Abstract
Plug-in Hybrid Electric Vehicles offer great promise for petroleum displacement. While most of the automotive companies are working on developing prototypes, some questions remain on how the powertrain should be controlled to minimize fuel consumption. Global optimization studies have demonstrated the need to have a prior knowledge of the drive cycle distance to ensure that the battery is consistently depleted, but also reaches the Charge Sustaining only at the end of the trip. In this paper, different control strategy philosophies will be implemented on several powertrain configurations (including series and power split) with different battery pack characteristics (from low to high energy). The vehicles will be exercised on real world drive cycles to evaluate the impact of each control strategy on several key parameters, including fuel efficiency, engine ON/OFF, battery RMS current… The advantages and drawback of each option will be discussed and we will demonstrate that different control options should be used depending on the amount of available battery energy.

Introduction
PHEVs have demonstrated great potential with regard to petroleum displacement. Since the benefits of PHEV technology rely heavily on the battery [1], the development of new generations of advanced batteries with a long life and low cost is critical. To satisfy this goal, the U.S. Department of Energy (DOE), as part of the FreedomCAR and Fuels Partnership, is funding the development and testing of battery technologies.

Previous studies that focused on the impact of other standard cycles [2] or powertrain configurations [3] demonstrated the need to further evaluate driving behaviors. Argonne has been working in collaboration with the U.S. Environmental Protection Agency (EPA), which has been interested in real-world fuel economy [4]. This paper addresses the impact of vehicle level control strategies on PHEV fuel efficiency using real world drive cycles.

Vehicle Description
The vehicle class used represents a midsize sedan. The main characteristics are defined in Table 1.

<table>
<thead>
<tr>
<th>Table 1: Main Vehicle Characteristics</th>
</tr>
</thead>
<tbody>
<tr>
<td>Glider mass (kg)</td>
</tr>
<tr>
<td>Frontal area (m²)</td>
</tr>
<tr>
<td>Coefficient of drag</td>
</tr>
<tr>
<td>Wheel radius (m)</td>
</tr>
<tr>
<td>Tire rolling resistance</td>
</tr>
</tbody>
</table>

Two vehicle configurations were selected depending on the degree of electrification:
An input power split with a fixed ratio between the electric machine and the transmission, similar to the Camry HEV, was used for HEV and for PHEV with low energy (4 and 8 kWh total battery energy). A series engine configuration was selected for PHEVs with large energy (12 and 16 kWh battery energy cases).

Component Sizing

To quickly size the component models of the powertrain, an automated sizing process was used [5]. A flowchart illustrating the sizing process logic is shown in Figure 1. Unlike conventional vehicles, which have only one variable (engine power), PHEVs have two variables (engine power and electric power). In our case, the engine is sized to meet the gradeability requirements.

To meet the all-electric range (AER) requirements, the battery power is sized to follow specific driving cycle while in all-electric mode. The batteries for the power split configurations are sized to follow the Urban Dynamometer Drive Schedule while the series configurations are based on the more aggressive US06. We also ensure that the vehicle can capture the entire energy from regenerative braking during decelerations. In this case, four battery energy values were selected: 4, 8, 12 and 16 kWh total.

Vehicle mass is calculated by adding the mass of each component to the mass of the glider. The mass of each component is defined on the basis of its specific energy and power densities.

To maintain an acceptable battery voltage (around 200 V), the algorithm changes the battery capacity rather than the number of cells to meet the AER requirements. To do so, a scaling algorithm [6] was developed to properly design the battery for each specific application.

Finally, the PHEV will operate in electric-only mode at a higher vehicle speeds than will regular hybrids. The architecture therefore needs to be able to start the engine at a high vehicle speed. In the power split configuration, the generator is used to start the engine. Because all of those elements are linked to the wheels via the planetary gear system, one needs to make sure that the generator (the speed of which increases linearly with vehicle speed when the engine is off) still has enough available torque — even at speed above 80 km/h — to start the engine in a timely fashion.

For the HEV powertrain, the battery is sized to capture the regenerative braking energy from the UDDS. The engine and both electric machines are sized to meet both gradeability (6% at 100 km/h at gross vehicle weight) and performance requirements (0-100 km/h under 9 sec). The control strategy used has been validated against vehicle test data from ANL’s Advanced Powertrain Research Facility.
Drive Cycle Description and Analysis

The real world drive cycles have been measured by the U.S. EPA. In 2005, more than 100 different drivers in Kansas City participated in the study. The user vehicles (model year 2001 and later) were instrumented and their driving statistics were collected for the duration of a day. While several measurements were taken, only vehicle speed was used as part of this analysis. Speed was collected on a second-by-second basis independently through the on-board diagnostic (OBD) port as well as from a GPS device [7]. The OBD speed data was favored over the GPS when both were available. Data was collected on conventional as well as hybrid vehicles, but for reasons of simplicity, we have chosen to examine the speed from the conventional vehicles only, though there were minor differences in their driving [8]. Figure 2 shows an example of real world drive cycles. The maximum acceleration and deceleration of each trip were analyzed to ensure data validity.

