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Evaluation of cold temperature performance of the JCS-VL41M PHEV battery using Battery HIL

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ABSTRACT

Plug-in hybrid electric vehicles (PHEVs) have been identified as an effective technology to displace petroleum by drawing significant off- board energy from the electrical grid. A plug-in vehicle uses a large capacity battery to operate in an electric-only or a blended mode of operation over a large SOC window (60-80% of total operational SOC) for maximum petroleum displacement. Some advanced chemistry batteries have show that low ambient (battery) temperature has a significant impact on the performance of a PHEV battery. This paper quantifies the impact of low ambient (battery) temperature on a PHEV electric range using Hardware-in-the-Loop (HIL) methods. Combining ultra capacitors with batteries could provide a solution to overcome PHEV battery performance limitations at low temperatures.

INTRODUCTION

High specific energy, energy density and good power density have made lithium-ion (Li-ion) technologies the preferred choice for PHEV batteries. The most significant challenges to the application of Li-ion technologies in vehicles are related to stability at high temperature, and safety, and battery performance at low temperature [1]. There is significant degradation in battery life at high temperatures. In current Li-ion batteries, over temperature, over charge and high temperature issues are largely addressed by incorporation of management circuits into batteries, which maintain the battery within a safe temperature and SOC envelope by interacting with the vehicle energy management [2],[3]. Protective devices are employed to prevent venting under abusive conditions [4]. Li-ion battery performance can decrease significantly at low temperatures, due to an increase in the internal resistance of the battery and inherent decrease in battery capacity. Previous work at Argonne National Lab on 'on-road' testing of charge sustaining hybrids at low temperatures [5] shows the power limitation of conventional hybrid batteries (NiMH) at low temperature, and the their impact on charge sustaining fuel economy. While several methods to externally heat the battery are possible, it is important to quantify the loss in battery performance and its impact on the PHEV 'all electric range' (AER) to serve as a baseline measurement.

At the Center for Transportation Research, Argonne National Lab, the performance of a JCS-VL41M (72 cell, 41ahr) Li-ion battery at low temperature, and its impact on a PHEV 'electric range' was quantified using Battery Hardware in the Loop. The loss in electric range can be attributed to increased internal battery resistance, restricted regen power, limited propulsion power at low temperatures, and decreased battery capacity. This paper compares these three modes of loss in AER range. Impact of aggressive driving (a more aggressive drive cycle) is also considered.

Combining Ultra capacitors with a PHEV battery can overcome some of the obstacles facing the application of Li-ion batteries in PHEVs. This paper also discusses 'active coupling' of these elements with robust controls to maximize energy storage system performance at low temperature.

BATTERY HARDWARE IN THE LOOP

EXPERIMENT SET-UP - Figure 1 shows a block diagram of the setup for the battery hardware-in-the-loop (HIL) test. A physical battery is connected to a virtual vehicle thorough a high-voltage DC power supply.

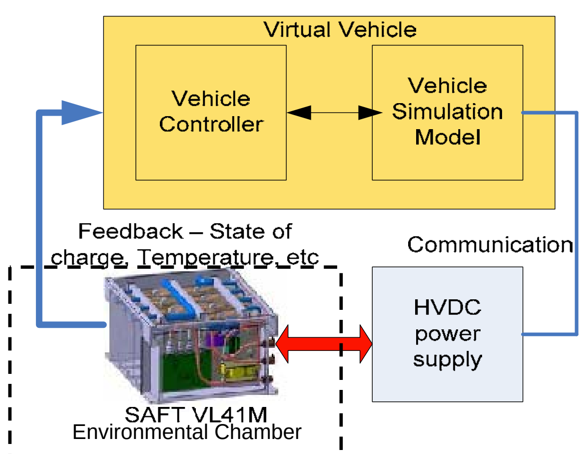

Fig 1.Block diagram of the Battery HIL test

The virtual vehicle model and controller are simulated by means of Matlab/Simulink using Argonne's vehicle systems modeling software – Power train System Analysis Toolkit (PSAT) [6]. The virtual vehicle subjects the battery to charge and discharge power profiles as if the battery were in a real PHEV. The high voltage DC power supply is able to sink and source power to and from the battery. Thus, the battery is 'exercised' as if it were in a real vehicle. CAN bus signals from the battery (state of charge, temperature etc) are fed back to the vehicle controller in real time, and used by the vehicle controller for energy management, as in a real vehicle.

