VEHICLE TECHNOLOGIES PROGRAM

INL/EXT-10-19030

2007 Toyota Prius 8841 with Energy CS Prius Conversion Plug-In Hybrid Battery Test Results

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June 2010

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ABSTRACT

The U.S. Department of Energy (DOE) Advanced Vehicle Testing Activity (AVTA) 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 5,400 miles of accelerated on-road testing on specified routes. A 2008 Toyota Prius with VIN 8841 (VIN JTDK820U767508841) was converted to an Energy CS Prius PHEV for testing. The battery testing was performed by the Electric Transportation Engineering Corporation (eTec) dba ECOtality North America (ECOtality). The Idaho National Laboratory (INL) and eTec collaborate on the AVTA for the Vehicle Technologies Program of the DOE.

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ACRONYMS

Ah	Amp-hour
AVTA	Advanced Vehicle Testing Activity
BOT	Beginning of Test
CD	Charge-Depleting
CS	Charge-Sustaining
DOE	U.S. Department of Energy
EOT	End of Test
eTec	Electric Transportation Engineering Corporation
HEV	Hybrid Electric Vehicle
HPPC	Hybrid Pulse Power Characterization
ICE	Internal Combustion Engine
INL	Idaho National Laboratory
kW	kilowatt
SOC	State of Charge
UDDS	Urban Dynamometer Drive Schedule

USABC	U.S. Advanced Battery Consortium
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's Advanced Vehicle Testing Activity conducts vehicle, battery, and infrastructure testing on several different vehicle technologies, including plug-in hybrid electric vehicles. This report provides test results for end-of-test (EOT) battery testing conducted on an Energy CS conversion of a 2008 Toyota Prius, number 8841 (VIN JTDK820U767508841) in the battery test laboratory and during vehicle operations. The Energy CS conversion kit consists of a 10-kWh, Lithium-ion supplemental battery pack from Valence Technology. EOT testing is conducted after a vehicle has completed approximately 5,400 miles of on-road accelerated testing. The battery laboratory test results include those from the Static Capacity test, Constant Power Discharge test, and Hybrid Pulse Power Characterization (HPPC) test.[3] Vehicle test results include those from the acceleration testing and the fuel economy testing.[4] A summary of the test results is provided in Appendix A.

The battery and vehicle testing was performed by the Electric Transportation Engineering Corporation. The Idaho National Laboratory and the Electric Transportation Engineering Corporation conduct the Advanced Vehicle Testing Activity for the U.S. Department of Energy's Vehicle Technologies Program.

1.1 Static Capacity Test Results

Results from the laboratory EOT Static Capacity test are provided in Table 1. BOT testing was not able to be conducted prior to the start of the accelerated mileage accumulation.

Table 1. Static Capacity test results

	Test Date	Rated Capacity (Ah)	Measured Capacity (Ah)	Measured Energy (kWh)
EOT	August 22, 2009	37.1	44.6	8.38

Figure 1 shown below is a graph of battery voltage versus energy discharged for the EOT Static Capacity test. This graph illustrates voltage values during constant current discharge versus the cumulative energy discharged from the battery at a C/1 constant current discharge rate.

[3] Static Capacity, Constant Power Discharge, and HPPC test procedures were performed in accordance with the *FreedomCAR Battery Test Manual for Plug-In Hybrid Electric Vehicles*, DOE/ID-11069, October 2003, Procedures 3.2 and 3.3, respectively.

[4] Acceleration testing and fuel economy testing procedures were performed in accordance with the Advanced Vehicle Testing Activity PHEV America test procedures ETA-PHTP02 and ETA-PHTP03, respectively.

