

Impact of Energy Management on the NPV Gasoline Savings of PHEVs

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Argonne National Laboratory

ABSTRACT

This paper evaluates the impact of energy management strategy on the cost benefits of a plug-in hybrid electric vehicle (PHEV) by taking into account the impact of PHEV energy management on battery life and petroleum displacement over the life of the vehicle.

Using Battery in the Loop (BIL), a real battery is subjected to transient power demands by a virtual vehicle. The vehicle energy management strategy is varied, resulting in different battery utilization scenarios. Battery life, which varies with battery utilization, is estimated for the different energy management scenarios. The same representative drive cycle is used over the different energy management strategies to isolate the impact of energy management on battery utilization.

PHEV gasoline savings, in comparison to a charge sustaining hybrid, are calculated for each of the energy management strategies, for a fixed distance of 40 miles. Comparison of the gasoline dollar savings suggests the optimum energy management strategy considering gasoline saved per day and battery utilization over vehicle life. The analysis is repeated for different driving distances to determine the optimum energy management strategy over different distances.

INTRODUCTION

Much insight into the energy management of currently available aftermarket PHEV conversions has been gained with chassis dynamometer benchmarking [1] and fleet testing [2] of aftermarket PHEVs. Numerous studies have focused on optimum energy management of PHEVs to achieve one or more of the following goals:

1. Maximize overall system efficiency [3], [4] over a certain daily travel.
2. Maximize utility factor (U.F.) weighted fuel economy [5].

3. Mitigate the impact of cold engine starts on emissions [6].

Another important factor that should be considered in deciding the energy management is battery life. Along with battery safety, this remains one of the significant technical barriers to the successful introduction of PHEVs into the market [7].

This paper considers the impact of different energy management strategies on battery life and fuel economy. For a given vehicle, the energy management strategy that maximizes the Net Present Value (NPV) of dollar savings of a PHEV over its lifetime when compared to an HEV is identified. For each vehicle level control strategy, 'equivalent' battery life (over the life of the vehicle) is estimated based on battery utilization. An NPV evaluation of different control strategies would help identify the control strategy leading to the optimum tradeoff between maximizing fuel displacement (maximum EV mode operation and therefore reduction in battery life) and long battery life (minimum EV mode operation, but low fuel economy savings) ([Figure 1](#)).

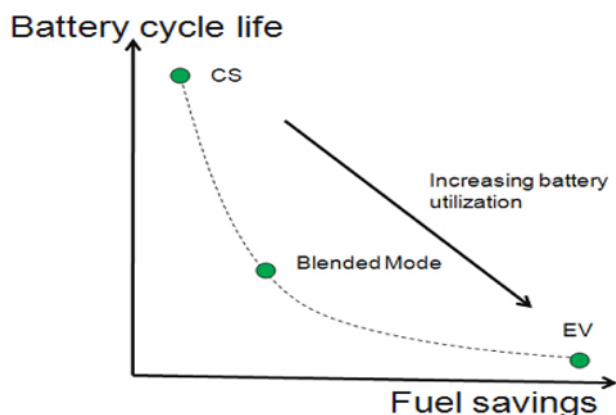


Figure 1. Trade-off between PHEV battery cycle life and fuel savings based on battery utilization

It should be noted that the NPV dollar savings are based solely on the gasoline dollar saved over the life of the vehicle, minus cost of electricity. Initial battery cost is a part of the vehicle cost, and is therefore not included in the comparison. The NPV of dollar saved should be compared to vehicle price differential to ascertain a PHEV's attractiveness.

BATTERY LIFE

PHEV battery life depends on battery utilization in the vehicle, and the state of the battery when the vehicle is not in use. An example of the latter would be the battery conditions like state of charge (SOC), temperature, when the vehicle is parked overnight and the duration for which the battery is in this condition, the grid charging profile of the battery, etc [8]. The impact of non-vehicle related factors on battery life is accounted for by the calendar life and shelf life [9]. The USABC target for calendar life is 15 years [10]. Battery life is significantly impacted by the large swings in battery SOC, battery temperature rise, initial battery temperature and battery RMS current when the battery is used in a PHEV [11], [12], [13]. The cycle life of a battery is defined as the number of deep discharge cycles the battery can be subjected to, before the battery capacity and power decrease to a certain level (normally assumed to be 80%) [9]. If the battery capacity and power fall beyond this lower limit, the performance of the vehicle is impacted. The USABC target for PHEV battery cycle life based on a 70% SOC swing is 5000 deep discharge cycles [10]. Recent cycle life test results on individual cells and modules have indicated that in laboratory settings, the target cycle life can be achieved [14].

