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2011 Chevrolet Volt VIN 0815 Plug-In Hybrid Electric Vehicle Battery Test Results

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ABSTRACT

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 plug-in hybrid electric vehicles (PHEVs), including testing the PHEV batteries when both the vehicles and batteries are new and at the conclusion of 12,000 miles of on-road fleet testing. This report documents battery testing performed for the 2011 Chevrolet Volt PHEV (VIN 1G1RD6E48BU100815). The battery testing was performed by the Electric Transportation Engineering Corporation (eTec) 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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ACRONYMS

Ah	amp-hour
BOT	beginning of test
CD	charge-depleting
CS	charge-sustaining
DOD	depth of discharge
DOE	Department of Energy
EOT	end of test
EVPC	Electric Vehicle Power Characterization
EVSE	electric vehicle supply equipment
kW	kilowatt
PHEV	plug-in hybrid vehicle
SOC	state of charge
V	volt
VDC	volt direct current
VIN	vehicle identification number
Vpc	volt per cell
Wh	watt-hour
USABC	United States Advanced Battery Consortium

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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 plug-in hybrid electric vehicles (PHEVs), including testing the PHEV batteries when both the vehicles and batteries are new (beginning-of-test, or BOT) and at the conclusion of 12,000 miles of accelerated on-road fleet testing (end-of-test, or EOT). The BOT testing takes place not immediately after vehicle receipt, but instead after the vehicle has been "broken in", meaning that its drivetrain components are sufficiently worn and functioning smoothly. The BOT for this vehicle took place at 8,478 miles, beginning on March 6, 2012. The EOT took place at 23,314 miles, beginning on October 15, 2012. This report provides test results for BOT and EOT battery testing conducted on a 2011 Chevrolet Volt PHEV with VIN 0815 (Full VIN: 1G1RD6E48BU100815) in both laboratory and on-road settings. The battery laboratory test results include those from the Static Capacity Test[3] and the Electric Vehicle Power Characterization (EVPC) Test and the Constant Power Discharge (CPD) Test[4]. Vehicle test results include those from Acceleration Testing and Fuel Economy Testing.[5]

The battery and vehicle testing was performed by the Electric Transportation Engineering Corporation (eTec) 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 beginning-of-test (BOT) and end-of-test (EOT) static capacity tests are provided below in Table 1. The rated capacity of the 2011 Chevrolet Volt battery is 45 Ah.

Table 1. Static capacity test results

	Test Date	Odometer (mi)	Measured Capacity (Ah)	Measured Energy (kWh)
BOT	March 6, 2012	8,478	41.8	15.2
EOT	October 15, 2012	23,314	40.9	14.9
Difference	—	14,836	0.9 (2.2%)	0.3 (2.0%)

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/3 constant-current discharge rate at BOT and EOT.

[3] Static Capacity and Constant Power Discharge test procedures are based on the USABC Electric Vehicle Battery Test Procedures Manual Rev 2, January 1996, Procedures 2 and 3, respectively.

[4] EVPC and CPD testing is based on the USABC Electric Vehicle Battery Test Procedures Manual Rev 3, publication pending.

[5] Acceleration Testing and Fuel Economy Testing procedures were performed in accordance with the AVTA PHEVAmerica test procedures ETA-PHTP02 and ETA-PHTP03, respectively.

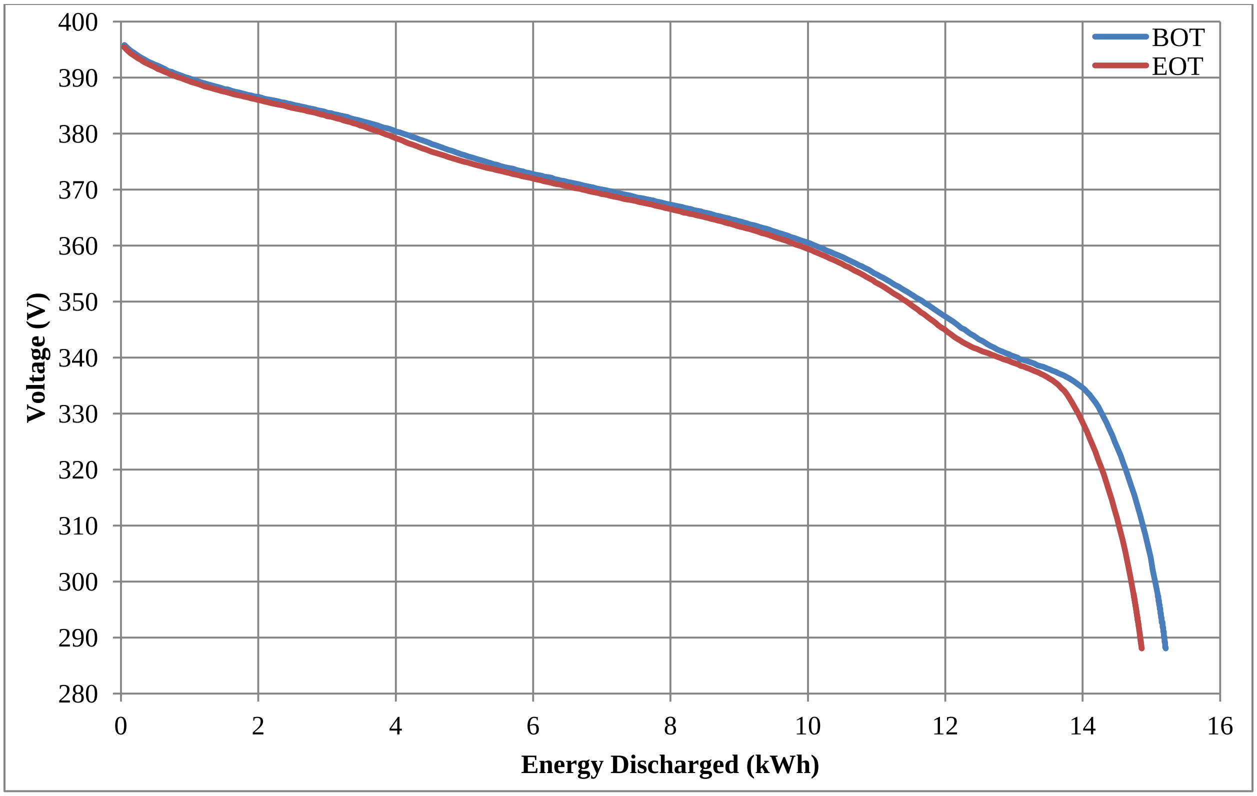

Figure 1. Voltage versus energy discharged during the static capacity test

1.2 Electric Vehicle Power Characterization Test Results

The EVPC Test commenced immediately following the Static Capacity Test. The EVPC results are summarized below in Table 2.

Table 2. EVPC test results

	Discharge Power Capability @ 80% DOD (kW)	Discharge Resistance @ 80% DOD (Ω)	Charge Power Capability @ 20% DOD (kW)	Charge Resistance @ 20% DOD (Ω)
BOT	115.9	0.1402	55.9	0.1097
EOT	100.9	0.1541	52.4	0.1232
Difference	15 (12.9%)	-0.014 (-9.9%)	3.5 (6.3%)	-0.135 (-12.3%)

Figure 2 and Figure 3 illustrate the battery's charge and discharge pulse resistance graphs which show internal resistance at various DODs. Each curve represents the resistance at the end of the specified pulse interval.

