# Research on PHEV Battery Requirements and Evaluation of Early Prototypes

May 16, 2007

Aymeric Rousseau, Neeraj Shidore, Richard Carlson, Vincent Freyermuth
Argonne National Laboratory

## Abstract

Plug-in Hybrid Electric Vehicles (PHEVs) have the ability to drastically reduce petroleum use. The FreedomCAR Office of Vehicle Technology is developing a program to study the potential of the technology. The first step in the program is to define the requirements of PHEV components. Because the battery appears to be the main technical barrier, from both performance and cost perspectives, research has focused on that component. Working with FreedomCAR energy storage and vehicle experts, Argonne National Laboratory (Argonne) researchers have developed a process to define the requirements of energy storage systems for plug-in applications. This paper describes the impact of All Electric Range (AER), drive cycle, and control strategy on battery requirements. First, battery requirements are defined for several vehicle classes and AER by using a vehicle simulation tool. Then, a subset of the simulation is validated by using the Li-ion JohnsonControlSaft VL41M using battery Hardware-in-the-Loop (HIL). Finally, the simulated requirements, based on following the Urban Dynamometer Driving Schedule (UDDS), are compared with an aftermarket Toyota Prius tested on a dynamometer at Argonne's Advanced Powertrain Research Facility (APRF).

## 1 Introduction

Relatively detailed comparisons between plug-in hybrid powertrains and hybrid powertrains were recently completed [1]. The most significant technical barrier to developing commercially viable Plug-in Hybrid Electric Vehicles (PHEVs) is the energy storage system. The challenge is to develop batteries that are able to perform the requirements imposed by a PHEV system and yet meet market expectations in terms of cost and life. In this context, a vehicle systems approach is needed to investigate the operational requirements specific to PHEV technology. Vehicle-level investigations determine the relationship between component technical targets and vehicle system performance and the potential of the entire system design to displace petroleum use. To evaluate the battery requirements for different PHEV options, several capabilities were combined, including simulation, hardware-in-the-loop (HIL), and vehicle testing.

Argonne's vehicle simulation tool, Powertrain System Analysis Toolkit (PSAT), was used with a battery model designed by Argonne's battery research group. PSAT [2, 3], developed with MATLAB and Simulink, is a vehicle-modeling package used to estimate performance and fuel economy. PSAT is the primary vehicle simulation package used to support the U.S. Department of Energy's (DOE's) FreedomCAR R&D activities. Component models and control strategies have been developed to PHEVs for several classes of vehicles [4]. In this paper, we analyze the impact of All Electric Range (AER) on fuel efficiency to provide direction on the most appropriate sizing strategy. Then, we evaluate the main battery parameters, including energy, power, current, and voltage. AER is defined, in this paper, as the distance that the vehicle can travel by only using energy from the battery while repeating the Urban Dynamometer Driving Schedule (UDDS).

To verify the simulated battery requirements and address the potential limitations of current battery technology, a battery HIL experiment was setup by using the JohnsonControl-Saft VL41M. During the test, only the battery is hardware — the rest of the vehicle is emulated. For PHEV operation, the 41-Ah Li-ion battery is connected to a DC power source, which is controlled by a real-time simulation model that emulates the rest of the power train. The vehicle model is derived from a simulation model developed by using PSAT. As only the battery is different from PSAT, one can easily evaluate the uncertainties associated with the battery model.

The Advanced Powertrain Research Facility (APRF) at Argonne National Laboratory handles the U.S. DOE's technology validation and benchmark testing of advanced vehicle technologies. Argonne tests new hybrid electric vehicles (HEVs) and PHEVs to provide data that are used to update DOE-funded vehicle simulation tools, such as PSAT. The data are also used to provide DOE and auto industry engineers with benchmark specifications that aid in forecasting future technology developments. Vehicle testing from an aftermarket Toyota Prius will be used to compare the requirement of batteries designed for the UDDS and current technology.

# 2 Battery Requirements

## 2.1 Modeling Assumptions

Vehicles representative of the midsize and SUV classes were sized to meet the performance criteria in Table 1.

**Table 1: Performance Requirements**

| Parameter | Unit | Value |
|---|---|---|
| 0–60mph | s | 9 +/- 0.1 |
| 0–30mph | s | 3 |
| Grade at 55 mph | % | 6 |
| Maximum Speed | mph | > 100 |

The main vehicle characteristics used in PSAT are defined in Table 2.

**Table 2: Main Simulation Assumptions**

| Parameter | Unit | Midsize Car | Crossover SUV | Midsize SUV |
|---|---|---|---|---|
| **Vehicle** | | | | |
| Curb weight | kg | 889 | 1100 | 1132 |
| Vehicle Test Mass (Conventional) | kg 1 | 629 | 1818 | 1893 |
| Frontal Area | $m^2$ 2. | 2 | 2.68 | 2.88 |
| Drag Coefficient | | 0.3 | 0.417 | 0.41 |
| **Components** | | | | |
| Electric Machine Peak Efficiency | % | 0.94 | 0.94 | 0.94 |
| Electrical Power | W | 800 | 1000 | 1200 |

As shown in Figure 1, the configuration selected is a pre-transmission parallel hybrid, similar to the one used in the DaimlerChrysler Sprinter Van [1].

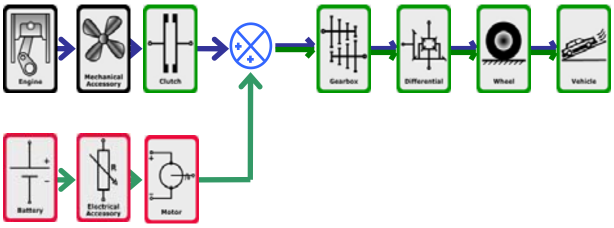

**Figure 1 Configuration Selected – Pre-Transmission Parallel HEV**

This study accounts for uncertainty in component specifications by considering two cases: a slow technology advancement case and a fast technology advancement case. Fast technology advancement represents the consequences of achieving the FreedomCAR goals, while slow technology advancement represents the consequences of achieving more conservative improvements. Specifically, these cases are used to capture the uncertainty in the improvement in the efficiency and specific power of the engine and electric motor.

## 2.2 Sizing Process

To quickly size the component models of the powertrain, an automated sizing process was developed [4]. While engine power is the only variable for conventional vehicles, HEVs have two variables because they have the additional electric machine power. PHEVs add yet another degree of freedom with the battery energy. On the basis of assumptions about the vehicle, the peak electric machine mechanical power is defined as the peak power required for the vehicle to follow the UDDS cycle. The battery peak discharge power is then defined as the electrical power that the motor requires to produce the peak mechanical power needed for the vehicle to follow the UDDS cycle. The engine is then sized to achieve the gradeability requirement of the vehicle.

