

PHEV Energy Management Strategies at Cold Temperatures with Battery Temperature Rise and Engine Efficiency Improvement Considerations

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ABSTRACT

Limited battery power and poor engine efficiency at cold temperature results in low plug in hybrid vehicle (PHEV) fuel economy and high emissions. Quick rise of battery temperature is not only important to mitigate lithium plating and thus preserve battery life, but also to increase the battery power limits so as to fully achieve fuel economy savings expected from a PHEV. Likewise, it is also important to raise the engine temperature so as to improve engine efficiency (therefore vehicle fuel economy) and to reduce emissions. One method of increasing the temperature of either component is to maximize their usage at cold temperatures thus increasing cumulative heat generating losses. Since both components supply energy to meet road load demand, maximizing the usage of one component would necessarily mean low usage and slow temperature rise of the other component. Thus, a natural trade-off exists between battery and engine warm-up.

This paper compares energy management strategies for a power-split PHEV for their ability to warm -up the battery and the engine, and ultimately the resulting fuel economy. The engine model predicts engine fuel rate as a function of engine utilization history and starting temperature, apart from speed and torque. The battery temperature rise model is a function of battery utilization. Engine and battery utilization is varied by changing the control parameter - wheel power demand at which the engine turns ON. The paper analyses the sensitivity of fuel and electrical energy consumption to

engine and battery temperature rise, for different driving distances and driver aggressiveness

INTRODUCTION

Impact of cold temperature on PHEV fuel efficiency has been previously published, for chassis dynamometer tests [1] as well as on - road testing [2]. Seasonal temperature variations in the northern cities in continental United States and around the world have established the significance of this cold temperature impact [1]. This is due to the restriction on battery power by the Battery Management System - BMS to preserve battery life [3] by preventing lithium plating on the anode due to a reduction in the intercalation process. Restriction in battery usage results in lower regenerative braking and lower propulsion power by the battery, causing a decrease in the fuel savings expected from PHEV operation. As the electrochemical reactions slow down at low temperature (Arrhenius law), higher activation energy is required for charging and discharging, which is reflected as an increase in internal impedance of the battery. This may cause a decrease in usable capacity of the battery, based on the SOC swing allowed in the charge depleting (CD) mode of operation. Due to the above reasons, there is a lot of emphasis on improving the battery temperature by using thermal management techniques. Several methods have been proposed to increase battery temperature, which include thermal preconditioning [4], keeping the battery warm through over-night charging, active heating of the battery through heating channels [5]. Recent publications by Argonne National Laboratory and others have shown that there is a significant penalty on PHEV fuel economy at cold engine

temperatures due to low engine efficiency [6], [7]. Therefore, there is an incentive to increase the engine temperature in a PHEV operation, as well.

Numerous studies have focused on optimum energy management of PHEVs to achieve one or more of the following goals:

1. Maximize overall system efficiency [8], [9] over a certain daily travel, at normal ambient conditions.
2. Maximize utility factor (U.F.) weighted fuel economy [10].
3. Mitigate the impact of cold (at normal ambient temperatures) engine starts on emissions [11].
4. Maximization of Net Present Value (NPV) savings of a PHEV [12].

The intent of this paper is to see if different vehicle energy management strategies cause a difference in battery warm-up time, engine warm-up time, and the result of this difference in on PHEV fuel and gasoline consumption over a fixed distance. While previous studies have established that charge-depleting operation until the end of driving distance (no charge sustaining operation) is the preferred energy management strategy for optimizing PHEV powertrain efficiency, (for a known drive profile) this paper examines if this point of maximum powertrain efficiency changes due to the cold initial temperature. For this study, the battery warm-up is due to the heat generated by the ohmic losses (Joule heating), and not due to any external heating of the cell or pre-warming of the battery. While battery utilization varies with energy management, the battery power limits recommended by the BMS are strictly adhered to. Differences in battery utilization result in differences in engine utilization, over a fixed drive cycle and fixed distance.

