P1.2 - Hybrid Electric Vehicle and Lithium Polymer NEV Testing

James Edward Francfort
Advanced Vehicle Testing Activity
Idaho National Laboratory
P.O. Box 1625, Idaho Falls, ID. 83415-3830
james.francfort@inl.gov

Abstract: *The U.S. Department of Energy's Advanced Vehicle Testing Activity tests hybrid electric, pure electric, and other advanced technology vehicles. As part of this testing, 28 hybrid electric vehicles (HEV) are being tested in fleet, dynamometer, and closed track environments. This paper discusses some of the HEV test results, with an emphasis on the battery performance of the HEVs. It also discusses the testing results for a small electric vehicle with a lithium polymer traction battery.*

Keywords: hybrid; neighborhood; electric; battery; fuel; economy; lithium; polymer; vehicle; testing.

Introduction

The U.S. Department of Energy's (DOE) Advanced Vehicle Testing Activity (AVTA) tests hybrid electric, pure electric, and other advanced technology vehicles to support the goal of providing benchmark data of emerging technologies for technology modeling, and research and development programs conducted by DOE and its industry partners. The AVTA is part of the DOE FreedomCAR & Vehicle Technologies Program. These testing activities are conducted by the Idaho National Laboratory and Electric Transportation Applications. This paper highlights the testing of hybrid electric vehicles (HEVs) and a small electric vehicle with a lithium polymer traction battery.

HEV Testing Activities

To date, the AVTA has accumulated 1.7 million test miles on 28 HEVs since August 2001. The HEVs and numbers of each model tested are: Generation (Gen) I Toyota Prius - 6, Honda Insight - 6, Gen I Honda Civic - 4, Honda Accord - 2, Gen II Toyota Prius - 2, 2 and 4-wheel drive (WD) Chevrolet Silverados - 1 each, 2 and 4-WD Ford Escapes - 1 each, Lexus RX 400h - 2, and Toyota Highlander - 2. The Silverado HEV uses a lead acid battery while the other HEV models all use nickel metal hydride batteries.

One of each HEV model is baseline performance tested, which includes dynamometer and closed-track testing for fuel economy and battery performance (Figure 1) with the air conditioning (AC) on and off. Baseline performance testing also characterizes the performance of other HEV attributes, including: maximum speed, acceleration, braking, and gradeability.

In fleet testing, at least two of each HEV model are operated for 160,000 miles within 36 months, during which maintenance and repair events, registration and insurance costs, and fuel economy (Figure 2) are recorded and used to compile life-cycle costs.[1] At the conclusion of 160,000 miles of fleet testing, the HEV fuel economies are retested, and the traction battery packs are tested. To date, two Insights, two Gen I Civics, and two Gen I Prius have completed end-of-life testing.

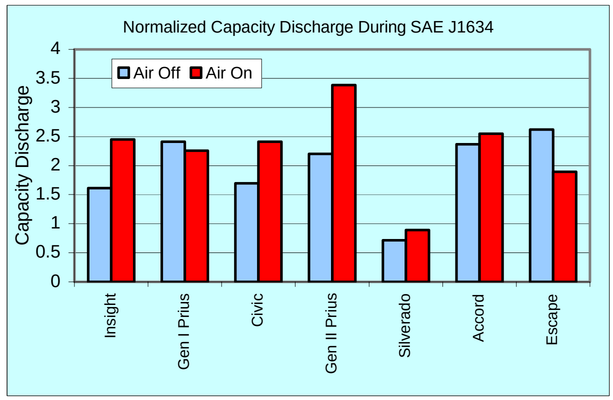

Figure 1. Normalized battery capacity test results obtained during dynamometer fuel economy testing on new HEVs per SAE J1634 with the AC on and off.