Seven AER values (7.5, 10, 20, 30, 40, 50, and 60 mi) were simulated. Because the batteries need to have different power-to-energy ratios, the battery model was further extended to include cells of the same chemistry, but with capacities in the range of 10–100 Ah and capacity-to-power ratios (C/P) of 0.75–3.0 times that of the VL41M cell, and for batteries containing any number of such cells. This modification was accomplished by developing a set of equations used to determine the multiplying factor for converting the lookup table developed for the parameters of the VL41M cell to the appropriate values for the desired cell capacity and power [4, 5].

## 2.3 Summary of PSAT Battery Requirements

Figure 2 shows the 2-s power pulses necessary to follow the UDDS driving cycle in All Electric Mode. Note that the power does not significantly change with an increase in AER. For every additional 10 mi of AER, an average of 1 kW is added as a result of the increased battery mass.

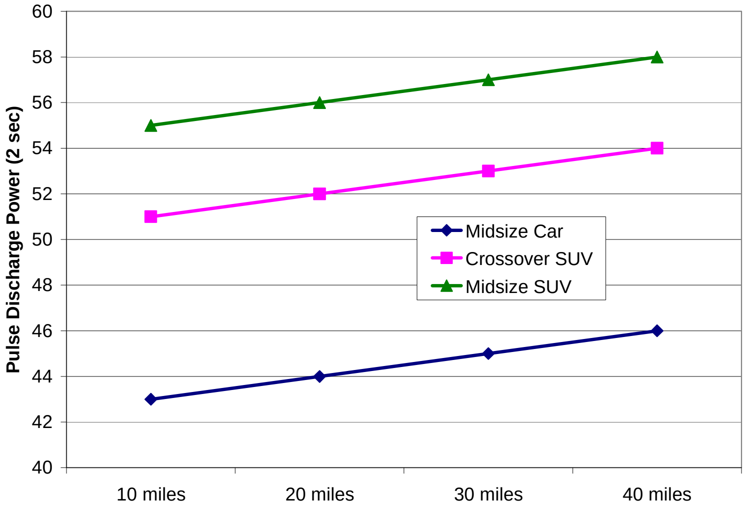

**Figure 2: 2-s Battery Power**

Because electricity consumption is constant regardless of the range that PHEV was designed to travel in charge-depleting mode, the total electrical consumption for this operating mode is a linear function of the charge-depleting range, as shown in Figure 3. Even if the average usable energy by unit of distance changes with the additional mass, a midsize car consumes 250 Wh/mi, a crossover SUV consumes 320 Wh/mi, and a midsize SUV consumes 380 Wh/mi.

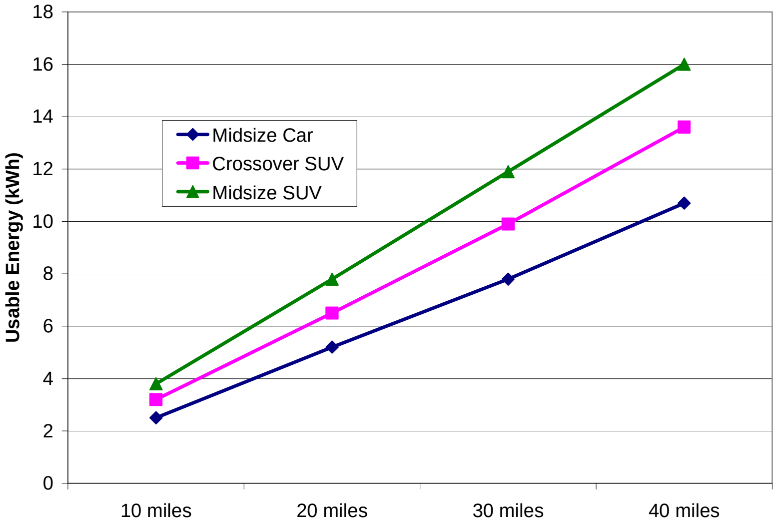

**Figure 3: Usable Energy Battery Requirements**

Because battery peak discharge power remains virtually constant as the PHEV range is increased and the battery energy increases linearly with PHEV range, the power-to-energy ratio of the battery varies hyperbolically with range, as Figure 4 shows. Figure 4 also shows that for each range, the SUV battery requires a lower power-to-energy ratio than the crossover SUV and midsize vehicle. This result agrees with Figure 3, which shows energy consumption, and Figure 2, which shows peak battery power. The peak battery power of the midsize SUV is 20% greater than that of the midsize car, while the energy consumption is 30% greater.

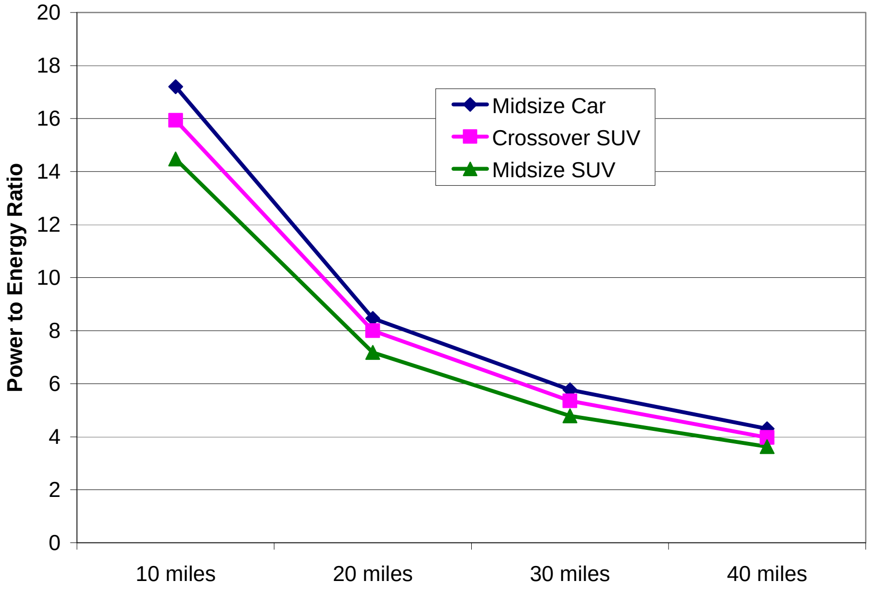

**Figure 4: Power-to-Energy Ratio**

## 2.4 Requirement Uncertainties

As for any simulation process, the assumptions are very important. In the previous paragraph, we defined assumptions to represent an average vehicle — we now define the uncertainties associated with the vehicle mass, frontal area, drag coefficient, and electrical accessories. Note that only one parameter is varied at a time. As a consequence, the performance is not maintained.