Figure 4 and Figure 5 illustrate the battery's charge and discharge pulse power capability graphs which show the calculated useable power at various DODs. Each curve represents the pulse power capability at the end of the specified pulse interval at the cell voltage limits.

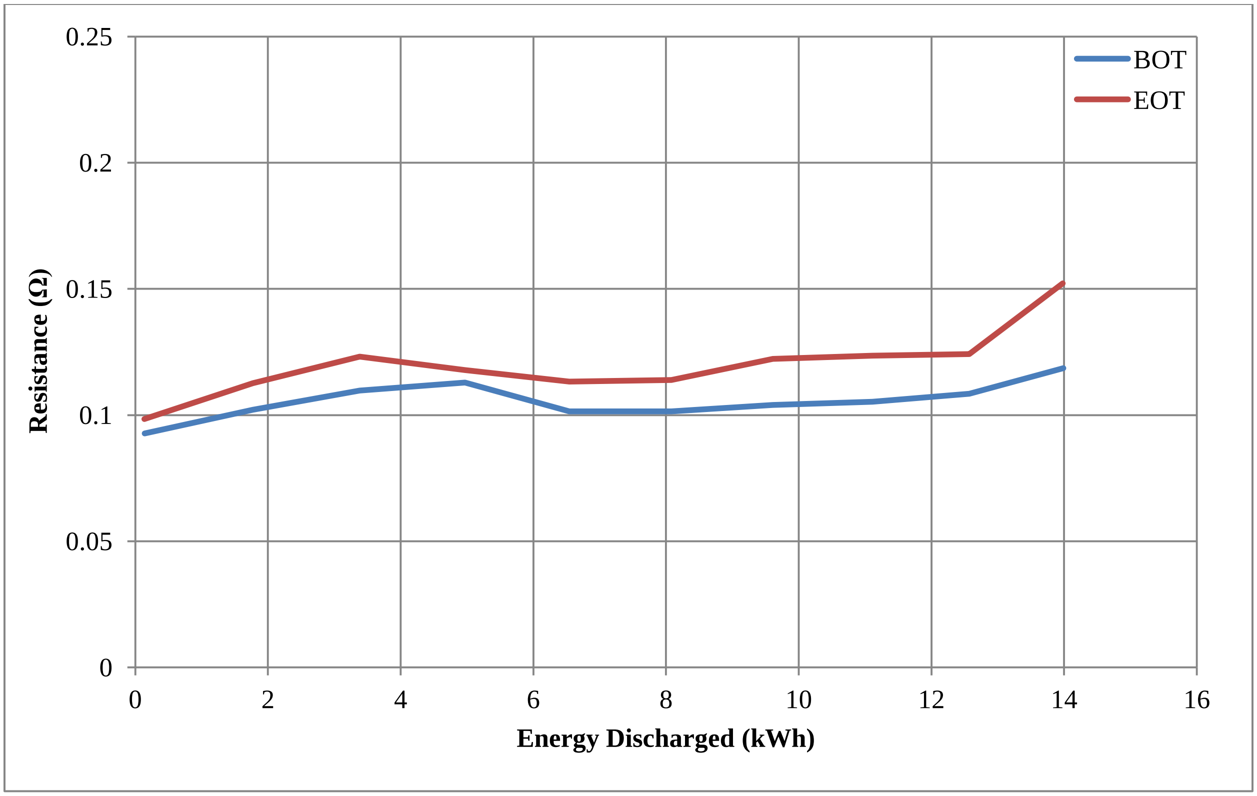

Figure 2. Charge pulse resistance versus energy discharged

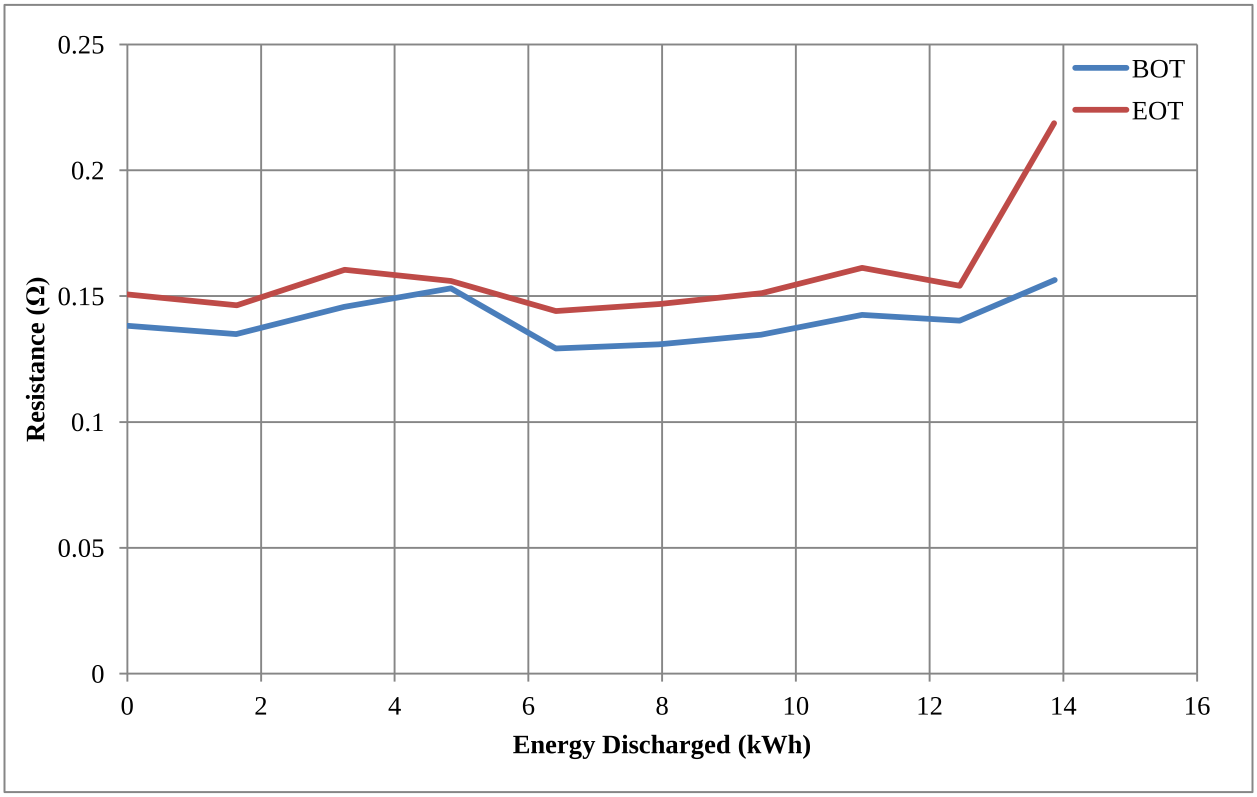

Figure 3. Discharge pulse resistance versus energy discharged

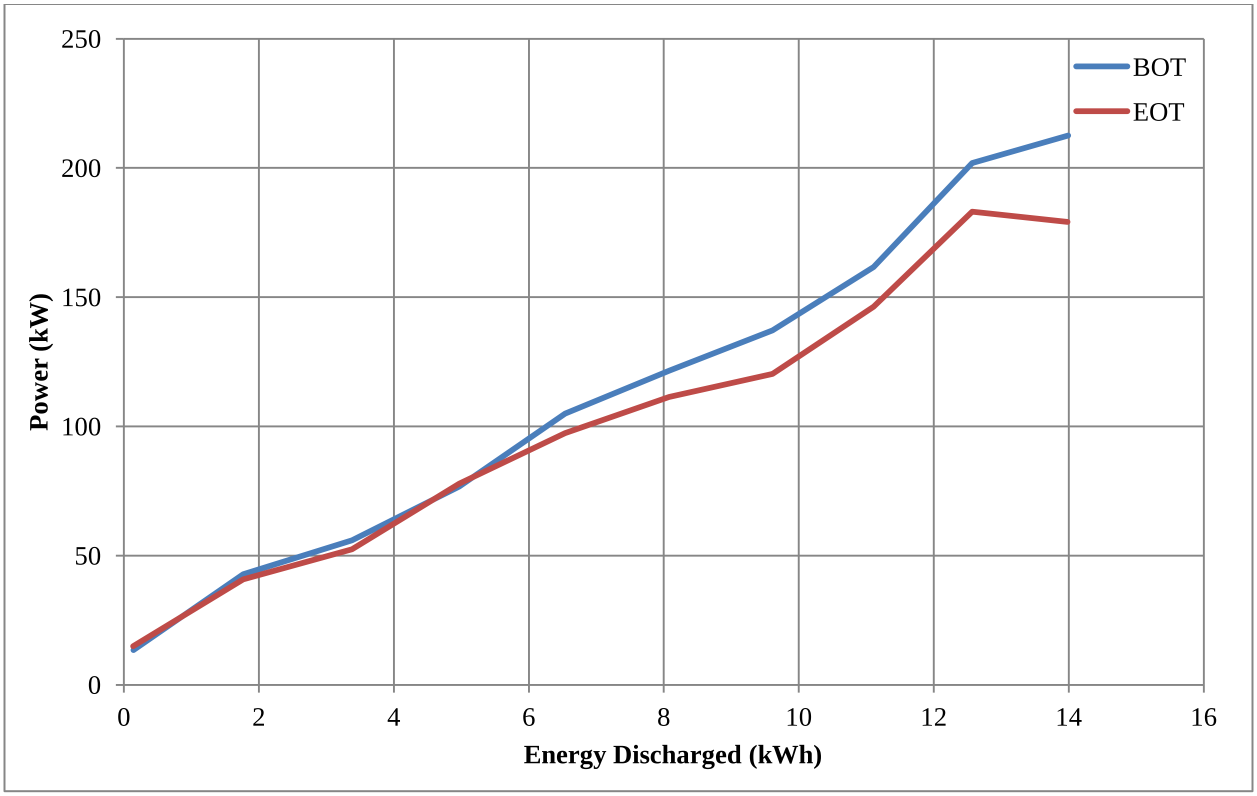

Figure 4. Charge pulse power capability versus energy discharged

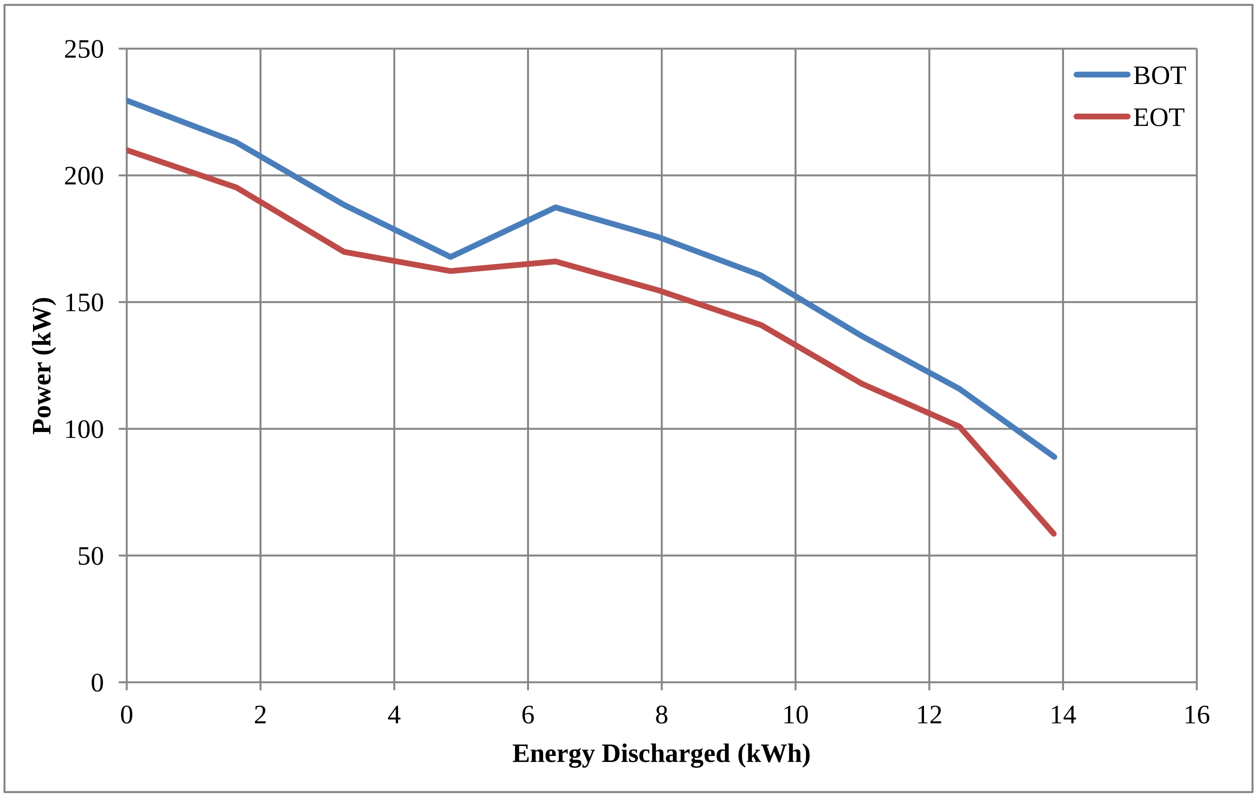

Figure 5. Discharge pulse power capability versus energy discharged

1.3 Constant Power Discharge Test Results

The CPD Test commenced immediately following the EVPC Test. The CPD Test results are summarized below in Table 3.

Table 3. Constant Power Discharge test results

	Capacity Discharged (Ah)	Energy Discharged (kWh)	Discharge Power Rate (kW)
BOT	41.9	15.56	15.25
EOT	39.9	14.27	15.25
Difference	2.0 (4.8%)	1.29 (8.3%)	—

1.4 Acceleration Test Results

Acceleration testing took place beginning on February 6, 2012. BOT and EOT battery performance results from vehicle on-track acceleration tests are summarized below in Table 4 for charge-depleting (CD) and charge-sustaining (CS) operation. The discharge current and power refer to the energy out of the battery.