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. 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 or electrical energy storage systems in general [7]. Figure 2 shows the Battery HIL set-up at Argonne.

Fig 2 Battery HIL control and data acquisition rack, and high voltage DC power supply JCS VL41M with coolant, power and control connections

BATTERY, VIRTUAL VEHICLE INFORMATION – As mentioned above, the battery used for this experiment is the liquid cooled, 41 Ah, JCS – VL41M. Table 1 provides some battery information at 20 degrees C temperature.

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

Battery Capacity	41 Ah at C/3 rate
Battery Nominal Voltage	260 V
Peak Power (discharge)	60 kW for 30 sec

Table 2: Specifications of the virtual vehicle

Vehicle Configuration, Vehicle class	Pre-transmission parallel, SUV
Vehicle Mass	2049 kg
Vehicle Battery	JCS SAFT -VL41M
Transmission	Five speed manual
Vehicle Coefficient of Drag, Frontal Area	0.41, 2.88 m^2

DESIGN OF EXPERIMENT (PART 1)

The virtual vehicle was subjected to EV operation on consecutive urban (UDDS) cycles, from an initial battery SOC of 90%, until the battery SOC decreased to 30% (SOC swing of 60%). To quantify the impact of temperature on the EV range of the vehicle, this test was repeated for three different battery module temperatures at the start of the test: 20°C, 0°C and -7°C. To protect battery life, the Battery Management Controller (BMC) restricts battery discharge and charge power below a temperature of 10°C. This battery usage restriction increases with decrease in temperature. Hence, EV operation on the urban cycle for the virtual vehicle mentioned above is not possible below -7°C.

These were the initial temperatures of the coldest module of the battery. Other modules were within 5°C of this coldest module. This liquid cooled battery was cooled down by simply circulating coolant from a portable liquid chiller (using 50-50 mix of glycol and water) at the target low temperature before the start of the test.

For the battery operation in a vehicle at -7°C and 0°C, a quick warm-up of the battery is desirable to eliminate temperature related battery power restrictions. Hence, for the -7°C and 0°C cases, external cooling was removed when the battery cycle testing started. For the initial temperature 20°C case there are no restrictions on the battery charge or discharge power. The battery user's manual suggests limiting battery temperature below 40°C for optimum battery life. To prevent the battery temperature from reaching this limit during the EV operation at an initial temperature of 20°C, coolant was circulated through the battery during the test.

The module temperature and SOC are communicated to the virtual vehicle by the Battery Management Controller (BMC) via CAN. The resolution on SOC is 1%. Module temperature resolution is 1°C.

To emulate a cold battery, the VL41M was cooled down to low temperatures (-7 and 0 degrees C) respectively, by circulating coolant at low temperatures through the battery. The battery cells are surrounded by the coolant water jacket, and hence the cells are only exposed to the cold temperature of the coolant water/bladder and not the normal ambient temperature of the lab in which the

HIL test stand/battery is situated. The VL41M battery, being a prototype for test bench applications, has a roughly quarter inch thick metal case, which houses the modules and the coolant loop, and the Battery Management System (BMS) and other safety and monitoring devices. Because of this design of the battery, and the fact that the battery is surrounded by the coolant jacket, it can be assumed that the impact of the external ambient temperature on the cells would be negligible as compared to the impact of the temperature of the coolant water jacket surrounding the cells. Also, it can be safely assumed that the impact of external ambient temperature, in heating up the battery, would be negligible as compared to the impact of the heat generated by the battery itself.

