

PHEV ‘All electric range’ and fuel economy in charge sustaining mode for low SOC operation of the JCS VL41M Li-ion battery using Battery HIL

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Abstract

Plug-in hybrid electric vehicles have been identified as an effective technology to displace petroleum by drawing significant off-board energy from the electrical grid. A plug-in vehicle is expected to operate in an electric-only or a charge-depleting mode over a large SOC window (60-80% of total operational SOC) for maximum petroleum displacement. The “all electric range” (AER) test quantifies the electric-only miles possible with the battery for a particular configuration and vehicle class.

At low SOC, the vehicle operates in the charge-sustaining (CS) mode, similar to the current hybrid electric vehicles. The SOC at which the battery operates in the CS mode is mostly determined by the impact on battery life. From a vehicle perspective, it is also important to quantify the sensitivity of vehicle fuel economy to CS operation at different SOC.

This paper describes the hardware-in-the-loop testing of a 41-Ah Li-ion battery designed for PHEV applications. Vehicle AER, temperature rise and battery performance in the CS mode at low SOC (35 to 20%) were evaluated. These tests indicate that CS operation at low SOC for an urban driving cycle has no effect on fuel economy. Thus, the lower limit set for SOC is a “life” decision, not a “performance” decision.

Keywords: Plug-in hybrids, batteries, charge-sustaining operation, petroleum displacement, battery performance, all electric range, battery temperature

1. Introduction

The batteries used in plug-in hybrid electric vehicles (PHEVs) are supposed to operate over a large state-of-charge (SOC) window. After an “overnight charge” of the battery from the utility grid to a certain high state of charge (e.g. 90% SOC), the vehicle will operate in a charge-depleting (CD) or an electric-only (EV) mode until a low state of charge is reached. This CD/EV operation of the PHEV with a high capacity battery ensures maximum savings on petroleum for daily commutes. For a fixed test driving profile (e.g., the urban cycle) the EV range is determined by the battery capacity. The all-electric-range (AER) test quantifies the EV range of the battery within the usable SOC window recommended by the battery manufacturer. The EV operation of a vehicle also represents the maximum battery usage and is a

good indicator of the maximum temperature rise that the battery would undergo during vehicle operation. We are investigating the change in EV range and change in temperature rise for a lithium-ion battery as a function of change in vehicle mass. This paper presents AER results for the JCS-VL41M battery for three vehicle classes. The JCS-VL41M battery is a 41Ah lithium-ion battery designed for PHEV applications.

After reaching a certain low state of charge, the PHEV would operate as a charge-sustaining (CS) hybrid. Simulation studies have predicted that operation of the vehicle in the CD mode until the end of the trip (no CS operation) would provide the maximum benefits for petroleum displacement [1,2]. Practical use of such control strategies is still not possible because the distance covered on a daily trip is not known. Hence, one can assume that the vehicle would operate in a predefined EV or CD mode until a low SOC is reached, and then continue in the CS mode.

The NiMH batteries of the present-day CS hybrids are operated in a small window around 50% SOC. These batteries offer an optimum balance of charge-discharge efficiencies at around 50% SOC. Plug-in hybrids, on the other hand, are expected to operate at much low states of charge when in the CS mode (for example, 30% SOC). Operation at a low state of charge (lower than 50%) increases the EV or CD range of the vehicle and thus increases the petroleum displacement. The battery manufacturer sets the lower SOC operation limit for the battery based on life considerations. It is also important, from a vehicle perspective, to determine the sensitivity of fuel economy to operation at different SOC. This paper quantifies the effect on vehicle fuel economy of operating the VL41M battery at low SOC.

2. Battery HIL

Figure 1 shows a block diagram of the setup for the battery hardware-in-the-loop (HIL) test. A real battery is connected to a virtual vehicle through a high-voltage DC power supply. The virtual vehicle model and controller are simulated by means of Matlab/Simulink using Argonne's vehicle systems modeling software – Powertrain System Analysis Toolkit or PSAT [3].

