INL/EXT-14-32109

# 2011 Hyundai Sonata 3539 - Hybrid Electric Vehicle Battery Test Results

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The Idaho National Laboratory is a U.S. Department of Energy National Laboratory
Operated by Battelle Energy Alliance

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**September 2014**

**Prepared for the**
**U.S. Department of Energy**
**Assistant Secretary for Energy Efficiency and Renewable Energy**
**Under DOE Idaho Operations Office**
**Contract DE-AC07-05ID14517**

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 Hyundai Sonata Hybrid (VIN KMHEC4A47BA003539). 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 |

# 2011 Hyundai Sonata 3539 – Hybrid Electric Vehicle Battery Test Results

## 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 Hyundai Sonata HEV, number 3539 (full VIN: KMHEC4A47BA003539), 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 | July 22, 2011 | 5,730 | 5.30 | 5.29 | 1,394 |
| EOT | May 29, 2013 | 160,116 | 5.30 | 4.15 | 1,060 |
| Difference | — | 154,386 | — | 1.14 (22%) | 334 (24%) |

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.

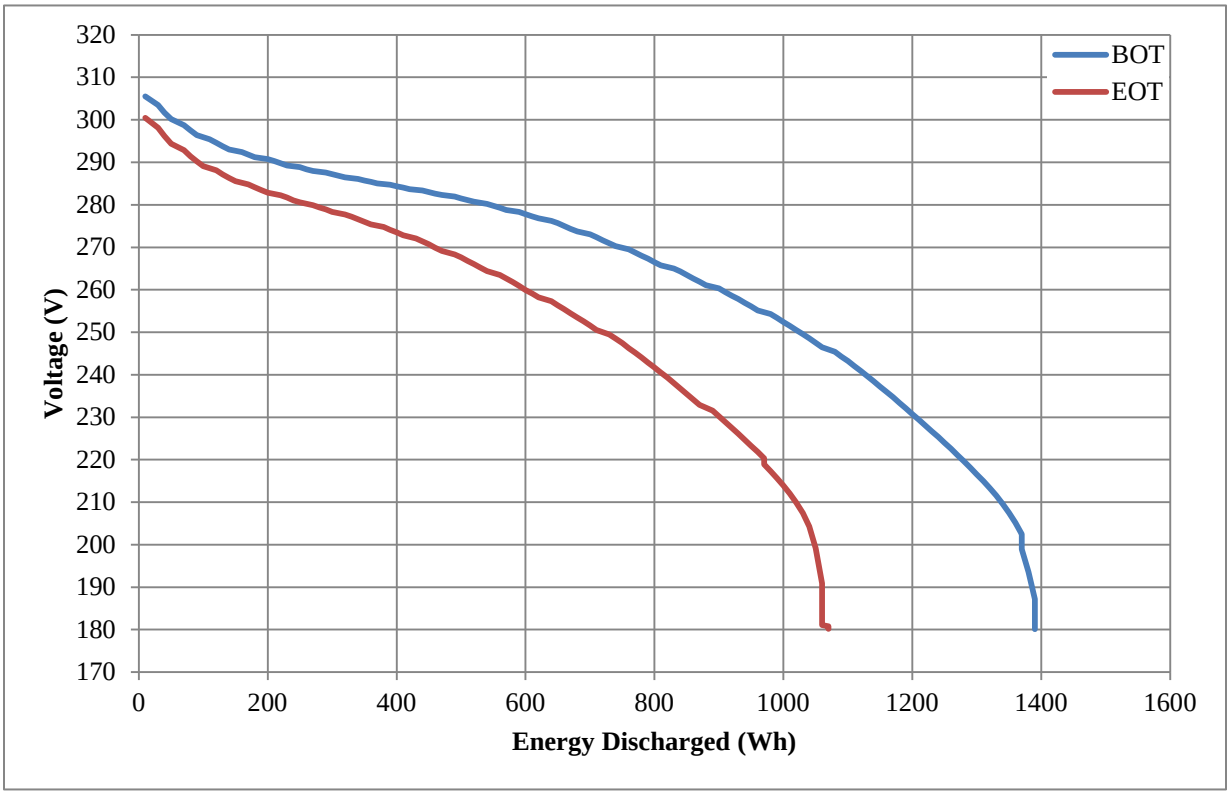


Figure 1. Voltage versus energy discharged during the static capacity test

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 | 48.9 | 34.1 | 4.3 | 2.4 |
| EOT | 23.4 | 29.3 | 4.3 | 2.4 |
| Difference | 25.5 (52%) | 4.8 (14%) | 0.0 (0%) | 0.0 (0%) |

