ABSTRACT

Plug-in Hybrid Electric Vehicles (PHEVs) offer the ability to significantly reduce petroleum consumption. Argonne National Laboratory, working with the FreedomCAR and Fuels Partnership, participated in the definition of the battery requirements for PHEVs. Previous studies have demonstrated the impact of such vehicle characteristics as vehicle class, mass, or electrical accessories on battery requirements. However, outstanding questions remain regarding the impact of drive cycles on the requirements. In this paper, we will first evaluate the consequences of sizing the electrical machine and battery power to follow the Urban Dynamometer Driving Schedule (UDDS) to satisfy California Air Resources Board (CARB) requirements and determine the number of other driving cycles that can be followed in Electric Vehicle (EV) mode. Then, we will study the impact of sizing the electrical components on other driving cycles.

INTRODUCTION

For the past couple of years, the U.S. Department of Energy (DOE) has invested considerable effort in the research and development of Plug-in Hybrid Electric Vehicle (PHEV) technology, because of the potential fuel displacement offered by the technology. The PHEV R&D Plan [1], driven by the desire to reduce dependence on foreign oil by diversifying the fuel sources of automobiles, describes the different activities required to achieve the goals. The U.S. DOE has been using Argonne’s Powertrain Systems Analysis Toolkit (PSAT) to guide its analysis activities, stating that “ANL’s Powertrain Systems Analysis Toolkit (PSAT) will be used to design and evaluate a series of PHEVs with various ‘primary electric’ ranges, considering all-electric and charge-depleting strategies.”

Because of the early stage of PHEV technology development, most studies have been focusing on fundamental engineering problems, such as determining component requirements and optimizing PHEV design. As a part of these studies, for example, the impact of such vehicle characteristics as vehicle class, mass, or electrical accessories on battery requirements has been conducted [2]. However, problems remain regarding the impact of drive cycles and powertrain configurations on battery requirements.

A discussion of component requirements would be incomplete without considering the large variety of drive cycles, in addition to the UDDS. Drive cycles vary with respect to their aggressiveness, distance, and other parameters. And, an EV-based PHEV driven more aggressively than the cycle for which it was originally designed will have to use its engine during charge-depleting (CD) operation or else fail to meet the higher-power road-load demand. For instance, California Air Resources Board (CARB) awards zero emission range credit on the basis of the distance a PHEV can be driven all-electrically over repetitions of the U.S. Environmental Protection Agency’s (EPA's) standard Urban Dynamometer Driving Schedule (UDDS). However, an EV-based PHEV designed to just satisfy the mild UDDS cycle may fail to achieve its all-electric range (AER) rating when driven more aggressively in the “real world.”

To help avoid this problem, the vehicle could, instead, be designed by considering AER operation on a more aggressive driving cycle, such as EPA’s US06 cycle, or a “real-world” driving cycle, such as LA92 cycle. Such a consideration, however, would lead to even larger or costlier electric motor and energy storage system (ESS) requirements. The alternative would be to allow engine assistance when the vehicle is driven more aggressively than the original AER-designed cycle.

In this study, we will describe the methodology used to size a midsize PHEV on the basis of CARB requirements instead of those of the UDDS cycle. We will also assess the impact of a various drive cycles on the vehicle’s power and energy requirements.

POWERTRAIN SYSTEMS ANALYSIS TOOLKIT (PSAT)

Developed by Argonne National Laboratory, PSAT [3, 4] is a state-of-the-art flexible and reusable simulation package used to simulate fuel consumption and performance for advanced powertrains. After a thorough assessment, the U.S. Department of Energy (DOE) selected PSAT as its primary vehicle simulation tool to support its FreedomCAR and Vehicle Technology Program. PSAT has been used for numerous studies to provide the U.S. government with guidance for future research. In 2004, PSAT also received an R&D100 award, which highlights the 100 best products and
technologies newly available for commercial use from around the world.