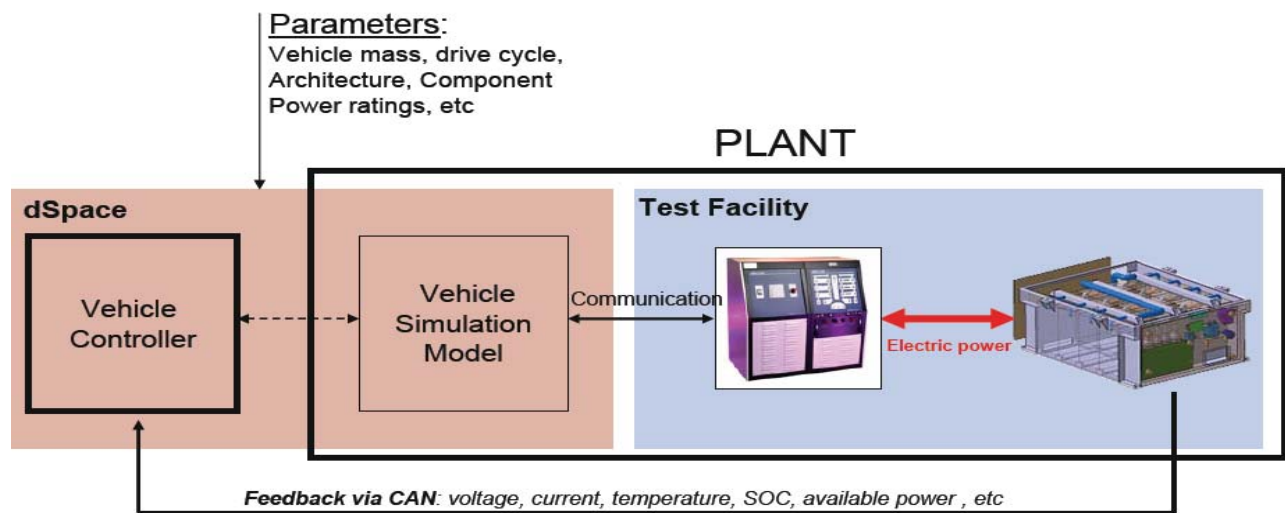


Figure 1: Battery HIL block diagram

The virtual vehicle and controller make it possible to have complete flexibility on vehicle configuration, vehicle parameters, and the energy management strategy and its parameters [4]. The battery HIL test also provides the advantage inherent in all HIL experiments: for a fixed vehicle and vehicle energy

management, any changes observed in the results are certain to have originated from the real battery. The virtual vehicle guarantees that there is no cycle-to-cycle or test-to-test variation on the vehicle level. The battery HIL test is hence an ideal tool for system-level evaluation of batteries [5,6] or electrical energy storage systems in general [7].

The PSAT vehicle model was incorporated into an HIL environment using PSAT-PRO [8], PSAT's companion for HIL. In PSAT-PRO, the battery model is removed and replaced by a controller area network (CAN) bus and other input/output equipment to communicate to the real battery. In addition, certain safety features are introduced into the vehicle model to enable the vehicle to react sensibly in case of a battery warning /fault. In PSAT-PRO, the PSAT control strategy is tuned for real hardware or can be completely changed on the basis of the needs of the experiment. The PSAT-PRO model, using the high-voltage DC power supply, sinks and sources power from the battery as if it were in a real vehicle. Battery voltage, temperature, estimated SOC, etc, are used by the vehicle controller as feedback to its energy management strategy, as in a real vehicle. The virtual vehicle is subjected to standard dynamometer cycles. The battery can be placed in a thermal chamber and operated at different ambient temperatures. The PSAT-PRO model is downloaded into a dSPACE controller to run in real time. Figure 2 shows the battery HIL setup. The battery in the picture is not in the thermal chamber but is cooled by process water at 20°C. Table 1 provides specifications for the VL41M battery [9].

