Impact of Naturalistic Driving Patterns on PHEV Performance and System Design

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ABSTRACT

The paper investigates the impact of the drive cycle choice on the Plug-in Hybrid Electric Vehicle (PHEV) design, and particularly the selection of component sizes. Models of representative Power-Split and Series PHEVs have been built and validated first. Then, the performance and energy/power usage metrics were obtained by simulating the vehicle behavior over real-world (naturalistic) drive cycles recorded during Field Operational Tests in South East Michigan. The PHEV performance predictions obtained with real-world driving cycles are in stark contrast to the results obtained by using a sequence of repeated federal drive cycles. Longer commutes require much higher peak power and consume much greater amount of energy per mile than EPA UDDS or HWFET cycle. The second part of the paper investigates the sensitivities of the PHEV attributes, such as the charge depleting range and the fuel economy in the charge sustaining mode, to component size variations. The results provide quantitative guidance pertaining to design decisions in the context of driving patterns.

INTRODUCTION

Plug-in Hybrid Electric Vehicles (PHEV) provide a viable option for connecting the two major infrastructures, transportation and the power grid, and in doing so replace some of the petroleum currently being used in vehicles with other sources of energy. Different configurations are being suggested by leading OEMs and while everyone agrees that PHEVs enable a paradigm shift for vehicle propulsion, the optimum configuration has yet to be determined. The work published so far, particularly by major OEMs, offers a number of possible solutions with design features and vehicle attributes varying in a very wide range. On one end of the spectrum is the series configuration with emphasis on a long All Electric Range (AER), such as the Extended Range Electric Vehicle (E-REV) under development at GM [1]. On the other end of the spectrum, a power-split configuration such as the Toyota Prius with relatively modestly sized electric components offers a very different solution, as the electric range is traded off for lower initial cost [2]. Achieving the true AER, with no engine-on intervals, requires a large enough traction motor and a battery capable of satisfying peak power demands. In case of smaller components integrated in a power-split system, the powertrain operation by necessity blends engine and battery power and we speak about the Charge Depleting (CD) mode rather than all electric operation. In both cases the propulsion system switches to the Charge Sustaining (CS) mode once the battery state-of-charge (SOC) reaches the threshold.

The best PHEV design for a given market segment will depend on a number of factors, from the fuel prices to government policies, but the engineering research has to accurately characterize the design tradeoffs that may be involved. Different aspects of PHEVs being currently addressed include power management strategies [3][4][5], comparing different architectures [6], devising procedures and standards for PHEV testing [7], battery development and battery size requirements [8][9]. Vehicle level tests of different prototype or limited series PHEVs have also been done [10] on vehicles such as Hymotion Prius, Energy CS Prius and Renault Kangoo. However, while driving patterns can be expected to significantly impact the results of any PHEV analysis, they have not received any attention until very recently. Instead, most of the work relied on sequences of repeated US federal driving schedules that were
originally devised for emissions certification at EPA laboratories. The FTP-75 or city driving schedule is used most often, and analysis over 40 miles of driving requires repeating this schedule more than five times. Clearly, low speed driving in a congested urban area is not typical for long commutes.

Two main factors that distinguish a PHEV from a HEV are significantly higher electrical energy storage capacity and ability to draw power from the grid. Larger batteries along with larger motors make it possible to provide more electric power for driving and achieve higher displacement of fuel used by the engine. This makes the performance of a PHEV more sensitive than a HEV or a conventional vehicle to the drive cycle being used for testing. A recent study by Tate at al. [1] recognizes this and uses driving data collected in Southern California for assessing vehicle energy usage, while Kwon et al. [11] examine impact of drive cycles on component requirements.

Our study aims to establish the performance and energy/power usage metrics by simulating the PHEV operation over naturalistic driving schedules recorded in South East Michigan. The naturalistic driving data were provided by the University of Michigan Transportation Research Institute (UMTRI) that conducted Field Operational Tests over the past several years to study driver interaction with advanced safety systems [16]. While at this point it would be premature to claim that these schedules can capture all aspects of real-world driving, they do represent typical commuting in the South East Michigan region with traffic conditions very different than Southern California [1]. We aim to develop insight into the impact of naturalistic driving patterns on power requirements and energy usage per mile, before moving on to a detailed study of the sensitivity of PHEV performance attributes to component requirements.

