Simulated Fuel Economy and Performance of Advanced Hybrid Electric and Plug-in Hybrid Electric Vehicles Using In-Use Travel Profiles

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Abstract **As vehicle powertrain efficiency increases through electrification, consumer travel and driving behavior have significantly more influence on the potential fuel consumption of these vehicles. Therefore, it is critical to have a good understanding of in-use or "real world" driving behavior if accurate fuel consumption estimates of electric drive vehicles are to be achieved. Regional travel surveys using Global Positioning System (GPS) equipment have been found to provide an excellent source of in-use driving profiles. In this study, a variety of vehicle powertrain options were developed and their performance was simulated over GPS-derived driving profiles for 783 vehicles operating in Texas. The results include statistical comparisons of the driving profiles versus national data sets, driving performance characteristics compared with standard drive cycles, and expected petroleum displacement benefits from the electrified vehicles given various vehicle charging scenarios.**

I. Introduction

Plug-in hybrid electric vehicles (PHEVs) have received increasing attention due to their potential for high fuel economy and petroleum displacement. The U.S. Environmental Protection Agency (EPA) has historically measured vehicle fuel economy using standard driving cycles such as the Urban Dynamometer Driving Schedule (UDDS) and the Highway Fuel Economy Test (HWFET). However, as new technologies and designs allow vehicles to become more fuel efficient, consumer behavior and driving profiles become more influential on the variation in actual fuel economy observed. For instance, aggressive driving or off-cycle behavior not captured by these standard drive cycles can greatly influence the actual fuel economy experienced by a given driver. This effect is accentuated with advanced technology vehicles such as hybrid electric vehicles (HEVs) and PHEVs. In the case of PHEVs, the distance driven between opportunities to charge the vehicle creates an additional and significant impact on its fuel use. In-use driving profiles containing a distribution of real world driving aggressiveness and distance between recharge opportunities can help further evaluate the expected fuel savings from various advanced vehicle technologies and designs.

II. Analysis

The real world drive cycle data for this study was obtained using Global Positioning System (GPS) technology. GPS devices use satellites to calculate second-by-second information about vehicle position, speed, and distance traveled. The GPS data used for this study was gathered by the Texas Department of Transportation and consisted of a total of 783 vehicles in Austin and San Antonio, Texas [1]. This GPS data was filtered and processed, and then used to generate 24-hour driving profiles for each vehicle in the study. The National Renewable Energy Laboratory's (NREL) vehicle-level simulation software, ADVISOR, was used to evaluate and compare the simulated performance of different types of vehicles and vehicle technologies on these in-use drive cycles [2].

Six different midsize platform vehicles were simulated on these cycles: a conventional vehicle (CV), an HEV, and four PHEVs. Of the four PHEVs, three had a parallel configuration with a blended control strategy, meaning that the internal combustion engine assisted the electric motor during times of high power demand. The three blended-strategy PHEVs are referred to as PHEV10, PHEV20, and PHEV40 because they were designed to travel approximately 10, 20, and 40 miles respectively on the UDDS before using any fuel. The fourth PHEV was a series configuration with a high-power battery energy storage system (ESS) and an electric motor capable of providing for all of the vehicle's power demands. The internal combustion engine in the series PHEV was only used to sustain the charge of the batteries for longer distance driving. This vehicle is referred to as PHEV40s and was designed to travel approximately 40 miles on the UDDS cycle before using any fuel. Table I lists some of the attributes of the vehicle models in the simulation. The engine, electric motor, and batteries were sized using methods similar to previous NREL hybrid vehicle technology studies [3].

TABLE I
SIMULATED VEHICLE ATTRIBUTES

				PHEV			
	Units	***CV***	***HEV***	***10***	***20***	***40***	***40s***
Engine Power	kW	123	77	77	78	80	85
Motor Power	kW	n/a	36	40	41	43	130
ESS Energy (total, DC)	kWh	n/a	1.7	4.5	8.2	16.4	16.4
Curb Mass	kg	1473	1552	1578	1614	1694	1789
CS Consumption*	L/100km	6.8	4.7	4.9	5.1	5.2	5.3
CD Consumption (AC)*	kWh/100km	n/a	n/a	18.2	18.2	18.4	18.9
Urban Electric-only Range	km	n/a	n/a	16.9	33.8	67.6	64.4
	mi	n/a	n/a	10.5	21	42	40

****Values reflect unweighted composite urban/highway consumption. The CD values represent pure CD performance (when no fuel use occurs on the standard UDDS/HWFET cycles).***

Of the two cities in this survey, the Austin data set contained 228 vehicles while the San Antonio data set contained 555 vehicles. The average daily driving distance in the Austin data was 55.4 km (34.3 miles) and was 65.5 km (40.7 miles) in the San Antonio data, yielding an overall average of 62.5 km (37.4 miles).