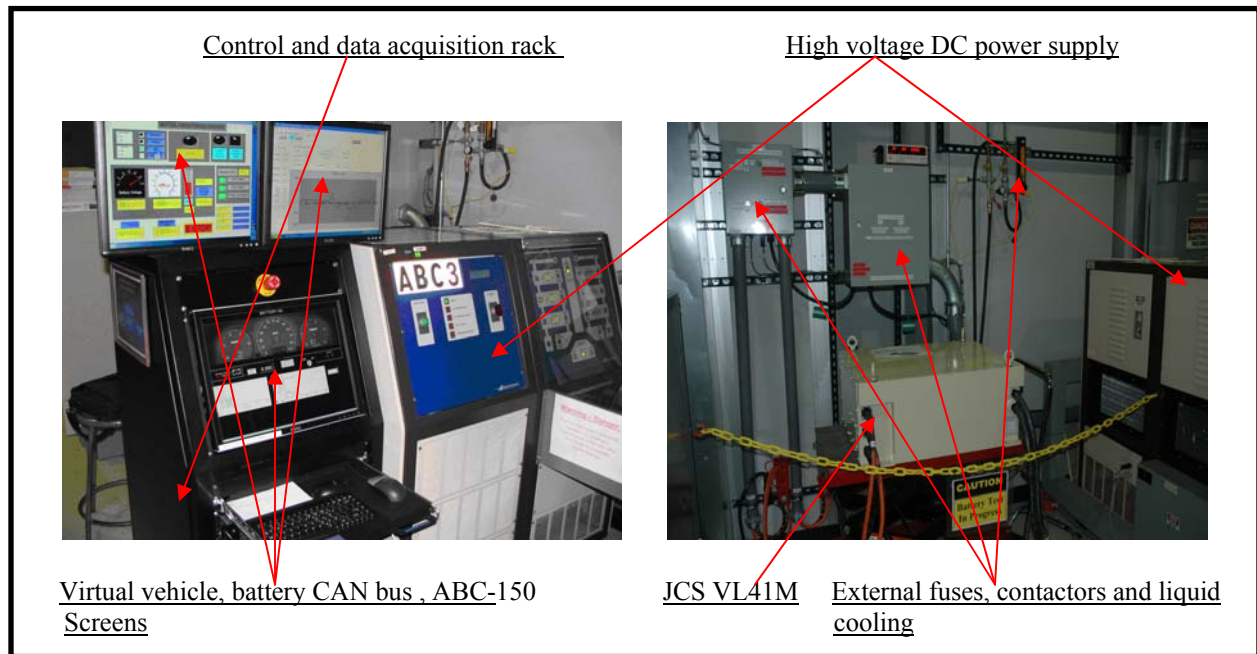


Figure 2: Battery HIL setup

Table 1: VL41M specifications (liquid cooled to ambient temperature)

Battery Capacity	41 Ah at C/3 rate
Battery Nominal Voltage	260 V
Peak Power	60 kW at 50 % SOC for 30 seconds

3. All-electric-range (AER) test

3.1 Experimental design

Our AER tests on the VL41M used pre-transmission parallel vehicles of three classes – midsize, crossover, and sport utility vehicle (SUV). For each class of vehicle, the battery was charged overnight to a high state of charge, close to 90%. The battery was then allowed to stabilize and cool to ambient temperature (20°C). The next day, the virtual vehicle was subjected to electric-only operation from an initial SOC of approximately 90% until the battery capacity was depleted by 24 Ah. For the EV operation across the three vehicle classes, the following were determined:

1. Distance covered in EV mode (miles)
2. Energy consumption per mile (Wh/mile)
3. Total battery energy consumption over the EV range (kWh)
4. Battery module temperature rise

3.2 Results

Table 2 provides the main results for the AER test on the VL41M. The first column gives the masses for the three vehicle classes. The initial battery temperature at the start of the test for the three vehicles was 21°C. Figure 3 graphs the rise in battery temperature over the EV test mode for the vehicles along with the drive cycle. The vertical blue, green, and red lines represent the end of the EV mode for the SUV, crossover, and the midsize vehicles, respectively.

Table 2: All-electric-range results for the VL41M

Vehicle Class ^a	Battery Ah depleted in the AER test	All electric range (miles)	Wh/mile	Rise in battery temperature over initial (°C)	Energy Consumed (kWh)
Midsize (1665 kg, 3663 lb)	24	21	277.01	6	5.3
Crossover (1845 kg, 4059 lb)	24	17.42	325.61	9	5.28
SUV (2049 kg, 4508 lb)	24	15.87	359.54	9	5.25

a. Vehicle mass given in parentheses.

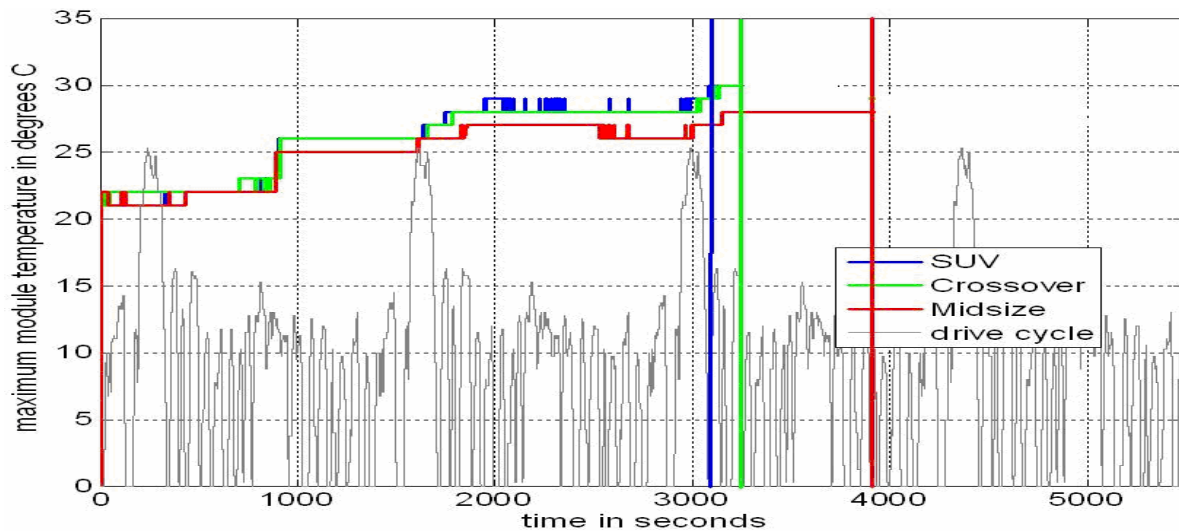


Figure 3: Rise in battery module temperature for the AER test

4. Charge-sustaining operation of VL41M

4.1 Vehicle information and energy management strategy

Table 3 provides information on the virtual vehicle used for the charge-sustaining tests.