In an actual vehicle, the number of deep discharge cycles, before the battery capacity reduces by 20%, might be much lower than the cycle life results under standard temperature and humidity conditions. Environmental impacts, and the cell voltage at which the battery is stored overnight, bring down this 'equivalent cycle life'. Based on limited cycle life and calendar life tests, it is impossible to correctly estimate this

equivalent cycle life. Therefore, for this experiment, three different equivalent cycle life scenarios are assumed for a 20% decrease in usable capacity based on a 60% SOC swing: 1000, 1500, and 3000 deep discharge cycles.

DESIGN OF EXPERIMENT

Multiple vehicle factors impact fuel and electrical consumption in a PHEV (Figure 2). Since the purpose of this study is to evaluate the impact of energy management on battery life and fuel economy, all other system level factors, except for energy management, are constant. The vehicle travels a given distance on a fixed drive cycle with different energy management strategies.

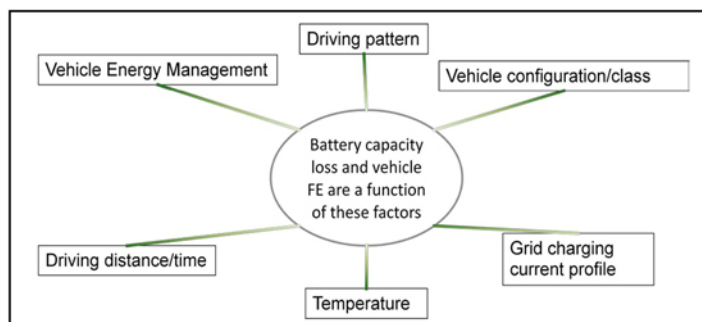


Figure 2. Several factors simultaneously impact battery utilization in a vehicle

The vehicle parameters that are kept constant throughout the experiment are:

Midsize power split vehicle with a vehicle test mass of 1921 kg. This includes cargo and driver mass of 136 kg, battery mass of 100 kg, and additional mass for the two electric machines and power electronics.

Drive cycle: LA92. This cycle has been selected as it represents approximately real world driving conditions.

Initial battery temperature: 25 °C.

Battery charged overnight to the same initial SOC (90%) using battery management system (BMS) controlled charging profile, which is also the starting or the initial SOC for each 'run'.

Initially, the NPV calculations are done for the different energy management strategies for a fixed daily distance of 40 miles, 300 times a year, for 15 years, to identify the energy management that is optimum for both battery life and fuel savings. As stated in the above section, these NPV calculations are performed for three different equivalent battery cycle lives – 1000, 1500, and 3000 cycles for a 60% SOC swing. Later, the driving distance is also varied, to

account for the impact of distance on the choice of the optimum energy management strategy.

Table 1 provides information on the powersplit powertrain used in the emulated vehicle; Table 2 lists the battery specifications for the 41 Ah Li-ion Johnson Control-SAFT pack used for the experiment.

Table 1. Vehicle powertrain specifications

Parameter	Value
Engine power (kW)	90
Motor power (kW)	80
ESS power (kW)	60 kW at 50% SOC for 30 seconds (physical battery)
Battery energy (kWh)	10.66
Total vehicle test mass (kg)	1,921

Table 2. Battery specifications

Battery capacity	41 Ah at C/3 rate
Battery nominal voltage	260 V
Peak power	60 kW at 50% SOC for 30 seconds

The assumption on equivalent battery cycle life (1000, 1500, and 3000 cycles) is for an SOC swing of 60%. With a smaller SOC swing during driving, the battery cycle life would improve dramatically. Lower SOC swing would also possibly result in lower battery temperature rise, and favor the cycle life of the battery. With comparable temperature rise during usage, the equivalent battery cycle life is a strong function of battery SOC. If the equivalent battery cycle life, for 60% SOC swing is 'x', then the battery equivalent cycle life for lower SOC swings is a non-linear function of 'x', as shown in Figure 3 below. The curve below has been approximated from the data published before in [11]. Since there is insufficient PHEV battery data, the curve is an approximation, however, the approximation is sufficiently accurate for the cost analysis that is to follow.

