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2010 Honda Civic Hybrid UltraBattery Conversion 5577 - Hybrid Electric Vehicle Battery Test Results

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July 2013

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Abstract

The U.S. Department of Energy Advanced Vehicle Testing Activity Program consists of vehicle, battery, and infrastructure testing on advanced technology related to transportation. The activity includes tests on hybrid electric vehicles (HEVs), including testing the HEV batteries when both the vehicles and batteries are new and at the conclusion of on-road fleet testing. This report documents battery testing performed for the 2010 Honda Civic HEV UltraBattery Conversion (VIN JHMFA3F24AS005577). Battery testing was performed by the Electric Transportation Engineering Corporation dba ECOtality North America. The Idaho National Laboratory and ECOtality North America collaborate on the AVTA for the Vehicle Technologies Program of the DOE.

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List of Acronyms

Ah	amp-hour
AVTA	Advanced Vehicle Testing Activity
BOT	beginning of test
C/3	the rate of battery discharge relative to one third its maximum capacity
DOD	depth of discharge
DOE	Department of Energy
EOT	end of test
HEV	hybrid electric vehicle
HPPC	Hybrid Pulse Power Characterization
HWFET	Highway Fuel Economy Test
INL	Idaho National Laboratory
kW	kilowatt
mi	mile
MPH	miles per hour
Ω	ohm
s	second
UDDS	Urban Dynamometer Drive Schedule
US06	high speed/high load drive-cycle dynamometer test

V	volt
VDC	volt direct current
VIN	vehicle identification number
Vpc	volt per cell
Wh	watt-hour

1 Test Results

The U.S. Department of Energy (DOE) Advanced Vehicle Testing Activity (AVTA) Program consists of vehicle, battery, and infrastructure testing on advanced technology related to transportation. The activity includes tests on hybrid electric vehicles (HEVs), including testing the HEV batteries when both the vehicles and batteries are new (i.e., beginning-of-test or BOT) and at the conclusion of 100,000 miles of on-road fleet testing (i.e., end-of-test or EOT). This report provides test results for BOT and EOT battery testing conducted on a 2010 Honda Civic Hybrid UltraBattery Conversion, number 5577 (full VIN: JHMFA3F24AS005577), from both laboratory and on-road test configurations. The battery laboratory test results include those from the Static Capacity Test and the Hybrid Pulse Power Characterization (HPPC) Test.[3] Vehicle test results include those from acceleration testing and fuel economy testing.[4]

The battery and vehicle testing was performed by the Electric Transportation Engineering Corporation dba ECOtality North America. The Idaho National Laboratory (INL) and ECOtality North America collaborate on the AVTA for the Vehicle Technologies Program of the DOE.

1.1 Static Capacity Test Results

Results from the laboratory BOT and EOT Static Capacity tests are provided in Table 1.

Table 1. Static Capacity Test results

	Test Date	Odometer (mi)	Rated Capacity (Ah)	Measured Capacity (Ah)	Measured Energy (Wh)
BOT	September 2, 2011	0	7.50	7.55	1,260
EOT	April 16, 2013	100,099	7.50	7.23	1,198
Difference	—	100,099	—	0.32 (4.2%)	62 (4.9%)

Figure 1 shows battery voltage[5] versus energy discharged. This graph illustrates voltage values during constant-current discharge versus cumulative energy discharged from the battery at a C/3 constant-current discharge rate at BOT and EOT.

[3] Static capacity and HPPC test procedures are based on the *FreedomCAR Battery Test Manual for Power-Assist Hybrid Electric Vehicles*, DOE/ID-11069, October 2003, Procedures 3.2 and 3.3, respectively. The measured capacity at BOT testing was used to determine the magnitude of current during all HPPC tests.

[4] Acceleration testing and fuel economy testing procedures were performed in accordance with the Advanced Vehicle Testing Activity HEVAmerica test procedures ETA-HTP02 and ETA-HTP03, respectively.

[5] BOT cell discharge voltage was set to 1.75 V while EOT cell discharge voltage was set to 1.80 V so as not to over discharge a cell during EOT testing.

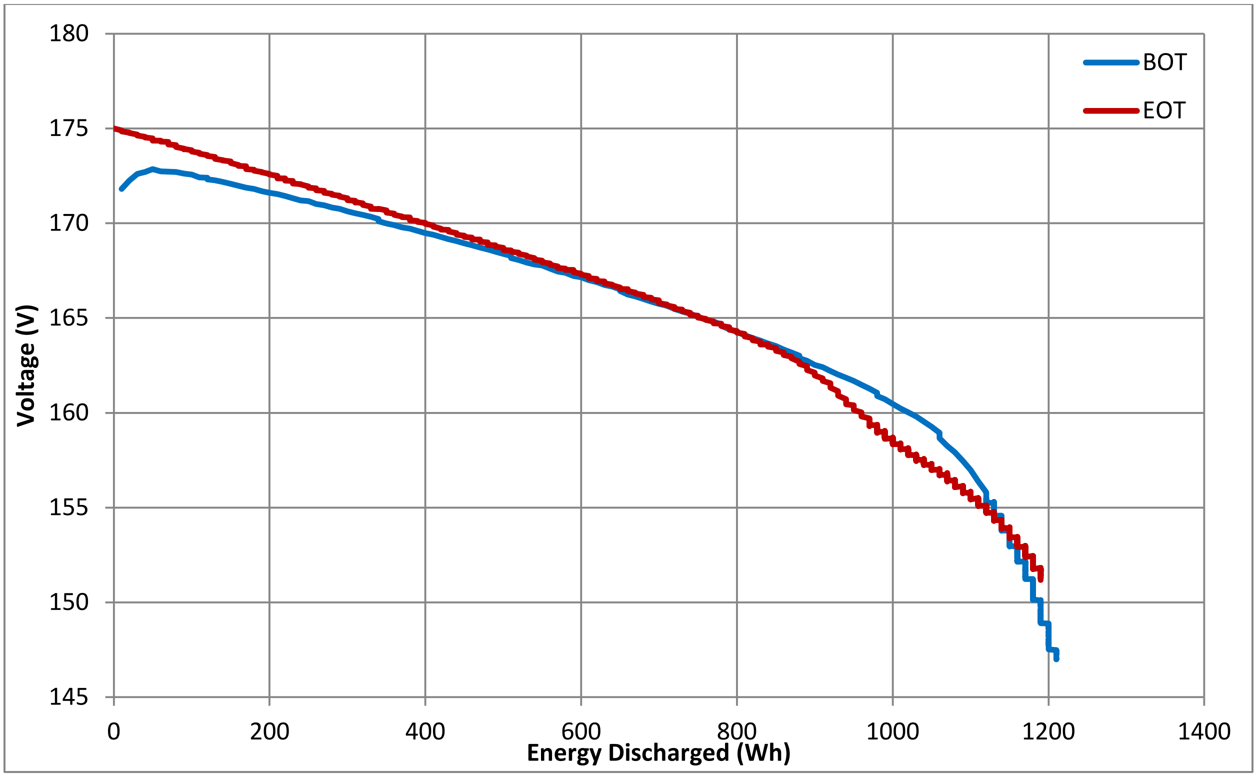

Figure 1. Voltage versus energy discharged during the Static Capacity test

1.2 Hybrid Pulse Power Characterization Test Results

The Hybrid Pulse Power Characterization (HPPC) test results are summarized below in Table 2. Figure 2 and Figure 4 illustrate the charge and discharge pulse resistance graphs of the battery, respectively. The internal resistance is depicted over a range of 10 to 90% depth of discharge (DOD), which is represented by the amount of energy discharged at each interval. Each curve represents the specified HPPC BOT or EOT resistance at the end of the 10-second pulse interval.