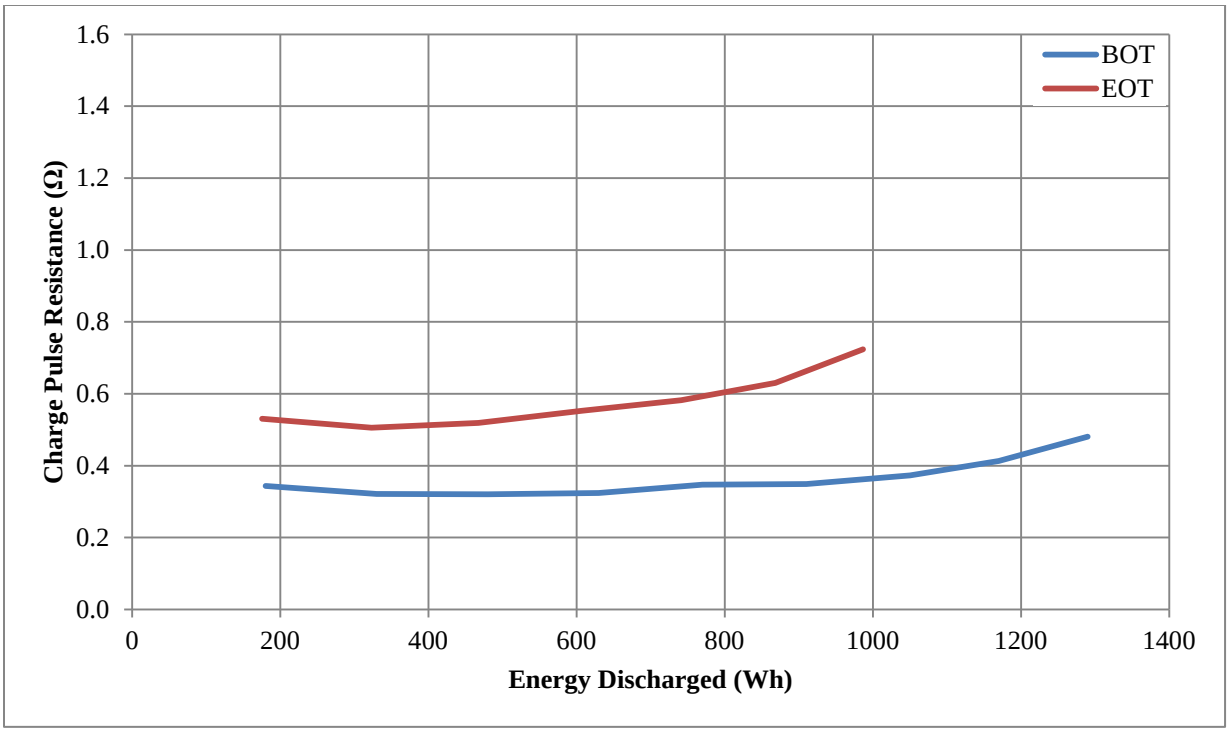


Figure 2. Ten-second charge pulse resistance versus energy discharged

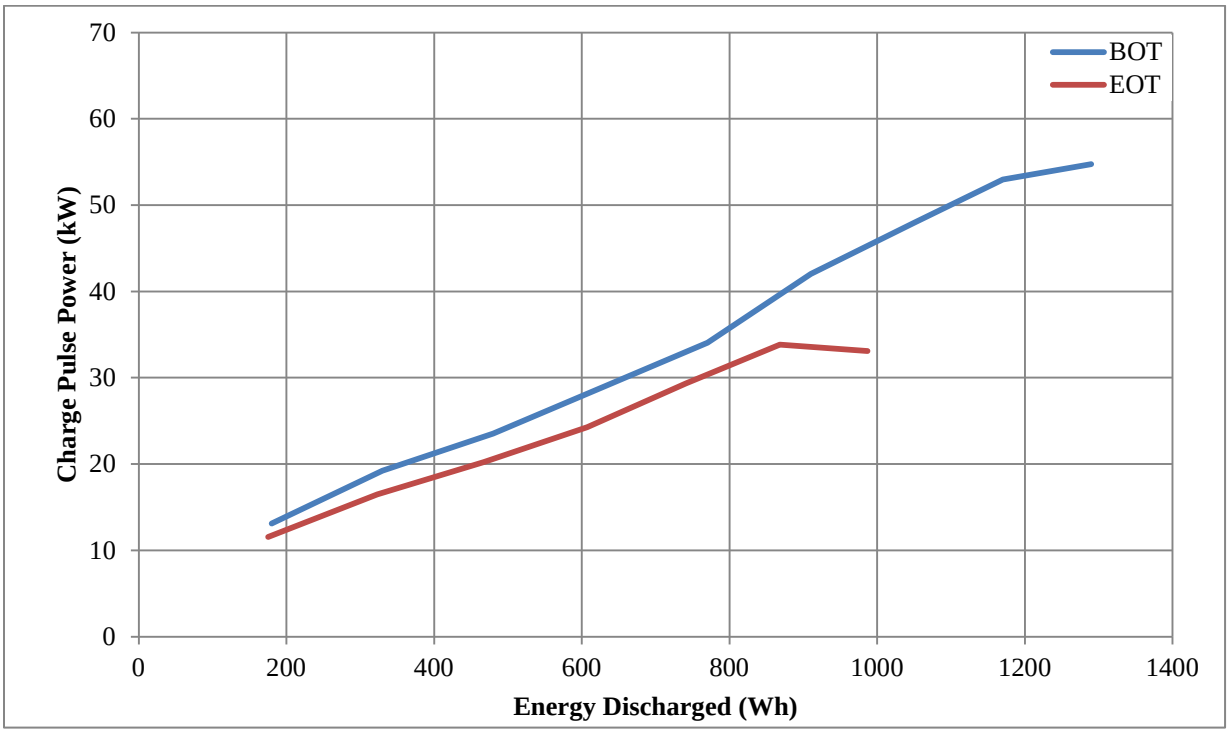


Figure 3. Ten-second charge pulse power capability versus energy discharged

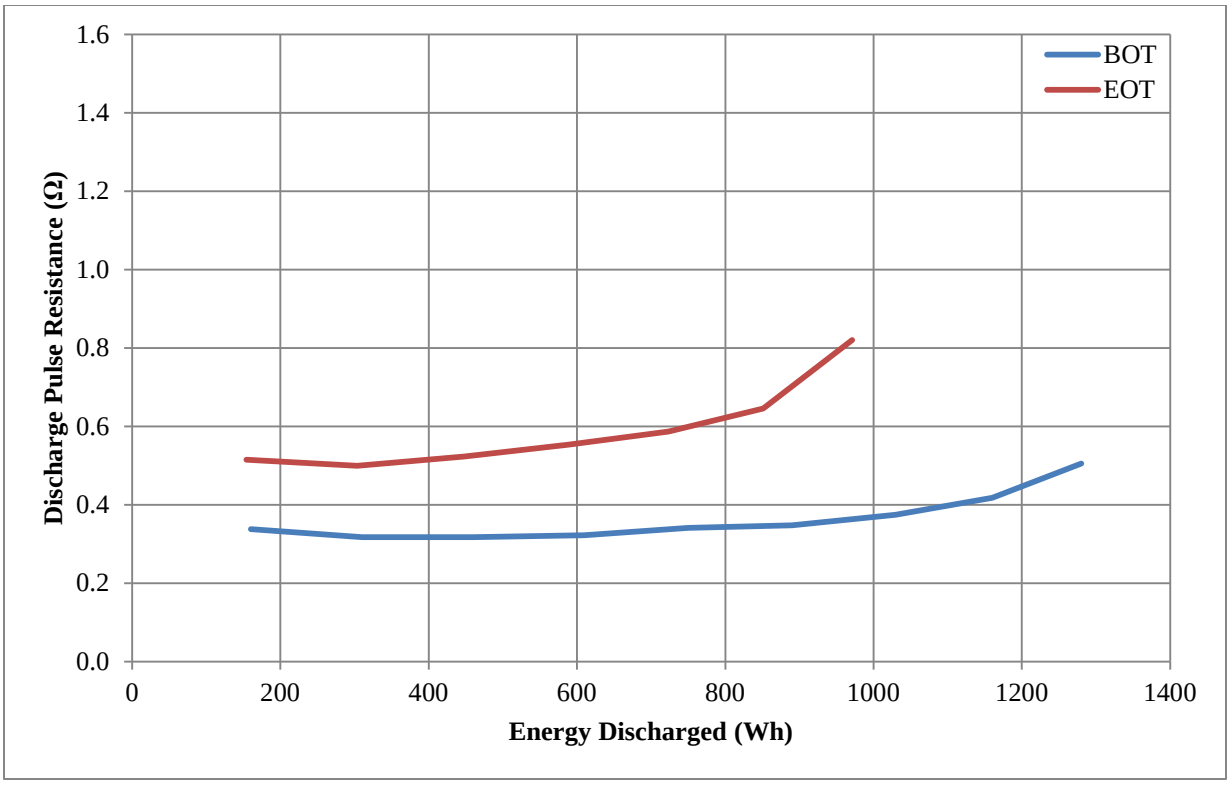


Figure 4. Ten-second discharge pulse resistance versus energy discharged

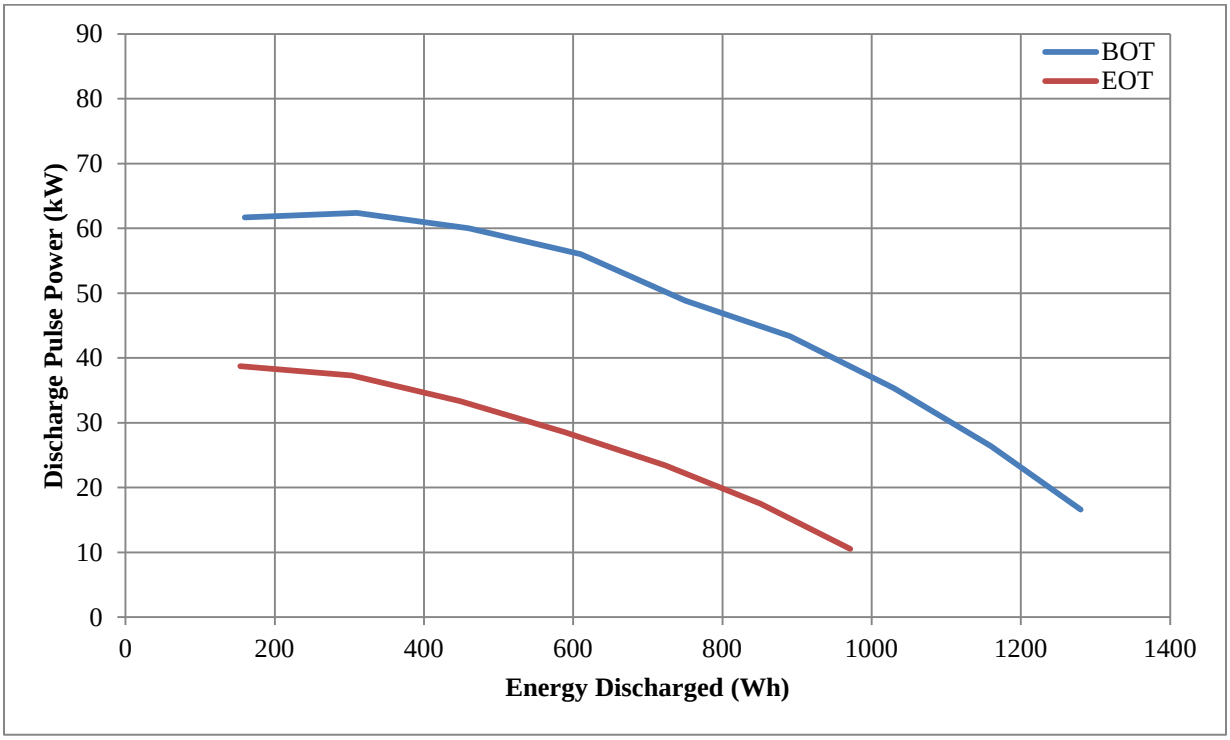


Figure 5. Ten-second discharge pulse power capability versus energy discharged

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. The BOT pulse power values meet the DOE power targets (denoted by the black, horizontal dashed line in Figure 6) for the battery energy discharged range of 360 to 1,178 Wh. The EOT pulse power values meet the DOE minimum power-assist HEV charge and discharge power targets (denoted by the black, horizontal dashed line in Figure 6) for the battery energy discharged range of 456 to 680 Wh.