Fig. 1 shows the utility factor curves for the Austin and San Antonio data sets compared to the utility factor curve generated from the 2001 National Household Travel Survey (NHTS) data. The utility factor is used to estimate the percentage of vehicle miles traveled (VMT) covered for a specified charge-depleting (CD) range [4]. The Austin and San Antonio curves are significantly higher than the NHTS curve, which means that a higher percentage of vehicles in the NHTS travel longer distances relative to the vehicles in the Austin and San Antonio GPS samples. The discrepancy could simply result from an under-sampling of long distance driving in the survey methodology for the GPS samples, and/or a greater incidence of longer distance rural driving in the national data set. Either way, it should be noted that the larger percentage of CD operation in the GPS data sets will result in higher fuel savings for the PHEVs than those vehicles would experience in a similar vehicle fleet containing more long distance trips (and hence more charge-sustaining, or CS, operation).

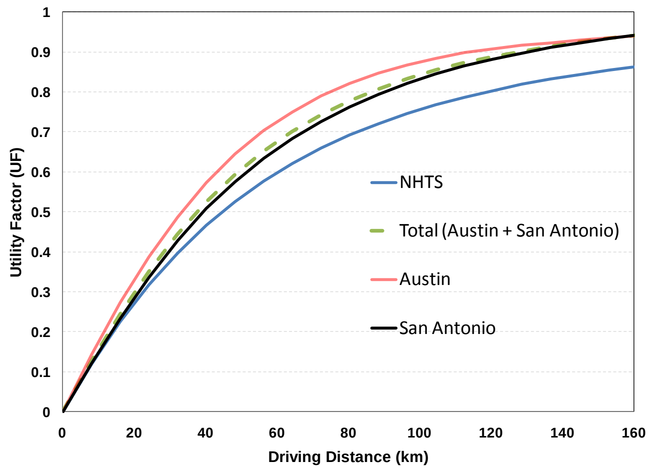

Fig. 1. Utility factor curves for Austin and San Antonio data sets compared to 2001 NHTS data

III. RESULTS

Fig. 2 shows the average fuel and electricity consumption weighted by vehicle day from the vehicle simulations for all of the vehicles in both the Austin and San Antonio data sets. Fig. 3 shows the distance- weighted average of fuel and electricity consumption for all vehicles. For the PHEVs, the graphs show the fuel and electricity consumption for both the base case and the opportunity charging (opchg) case. The base case assumes the PHEVs are recharged once per day (overnight). The opportunity charging case is a best case scenario that assumes that the vehicle has the opportunity to be plugged in every time the vehicle is stopped for more than two minutes. The vehicles are recharged at a rate of 1.56 kW AC with a charger efficiency of 90%.

Since most public parking lots do not have outlets in every stall to plug vehicles into, the base case is more likely representative of the real world. However, some consumers may make many trips throughout the day, returning home between trips. One example would be a stay-at-home parent who shuttles their children from place to place and returns home between trips. For this type of situation, the opportunity charging case may be a better representation. If public parking lots were to have outlets available to plug vehicles into, the fuel savings would be very significant, as shown by the significant increase in fuel economy from the base case to the opportunity charging case.

Note that the average fuel consumption of the PHEV40 opportunity charging case is less than the PHEV40s base case when averaging across all kilometers driven, whereas the opposite is true when averaging the results by vehicle day. This is because in the vehicle-weighted average, the vehicles that are driven short distances only in CD mode are given equal weight to those that travel far enough to enter CS mode. The distance-weighted averages, however, give more weight to the vehicles traveling long distances, and therefore include more CS operation in the averages (which also leads to higher fuel consumption results for all PHEV cases with distance vs. vehicle based averaging). Opportunity charging between trips can enable much more CD operation for the longer driving vehicles, and hence shows a larger relative fuel savings benefit when weighting by daily kilometers driven. Since the vehicle weighted average in Fig. 2 is representative of the average fuel consumption per vehicle day, it is better representation of an average consumer's fuel use, while the distance weighted average in Fig. 3 is a better representation of the average fuel consumption of the overall fleet (and the aggregate fuel displacement potential of each technology for this particular set of drivers).