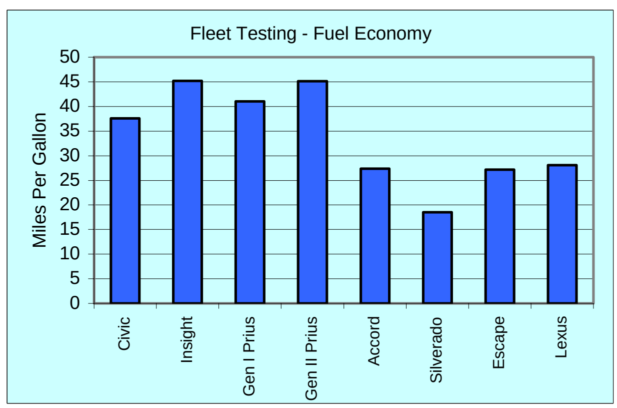

Figure 2. Baseline performance fuel economy HEV testing results.

End-of-Life HEV Battery Testing

During end-of-life testing (defined as after 160,000 fleet test miles), each HEV is retested for fuel economy (per SAE J1634) with the AC on and off. In addition, traction battery pack capacity and power tests were performed during end-of-life testing in accordance with the FreedomCAR Battery Test Manual For Power-Assist Hybrid Electric Vehicles.[2] The battery tests consist of a static capacity test with a low discharge rate and the Hybrid Pulse Power Characterization (HPPC) test with a short duration, high discharge rate, to simulate peak loading observed during the SAE J1634 driving cycle.

End-of-life HEV Battery Test Method. For the static capacity test, the battery pack for each end-of-life HEV was conditioned to a full state-of-charge (SOC) in accordance with the battery manufacturer's recommended charging procedures, terminating the charge after the pack voltage had reached its peak voltage and then dropped 10 milli-volts per cell. After the full charge and an 8-hour rest period to allow for cell stabilization, the battery pack was discharged at its C1 discharge rate (the current equal to the manufacturer's 1-hour nominal capacity rating). The battery pack was discharged until the average cell voltage across the battery pack was 1.00 volts per cell. The total ampere-hours (Ah) delivered by the battery pack were recorded, thus completing one charge/discharge cycle. This cycling procedure was repeated until the results of three consecutive cycles yielded an Ah discharge rate that did not vary more than 3% between three consecutive tests.

The HPPC testing was performed to determine the SOC at which the battery pack could no longer comply with the power demanded by the HEV motor controller during an SAE J1634 fuel economy drive cycle. To determine the parameters required to conduct the HPPC test (i.e., the magnitude of the charge and discharge pulse), the peak power demand from the SAE J1634 baseline performance testing for each new HEV model was examined.

From these data, the top 0.5% battery pack charge current data were averaged to provide a single charge current value. This charge current value was used to represent the magnitude of the charge pulse for HPPC testing. Similarly, the top 0.5% discharge current data were averaged to provide a single value used to establish the magnitude of the HPPC test discharge pulse.

With the magnitude of the charge and discharge pulse established, the battery pack was subjected to a single pulse discharge and single pulse charge at each percent SOC level, starting at 90% and decrementing at 10% SOC intervals until the battery pack voltage reached an average of 0.8 volts per cell. Between each test cycle, which consisted of one charge/discharge pulse at each percent SOC level, the battery pack was discharged at its C1 rate to reach the next 10% SOC interval. Upon reaching the termination criterion, the percent SOC and its equivalent Ah rating were recorded.

End-of-life HEV Battery Test Result. Because the initial traction battery pack capacity of each HEV was not determined when the HEV was new, the characterization results obtained from the end-of-life testing were compared to the nominal (manufacturer) rated battery capacity (Figure 3).

For static battery pack capacity testing, each end-of-life HEV demonstrated a reduced battery pack capacity. The two Civics demonstrated an average remaining battery pack capacity of 68.3%, the two Insights an average of 84.6% remaining, and the two Priuses an average of 39.2% remaining.[3]

All six of the HEV batteries tested were capable of absorbing the charge pulses without reaching the voltage limit placed on them, including the charge pulse at 90% SOC. Therefore, it is reasonable to conclude that the battery's ability to absorb energy had not degraded as a result of 160,000 miles of fleet testing.