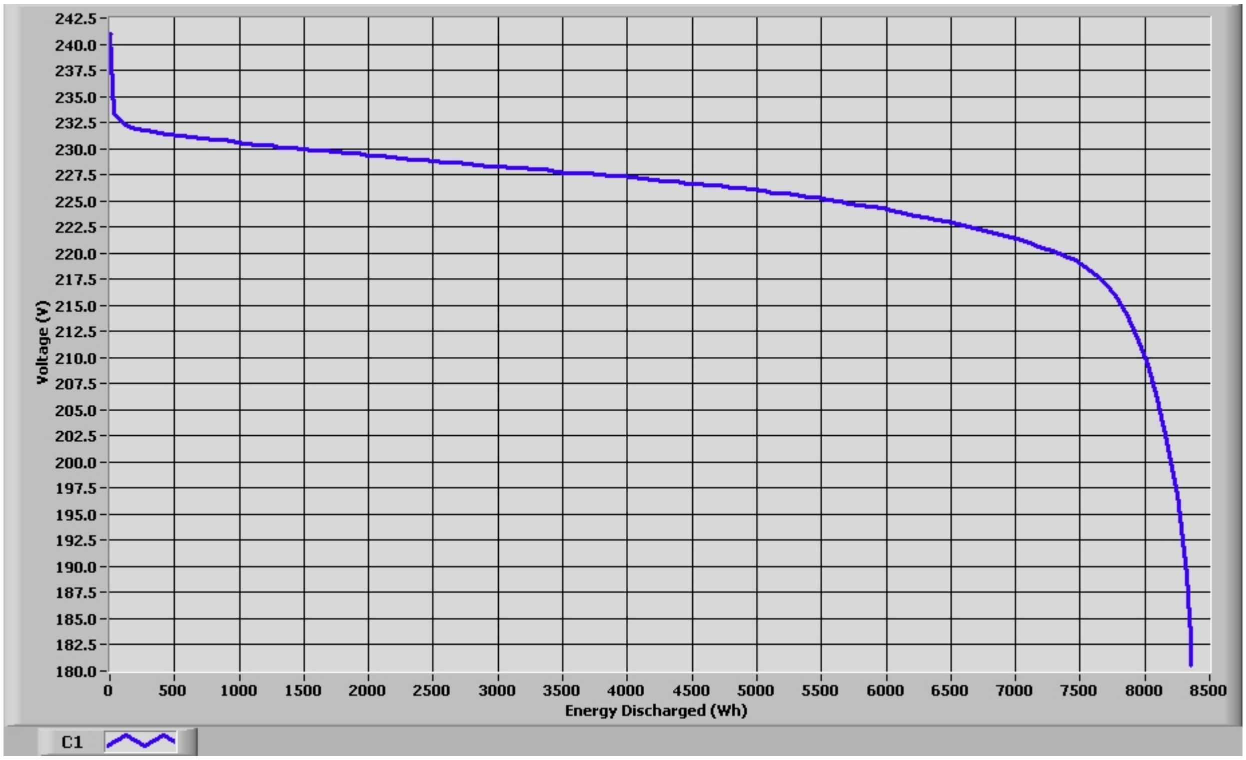

Figure 1. Voltage versus energy discharged during Static Capacity test

1.2 Constant Power Discharge Test Results

Results from the laboratory EOT Constant Power Discharge test are provided in Table 2. The result of the EOT test was above the U.S. Department of Energy's available energy performance goal for charge-depleting operation of 3.4 kWh.

Table 2. Constant Power Discharge test results

	Capacity Discharged (Ah)	Energy Discharged (kWh)	Time to Completion (min)
EOT	37.0	8.38	50.0

1.3 Hybrid Pulse Power Characterization Test Results

HPPC test results are summarized in Table 3.

Table 3. HPPC test results

	10s Discharge Power (kW)	1s Discharge Power (kW)	10s Charge Power (kW)	1s Charge Power (kW)	Maximum Cell Voltage (V)	Minimum Cell Voltage (V)
BOT	53.4	51.7	34.6	47.9	3.6	2.5

Figures 2 and 4 illustrate the battery's charge and discharge pulse resistance graphs, which show internal resistance at various depths of discharge. Each curve represents the specified resistance at the end of the 10s pulse interval.

Figures 3 and 5 present the battery's charge and discharge pulse power graphs, which show pulse power at various depths of discharge. Each curve represents the specified available power at the end of the 10s pulse interval at the cell voltage limits.