Table 4. Acceleration test results for BOT and EOT on-track acceleration tests

	Average Discharge Power Over Initial 30 s (kW)[6]	Energy Discharged Over Full Run (kWh)	Capacity Discharged Over Full Run (Ah)	Peak Discharge Power Over Full Run (kW)	Peak Discharge Current Over Full Run (A)
BOT CD	97.8	0.997	2.893	112.3	321.0
BOT CS	73.1	0.628	1.955	93.8	300.8
EOT CD	97.8	1.07	3.035	113.3	318.0
EOT CS	73.6	0.611	1.889	109.7	338.7

Figure 6 and Figure 7 show battery power versus time during the charge depleting and charge sustaining acceleration tests at EOT and BOT. These graphs are the basis for power calculations over specified time or over the full test run 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 nearly the peak value. For the charge-depleting tests, the power then remains relatively constant until battery or vehicle system dynamics cause the power to adjust while holding a top speed. For charge-sustaining tests, the power adjusts based on vehicle dynamics, which include the battery management system, to allow the battery power to combine with power from the gasoline engine to provide total power output.

[6] For acceleration testing, the average discharge power over the first 30 seconds is shown as an indirect metric comparable to the EVPC discharge pulse power capability. While limitations such as vehicle dynamics, conductor size, battery terminal size, etc., will rarely allow the battery to perform in-vehicle to the same power output levels shown capable in laboratory testing, the comparison of these values allows for a better understanding of the theoretical capability of the battery pack versus actual application.

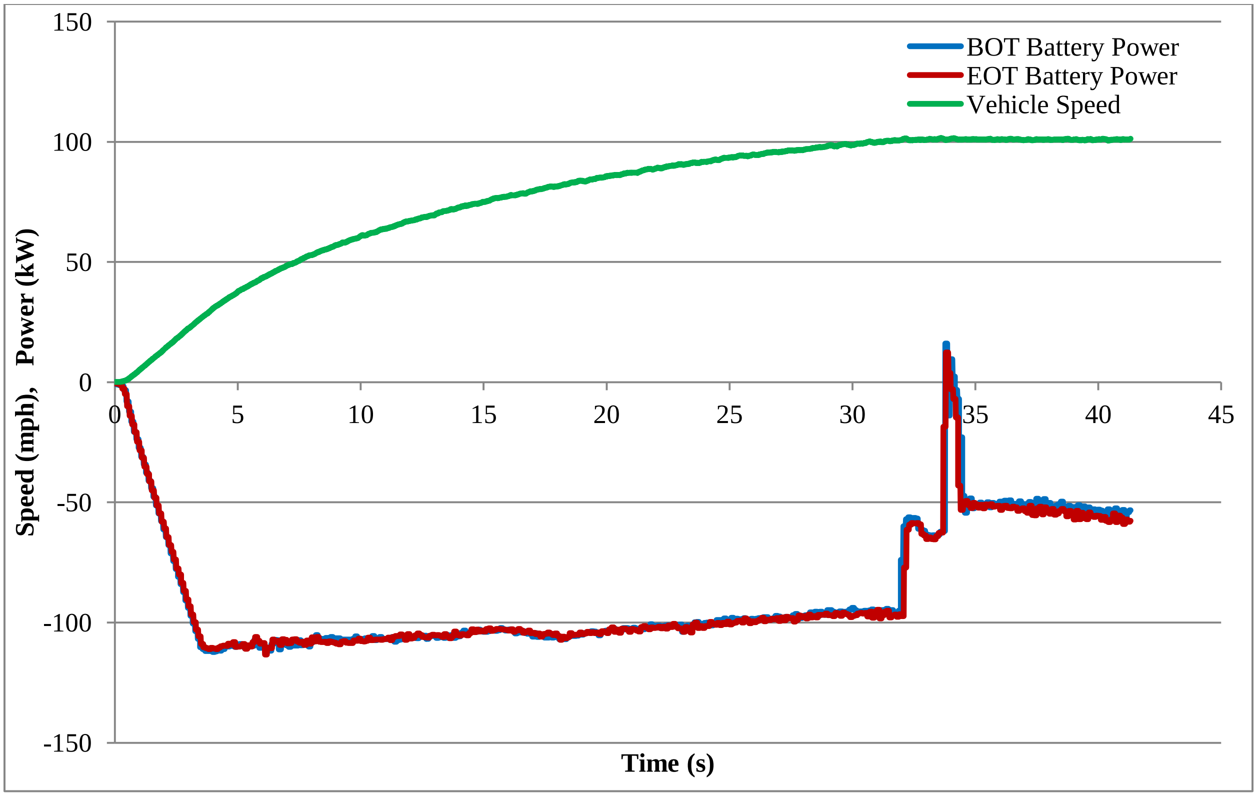

Figure 6. Charge-depleting battery power and vehicle speed versus time from acceleration testing