RESULTS (PART1)

Figure 3 shows the plot of SOC versus time for the three initial temperature conditions. As expected, the battery discharges quicker at lower temperatures, resulting in a lower EV range.

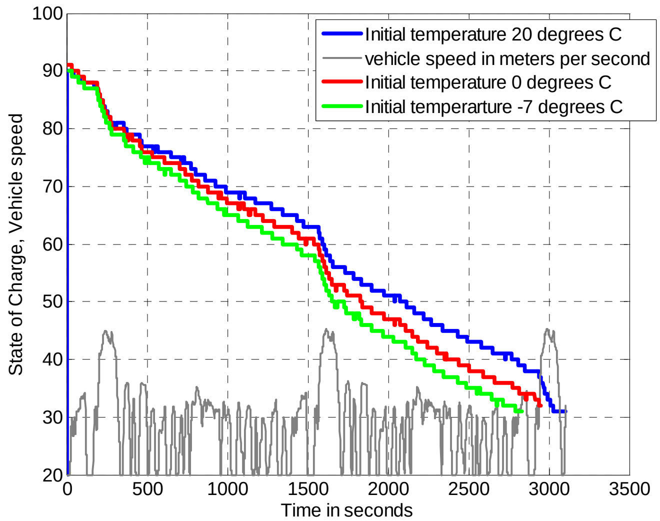

Fig 3. Drop in state of charge for the three initial temperatures over consecutive urban cycles.

Table 3 shows a decrease in AER for the 3 different initial temperatures. It can be observed that this reduction in AER is linear with decrease in temperature.

Table 3: Decrease in AER with decrease in temperature

Initial Battery Temperature	All Electric range from 90% to 30% SOC on the UDDS	% drop in AER
20 degrees C	17.4 miles	0
0 degrees C	15.7	9%
-7 degrees C	15.0	13%

ANALYSIS (PART 1)

It is important to understand the reason behind this decrease in EV range of the vehicle with decrease in initial temperature. Decrease in AER with temperature is assumed to be is caused by decrease in the amount of energy delivered by the battery (Table 4). Energy delivered by the battery is calculated from battery terminal voltage and battery current.

Table 4 Decrease in kWh delivered by the battery with decrease in initial temperature

Initial Temperature	Battery kWH	ΔkWH
20	6.2	0
0	5.6	0.6
-7	5.5	0.7

This decrease in the energy delivered by the battery can be split into three contributing factors (equation 1):

1. Increased battery internal resistance with temperature.
2. Battery propulsion and regenerative (regen) power are restricted at low temperatures. (Figure 4). At -7°C the battery had barely enough propulsion power for a UDDS cycle. As regen power is restricted more and more with decreasing temperature, less regen energy is captured at low temperatures.
3. Other losses: There is inherent decrease in battery capacity with temperature due to reduction in chemical activity. This loss of capacity cannot be directly calculated from the measurements taken during the experiment. As such, these losses are combined as 'other losses' and are calculated from the measurable quantities, i.e. resistance losses and regen energy losses (equation 2).

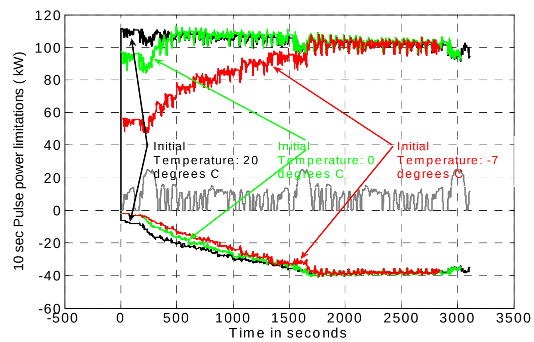

Fig 4. Propulsion and regen pulse power restrictions (red; -7°C initial temp., green; 0°C initial temp., black; 20°C initial temp.).

$$\Delta kWH = \Delta I^2 Rt + \Delta \text{Regen Energy} + \Delta \text{Other Losses}..(1)$$

$$\Delta \text{Other Losses} = \Delta kWH - (\Delta I^2 Rt + \Delta \text{Regen Energy})..(2)$$

Where

ΔkWH = difference in kWh delivered by the battery at 20°C case and colder (-7°C, 0°C) case.