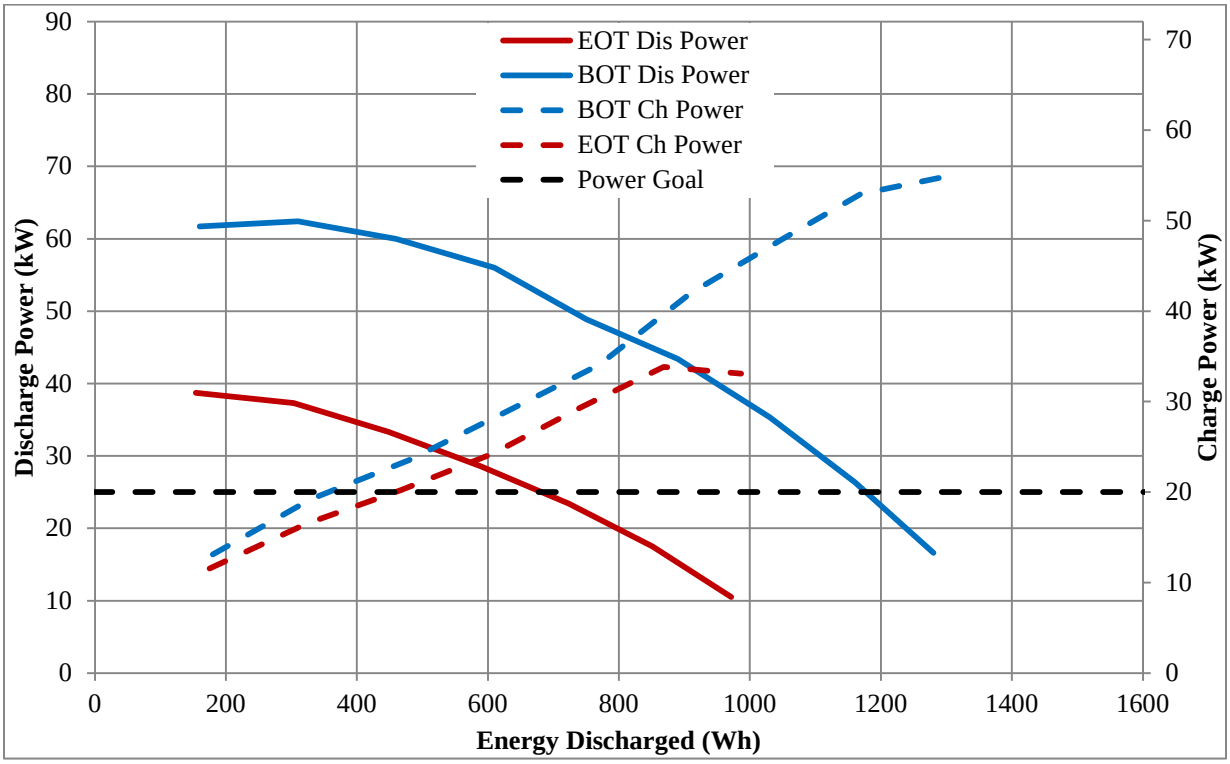


Figure 6. Discharge and charge power capabilities versus energy discharged

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. A portion of the BOT usable energy curve of the Sonata 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 38.5 kW at 300 Wh. The maximum energy that can be delivered while meeting the DOE power target is 820 Wh at 25 kW. This indicates that at the time of BOT testing, the Sonata battery performance was above the DOE targets. No portion of the EOT usable 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 23.6 kW at 300 Wh. The maximum energy that can be delivered while meeting the DOE power target is 220 Wh at 25 kW. This indicates that at end of test, the Sonata battery performance was below the DOE targets.

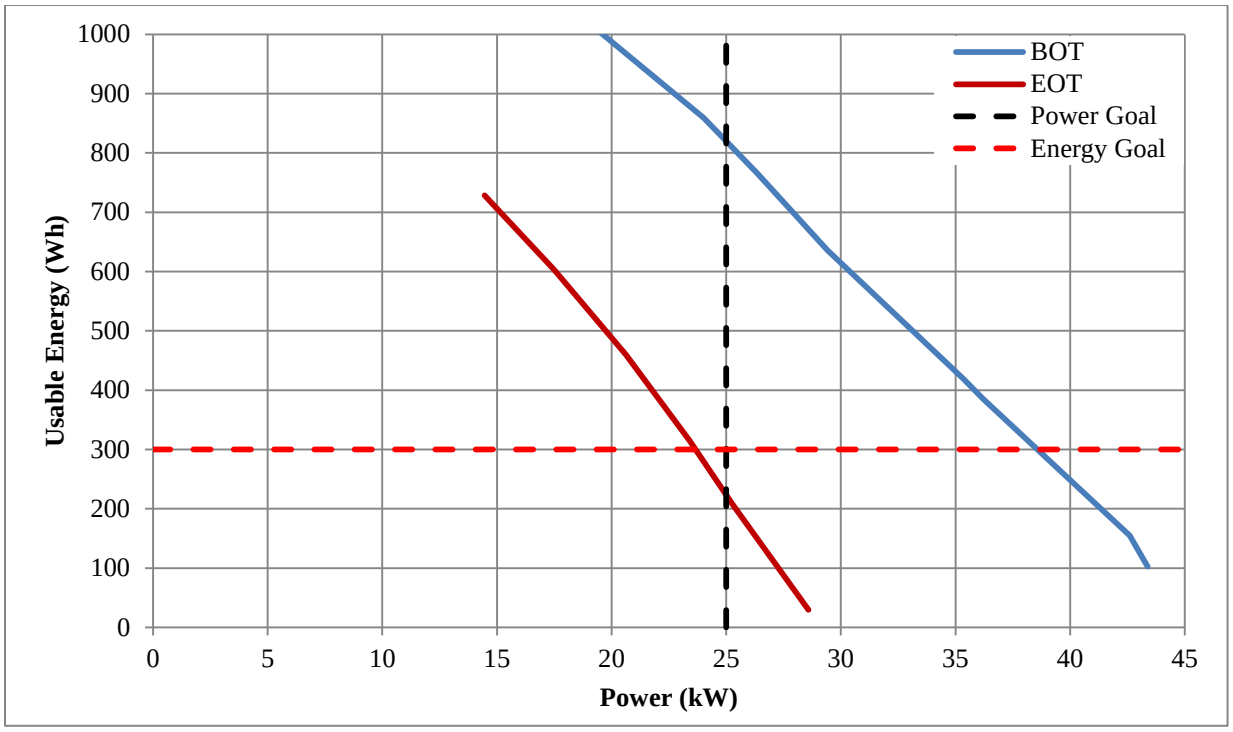


Figure 7. Usable energy versus power

## 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 | 26.5 | 194 | 0.75 | 43.3 | 246.5 | 3.424 |
| EOT | 28.0 | 247 | 1.05 | 46.7 | 224.2 | 3.114 |

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, which may include battery control logic, causing a reverse in power direction to charge the battery.

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.