Table 3: Specifications of the virtual vehicle for CS tests

Vehicle Configuration, Vehicle class	Pre-transmission parallel, SUV
Vehicle Mass	2045 kg
Vehicle Battery	JCS SAFT -VL41M

Engine	2.2 L, 106 kW peak power
Transmission	Five speed manual
Vehicle Coefficient of Drag, Frontal Area	0.41, 2.88 m ²

The energy management strategy in the charge-sustaining mode used for the battery HIL was developed by using PSAT for plug-in hybrid vehicles. Figure 4 represents the energy management strategy. The state of charge in the charge-sustaining mode is regulated by a proportional integral (PI) controller. Based on the actual SOC feedback from the battery, the PI asks for either positive or negative power to regulate the SOC. If the summation of the PI power demand and the instantaneous power demand at the wheels is more than 12.5 kW, the engine turns ON and supplies the power needed at the wheels and the power needed to maintain SOC. The engine remains ON for a certain minimum amount of time and turns OFF as soon as the power demand is lower than 3 kW. The SOC PI controller and the threshold for engine turn ON were tuned in PSAT-PRO to achieve a charge-balanced condition in the charge-sustaining mode.

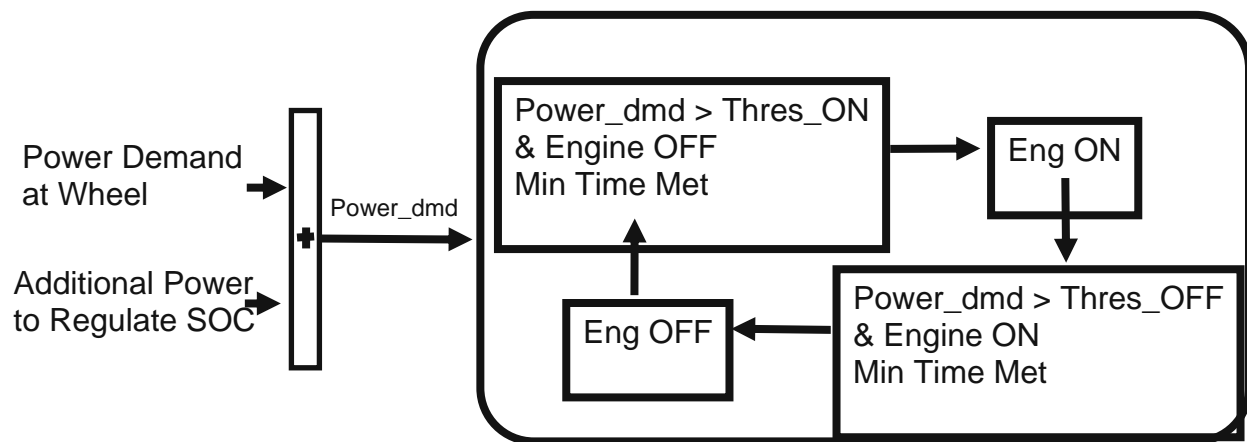


Figure 4: Energy management in charge sustaining mode of operation

Power_dmd: power demand at wheel and additional power to regulate SOC
 Thres_ON: minimum power required to turn the engine ON – 12.5 kW
 Thres_OFF: power required to turn the engine OFF – 3 kW

As can be deduced from Fig. 4, the battery power demand in the charge-sustaining mode depends only on the relative difference between the actual and target SOC, not the absolute SOC. Therefore, the average positive and negative battery power demand is the same for any target SOC between 40% and 20%.

4.2 Experimental design for charge-sustaining mode

As stated in the introduction, the lower SOC for the battery is based on the effect on battery life of operation at different SOC. The effect of the increase of resistance on vehicle fuel economy has not been previously quantified.

4.2.1 Six consecutive urban cycles – EV mode from 90% to a low SOC (Set 1)

This study is focused on the battery performance under charge-sustaining operations at different SOC. A PHEV is expected to operate in the charge-sustaining mode at low SOC only after having been through an EV or a CD mode. Thus, battery conditions for a charge-sustaining-only test are truly representative of battery performance in an actual vehicle only if each test is started with an EV mode at a high state of

charge, and the battery is allowed to discharge to a low state of charge after which the vehicle would be switched to charge-sustaining operation. The charge-sustaining part is used for analysis and comparison.

To test the battery performance in the charge-sustaining mode, the virtual vehicle was subjected to 6 consecutive cycles of the Urban Dynamometer Driving Schedule (UDDS). Before the start of the test, the battery was charged to a high state of charge (around 90%) and allowed to rest overnight. The vehicle was run in the EV mode until a pre-determined low state of charge was reached (e.g., 30%), and the vehicle then continued in the charge-sustaining mode until the end of the 6 urban cycles. Figure 5 plots the state of charge and vehicle speed for the EV and CS modes over the 6 consecutive urban cycles. The initial battery and coolant temperature for each set of 6 urban cycles is 20°C. This test is repeated for charge-sustaining operation from 20% to 35% SOC at an interval of 5% SOC.