$\Delta I^2 Rt$ = Difference (increase) in the heat energy lost due to increase in the internal resistance with temperature.

$\Delta \text{Regen Energy}$ = Difference in regen energy captured at 20°C case and regen energy captured at lower temperatures (-7°C, 0°C) case.

Table 5 (a) shows the $\Delta I^2 Rt$ calculation for the initial temp of -7°C and 0°C case, when compared to 20°C case. The internal resistance at different SOCs was estimated from the V-I curve at that particular SOC.

Table 5(a): $\Delta I^2 Rt$ between 20°C, 0°C and -7°C cases

	Resistance losses at 20°C = 279 Wh
Resistance losses for the 0°C initial temp case: 320 Wh	$\Delta I^2 Rt$ between 20°C and 0°C 320 -279 = 41 Wh
Resistance losses for the -7°C initial temp case: 364 Wh	$\Delta I^2 Rt$ between 20°C and -7°C 364-279 = 85 Wh

Table 5(b): $\Delta \text{Regen Energy}$ for 20°C, 0°C and -7°C

	Regen energy captured at 20°C case = 938 Wh
Regen energy captured at Initial temp of 0°C 756 Wh	$\Delta \text{Regen Energy}$ between 20°C and 0°C case 938 -756 = 182 Wh
Regen energy captured at initial temp of -7°C 685 Wh	$\Delta \text{Regen Energy}$ between 20°C and -7°C case 938-685 = 253 Wh

Using equation (2), the 'other losses' can be calculated:

Table 5(c): $\Delta \text{Other Losses}$ between 20°C, 0°C and -7°C

	$\Delta \text{Other Losses}$
Initial temperature of 0°C	307 Wh
Initial temperature of -7°C	392 Wh

Distributing the loss in battery energy delivered to the vehicle into three categories, i.e. $\Delta \text{Regen Energy}$, $\Delta I^2 Rt$ and $\Delta \text{Other Losses}$, it is necessary to quantify the primary effect, i.e. which form of loss has the biggest impact on decrease in the EV range of the vehicle. Table 6 shows the difference in Regen, difference in resistance losses and difference in other losses between the 20°C, 0°C, -7°C as a percentage of the total difference in Wh delivered to the vehicle at 0°C, -7°C and 20°C.

Table 6: Contribution of each loss to the total reduction in Battery kWh to the vehicle

	ΔWh compared to Wh delivered at 20°C	ΔRegen as % of ΔWh	$\Delta I^2 Rt$ as % of ΔWh	ΔOther losses as % of ΔWh
Initial temp. of 0°C	530	34%	8%	58%
Initial temp. of -7°C	730	34%	12%	54%

OBSERVATIONS (PART 1)

1. A large part of the decrease in kWh delivered to the vehicle at low temperatures is due to the limitations on battery regen power. This decrease remains the same, as a percentage of the total decrease in kWh at the two cold temperatures. Restrictions in battery regen power are determined by the battery controller, largely to ensure battery life. This is a control parameter and not a physical parameter.

2. Battery resistance is higher at -7 degrees C as compared to 0 degrees C, which would explain the increase in $\Delta I^2 Rt$ losses (% of ΔWh) and even in absolute numbers.

DESIGN OF EXPERIMENT (PART 2)

It is important to determine the impact of aggressive driving on the distribution of decrease in battery kWH with temperature. Hence the same test above was repeated for 20°C and 0°C with a more aggressive cycle (UDDS X1.2 – Figure 5). Again, there was no circulation of chilled battery coolant for the 0°C case, while battery coolant was being circulated for the 20°C case.