Figure 3 and Figure 5 illustrate the charge and discharge pulse power capability graphs of the battery, respectively. The power capability is depicted over a range of 10 to 90% DOD, which is represented by the amount of energy discharged at each interval. Each curve represents the calculated HPPC BOT or EOT available power capability at the end of the 10-second pulse interval at the cell voltage limits.

Table 2. HPPC test results

	10s Charge Power Capability (kW)	1s Charge Power Capability (kW)	10s Discharge Power Capability (kW)	1s Discharge Power Capability (kW)	Maximum Cell Voltage (V)	Minimum Cell Voltage (V)
BOT	8.23	16.2	9.12	10.0	2.45	1.8
EOT	8.15	14.4	7.16	7.93	2.45	1.8
Difference	0.08 (1.0%)	1.80 (11%)	1.96 (21%)	2.07 (21%)	—	—

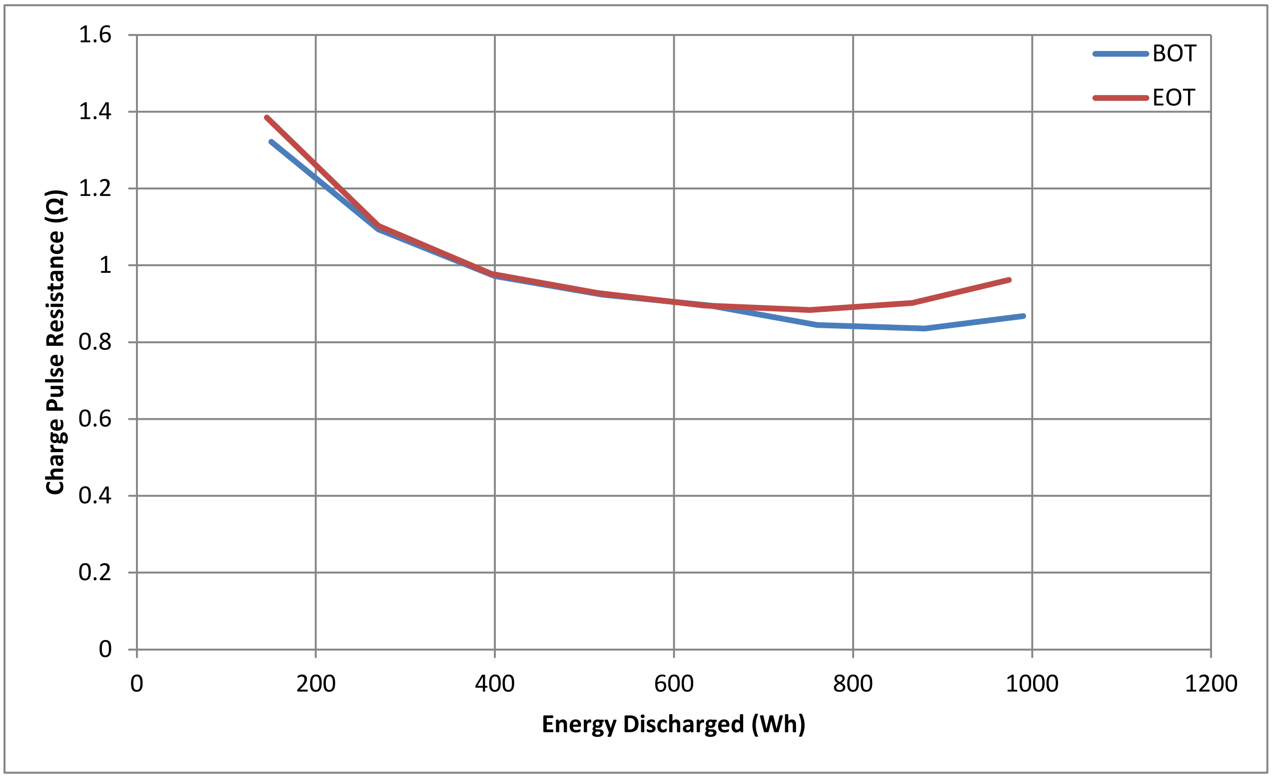

Figure 2. Ten-second charge pulse resistance versus energy discharged

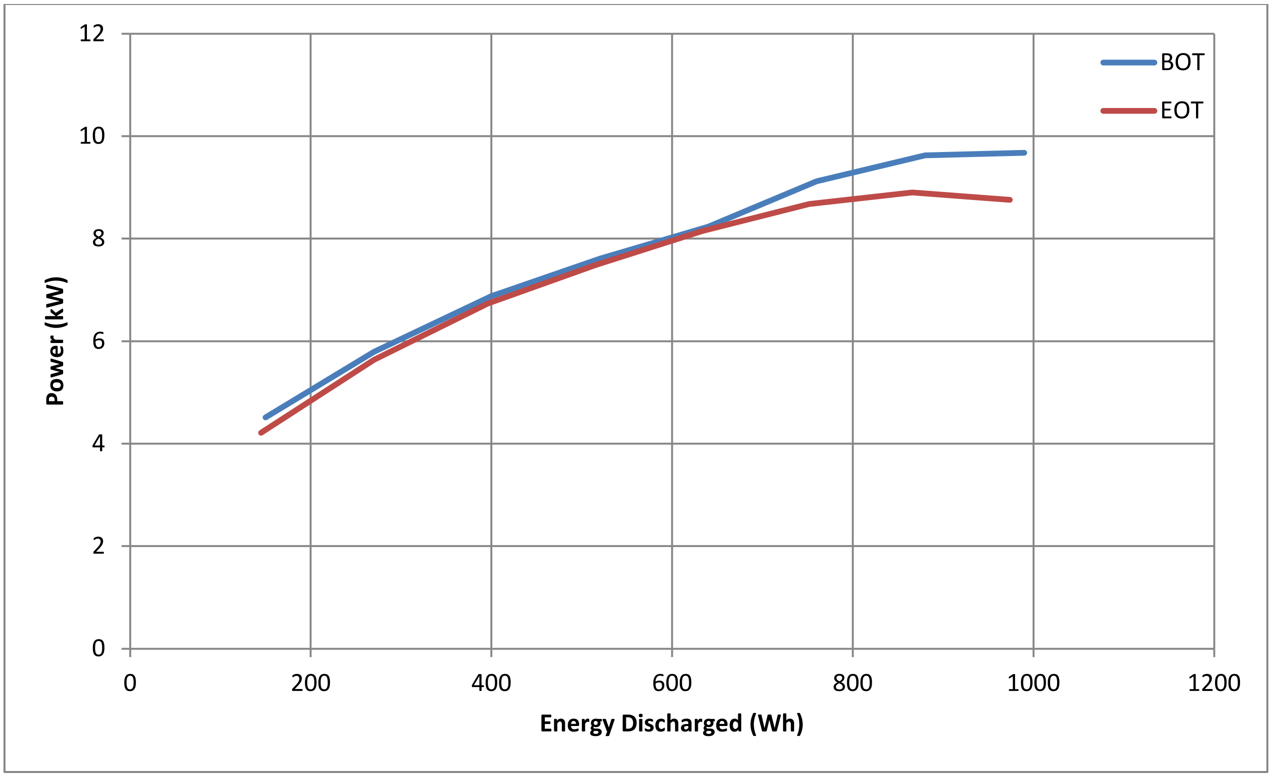