Figure 5 shows the impact of vehicle mass on the usable energy per unit of distance. Note that the impact is similar from one configuration to another. For every 100 kg in vehicle mass added, 10–11 Wh/mi are used.

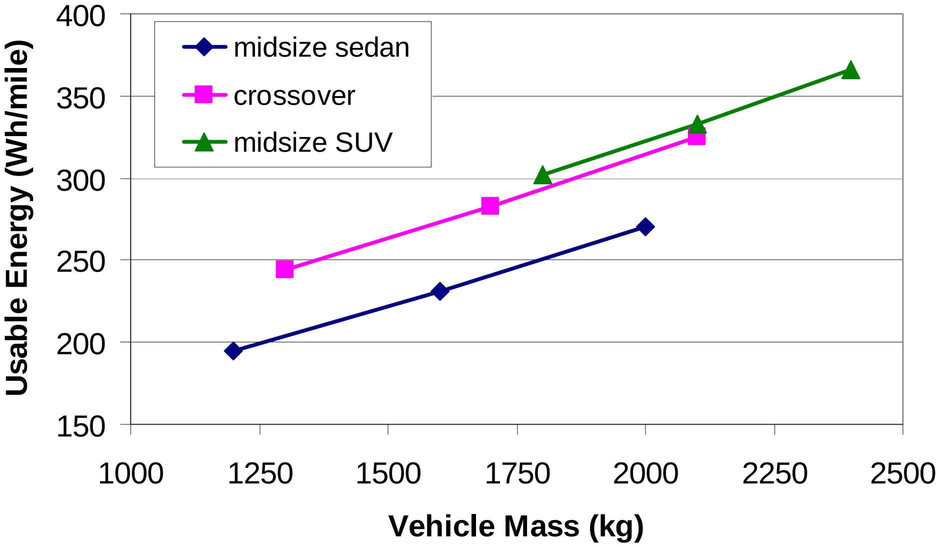

**Figure 5: Vehicle Mass Uncertainties**

Figure 6 shows the impact of the frontal area and drag coefficient on the usable energy per unit of distance. Note that the impact is also similar from one configuration to another. In this case, however, it has a minimal impact on the requirements of the battery.

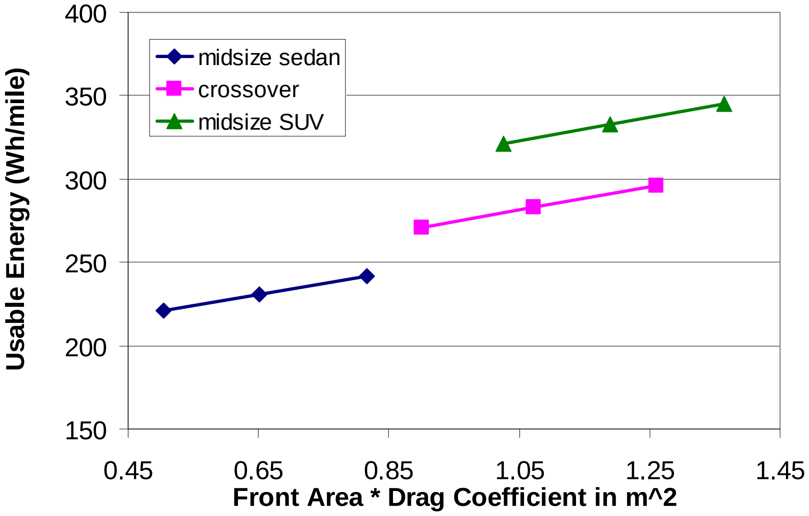

**Figure 6: Frontal Area * Drag Coefficient Uncertainties**

Figure 7 shows the impact of the electrical accessory loads on the usable energy per unit of distance. Frontal area, drag coefficient, and vehicle mass are characteristic of the vehicle and do not significantly change during the life of the vehicle, but the accessory load varies from season to season. Note that the impact is here significant. The low end of the spectrum (200 W) represents the minimum load that will be used on the dynamometer during vehicle testing, and the high end represents the use of air conditioning. If we take the example of the midsize car, the requirements vary from 215 to 310 Wh/mi, which is a variation of more than 40%. Although the initial requirements were defined to use an average accessory load (ranging from 800 to 1200 W for the different vehicle classes), one needs to be aware of the danger of defining the AER on the UDDS, which would represent the best-case scenario. On average, the usable energy per unit of distance increases by 5.5 Wh/mi for every 100 W of electrical accessory load.

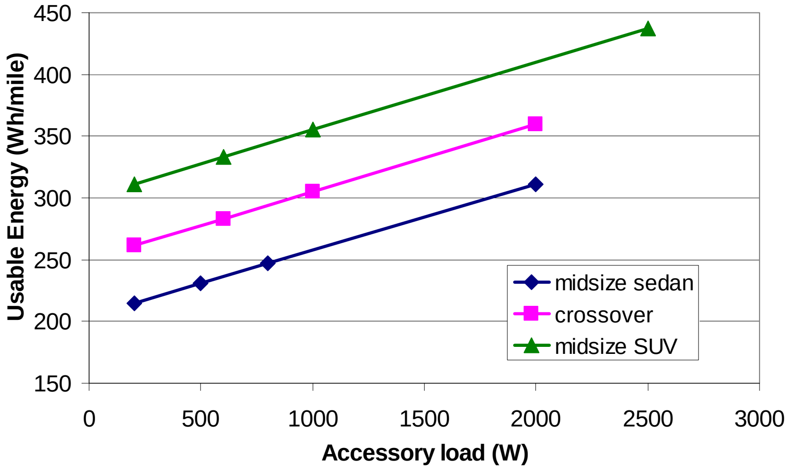

**Figure 7: Electrical Accessory Uncertainties**

# 3 Battery Requirements Verification Using HIL (NS)

## 3.1 Battery HIL concept

Battery HIL involves evaluation of a battery in an emulated vehicle environment. Figure 8 shows a conceptual block diagram of a battery HIL setup. As shown in the figure, a real battery (hardware) is connected to an emulated vehicle system (real-time simulation model of the remaining power train and vehicle controller). The vehicle controller, through a DC power supply, subjects the battery to charge and discharge events, similar to those that the battery would undergo in a real vehicle. In turn, the vehicle controller uses real- time feedback from the battery (in terms of voltage, state of charge, and temperatures) to make energy-management decisions for the emulated power train and the real battery, so that the emulated vehicle meets vehicle level specifications (fuel economy, performance) as it follows a predefined drive cycle.

