond current HEV technology.

PHEV technology provides the potential to displace a significant portion of transportation petroleum consumption by using electricity for portions of trips. A PHEV is an HEV with the ability to "plug-in" so as to recharge its ESS with electricity from the utility grid. With a fully-charged ESS, the vehicle will bias towards using electricity rather than liquid fuels. A key benefit of plug-in hybrid technology is that the vehicle no longer depends on a single fuel source. The primary energy carrier would be electricity generated using a diverse mix of domestic resources including coal, natural gas, wind, hydroelectric, and solar energy. The secondary energy carrier would be a chemical fuel stored on the vehicle (i.e., gasoline, diesel, ethanol, or even hydrogen). Although PHEVs must still overcome technical challenges related to ESS cost, size, and life, the technology nevertheless provides a relatively near-term petroleum displacement option (*6*).

Full assessment of the fuel savings potential requires evaluating PHEV fuel use relative to both conventional vehicles and other advanced technology vehicles, such as HEVs. This is traditionally accomplished by using controlled chassis dynamometer testing over standardized certification cycles (e.g., the Urban Dynamometer Driving Schedule (UDDS), the Highway Fuel Economy Test (HWFET) and/or the US06 Cycle). Several past studies have evaluated PHEV fuel economy benefits by running simulations over such certification cycles (*7, 8*). Although this use of standard test cycles represents a widely accepted analysis approach, the results are somewhat limited since the cycles do not necessarily represent actual driving behavior. As an alternative, test profiles can be created from real-world vehicle driving data in order to simulate the technology's particular "in-use" fuel consumption benefits. The large sensitivity of PHEV fuel and electricity use to cycle distance and intensity makes it particularly important to consider real-world usage patterns when evaluating the technology (*9*).

Unfortunately, the limited availability of usable travel data typically prohibits extensive performance evaluation over real-world driving patterns. Conventional paper-based travel surveys do not provide sufficiently detailed information to perform advanced vehicle simulations. However, real-world drive cycles can be derived from the second-by-second information on vehicle position, heading, and speed collected from GPS devices. GPS technology uses satellite signals to track the location of vehicles, and can enhance traditional travel survey data collection methods. The purpose of this paper is to illustrate the use of GPS travel data for assessing the performance of PHEV technologies in a real-world context. This is accomplished by comparing the use of liquid fuel and electric energy for PHEVs, HEVs, and conventional vehicles. Detailed vehicle simulations provide the comparison results, both for driving over standard certification cycles, and for driving over a sampling of real-world cycles obtained from an actual urban "fleet" of GPS-instrumented vehicles.

OBTAINING DRIVE CYCLES FROM GPS TRAVEL SURVEY DATA

Metropolitan planning organizations (MPOs) regularly collect travel survey data in order to update transportation demand forecasting models and identify transportation needs and areas of traffic congestion within the survey region. These surveys typically consist of mail-out/mail-back travel diaries, and may also include a computer-assisted telephone interview (CATI) component. In recent years, several MPOs have begun investigating use of GPS technology in order to improve the accuracy and completeness of personal travel data collection. The first significant deployment of GPS equipment in a travel survey occurred in Austin, Texas, in 1998. However, the usefulness of the data was limited due to the U.S. government's intentional degradation of GPS data signals (known as "Selective Availability"). On May

1, 2000 President Clinton announced the termination of Selective Availability, which led to tenfold improvements in GPS data accuracy down to 5-10 meters, literally overnight. It has only been in the relatively recent time period following this change that continually improving GPS accuracy and declining equipment costs have made it practical to include a GPS data collection component in traditional travel surveys.

The East-West Gateway Coordinating Council became one of the initial pioneers by including a GPS component in the 2002 St. Louis Regional Travel and Congestion Survey. The GPS devices in the St. Louis, Missouri, study were used to investigate trip characteristics of a subsample of participants in the larger survey. The purpose of comparing the GPS and CATI survey results was to gain insight into the extent of underreported or misreported trips, which has long been a problem with household travel studies due to the self-reporting nature of traditional survey methods. For more details on the full survey and the GPS augment than is provided in this section, the interested reader should consult the final reports on the St. Louis survey methodology and results (*10, 11*).