![Drive Cycle](image)

**Figure 2: Example of Real-World Drive Cycles**

Figure 3 shows the distribution of the distance during daily driving. Fifty percent of the drivers drive more than 40 miles per day. The cumulative driving distance computed from the U.S. National Household Travel Survey (NHTS) data. It appears that a greater number of short trips characterize the NHTS curve.

![Distance Distribution](image)

**Figure 3: Distance Distribution of Daily Driving**

Each daily drive can be decomposed into several trips. A trip is defined by events for which the driver turns the ignition on and off. Figure 4 shows the distance distribution of each trip. An average trip is 11 miles.
Vehicle Control Strategy Description

Different vehicle level control strategies were implemented, depending on the powertrain configuration that was considered. Each control option is briefly described below.

Load Engine Power Strategy (load following): A power threshold, depending on the battery state of charge (SOC), is used to turn the engine ON. As a result, the engine can be turned ON during CD. As shown in Figure 5, to maximize charge depletion, when the engine is ON, it provides only the requested wheel power without recharging the battery.

Differential Engine Power Strategy: As shown in Figure 6, the electric machine supplies all the power demanded by the system up to a predefined threshold. After exceeding the threshold, the electric machine continues to supply the threshold value, and the engine runs to supply the incremental power demand.
Optimum Engine Power Strategy: Similar to the previous control, the engine is turned ON based on a variable power threshold. However, the strategy attempts to restrict the engine operating region close to the peak efficiency of the engine (cf. Figure 7). As a result, the engine might be used to recharge the battery during charge depleting (CD).

EV/CS (thermostat) Strategy: The EV/CS control strategy was implemented for the series configuration. The controller has been designed to drive as long as possible by using energy from the battery, which depletes its SOC from 90% SOC to 30% SOC. The engine turns ON only if the road load exceeds the power capability of either the battery or the motor. Once the battery reaches charge sustaining (CS), the engine is used as a thermostat to regulate the SOC.

For each vehicle control strategy and each vehicle, the power threshold leading to engine ON was tuned to obtain a 10-, 20-, 30-, 40-, and 50-mile CD range on the UDDS cycle. The 4-kWh configuration has a 10.47-mile EV range on the UDDS, while the 8-kWh was 21.64 miles. The maximum power threshold for the engine is the maximum continuous power of the electric machine, as shown in Equation (1).

\[ P_{\text{thr,max}} (4\text{-kWh vehicle}) = P_{\text{mot,max}} (4\text{-kWh vehicle}) = 34.6 \text{ kW}, \text{ and} \]

\[ P_{\text{thr,max}} (8\text{-kWh vehicle}) = P_{\text{mot,max}} (8\text{-kWh vehicle}) = 35.2 \text{ kW}. \]

The minimum power threshold is set to 3 kW. The threshold is sized with a secant method algorithm and a tolerance of 0.5 mile for the CD range. An example of vehicle level control strategy parameters is shown in Table 2.
Table 2. Power Threshold Parameters: Load Following Engine Power Strategy

<table>
<thead>
<tr>
<th>CD range</th>
<th>$P_{\text{thr}, \text{threshold}}$ (4 kWh)</th>
<th>$P_{\text{thr}, \text{threshold}}$ (8 kWh)</th>
</tr>
</thead>
<tbody>
<tr>
<td>10 miles</td>
<td>$P_{\text{thr,} \text{max}} = 34,600$ W</td>
<td>$P_{\text{thr,} \text{max}} = 35,200$ W</td>
</tr>
<tr>
<td>20 miles</td>
<td>$18,918$ W</td>
<td>$P_{\text{thr,} \text{max}} = 35,200$ W</td>
</tr>
<tr>
<td>30 miles</td>
<td>$15,296$ W</td>
<td>$22,045$ W</td>
</tr>
<tr>
<td>40 miles</td>
<td>$12,662$ W</td>
<td>$18,726$ W</td>
</tr>
<tr>
<td>50 miles</td>
<td>$11,310$ W</td>
<td>$17,275$ W</td>
</tr>
</tbody>
</table>

Figure 8 summarizes the vehicle configurations, battery energies, control strategy philosophies, and parameters analyzed in the study.