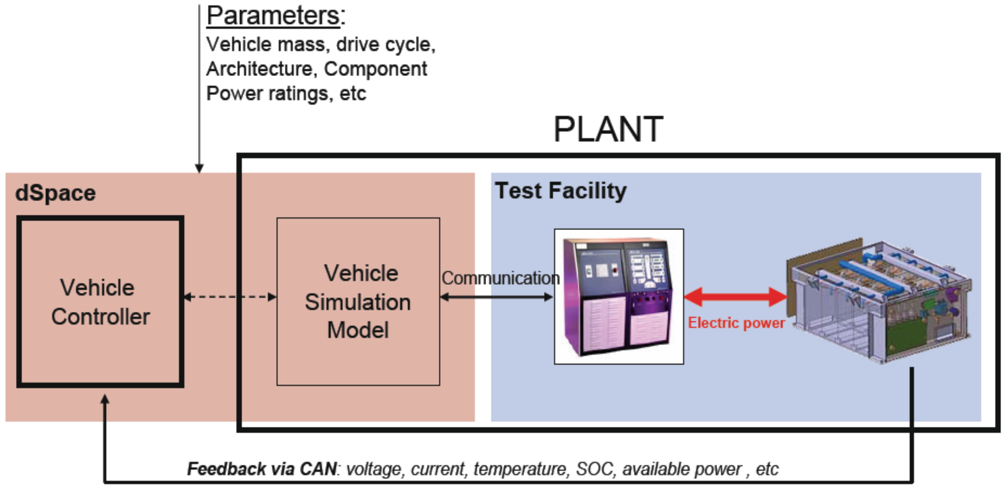

**Figure 8: Battery HIL – Conceptual Block Diagram**

A virtual vehicle and controller permits easy changes to such vehicle parameters as mass, drive cycle, and architecture. The vehicle control strategy can also be modified. Thus, the battery can be evaluated for numerous system parameters, in a relatively short amount of time. This makes battery HIL a very powerful tool for characterizing battery utilization with maximum flexibility in vehicle parameters.

## 3.2 Battery HIL Setup at Argonne National Laboratory

Figure 9 shows the setup of the battery HIL experiment at Argonne. The simulation model of the vehicle controller and the power train was developed in PSAT-PRO. PSAT-PRO is a companion tool of PSAT for HIL/RCP (Rapid Control Prototyping) applications. The PSAT-PRO model of the controller and the vehicle is compiled into a D-Space system for real-time simulation and control of the ABC-150, which sinks and sources power from the battery. The battery provides voltage, current, state of charge, and other feedback to the vehicle controller via CAN (Controller Area Network). Pack voltage and current are also measured external to the battery by a potential divider and a current clamp, respectively. The ABC-150 is connected to the battery thorough fuses and external contactors. Table 3 gives some information about the battery, and table 4 gives information on the virtual vehicle, which is being used for the experiment. The SAFTVL41M on the battery HIL test stand is liquid cooled with process water at a constant temperature of 20ºC, at a flow rate of 180 L/h.

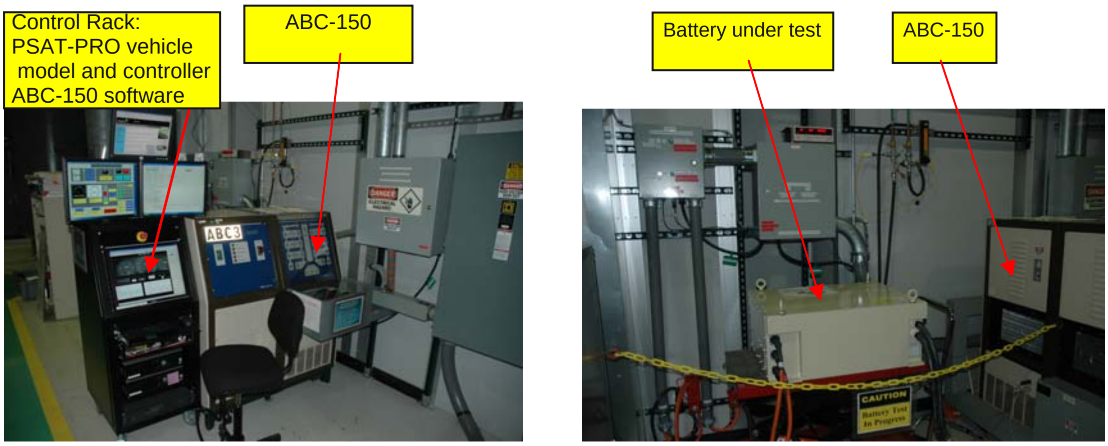

**Figure 9: Battery Hardware in the Loop – Setup**

**Table 3: SAFT-JCS VL41M specifications**

| Parameter | Unit | Value |
|---|---|---|
| Capacity | Ah | 41 at C/3 |
| Operating Voltage | V | 194.4 – 288 V |
| Continuous Current | A | 150 A continuous for 30 s at 30°C |
| Discharge Power | kW | 61 kW for 30  at 50% SOC at 30°C |

**Table 4: Virtual Vehicle specifications**

| Vehicle Configuration | Pre-transmission parallel |
|---|---|
| Vehicle Class | Midsize |
| Vehicle Test Mass | 1661 kg |
| Frontal Area | 2.2 $m^2$ |
| Drag Coefficient | 0.29 |
| Transmission | 5-speed manual |
| Accessory Load – Electrical | 200 W average |
| Electric Machine | 75 kW peak at base speed of 3000 RPM |

### 3.3 Battery HIL Testing — All Electric Range (AER) Operation

The SAFTVL41M Li-ion battery pack is being evaluated for use in a PHEV. Because of the high capacity of the pack, the virtual vehicle is capable of significant “electric-only” operation. Operation in “electric-only” or predominantly electric (charge-depleting) mode is expected to be a significant part of a plug-in hybrid’s daily commute, because maximum petroleum displacement benefits are gained in these two modes of operation. The “electric-only” mode is a worst-case scenario of the charge-depleting mode and exerts maximum instantaneous power demands from the battery. It is important to evaluate the battery performance in this “worst-case” mode (i.e., the AER achieved, the battery losses, battery efficiency, etc.). Quantifying this performance helps in determining the best use of the battery in a vehicle (i.e., which vehicle class is it suitable for?). The impact of prescribed limitations of the battery (e.g., operational SOC range, charge and discharge power as a function of SOC, etc.) on the AER can be evaluated. The battery cooling system can be designed after looking at the heat rejected by the battery in this worst-case scenario. Battery life and performance degradation can be predicted from the results of the AER test. Figure 10 shows the operation of the battery in AER range. The battery’s initial state of charge was 89%, and the battery was subjected to consecutive urban (UDDS) cycles in all-electric mode until the SOC reached 29%. Figure 11 shows the coolant supply and return temperatures, as well as an actual module temperature. While running the test, we obeyed manufacturer-recommended restrictions on battery charge and discharge currents. Disregarding these instructions will give different results. Table 5 is a summary of some battery results for the test.