In the full St. Louis survey, 5,094 households were used to represent 968,533 households and 2,428,730 persons in the region. Households participating in the GPS augment to the survey were provided a GeoStats GeoLogger^{TM} data collection device for up to three vehicles in the household. To utilize the data logger, the survey participant needed only to plug the power connector into the vehicle's cigarette lighter socket and use a magnetic mount to attach the combination GPS receiver/antenna to the roof of the vehicle. To filter out nonmoving events, each GeoLogger was set to record data points for vehicle speeds greater than 1 mph at one-second logging frequencies. The data recorded included date, time, latitude, longitude, speed, heading, altitude, number of satellites, and horizontal dilution of precision (a measure of positional accuracy). A 150 household subsample of the 5,094 households successfully completing the CATI survey also successfully completed the GPS portion of the survey. From these 150 households, 300 vehicles received GPS instrumentation, and 227 of these 300 vehicles recorded travel on the assigned travel day (a weekday between September 5 and December 12, 2002).

To satisfy the additional use of the GPS data identified in this paper, the second-by-second speed vs. time history logged by the 227 vehicles was converted into a set of 24-hour driving profiles to describe the behavior of these vehicles over a full day. The authors then used a vehicle simulation model to predict the performance and energy consumption of a simulated vehicle operating over the driving profiles. Simulation or testing time constraints often necessitate constructing a single composite cycle to approximately represent such a large set of driving profiles. However, the rapid computational speed of the model described in the following section enables individual simulation of vehicle performance over each distinct 24-hour drive cycle. The subsequent fleet-level simulation result enhances understanding of the distribution and details of vehicle performance that a single composite cycle cannot provide.

The sample distribution for the GPS portion of the St. Louis survey was designed to mirror the population breakdown in the St. Louis area as well as the full study sample distribution. However, extracting conclusions about the larger St. Louis population from the simulation results using GPS-derived drive cycles requires first applying expansion factors to appropriately weight each category of vehicle/household based on its proportion in the larger population (based on household size, location, income, etc). Because the GPS subsample represents such a small portion of the total population, the uncertainties associated with applying expansion factors can be quite large. Nevertheless, analyzing vehicle performance over hundreds of real-world drive cycles can certainly provide expanded insight over solely simulating a handful of synthetic profiles. By referencing recent travel surveys that include a GPS component, large numbers of real-world simulation cycles can be extracted from data originally obtained for another purpose, thus furthering the usefulness of the survey information.

PREPARING AND RUNNING VEHICLE SIMULATIONS

In order to assess PHEV performance expectations over this set of real-world drive cycles, the second-by-second speed profiles for each surveyed vehicle were provided as inputs to a vehicle systems simulation tool called ADVISOR^{TM}. This software program was developed at the National Renewable Energy Laboratory with support from the U.S. Department of Energy (DOE) and has been refined over many years. ADVISOR can assess the fuel consumption and performance of advanced technology vehicles, such as hybrid electric, fuel cell, and PHEVs (*12*). It also includes models for conventional and electric vehicles. The tool provides sufficient detail to understand the impact of component sizing and energy management decisions, yet is fast enough to analyze 24 hours of driving for a fleet of vehicles in a reasonable amount of time.

The driving profile serves as a key input to the program, along with component attributes. Starting from the acceleration demands of the driving profile, ADVISOR determines the operating point (torque and speed or current, and voltage) of each component within the powertrain at each instant in time while accounting for component losses and limitations. ADVISOR has the ability to model a variety of powertrain configurations including parallel, series, and power-split hybrid architectures. For this study all hybrids have been assumed to be in a parallel architecture so that the engine and electric motor can both provide power in parallel to the drive shaft at any time.

A previous paper (*13*) analyzed the various design options for PHEVs. The two primary PHEV design parameters are the usable energy content of the battery and the rated power of the battery. All other parameters depend on the choice of battery power and energy, the vehicle attributes, and the performance constraints. For this study, the vehicles were assumed to be representative midsize sedans (similar to a Chevrolet Malibu or a Toyota Camry) with performance that would be competitive in today's market. Table 1 summarizes the attributes of the vehicles considered.