DESIGN OF EXPERIMENT

Modeling and simulation techniques will be used to determine the impact of energy management strategies on battery temperature rise, engine temperature rise, and ultimately on the PHEV fuel efficiency over a fixed drive cycle, driving distance.

A powersplit plug-in hybrid vehicle, built in AUTONOMIE [13], is used for this experiment. The vehicle is a Prius powertrain [17], with the battery replaced by a 41 Ah Li-ion battery. Specifications for the battery which replaces the Prius battery pack, is included in [Table 1](#) below.

Table 1. PHEV battery specifications

Parameter	Value
ESS power (kW)	60 kW at 50% SOC for 30 seconds (physical battery)
Battery energy (kWh)	10.66
Battery Capacity (Ah)	41
Total vehicle test mass (kg)	1,549

The vehicle runs over consecutive LA92 cycles over a fixed distance. The initial temperature of the vehicle, engine and the battery at the start of the simulation, is -6°C . It should be noted that reference to ‘cold battery’ or ‘cold engine’ indicates that the initial temperature of the said components is -6°C . The battery and engine temperatures increase with time, providing a larger power envelope and higher efficiency, respectively.

The engine, for the vehicle under consideration, turns ON based on a certain value of wheel power (road load) demand, i.e. the engine turns ON when a certain value of wheel power demand threshold is crossed. Different blended mode scenarios (different engine and battery utilization scenarios) are created by changing the vehicle controller parameter which turns ON the engine based on vehicle road load demands (wheel power demand). The engine also turns ON due to the generator speed limit. For each energy management (different engine turn ON thresholds based on road load demand), fuel consumption and battery utilization are compared. When the vehicle operates in the CS mode, the wheel power demand threshold, at which the engine turns on, is the same, in order to balance the battery SOC.

The study is conducted in three parts:

For the first part, in order to isolate the impact of battery temperature rise and engine temperature rise on the PHEV fuel and electrical energy consumption, 4 sets of simulations are performed. For each set of simulations, the vehicle is subjected to 40 miles of LA92 driving for the same set of engine- ON thresholds. The four sets of simulations are:

1. Baseline simulations using a scenario with an engine, and a battery at normal ambient (20°C) temperature.
2. Simulation with a cold battery (-6°C) and an engine at 20°C , to isolate the impact of a cold battery.
3. Simulations with a battery at 20°C and an engine at an initial temperature of -6°C , to isolate the impact of a cold engine.

4. Simulations with both a cold battery and a cold engine (both at -6°C).

In the second part, powertrain efficiency is calculated for the normal ambient conditions for different engine ON thresholds and compared to the powertrain efficiency when both the battery and the engine are cold. For the case of the cold engine and cold battery, the point of highest powertrain efficiency, which represents the trade-off between engine efficiency improvement and battery utilization, is identified. The vehicle is subjected to 40 miles of LA92 for this part of the study.

In the last part of the study, the impact of system parameters, like cycle aggressiveness, drive distance, battery power on the cold temperature performance of the vehicle are evaluated. The cold temperature behavior of the engine and the battery are modeled using data gathered from cold temperature testing, and the modeling methods and assumptions are outlined below.

ASSUMPTIONS

In a real vehicle, the electrical and gasoline fuel economy at cold temperature is impacted by the lower efficiency of the rest of the powertrain (apart from the engine and the battery). Since this study is a comparison of vehicle behavior under different settings of engine ON due to wheel power demand, decrease in efficiency of the rest of the powertrain is a common factor, which can therefore be neglected. Also, engine (ECU) operation at cold start (rich combustion, spark retard) to increase engine temperature and exhaust temperature for catalyst light-off has not been modeled. As stated earlier, numerous methods have been implemented to provide external heating to the battery. For the cold temperature scenario, it is assumed that there is no external heating method. The rise of battery temperature is on account of the heat generated by the battery itself (joule heating). It should be noted that the aim of this study is to compare different engine and battery utilization scenarios for their impact on battery temperature rise, engine temperature rise at cold temperature. Therefore, the above assumptions do not impact the results of the 'apples to apples' comparison. Details of the battery and engine thermal model are laid out in the next section.