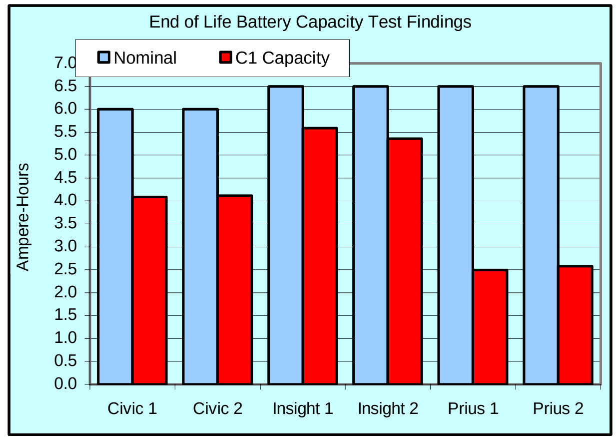

Figure 3 HEV battery pack capacity when new (nominal) and at end-of-life.

End-of-life HEV Fuel Economy Testing Results Versus the Onboard Display. During end-of-life fuel economy testing, the onboard computer generated fuel economy display was recorded and compared to the actual fuel economy results obtained when using the end-of-life coast down coefficients. For every case and vehicle tested, it was observed that the onboard vehicle computer displayed fuel economies higher than the actual measured SAE J1634 fuel economies (Table 1).

Table 1. End-of-life fuel economy results compared to the onboard computer reported fuel efficiency.

End-of-life Phase II Test HEV	Onboard computer fuel economy percentage above end-of-life testing
Civic 1 AC off	+21.7%
Civic 1 AC on	+21.0%
Insight 1 AC off	+11.0%
Insight 1 AC on	+11.7%
Prius 1 AC off	+15.7%
Prius 1 AC on	+14.7%

End-of-life HEV Battery Capacity per Mile. The increased demand on the HEV propulsion system can be demonstrated when battery capacity expended per mile during the end-of-life fuel economy testing is compared to the fuel economy tests when the HEVs were new. The data presented in Figure 4 were normalized for a cross-vehicle comparison by taking the overall energy output (in Ah) for the battery pack over the SAE J1634 test and dividing it by the nominal (manufacturer) battery capacity (in Ah). Dividing this battery value (energy output/nominal battery capacity) by the distance traveled during testing yielded a percent battery pack capacity usage value per mile, which was higher for all tests at end-of-life than when the HEVs were new. Phase-II refers to a second set of end-of-life dynamometer tests that used coast down coefficient inputs derived from coast down testing the HEVs at 160,000 miles instead of the coast down coefficients obtained when the HEVs were new.

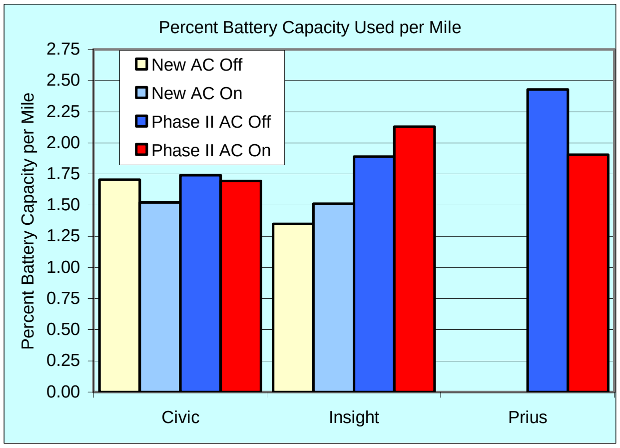

Figure 4. HEV battery-pack capacities used per mile when the HEVs were new and at end-of-life (160,000 miles). The new-Prius data was collected differently than the Insight and Civic. Therefore it is not presented for comparison to the end-of-life Prius data.

Other HEV Battery-Related Issues. When in fleet testing, the traction battery pack in a Honda Insight failed at 72,000 miles. The failure cause is not definitively known. However, it is believed that the battery control module failed first, and this caused the traction battery to be fully discharged. Both the traction battery pack and the battery control module were replaced by Honda under warranty.