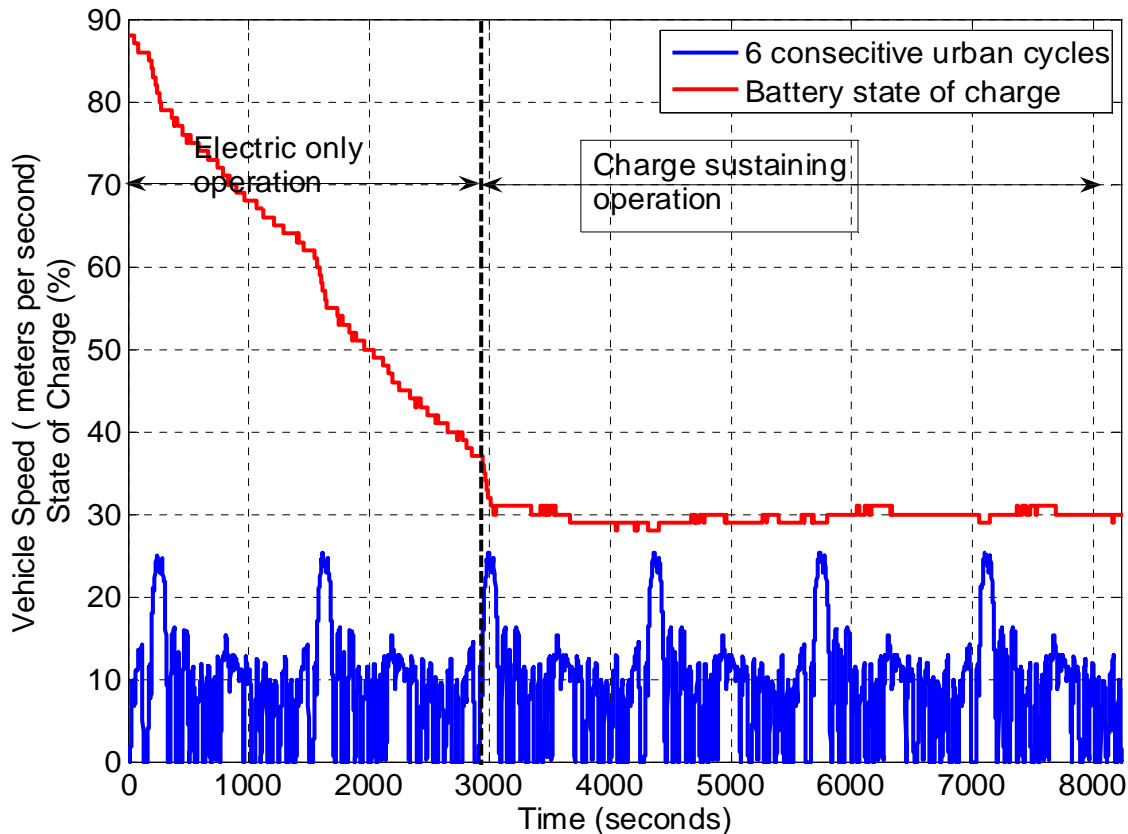


Figure 5: State of charge and vehicle speed for electric-only and charge-sustaining modes over 6 consecutive urban cycles

4.2.2 Three consecutive urban cycles at low SOC (Set 2)

The battery, when charge sustaining at 20% SOC, is subjected to a much longer EV range as compared to when charge sustaining is at 35% SOC. The battery modules are hence significantly higher in temperature when charge sustaining at 20% as compared to 35%. To isolate the effect of temperature on the charge-sustaining operation, another set of tests was conducted.

In these tests, the battery was allowed to rest at a low state of charge (e.g., 30%) overnight. The next day, the battery was subjected to 3 consecutive urban cycles in the charge-sustaining mode at that low state of charge. This test was repeated for other low states of charge (20 to 35% SOC with a step of 5% SOC), with one test at a particular SOC per day. Figure 6 shows the battery operation over 3 consecutive urban cycles in charge-sustaining mode.

4.2.3 Calculation of battery efficiency for Sets 1 and 2

For Set 1 and Set 2, the battery efficiency in the charge-sustaining mode was calculated over a period in which the battery Ah balanced out (Figure 6).