Figure 3. Ten-second charge pulse power capability versus energy discharged

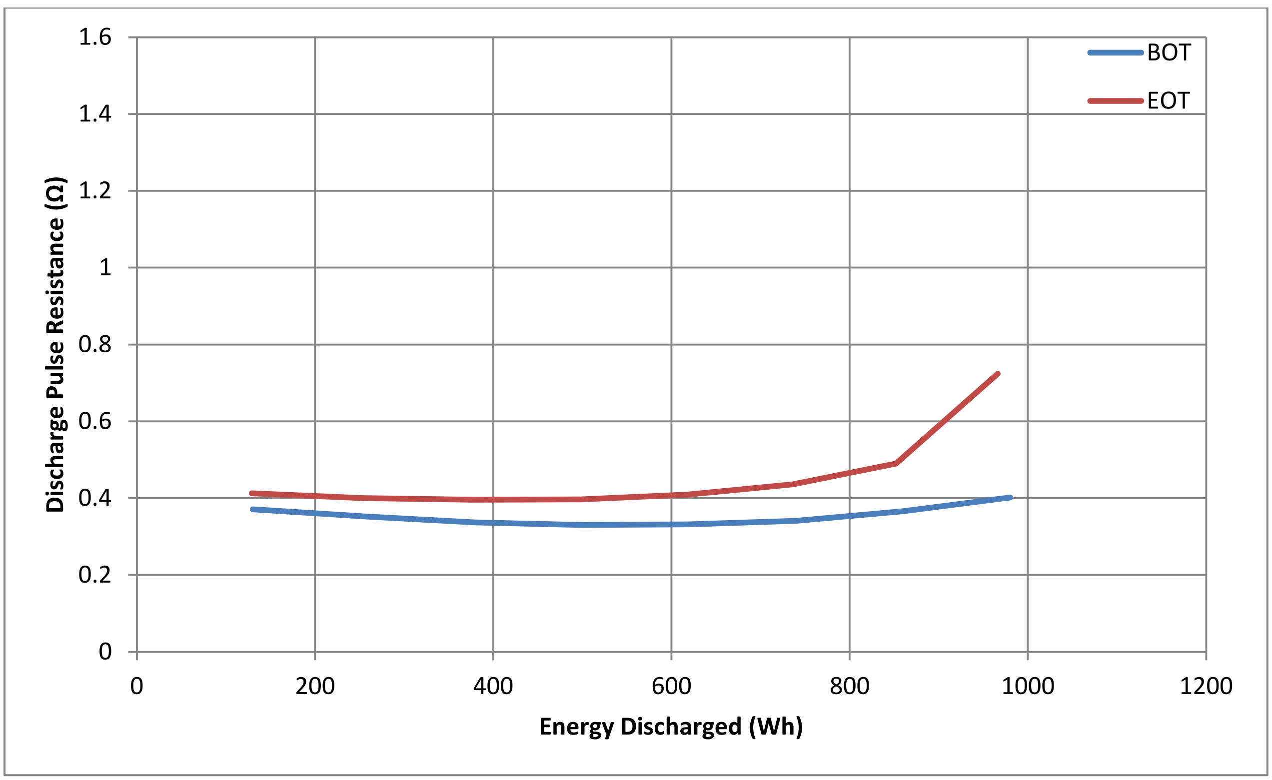

Figure 4. Ten-second discharge pulse resistance versus energy discharged

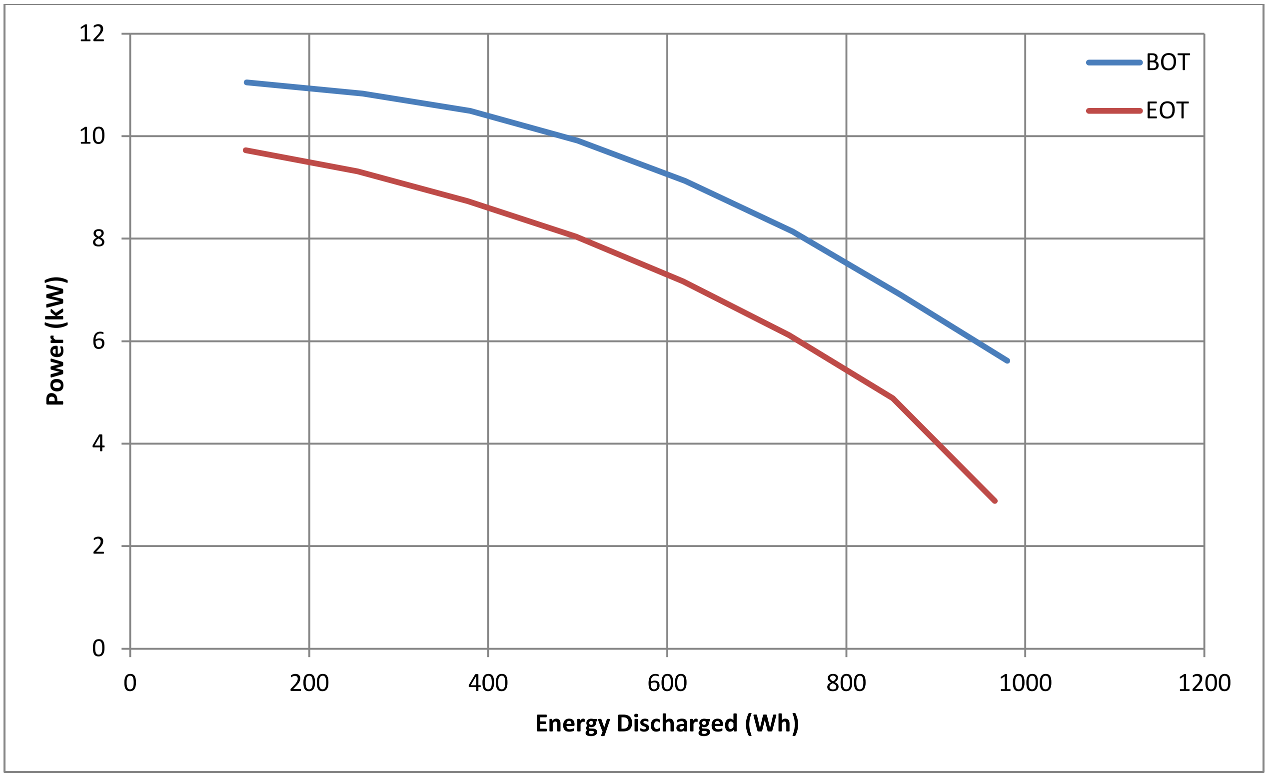

Figure 5. Ten-second discharge pulse power capability versus energy discharged

Figure 6 is a plot of the BOT and EOT HPPC 10-second pulse power charge and discharge power capability values of the battery as a function of energy discharged. The graph shows the power values over the range of energy discharged, with discharge power on the primary (left) axis and charge power on the secondary (right) axis. The DOE targets for a hybrid power-assist battery for discharge power (25 kW) and charge regenerative power (20 kW) are included for comparative purposes. The BOT and EOT pulse power values do not meet the DOE power targets (denoted by the black, horizontal dashed line in the figure) for any battery energy discharge range.

