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2011 Honda CR-Z 4466 - Hybrid Electric Vehicle Battery Test Results

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September 2014

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1. Intertek Testing Services NA
2. Idaho National Laboratory

ABSTRACT

The U.S. Department of Energy's 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, including testing traction batteries when both the vehicles and batteries are new and at the conclusion of 160,000 miles of on-road fleet testing. This report documents battery testing performed for the 2011 Honda CR-Z (VIN JHMZF1C67BS004466). Battery testing was performed by Intertek Testing Services NA. The Idaho National Laboratory and Intertek collaborate on the Advanced Vehicle Testing Activity for the Vehicle Technologies Office of the U.S. Department of Energy.

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ACRONYMS

Ah	amp-hour
BOT	beginning of test
DOE	Department of Energy
EOT	end of test
HEV	hybrid electric vehicle
HPPC	Hybrid Pulse Power Characterization
HWFET	Highway Fuel Economy Test
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

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1 TEST RESULTS

The U.S. Department of Energy's (DOE) 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 (HEV), including testing traction batteries when both the vehicles and batteries are new (i.e., beginning-of-test or BOT) and at the conclusion of 160,000 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 2011 Honda CR-Z HEV, number 4466 (full VIN: JHMZF1C67BS004466), 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.[1] Vehicle test results include those from acceleration testing and fuel economy testing.[2]

The battery and vehicle testing was performed by Intertek Testing Services NA. The Idaho National Laboratory and Intertek collaborate on the Advanced Vehicle Testing Activity for the Vehicle Technologies Program of 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	Dec 30, 2010	3,995	5.75	5.79	600
EOT	Jan 16, 2014	160,266	5.75	5.11	530
Difference	—	156,271	—	0.68 (12%)	70 (12%)

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

1.2 Hybrid Pulse Power Characterization Test Results

The HPPC test results are summarized 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, 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% depth of discharge, which is represented by the amount of energy discharged at each interval. Each curve represents the calculated

1 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.

2 Acceleration testing and fuel economy testing procedures were performed in accordance with the Advanced Vehicle Testing Activity HEV America test procedures ETA-HTP02 and ETA-HTP03, respectively.

HPPC BOT or EOT available power capability at the end of the 10-second pulse interval at the cell voltage limits.

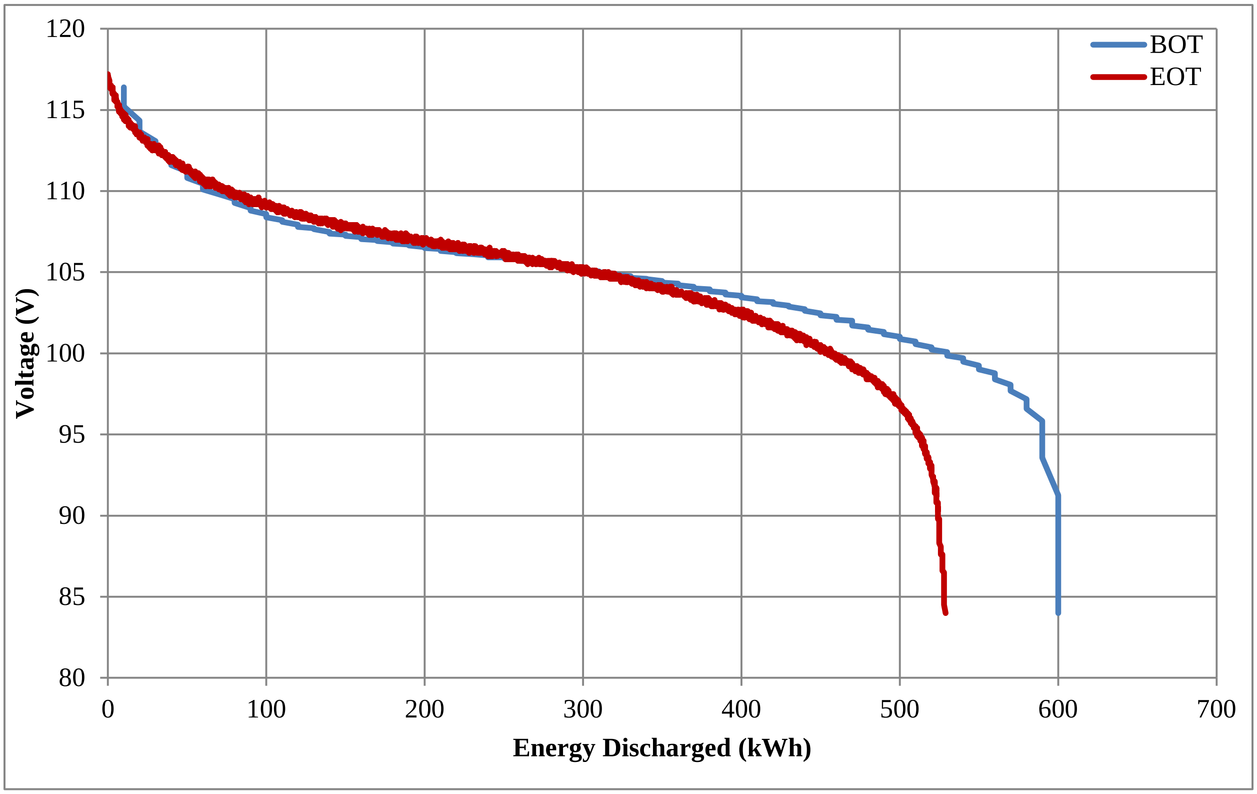

Figure 1. Voltage versus energy discharged during the static capacity test

Table 2. Hybrid Pulse Power Characterization test results

	10 s Discharge Power Capability at 50% DOD (kW)	**10 s Charge Power Capability at 50% DOD (kW)**	**Maximum Cell Voltage (V)**	**Minimum Cell Voltage (V)**
BOT	8.74	8.81	1.5	1.0
EOT	8.42	7.87	1.5	1.0
Difference	0.32 (3.7%)	0.94 (11%)	0 (0%)	0 (0%)