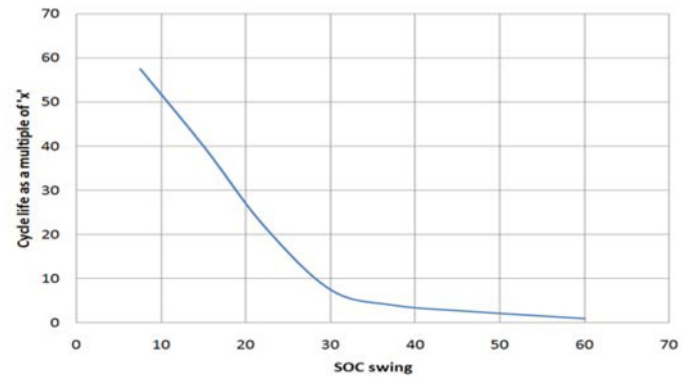


Figure 3. Relationship between SOC swing and increase in cycle life

Even though the battery attains end of life status (20% decrease in usable capacity) after 'x' number of 60% SOC swing deep discharge cycles, where x = 1000 or 1500 or 3000 deep discharge cycles, there is sufficient capacity and power left in the battery so that the fuel economy of the PHEV would still be better than a charge sustaining hybrid. Therefore, from NPV savings perspective, there would be continued gasoline savings even though the battery has reached end of life, the CD range of the vehicle would decrease due to a reduction in the usable capacity of the battery. From cycle life testing of the SAFT VL41M cells at Southern California Edison [15], it has been observed that capacity fade is a linear function of # deep discharge cycles. Although this relationship is expected to be highly non-linear as a substantial capacity fade is seen, for the current paper it is assumed that the capacity fade continues to be linear even after the battery has reached 'end of life'. With an assumption of 300 uses per year, and one overnight charging event, the vehicle life in terms of number of deep discharge cycles is $300 \times 15 = 4500$ deep discharge cycles, assuming a vehicle life of 15 years. Figure 4 shows the battery capacity assumptions as they relate to battery life, used for this analysis.

For the powertrain specified above, the dollar NPV savings over the vehicle life will be calculated for four different energy management strategies. For each case, the engine is started at a different threshold of wheel power demand. The four power thresholds that result in four different energy management strategies are 20 kW, 25 kW, 30 kW and 40 kW. For the vehicle, generator speed limits are high, and therefore generator speed limit does not influence the engine -ON decision. The vehicle energy management issues an engine -ON signal solely based on wheel power demand. Each energy management strategy results in a particular fuel consumption and battery SOC swing, over a constant distance of 40 miles. As stated earlier, it is assumed that the equivalent battery cycle life is proportional to the SOC swing, and temperature rise is fairly constant across the different energy management scenarios. In order to verify that the energy management strategies do yield a comparable battery

temperature, and to record the SOC swing of a real battery, a virtual vehicle with the above powertrain configuration was created in PSAT [16] and a real battery of the rating specified in Table 2 was subjected to the energy management strategies using BIL principle.

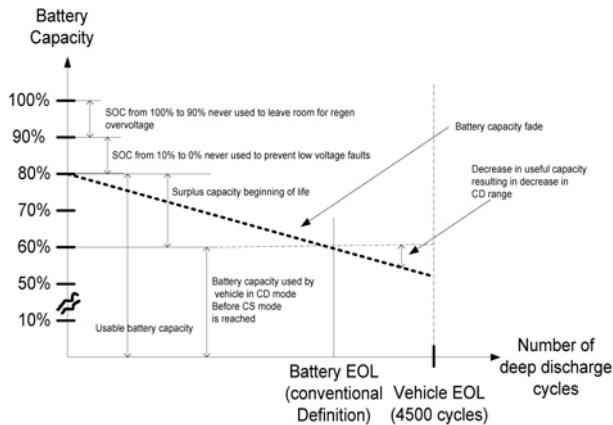


Figure 4. Battery capacity assumptions for the analysis before and after end of life

BIL is used to record utilization data of a real PHEV battery in a virtual vehicle (defined above) over different energy management strategies with the virtual vehicle defined above. For each energy management strategy, fuel economy numbers are also obtained for the virtual vehicle. Based on the battery utilization data obtained, battery cycle life is estimated and used for the cost analysis with the fuel economy numbers. The detailed process is shown in Figure 5.