TABLE 1 Simulated Vehicle Attributes

	Units	Conventional	Hybrid	PHEV20	PHEV40
Engine Power	*kW*	121.7	82	79.4	81.9
Motor Power	*kW*	n/a	39	43.6	48
ESS Power	*kW*	n/a	50	47	51.8
ESS Energy (total)	*kWh*	n/a	1.9	9.4	18.5
Curb Mass	*kg*	1429	1399	1488	1567
Fuel Economy (urban/highway)	*mpg*	26	39.2	54	67.4
Electric Consumption (urban/highway)	*Wh/mi*	n/a	n/a	95	157
All Electric Range – urban	*miles*	n/a	n/a	22.3	35.8

The increased mass of the PHEV will increases its energy consumption rate. However, the larger ESS allows it to use the electric drivetrain more often to provide an overall energy efficiency improvement and petroleum displacement benefit. The ESS and traction motor have been sized to provide sufficient power to drive the entire UDDS without the use of the engine. The distance a PHEV can drive on a particular cycle before having to turn on its engine is known as the all-electric range. The PHEV20 in this study has been sized with sufficient energy to drive roughly 20 miles on the UDDS without the use of the engine. Likewise, the PHEV40 has sufficient energy to drive roughly 40 miles on the UDDS. On other more aggressive cycles, the all-electric operation will be less than as designed for urban travel, since the engine will need to supplement the electric motor power output in order to follow the driving profile. Higher electric drive power ratings would permit all-electric operation on more aggressive cycles, but would drive up the cost of the PHEV. However, retaining at least the UDDS minimum all-electric power sizing requirement enables the PHEVs to receive significant bonus credits toward the California Air Resources Board's zero-emission vehicle regulation by demonstrating substantial zero emission range on the UDDS cycle (*14*). The design distances of 20 and 40 miles represent reasonable benchmark values out of the possible PHEV design range, and allow typical drivers to significantly benefit from the grid recharge energy stored on board the vehicle (assuming a once-daily recharge). According to national statistics, 50% of drivers operate their vehicles 30 miles or less on a given day (*15*).

The energy management strategy for the PHEVs in this study attempts to run all-electrically (without the use of a combustion engine) as much as possible as long as the battery has sufficient energy. However, if the electric drivetrain power is insufficient to satisfy the immediate needs of the driver, the combustion engine supplements the electric drivetrain. After depleting the stored energy in the battery, the vehicle transitions to a "charge-sustaining" mode, in which the engine becomes the primary power source, and the ESS simply helps the engine to operate as efficiently as possible. The ESS "sustains" its average charge level as the vehicle continues driving, operating just like an HEV until it is parked and recharged at the end of the day. The energy management strategy summarized here is described in more detail in other publications, which refer to it as a "blended charge-depleting strategy" (*16*) or as an "electric vehicle centric strategy." (*17*) The strategy maximizes petroleum displacement for a given set of components over an unknown driving distance, and provides nearly the same petroleum displacement as all-electric designs for aggressive driving (which require larger and more expensive components).

ANALYSIS RESULTS

The 227 full-day driving profiles derived from the St. Louis GPS survey together represent 8650 miles of travel. Figure 1 shows the distribution of daily distance traveled for this sample data set. Approximately 5% of the vehicles traveled more than 100 miles with the one vehicle traveling 270 miles. As mentioned previously, PHEV fuel efficiency and petroleum displacement impact is strongly associated with the daily distance traveled between recharge events.