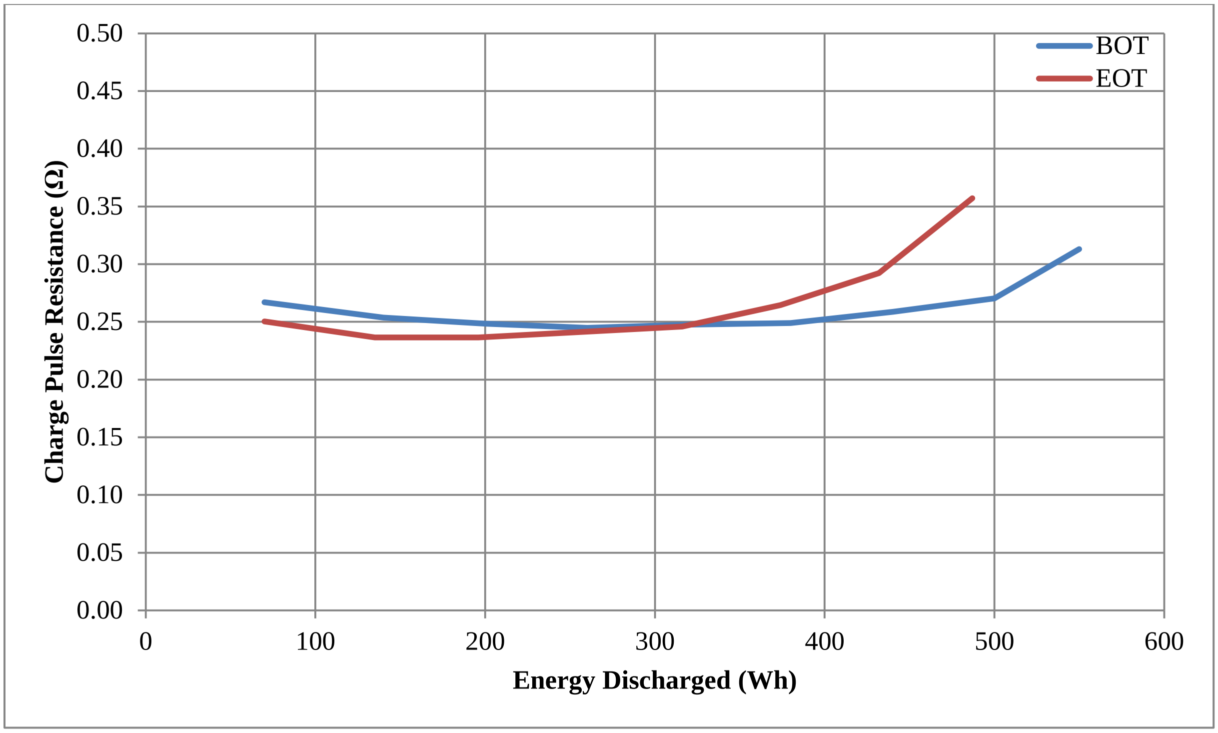

Figure 2. Ten-second charge pulse resistance versus energy discharged

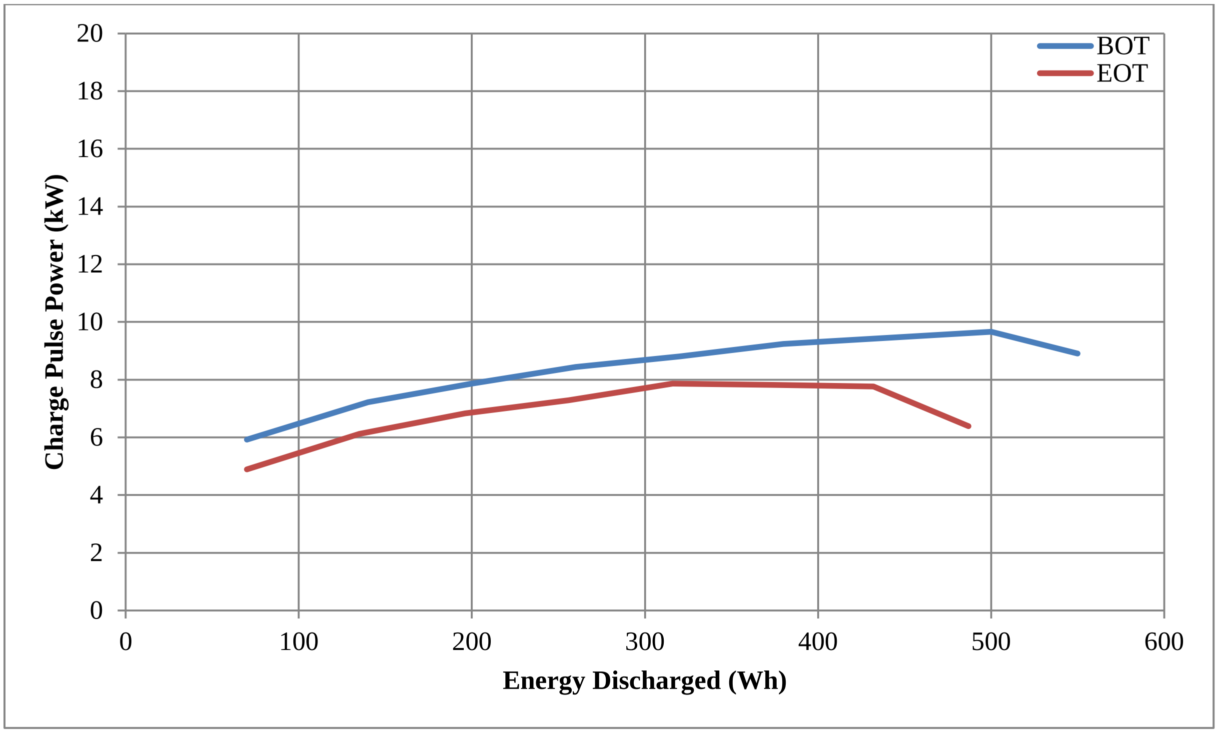

Figure 3. Ten-second charge pulse power capability versus energy discharged

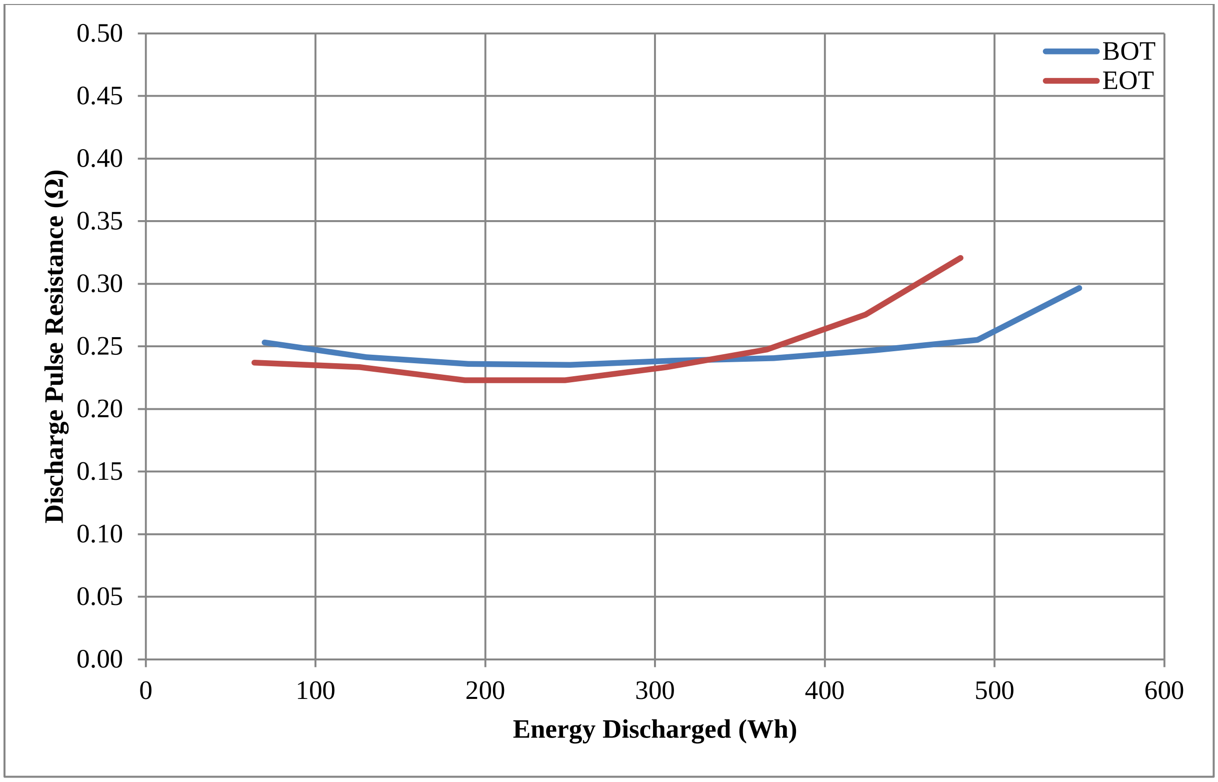

Figure 4. Ten-second discharge pulse resistance versus energy discharged

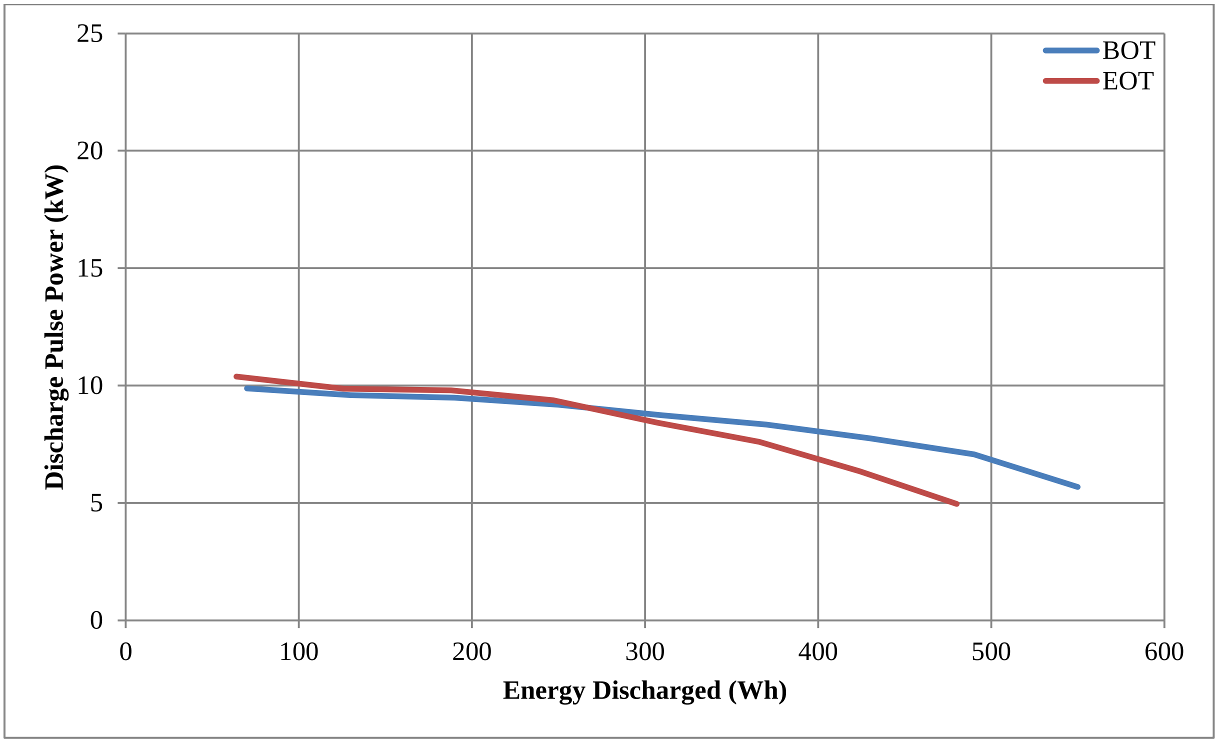

Figure 5. Ten-second discharge pulse power capability versus energy discharged

Figure 6 is a plot of the BOT and EOT HPPC 10-second pulse 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 (i.e., 25 kW) and charge regenerative power (i.e., 20 kW) are included for comparative purposes. Neither the BOT or EOT pulse power values meet the DOE power targets (denoted by the black, horizontal dashed line in the figure) for any battery energy discharged range.