Since there are two sources of energy on-board of a PHEV, it might not be possible to operate both in the most energy efficient patterns due to road power demands and functional constraints [12]. Changing the component sizes can have considerable impact on vehicle energy usage owing to the component efficiency maps [6]. We present the tradeoffs involved in system design through a sensitivity study of PHEV fuel consumption and CD range/AER as a function of component sizing. This is done for two PHEV configurations, a power-split and a series configuration, using naturalistic driving patterns.

The effects of naturalistic driving on PHEV performance are discussed first. The vehicle models and the naturalistic driving data used for this study are explained. Simulation results are shown and discussed in the light of relevant previous results. Then the sensitivity studies of components for both power-split and series powertrain configurations are given. The battery, engine and driving motor/generator sizes are considered. Observed sensitivity of CD range/AER and Fuel Consumption is explained through detailed analyses of the correlation between driving patterns and locations of operating points on efficiency maps. The paper ends with conclusions.

EFFECTS OF NATURALISTIC DRIVING ON PHEV PERFORMANCE

VEHICLE MODELS - PSAT [13], a powertrain-modeling package developed in MATLAB-SIMULINK was the used for simulating representative power-split and series electric hybrid configurations. PSAT generates a forward-looking model and offers the ability to quickly compare several powertrain configurations. The Power-Split Vehicle was modeled with the characteristics of the Energy CS Toyota Prius and the Series Vehicle was modeled after the upcoming GM Volt. The ability to easily scale the components was helpful in conducting the sensitivity study discussed later.

The Energy CS Prius is a power-split PHEV that replaces the stock battery pack and battery control module in a production Toyota vehicle with a 9 kWh Li-ion pack and a custom battery control module. The latter communicates with the hybrid control system via CAN (controller area network) communication. PSAT library includes a model for MY04 Prius which has been previously validated at Argonne National Lab (ANL) [14]. This was a starting point for modifications required to simulate the Energy CS Prius PHEV. The battery model was replaced with the 6Ah 75 cell SAFT Li-ion battery model and scaled to 9 kWh. The scaling was done by increasing the capacity (Ah), which resulted in the change of the power limits of the battery while the number of cells was kept constant as suggested in [9]. The controller was revised to switch the engine on at higher vehicle speeds, and when the power demand exceeds the battery or motor power limits. The controller modifications were based on information published in [10]. The penalty for the cold start was calculated by the extra amount of fuel used in the Prius Engine as given in [15]. Taking this penalty into consideration our simulation provided fuel consumption results within 2.5% of measurements on the actual vehicle [10]. To validate the battery charge depletion characteristics we compared the range of driving in charge depleting (CD) mode and the results were found to be within 1%.

The representative series PHEV was modeled with component sizes and control strategy similar to the upcoming Chevy Volt [1]. The powertrain model has a moderately sized engine (53 kW) coupled to a generator (58 kW), which can charge a Li-ion battery (16 kWh), and this battery powers a motor (120 kW) which propels the vehicle. The component sizes and modifications made are listed in Tables A1 and A2 in the Appendix.

NATURALISTIC DRIVING DATA - University of Michigan Transportation Research Institute (UMTRI) conducted Field Operational Tests over the past several
years to promote development of various vehicle safety devices and systems and to assess driver behavior [16]. The databases were created using a fleet of 11 Nissan Altimas, equipped with data acquisition systems capable of recording over 200 channels of data, of which the time-speed traces were of particular interest. The data recorded was for driving in South East Michigan. UMTRI provided a sample of 45 "trips" from the database. The trips cover a wide variety of driving distances and styles from 0.3 miles to 139 miles and were divided into short, medium and long cycles (Figure A1 in the Appendix). The groups contained cycles with less than 9 mi (15 cycles), less than 20 mi (21 cycles) and greater than 20 miles (9 cycles), respectively. This grouping was based on the NHTS survey of daily driving patterns [17], with the intention to capture roughly 1/3 of total driving with each category. As a preliminary study before simulating the vehicles, some simple statistics of naturalistic driving cycles were examined and compared to federal cycles, see Table A3 in the Appendix. Accelerations at higher velocities result in higher vehicle power demands than the same accelerations at lower velocities as the resistive force terms like drag are functions of velocity. Hence, the naturalistic drive cycles have higher maximum velocities and less stops/mile indicate a more aggressive driving behavior. This is particularly evident in case of longer trips. Not surprisingly, standard deviation trends indicate a relatively large variation in the naturalistic data.