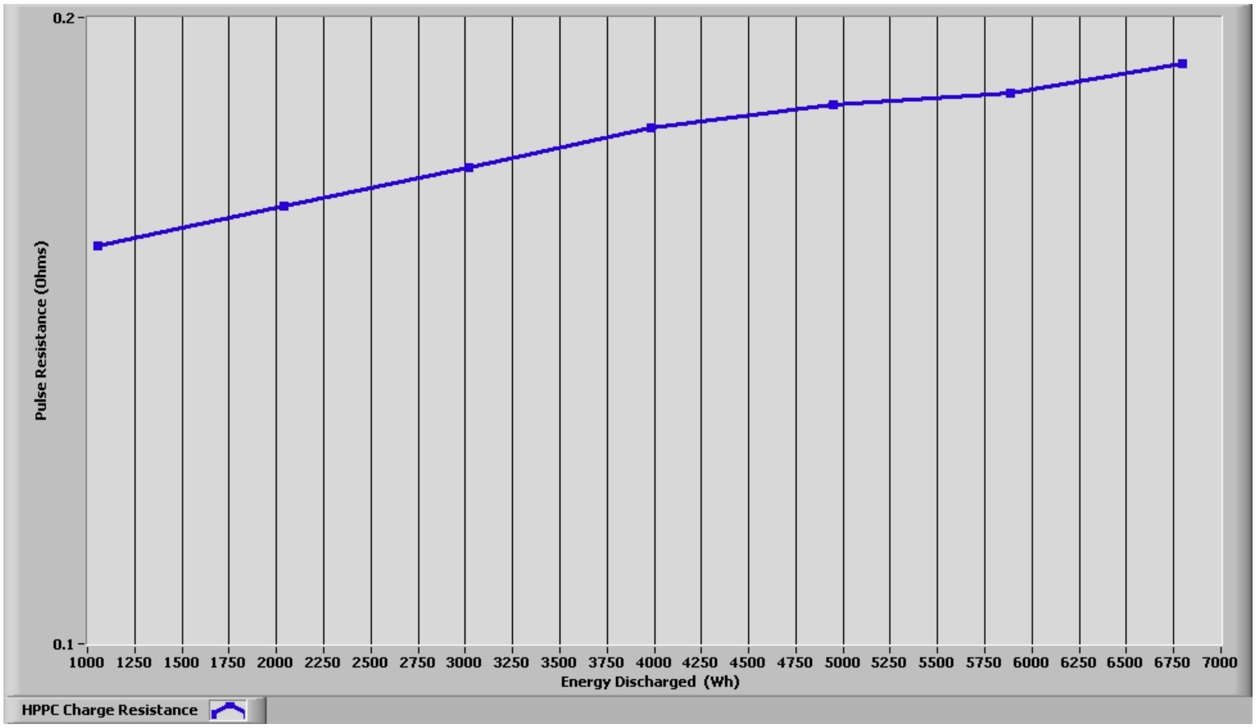

Figure 2. Ten-second charge pulse resistance versus energy discharged during HPPC test