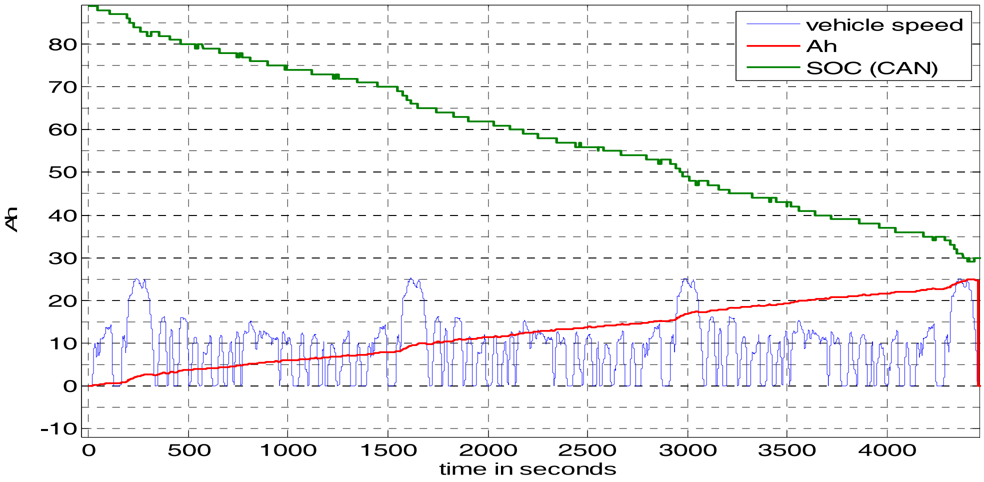

Figure 10: Battery State of Charge and Ah

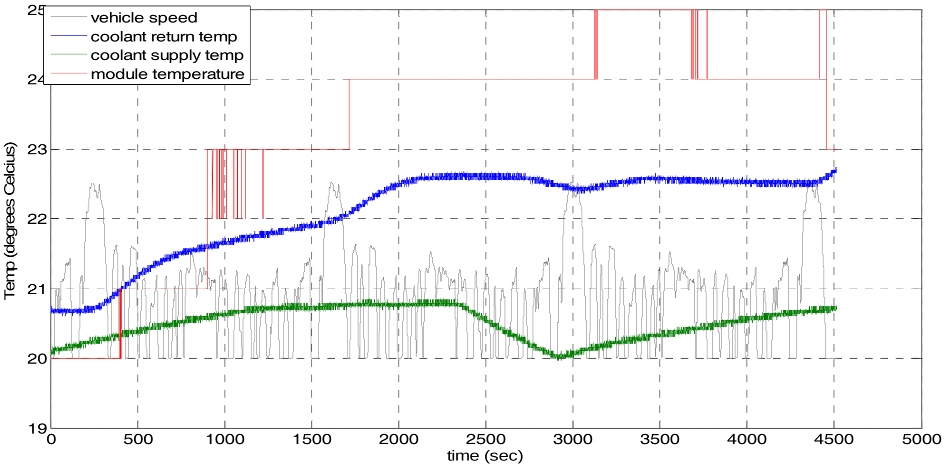

Figure 11: Battery Coolant Supply, Return and Module Temperatures

Table 5: Summary of Results

| | |
|---|---|
| AER from 0.89 to 0.29 SOC | 24.79 mi |
| Battery Ah Depleted | 25 Ah |
| Battery Electrical Energy | 6.29 kWh |
| Energy Consumption | 253.7 Wh/mi |
| Average Instantaneous Heat Rejected by Battery | 213 W |

## 3.4 Comparison with PSAT Simulations

A simulation was performed in PSAT with the same vehicle, the only difference being the battery model. Table 6 summarizes the comparison between simulation and test. Note that the energy requirement is within 5%, which validates the simulation approach.

Table 6: Comparison between HIL and PSAT

| Units | | HIL | PSAT |
|---|---|---|---|
| AER from 0.9 to 0.3 SOC | mi | 24.79 | 26 |
| Battery Ah Depleted | Ah | 25 | 24.7 |
| Battery Electrical Energy | kWh | 6.29 | 6.57 |
| Energy Consumption | Wh/mi | 253.7 | 241 |

The remainder of this paragraph focuses on understanding the differences between the hardware and the battery model. Figure 12 shows the test battery current for each of the three UDDS driving cycles. Note that the current during regenerative braking increases from one cycle to another as a result of lower battery SOC.

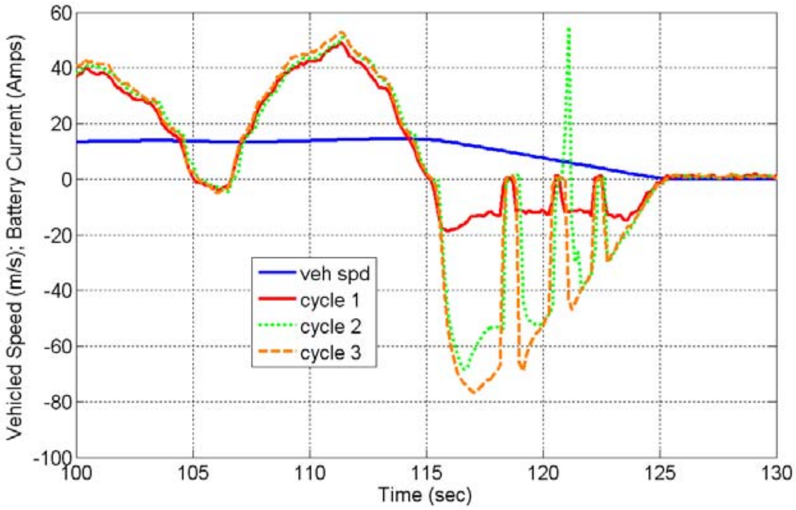

Figure 12: Evolution of Current during Regenerative Events for HIL

Figure 13 shows the simulated battery current for each of the three UDDS driving cycles. While the current also increases during regenerative braking from one cycle to another, the main difference occurs during the first cycle where no regenerative braking occurs in PSAT. For the following cycles, the simulation and test values are similar.