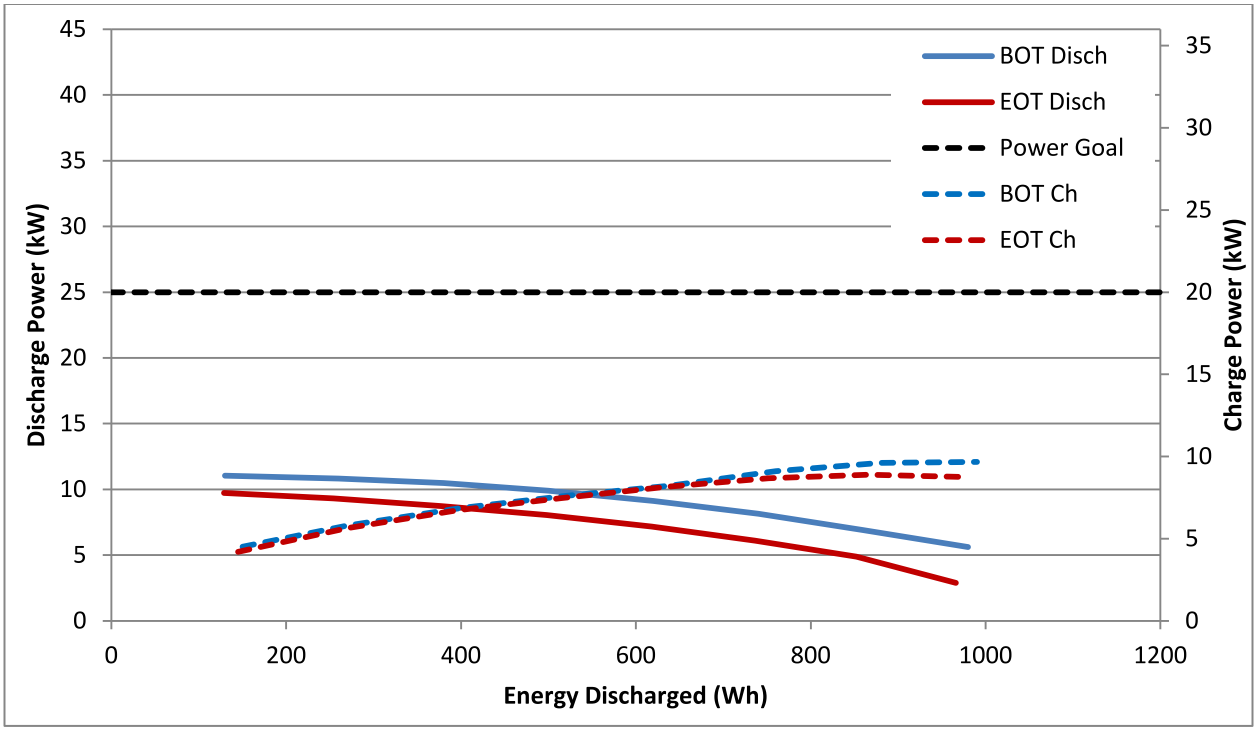

Figure 6. Peak discharge and charge power versus energy discharged

Figure 7 is a plot of the BOT and EOT useable energy as a function of battery power. The x-axis indicates a desired discharge power level and the y-axis indicates the useable energy at that power. The dashed horizontal line shows the DOE minimum power-assist HEV energy target of 300 Wh. The dashed vertical line shows the DOE minimum power-assist discharge power target of 25 kW. The BOT useable energy curve of the UltraBattery Civic battery falls above and to the left of the intersection of DOE energy and power targets. The maximum power that can be delivered while meeting the DOE energy target is 7.5 kW at 300 Wh. No energy can be delivered while meeting the DOE power target of 25 kW. This indicates that at the time of BOT testing, the UltraBattery Civic battery performance was below DOE targets. The EOT useable energy curve of the battery falls above and to the left of the intersection of the DOE energy and power targets. The maximum power that can be delivered while meeting the DOE energy target is 6.6 kW at 300 Wh. No energy can be delivered while meeting the DOE power target of 25 kW. This indicates that at the time of EOT testing, the UltraBattery Civic battery performance was below DOE targets.

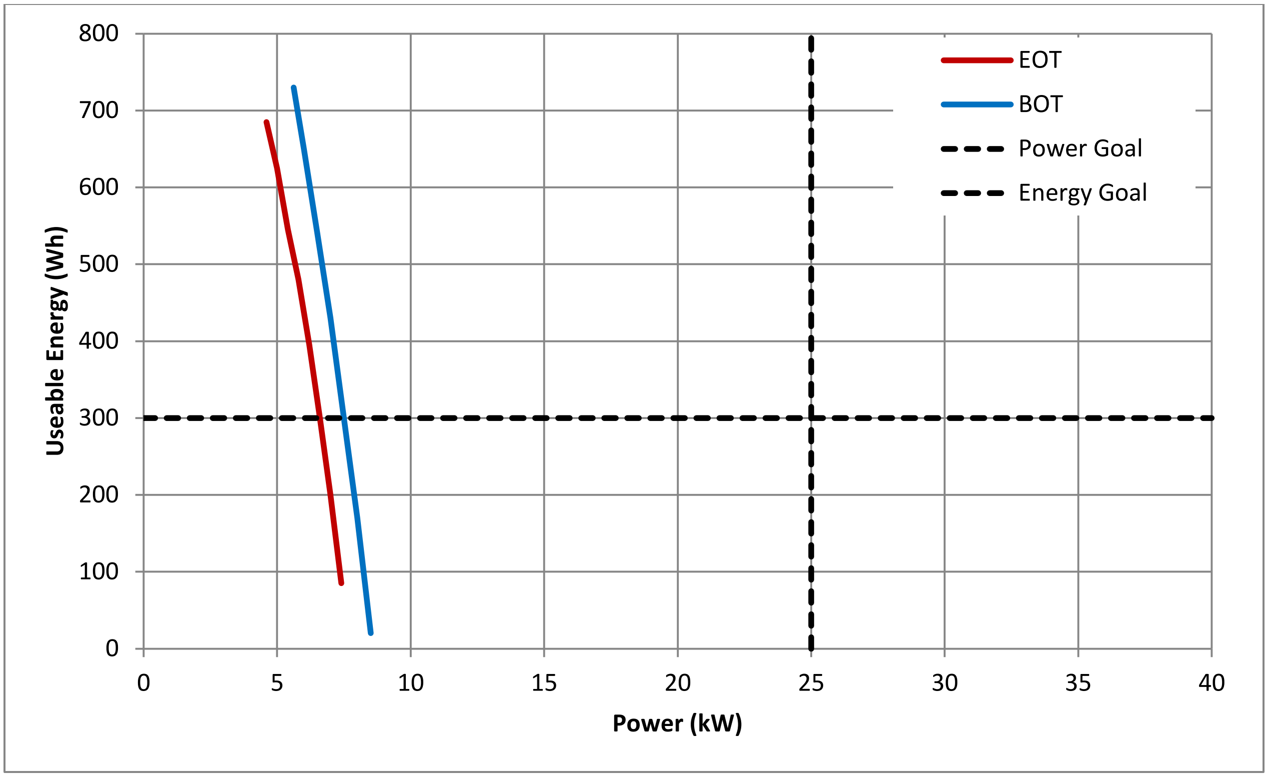

Figure 7. Useable energy versus power

1.3 Acceleration Test Results

BOT results from vehicle on-track acceleration tests are summarized in Table 3.

Table 3. BOT acceleration test results[6]

	Average Discharge Power Over 10s (kW)	Energy Discharged Over Test (Wh)	Capacity Discharged Over Test (Ah)	Peak Power Over Test (kW)	Minimum Discharge Pack Voltage (V)	Minimum Discharge Cell Voltage (V)
BOT	5.61	49	0.31	6.83	155.2	1.85

Figure 8 shows battery power versus time during the acceleration test at BOT. This graph is the basis for power calculations over specified time or distance intervals and the cumulative discharged energy capacity during the duration of the test. At the beginning of the acceleration test, the power quickly increases from approximately 0 kW to a peak value. The power then changes based on battery or vehicle system dynamics, which may include battery control logic, cause a reverse in power direction to charge the battery.

Figure 9 shows the battery voltage versus time during the one-mile acceleration test at BOT. Values are analyzed to determine the minimum voltage allowed by the battery control module, if possible. Although the test may not yield a definitive minimum voltage value, it can provide an approximation for comparison to the HPPC analysis results. This graph also shows the impact of power electronics and battery controller on the voltage response.