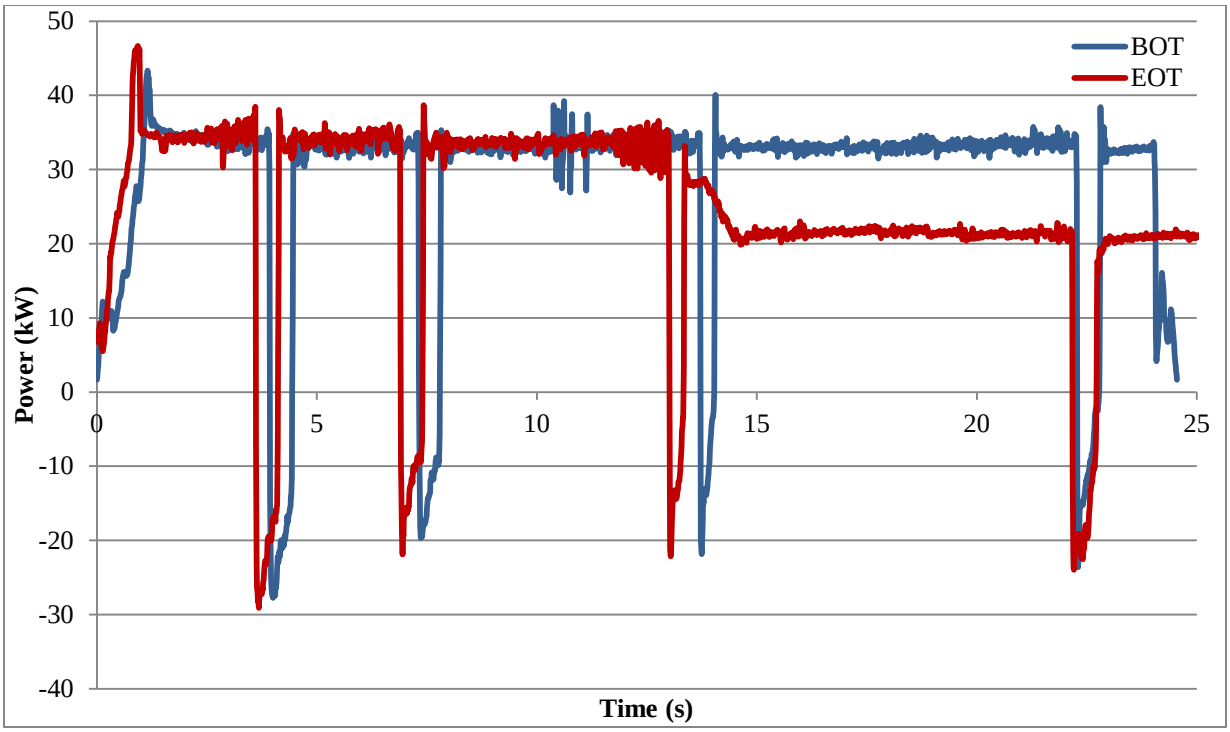


Figure 8. Battery power versus time from acceleration testing

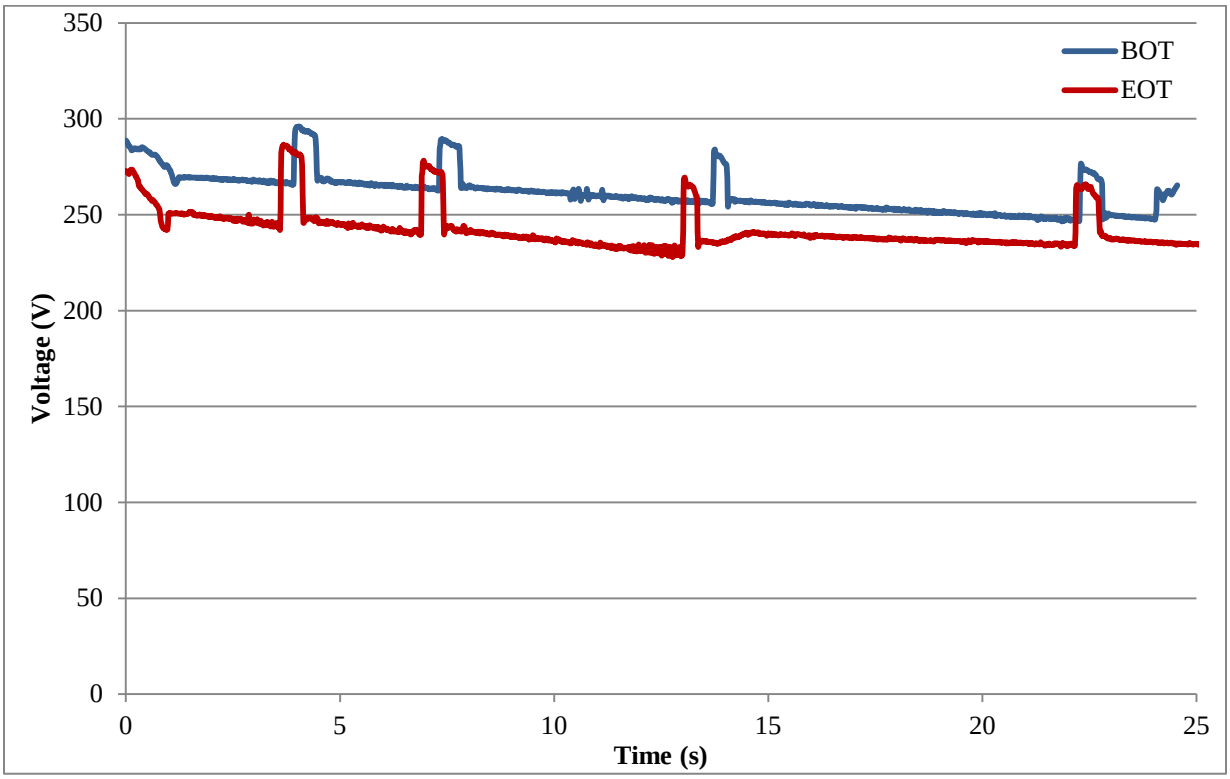


Figure 9. Battery voltage versus time from acceleration testing

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.