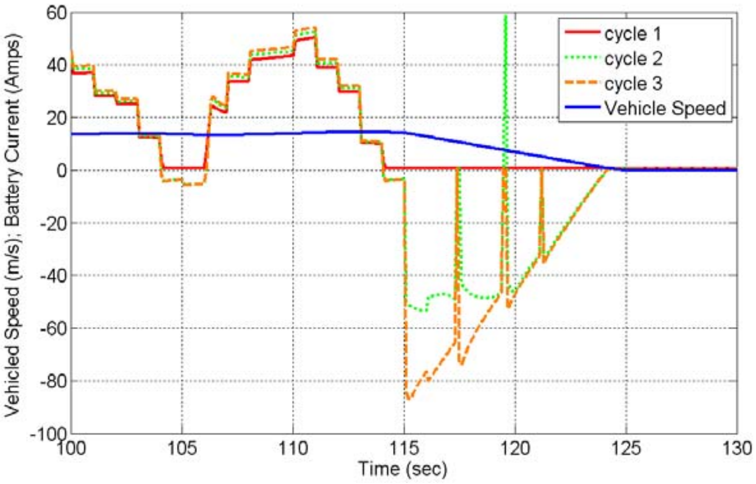

Figure 13: Evolution of Current during Regenerative Events for PSAT

Figure 14 shows both simulated and measured SOC. The difference in currents during the early cycles does not significantly affect the SOC.

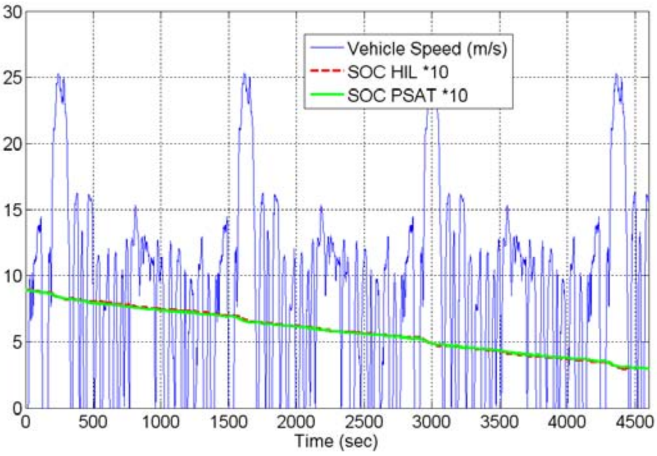

Figure 14: SOC Comparison

Figure 15 shows the battery pack voltages. The higher value for the battery HIL is the main reason behind the higher electrical consumption. This difference may be due to underestimated battery losses or open circuit voltages.

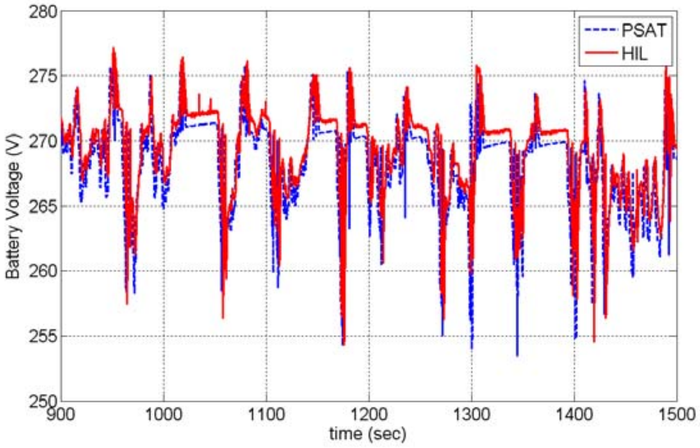

Figure 15: Voltage SOC Comparison

The comparison between the hardware and the model showed an uncertainty of 5% for the energy requirement, which validates the overall simulation results. In the future, the performance of the battery will be characterized from HPPC tests, and the model will be refined.

# 4 Vehicle Testing

## 4.1 Vehicle Description

A PHEV Prius containing a 5-kWh battery pack was tested on a four-wheel chassis dynamometer at the Advanced Powertrain Research Facility at Argonne National Laboratory. The system was tested for fuel economy, electrical energy consumption, and tailpipe emissions. The analysis of the test data can be used as part of a benchmarking effort to determine the battery power and energy requirements of PHEVs.

The Hymotion PHEV Prius, shown in Figure 16, contains a supplemental Li-ion battery pack to provide and addition 5 kWh of electrical energy storage [6]. This system includes a clever control system to enable the Prius to operate in a CD mode. CAN communication is used to communicate with the production Prius powertrain controller and operate the vehicle in EV mode at speeds of up to 40 mph or until a power requirement threshold is exceeded. As a result, the powertrain primarily uses electrical energy during urban driving, which minimizes engine operation and thus reduces fuel consumption. This vehicle does not have a true AER because of the engine operation requirements, but the vehicle is a good representation of a near-term PHEV. This testing is used to characterize the energy and power requirements of a battery system in a vehicle.

**Figure 16: Hymotion PHEV Prius on Chassis Dynamometer with Hymotion 5-kWh Battery System Installed in Parallel to the Production Battery**

Before the installation of the Hymotion battery system, the Toyota Prius was tested extensively as a production HEV at Argonne by using the dynamometer coefficients of the 2004 production Prius. For direct comparison, the same coefficients were used for the Hymotion PHEV testing, but since the Hymotion battery system weighs 73 kg, the test weight was increased to 1,546 kg. The dynamometer coefficients used for the Hymotion PHEV Prius testing are shown in Table 7.

**Table 7: PHEV Prius Dynamometer Coefficients**

| Coefficients | A | B | C |
|---|---|---|---|
| Target | 19.918 | 0.1393 | 0.0164 |
| Dyno Set | 3.604 | -0.1538 | 0.0179 |

For the PHEV Prius testing, a 32-channel National Instruments PXI chassis was used to collect the signals from the in-vehicle sensors, as well as the dynamometer and test cell sensors. A Hioki “HiTESTER” was used to measure the current and voltage of both onboard battery systems and integrate Ah and kWh. A CAN bus-to-USB communication device was used to read and record parameters from the vehicle CAN bus that are used by the powertrain ECU, as well as parameters from the Hymotion controller (such as SOC and various temperatures). An OBD (On-Broad Diagnostic) scan tool was also used to read and record other communication parameters from the vehicle CAN bus used by the Prius powertrain and battery ECU.