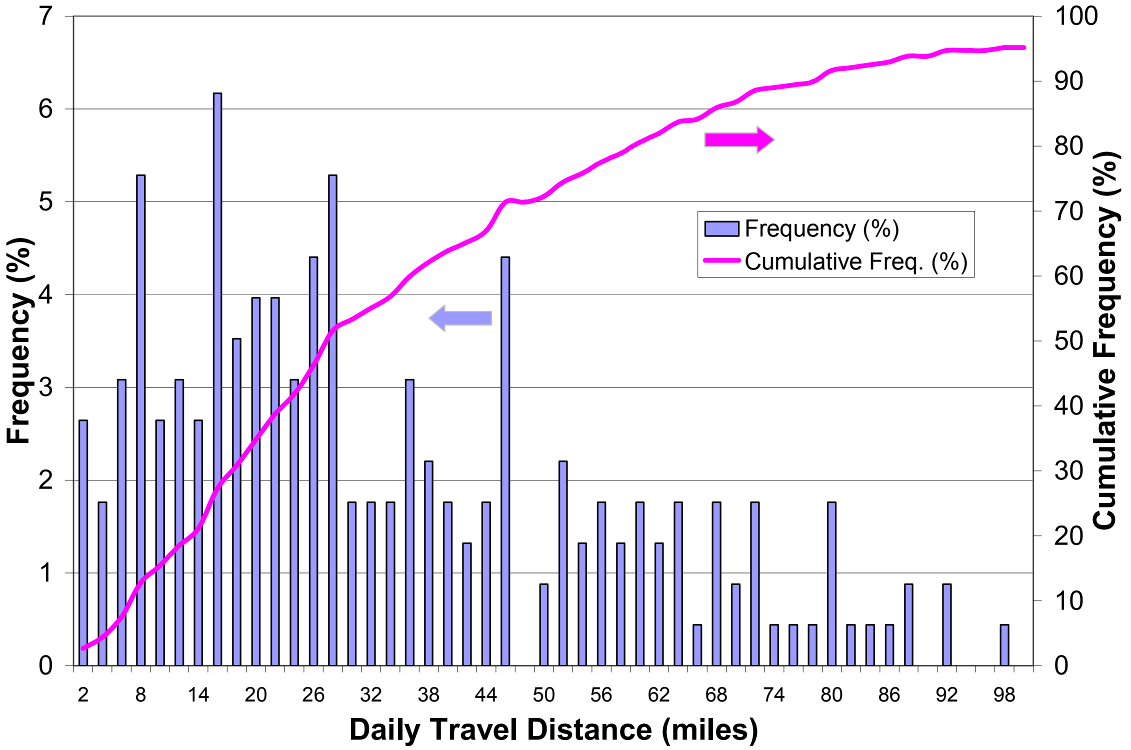

FIGURE 1 Daily driving distance distribution for 227 vehicles in the St. Louis metropolitan area.

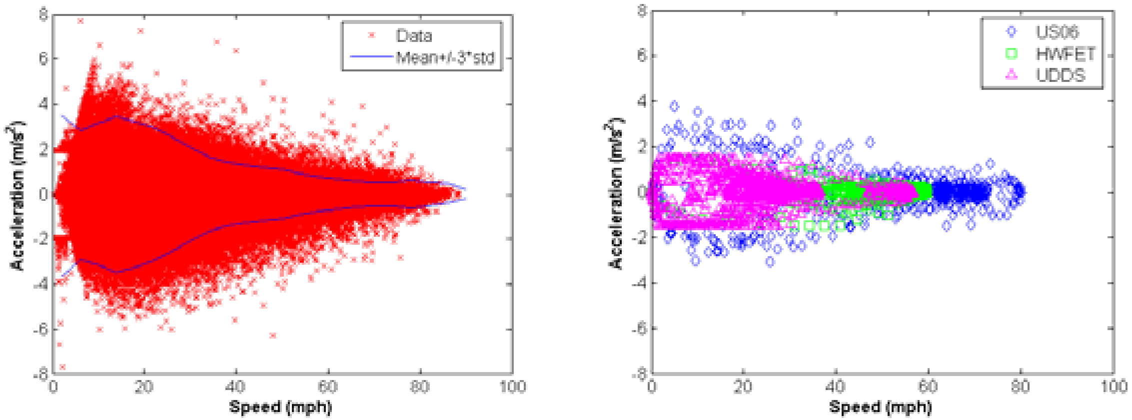

FIGURE 2 Comparison between acceleration characteristics of real-world and standard driving cycles.

In addition to the daily driving distance, the real data provides valuable insight into driving behavior. As it relates to vehicle design, the rate of acceleration and the speed at which this acceleration occurs is critical in determining the required power capabilities of the hybrid vehicle components. In Figure 2, acceleration is plotted against speed for the entire set of vehicles in the sample real-world data set on the left and for three standard driving profiles on the right. The UDDS and HWFET are used to represent typical urban and highway driving by the U.S. Environmental Protection Agency (EPA) for the purposes of standardized labeling of vehicle fuel economies. The US06 cycle includes more high-speed and more aggressive accelerations than either the UDDS or HWFET. The EPA has proposed using results from the US06 to improve vehicle fuel economy labeling to be more representative of what consumers might expect to see in use. This figure clearly shows that even the US06 cycle does not fully encompass the range of accelerations seen in this real-world driving sample.

The four vehicles described in Table 1 were each simulated over all 227 driving profiles. Figure 3 presents a summary of the simulation results. The vertical bars are associated with the left axis and represent the percentage of the 227 vehicles in use (driving) throughout the day. Morning, midday, and evening peaks in usage are clearly observed. The lines represent the cumulative liquid fuel consumed over the course of the day by the entire fleet of 227 simulated vehicles assuming all vehicles are the specified architecture. As the chart shows, the simulated HEV vehicle fleet reduced fuel consumption by about 29% relative to the conventional case. The PHEV20 technology reduced consumption by almost 55% and the PHEV40 reduced consumption by about 66%. As described in the previous section, PHEVs achieve such large petroleum displacement by relying on stored electrical energy up to the electric motor and ESS power and energy limits. PHEVs are assumed to begin each day fully charged and not charge again until they have finished driving for the day. All together, the simulated fleet consumed 1212 kWh and 1821 kWh for the PHEV20 and PHEV40 configurations respectively.