PSAT is designed to serve as a single tool that can be used to meet the requirements of automotive engineering throughout the development process, from modeling to control. Because of time and cost constraints, designers cannot build and test each of the many possible powertrain configurations for advanced vehicles. PSAT, a forward-looking model, offers the ability to quickly compare several powertrain configurations.

When a vehicle is designed for a specific application, the goal is to select the powertrain configuration that maximizes the fuel displaced and yet minimizes the component sizes. In this study, a midsize pre-transmission parallel hybrid configuration will be sized to achieve performance similar to that of a midsize conventional. The component sizes, as well as the energy consumption and driving distance, will be compared on various driving cycles.

**VEHICLE DESCRIPTION**

A pre-transmission parallel hybrid configuration was selected as a reference configuration for this study, as shown in Figure 1. This configuration is very similar to the one used by DiamlerChrysler for the PHEV Sprinter [5]. The electric machine is located in between the clutch and the multi-gear transmission.

![Figure 1: Pre-transmission Parallel Architecture](image)

The main characteristics are defined in Table 1.

**Table 1: Main Vehicle Characteristics**

<table>
<thead>
<tr>
<th>Characteristic</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Glider mass</td>
<td>990 kg</td>
</tr>
<tr>
<td>Frontal area</td>
<td>2.1 m²</td>
</tr>
<tr>
<td>Coefficient of drag</td>
<td>0.31</td>
</tr>
<tr>
<td>Wheel radius</td>
<td>0.317 m</td>
</tr>
<tr>
<td>Tire rolling resistance</td>
<td>0.008</td>
</tr>
<tr>
<td>Gear Ratio</td>
<td>3.42, 2.14, 1.45, 1.03, 0.77</td>
</tr>
<tr>
<td>Final Drive Ratio</td>
<td>3.75</td>
</tr>
</tbody>
</table>

**VEHICLE SIZING**

The components were sized to meet the same vehicle performances over different cycles:

- 0–60: < 9 s
- Gradeability of 6% at 65 mph
- Maximum speed: >100 mph
- Range of 10, 20, and 40 miles

To quickly size the component models of the powertrain, an automated sizing process was developed. A flow chart illustrating the sizing process logic is shown in Figure 2. Although engine power is the only variable for conventional vehicles, PHEVs have two variables: engine power and electric power. In our case, the engine is sized to meet the gradeability requirements, and the battery is sized to meet the performance requirements (as well as the AER requirements). We also ensure that the vehicle can capture the entire energy from regenerative braking during decelerations on the UDDS. The vehicle mass is calculated by adding the mass of each component to the glider mass. The mass of each component is defined on the basis of its specific power densities.

To meet the AER requirements, the battery power is sized to follow the UDDS driving cycle while in all-electrical mode. Finally, the battery energy is sized to achieve the required AER of the vehicle. The AER is defined as the distance the vehicle can travel on the UDDS until the first engine start. Note that a separate control algorithm is used to simulate the AER. This algorithm forces the engine to remain off throughout the cycle, regardless of the torque request from the driver.

To maintain an acceptable battery voltage (around 200 V), the algorithm will change the battery capacity rather than the number of cells to meet the AER requirements. To do so, a scaling algorithm has been developed to properly design the battery for each specific application.
<table>
<thead>
<tr>
<th>Parameter</th>
<th>10AER</th>
<th>20AER</th>
<th>40AER</th>
</tr>
</thead>
<tbody>
<tr>
<td>Engine Power (kW)</td>
<td>79.5</td>
<td>79.6</td>
<td>82.4</td>
</tr>
<tr>
<td>Motor Power (kW)</td>
<td>44.2</td>
<td>45.8</td>
<td>47.2</td>
</tr>
<tr>
<td>ESS Power (kW)</td>
<td>64.7</td>
<td>65.7</td>
<td>68.2</td>
</tr>
<tr>
<td>ESS Capacity (A•h)</td>
<td>19.4</td>
<td>38.4</td>
<td>67.4</td>
</tr>
<tr>
<td>Number of Cell for ESS</td>
<td>57</td>
<td>57</td>
<td>66</td>
</tr>
<tr>
<td>Total Vehicle Mass (kg)</td>
<td>1546</td>
<td>1583</td>
<td>1659</td>
</tr>
</tbody>
</table>

