

Maximizing Net Present Value of a Series PHEV by Optimizing Battery Size and Vehicle Control Parameters

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R. Vijayagopal
Argonne National Laboratory

P. Maloney
The MathWorks Inc.

J. Kwon and A. Rousseau
Argonne National Laboratory

ABSTRACT

For a series plug-in hybrid electric vehicle (PHEV), it is critical that batteries be sized to maximize vehicle performance variables, such as fuel efficiency, gasoline savings, and zero emission capability. The wide range of design choices and the cost of prototype vehicles calls for a development process to quickly and systematically determine the design characteristics of the battery pack, including its size, and vehicle-level control parameters that maximize the net present value (NPV) of a vehicle during the planning stage. Argonne National Laboratory has developed Autonomie, a modeling and simulation framework. With support from The MathWorks, Argonne has integrated an optimization algorithm and parallel computing tools to enable the aforementioned development process. This paper presents a study that utilized the development process, where the NPV is the present value of all the future expenses and savings associated with the vehicle. The initial investment on the battery and the future savings that result from reduced gasoline consumption are compared. The investment and savings results depend on the battery size and the vehicle usage. For each battery size, the control parameters were optimized to ensure the best performance possible with the battery design under consideration. Real-world driving patterns and survey results from the National Highway Traffic Safety Administration were used to simulate the usage of vehicles over their lifetime.

INTRODUCTION

Plug-in hybrid electric vehicles (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. The objective of the study is to determine the most effective battery power and energy, based on different cost assumptions, to optimize the net present value (NPV). To achieve that goal, Autonomie, Argonne's vehicle simulation tool, is used along with an optimization algorithm developed by The MathWorks. The PHEV used for this analysis is a midsize passenger car. The characteristics of this vehicle are shown in [Table 1](#).

Components and their sizes differed when comparing a conventional vehicle and series PHEV. While the battery size changed, the other hybrid powertrain components were left unaltered. This allowed the focus to be placed entirely on the effect of battery size and its economic impact on the vehicle cost.

The cost of the battery was considered as an investment, and the gasoline savings (compared with a conventional vehicle) was considered as a cost savings. Since the investment and operating cost was very specific to vehicle use during its lifetime, many assumptions were based on the Vehicle Survivability and Travel Mileage Schedules published by the

Table 1. PHEV specifications

Component	Technology	Specification	Comments
Motor	PM induction	120-kW peak	Steady-state efficiency map
Engine	Gasoline	110 kW	Hot, steady-state fuel map
Generator	PM induction	50-kW peak	Steady-state efficiency map
Battery pack	Soft, Li	16 kWh, scalable	Internal resistance, open circuit voltage as a function of battery state-of-charge
Vehicle	Series PHEV	Midsize sedan	Drag coefficient: 0.31; frontal area: 2.06; test weight: 1,350 kg

National Highway Traffic Safety Administration (NHTSA) [2].

VEHICLE USAGE ASSUMPTIONS

The series PHEV was compared with a conventional midsize vehicle assumed to have an overall fuel economy of 7.9 liter/100 km (30 mpg), which is typical of a midsize sedan. The gasoline price was assumed to be \$0.86/liter (\$3.24/gallon). While we understand that fuel prices will vary in the future, such variations were not considered in this study. The studies conducted by NHTSA support the assumption that an average passenger car will travel over 240,000 km during its lifetime [2].

Figure 1 shows an assumption made about the decrease in vehicle daily distance over the life of the vehicle. The vehicle daily distance degradation was estimated based on average driving distances observed in NHTSA surveys [2] and real-world driving data recorded from a group of Kansas City drivers [3]. The NHTSA survey and real-world daily distance data were based on conventional vehicles, thus making the distance-degradation assumption in Figure 1 subject to further review as new survey and field data are obtained from vehicles with new technologies.