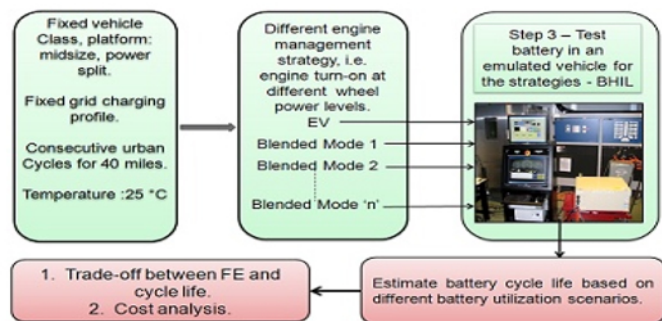


Figure 5. Experiment process

BATTERY IN THE LOOP

Figure 6 shows the block diagram for Battery IL. Battery IL is used for battery focused PHEV studies, without the need for a real vehicle.

The virtual vehicle - which is a real time simulation model of the vehicle described in the earlier section, subjects the battery through power profiles, as it follows a preset drive

trace (the LA92). The high voltage DC power supply (ABC-170) sinks and sources current from and to the battery. Feedback from the battery (SOC, temperature, cell voltage, and power restrictions as a function of temperature and SOC) are communicated to the virtual vehicle controller in real time, to be used as a part of the energy management. This feedback loop from the battery makes battery HIL different from conventional testing of batteries/modules/cells. For example, the vehicle controller is reading SOC as a feedback variable from the battery. If the vehicle controller detects a low SOC, the controller will use the engine more often as the vehicle follows the vehicle speed trace. The virtual vehicle follows standard dynamometer cycles, such as the UDDS or the highway drive cycle. Similarly, the vehicle controller continuously monitors the battery module temperature as a feedback variable. It also controls the battery cooling system and the virtual vehicle, so as to maintain the battery temperature within prescribed limits and to achieve other control strategy goals.

<figure 6 here>

The PSAT vehicle model is modified for CAN, Serial, and Analog/Digital I/O before targeting to the dSPACE system. Battery power constraints (as a function of temperature and SOC), provided by the battery manufacturer, are incorporated into the PSAT blocks. The power constraints cannot be stated because the information is proprietary. Safety interlocks are also added to the virtual vehicle [17].

Battery HIL has been used for the following experiments (Figure 7):

1. Impact of vehicle parameters on battery utilization and battery behavior, e.g., energy management strategies at cold ambient for quick rise in battery temperature.
2. Impact of battery conditions on vehicle performance parameters, e.g., impact of cold battery conditions on vehicle AER [18].

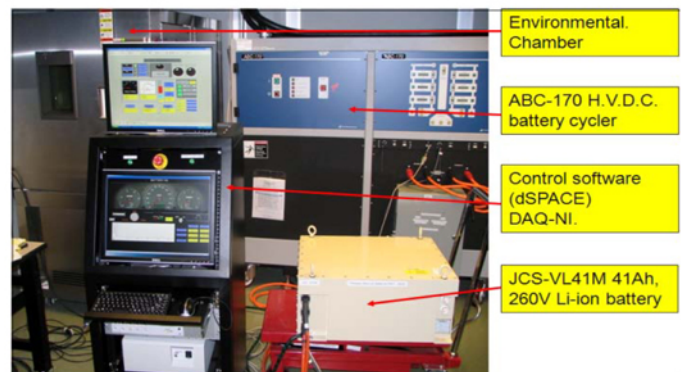


Figure 7. Battery HIL set-up at Argonne National Laboratory