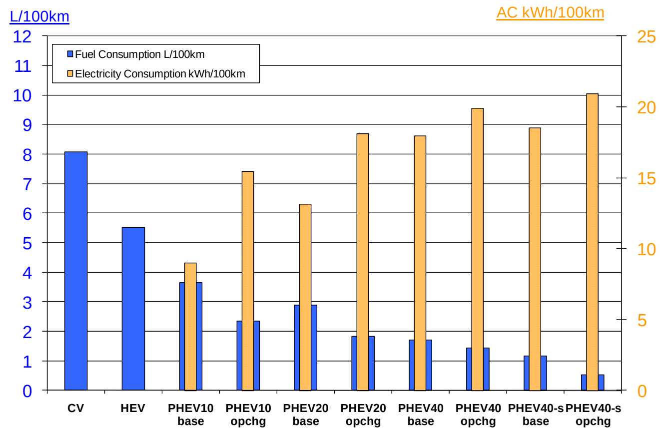

Fig. 2. Average fuel and electricity consumption weighted by vehicle day for Austin and San Antonio data sets

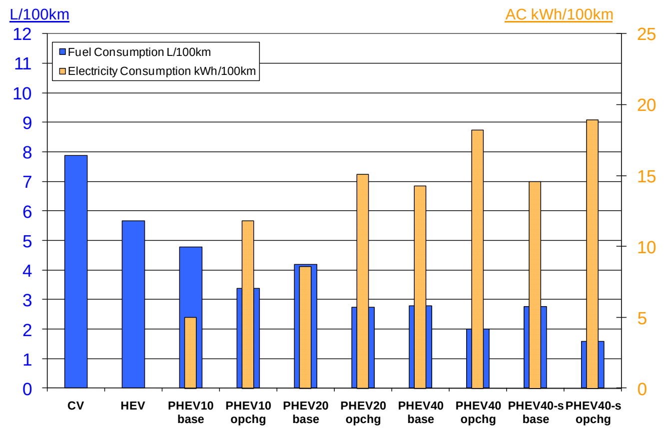

Fig. 3. Average fuel and electricity consumption weighted by total miles traveled for Austin and San Antonio data sets

The fuel consumption distribution for each vehicle variant over the Austin and San Antonio data sets is shown in Fig. 4 and Fig 5. Note that the PHEV20 has a very wide distribution compared to the PHEV10 and PHEV40. Because a high percentage of daily driving is greater than 10 miles, the PHEV10 usually operates in CS mode. Likewise, because a high percentage of daily driving is less than 40 miles, the PHEV40 usually operates in CD mode. The PHEV20, however, doesn't strongly favor either mode since a high percentage of vehicles drive between 10 and 40 miles per day. Also note that the PHEV40s has a very high peak at 0 L/100km. Unlike the PHEV40, it does not use fuel for aggressive accelerations and therefore uses no fuel unless it travels more than 40 miles. Finally, Fig. 4 and Fig. 5 also demonstrate the noticeably large percentage variation in fuel consumption of the vehicles with increased electrification as compared to the CV. The distribution differences highlight the increased sensitivity of PHEV fuel consumption (particularly for blended-strategy PHEVs) to variations in driving patterns and conditions.