Katech NEV / Kokam Lithium Polymer Testing

The AVTA received an Invita Neighborhood Electric Vehicle (NEV) from the Korea Automotive Technology Institute (KATECH) for baseline performance and battery testing according to the AVTA's NEVAmerica testing procedures.[4] As background, NEVs are four-wheeled vehicles defined by the National Highway Traffic Safety Administration as subject to Federal Motor Vehicle Safety Standard No. 500 (49 CFR 571.500). Per FMVSS 500, NEVs have top speeds between 20 and 25 mph and are defined technically as *low speed vehicles* (LSVs). LSVs are widely referred to as NEVs. The Invita was equipped with a Kokam Engineering lithium polymer battery, which was to be characterized as part of the baseline performance testing. However, problems with the vehicle resulted in a more limited testing regime.

Katech NEV Testing Results

On arrival, Cell 7 of the 18-cell lithium polymer battery pack was damaged. After replacing Cell 7, the vehicle was driven and charged to cycle the battery pack in preparation of baseline performance testing. It was discovered that the software in the onboard charger was not performing as intended and was terminating the charge sequence when any one of the cells reached a predetermined voltage, thus not allowing the lower voltage cells to equalize. Because the battery SOC was in the 80% range at the end of a charge sequence, Kokam advised that testing should begin despite the flawed charging algorithm. The Invita was constant speed range tested[5] to determine the official range of the vehicle.

Just over an hour into the constant speed range test, the voltages for Cells 2 and 16 began to fall more rapidly than the other cells, and by 34 miles Cell 2 had reached the Kokam specified 3.0-volt cutoff point; this range was considerably lower than expected. After charging and discharging the battery pack, it was determined that Cell 2 did not have the Ah capacity of the other cells and would not be able to maintain the vehicle load requirements during range testing. In addition, Cell 16 was found to be consistently undercharged when the onboard charger would terminate; it was always the lowest in voltage by up to 0.4 volts. A new offboard charger was used to successfully charge and equalize all 18 cells, and the vehicle was determined to be ready again for constant speed range testing. During preliminary range testing, however, Cell 2 proved to still lack capacity, so it was replaced.

During the official constant speed range test, the Invita was driven for 1 hour 47 minutes, consuming 91.3 Ah and 6.19 kilowatt-hours, while traveling a total of 47.9 miles. Cell 16 was the first cell to reach 3.0 volts, but the others were close behind; the cell's voltages remained fairly close during the entire test. When comparing the range attained to the range data provided by Kokam,[6] it appeared that the battery pack had either degraded or was not operating at full capacity. Therefore, it was decided to limit the vehicle testing to the above constant speed range test and the few tests already conducted, including acceleration time to 20 mph on a level grade (5 seconds), maximum speed attainable on a level grade (25 mph), and maximum grade attainable from a standing start at gross vehicle weight rating (24%).

Kokum Charger Testing Results

The Figure 5 data plots are from the charging cycles performed to determine the performance of the onboard charger. The data show that the charger was not equalizing the pack. At the beginning of the charge, Cell 1 was reported as fully charged, but it was only at 4.18 volts. The charger terminated when Cell 17 reached 4.34 volts.

The external charger from Kokam successfully charged every cell to 4.25 volts, with only one anomaly (Figure 6). Charging began at 8:50 a.m. and shortly after 9 a.m. Cell 1 faulted because of a communications error in the charger. It was not until 10:42 a.m. that the charger was reset so that Cell 1 could begin charging again.

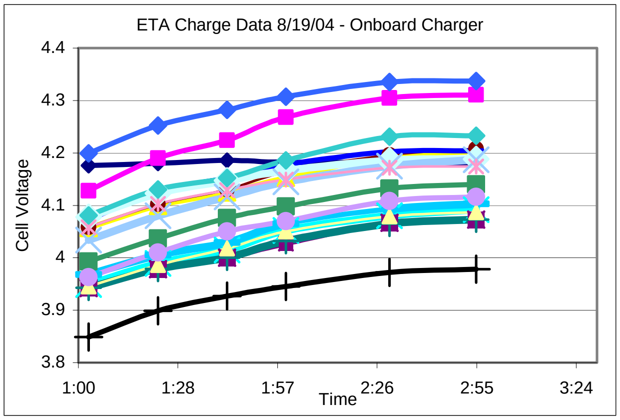

Figure 5. Onboard Kokam charger data plots.