To properly evaluate the charge-depletion characteristics and the amount of petroleum displacement by a PHEV, the vehicle was tested through the full discharge range of the pack by running repeated UDDS cycles until the charge-sustaining operation was entered and the battery SOC was charge balanced over an entire drive cycle. The plug-in battery pack was recharged overnight to prepare for more testing the following day.

The PHEV Prius has a single mode of operation, which is a maximum charge-depletion mode (the EV mode of the production Prius) that minimizes engine operation to minimize fuel consumption. The Hymotion system can also be completely disabled, which causes the vehicle to revert to the charge-sustaining control strategy of the production Prius by using only the battery pack of the Prius.

## 4.2 Vehicle Testing — UDDS Charge-Depletion Operation

Beginning from a cold start, the PHEV Prius was tested on consecutive UDDS cycles. The battery energy was depleted through the $2^{nd}$ hill of the fourth consecutive UDDS. In total, 25 mi were driven in charge-depletion mode. During those cycles, the powertrain operated primarily in EV mode, except above 40 mph or when the EV mode power threshold was exceeded. After completion of the repeated UDDS cycles, 4.3 AC kWh of energy was measured to fully recharge the battery pack. This charging event took approximately six hours. Because 3.2 DC kWh of energy was used over the UDDS cycles, the overall charging efficiency is approximately 75%. Table 8 shows the unadjusted results from the five consecutive UDDS cycles. The operating cost calculation assumes $2.75/gal, $0.102/kWh [7], and a charging efficiency of 75%.

Figure 17 shows the consecutive UDDS cycles. The red dots on the graph indicate when the engine is operating and consuming fuel. Note the accumulated fuel consumed is much lower for the Hymotion charge-depleting PHEV Prius (PHEV), as compared to the stock charge-sustaining Prius. This is accomplished by electrical energy consumption, which displaces petroleum consumption. After the vehicle fully depletes the usable battery energy, it operates in the standard charge-sustaining mode, just as a production Prius operates.

**Table 8: Hymotion Prius, Consecutive UDDS Results**

| UDDS | #1 | #2 | #3 | #4 | #5 |
|---|---|---|---|---|---|
| Miles Driven (mi) | 7.48 | 7.48 | 7.48 | 7.48 | 7.47 |
| Fuel Used (gal) | 0.051 | 0.037 | 0.040 | 0.101 | 0.113 |
| Electrical Energy Consumed (DC kWh) | 0.93 | 0.96 | 0.94 | 0.23 | -0.12 |
| Fuel Economy (mpg) | 148 | 200 | 187 | 74.3 | 66.4 |
| Electrical Consumption (DC Wh/mi) | 123 | 128 | 125 | 30.6 | 15.9 |
| Operating Cost ($/mi) | 0.035 | 0.031 | 0.032 | 0.041 | 0.039 |

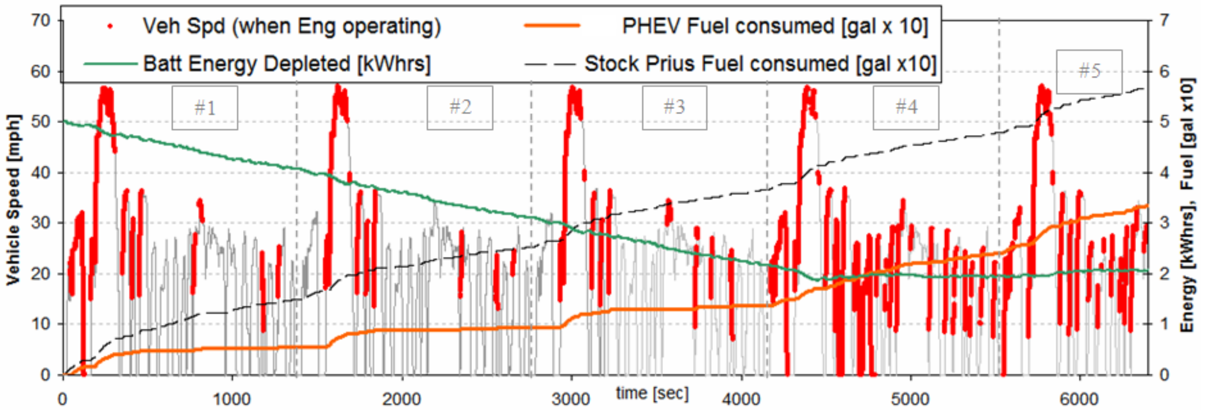

**Figure 17: Hymotion Prius Driven on Repeated UDDS Cycles; Cold Start from 100% SOC to Charge-Sustaining Operation**

## 4.3 Comparison with Battery Requirements from Simulation

Because PSAT does not handle cold start, the second UDDS cycle from the test will be compared with the simulation. The vehicle and component parameters used during testing are reproduced in PSAT, including the ABC dynamometer coefficients and the electrical accessories. Note that the electrical accessories for the 2004 Prius on the UDDS are 220 W.

The PHEV model was developed on the basis of the previously validated 2004 Prius model [8]. The control strategy and the battery were modified to represent the PHEV test vehicle. The battery used is based on the VL41M, which is different from the one in the Hymotion vehicle. During vehicle testing, we noticed that the engine operated at low power, unlike its conventional HEV counterpart, as shown in Figure 18.

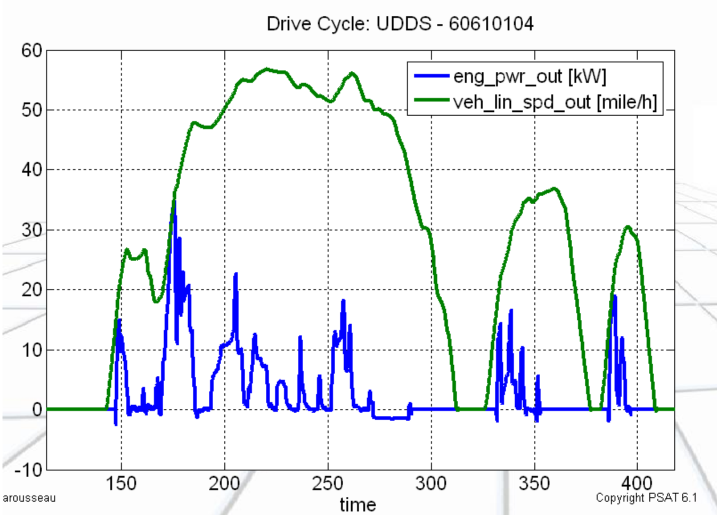

Figure 18: Engine Power on Hymotion Prius UDDS

Previous control strategy studies using global optimization [9] demonstrated that it was better to use the engine close to its most efficient point and charge the battery. As a consequence, the control strategy was modified in PSAT to be able to efficiently use the engine when it is ON. The electrical consumption decreases to 72 Wh/mi.