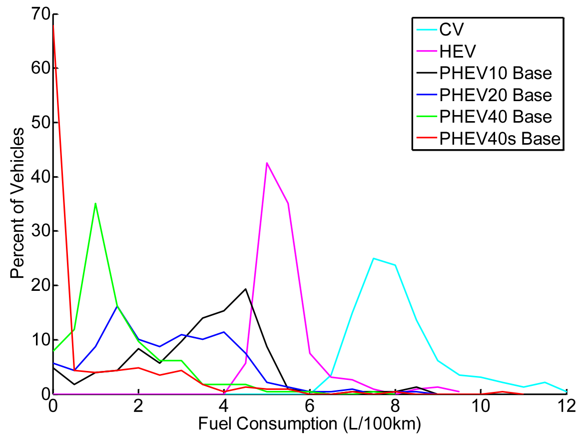

Fig. 4. Fuel consumption distribution for Austin data set

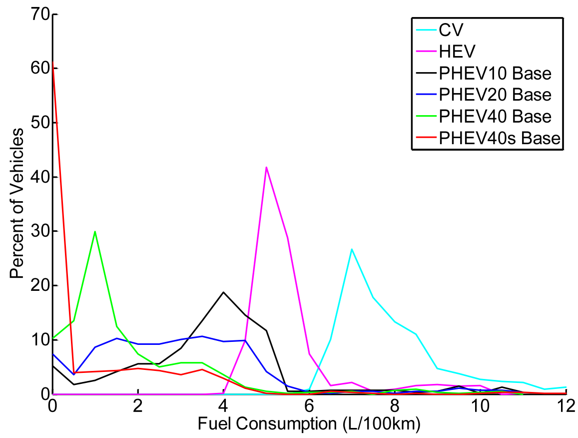

Fig. 5. Fuel consumption distribution in San Antonio data set

Fig. 6 and Fig. 7 show the electricity consumption distribution for each vehicle in the Austin and San Antonio data sets. As expected, the electricity consumption follows somewhat of an inverse trend compared to the fuel consumption. The PHEV10 uses less electricity because of lower storage capacity, causing it to run in CS mode more often, while the PHEV40 consumes more due to its high capacity, allowing it run in CD mode more often. The PHEV20 spends similar amounts of time in both modes, giving it a wide distribution similar to the fuel consumption distribution. The PHEV40s consumes the most electricity since it does not rely on the internal combustion engine to assist it with aggressive accelerations. However, the electricity consumption differences with the blended-strategy PHEV40 are small, suggesting that the PHEV40 makes just as good use of the energy stored in its batteries as the PHEV40s. (This observation is also supported by the near identical distance-weighted average consumption characteristics between the two vehicles).

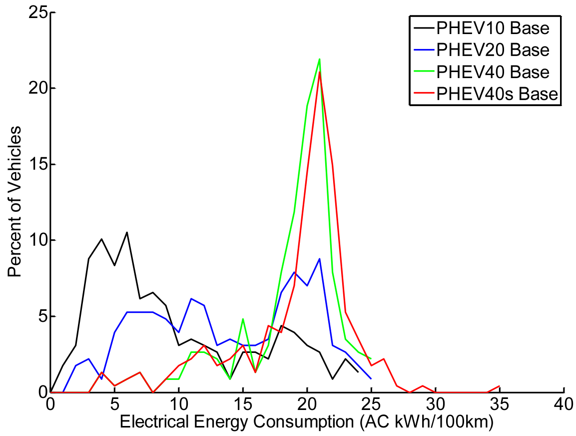

Fig. 6. Electrical energy consumption (AC kWh/100km) distribution in Austin data set

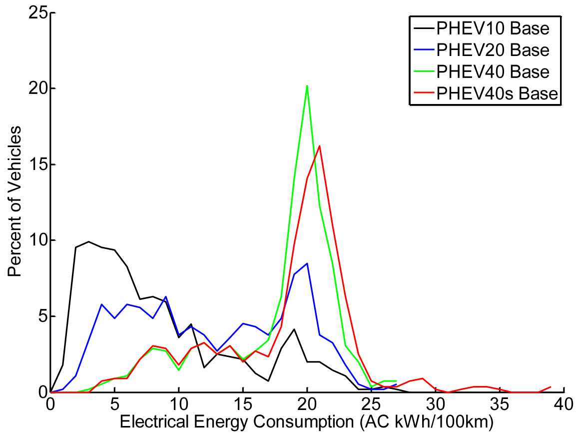

Fig. 7. Electrical energy consumption (AC kWh/100km) distribution in San Antonio data set

In order to design a vehicle that has an all-electric range in the real world that approaches that on the UDDS cycle, the electric motor must be larger to accommodate the higher power demands that often occur in real world driving. This raises questions as to how much larger the electric motor should be, and how significant of an impact a larger motor will make. Some insights that are needed to begin understanding and answering these questions are found in the analysis of these high power demands to determine how often they occur, how much additional fuel is consumed during these periods, and if there are any noticeable patterns or trends related to other parameters.