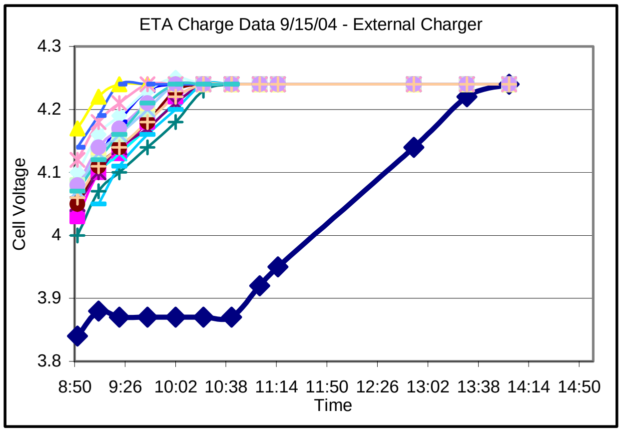

Figure 6. Offboard charger data plot with Cell 1 fault.

Kokam Lithium Polymer Battery Test Plan

Characterization testing of the lithium polymer battery began with three procedures: a C/3 energy capacity test, a dynamic stress test, and a peak power test. The C/3 energy capacity test was to determine the energy capacity of the pack by discharging it at 33 amps (C/3) from full charge (4.25 volts) to empty (2.7 volts per cell), repeating the process until the energy taken out was repeatable within 2%. Because the battery pack needed to be balanced and equalized, a computer-driven battery cycler was programmed to charge the pack until it reached 73.8 volts, then the Kokam offboard charger was connected to the cells to fully charge them to 4.25 volts. Because the Kokam charger could only charge 13 cells at a time, Cells 1–7 and 10–15 were charged first, then the remaining five cells were charged. After all the cells were fully charged, the battery cycler discharged the pack at 33.33 amps until the pack voltage dropped to 48.6 volts, at which point the battery cycler began charging the pack again for the next iteration. Once the energy removed was within 2% of the last two iterations, the test would be deemed complete.

The dynamic stress test was to follow the C/3 test. This test discharges the battery pack at varying power levels while monitoring the pack voltage, current, and temperature to determine how the pack responds to the changing load. The charging sequence of the test is identical to that of the C/3 energy capacity test, but only one cycle was called for by the test plan.

The peak power test was to discharge the pack at 425 amps for 30-second pulses and then reduce the discharge rate to 111 amps until 10% of the energy had been removed. The battery cycler was then to continue this process until either 100% of the pack's energy had been removed or the pack's voltage dropped below 48.6 volts. The charging sequence of the test is identical to that of the dynamic stress test.

Kokam Lithium Polymer Battery Test Results

The testing was stopped during the C/3 energy capacity test because the battery pack could not withstand cycling without cell failures. After the third discharge/charge sequence was completed on the battery cycler, it was discovered that Cell 6 had failed. Its voltage read 0.5 volts after the charge. The cell was replaced, and the testing sequence was started over. After the second discharge/charge sequence was complete, it was discovered that Cell 1 had failed, with its voltage reading 0.2 volts. At that point it was decided to stop all pack testing.

During the discharge cycles, the battery pack supplied 102.21, 94.34, and 96.05 Ah consecutively before Cell 6 failed. After replacing Cell 6, the battery pack supplied 98.34 and 98.11 Ah before Cell 1 failed. The battery testing was terminated after this failure.

References

1. HEV testing results reports and fact sheets can be found at: http://avt.inl.gov/hev.shtml

2. *FreedomCAR Battery Test Manual For Power-Assist Hybrid Electric Vehicles*. DOE/ID-11069. Idaho National Engineering and Environmental Laboratory. Draft. April 2003.

3. H*ybrid Electric Vehicle End-of-Life Testing On Honda Insights, Honda Gen I Civics and Toyota Gen I Priuses*. INL/EXT-06-01262. Idaho National Laboratory. Idaho Falls, ID. February 2006.

4. See http://avt.inl.gov/nev.shtml for a complete list of NEV testing specifications and procedures.

5. *Electric Vehicle Constant Speed Range test*. Electric Transportation Applications. December 2004.

6. *KATECH (Lithium Polymer) 4-Passenger NEV Range and Battery Testing Report*. INL/EXT-05-00479. Idaho National Laboratory. July 2005.