Because the vehicles utilize two different energy sources, it is useful to compare the vehicle configurations on the basis of total energy costs. Assuming costs of $2.41/gallon for gasoline and $0.09/kWh for electricity (national averages for 2005) results in average operating costs of 9.1¢/mile for the conventional fleet, 6.5¢/mile for the HEV fleet, 5.4¢/mile for the PHEV20 fleet, and 5.1¢/mile for the PHEV40 fleet. The reader should note, however, that the initial purchase price for each technology case will likely follow the opposite trend of the energy cost estimates (*18*).

The simulation results indicate that PHEVs would provide substantial petroleum displacement benefits and reduce vehicle fuel costs for this “real-world fleet.” The reduced engine use, particularly during the morning commute in Figure 3 (when emissions provide the greatest contribution to smog formation), indicates that PHEVs may also provide an emissions benefit. However, further simulations will be necessary to quantify the emissions impact of PHEV technology, since vehicle emissions are highly dependent on transient and on/off engine operation.

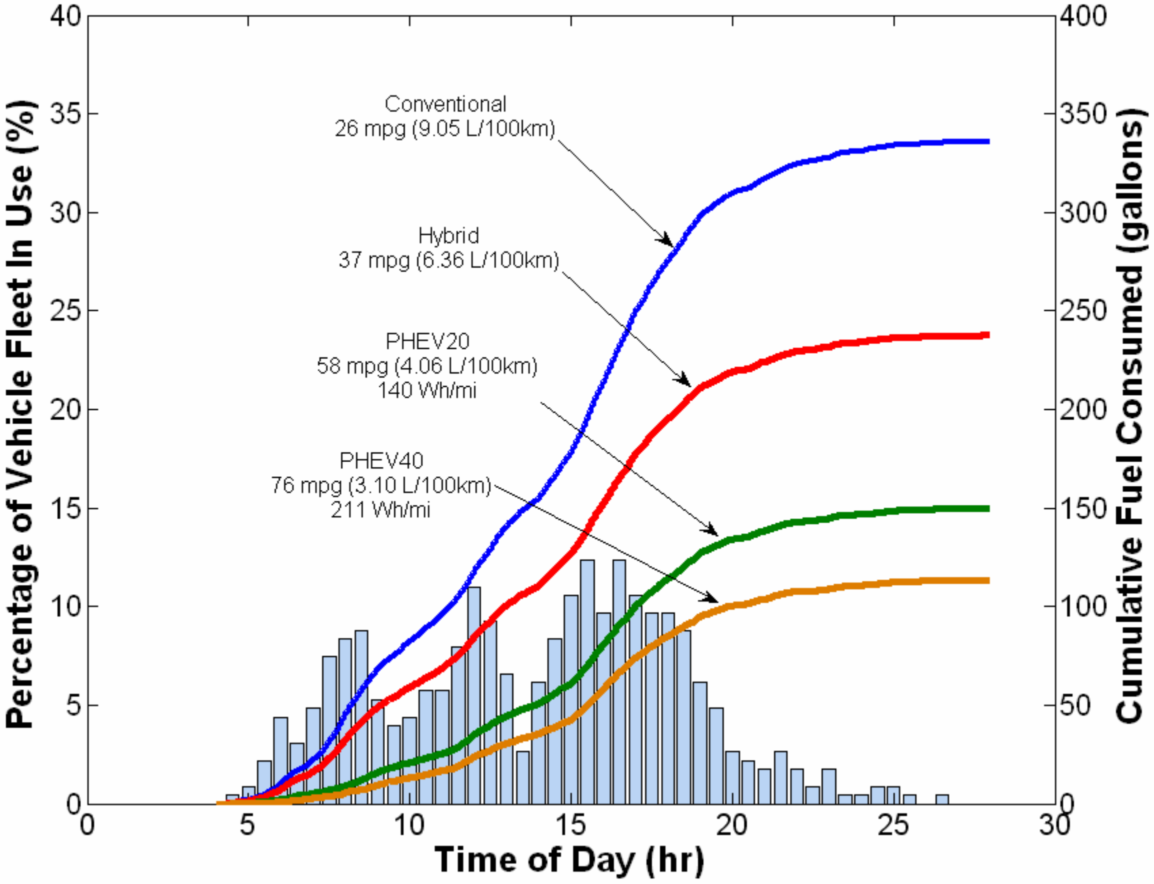

FIGURE 3 In-use activity pattern for 227 vehicles (solid bars, left axis) and cumulative fleet plus average vehicle consumption results for four vehicle technologies (colored lines, secondary axis).