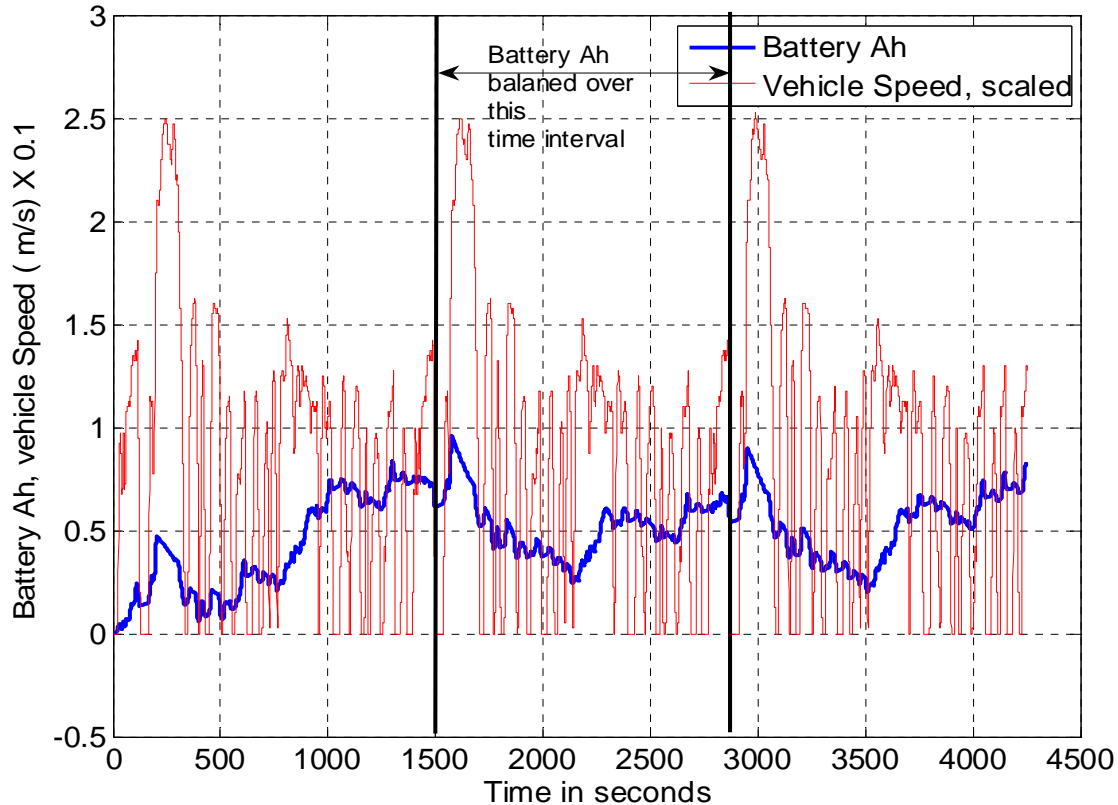


Figure 6: Battery operation over three consecutive urban cycles (Set 2). Battery efficiency for Set 1 and 2 is calculated over a section in which the battery Ah exactly balanced out.

The battery efficiency over a charge (Ah)-balanced region is the ratio of battery discharge energy (energy used for traction) to the battery charge energy (energy into the battery through regenerative braking and engine charging of the battery).

4.3 Results and Observations

Battery efficiency in the charge-sustaining mode and fuel economy were calculated for charge-sustaining operation at 35%, 30%, 25%, and 20% SOC. Battery root-mean-square (RMS) current and battery module temperature for the CS mode were also recorded. Any change in battery performance is indicated by a decrease in battery efficiency. We also determined the effect of the change in battery efficiency on fuel economy.

4.3.1 Battery performance for Set 1

As stated earlier, the PHEV battery operation in the CS mode at a low state of charge is most likely to be used after an EV or a CD mode. Figure 7 shows the battery efficiency (dark blue) and estimated fuel economy (purple) as a function of state of charge in the charge-sustaining mode after an electric-only discharge of the battery from 90% SOC to the target low state of charge.