SIMULATION RESULTS - Both PHEVs were simulated over the 45 naturalistic trips as well as the standard cycles –UDDS, HWFET and US06. All predictions shown in this section pertain to specific energy usage per mile, hence the calculations were carried out for a single trip. The two vehicle models have different mass and resistance coefficients and this is reflected in energy consumption patterns and maximum power demands, shown in figures 1, 2 and 3 below.

<table>
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<tr>
<th>Cycle</th>
<th>Battery Energy (kWh/mi)</th>
<th>Fuel (0.001*gal /mi)</th>
<th>Total Energy (kWh/mi)</th>
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<tr>
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<td>1.42</td>
<td>0.181</td>
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<tr>
<td>HWFET</td>
<td>0.175</td>
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<td>US06</td>
<td>0.191</td>
<td>12.9</td>
<td>0.331</td>
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<td>Average Naturalistic</td>
<td>0.163</td>
<td>8.32</td>
<td>0.250</td>
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Table 1 – Specific energy consumption calculated using the Power Split PHEV Simulation

For a Power-Split PHEV, a comparison of the averages for naturalistic cycles in Table 1 with the results for standard cycles shows that federal cycles are not representative of real-world driving. Much higher fuel consumption indicates that higher velocities and power demands observed for naturalistic driving lead to more frequent and more intense engine operation. UDDS and HWFET are too mild and hence both the total energy and fuel consumption are underestimated. Energy consumption for the US06 is somewhat higher than the average naturalistic cycle, so US06 can be useful in the case when longer commutes from suburban locations are anticipated.

![Maximum Propelling Power Distribution](image1.png)

![Maximum Braking Power Distribution](image2.png)

Figure 1 – a) Maximum Propelling Power Distribution, and b) Maximum Braking Power Distribution, for 45 Naturalistic trips for Plug-in Power Split Hybrid Electric Vehicle

Figures 1a and 1b show histograms of propulsion power distributions for a power-split vehicle calculated using the set of naturalistic driving schedules. The vertical red lines are added to illustrate maximum power demands of the federal cycles. It can be seen that none of the 45 naturalistic cycles have a lower maximum propelling power demand than the UDDS. In [2], based on simulations with UDDS, it is suggested that a battery and motor size capable of handling 40kW power demand will enable electric operation 100% of the time (or charge depleting mode) and the electric operation would drop to only 95% with a 20 kW battery-motor unit. Figure 1a confirms this, but also shows a stark contrast in results for naturalistic drive cycles. Even with a 65 kW battery-motor only 90% of the cycles would have all electric, and this number drops to about 20% with a 40 kW battery-motor unit. A similar analysis of the negative power
values (Figure 1b) shows that complete regenerative braking for 50% of the cycles can be achieved is the battery-motor unit is capable of absorbing 60 kW. This number climbs to 85% if the electrical side can absorb 80 kW.

If pure AER is desired in case of a Series vehicle, the prerequisite is to ensure that both the battery and the driving motor are capable of handling peak road power demands. Only after the power-limit is satisfied the battery capacity is considered and its size is dictated by the desired range and vehicle specific energy consumption. In Figure 2 the black dots represent results for net battery specific energy (energy used per mile) obtained using each of the naturalistic driving schedules. These points are compared to the horizontal lines (red) indicating the specific energy consumption for the federal cycles.

Designing a vehicle with battery energy capacity sufficient to fulfill the energy needs of UDDS or even HWFET would result in insufficient all-electric capability for more than 84% of the drivers. On the other hand, if the battery was designed using the US06 cycle it would satisfy all-electric capability for more than 91% of the drivers. These conclusions are in-line with [1], i.e. if pure AER is an imperative in PHEV design and only federal cycles were available, US06 would be a good choice.

Figures 3a and 3b show histograms of propulsion power distributions calculated for a series PHEV using the set of naturalistic driving schedules. Figure 3a indicates that satisfying maximum power requirements for 95% of the cycles would require a motor rated at more than 100 kW. The battery should be capable of providing this amount of power for the complete range of its usable SOC. To satisfy all the propelling power demands for at least 50% of the drivers the electrical side should be capable of more than 70 kW. In Figure 3b, the maximum braking power values are as high as 195 kW, but only 9% of values are higher than 120 kW. Hence, a motor/generator rated at 120 kW would be able to capture full braking energy for most drivers, while an 80 kW motor/generator enables 100% regeneration for only 50% of the drivers.