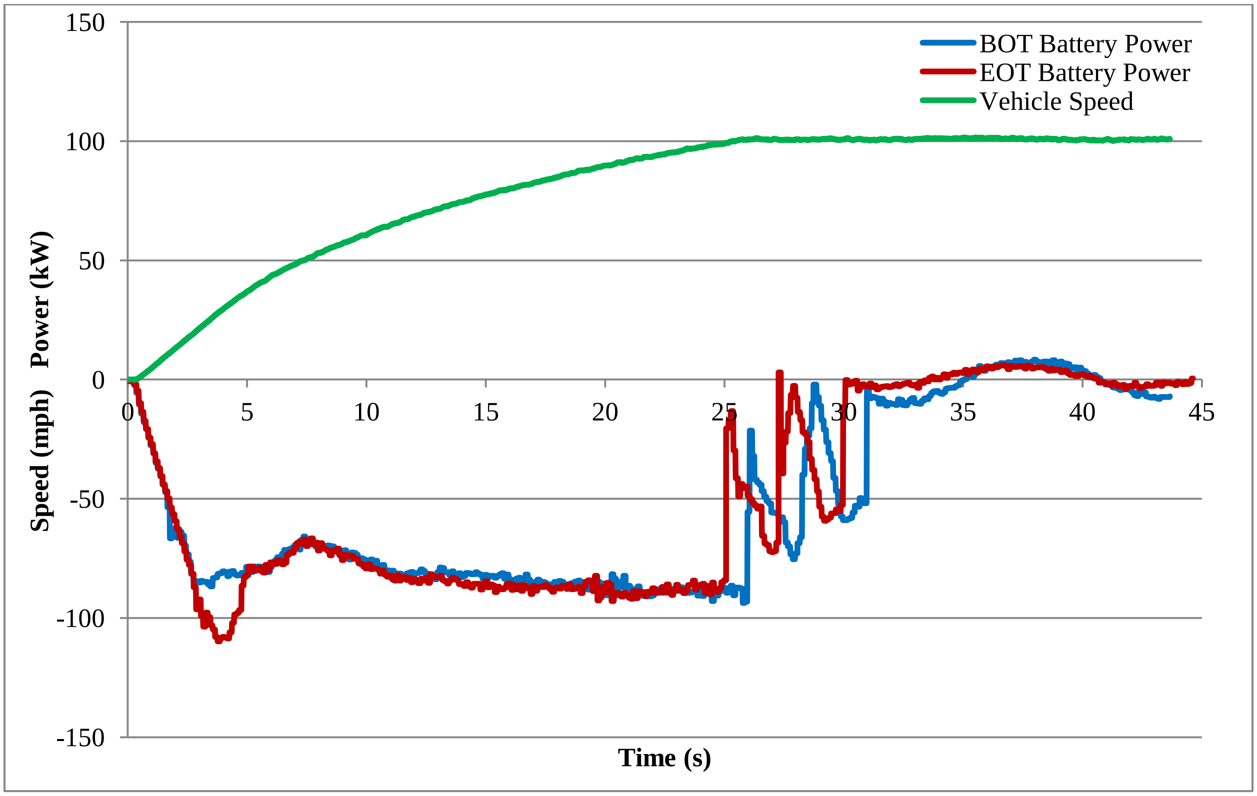

Figure 7. Charge-sustaining battery power and vehicle speed versus time from acceleration testing

Figure 8 and Figure 9 show the charge-depleting and charge-sustaining battery voltage versus time plots during acceleration testing at BOT and EOT. Values are analyzed to determine the minimum voltage allowed by the battery control module for each vehicle mode (charge-depleting and charge-sustaining), if possible. This graph also shows the impact of power electronics and battery management system on the voltage response.