Although the PHEVs were designed to travel 10, 20, and 40 miles respectively on the UDDS, approximately 90% of the daily travel profiles caused the parallel/blended PHEVs to use fuel during CD mode. This means that 90% of the time, the internal combustion engine initially began using fuel because of high power demand, not because the state of charge of the energy storage system was too low. This is due to higher accelerations observed in the real world data compared to the UDDS cycle. Over 45% of the time, such a high acceleration caused an engine turn-on in the parallel/blended PHEVs within the first mile of the driving profile. Fig. 8 and Fig. 9 show the all-electric range for the PHEV40 in the Austin and San Antonio data sets, respectively. The red bars indicate the total distance traveled for vehicles that traveled all-electrically, while the blue bars indicate the distance traveled to the first occurrence of the internal combustion engine turning on.

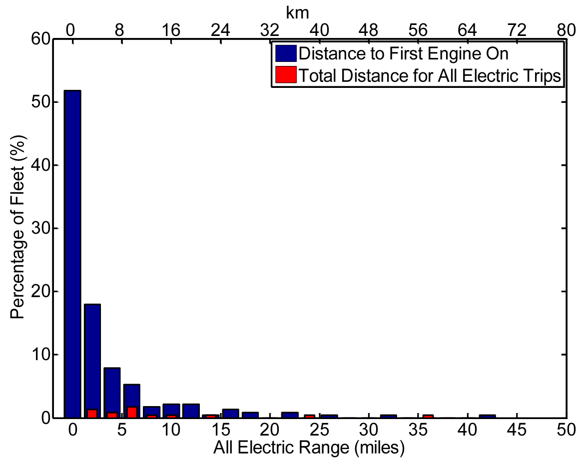

Fig. 8. All-electric range for the PHEV40 in Austin data set

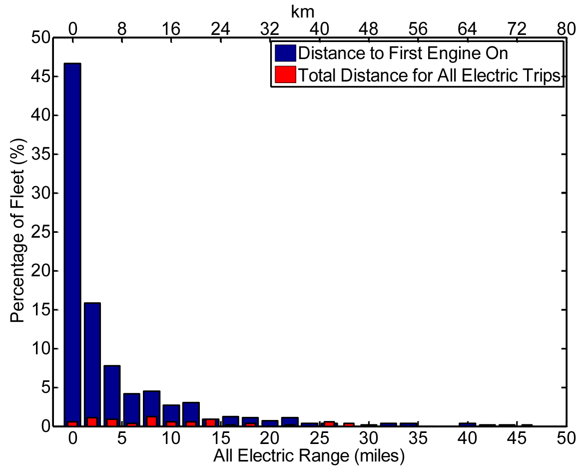

Fig. 9. All-electric range for the PHEV40 in San Antonio data set

Fig. 10 shows the maximum power demand per vehicle day. Since the actual power needed for each vehicle also depends on the mass of the vehicle, the power displayed is in units of kW/kg in order to simplify the comparison of the vehicles since they each have a different mass. In the actual simulations, there were some occurrences of much higher power demands than those displayed in Fig. 10. However, these high power demands were most likely caused by sports cars or other vehicles with a much higher specific power than the standard mid-size sedan used in the model and are not necessary for everyday driving. Therefore, maximum power demands that are higher than the maximum power of this study's CV's engine are not included in the results shown in Fig. 10 or Fig. 11.

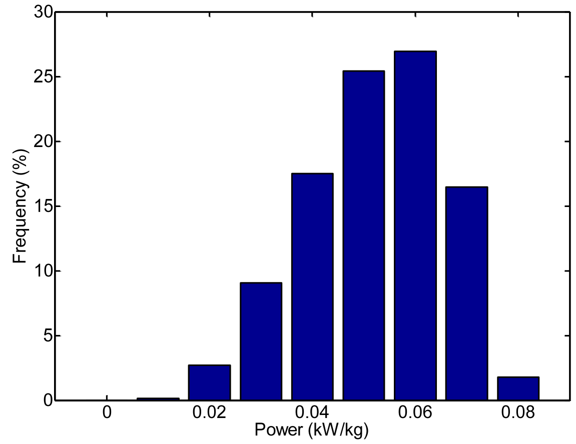

Fig 10. Maximum power demand distribution for all vehicles in Austin and San Antonio data sets