As shown in Figure 3, the AER does not significantly influence the component power requirements because of the high specific power of the Li-ion battery used in the model. The peak power of the battery is only increased by 6.4 kW from 64.7 kW to 68.2 kW as the range increases from 10 miles to 40 miles. Because of the small increase in vehicle mass with increased AER, a PHEV with a 40-mile range requires a battery with approximately four times more energy than a PHEV with a 10-mile range, as shown in Figure 4. The usable energy depends on the battery SOC range (90–30% in our case). In addition, the total energy of the batteries has been oversized by 20% to maintain similar performance between beginning and end of life.

**VEHICLE CONTROL STRATEGY ALGORITHMS**

The PHEV vehicle operations can be divided into 2 modes, as shown in Figure 5:

- **Charge depleting (CD):** When the battery state of charge (SOC) is high, the vehicle operates under a so-called blended strategy. Both the battery and engine can be used. However, whenever possible, preference is given to the battery, which loses charge. Engine usage increases as SOC decreases. The engine tends to be used in heavy acceleration as well, even though the SOC is high. For fuel economy purposes, this blended strategy is defined for a battery going from full charge to a self-sustained SOC, typically from 90% down to 30% SOC.

- **Charge sustaining (CS):** Once the battery is down to 30%, the vehicle operates in CS mode, similar to a regular hybrid vehicle.

**Figure 3:** Component Sizes over UDDS

**Figure 4:** Total Battery Energy over UDDS

**Figure 5:** Illustration of Charge-Depleting (CD) vs. Charge-Sustaining (CS) Modes
However, only the CD strategy is considered in this study because the purpose is to meet required AER during CD operation.

Depending on how the engine is used, the control strategy can be divided into two modes. The first one can be called Engine Minimum Assistance. The vehicle operates all-electrically until the driving demand exceeds the power capability of the electric machine. As shown in Figure 6, the engine is turned on only when the power capability of motor reaches its maximum power curve. The engine provides the delta power between required power at the gearbox input and maximum motor power. This strategy is used to define the maximum share of the drive cycle that can be driven in EV mode.

The second control option, Engine Assistance at Best Efficiency, operates similarly to Engine Minimum Assistance. As shown in Figure 7, the engine is also turned on when the electric motor power reaches its maximum power curve, but the engine now operates close to its best efficiency curve. The surplus power from the engine is used to charge the battery.

Additional logic is included to ensure proper drive quality by maintaining the engine ON for a defined duration. In addition, to avoid unintended engine ON events resulting from spikes in power demand, the requested power has to be above the threshold for a predefined duration. The engine OFF logic conditions are similar to those of engine ON. During CD mode, the battery SOC regulation is turned off.

CHARACTERISTICS OF DRIVING CYCLES

To satisfy the CARB requirement to be qualified for a zero-emission credit, an AER-focused PHEV has to be driven all-electrically over repetitions of the UDDS cycle. However, how a vehicle sized to meet these requirements would behave on other drive cycles needs to be determined.

To assess the impact of additional drive cycles on the vehicle operating conditions, six additional driving cycles are selected: Japan1015, Highway EPA Cycle (HWFET), New European Drive Cycle (NEDC), SC03, LA92, and US06. This selection of driving cycles provides a spectrum of aggressiveness and driving range.

The main characteristics of the drive cycle are shown in Figures 8 and 9, from the least-aggressive (Japan1015) to the most-aggressive (US06) drive cycle. Japan1015, NEDC, and UDDS represent city driving patterns, including softer accelerations, lower speeds, and shorter driving distances. The LA92 and US06 have been selected to represent harder accelerations, higher speeds, and longer driving distances.
To assess the behavior of an AER-based PHEV designed on UDDS over other cycles, the three vehicles (10, 20, and 40 miles AER) were simulated on the driving cycles.