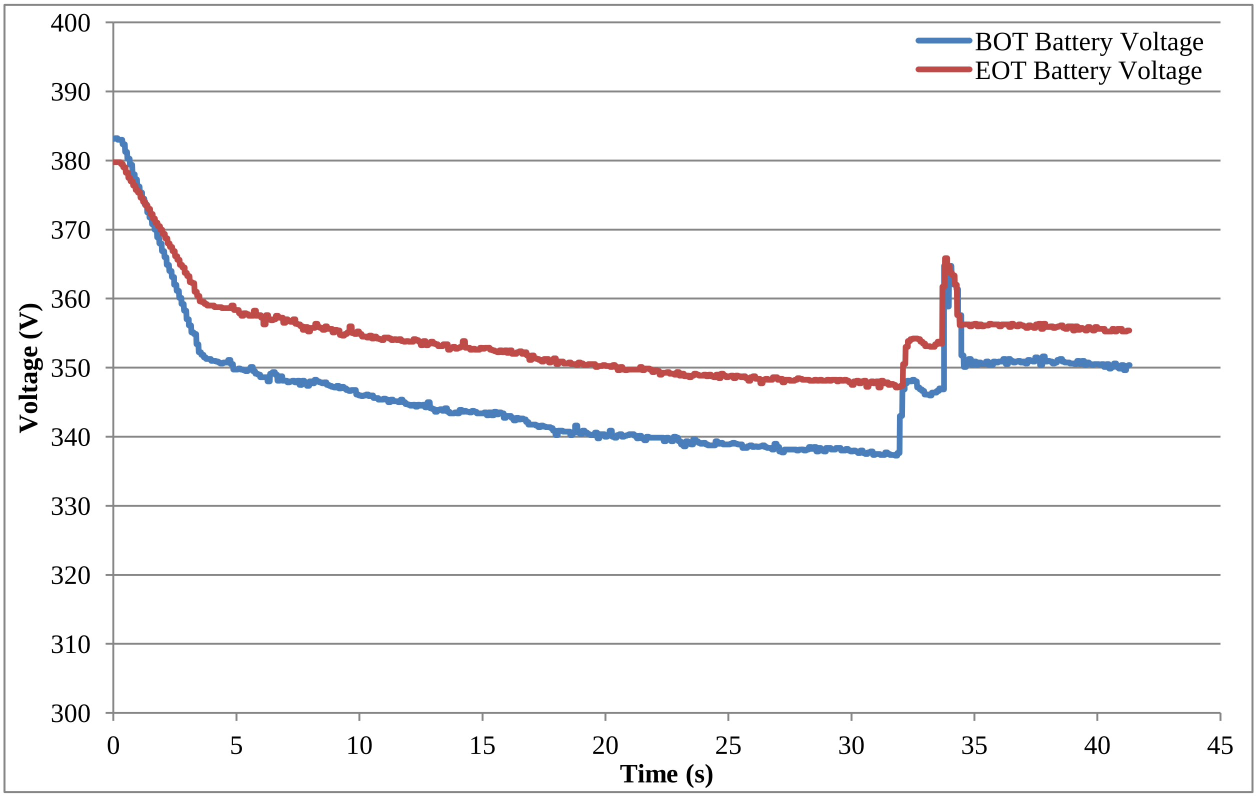

Figure 8. Charge-depleting battery voltage versus time from acceleration testing

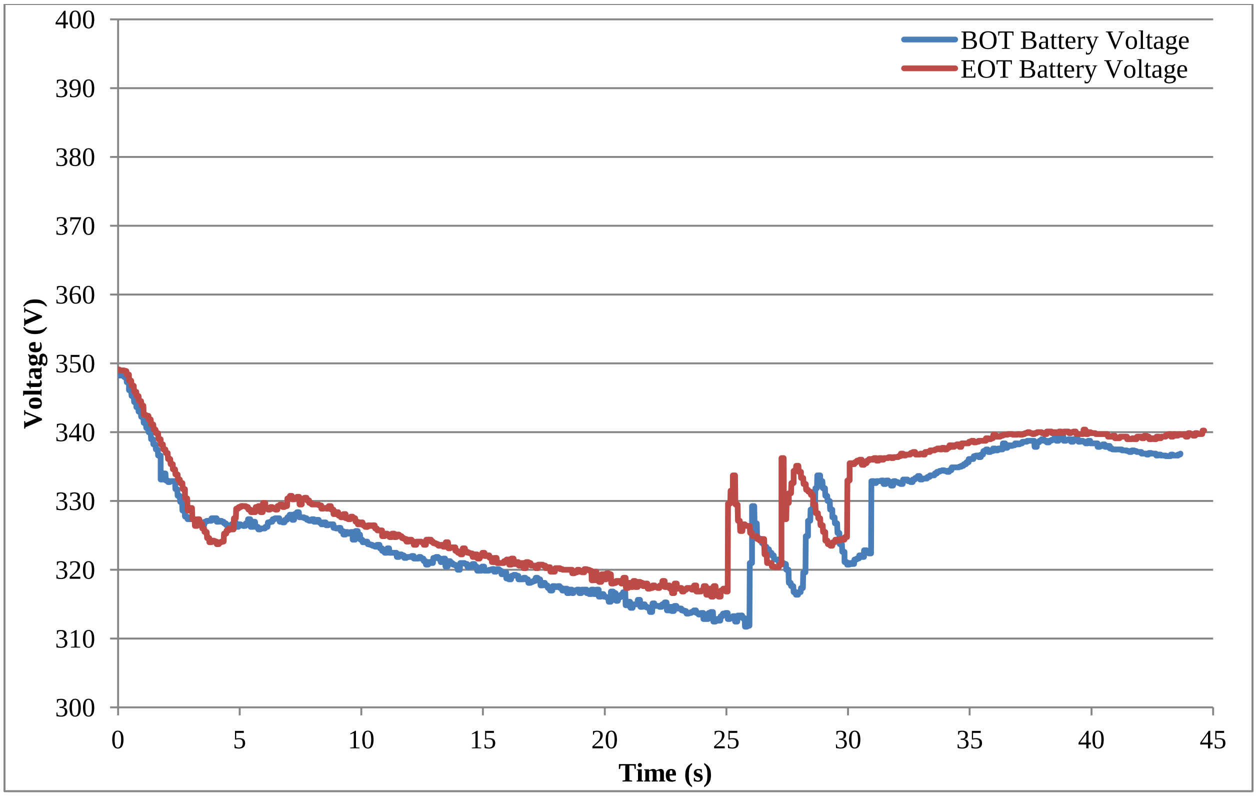

Figure 9. Charge-sustaining battery voltage versus time from acceleration testing

Figure 10 and Figure 11 show charge-depleting and charge-sustaining battery current and vehicle speed versus time plots during acceleration testing 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 6 and Figure 7 can be obtained by simply multiplying the voltage values from Figure 8 and Figure 9 by the current values in Figure 10 and Figure 11 for charge-depleting and charge-sustaining, respectively.

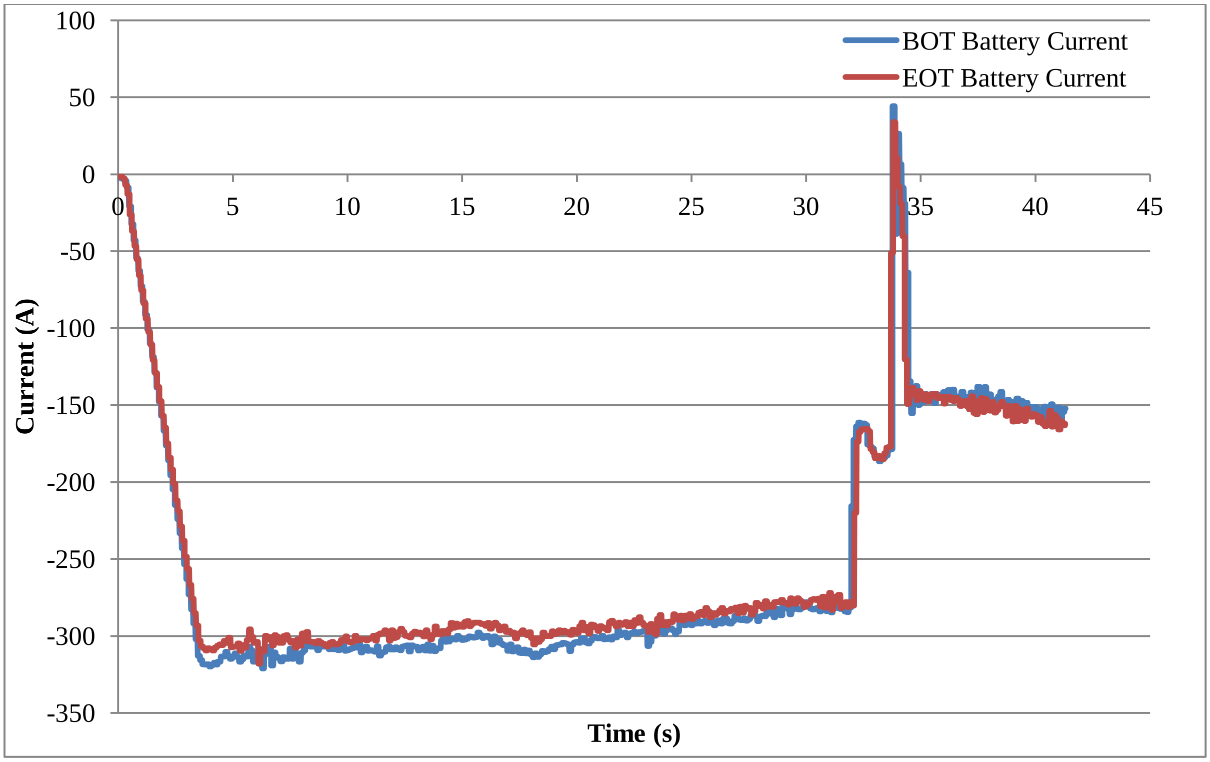

Figure 10. Charge-depleting battery current versus time from acceleration testing

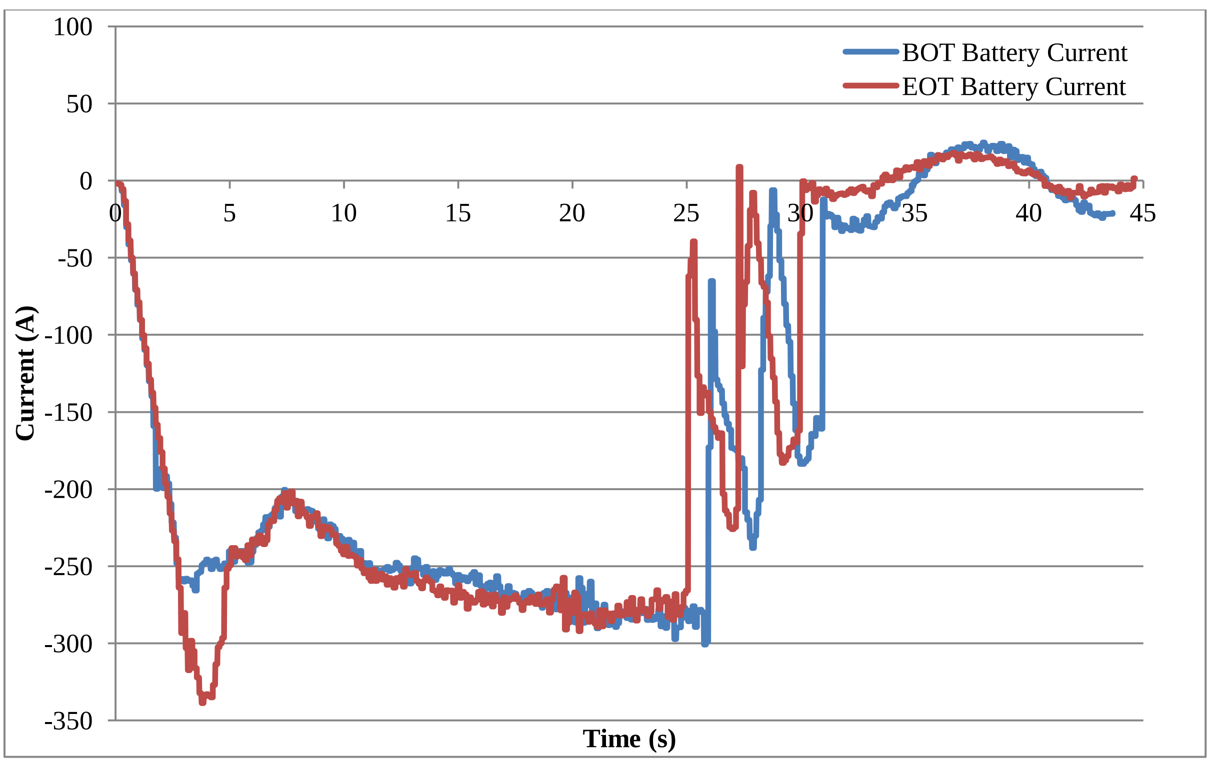

Figure 11. Charge-sustaining battery current versus time from acceleration testing