Finally, as discussed previously, the electrical consumption on the UDDS is not representative of real-world driving. For this reason, a last set of simulations was performed with an 800-W accessory load, the same value that was used for the midsize vehicles. The electrical consumption then becomes 103 Wh/mi.

Table 9 summarizes the comparison between the test and simulation reproducing the HyMotion control strategy, as well as improved engine control and more realistic electrical accessory loads.

| | Electrical Consumption (Wh/mi) | Fuel Economy (mpg) |
|---|---|---|
| HyMotionTest – Third UDDS | 125 | 187 |
| PSAT – Improved Engine Operating Conditions | 72 | 160 |
| PSAT – Improved Engine Operating Conditions and Increased Accessory Loads (800 W) | 103 | 160 |

Table 9: Energy Consumption for Prius System — UDDS driving cycle

Even if the simulated Prius is lighter than the average midsize simulated (1546 vs. 1661 kg), the energy required is less than 50% that used when the UDDS is performed in EV mode (103 vs. 250 Wh/mi). As a consequence, the energy requirements would be less stringent, allowing the possibility of introducing PHEVs sooner.

The following tables (9, 10, and 11) summarize the energy requirements uncertainties from modeling, HIL and simulation.

| | **Midsize Car** | **Crossover SUV** | **Midsize SUV** |
|---|---|---|---|
| Reference Value for the Uncertainty | 230 | 280 | 330 |
| Vehicle Mass Uncertainty(1) | 195>X>270 | 245>X>325 | 300>X>365 |
| FA and Cd Uncertainty(1) | 220>X>240 | 270>X>300 | 320>X>345 |
| Electrical Acc. Uncertainty(1) | 215>X>310 | 262>X>360 | 310>X>435 |
| Representative Average Selected | 250 | 320 | 380 |

**Table 10: Energy Consumption (Wh/mile) for Pre-transmission Parallel HEV from PSAT**

(1) Only one parameter is modified starting from the average.

| | **Comparison with HIL** |
|---|---|
| HIL | 253 |
| PSAT | 241 |

**Table 11: Energy Consumption (Wh/mile) for Pre-transmission Parallel HEV from PSAT**

| | **Comparison with Vehicle Testing** |
|---|---|
| Test | 125 |
| PSAT with Improved Control | 72 |
| PSAT with Elec. Acc. | 103 |

**Table 12: Energy Consumption (Wh/mile) for Pre-transmission Parallel HEV from PSAT**

# 5 Conclusion

Based on the UDDS driving cycle, the battery energy and power requirements have been defined for a pre-transmission parallel HEV for several vehicle platforms, including midsize car, crossover SUV, and midsize SUV. When using average accessory loads representative of real-world driving, the energy consumption is 250 (midsize car), 320 (crossover SUV), and 380 (midsize SUV) Wh/mi. Uncertainties based on vehicle mass, frontal area, drag coefficient, and electrical accessories were evaluated. The electrical accessory loads represent the greatest uncertainty, with an additional 5–6 Wh/mi for every 100 W.

By using battery HIL, the battery requirements of a specific pre-transmission parallel HEV midsize vehicle were validated within 5% for the energy. As the other simulations are based on the same battery model, the overall PSAT results are also validated within that uncertainty. Future work will include refining the battery model to minimize the differences in voltage.

Because it is likely that the first PHEV introduced will be based on existing HEV configurations, a power split PHEV was tested and the battery energy characterized. By using an improved control strategy in PSAT combined with real-world accessory loads, it was shown that the energy requirements could be decreased by as much as 50%, in comparison with following the UDDS in EV mode. Using the engine during the charge-depleting mode could allow faster introduction of PHEVs by lowering the battery energy requirements, leading to longer battery life and lower costs.

In order to better understand the impact of every parameter on the battery requirements, in addition to vehicle assumptions and control strategies, future studies will also focus on additional vehicle powertrain configurations, including series and additional power split HEVs.

## References

[1] Graham, B., “Plug-in Hybrid Electric Vehicle, A Market Transformation Challenge: the DaimlerChrysler/EPRI Sprinter Van PHEV Program,” EVS21, April 2005.

[2] Argonne National Laboratory, PSAT (Powertrain Systems Analysis Toolkit), http://www.transportation.anl.gov/.

[3] Rousseau, A.; Sharer, P.; and Besnier, F., “Feasibility of Reusable Vehicle Modeling: Application to Hybrid Vehicles,” SAE paper 2004-01-1618, SAE World Congress, Detroit, March 2004, http://www.eere.energy.gov/vehiclesandfuels.

[4] Sharer, P.; Rousseau, A.; Nelson, P.; and Pagerit, S., “Vehicle Simulation Results for Plug-in HEV Battery Requirements,” EVS23, Japan, October 2006

[5] Nelson, P., “Modeling the Performance of Lithium-Ion Batteries for Fuel Cell Vehicles,” SAE paper 2003-01-2285 in SP-1789, Costa Mesa, CA, June 23–25, 2003.

[6] Carlson, R., et al., “Testing and Analysis of Three Plug-in Hybrid Electric Vehicles,” SAE paper 2007-01-0283, SAE World Congress, Detroit, April 2007.

[7] http://www.arb.ca.gov/msprog/zevprog/symposium/presentations/maccurdy.pdf

[8] Rousseau, A.; Sharer, P.; Pagerit, S.; and Duoba, M., “Integrating Data, Performing Quality Assurance, and Validating the Vehicle Model for the 2004 Prius Using PSAT,” SAE paper 2006-01-0667, SAE World Congress, Detroit (April 2006)

[9] Karbowski, D.; Rousseau, A.; Pagerit, S.; and Sharer, P., “Plug-in Vehicle Control Strategy: From Global Optimization to Real Time Application,” EVS22, Yokohama, October 2006