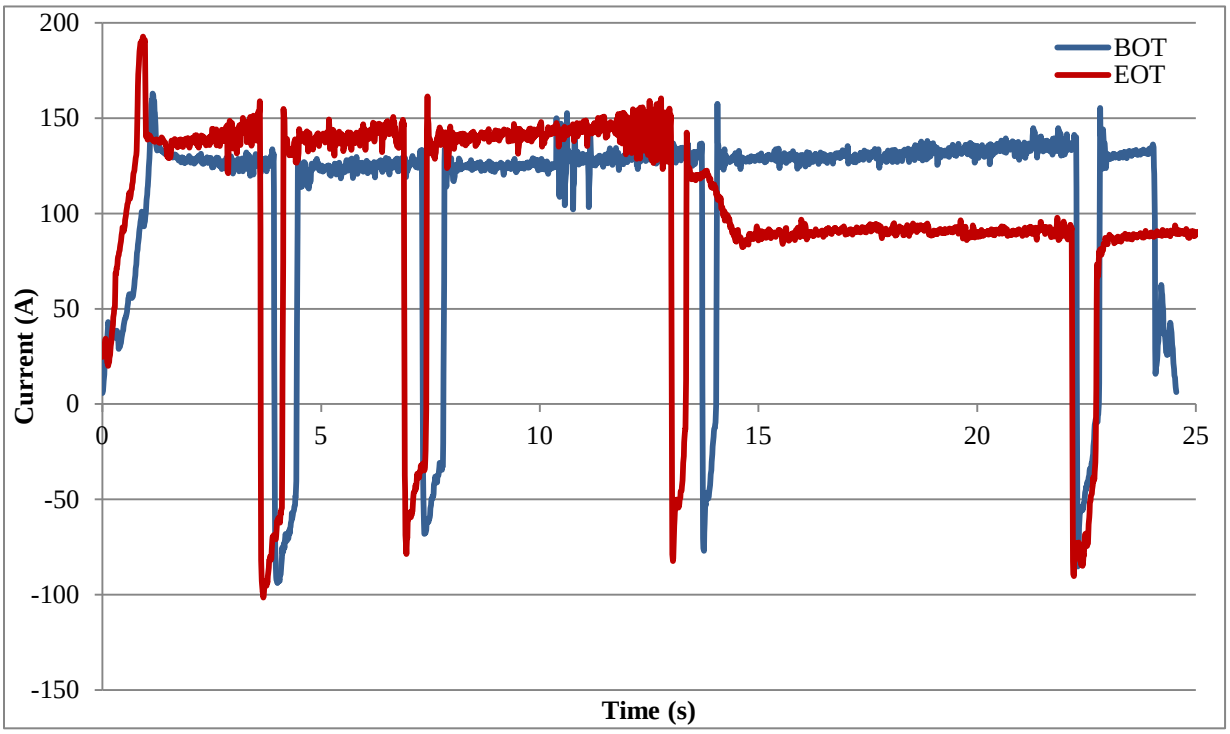


Figure 10. Battery current versus time from acceleration testing

## 1.4 Fuel Economy Test Results

Battery performance results were obtained from testing conducted on a chassis dynamometer with Hyundai Sonata Hybrid 4932 at Argonne National Laboratory. The Urban Dynamometer Drive Schedule (UDDS), Highway Fuel Economy Test (HWFET), and US06[4] 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 | US06 |
|---|---|---|---|
| **Peak Discharge Power (kW):** | 39.3 | 36.0 | 43.5 |
| **Peak Charge Power (kW):** | 25.3 | 26.3 | 30.8 |
| **Measured Discharge Energy (kWh):** | 1.15 | 1.70 | 1.94 |
| **Measured Charge Energy (kWh):** | 1.03 | 2.05 | 2.06 |
| **Measured Discharge Capacity (Ah):** | 3.75 | 6.16 | 7.01 |
| **Measured Charge Capacity (Ah):** | 3.94 | 7.01 | 7.10 |
| **Minimum Pack Voltage (V):** | 252.7 | 260.3 | 256.4 |
| **Maximum Pack Voltage (V):** | 304.2 | 307.1 | 305.5 |
| **Discharge/Charge Capacity Ratio:** | 0.952 | 0.879 | 0.987 |

[4] UDDS, HWFET, and US06 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 US06 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 US06 cycle, which is a 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 in the other two cycles.