[6] Due to restrictions at the test track where acceleration tests were performed, the vehicle could not be accelerated for one full mile.

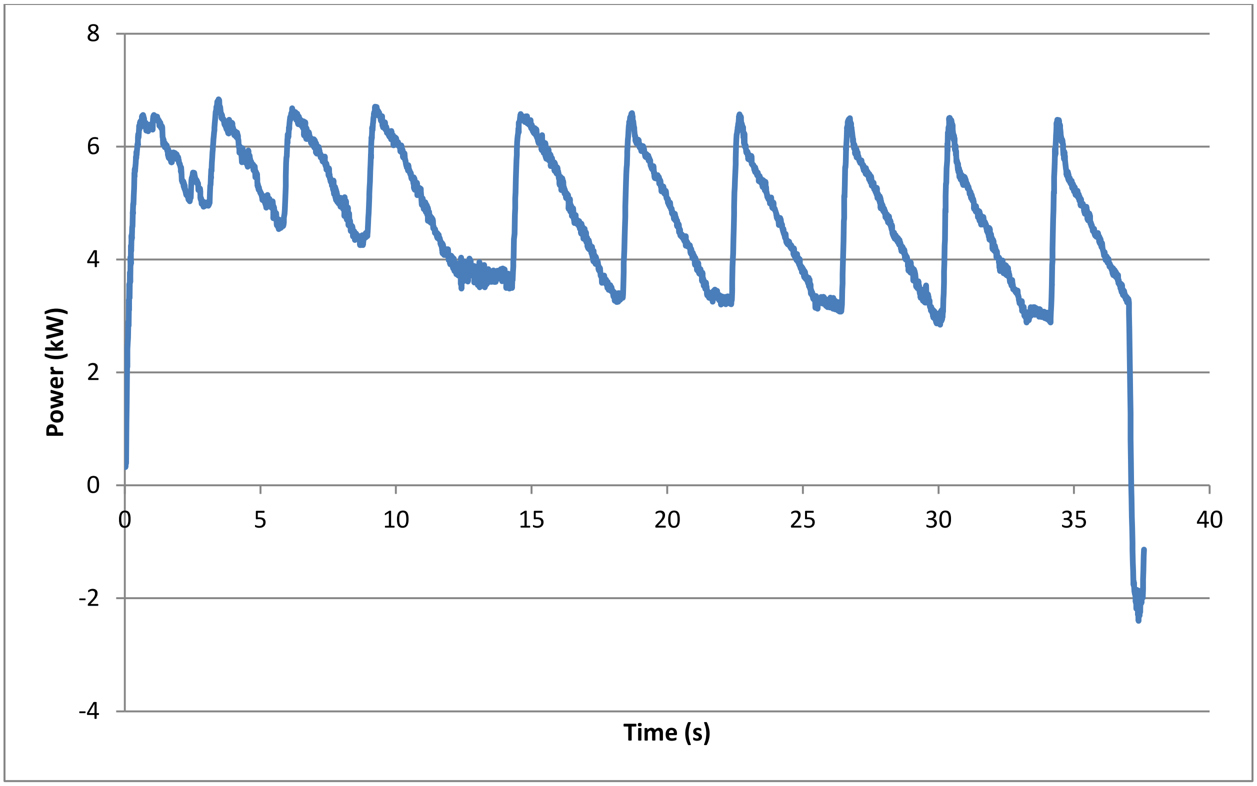

Figure 8. Battery power versus time from acceleration testing

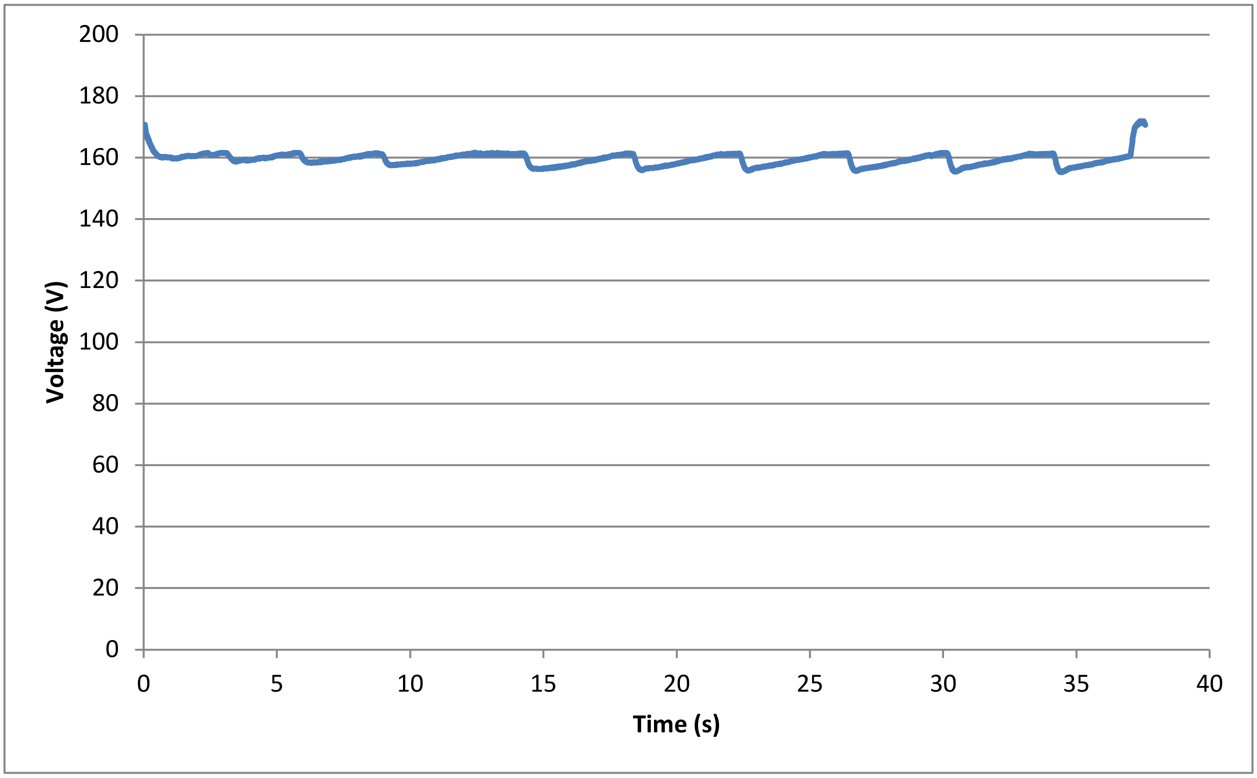

Figure 9. Battery voltage versus time from acceleration testing

Figure 10 shows battery current versus time during the one-mile acceleration test at BOT. This graph also is the basis for determining the discharged capacity during the test run. Lastly, the power results in Figure 8 can be obtained by simply multiplying the voltage values from Figure 9 by the current values in Figure 10.