The energy required to heat the cabin is a significant accessory load for cold temperature operation, and has an impact on the fuel efficiency of the vehicle. For this study, the following assumptions have been made to account for the energy required to heat the cabin:

- The vehicle has a PTC heater core as well as a regular heater core to heat the cabin using engine coolant heat.
- The engine coolant is used to heat the cabin if the coolant temperature is above 65°C . If the coolant temperature is less

than 65°C , the PTC heater is used to provide heat to the cabin.

- While actual data on exact heating load demand versus time could not be obtained, assumption on accessory load power demand is based previously published data [14], [15]. It is assumed that the cabin heating accessory load is constant at 4 kW for the first 100 seconds of the cycle, and then reduces gradually to 400 W as the cabin warms up (Figure 1 depicts the load profile for the first 600 seconds). As stated earlier, the PTC heater and the engine share the cabin heat load based on engine temperature.

MODELLING OF THE THERMAL BEHAVIOR OF THE ENGINE AND THE BATTERY

MODELING OF THE BATTERY TEMPERATURE RISE

As stated earlier, the battery temperature rise is solely a function of heat generated by the battery, based on battery utilization. Battery temperature data from cold temperature evaluation of the JCS VL41M [16] (41 Ah, 260 V Nominal), has been used to generate function which calculates temperature rise as a function of $\int A^2 dt$ where A is the battery current in Ampere.

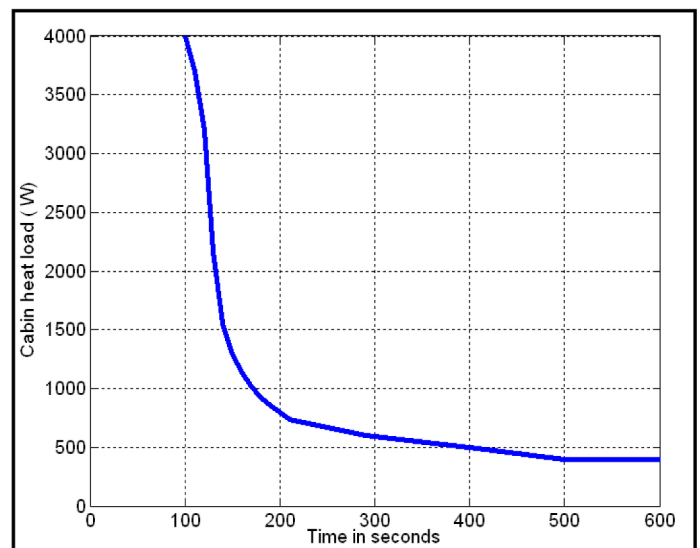


Figure 1. Cabin heat load demand for the first 600 seconds

Figure 2 shows actual recorded temperature rise which has been used to generate the equation (1) below. For this simple temperature rise model, it is assumed that battery temperature rise is solely driven by the battery current, and that other factors which impact temperature rise (changes in ambient

temperature etc) can be neglected, in comparison to the battery current.