1.5 Fuel Economy Test Results

This section contains battery performance results from two testing regimes: (1) testing conducted on a chassis dynamometer (using the Urban Dynamometer Drive Schedule (UDDS), Highway Fuel Economy Test (HFET), and US06[7]) at BOT; and (2) testing the vehicle in an on-road fleet[8]. Dynamometer data and calculations are summarized in Table 5.

Table 5. Battery performance results from dynamometer drive cycle testing

	UDDS	HWY	US06
Average Net Capacity Discharge for CD Miles per Cycle[9] (Ah):	4.544	6.505	6.935
Average Net Capacity Discharged for CS Miles per Cycle[8] (Ah):	0.156	0.234	0.609
Total Net Energy Discharge for all Miles in CD Mode[10] (kWh):	8.72	8.88	8.97
Total Net Capacity Discharge for all Miles in CD Mode[9] (Ah):	27.67	26.93	26.75
Transition from CD to CS Pack Voltage (V):	345.2	345.7	337.7
CD Max Drive Power – all cycles (kW):	55.7	49.5	79.3
CD Max Drive Current – all cycles (A):	147.6	135.8	212.0
CD Max Regenerative Power – all cycles (kW):	40.4	52.0	70.4
CD Max Regenerative Current – all cycles (A):	106.7	135.5	195.7
CD Average Current – all cycles (A):	10.7	28.8	35.2

Fleet data results are summarized in Table 6. The vehicle accumulated 14,836 miles from May 8, 2012 to September 28, 2012, while using 1001.1 kWh of AC energy and 411.3 gallons of fuel.

Table 6. On-road fleet testing performance results

Cumulative AC Energy Used (kWh):	1,001.1
Percent of City Miles Driven (%):	50.0
Percent of Highway Miles Driven (%):	50.0
Fuel Economy (mpg):	36.1
Fuel Economy (mpgge[11]):	33.6

Figure 12 shows the on-road vehicle usage over the duration of fleet testing by presenting the cumulative and monthly fuel economy, mileage accumulated, and monthly AC energy used. The monthly fuel economy is derived from the amount of fuel consumed, based on fleet fueling records recorded at the end

[7] Urban Dynamometer Drive Schedule, Highway Fuel Economy Test, and US06 were performed as defined by the Environmental Protection Agency. The definition of each drive schedule can be found at http://www.epa.gov/nvfel/methods/uddsdds.gif.

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

[9] These values were calculated by averaging the vehicles discharge capacity over multiple cycles for the given drive cycle. Each cycle used started and ended in the mode stated; no blended drives with both CD and CS operation were considered in this calculation.

[10] These values were calculated by summing the net capacity or energy discharged for consecutively run drive cycles of the same type while the vehicle remained in charge-depleting mode. If the vehicle mode changed in the middle of a cycle, calculations for capacity and energy discharged were made up to the change in mode and added to the total value.

[11] The fuel economy in miles-per-gasoline-gallon-equivalent (mpgge) is calculated by dividing the total mileage accumulated by the sum of the gallons of gasoline used and gasoline energy equivalent of the electrical energy (i.e., the amount in kWh divided by 33.7 kWh per gallon of gasoline). The disaggregation of CD versus CS miles is not available, so the total mileage is used only.

of the month, and the mileage accumulated, based on vehicle odometer readings recorded at the end of the month. The AC energy used is recorded by an energy meter inside the blink EVSE unit used for charging and reported by the blink network for each charge event.

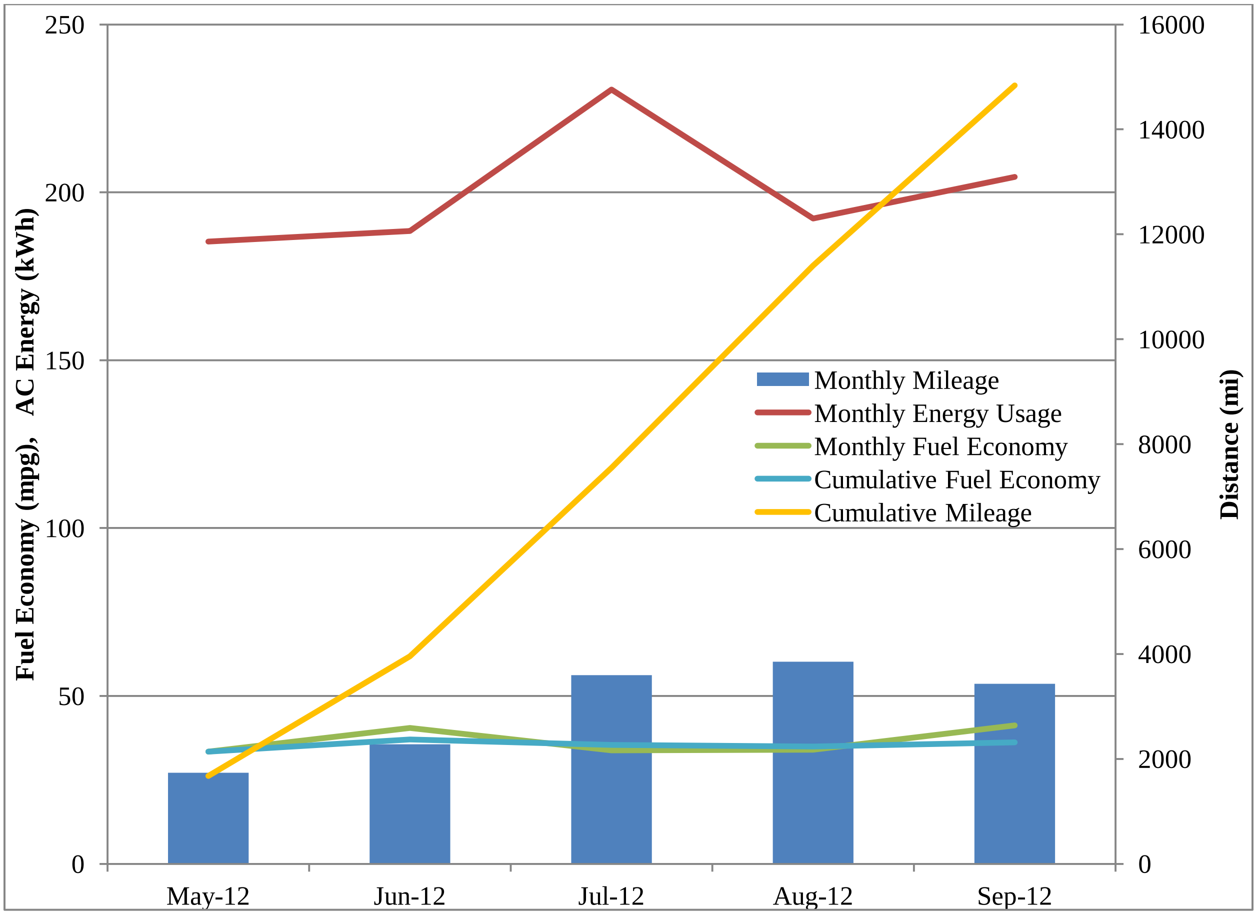

Figure 12. On-road monthly and cumulative fuel economy, distance traveled, and monthly AC energy usage