Figure 3 shows the estimated consumption for each fleet scenario as a single result. Because detailed simulations were completed for each vehicle's drive cycle, it is also possible to examine the specific vehicle-level simulation results. Figure 4 shows the distribution of fuel consumption values for all of the vehicles in each of the four configuration scenarios. The bars represent the percentage of the fleet of 227 vehicles that achieved fuel consumption values within the indicated consumption range (each bar represents a range of 0.5L/100km). The vertical lines represent the fuel use on standard cycles (red: US06, and green: City/Highway composite). The city and highway composite value is determined by weighting the UDDS fuel economy by 55% and the HWFET fuel economy by 45%. The presented certification cycle ratings follow the recommended procedure for measuring and reporting PHEV fuel economy (*9*).

The first important insight from Figure 4 is that a large portion of the PHEV20 and PHEV40 vehicles in the real-world sample have consumption values much lower than those predicted by standard certification cycles, whereas a large portion of the conventional, and HEV results are greater than those technologies' standard cycle results. From the perspective of most drivers in this real-world fleet, this result suggest that a PHEV is likely to over-deliver on fuel efficiency expectations, while conventional and HEVs will likely under-deliver. A second important observation is that for both the PHEV20 and the PHEV40 nearly all vehicles in the fleet have fuel consumption values less than *all* of the conventional or

HEV vehicles. Whereas Figure 3 indicated PHEVs provide a large average fleet petroleum consumption benefit, this result suggests that the reduced petroleum consumption is experienced across the range of individual vehicle real-world driving profiles.