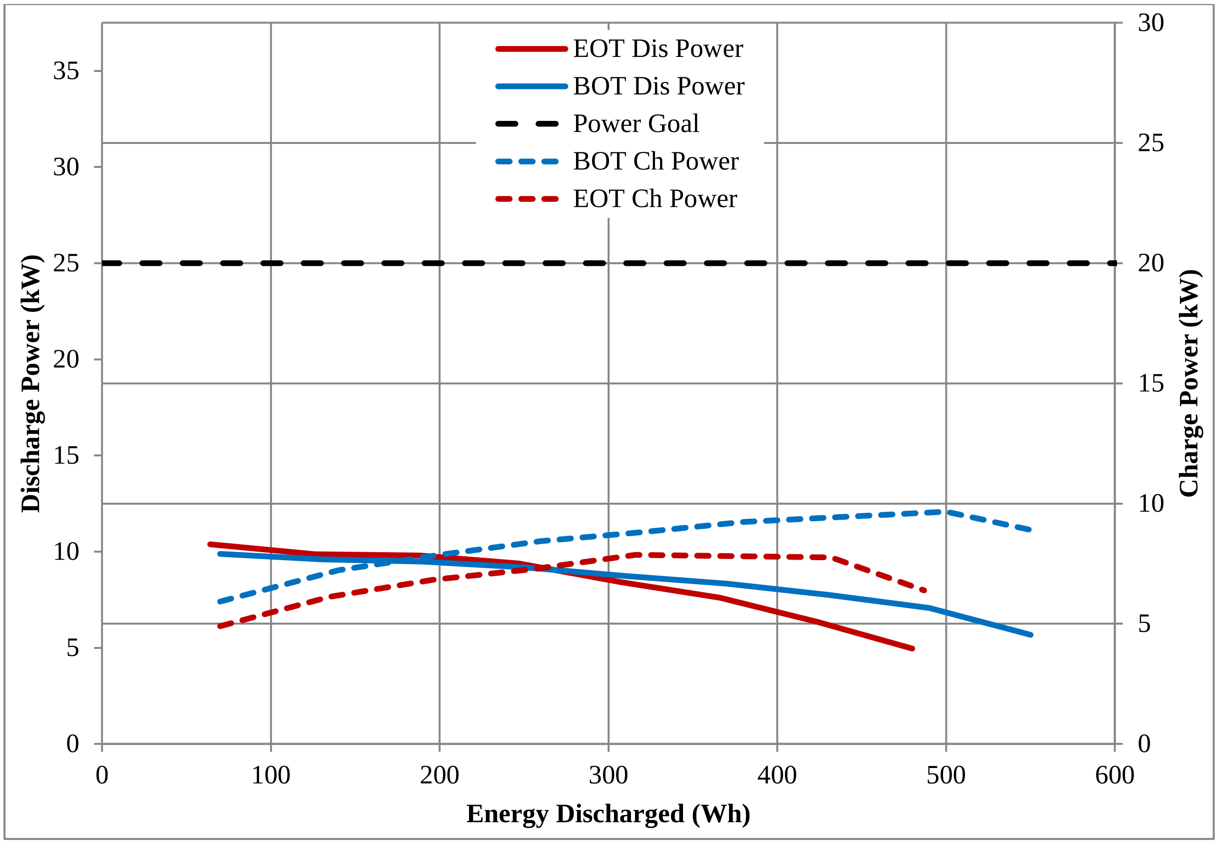

Figure 6. Discharge and charge power capabilities versus energy discharged

Figure 7 is a plot of the BOT and EOT usable energy as a function of battery power. The x-axis indicates a desired discharge power level and the y-axis indicates the usable 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 HEV discharge power target of 25 kW. No portion of the BOT useable energy curve of the CR-Z battery falls above and to the right of the intersection of DOE energy and power targets. The maximum power that can be delivered while meeting the DOE energy target is 7.4 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 CR-Z battery performance was below DOE targets. No portion of the EOT useable energy curve of the battery falls above and to the right of the intersection of the DOE energy and power targets. The maximum power that can be delivered while meeting the DOE energy target is 6.1 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 CR-Z battery performance was below DOE targets.

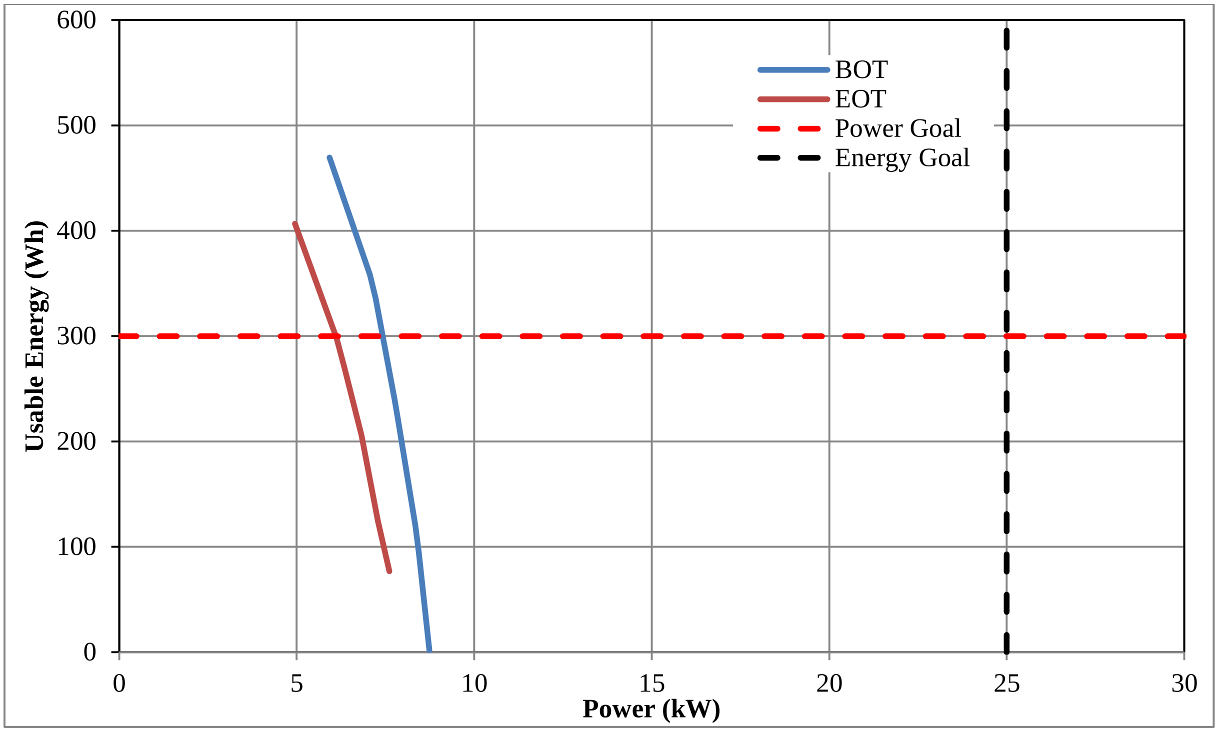

Figure 7. Usable energy versus power

1.3 Acceleration Test Results

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

Table 3. BOT and EOT acceleration test results[3]

	Average Discharge Power Over 10 s (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	8.53	107.1	1.11	11.9	87.2	1.04
EOT	8.21	87.2	0.91	10.5	91.8	1.09

Figure 8 shows battery power versus time during the one-mile acceleration test at BOT and EOT. 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 remains relatively constant based on battery or vehicle system dynamics (such as gear shifting), which may include battery control logic cause the power to reduce exponentially.

Figure 9 shows the battery voltage versus time during the 1-mile acceleration test at BOT and EOT. 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 a battery controller on the voltage response.

[3] Because of the speed restrictions at the test track where acceleration tests were performed, the vehicle could not be accelerated for 1 full mile.