Simulating the series PHEV over a 139 mile naturalistic drive cycle provided us a first glimpse of engine usage, as the vehicle runs in the charge sustaining mode for extended periods of time. This is the reason why specific battery energy dropped to very low levels – simply the battery got depleted and a large portion of total energy came from the engine. The fuel economy was around 40 MPG over the complete trip. This confirms the challenge in designing Series HEV platforms, namely the multiple energy conversions in the system and accompanying multiplication of efficiency factors adversely affects fuel economy in charge sustaining mode [3, 6].

**COMPONENT SENSITIVITY STUDIES**

The purpose of the sensitivity study is to understand the effect of component sizes on vehicle energy consumption, both electric and gasoline. Four
naturalistic drive cycles and the federal UDDS were chosen for this analysis. The four naturalistic cycles were chosen to represent different driving patterns such as urban, suburban and highway. Table A4 in the Appendix summarize characteristics of the chosen cycles and Figures A2 and A3 (in Appendix) show plots of the cycles. In every study, it was ensured that vehicle had enough power to complete the cycles. The ranges of component sizes were chosen based on this criterion, and values are indicated in Table A5 of the Appendix.

During the sensitivity studies the motor power is scaled by proportionally changing the torques while keeping the operating speeds constant. To scale the battery, the capacity (Ah) is varied and the voltage is kept constant. This results in a proportional change in the battery power limits and energy capacity. The engine power is scaled by proportionally changing the torque, thus simulating the increase of displacement while preserving full similarity of design. If the electric capacity of the powertrain is changed, the engine threshold power is changed to reflect the true capability of the electric side. The operating points and average efficiencies discussed below imply operating efficiencies of the components over complete drive cycles.

SENSITIVITY STUDY FOR THE POWER SPLIT VEHICLE - The results for this study are obtained by simulating the power-split vehicle over repetitions of the cycles given in Table A4 for a distance of 60 miles. This was done to let the battery deplete from its initial SOC to the threshold SOC, and then continue in the charge-sustaining mode for at least 20 miles in case of the UDDS cycle. Hence, the total distance is the same in all cases, but portion of driving in CS mode varies. While we examine trends related to each of the main components in PHEV system, our approach emphasizes the system-level effects and impact of component duty-cycles on overall efficiency.

Motor - as the motor size is increased from 50 kW to 70 kW the MPG increases slightly, for a maximum of 1%. Slight change in MPG numbers is directly related to the motor effectiveness in using electric energy, i.e. the more efficient the motor the less power it draws from the battery for the same speed and load, hence resulting in reduced overall engine usage. The motor efficiency maps change with motor sizes, as shown in Figures 4a and 4b. The operating points of the long-suburban cycle are superimposed on the maps, since sensitivity was greater for this cycle than the other cycles. In Figure 4b, we see that the area of concentrated operating points actually falls in the region of relatively lower efficiencies in case of a 70kW motor. However, larger motor uses the battery energy more effectively during the CD mode, hence reducing the energy required from the engine to complete the trip and offsetting slight loss of efficiency.

In summary, the impact of motor size on MPG is small, and other factors should be used for motor selection, such as the performance, interactions with other components in the system, and cost. The features of the power-split system and its control create strong interdependencies between components, and that is one of the reasons why the system is relatively in-sensitive to variations of just the motor. This explains the choice of keeping the motor/generators moderately sized advocated in [2].

![Figure 4 - Motor Efficiency maps with superimposed operating points of long-suburban cycle for a) 50 kW Motor, and b) 70 kW motor.](image)
Figures 6a and 6b show higher predicted heat losses at lower SOC. In addition, internal resistances monotonically increase with SOC in the range 0.4 to 1. Higher resistances mean greater power losses, so having a large battery that spends more time at higher SOC results in higher internal resistance losses compared to the small battery. This creates a tradeoff between the effect of heat losses and internal resistance losses. Our results clearly indicate the more dominant effect of heat losses, and illustrate benefits of working with a larger battery. The diminishing returns in overall efficiency observed in Figure 5 are the consequence of the milder change of heat losses with SOC in case of a larger battery.