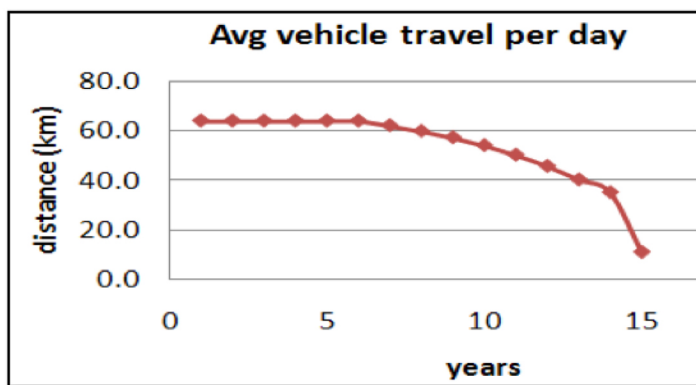


Figure 1. Vehicle daily distance

consumption values for the series PHEV with varying battery sizes. The main characteristics are shown in Table 2. Many simulation runs over these cycles were necessary to optimize the battery size.

Table 2. Characteristics of the real-world driving patterns used for simulating fuel economy

Parameter	Value
Average daily driving distance	58 km
Average vehicle speed	52 km/h
Average energy consumption	286 Wh/mi

The energy & power requirements for the daily drives used in this study are shown in Figures 2, 3 & 4.

It should be noted that more than 95% of the daily drives shown in Figures 2, 3, 4 can be completed with 11 kWh of stored electric energy. Similarly, about 50 kW of peak power are needed for about 95% of the daily drives, even though the average power requirement for the daily drives is less than 8 kW.

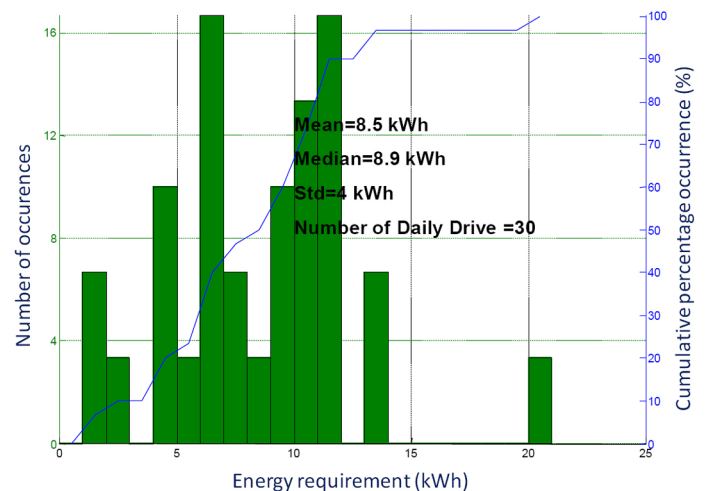


Figure 2. Energy requirement for daily drives

The fuel consumption of any vehicle depends on how it is driven. The studies conducted in Kansas City [3] gave an accurate picture of real-world driving characteristics in a North American city. A representative sample from the real-world drives was used in this study to estimate the fuel