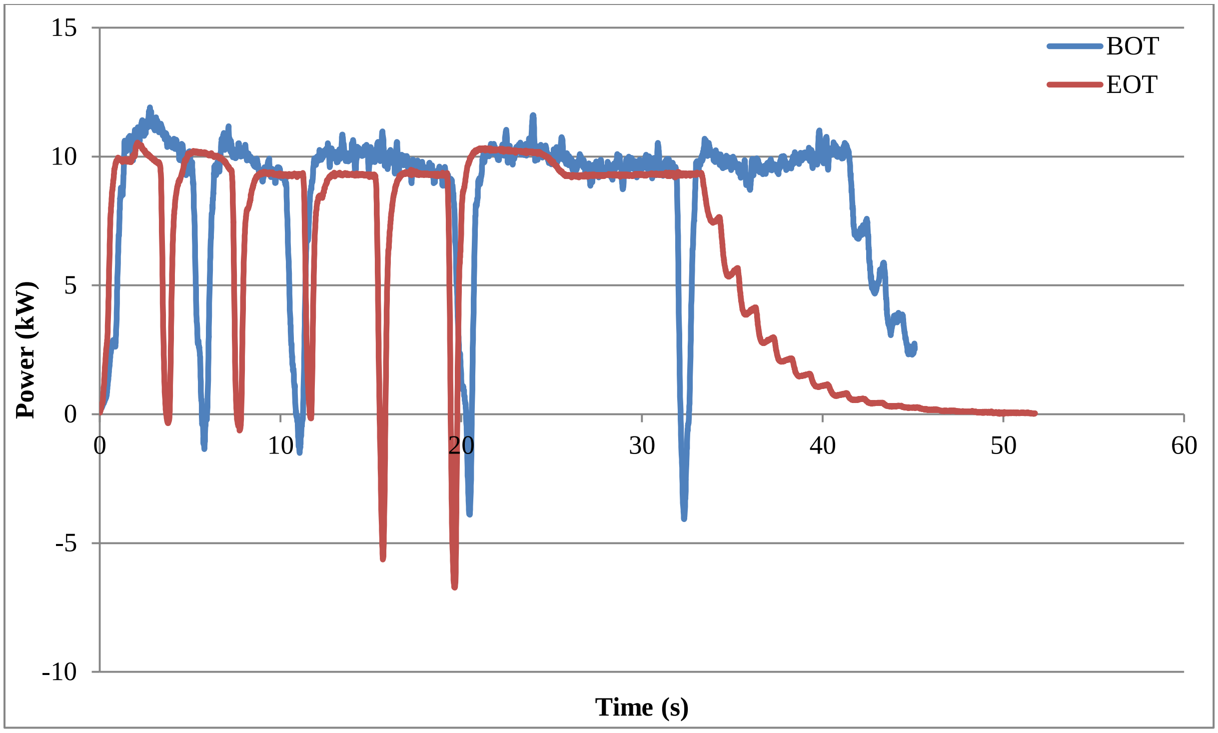

Figure 8. Battery power versus time from acceleration testing

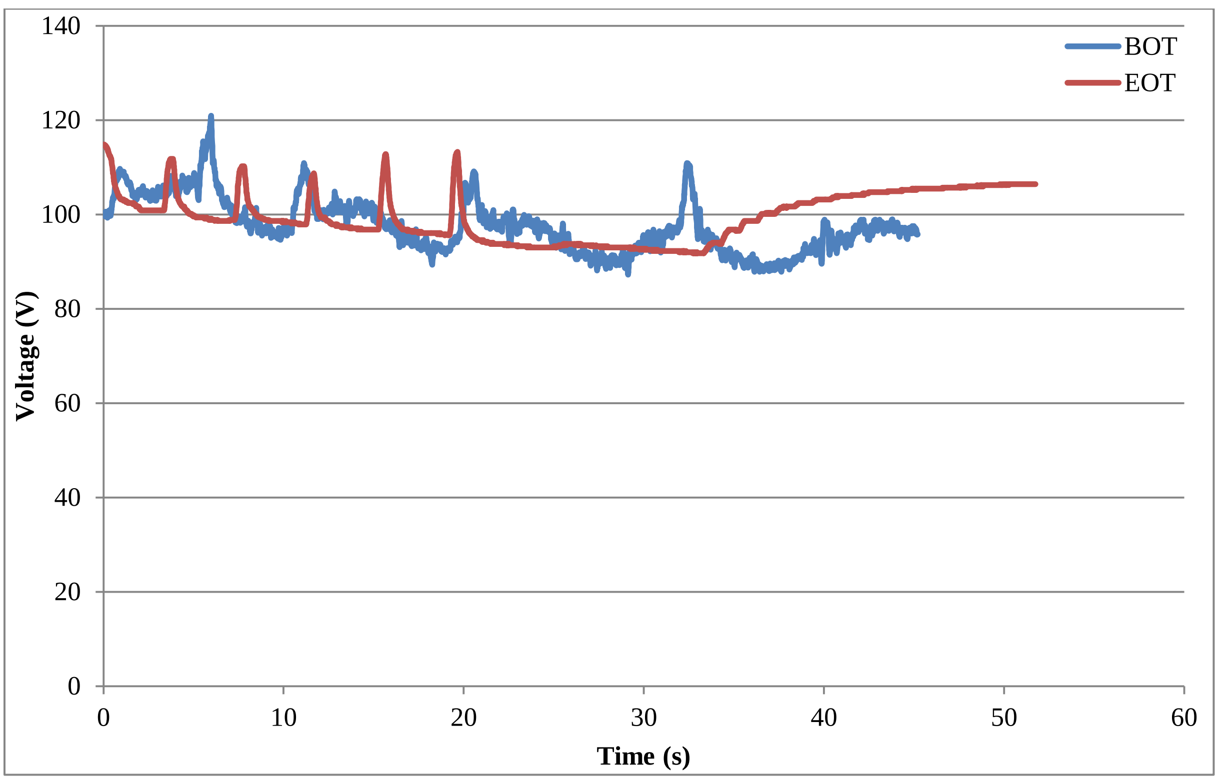

Figure 9. Battery voltage versus time from acceleration testing

Figure 10 shows battery current versus time during the 1-mile acceleration test at BOT and EOT. 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.