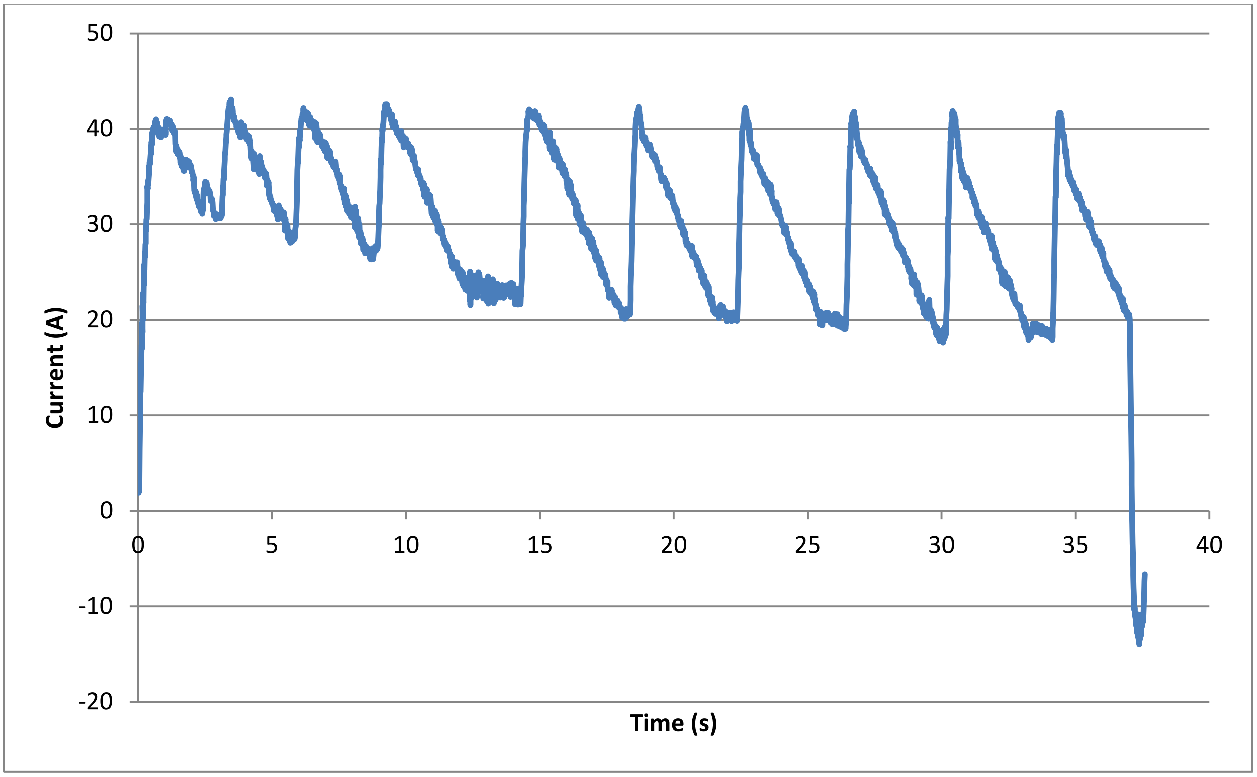

Figure 10. Battery current versus time from acceleration testing

1.4 Fuel Economy Test Results

Battery performance results from testing conducted on a chassis dynamometer (using the Urban Dynamometer Drive Schedule (UDDS), HWFET, and US06[7] at BOT and average fuel economy recorded while the vehicle was operating in an on-road fleet[8], in a mix of city and highway routes. Battery performance results are summarized in Table 4.

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[7] Urban Dynamometer Drive Schedule, HWFET, and US06 was performed as defined by the Environmental Protection Agency. The definitions of each cycle can be found at http://www.epa.gov/nvfel/testing/dynamometer.htm#vehcycles

[8] On-road fleet testing is performed by the ECOtality North America (in conjuncture with EZ-Messenger courier services). The vehicles are driven a combination of city and highway routes by several different drivers to expedite the mileage accumulation required to reach EOT.

Table 4. Battery performance results from the UDDS, Highway, and US06 dynamometer drive-cycle testing

	UDDS	HWFET	US06
Peak Discharge Power (kW):	7.32	6.79	7.48
Peak Regen Power (kW):	2.01	2.02	2.49
Measured Discharge Energy (kWh):	0.20	0.19	0.26
Measured Charge Energy (kWh):	0.18	0.25	0.27
Measured Discharge Capacity (Ah):	1.18	1.13	1.55
Measured Regen Capacity (Ah):	0.98	1.38	1.48
Minimum Pack Voltage (V):	159.7	163.6	159.7
Maximum Pack Voltage (V):	201.3	201.5	201.5
Discharge/Regen Ratio:	1.204	0.819	1.047

Figures 11, 12, and 13 show how the hybrid battery pack is utilized in comparison to vehicle speed for UDDS, HWFET, and US06 dynamometer drive-cycle testing, respectively. For each, the battery pack utilization is directly correlated to the driving style being performed in the drive-cycle. During the UDDS cycle, which simulates city driving with mildly aggressive accelerations and braking, the battery pack is in a perpetual state of transition between discharging and charging. During the HWFET cycle, which simulates highway driving where the vehicle is in nearly continuous motion, the battery pack shows a more steady-state use. During the US06 cycle, which is combined simulation of city and highway driving with a higher average speed, and aggressive accelerations and braking, the battery pack shows a combination of steady-state and transient use while at a higher average current input and output than the other two cycles.

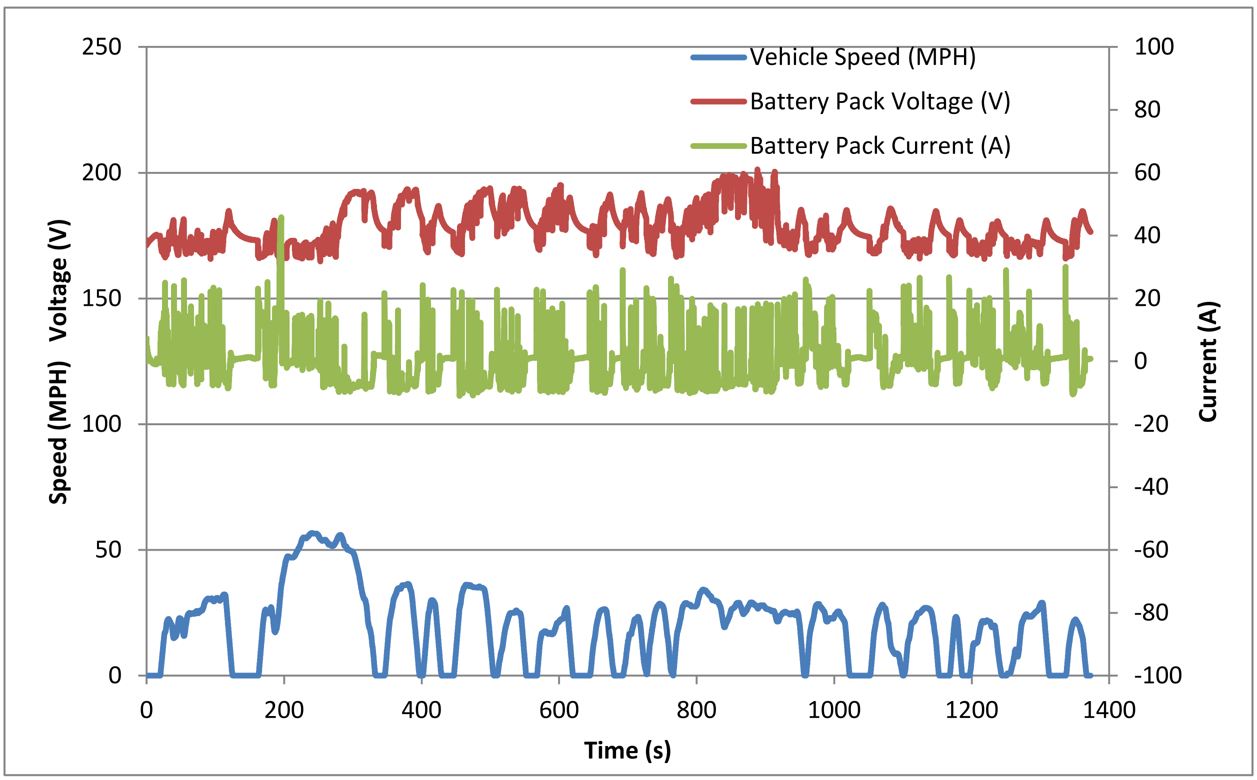

Figure 11. Battery pack current, voltage, and vehicle speed for a UDDS dynamometer drive-cycle.