**Figure 8. Summary of the Considered Configurations and Controls**

**Fuel Consumption Results**

Figure 9 shows the mean values from running the different vehicle and control options on the Real World Drive Cycles from Kansas City, as provided by the U.S. Environmental Protection Agency (EPA). A significant spread of the fuel consumptions occurs for the same vehicles. For example, the mean fuel consumption of the power split with 4-kWh battery energy ranges from 3.6 l/100 km to 5.5 l/100 km because of impacts such as driving distance and driver aggressiveness.
While all the different combinations were simulated, only the best couple of options from a fuel consumption standpoint are presented below. In general, all the vehicle level controls tuned for long CD distances led to higher fuel consumptions since the battery was not consistently depleted at the end of the trip. Since the selection process of the vehicle level control strategy is similar for the different options, only the case with the 4kWh battery energy will be discussed.

Figure 10 depicts the distribution of the five control strategies that achieved the lowest fuel consumption for the power split with a 4-kWh battery. The differential engine power strategy tuned for 10 and 20 miles CD on the UDDS achieves the lowest fuel consumption, with the 20-mile case being the most efficient. While most engineers believe that the battery should be discharged as quickly as possible to minimize fuel consumption, this result highlights the need to take driving distance into account during the control strategy development process.

However, the difference between the four controllers is small. As a consequence, additional parameters must be considered to make an appropriate selection.
Electric Consumption

Figure 11 shows the distribution of the electrical consumption for the same control strategies. All the batteries display similar behavior, with the highest density close to 50 Wh/km. This is explained by the fact that a PHEV with low battery energy tends to use the electricity during low power demands, thereby leading to smaller electrical consumptions.

To select the final vehicle controls, the number of engine ON and battery RMS was taken into account.
Number of Engine Starts

Figure 12 shows the distribution of the number of engine starts per mile. The optimum engine power strategy has a lower number of starts compared with the other configurations. Waiting too long in between engine starts might lead to the catalyst cooling down and increased emissions. In this study, we assumed that, during the first start, the engine was controlled to ensure proper warm up of the catalyst and that the time in between starts was short enough to avoid any additional engine “cold” start.

Battery RMS Current Evaluation

Figure 13 depicts the distribution of the battery RMS current, which has an impact on the battery life. The differential engine power control strategy tuned for a 20-mile CD has a much lower battery RMS current than the other options.
**Control Strategy Selection**

Figure 14 details the mean values of both electrical and fuel consumptions for the selected control strategies of the different powertrain options. The lowest fuel consumption reductions are achieved for the largest electrical consumptions. As demonstrated in previous studies, the fuel and electrical consumptions have a linear relation.

While the series configurations share the thermostat controller, both power split options (4 kWh and 8 kWh) use different control philosophies:

- the Load Following Engine Power tuned for 10 miles CD range on the UDDS for the 4 kWh
- the Optimum Engine Power tuned for 20 miles CD range on the UDDS for the 8 kWh

The results demonstrate that the engine ON/OFF power thresholds should increase with the battery energy. In addition, increased energy leads to additional freedom related to the engine operating conditions: while the engine power demand is still dependant on the road load demand for low energy batteries, one can use the engine closer to its best efficiency curve when greater battery energy is available.

**Conclusion**

Four midsize PHEV vehicles, along with the reference conventional, were modeled. Both a power split configuration (for low battery energy cases) and a series configuration (for high battery energy cases) were selected. For each option, several vehicle level control strategies were developed. The main parameter influencing the CD distance was tuned to achieve different CD ranges on the UDDS cycle. The vehicles were simulated on more than 110 Real World Drive Cycles provided by the U.S. EPA.

The results demonstrated that, while the battery should always be “empty” at the end of a trip, depleting it as fast as possible will not consistently lead to the lowest fuel consumption, especially for low energy vehicles. Each vehicle control option was analyzed for both fuel consumption and electrical consumption. The most promising options were then compared based on engine ON/OFF and battery RMS current.
While the series configurations share the thermostat controller, different vehicle level control strategies have been selected for the power split configurations based on the battery energy.

Acknowledgements

This work was supported by DOE’s FreedomCAR and Vehicle Technology Office under the direction of Lee Slezak. The submitted manuscript has been created by UChicago Argonne, LLC, Operator of Argonne National Laboratory (“Argonne”). Argonne, a U.S. Department of Energy Office of Science laboratory, is operated under Contract No. DE-AC02-06CH11357. The U.S. Government retains for itself, and others acting on its behalf, a paid-up nonexclusive, irrevocable worldwide license in said article to reproduce, prepare derivative works, distribute copies to the public, and perform publicly and display publicly, by or on behalf of the Government.

References