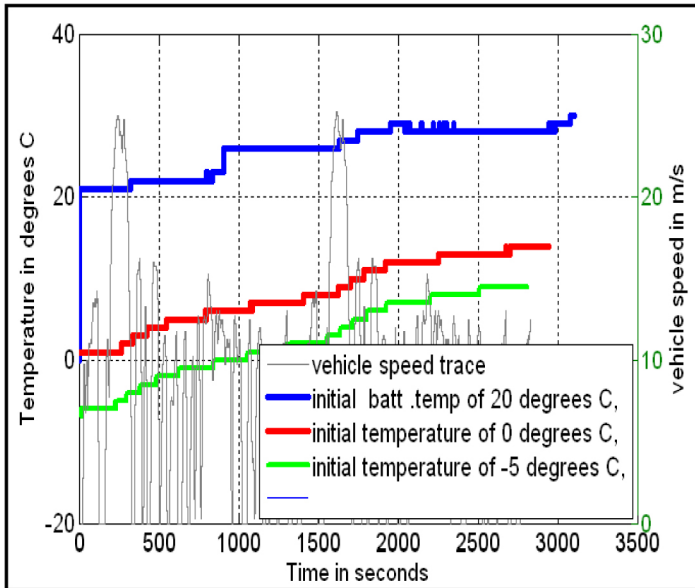


Figure 2. Battery temperature data from the testing of the PHEV 41 Ah battery, used to model battery temperature rise behavior

The battery cells are surrounded by the coolant bladder/jacket, and hence the coolant jacket acts as an insulator preventing external factors from impacting the cells. The coolant is not being circulated at the cold temperatures. While other more accurate methods of modeling battery temperature rise, including finite element analysis, are possible, such detailed modeling is not needed for the comparative study being considered in this paper. The relation between temperature rise and $\int A^2 dt$ is given by the following equation:

$$T = T_0 - aT_0 \int A^2 dt + b \int A^2 dt$$

Where

T = Battery temperature.

T_0 = Initial battery temperature (-6°C).

a, b = Constants with values 0.06×10^{-6} and 2×10^{-6} respectively.

MODELING OF ENGINE THERMAL BEHAVIOR

Response surface modeling techniques (RSM) were applied to experimental vehicle data collected over several cycles while operating in a 266°K ambient temperature test cell over

both the urban dynamometer driving schedule (UDDS) and the US06 Federal Test procedures. Using the data collected, engine speed, load, and engine coolant temperature were selected as input variables to the fueling estimate, and the engine fueling rate was measured at each value of the input variables during the cycle. (See [Appendix](#) for equation). These data were then used to generate the response surface output of BSFC. [Figure 3](#) gives an overview of the engine operating points used to create the fueling RSM. The response of engine fueling rate as a function of the engine speed, load, and coolant temperature was best fit modeled as a quadratic polynomial including several interaction terms.

Results of the integrated model fueling rate versus actual data for a 266°K cold start UDDS cycle are shown in [Figure](#). From this plot of fuel consumed versus time, the fueling estimate can be seen to match the experimental data very closely. The coolant temperature estimate also shows a reasonable match with the experimental data over four back-to-back UDDS cycles. [Figure 5](#) shows the model fit relative to both oil and coolant temperature. The Pearson's co-relation coefficient for the fit (R square) is 0.99.

For details on the modeling of engine thermal behavior, interested readers are referred to [\[13\]](#).

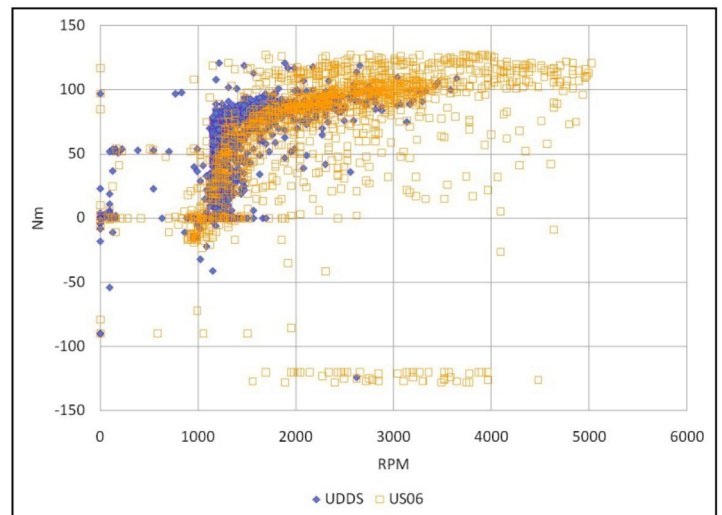


Figure 3. 2008 Toyota Prius Hymotion PHEV conversion 266 K cold start UDDS and US06 cycle cold start speed/brake load test points used as RSM model inputs.