**ENGINE MINIMUM ASSISTANCE** - As discussed previously, the goal of the engine minimum assistance control strategy is to determine the maximum capabilities of the battery on several drive cycles when the engine is used only to provide the difference of the torque requested to follow the drive cycle.

Figure 10 shows the distances driven by an AER-based PHEV for 10-, 20-, and 40-mile ranges until the battery SOC reaches 30%, where the operating mode changes from CD to CS. Note that the AER is maintained for the Japan1015, NEDC, HWFET, and UDDS, but it drops for the most-aggressive cycles by as much as 30% on the SC03 and LA92 and 35% on the US06.

Figure 11 illustrates the utilization of the engine during CD mode for the 10AER vehicle. The engine is used only when the vehicle power demands are higher than those of the electric machine. During the moderate driving cycles (such as Japan1015, NEDC, HWFET, and UDDS), the engine never turns on because the electric machine is capable of satisfying the full vehicle power demand. However, during higher-power demand cycles (such as SC03, LA92, and US06), the engine is used to provide additional assistance when the power demands of given driving cycles exceed the maximum power that the electric motor can provide.

Figure 11 also shows that the energy consumption required by an AER-based PHEV driven on UDDS is 241.5 Wh/mi. In addition to higher power, the aggressive drive cycles also require greater electrical consumption, which explains the drop in AER shown previously.
Figure 12 shows the distribution of the electric machine power on the UDDS and the US06 drive cycles. Note that the average electric machine power is much higher for the US06 than for the UDDS.

Although the UDDS only required ~45 kW to follow the trace, the US06 needs approximately 65 kW during hard acceleration at the input of the gearbox. As a consequence, the engine has to be started to follow the trace. Figure 13 shows the minimum engine power distribution.

Figure 13: Comparison of Engine Power Distributions between Vehicle Driven on UDDS and US06 (10AER)

It is also important to note that the PHEV uses more energy from the engine as the aggressiveness of cycle increases. As shown in Figure 15, the energy consumed by the engine increases to 80.2 kWh for the US06, which is 15% of the total energy required to follow the cycle.

Figure 15: Energy Distribution between Motor and Engine Sized on the basis of UDDS over Various Driving Cycles

To overcome the poor engine-operating efficiency that results from the engine’s minimum-assistance strategy, the engine is used closest to its best-efficiency curve to maximize system efficiency.

ENGINE ASSISTANCE AT BEST EFFICIENCY - Figure 16 illustrates the impact of engine operation close to the best efficiency during CD mode with respect to the intensity of the driving cycle and distance for 10AER. As the engine is now used to charge the battery, the range
Figure 16: Distance Driven by a PHEV Designed on the basis of UDDS with Engine Assistance at Best-Efficiency Strategy over Various Driving Cycles (10AER) is increased for the aggressive driving cycles. The largest improvement occurs for the US06, which represents the most-aggressive driving pattern with a longer driving distance.

The driving range on the US06 improves significantly because engine's utilization is spread out with higher efficiency to reduce the use of the electric motor and battery. As the driving cycle becomes more aggressive, the more the range improves. As seen in Figure 17, total energy consumption on US06 was improved by approximately 6.4 for 10AER. The energy consumption of the engine on the US06 remains unchanged, at approximately 70.8 Wh/mi, while the energy consumption of the electric motor decreases from 413.4 Wh/mi to 382.4 Wh/mi.

Overall, the fuel consumption of the system is improved from 484.2 Wh/mi to 453.2 Wh/mi for 10AER. Even though the engine consumes the same amount of input energy per unit mile, the output energy produced by the engine (output energy of the electric machine) is significantly improved because of the higher engine efficiency. The average engine efficiency with the engine assistance at best-efficiency strategy over US06 is improved by up to approximately 32%.

Figure 17: Energy Consumption of PHEV Designed on the basis of UDDS, Driven with Engine Assistance at Best-Efficiency Strategy over Various Cycles (10AER)

DESIGNING A PHEV ON THE BASIS OF DIFFERENT DRIVING CYCLES

To help meet the AER requirements on more-aggressive cycles when the vehicle is designed on UDDS, the vehicle could, instead, be designed considering the AER operation on various driving cycles.