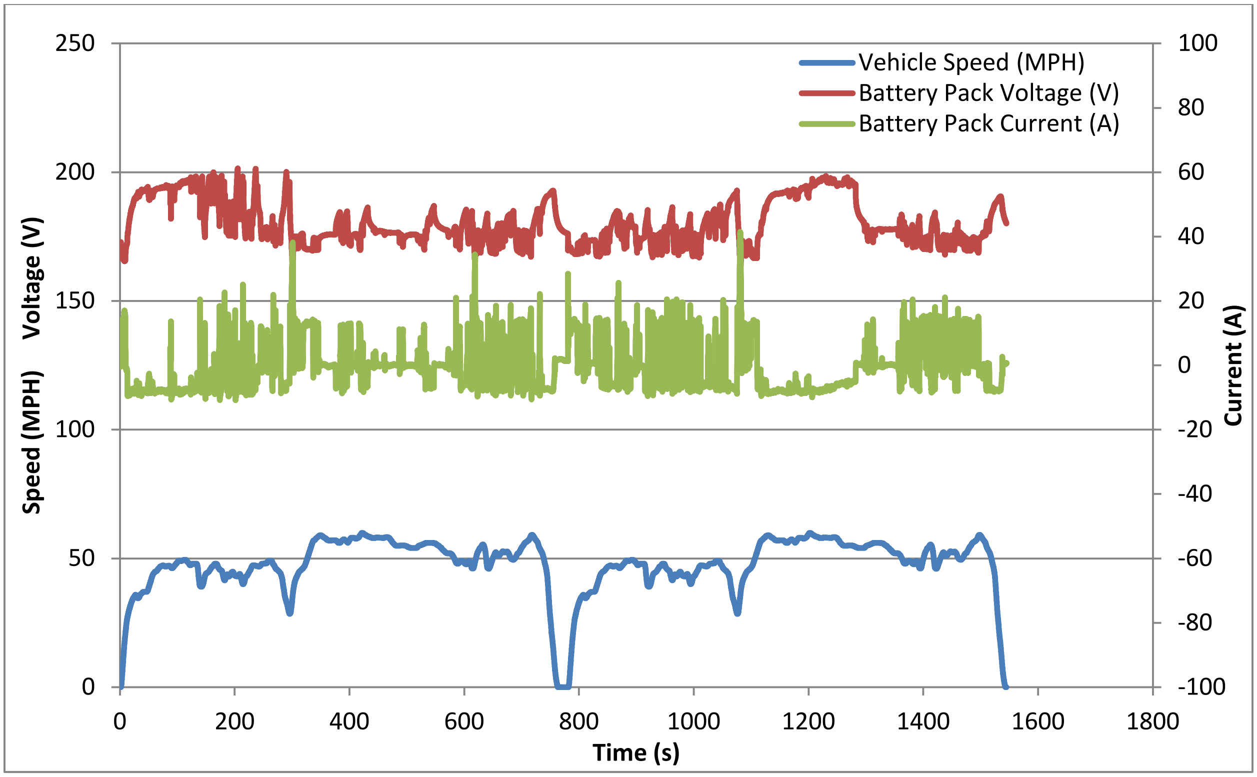

Figure 12. Battery pack current, voltage, and vehicle speed for a HWFET dynamometer drive-cycle.

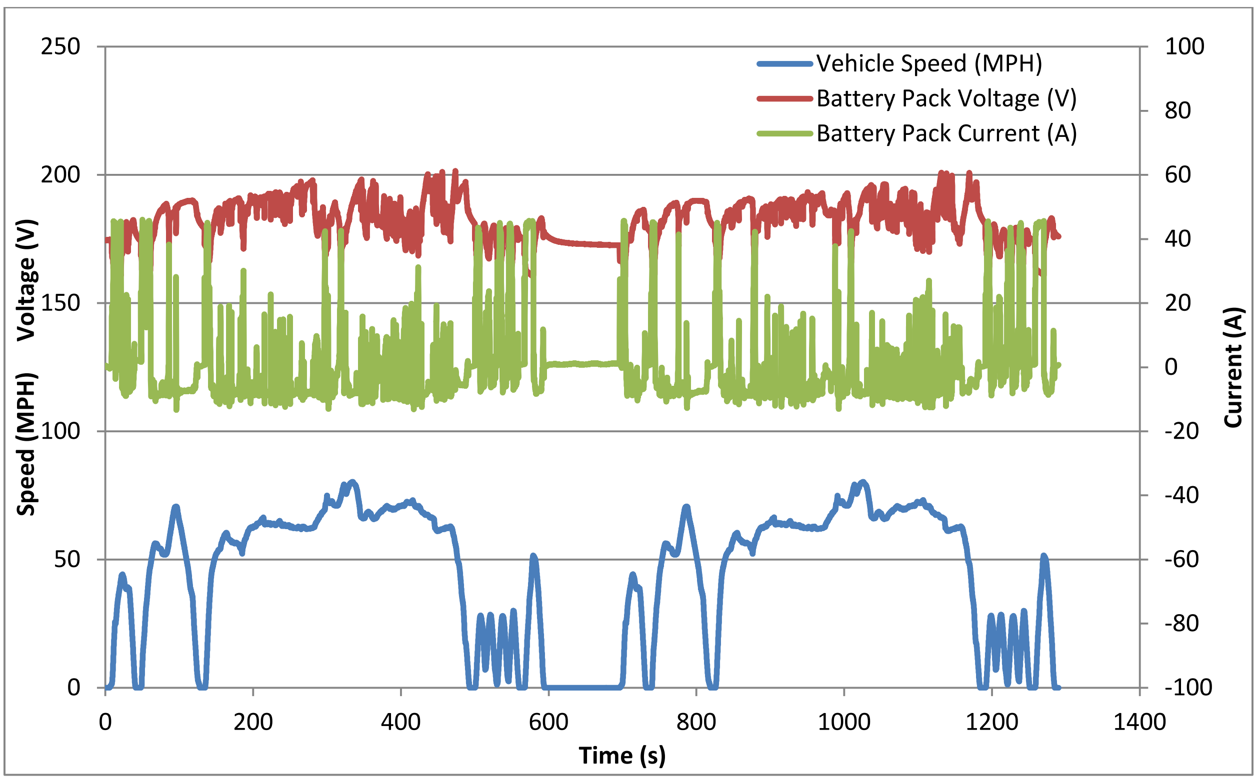

Figure 13. Battery pack current, voltage, and vehicle speed for a US06 dynamometer drive-cycle.

1.5 On-Road Test Results

Figure 14 presents the combined monthly fuel economy and cumulative fuel economy for the UltraBattery Civic HEV 5577 that underwent on-road fleet testing. The monthly fuel economy is derived from the amount of fuel consumed, based on fleet fueling records, and the distance traveled, based on vehicle odometer readings, for each vehicle within that month. The cumulative fuel economy is a running total of each month's fuel consumption and distance traveled. The ending cumulative fuel economy over the course of fleet testing was 38.2 mpg. While the vehicle fuel economy cannot be directly correlated to operation of the battery pack with only these data, the vehicle fuel economy in Figure 14 is steady over the entirety of testing, even with battery degradation demonstrated by the EOT battery testing.