The standard UDDS cycle has a maximum power demand of 0.019 kW/kg, which is well below the average of 0.052 kW/kg shown in this study. In fact, only 1% of the vehicle days in this study had maximum power demand requirements that were less than the UDDS demand of 0.019 kW/kg. Therefore, if designing a vehicle to achieve similar all-electric range in the real world as it does on the UDDS cycle, the size of the electric motor must be increased significantly so that it requires assistance from the internal combustion engine less often. Fig. 11 shows the potential all-electric driving benefits of increasing the size of the electric motor based on the San Antonio and Austin data sets. Note, however, that in addition to increasing the electric motor size, the battery must be made more powerful at the same time to avoid turning on the engine. These changes will lead to a more expensive electric drive train.

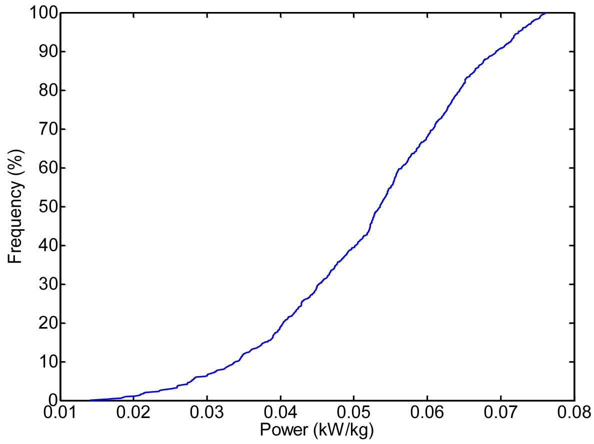

Fig. 11. Benefits of increasing motor-size

IV. Conclusions

PHEVs can consume significantly less fuel than CVs or HEVs and have a potential to play a key role in reducing U.S. petroleum consumption and carbon emissions in the future. Computer simulations using GPS data to generate in-use driving profiles are a convenient and useful way to evaluate vehicle performance, and fuel economy in the real world. These simulations can be used to size components such as the electric motors, internal combustion engines, and energy storage systems. They can also be useful in optimizing control strategies and other vehicle design choices.

The historic UDDS and HWFET cycles by themselves provide a limited representation of real world driving, particularly when it comes to predicting fuel use for PHEVs and when used as a base for evaluating vehicle designs. This is largely due to aggressive driving and higher accelerations observed in the real world. The daily driving distance compared to the size of the energy storage system also plays a significant role in determining PHEV fuel use, whereas CV fuel economy is affected very little by daily driving distance.

Increasing the size of the electric motor and energy storage system significantly beyond the power requirements of the UDDS and HWFET cycles is necessary to achieve substantial all-electric PHEV operation in the real world (i.e., driving where the engine never turns on). These changes would likely result in minimal measured performance difference on the UDDS and HWFET, and would increase the cost of the vehicle. The simulations in this study suggest that for once nightly charging the real-world fuel savings may also be minimal relative to a PHEV with comparable battery storage and an electric drive sized for the UDDS and HWFET. Opportunity charging is an effective way to increase the fuel savings of any PHEV variant; however, the higher electric power PHEV does seem to derive even greater benefit from opportunity charging than its lower-power blended-strategy counterpart.

Future research efforts may include performing similar simulations using GPS data from other regions of the country and from multi-day data sets. Vehicle performance in different regions could be compared to determine if driving behavior varies based on region or geographic location. If there is a correlation, vehicles could be designed for optimal performance in the specific region in which they will be used.

Demographic data could also help determine if different types of consumers have different driving habits. Again, if this is proven to be true, vehicles could be optimized for specific types of consumers. Preliminary studies by Argonne National Laboratory have begun to explore the relationship between population density and driving habits [5].

Future efforts should also incorporate changes in road grade into the simulations, as steep road grades will significantly impact vehicle power demands and in turn performance. This is especially important for very hilly regions, such as the mountain west. NREL is currently working to integrate this feature into its database of in-use driving profiles

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