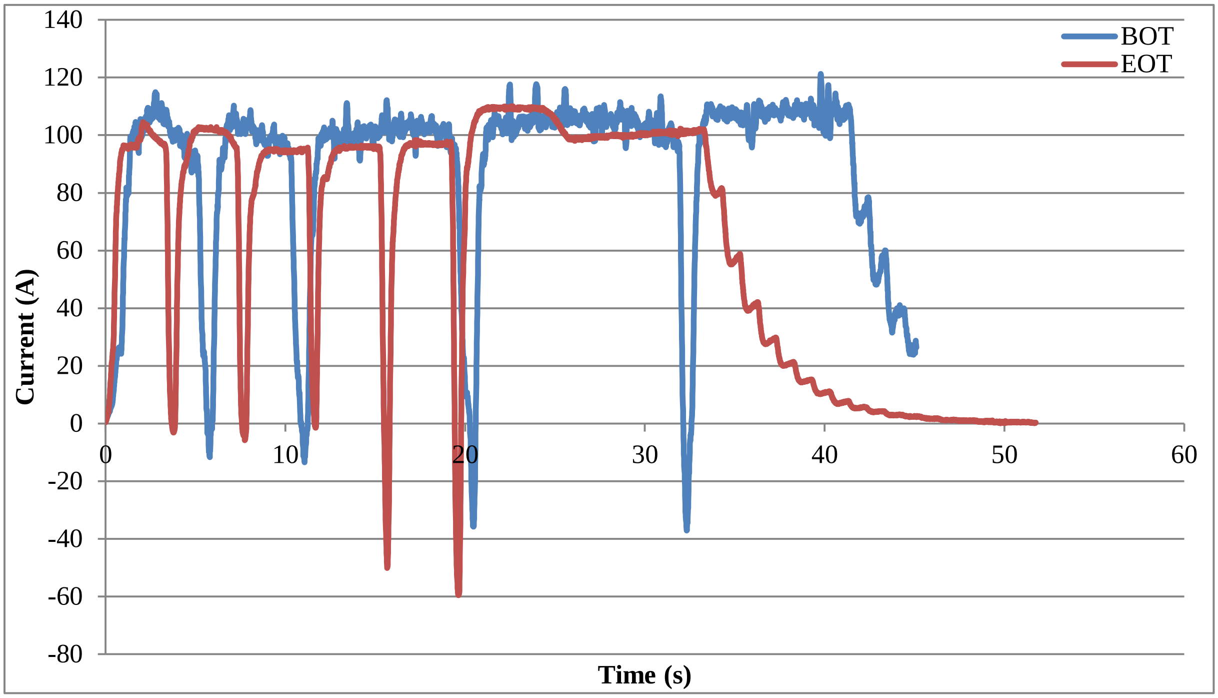

Figure 10. Battery current versus time from acceleration testing

1.4 Fuel Economy Test Results

Battery performance results were obtained from testing conducted on a chassis dynamometer with Honda CR-Z 4932 at Argonne National Laboratory. The Urban Dynamometer Drive Schedule (UDDS), Highway Fuel Economy Test (HWFET), and a UDDS[4] at an elevated temperature of 95 ºF with a simulated solar load of 850 W/m^2 were conducted at BOT. Battery performance results from the dynamometer drive cycle testing are summarized in Table 4.

Table 4. Battery performance results from the dynamometer drive-cycle testing

	UDDS	**HWFET**	**UDDS (at 95^{o}F+850 W/m^2)**
Peak Discharge Power (kW):	10.1	9.43	9.08
Peak Charge Power (kW):	6.23	5.76	7.86
Measured Discharge Energy (kWh):	0.15	0.10	0.23
Measured Charge Energy (kWh):	0.13	0.12	0.20
Measured Discharge Capacity (Ah):	1.23	0.88	1.90
Measured Charge Capacity (Ah):	1.15	1.09	1.78
Minimum Pack Voltage (V):	127.5	125.7	126.5
Maximum Pack Voltage (V):	103.5	104.9	96.7
Discharge/Charge Capacity Ratio:	1.07	0.81	1.07

[4] UDDS and HWFET drive cycles were 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

Figures 11, 12, and 13 show how the hybrid battery pack is utilized in comparison to vehicle speed for the UDDS, HWFET, and UDDS at the elevated temperature and simulated solar load cycles. 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 frequently transitions between discharging and charging. During the HWFET cycle, which simulates highway driving where the vehicle is in nearly continuous motion, the battery pack is cycled less frequently. During the UDDS at the elevated temperature of 95 ºF and simulated solar load of 850 W/m^2, the battery pack performs the same as the original UDDS cycle.

