Impact of Real-World Drive Cycles on PHEV Battery Requirements

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ABSTRACT
Plug-in hybrid electric vehicles (PHEVs) have the ability to significantly reduce petroleum consumption. Argonne National Laboratory (Argonne), working with the FreedomCAR and Fuels Partnership, helped define the battery requirements for PHEVs. Previous studies demonstrated the impact of the vehicle’s characteristics, such as its class, mass, or electrical accessories, on the requirements. However, questions on the impact of drive cycles remain outstanding. In this paper, we evaluate the consequences of sizing the electrical machine and the battery to follow standard drive cycles, such as the urban dynamometer driving schedule (UDDS), as well as real-world drive cycles in electric vehicle (EV) mode. The requirements are defined for several driving conditions (e.g., urban, highway) and types of driving behavior (e.g., smooth, aggressive).

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.

This development is guided by a set of requirements [2, 3, 4, 5]. We used the Powertrain System Analysis Toolkit (PSAT) to define the initial values for two time frames (short term and long term) and two vehicle classes (midsize car and small sport utility vehicle [SUV]). However, we considered only a single set of assumptions for the powertrain configuration (pre-transmission), component technology (current time frame), and drive cycle (UDDS).

Previous studies that focused on the impact of other standard cycles [6] or powertrain configurations [7] 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 in the past few years [8]. This paper addresses the impact of real world drive cycles on PHEV battery requirements from both a power point of view and an energy point of view.

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>
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<tbody>
<tr>
<td>Glider mass (kg)</td>
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<tr>
<td>Frontal area (m²)</td>
</tr>
<tr>
<td>Coefficient of drag</td>
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<tr>
<td>Wheel radius (m)</td>
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<td>Tire rolling resistance</td>
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The vehicle configuration selected an input power split with a fixed ratio between the electric machine and the transmission, similar to the Camry HEV.

COMPONENT SIZING
To quickly size the component models of the powertrain, an automated sizing process was developed [9]. 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 gradability requirements.

To meet the all-electric range (AER) requirements, the battery power is sized to follow each specific driving
cycle while in all-electric mode. We also ensure that the vehicle can capture the entire energy from regenerative braking during decelerations. Finally, battery energy is sized to achieve the required AER of the vehicle for the daily driving or trip considered. The AER is defined as the distance the vehicle can travel on the specific cycle until the first engine start. Note that a specific 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.

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 power density.

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 [8] was developed to properly design the battery for each specific application.

Finally, the PHEV will operate in electric-only mode at a higher vehicle speed 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 high speed — to start the engine in a timely fashion.

DRIVE CYCLES 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 [reference the KC main report EPA report, "Kansas City PM Characterization Study – Final Report,” Based on EPA Contract Report (ERG No. 0133.18.007.001), 2008.]. 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 [EPA document number: 420r06017, Final Technical Support Document: Fuel Economy Labeling of Motor Vehicle Revisions to Improve Calculation of Fuel Economy Estimates, 2006]. Figure 2 shows an example of real world drive cycles. The maximum acceleration and decelerations of each trip were analyzed to ensure data validity.

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 red curve shows the cumulative driving distance computed from the National Household Travel Survey (NHTS) data. It appears that a greater number of short trips characterize the NHTS curve.
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.

Figure 4: Distance Distribution of Each Trip

Figure 5 shows the relationship between maximum vehicle speed and trip distance. The maximum vehicle speed increases with distance. The trend for average vehicle speed is similar. These results are expected, considering people often choose where to live on the basis of the maximum commute time. Drivers close to a highway would be more inclined to live further away from work than others who drive only in the city.

Figure 5: Relationship between Maximum Speed and Trip Distance

Figure 6 shows the relationship between trip duration and distance. The average daily driving time is 1.1 hours. Considering that most people make two major trips (to and from work) each day, each trip to work lasts an average of 30 minutes.

Figure 6: Relationship between Trip Duration and Distance

BATTERY CALCULATION DEFINITIONS

The maximum battery power (Pess) was calculated on the basis of several assumptions. Here are descriptions of various terms:

- **Pess Max Sizing** — Maximum battery power from component sizing over the entire trip or cycle at 20% battery state-of-charge (SOC). This value is usually greater than Pess Max Simu, since it can be achieved at any time in the trip. Each trip has a single value.

- **Pess Max Simu** — Maximum battery power obtained from the simulation over the entire trip or cycle. Each trip has a single value.

- **Pess Max Per Hill** — Maximum battery power obtained from the simulation for each hill. A hill is defined by a vehicle speed trace between two stops. Each trip has several values.

- **Pess All Points** — Battery power distribution for every point of the drive cycle (second by second). Each trip has n values.

Both battery power and energy are analyzed at different levels in the following sections: daily driving, trips, hill, and continuous.