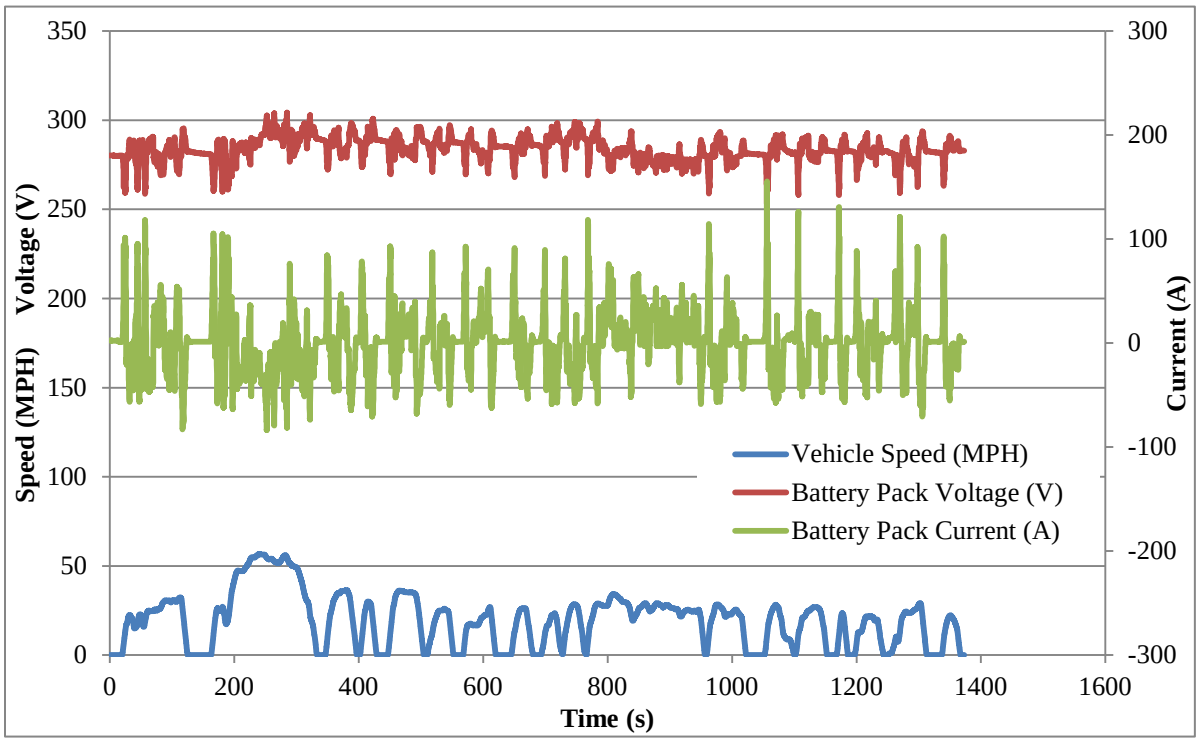


Figure 11. Battery pack current, voltage, and vehicle speed for a UDDS cycle

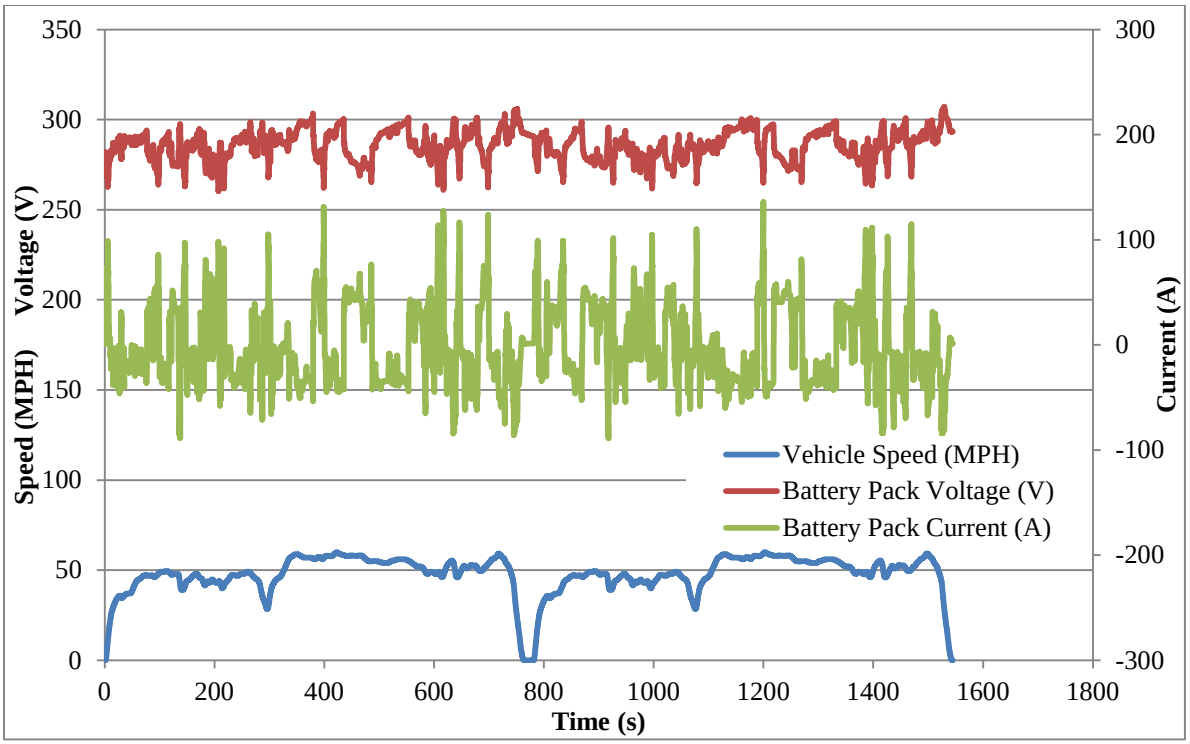


Figure 12. Battery pack current, voltage, and vehicle speed for two back-to-back HWFET cycles

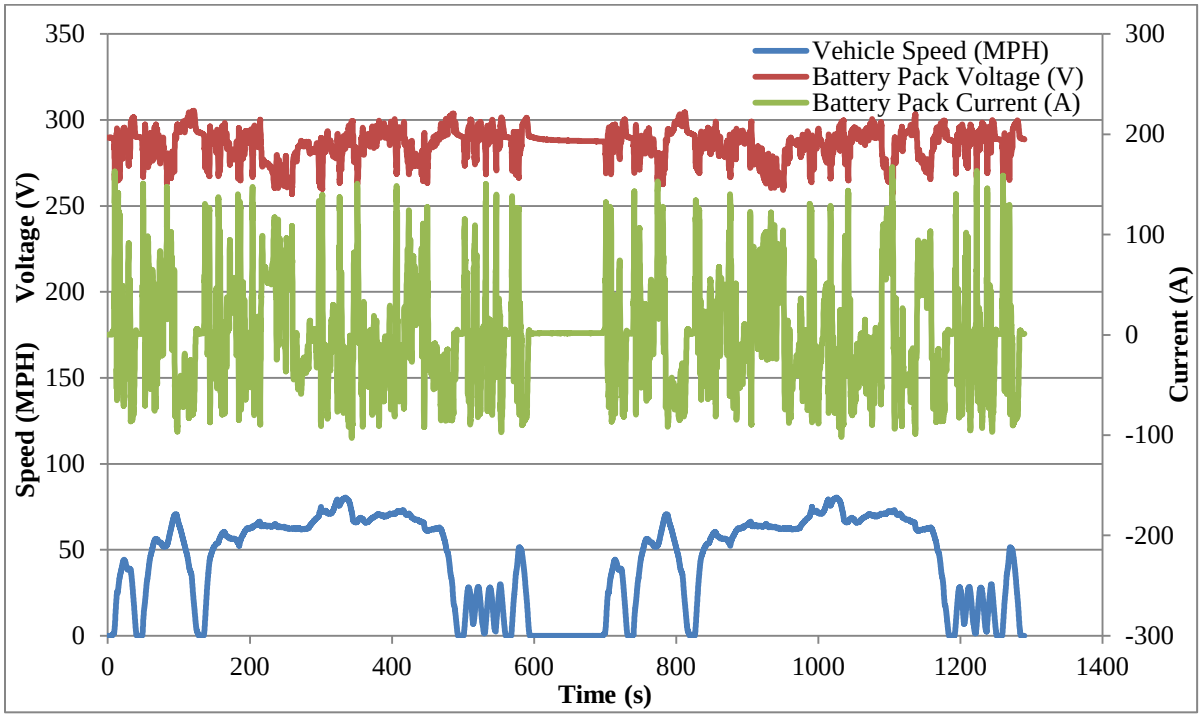


Figure 13. Battery pack current, voltage, and vehicle speed for two back-to-back US06 cycles

## 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 27% city[6] and 73% highway routes. Figure 14 presents the combined monthly fuel economy and cumulative fuel economy for the Sonata HEV 3539 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 34.0 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, even with battery degradation demonstrated by the EOT battery testing, increasing from 31 mpg to 34 mpg.