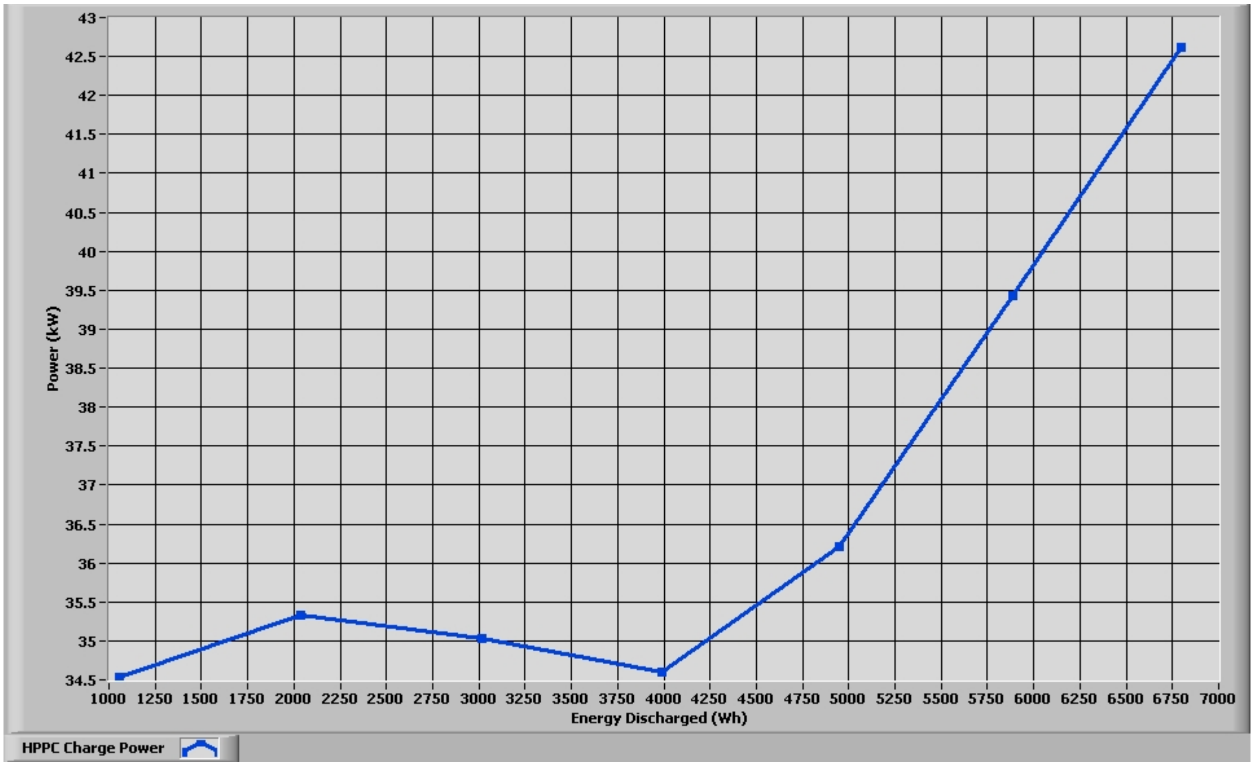

Figure 3. Ten-second charge pulse power versus energy discharged during the HPPC test