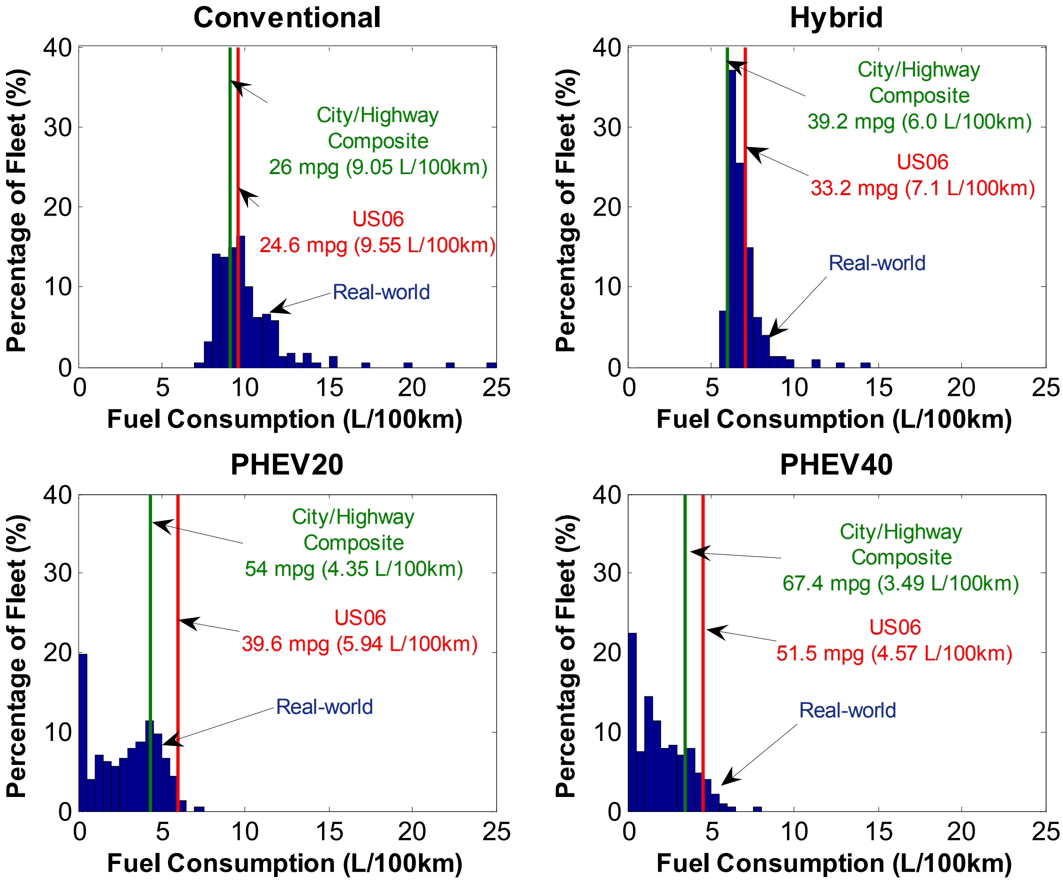

FIGURE 4 Comparison of fuel consumption distributions for various vehicle architectures.

Much recent discussion of plug-in hybrids has focused on the ability of the vehicles to operate without the use of the combustion engine (to maximize the previously defined “all-electric range” of the vehicle). As stated for this analysis, the PHEV20 and PHEV40 were respectively designed to provide approximately 20 miles and 40 miles of all-electric range capability on the UDDS cycle. Since Figure 2 shows the real-world cycles examined in this study to be much more aggressive than the UDDS, the actual in-use, all-electric range could be substantially less than the designed 20- and 40-mile distances. Figure 5 confirms that a large percentage of the vehicles achieved less than 5 miles of all-electric range over the real-world cycles. Careful comparison of the two charts in Figure 5 reveals that the mass-compounding, component-sizing procedure evidently produced slight differences between the two vehicles, which translated into a handful of cycle accelerations within the first few miles of driving, triggering an engine turn-on in the PHEV40 but not in the PHEV20 case. In spite of the “noise” this creates in the result, it is clear that most of the real-world driving simulations fall well short of the UDDS-designed, all-electric range capability. Nevertheless, it is important to recognize that the PHEVs achieve significant petroleum displacement without necessarily realizing a substantial all-electric range.

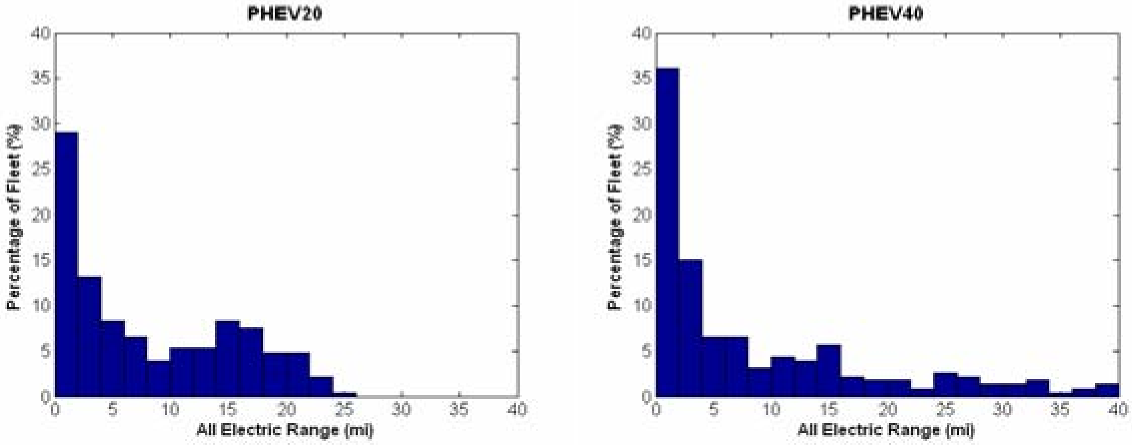

FIGURE 5 In-use all-electric range performance of PHEVs designed for urban cycle all-electric range.

CONCLUSIONS

Relatively recent advances in GPS technology and reductions in equipment cost have enabled MPOs to begin incorporating a GPS component into the travel surveys they conduct. GPS helps enhance the data collected for the intended transportation planning purpose, but also presents an opportunity for new uses of the data due to the enhanced temporal resolution on individual vehicle driving profiles. In particular, vehicle simulation tools can utilize the resulting second-by-second drive cycles to make predictions on how different vehicle technologies will perform under the real-world driving conditions captured by the GPS survey. The speed and accuracy of modern vehicle system simulation tools, such as the ADVISOR software discussed in this paper, enable direct simulation of a range of vehicle technologies over each individual 24-hour driving profile collected in the survey. Examining performance over a range of real-world cycles provides insights beyond only conducting a small number of simulations over “standard” cycles or an aggregate cycle intended to “represent” the spectrum of real-world cycles collected.