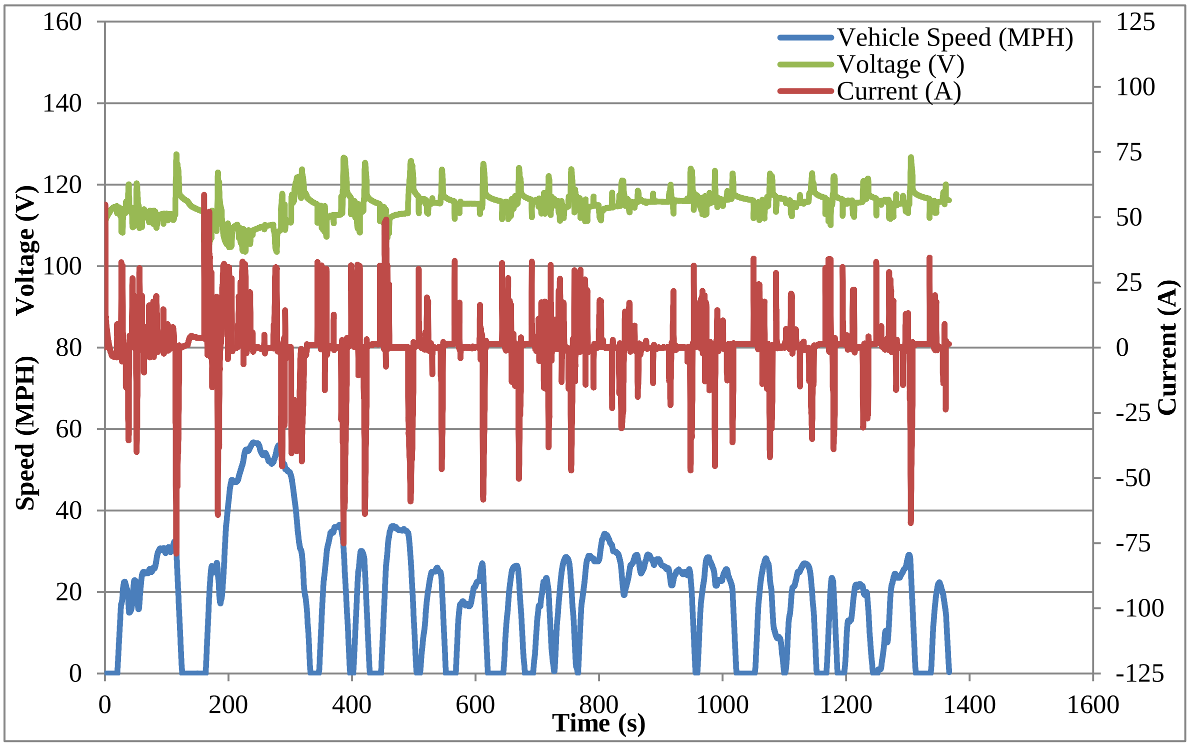

Figure 11. Battery pack current, voltage, and vehicle speed for the UDDS cycle

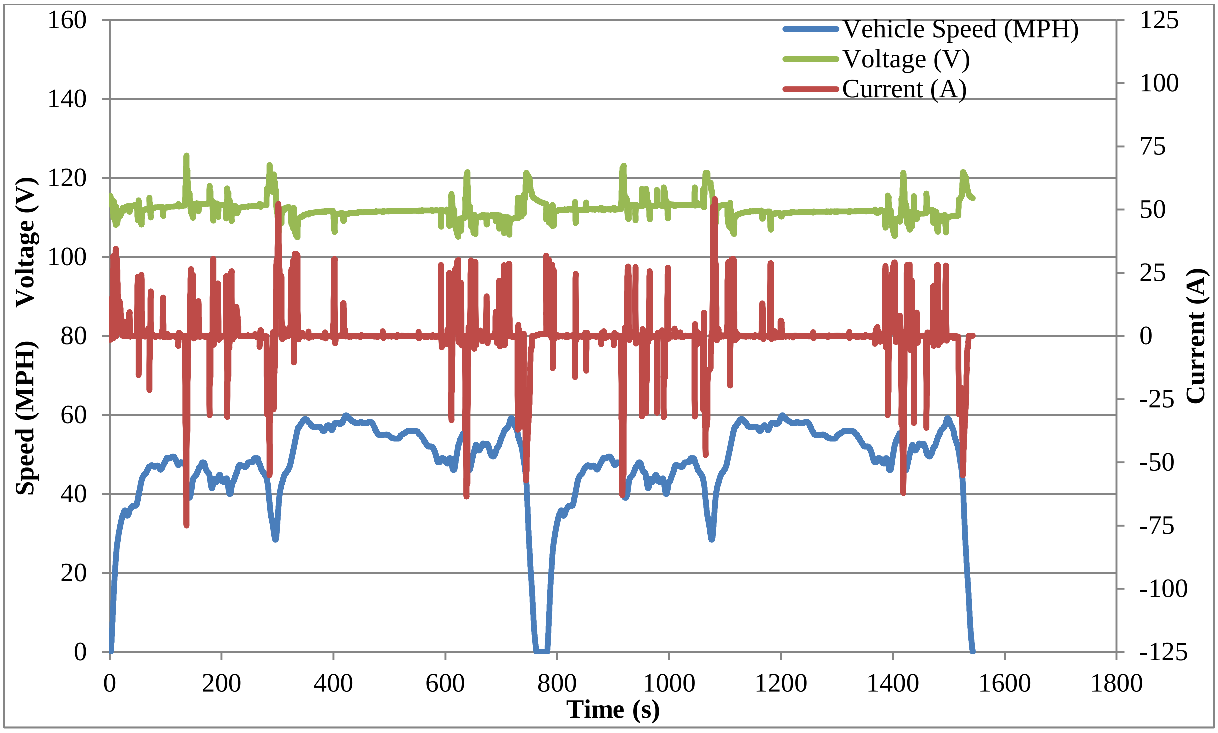

Figure 12. Battery pack current, voltage, and vehicle speed for two back-to-back HWFET cycles

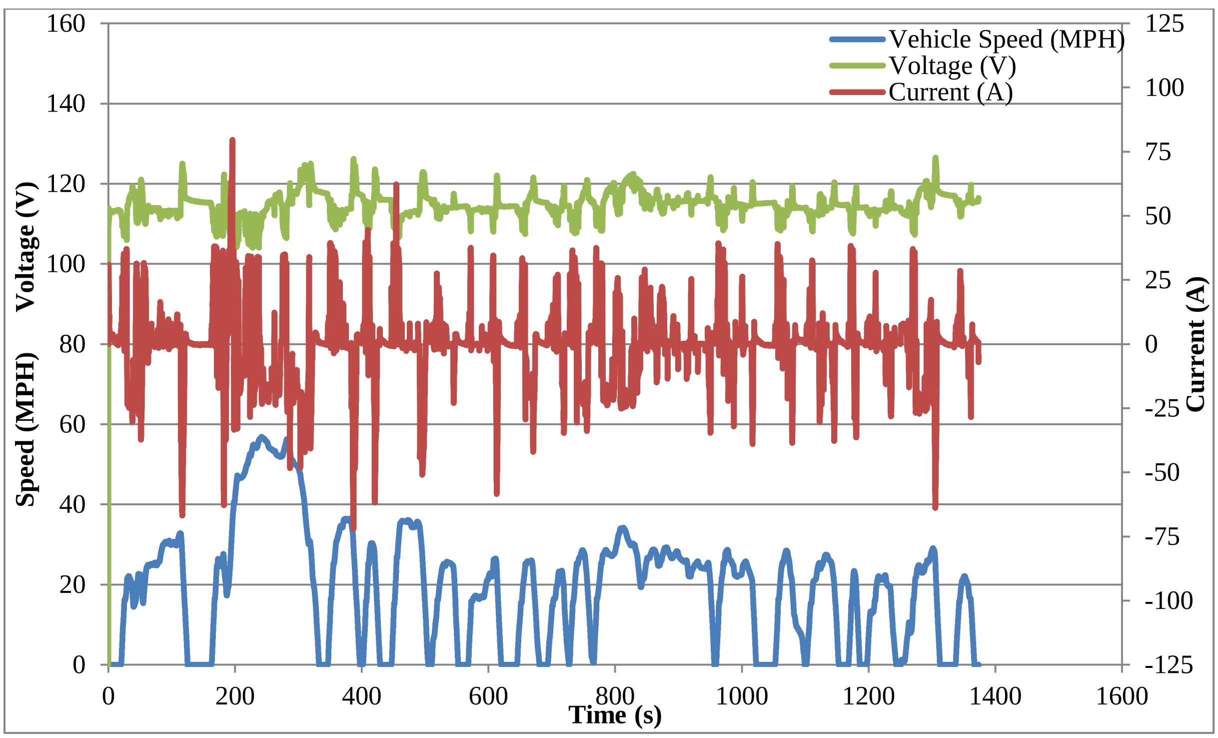

Figure 13. Battery pack current, voltage, and vehicle speed for a UDDS cycle with the elevated ambient temperature of 95 ºF and simulated solar load of 850 W/m^2

1.5 On-Road Test Results

On-road fuel economy for the vehicle was recorded while the vehicle was operating in a fleet[5] with approximately 35% city[6] and 65% highway routes. Figure 14 presents the combined monthly fuel economy and cumulative fuel economy for the CR-Z HEV 4466 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 the fleet testing was 36.8 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 relatively steady over the entirety of testing.