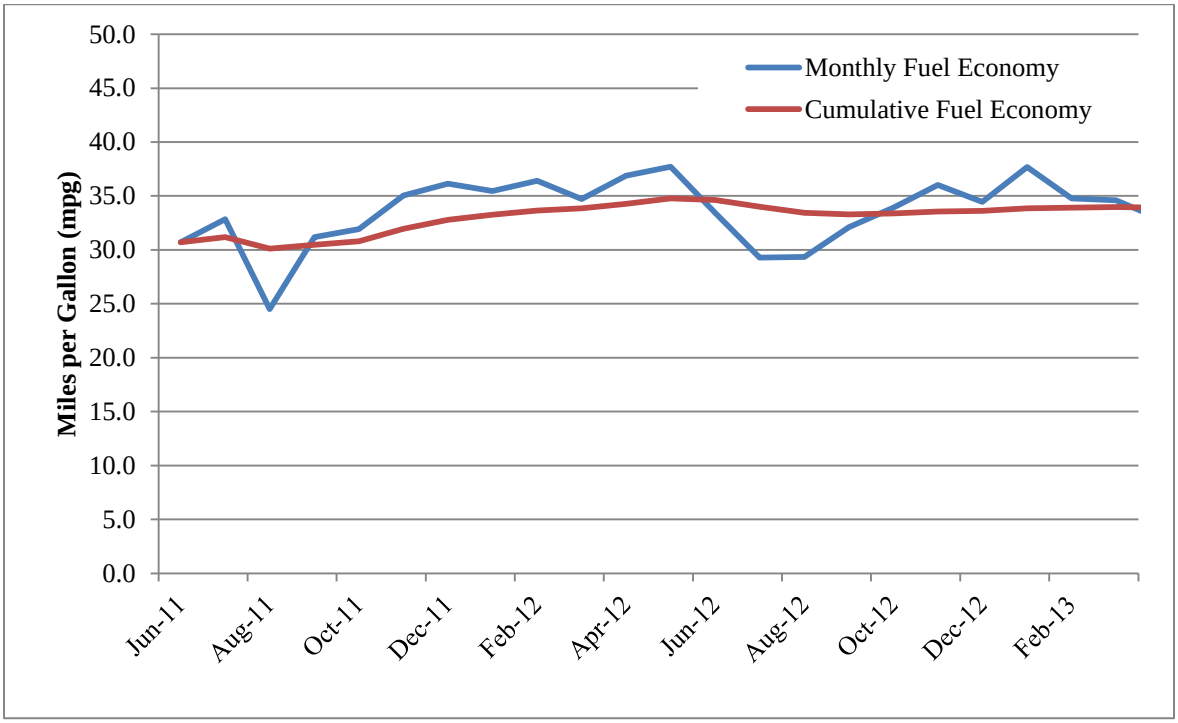


Figure 14. Monthly and cumulative fuel economy.

# 2 SUMMARY

The Hyundai Sonata 3539 experienced a 22% decrease in battery capacity and dropped below DOE targets for all aspects of the HPPC test over the duration of 154,386 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: Hyundai<br>Model: Sonata<br>Year: 2011<br>Motor Power Rating[a]: 34 kW<br>VIN #: KMHEC4A47BA003539 | Manufacturer: LG-Chem<br>Battery Type: Lithium-ion Polymer<br>Rated Capacity: 5.3 Ah<br>Nominal Pack Voltage: 270 VDC<br>Nominal Cell Voltage: 3.75 V<br>Number of Cells: 72 |
| **BOT Vehicle Performance Test Results[b]** | **EOT Vehicle Performance Test Results[b]** |
| **Acceleration Test** | **Acceleration Test** |
| Average Discharge Power Over 10 seconds[c]: 26.5 kW<br>Peak Discharge Power Over Test: 43.3 kW<br>Energy Discharged Over Test[d]: 195 Wh<br>Capacity Discharged Over Test[d]: 0.75 Ah<br>Minimum Discharge Pack Voltage: 246.5 VDC<br>Minimum Discharge Cell Voltage: 3.424 V | Average Discharge Power Over 10 seconds[c]: 28.0 kW<br>Peak Discharge Power Over Test: 46.7 kW<br>Energy Discharged Over Test[d]: 163 Wh<br>Capacity Discharged Over Test[d]: 0.68 Ah<br>Minimum Discharge Pack Voltage: 228 VDC<br>Minimum Discharge Cell Voltage: 3.167 V |

**Fuel Economy Chassis Dynamometer Testing**

| | UDDS | HWFET | US06 |
|---|---|---|---|
| Peak Discharge Power (kW): | 39.3 | 36.0 | 43.5 |
| Peak Charge Power (kW): | 25.3 | 26.3 | 30.8 |
| Measured Discharge Energy (kWh) | 1.15 | 1.70 | 1.94 |
| Measured Charge Energy (kWh) | 1.03 | 2.05 | 2.06 |
| Measured Discharge Capacity (Ah): | 3.75 | 6.16 | 7.01 |
| Measured Charge Capacity (Ah): | 3.94 | 7.01 | 7.10 |
| Minimum Pack Voltage (V) | 252.7 | 260.3 | 256.4 |
| Maximum Pack Voltage (V) | 304.2 | 307.1 | 305.5 |
| Discharge/Charge Capacity Ratio[e]: | 0.952 | 0.879 | 0.987 |

**Beginning-of-Test Battery Laboratory Test Results**

| Hybrid Pulse Power Characterization Test | Static Capacity Test |
|---|---|
| Peak Pulse Discharge Power @ 10 s[f]: 48.9 kW<br>Peak Pulse Charge Power @ 10 s[f]: 34.1 kW<br>Maximum Cell Charge Voltage: 4.3 V<br>Minimum Cell Discharge Voltage: 2.4 V | Measured Average Capacity: 5.29 Ah<br>Measured Average Energy Capacity: 1,394 Wh<br>Vehicle Odometer: 5,730 mi<br>Date of Test: July 22, 2011 |

**End-of-Test Battery Laboratory Test Results**

| Hybrid Pulse Power Characterization Test | Static Capacity Test |
|---|---|
| Peak Pulse Discharge Power @ 10 s[f]: 23.4 kW<br>Peak Pulse Charge Power @ 10 s[f]: 29.3 kW<br>Maximum Cell Charge Voltage: 4.3 V<br>Minimum Cell Discharge Voltage: 2.4 V | Measured Average Capacity:4.15 Ah<br>Measured Average Energy Capacity:1,060 Wh<br>Vehicle Odometer: 160,116 mi<br>Date of Test: May 29, 2013 |

| Degradation of Battery Over Test Period[g] | |
|---|---|
| **Hybrid Pulse Power Characterization Test** | **Static Capacity Test** |
| Peak Pulse Discharge Power @ 10 s[f]: 25.5 kW (52%)<br>Peak Pulse Charge Power @ 10 s[f]: 4.8 kW (14%) | Measured Average Capacity: 1.14 Ah (22%)<br>Measured Average Energy Capacity: 334 Wh (24%) |

**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 Sonata VIN 4932.
c. The peak power at a specified duration is the average power value over a specified interval.
d. The capacity 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.