For the specific example of PHEV technology, the detailed GPS drive cycles can provide information on the time of day and duration of different driving behaviors, as well as where the vehicle parks when not in use. This information can be used to predict different charging scenarios that a PHEV fleet might experience throughout a given day. Further analysis (not directly discussed in this paper) examines the implications of fleet recharging on the electrical utility grid in addition to the impacts on the vehicles themselves. For instance, assuming PHEVs utilize an employer-provided charger when the GPS indicates the vehicles are parked at work could result in even lower vehicle petroleum consumption, but greater challenges for the local utility to meet peak daytime electricity demand.

Real-world fleet driving data can also help quantify the range of vehicle operation patterns and acceleration intensities. This information can help vehicle designers make more informed design decisions, such as understanding how much all-electric range actual drivers are likely to experience for a PHEV’s given battery and motor size. Finally, the detailed fleet driving simulations can help predict the benefit that advanced vehicle technologies (which can be sensitive to driving type and distance) could provide in real-world use. Over the 227 drive profiles taken from the St. Louis GPS survey, the simulations in this paper predict that if a fleet of conventional midsize vehicles following this driving distribution were replaced with a fleet of comparably sized PHEVs, the total daily petroleum use would be roughly cut in half.

While these simulation results represent an important step towards better quantifying the benefit of advanced technology vehicles in real-world drive cycles, several refinements are required before broad conclusions can be drawn about widespread introduction of these new vehicles. First of all, the vehicles will likely be offered in a variety of platforms other than “midsize sedans” and will replace a variety of different conventional vehicle types. Vehicle make and model information is available in the St. Louis data set, so the next step planned for this particular analysis is to investigate the impact of replacing the conventional midsize vehicles with midsize PHEVs—the conventional sport utility vehicles with sport utility PHEVs etc. —rather than assuming all vehicles in the fleet are identical. Such segmented vehicle class analysis will more precisely predict the fleet petroleum and electricity consumption by the various technology options, which could be overpredicted or underpredicted currently by the simplified 100% midsize vehicles assumption. This refinement will also improve the accuracy of extended analyses to quantify the potential cost increment for replacing each fleet vehicle with an advanced technology equivalent.

Aspects of the GPS sample itself also limit the ability to draw far-reaching conclusions from this particular analysis. It is possible to apply statistical expansion factors to the results in order to move closer to making conclusions about the potential PHEV impact in the larger St. Louis area (and subsequent efforts will discuss data expansion in more detail). However, because the 227 GPS driving profiles represent such a small fraction of the vehicles in the area, the uncertainties accompanying any data expansion will be significant. Proper data expansion is needed for making larger conclusions beyond the "sample" in order to account for effects such as potential correlation between household (and/or vehicle) attributes and driving behavior. For instance, some of the surveyed vehicles came from the same household and the various surveyed households represented a range of income brackets; these and other variables might impact the vehicles' typical driving distance, which can greatly influence an advanced technology's predicted benefit. Based on the demographic distribution in the larger population, the results need to be weighted with respect to the corresponding determined correlations. Along with challenges from the small size of the GPS subsample (and the fact that it was not originally intended for expansion to the full St. Louis population), an additional limitation of the data set used for this study is the fact that only profiles from weekday and not weekend travel were collected. Weekend travel may differ from weekday travel, and in order to gain a full picture of the petroleum displacement potential from an advanced technology vehicle such as a PHEV, this potential difference needs to be captured by the collected data.

The authors of this study have actively sought and continue to seek out additional data sets on which to perform similar simulations (with particular emphasis placed on obtaining larger sample sizes and surveyed data for all seasons and days of the week, if possible). Geographical diversity is also of interest, as the ability to reduce petroleum consumption is of national as well as local concern. As GPS survey costs continue to decline, the availability of this data continues to increase, as do the opportunities to extract additional value from such already collected information. Moving forward, it will also be possible in future surveys for multiple users of this type of data to partner together in order to increase the scope and quality of the GPS driving information and subsequent results expansion. As demonstrated by this study, a coordinated effort to expand the use of GPS data could lead to improved prediction of how specific advanced technologies will benefit a particular area.

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