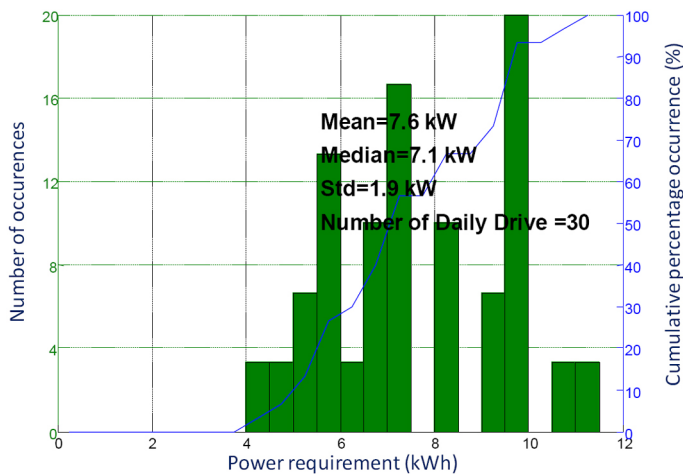


Figure 3. Average power requirement for daily drives

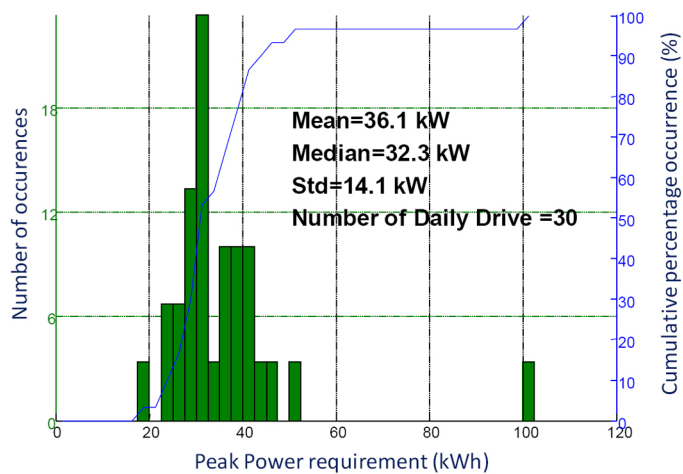


Figure 4. Maximum power requirement for daily drives

BATTERY COST ASSUMPTIONS

In simple terms, a larger battery on a PHEV requires a larger initial investment. However, it also results in lower gasoline consumption and, therefore, more savings in the future. A smaller battery involves a lower initial cost and lower savings related to reduced gasoline consumption in the future. Hence, the quest for an optimum battery size involves minimizing gasoline consumption by varying the battery size (see Figures 5 and 6). For this study, two battery cost scenarios were considered.

1. Short-term cost estimate: Equation 1 represents the current battery cost and is significantly higher than the long-term cost estimate. The optimization results using this cost assumption would indicate what is most beneficial considering present circumstances.

$$\text{Battery cost, \$/kWh} = 32 \times \text{battery power to energy ratio} + 600$$

Eq. (1)

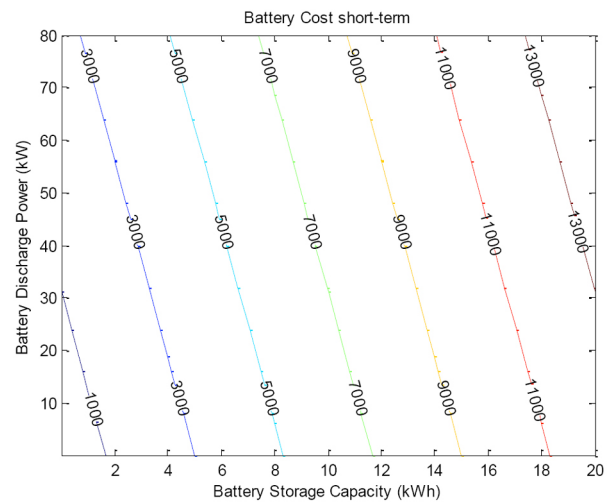


Figure 5. Battery cost variation with battery size (short-term estimate)

2. Long-term cost estimate: Equation 2 has been developed to represent the battery cost based on the research performed by the U.S. Department of Energy (DOE). The battery sizing using the long-term cost would indicate the optimum choice for consumers when the battery becomes cheaper due to either market conditions or subsidies.

$$\text{Battery cost, \$/kWh} = 20 \times \text{battery power to energy ratio} + 125$$

Eq. (2)

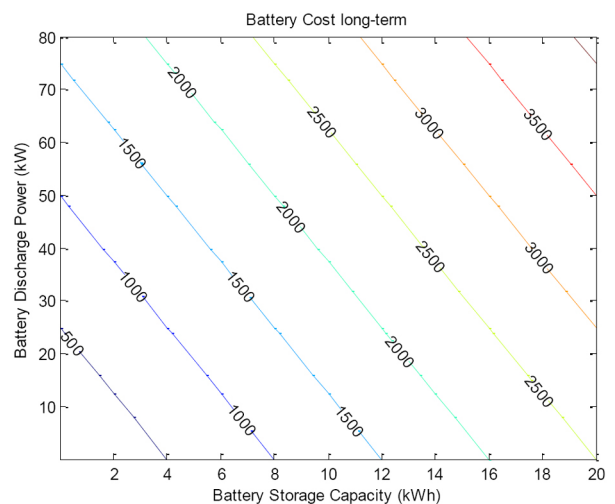


Figure 6. Battery cost variation with battery size (long-term estimate)

If future targets are met, a battery that currently costs about \$12,000 (in the short-term estimate) will cost only about \$3,000 in the future (long-term estimate). With such a difference in battery cost, the optimization exercise will show significantly different choices in the short-term and long-term results.