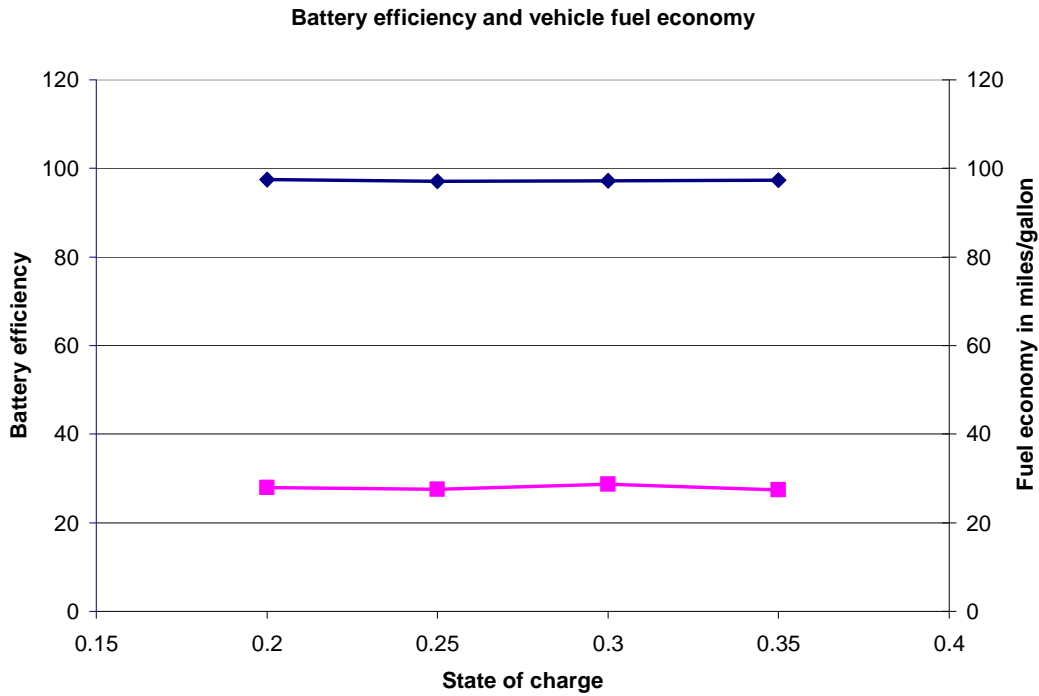


Figure 7: Battery efficiency and estimated vehicle fuel economy in charge-sustaining mode after an electric-only operation from 90% SOC to target SOC

The RMS current in the charge-sustaining mode is approximately 22 A. This current increases slightly as the target SOC for CS operation decreases from 35% to 20% SOC, since the battery operates at lower voltages.

Figure 7 indicates that battery efficiency is practically constant over the different states of charge (around 97%). Naturally, the fuel economy is also the same (around 27.5 mpg).

For all the target SOC in the charge-sustaining mode, the vehicle was operated in EV mode from a high state of charge (~90%) until the target SOC was reached. The vehicle energy management system then shifted to a charge-sustaining mode. Hence, the lower the target SOC for the charge-sustaining mode, the greater the distance covered by the vehicle in EV mode, potentially increasing the petroleum displacement. Longer operation in the EV mode also increases the battery module temperature.

Table 4: Electric-only miles and increase in module temperature for different target SOC

Target SOC for CS operation	Δ SOC	Electric range in miles	Final module temperature in °C (rise in temperature in °C)
0.35	0.54	15.99	29 (8)
0.30	0.58	16.74	30 (9)
0.25	0.62	17.9	31 (10)
0.20	0.67	19.51	32 (11)

Table 4 shows the electric-only miles covered by the PHEV for different target SOC in the charge-sustaining mode, along with the temperature rise in the battery modules. It is extremely difficult to start the experiment at a state of charge of exactly 90%. Therefore, the initial SOC varies slightly. Column 2 of the table shows the Δ SOC (initial high SOC – target SOC) for the different target SOC in the charge-

sustaining mode. Column 4 indicates the rise in module temperature of the hottest module, when the target SOC for CS mode was reached. The initial module temperature for all the tests was 21°C. The module temperature information is transferred to the vehicle control system by the battery management controller over CAN. The resolution of the temperature information is 1°C.

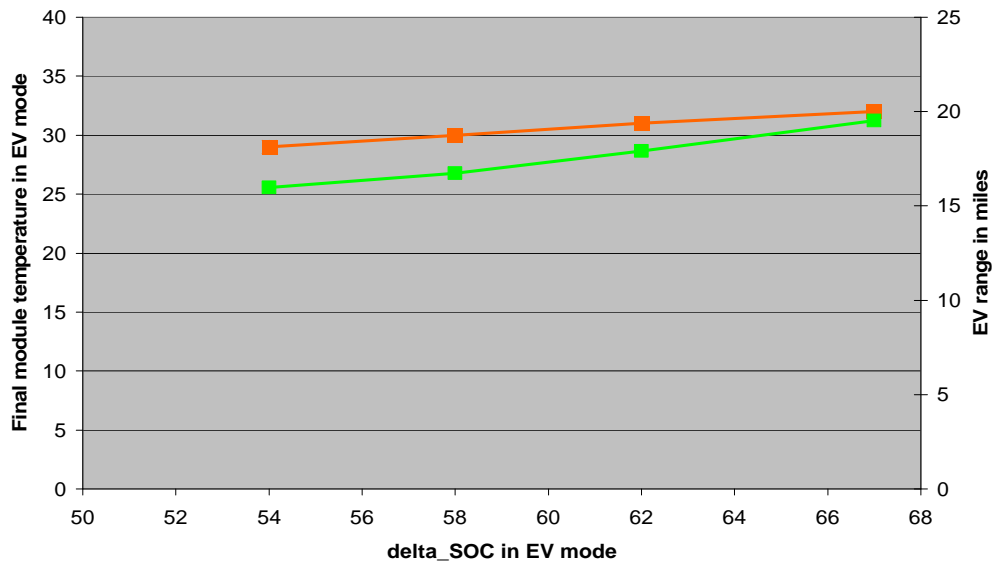


Figure 8: Battery module temperature at the end of the EV range and corresponding increase in the EV range

Figure 8 indicates that the EV range and final module temperature show a linear increase with Δ SOC. The RMS current for the testing regime is approximately 22 A.

4.3.2 Battery performance for Set 2

As indicated earlier, it is desirable to compare the results above to charge-sustaining performance results without the temperature rise caused by an EV mode. The battery performance in the charge-sustaining mode can then be compared for similar temperatures.