Figure 5 - Battery Operating Efficiency Variation for Plug-in Power Split Vehicle

Figure 7 illustrates engine average efficiency trends as a function of battery and motor size. The engine operating efficiency decreases with increasing battery size and the drop is relatively higher for larger batteries sizes. Increased engine-on threshold with increasing battery size decreases engine usage and average power demand. Engine operates most efficiently at high power demands (high torque and medium speeds), as seen in Figure 8. Hence, reducing average engine load with increased battery size decreases engine efficiency (see Fig. 8b). In addition, while the engine-on threshold drops linearly with increasing battery size, the engine power demand decrease more rapidly due to features of drive cycles. Both naturalistic and federal cycles have an approximately Gaussian distribution of power demands (see Figure 9), hence cutting-off higher power regions results in progressively more operation at part load. This is visible in Fig. 8, as the areas with most density of operating points shift down and left on the BSFC map for a larger engine (see Fig. 8b).

Figure 6 – Battery Heat Losses over 60 miles of repeated UDDS for a) 5kWh battery, and b) 7kWh battery.

Figure 7 - Engine Operating Efficiency Variation for Plug-in Power Split Vehicle
Fuel economy - examination of the compounded effects in Figure 10 indicates progressively higher MPG with increasing battery size, and milder beneficial effect of the reduced engine size. Obviously, the main trend with battery size is driven by larger portion of CD driving, as trip lengths are the same in all cases. Higher power limits of the larger battery are also a factor in both driving and braking.

Another key point illustrated in Fig. 10 is the extreme difference in magnitude of fuel economy between predictions obtained with the UDDS cycle and the naturalistic short-suburban. The UDDS is obviously much less demanding, and does not represent the real-world driving on larger commutes. The variation of MPG with battery size is less non-linear in case of a short-suburban cycle because of more blending between the battery and engine power.

**SENSITIVITY STUDY FOR SERIES VEHICLE -**
Similar approach was used for studying the sensitivity of the series PHEV to variations of component sizes. The trends are quite different, as the series architecture leads to very different interactions in the system than power-split configuration. The AER becomes an important attribute, as series configuration lends itself easily to all–electric operation as long as electrical components are capable of provided required power.

**Motor** - the AER (in CD mode) and MPG (in CS mode) vary negligibly with motor size. The reduction of ~3% is observed with increase in motor size from 100 to 140 kW. This mainly due to less frequent increase in size leads to reduced relative load of the motor and consequently reduced average efficiency, and increases vehicle mass. The impact of relative load has been illustrated before using the power-split PHEV results in Figures 4a and 4b. While the actual numbers vary in case of a series vehicle the trends are consistent and we
do not show a new set of maps here in order to limit the length of the paper.

The variation of MPG between drive cycles is large, e.g. it varies between 32 (long-highway cycle) and 58 (UDDS cycle). This is mainly due to hugely different specific energy (energy-per-mile) consumption over a real-world cycle. UDDS results show some sensitivity to the motor size due to frequent low-load operation, while in the case of naturalistic long-highway cycle there is almost no sensitivity – the motor simply remains in the relatively high-load and high-efficiency zone most of the time. The only advantage of increasing the motor power rating above 100 kW is the improvement in 0-60 mph time. Thus it is best to use the smallest motor that satisfies all road power demands.

**Battery and Engine** – as battery size increases it operates more efficiently (as explained in the sensitivity study section for the power-split), the increase in its mass offsets this effect. For the batteries used in the simulation their mass increased by 21.89 kg per increase in kWh. Hence the AER increases almost linearly with increase in battery capacity (Figure 11). The effect of the driving cycles is remarkable, as simulations using a sequence of UDDS cycles yields much higher MPG than real-world driving. As an example, in case of a 15 kWh battery the predicted AER with UDDS cycles is 46 miles and with a short-suburban ~33 miles. The battery is allowed to deplete only to SOC of 40%.

Investigating the MPG of a series PHEV is meaningful only on the CS mode. Trends with engine and battery size are illustrated in Figure 12. The effect of engine size on MPG is relatively small, ~8% over 40-70 kW range. Not surprisingly, the battery size produces even smaller impact, on the order of ~2% over 11-19 kWh range. This relative insensitivity of MPG means that we can prioritize component sizing for desired CD mode of the series PHEV, and then satisfy the necessary constraints for the CS operation, rather than optimizing for both scenarios and obtaining a tradeoff.