BATTERY DISCHARGING POWER ANALYSIS

The first parameter to be analyzed is the discharging battery power. Figure 7 shows the distribution of discharging peak power per trip along with a comparison of the standard drive cycles. The trip average peak value is 78 kW. If we size the battery component on the UDDS (which is the normal fuel economy test cycle), only 22% of the trips can be completed only on electrical power due to the battery power limitation. As a consequence, the engine will start on most trips in order to supplement the batteries based on the current component requirements. Conversely, if the engine
doesn’t turn on, the acceleration provided would not meet the demand from the driver in these moments.

Figure 7: Distribution of Discharging Peak Power per Trip

Figure 8 shows the distribution of discharging peak power for all the cycle points. While Figure 7 shows that most cycles required more peak power than the peak power defined for the UDDS, the cycles can be driven more than 98% of the time in electric-only mode because of the power limitation. As a result, we can conclude that, even if the events occur frequently, they do not last for a long time.

Figure 8: Distribution of Discharging Peak Power for All Points

Figure 9 confirms that conclusion. In fact, 80% of the demands for more than 50 kW last for only 1 to 2 minutes. If a control strategy based on maximum charge depletion is used, emissions during engine cold start should be carefully monitored. Real-world criteria pollutant emissions, may be increased due to more frequent start transients after the catalytic converters have cooled down.

Figure 9: Distribution of the Duration of Battery Power of More Than 50 kW

One of the main issues with regard to any vehicle is related to emissions during the first engine start. Figure 10 shows when the starts should occur if the battery is sized on the UDDS drive cycle (50-kW peak). The first excess battery power only lasts between 2 and 3 minutes 50% of the time. This amount of time would be that allowed to, for example, warm the catalyst with an electrical load.

Figure 10: Distribution of the First Occurrence of Battery Power of More Than 50 kW

Since the drive cycle has a major influence on the power demand, one also needs to analyze when the high-power events occur. Figure 11 shows that most of the battery power demands above 50 kW occur at high vehicle speeds. It is assumed that most of these events occur as drivers merge onto a highway, a process that requires a large amount of acceleration.
BATTERY CHARGING POWER ANALYSIS

During the simulation, the maximum value of the battery power during deceleration events is also measured. Figure 12 shows the distribution of the charging peak power per trip as well as a comparison with additional standard drive cycles. If the battery is sized on the UDDS, 21% of the cycles can fully recover the energy.

However, what matters for the regenerative braking events is the percentage of energy that can be recuperated. Figure 13 shows that for every point during deceleration, 92% of the energy can be recuperated when the battery is sized on the basis of the UDDS. The additional 8% would actually require significant additional power (up to 50 kW).

BATTERY ENERGY ANALYSIS

In addition to power, energy is a major parameter for characterizing a battery. Figure 14 shows the distribution of the usable battery energy for each daily driving cycle. The amount required to complete 50% of daily driving is 12 kWh of usable battery energy. The current short-term requirement for DOE (3.4 kWh) would allow 6.3% of the trips, while the long-term goal of 11.6 kWh would provide for 47%.

Since most people drive two trips per day, charging at work would allow the current long-term requirements to fulfill more than 98% of the trips, though the cost of electricity may be higher than if the charging were only conducted at night. The short term requirements would encompass 45% of the trips.
Figure 15: Distribution of the Battery Energy for Trips Longer Than 2 Miles

Figure 16 shows the usable energy as a function of distance for each daily driving cycle. Each point represents a trip. The UDDS (bottom, 230 Wh/mi), LA92 (middle, 330 Wh/mi), and US06 (top, 400 Wh/mi) cycles are also drawn. Almost all the real-world drive cycles are more aggressive than the UDDS. The US06 appears on the other side to represent the maximum limit. Finally, the LA92 seems to properly characterize the drivers from the data set. As a consequence, depending on the aggressiveness of the cycle, a vehicle with 10 kWh of usable battery energy will have an all-electric distance varying from 25 to 42 miles.

Figure 17: Electrical Energy Consumption Distribution

CONCLUSIONS

The real-world drive cycles of more than 110 cycles from Kansas City were used to assess the impact of trips on PHEV component requirements. The PHEV requirements analysis is valid only for the set of drive cycles considered and should not necessarily be used to generalize to the rest of the US market. Several points can be drawn from this analysis:

- Aggressive driving will put limits on the all-EV range, which, in turn, favors a blended mode operational strategy.
- When the battery is sized for the UDDS,
  - 3% of the daily driving and 20% of the trips can be completed in EV because of the power limitation. However, the power requirements are sufficient 97% of the time.
  - 1.5% (short-term goal) and 50% (long-term goal) of the daily driving can be completed in EV because of the energy limitation.
- The real-world drive cycles are generally more aggressive than the UDDS, resulting in larger energy requirements to drive the same distance.
- LA92 seems to better represent current drive cycle aggressiveness.

In the future, additional real-world drive cycles from different locations and the effect of road grade will be considered. Also, other parameters, such as air conditioning, will be analyzed to evaluate their impact on the component requirements. Finally, a trade-off analysis between fuel efficiency and cost will be performed to maximize fuel displacement while minimizing cost.
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REFERENCES


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