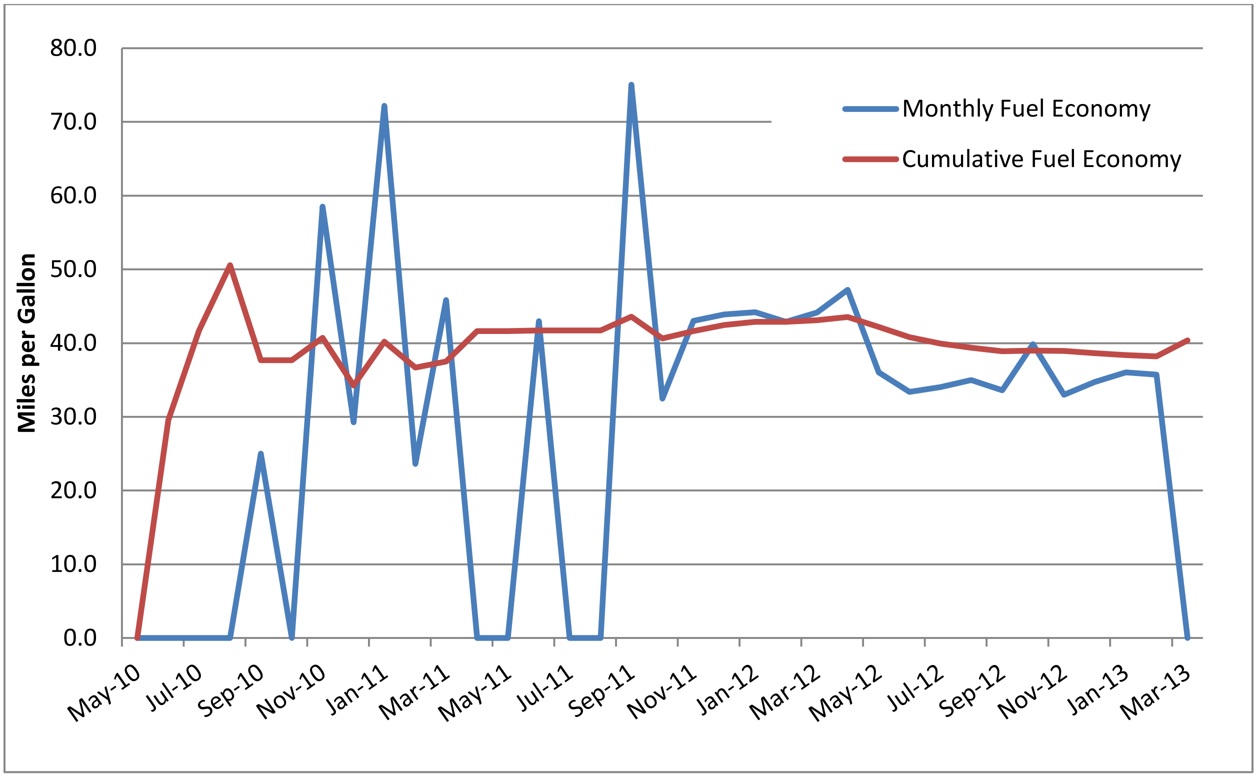

Figure 14. Monthly and cumulative fuel economy

2 Conclusion

The Honda Civic Hybrid UltraBattery Conversion 5577 experienced a 4.2% decrease in battery capacity and stayed below DOE targets for all aspects of the HPPC test over the duration of 100,099 miles of fleet testing.

Appendix A - Vehicle Specifications and Test Results Summary

Vehicle Specifications	Battery Specifications
Manufacturer: Honda Model: Civic Year: 2010 Motor Power Rating[a]: 14.9 kW (peak), permanent magnet AC synchronous VIN #: JHMFA3F24AS005577 Modification: Stock OEM battery pack replaced with East Penn UltraBattery pack and custom Battery Management System (BMS)	Manufacturer: East Penn Manufacturing Type: Lead-Carbon Number of Cells: 84 Nominal Cell Voltage: 2.1 V Nominal System Voltage: 176.4 V Nominal Pack Capacity: 7.5 Ah Cooling: Active/Cabin Air

Beginning-of-Test Vehicle Baseline Performance Test Results[b]

Acceleration Test

Average Discharge Power Over 10 seconds[c]: 5.61 kW
Peak Discharge Power Over Test: 6.83 kW
Energy Discharged Over Test[d]: 49 Wh
Capacity Discharged Over Test[d]: 0.31 Ah
Minimum Discharge Pack Voltage: 155.2 VDC
Minimum Discharge Cell Voltage: 1.85 V

Fuel Economy Chassis Dynamometer Testing

	UDDS	HWFET	US06
Peak Discharge Power (kW):	7.32	6.79	7.48
Peak Regen Power (kW):	2.01	2.02	2.49
Measured Discharge Energy (kWh):	0.20	0.19	0.26
Measured Charge Energy (kWh):	0.18	0.25	0.27
Measured Discharge Capacity (Ah):	1.18	1.13	1.55
Measured Regen Capacity (Ah):	0.98	1.38	1.48
Minimum Pack Voltage (V):	159.7	163.6	159.7
Maximum Pack Voltage (V):	201.3	201.5	201.5
Discharge/Regen Ratio[e]:	1.204	0.819	1.047

Beginning-of-Test Battery Laboratory Test Results

Hybrid Pulse Power Characterization Test	Static Capacity Test
Peak Pulse Discharge Power @ 10 seconds[f]: 9.12 kW Peak Pulse Discharge Power @ 1 seconds[f]: 10.0 kW Peak Pulse Charge Power @ 10 seconds[f]: 8.23 kW Peak Pulse Charge Power @ 1 seconds[f]: 16.2 kW Maximum Cell Charge Voltage: 2.45 V Minimum Cell Discharge Voltage: 1.8 V	Measured Average Capacity: 7.55 Ah Measured Average Energy Capacity:1,260 Wh Vehicle Odometer: 0 miles Date of Test: September 2, 2011

End-of-Test Battery Laboratory Test Results

Hybrid Pulse Power Characterization Test	Static Capacity Test
Peak Pulse Discharge Power @ 10 seconds[f]: 7.16 kW Peak Pulse Discharge Power @ 1 seconds[f]: 7.93 kW Peak Pulse Charge Power @ 10 seconds[f]: 8.15 kW Peak Pulse Charge Power @ 1 seconds[f]: 14.4 kW Maximum Cell Charge Voltage: 2.45 V Minimum Cell Discharge Voltage: 1.8 V	Measured Average Capacity: 7.23 Ah Measured Average Energy Capacity:1,198 Wh Vehicle Odometer: 100,099 miles Date of Test: April 16, 2013

Degradation of Battery Over Test Period[g]	
Hybrid Pulse Power Characterization Test	**Static Capacity Test**
Peak Pulse Discharge Power @ 10 seconds[f]: 1.96 kW (21%) Peak Pulse Discharge Power @ 1 seconds[f]: 2.07 kW (21%) Peak Pulse Charge Power @ 10 seconds[f]: 0.08kW (1.0%) Peak Pulse Charge Power @ 1 seconds[f]: 1.80 kW (11%)	Measured Average Capacity: 0.32 Ah (4.2%) Measured Average Energy Capacity: 62 Wh (4.9%)

Notes:

a. Motor power rating refers to the manufacturer's peak power rating for the motor(s) supplying traction power.
b. Vehicle test results are derived from baseline testing of UltraBattery Civic VIN 5577.
c. The peak power at a specified duration is the average power value over a specified interval.
d. The capacity\energy value is defined as the net value over a 1-mile, full-throttle acceleration test.
e. Ratio is calculated as the ratio of measured capacity discharge to measured capacity regenerated. The initial and final states of charge are not specifically known, but are controlled by the battery management system and are within its normal range.
f. Calculated value based on selected battery voltage limits and at 50% SOC of measured capacity at the time of BOT testing.
g. All values are the degradation or difference in the battery from initial laboratory test to final laboratory test.