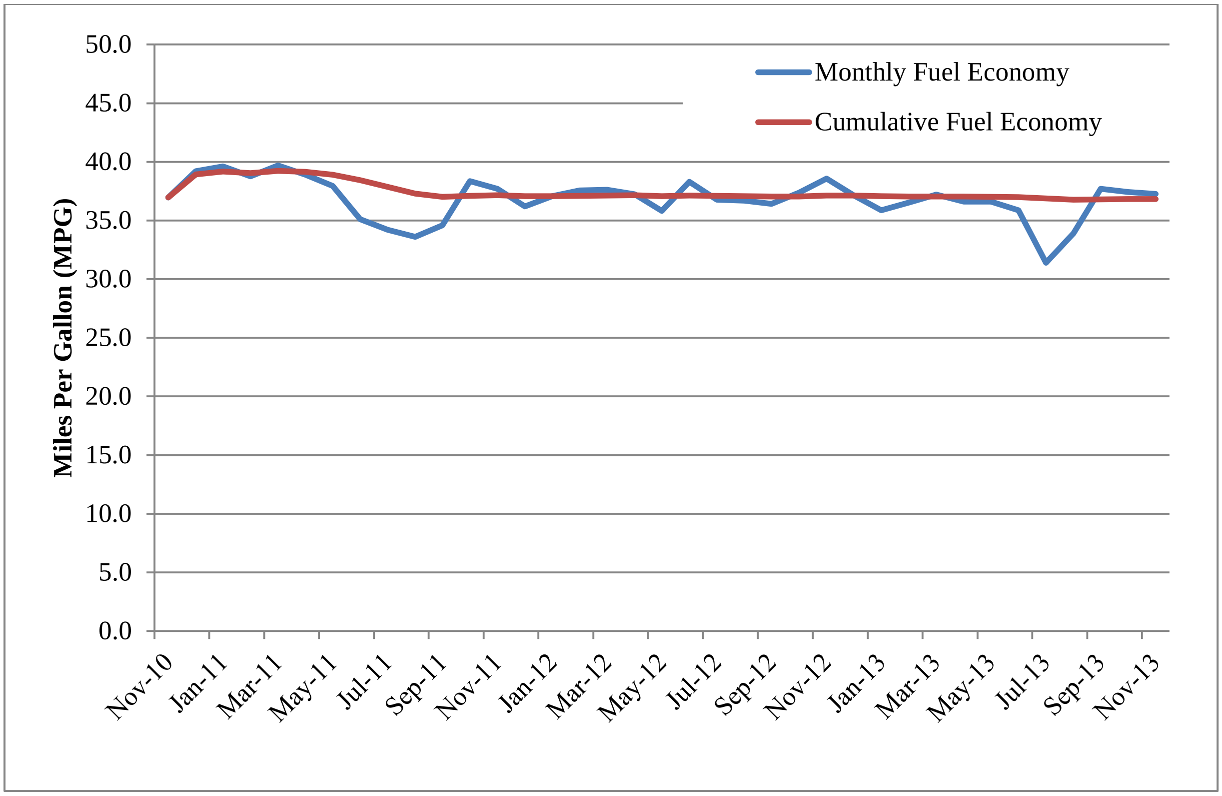

Figure 14. Monthly and cumulative fuel economy

2 SUMMARY

The Honda CR-Z 4466 experienced a 12% decrease in battery capacity and stayed below DOE targets for all aspects of the HPPC test over the duration of 156,271 miles of fleet testing.

[5] On-road fleet testing is performed by Intertek (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.

[6] City routes are determined as trips with an average speed less than 42 mph.

Appendix A

Vehicle Specifications and Test Results Summary

Vehicle Specifications	Battery Specifications
Manufacturer: Honda Model: CR-Z Year: 2011 Motor Power Rating[a]: 10 kW VIN #: JHMZF1C67BS004466	Manufacturer: Hitachi Battery Type: Nickle Metal Hydride (NiMH) Rated Capacity: 5.75 Ah Nominal Pack Voltage: 109.2 VDC Nominal Cell Voltage: 1.3 V Number of Cells: 84

BOT Vehicle Performance Test Results[b]	EOT Vehicle Performance Test Results[b]
Acceleration Test	**Acceleration Test**
Average Discharge Power Over 10 seconds[c]: 8.53 kW Peak Discharge Power Over Test: 11.9 kW Energy Discharged Over Test[d]: 107.1 Wh Capacity Discharged Over Test[d]: 1.11 Ah Minimum Discharge Pack Voltage: 87.2 VDC Minimum Discharge Cell Voltage: 1.04 V	Average Discharge Power Over 10 seconds[c]: 8.21 kW Peak Discharge Power Over Test: 10.5 kW Energy Discharged Over Test[d]: 87.2 Wh Capacity Discharged Over Test[d]: 0.91 Ah Minimum Discharge Pack Voltage: 91.8 VDC Minimum Discharge Cell Voltage: 1.09 V

Fuel Economy Chassis Dynamometer Testing

	UDDS	HWFET	UDDS (at 95 $^{\circ}$F +850 W/m^2)
Peak Discharge Power (kW):	10.1	9.43	9.08
Peak Charge Power (kW):	6.23	5.76	7.86
Measured Discharge Energy (kWh):	0.15	0.10	0.23
Measured Charge Energy (kWh):	0.13	0.12	0.20
Measured Discharge Capacity (Ah):	1.23	0.88	1.90
Measured Charge Capacity (Ah): A(Ah(Ah):	1.15	1.09	1.78
Minimum Pack Voltage (V):	127.5	125.7	126.5
Maximum Pack Voltage (V):	103.5	104.9	96.7
Discharge/Charge Capacity Ratio:	1.07	0.81	1.07

Beginning-of-Test Battery Laboratory Test Results

Hybrid Pulse Power Characterization Test	Static Capacity Test
Peak Pulse Discharge Power @ 10 s[f]: 8.74 kW Peak Pulse Charge Power @ 10 s[f]: 8.81 kW Maximum Cell Charge Voltage: 1.5 V Minimum Cell Discharge Voltage: 1.0 V	Measured Average Capacity: 5.79 Ah Measured Average Energy Capacity: 600 Wh Vehicle Odometer: 3,995 mi Date of Test: December 30, 2010

End-of-Test Battery Laboratory Test Results

Hybrid Pulse Power Characterization Test	Static Capacity Test
Peak Pulse Discharge Power @ 10 s[f]: 8.42 kW Peak Pulse Charge Power @ 10 s[f]: 7.87 kW Maximum Cell Charge Voltage: 1.5 V Minimum Cell Discharge Voltage: 1.0 V	Measured Average Capacity: 5.11 Ah Measured Average Energy Capacity: 530 Wh Vehicle Odometer: 160,266 mi Date of Test: January 16, 2014

Degradation of Battery Over Test Period[g]	
Hybrid Pulse Power Characterization Test	**Static Capacity Test**
Peak Pulse Discharge Power @ 10 s[f]: 0.32 kW (3.7%) Peak Pulse Charge Power @ 10 s[f]: 0.94 kW (11%)	Measured Average Capacity: 0.68 Ah (12%) Measured Average Energy Capacity: 70 Wh (12%)

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 CR-Z VIN 2982.
c. The peak power at a specified duration is the average power value over a specified interval.
d. The capacity and energy values are defined as the net values 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.