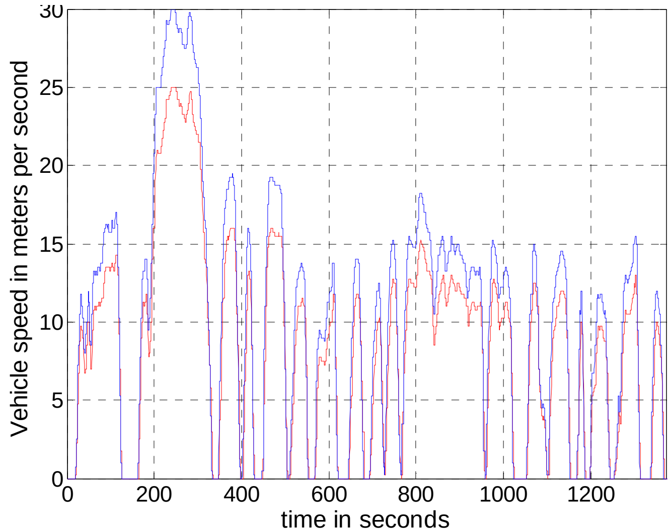

Fig 5. UDDS and UDDSX1.2

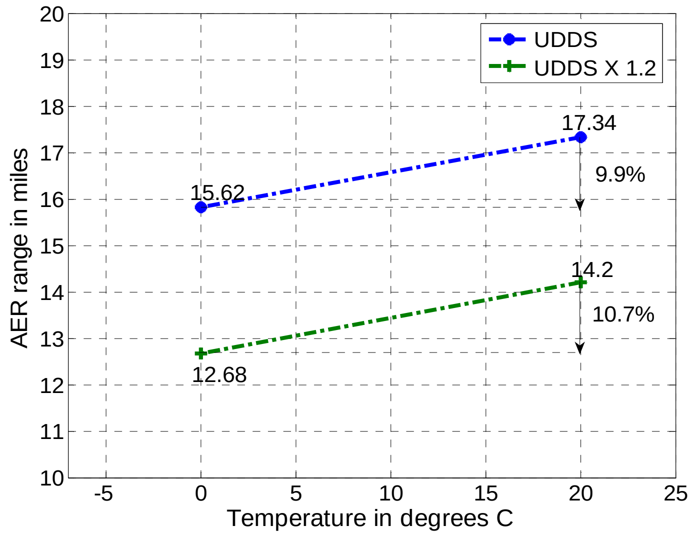

Fig 6: AER comparison between UDDS and UDDS X1.2 for 20°C, 0°C

Figure 6 compares the AER for UDDS and UDDSX1.2 for the initial temperatures of 20°C and 0°C.

ANALYSIS (PART 2)

As can be seen from Figure 6, for UDDS X 1.2, there is a 10.7% decrease in AER for an initial temperature of 0°C as compared to the 20°C initial temperature. When the battery energy delivered to the virtual vehicle is compared, it can be seen that the energy delivered to the vehicle is 600 Wh less in the 0°C initial temperature case, as compared to an initial temperature of 20°C. (ΔWh = 600). The contribution of each of the losses (increase in internal resistance, decrease in regen energy captured, and increase in other losses is stated in table 7 (similar to table 6 for the UDDS case).

To see if aggressive driving impacts the contribution of each of the losses toward the total loss in Wh, Table 7 above is compared to Table 6 results for 0°C.

Table 7: Contribution of each loss to the total reduction in Battery kWh to the vehicle

	ΔWh compared to Wh delivered at 20°C	ΔRegen as % of ΔWh	ΔI^2Rt as % of ΔWh	ΔOther Losses as % of ΔWh
UDDS	530	34%	8%	58%
UDDS X1.2	600	20.3%	22%	57.7%

Table 8: Contribution of each of the losses to total loss in Wh delivered to the vehicle by the battery – UDDS and UDDS X1.2

OBSERVATIONS (PART 2)

1. The contribution of ΔRegen Energy to reduction in battery Wh transferred to the vehicle is much lesser with aggressive driving. This can be attributed to a faster rise in battery temperature in the case of UDDS X1.2 (again, no cooling), which removes the temperature related restrictions on battery charge/discharge power.
2. With an increase in the aggressiveness of the cycle, there is an increase in the ΔI^2Rt losses of the battery.
3. The 'other losses' from the battery, which cannot be quantified by this experiment, remain roughly the same, as a percentage of the total losses. This may be because the faster rise in battery temperature negates any increase in percent of contribution of these losses.