Figure 9 indicates no difference among battery efficiency results when comparing set 1 and set 2. The same holds for the fuel economy of the virtual vehicle. Table 5 compares the battery performance numerically; it can be seen that the battery efficiency is only very slightly lower in the charge-sustaining-only case. This slight decrease can be attributed to the lower temperature at which the battery operates in charge-sustaining-only operation.

Table 5: Battery efficiency comparison for Set 1 and Set 2

State of charge	Battery efficiency in charge-sustaining-only operation	Battery efficiency in charge sustaining following an EV mode
~0.35	96.92	97.36
~ 0.30	96.94	97.17
~ 0.25	96.98	97.13
~ 0.20	96.9	97.49

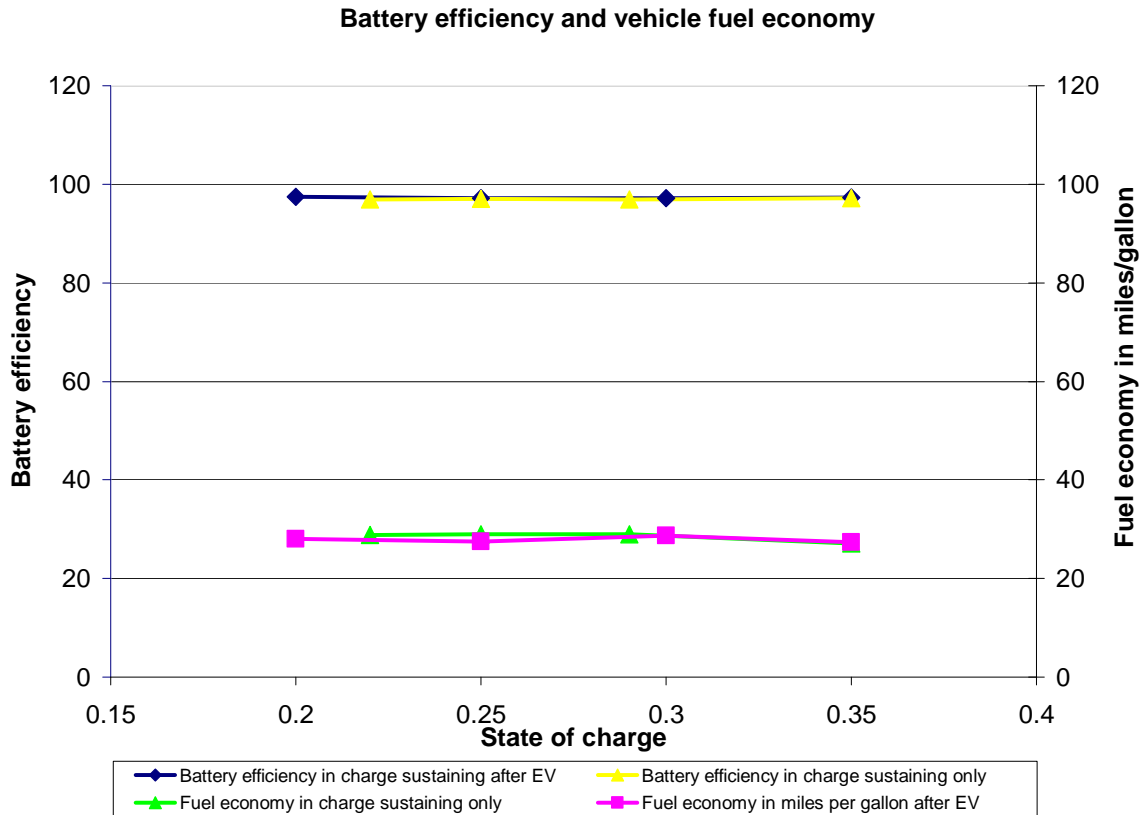


Figure 9: Comparison of battery performance in charge-sustaining operation with and without EV mode

The maximum temperature reached by the module is 25°C (i.e., a rise of 4°C above the initial temperature), which is lower than the maximum in the earlier tests by about 5°C. The RMS current in charge-sustaining mode is 22 A.

5. Conclusion

All-electric-range results for the VL41M battery are presented in this paper for three classes of vehicle. Charge-sustaining tests on the VL41M for an SUV-sized pre-transmission parallel vehicle show that operation at 20% to 35% SOC has no impact on vehicle fuel economy for an urban cycle. Thus, the lower limit set on SOC is a “life” decision, not a “performance” decision. The VL41M battery is capable of 400 A of discharge current for up to 10 seconds; the RMS current for the urban cycle based on the current control strategy is 22 A. It would be interesting to conduct the same test for cycles which demand higher RMS currents (e.g., US06) and observe if vehicle fuel economy is more sensitive to state of charge. The results stated above can also be compared to similar tests done at cold or hot battery (ambient) conditions, where the battery resistance is expected to be significantly different from the resistance at 20°C.

6. References

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