Figure 18 provides an illustration of the components power-sized on various driving cycles for 10 AER. Note that the engine power has no impact on the driving cycles because the engine power is only sized to meet the gradability requirement (6% grade at 65 mph). In this case, the engine assistance is not required, theoretically, because the electric motor and ESS power capability are meant to match the maximum power requirement of the expected cycles. However, the electric motor and ESS power have the greater impact on driving cycle, and the peak power of the electric motor is increased by up to 50% as the driving cycle changes from UDDS to US06 and decreased by up to 50% as it changes from UDDS to Japan1015.

Figure 19 illustrates the impact of sizing a PHEV on the basis of various driving cycles. The impact of sizing a PHEV on the basis of each driving cycle is very minimal compared to sizing a PHEV on the basis of the UDDS.
for low-power demand cycles, such as Japan1015, NEDC, HWFET, and UDDS. However, the greater impacts are shown on more-aggressive cycles, such as SC03, LA92, and US06. Note that although a PHEV sized on the basis of US06 improves its total energy consumption from 420 Wh/mi to 380 Wh/mi without turning on the engine, it increases the size of the electric motor from 44.2kW to 58.2kW, which leads to larger and costlier electric-drive requirements. As seen in Figure 20, no engine assistance is used on any driving cycle.

This high-power electric drive capability does have some advantages. If the engine never turns on even during a very aggressive driving cycle, the vehicle will emit zero tailpipe pollutants. This potential emissions benefit led the CARB to award PHEVs achieving 10 miles of AER a much larger credit weighting toward the state’s zero-emission-vehicle (ZEV) regulation, as compared to PHEVs employing an engine-assistance strategy. Also, such PHEVs can provide the driver with the feel of quiet, smooth all-electric operation while completing the all-electric drive range without the engine.

However, oversizing the electric motor and ESS has a significant disadvantage: cost. To make the battery economically viable, a higher-energy, constant-power ESS should be constructed from batteries with a lower power-to-energy ratio that are less expensive on a dollar-per-kW basis greater than in the current HEV battery. This is one of the drawbacks in developing a full-EV-capability PHEV for the AER requirement.

CONCLUSIONS

In this study, the sensitivity of driving distance and energy consumption of a midsize pre-transmission parallel PHEV to increased cycle aggressiveness was studied.

The simulation results demonstrated that:

- The choice of driving cycle directly influences decisions on PHEV design. A PHEV is sensitive to increased cycle aggressiveness and driving range because it will be unable to satisfy significant power demands during CD mode all electrically as designed.
When assistance from the engine is necessary, engine assistance at best efficiency strategy has an advantage in terms of improving driving range and lowering energy consumption of the designed PHEV. However, this strategy boosts the energy consumption by the engine, which leads to more emissions than one with engine minimum assistance strategy.

A PHEV sized on the basis of aggressive driving cycles (such as LA92 and US06) requires larger and more expensive electric components but offers AER operations, the benefits of which include qualifying for greater credits toward satisfying CARB’s ZEV regulation and a smoother-driving quality.

There are many trade-offs among costs, emissions, energy consumptions, and customer appeal during the decision-making process to design a PHEV. For instance, although cost remains a major challenge in PHEV development, the additional cost increment for this extra power capability could be worthwhile, especially since the increased electric power would improve the vehicle’s acceleration capability and drive quality. Another worthwhile consideration could be the extra-cost increment for extra power capability to receive greater credits toward satisfying CARB’s ZEV regulation for real-world driving.

Overall, this study demonstrated that the PHEV designed to satisfy UDDS may fail to achieve AER for real-world driving. The alternative to overcome this failure could be to employ a CD vehicle strategy with the engine operating at best efficiency, which would deliver effective utilization of the engine's energy during CD operation and could have a relatively small loss in fuel efficiency when the vehicle is driven shorter distances.

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REFERENCES


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