**Figure 11 – AER variation with battery size for Plug-in Series Vehicle**

Figure 12 – MPG Variation for Plug-in Series Vehicle in charge-sustaining mode

The battery size range used in the simulation is 11-19 kWh. Thus engine power demands during CS operation are generally high and engine operates efficiently for all sizes. As an illustration, the medium-size 58 kW engine operates most of the time in the peak efficiency region of the BSFC map (see Figure 13a), but the operating points on the BSFC map of a larger 70 kW engine are positioned even better (see Fig. 13b), as the torque is high but the speeds are somewhat reduced.

There is some loss of engine efficiency on the low-end of the spectrum, since battery charging limits allow relatively high levels of engine power and push engine operation into higher speed, lower BSFC region. The cumulative effect is illustrated in Figure 14, for both the UDDS cycle and short-suburban cycle calculations. The surfaces separate for reduced engine size, and the sensitivity of engine efficiency to engine size increases progressively when the naturalistic short-suburban cycle is used. Fine tuning of PHEV supervisory controller based on a larger sample of anticipated vehicle missions will be considered in the future to reduce the engine efficiency penalty with reduced size. The findings indicate that in case of a series PHEV, the battery size choice will be driven mainly by the desired AER and cost, while the analysis of the CS mode will decide on the engine that best matches the electrical storage/propulsion sub-system for anticipated driving conditions. The driving schedules clearly have dramatic effect on predicted AER and real-world driving has to be considered when characterizing sensitivities and preparing for design decisions.
It should also be noted that the MPG variation with engine size in the series configuration (for CS mode only) differs significantly from the power-split configuration. In the series configuration the engine is used only for sustaining the charge, and large batteries (>10 kWh in our studies) lead to higher charging power. In the power-split configuration the engine is used to supplement the electric power for propulsion, as well as for charge sustaining. The engine operating efficiency is more dependent on the road power demands in the power split than in the series. The short suburban cycle has a wider distribution of road powers compared to the UDDS making MPG less sensitive to the engine size in the power split configuration, but also reducing significantly the attainable MPG. In the series configuration the road power demands are supplied by the battery and the engine operation is dictated by the charging limits (hence the sensitivity to battery size) and details of the control strategy.

Simulation analysis indicates strong dependency of PHEV CD range and fuel economy in CS mode on driving schedules, with generally much higher power demands exhibited by naturalistic schedules. Therefore, maximizing the electric operation in CD mode and possibly achieving the all-electric range with a series PHEV would require significantly larger electrical components in case the real-life conditions are considered rather than just the federal city schedule (UDDS). The power and energy usage results show that UDDS and HWFET have maximum energy per mile requirements which correspond to roughly 10% of naturalistic driving captured with a sample of 45 cycles. The US06 cycle is more aggressive and covers 90% of the specific energy range observed in naturalistic driving, but it does not account for the variability or the trip length distributions of naturalistic cycles. Hence, if PHEV design is intended to address consumer expectations under real-world conditions, considering naturalistic driving patterns is crucial. This is particularly important if pure AER range is desired.

Sensitivity studies were performed to determine how much are the PHEV attributes affected by the sizes of
the battery, the motor and engine. For the power split PHEV, the MPG was found to be most sensitive to the battery size. Fuel economy improved significantly with larger batteries, as they reduce engine usage for a given trip length, and exhibit reduced heat losses and more efficient discharging. MPG is also sensitive to engine size. Somewhat smaller engine demonstrates better fuel economy, as the features of the power-split system and supervisory control move engine operating points towards relatively higher torque. Vehicle MPG is not very sensitive to motor size; hence, the selection should be made based on desired acceleration performance and possible desire to reduce the engine-on intervals during CD operation.