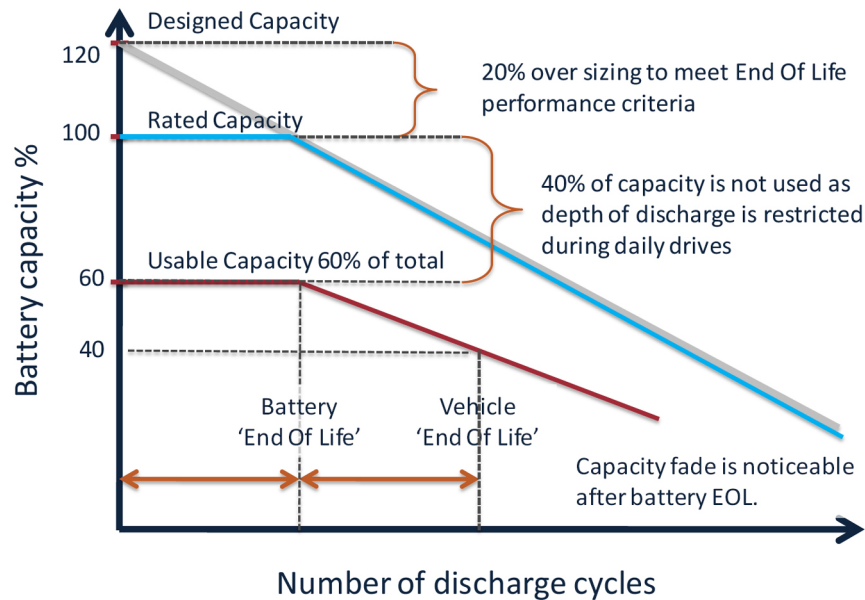


Figure 7. Battery capacity variation with battery use

BATTERY CAPACITY ASSUMPTIONS

The battery capacity reduces during its life. It was assumed that the battery has a surplus capacity at the beginning of its life to ensure the rated capacity until its 'end of life' (e.g., a 10-kWh battery would be able to provide 10-kWh of storage until its 'end of life'). Beyond this 'end of life,' the degradation in battery capacity would be noticeable and characterized by a linear reduction in battery capacity, as shown in [Figure 7](#).

It should be noted that at the end of the assumed vehicle life of 15 years (4,500 cycles), the battery is still capable of storing energy [4]. The battery degradation was assumed to affect the vehicle fuel consumption. However, since the vehicle use was assumed to decrease with the vehicle age, the effect of the battery degradation with age was not taken into account. Under these circumstances, battery replacement at a future date was assumed to promise little return on investment.

BATTERY SIZE OPTIMIZATION

Battery size is determined by the energy stored in the pack and the rate at which that energy can be used. The energy and power variables for a battery pack provided a two-dimensional design space, as shown in [Figure 8](#), where the battery specification had to be limited.

The battery size lower limits were set at 2-kWh of energy and 8-kW of discharge power capability. The lower limits approximated current HEV battery sizes and were slightly lower than the minimum size needed to earn PHEV tax credits [3]. The upper limits were fixed at 20 kWh and 80 kW on the basis of initial simulation studies and NPV estimates.

The battery model used in Autonomie [6] can be scaled to any desired battery energy capacity or power discharge rating. This scaling maintains the voltage at 200 V, while adjusting the capacity (Ah) value of the cells and the internal resistance to meet the desired energy and power ratings.

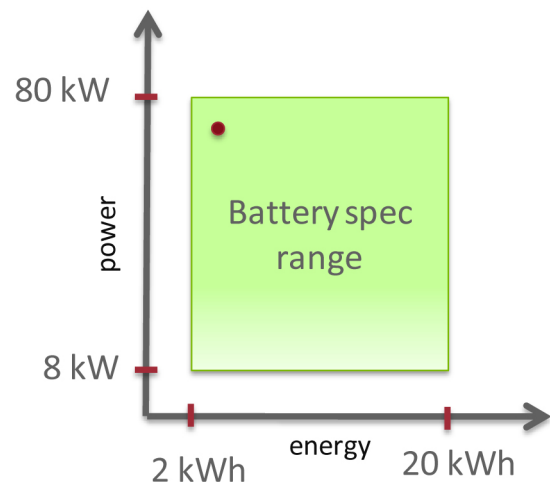


Figure 8. Battery design space

VEHICLE CONTROL PARAMETERS OPTIMIZATION

For this study, we assumed a controller that turns the engine ON based on the criteria mentioned below:

1. If the battery power alone is insufficient to drive the vehicle;
2. If the battery state of charge (SOC) falls below the desired charge-sustaining SOC target value; and