SUMMARY

This paper has quantified the impact of temperature on the electric range of a PHEV, when evaluated in an HIL 'virtual vehicle'/physical electrical load environment. The loss in PHEV all electric operation range is due to reduction in total electrical energy delivered by the battery to the vehicle. This can be attributed to increased internal resistance, limitations in regen and propulsion power at low temperature, and other reasons for decrease in battery capacity. Contribution of each of the above mentioned factors to reduction in electrical energy delivered by the battery has been discussed.

Impact of aggressive driving on the contributions is assessed.

FUTURE WORK

This focus of this paper has been to give a baseline assessment in the loss in performance of a PHEV Li-ion battery in cold weather conditions. There are other Li-ion chemistries, aimed at the automotive market and near production, that claim to be immune to problems of cold weather operation (8).

As mentioned earlier in this paper, one of the options in PHEV energy storage systems is to actively heat the energy storage system components, presumably while charging from grid power. Researchers at ANL are planning on benchmarking such systems, and the net energy consumption to maintain the pack temperature in cold weather, versus other methods to handle this issue.

Figure 7, below, from a recent study (5), shows that in -12°C initial conditions, a Toyota Camry hybrid, with air cooled battery (1.4 kWhr NiMH) took ~50 minutes of operation to return to 20°C operation. This is far longer than the average commute. Studies are currently under way for a much larger (5kWhr Li-ion) energy storage system for a PHEV, in similar conditions. It is expected that pack temperature will rise much slower for a greater thermal mass associated with a larger battery.

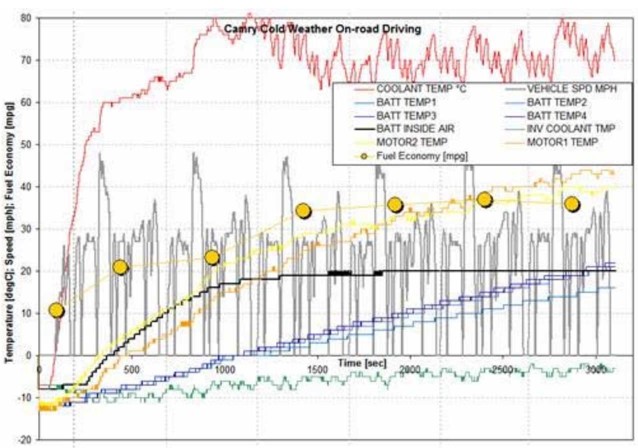

Figure 7- Cold Weather operation (-12°C) of an HEV Camry, with air cooled NiMH battery pack

Another option being explored at ANL is 'Active' coupling of ultra capacitors and batteries, to overcome low temperature performance issues. In this case, a series string of 108 ultracapacitors, 650F each, are placed in parallel with Li-ion battery pack to share the PHEV electrical load demands. The active combination means that the power electronics module 'actively' decouples load transients from the Li-ion battery such that the ultracapacitors handle peak loads, while the battery is subjected to averaged/low dynamic loads. Cost vs net benefit, as always, is one of the primary goals of this study. Figure 8 shows the capacitor array, ~22"W x 24"D x 3" high, and a physical photo of the ultracapacitors.

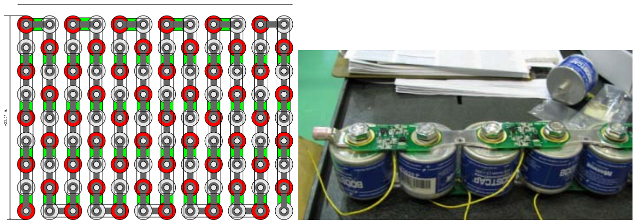

Figure 8- 650 Farad U-cap, 108 cell series string

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