The analysis of the series PHEV is dominated by the impact of component sizes on AER. Obviously the AER is directly affected by the battery capacity. Interestingly, the AER increases almost linearly with battery size, as the effects of increased vehicle mass and more efficient battery operation offset each other. Vehicle MPG in CS mode is most sensitive to engine size as there is no net energy coming from the battery. Small engines (<55 kW) are inefficient due to operation at higher speeds. Fuel economy as a function of engine size tapers off around $P_{\text{engine}} = 58$ kW, and further increase in engine size does not improve fuel economy. The magnitudes of predicted PHEV attributes vary dramatically with changes of driving schedules, e.g. predicted all electric range with the 15 kW-h battery would be ~33 miles in case of naturalistic driving on a short suburban cycle, rather than 46 miles with the UDDS.

The sensitivity of vehicle attributes to each component is subject to the drive cycle used. In general naturalistic drive cycles display higher peak power and a wider distribution of power demands than federal cycles. This forces operation of components at relatively higher loads, and the effects on batteries may be quite different than the effect on motors. Thorough system-level analysis is required to fully characterize the relationships and quantify the tradeoffs. The extension of the study to pursue application of optimization algorithms for design decisions is apparent.

ACKNOWLEDGMENTS

We would like to thank Zevi Baraket and Tim Gordon of UMTRI for providing the naturalistic driving data and for their valuable insights pertaining to driver behavior.

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APPENDIX

<table>
<thead>
<tr>
<th>Component</th>
<th>Specifications</th>
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<tr>
<td>Engine</td>
<td>MY04 Prius 1.497 L gasoline, 57 kW</td>
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<td>Motor/Generators</td>
<td>30 kW peak, 15 kW continuous 50 kW peak, 25 kW continuous</td>
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<td>Battery</td>
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<td>Final Drive Ratio</td>
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<td>Resistance Coefficients</td>
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Table A1 – Powertrain Model Specifications for representative Power Split Vehicle

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<th>Cycle Type</th>
<th>Average Velocity (mph)</th>
<th>Standard Deviation of Velocity (mph)</th>
<th>Average of Maximum Velocities (mph)</th>
<th>Stops/Mile</th>
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<td>Short (15)*</td>
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<td>16.44</td>
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<td>Medium (21)</td>
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*Numbers in parenthesis are number of cycles in each group

Table A2 – Powertrain Model Specifications for representative Series Vehicle

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<td>Motor/Generators</td>
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<td>Resistance Coefficients</td>
<td>$f_0 = 88.6 \text{ N}, f_1 = 0.14 \text{ N-s/m}, f_2 = 0.4392 \text{ N-s}^2/\text{m}^2$</td>
</tr>
</tbody>
</table>

Table A3 - Statistics for different cycles used for simulation

<table>
<thead>
<tr>
<th>Cycle</th>
<th>Duration (s)</th>
<th>Distance (mi)</th>
<th>Maximum Velocity (mph)</th>
</tr>
</thead>
<tbody>
<tr>
<td>UDDS</td>
<td>1369</td>
<td>7.45</td>
<td>56.70</td>
</tr>
<tr>
<td>long-suburban</td>
<td>2297</td>
<td>20.84</td>
<td>63.13</td>
</tr>
<tr>
<td>short-suburban</td>
<td>731</td>
<td>7.21</td>
<td>60.65</td>
</tr>
<tr>
<td>short-urban</td>
<td>960</td>
<td>6.58</td>
<td>50.45</td>
</tr>
<tr>
<td>long-highway</td>
<td>1441</td>
<td>20.80</td>
<td>78.35</td>
</tr>
</tbody>
</table>

Table A4 – Drive Cycles Used for sensitivity studies: 1 federal, 4 naturalistic drive cycles.

Table A5 – Component Size ranges for sensitivity studies

<table>
<thead>
<tr>
<th>Vehicle Type</th>
<th>Motor Size</th>
<th>Battery Size</th>
<th>Engine Size</th>
</tr>
</thead>
<tbody>
<tr>
<td>Power-Split</td>
<td>50-70 kW</td>
<td>3-9 kWh</td>
<td>40-70 kW</td>
</tr>
<tr>
<td>Series</td>
<td>100-140 kW</td>
<td>11-19 kWh</td>
<td>40-70 kW</td>
</tr>
</tbody>
</table>

Figure A1 – Velocity vs. Time plot of 45 Naturalistic Cycles used for simulation, a) Short Cycles, b) Medium Cycles, c) Long Cycles
Figure A2 – Velocity vs. Time plots of Drive Cycles used for sensitivity studies

Figure A3 – Velocity vs. Distance plots of Drive Cycles used for sensitivity studies