1.6 Conclusion

The testing of Chevrolet Volt 0815 included BOT and EOT battery tests and 14,836 miles of fleet testing in between. For vehicle battery packs, end-of-life (EOL) criteria is determined to be when the discharge capacity or discharge energy degradation exceeds 23% of the rated value, as specified in the USABC Electric Vehicle Battery Test Procedures Manual Rev 3 (publication pending). The Chevrolet Volt with VIN 0815 experienced a degradation of 2.2% in battery capacity. The battery of Chevrolet Volt 0815 is therefore well below the EOL threshold. The battery of Volt 0815 also had a degradation of 12.9% and 6.3% in discharge and charge power capability at 80% and 20% DOD, respectively, over the duration of 14,836 miles of fleet testing

Appendix A
Vehicle Specifications and Test Results Summary

Vehicle Specifications	Battery Specifications
Base Vehicle: 2011 Chevrolet Volt VIN: 1G1RD6E48BU100815 Propulsion System: Multi-Mode PHEV (EV, Series, and Power-split) Engine: DOHC I-4, 1.4 L, 63 kW @ 4800 rpm Number of Electric Machines[1]: 2 Motor: 111kW (peak), DC Permanent Magnet, Liquid Cooled	Manufacturer: LG Chem Battery Type: Lithium-ion Rated Capacity: 45 Ah Rated Energy: 16 kWh Nominal Pack Voltage: 355.2 VDC Nominal Cell Voltage: 3.7 V Number of Cells: 288 Thermal Management: Active, Liquid cooled/heated
Beginning-of-Test Vehicle Baseline Performance Test Results[2]	
CD Acceleration Test	**CS Acceleration Test**
Average Discharge Power Over 10 seconds: 88.9 kW Energy Discharged Over Full Run: 0.997 kWh Capacity Discharged Over Full Run: 2.893 Ah Peak Discharge Power Over Full Run: 112.3 kW Peak Discharge Current Over Full Run: 321.0 A	Average Discharge Power Over 10 seconds: 66.3 kW Energy Discharged Over Full Run: 0.628 kWh Capacity Discharged Over Full Run: 1.955 Ah Peak Discharge Power Over Full Run: 93.8 kW Peak Discharge Current Over Full Run: 300.8 A
Fuel Economy Testing (UDDS, HWY, US06)	
Average Net Capacity Discharge for CD Miles per Cycle: 4.544 Ah, 6.505 Ah, 6.935 Ah Average Net Capacity Discharge for CS Miles per Cycle: 0.156 Ah, 0.234 Ah, 0.609 Ah Total Net Energy Discharge for All Miles in CD Mode: 8.72 kWh, 8.88 kWh, 8.97 kWh Total Net Capacity Discharge for All Miles in CD Mode: 27.67 Ah, 26.93 Ah, 26.75 Ah Transition from CD to CS Pack Voltage: 345.2 V, 345.7 V, 337.7 V CD Max Drive Power – all cycles: 55.7 kW, 49.5 kW, 79.3 kW CD Max Drive Current – all cycles: 147.6 A, 135.8 A, 212.0 A CD Max Regenerative Power – all cycles: 40.4 kW, 52.0 kW, 70.7 kW CD Max Regenerative Current – all cycles: 106.7 A, 135.5 A, 195.7 A CD Average Current – all cycles: 10.7 A, 28.8 A, 35.2 A	
On-Road Fleet Testing	
Fuel Economy: 36.2 mpg AC Energy Used: 1,001.1 kWh Percent of City Miles Driven: 50.0% Percent of Highway Miles Driven: 50.0%	
End-of-Test Vehicle Baseline Performance Test Results	
CD Acceleration Test	**CS Acceleration Test**
Average Discharge Power Over 10 seconds: 88.5 kW Energy Discharged Over Full Run: 1.070 kWh Capacity Discharged Over Full Run: 3.035 Ah Peak Discharge Power Over Full Run: 113.3 kW Peak Discharge Current Over Full Run: 318.0 A	Average Discharge Power Over 10 seconds: 70.2 kW Energy Discharged Over Full Run: 0.611 kWh Capacity Discharged Over Full Run: 1.889 Ah Peak Discharge Power Over Full Run: 109.7 kW Peak Discharge Current Over Full Run: 338.7 A

Battery Beginning-of-Test Laboratory Test Results	
Electric Vehicle Power Characterization Test	**Static Capacity Test**
Discharge Power @ 80% DOD: 115.9 kW Discharge Resistance @ 80% DOD: 0.1402 Ω Charge Power @ 20% DOD: 55.9 kW Charge Resistance @ 20% DOD: 0.1097 Ω Maximum Cell Charge Voltage: 4.15 V Minimum Cell Discharge Voltage: 3.00 V	Measured Average Capacity: 41.8 Ah Measured Average Energy Capacity: 15.2 kWh

Battery End-of-Test Laboratory Test Results[2]	
Electric Vehicle Power Characterization Test	**Static Capacity Test**
Discharge Power @ 80% DOD: 100.9 kW Discharge Resistance @ 80% DOD: 0.1541 Ω Charge Power @ 20% DOD: 52.4 kW Charge Resistance @ 20% DOD: 0.1232 Ω Maximum Cell Charge Voltage: 4.15 V Minimum Cell Discharge Voltage: 3.00 V	Measured Average Capacity: 40.9 Ah Measured Average Energy Capacity: 14.9 kWh

Degradation of Battery Over Test Period[3]	
Electric Vehicle Power Characterization Test	**Static Capacity Test**
Discharge Power @ 80% DOD: 15 kW (12.9%) Discharge Resistance @ 80% DOD: -0.014 Ω (-9.9%) Charge Power @ 20% DOD: 3.5 kW (6.3%) Charge Resistance @ 20% DOD: -0.135 Ω (-12.3%)	Measured Average Capacity: 0.9 Ah (2.2%) Measured Average Energy Capacity: 300 Wh (2.0%)

Notes:

1. Motor power rating refers to the manufacturer's peak power rating for the motor(s) supplying traction power.
2. The BOT battery laboratory tests took place March 6, 2012, when the vehicle odometer was at 8,478 miles; the EOT battery laboratory tests took place on October 15, 2012, when the vehicle odometer was at 23,314 miles.
3. All values are the degradation or difference in the battery from initial laboratory test to final laboratory test.