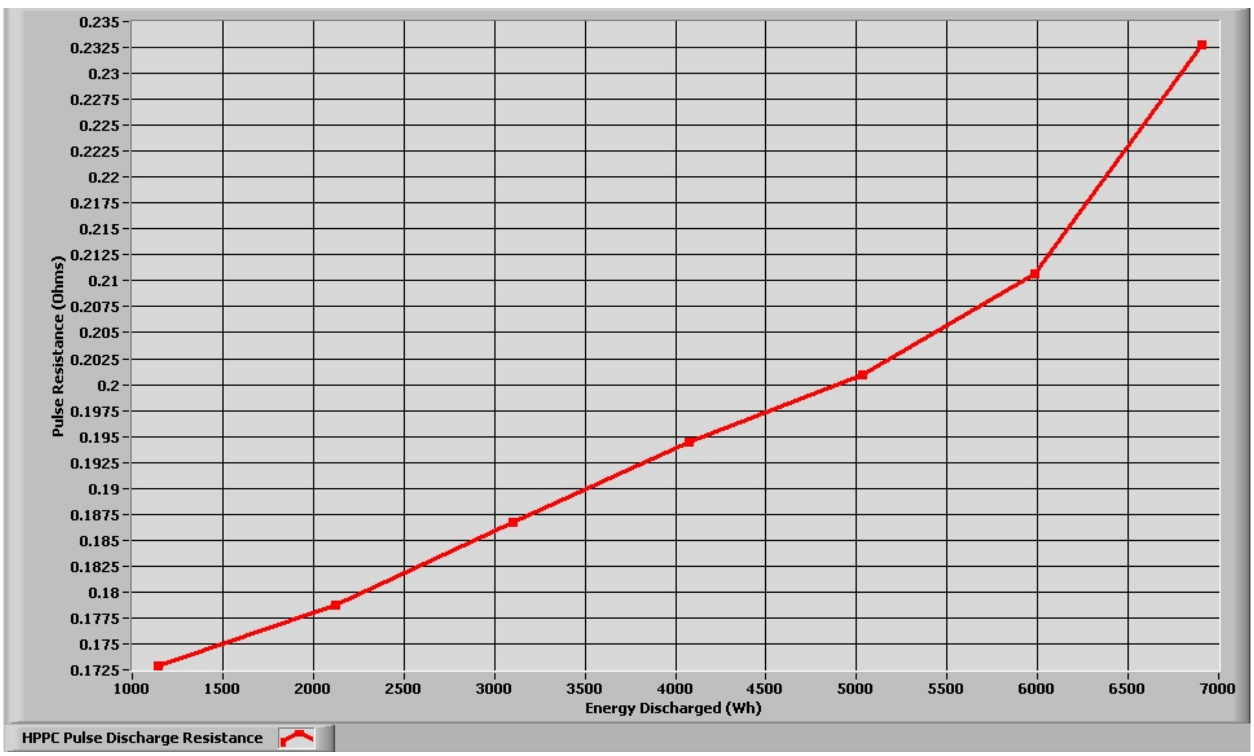

Figure 4. Ten-second discharge pulse resistance versus energy discharged during the HPPC test

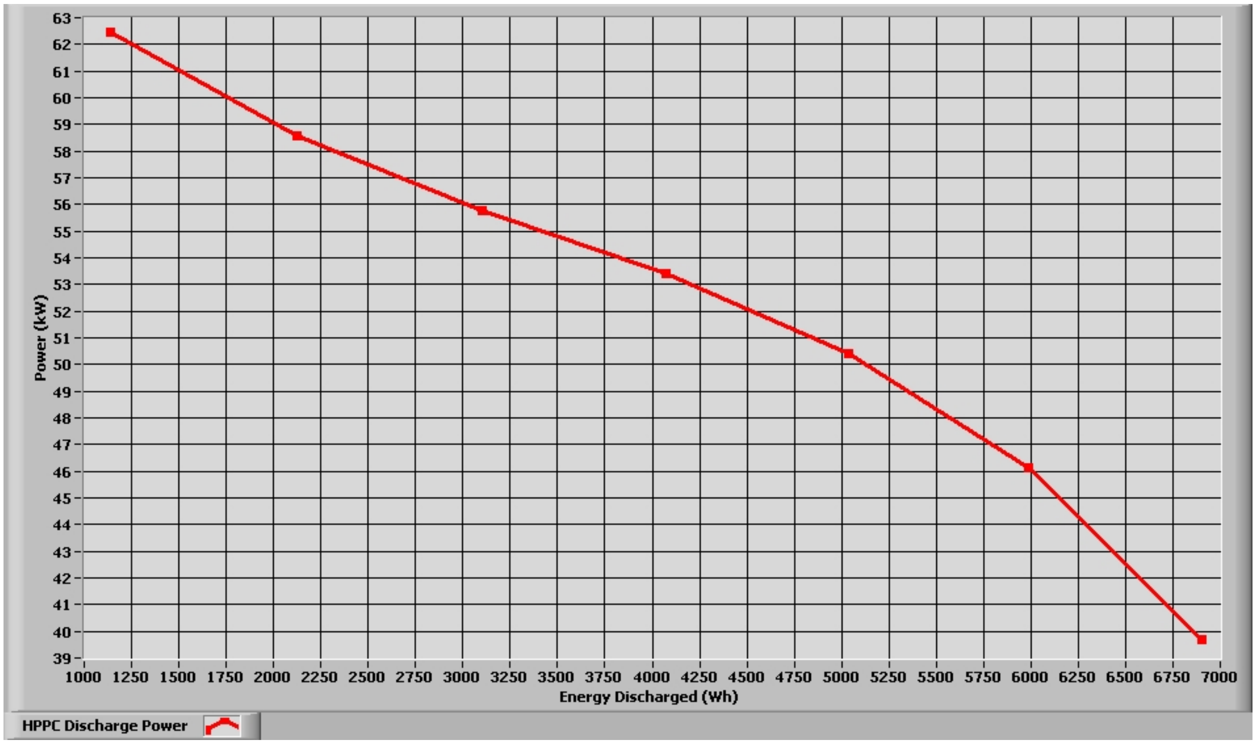

Figure 5. Ten-second discharge pulse power versus energy discharged during the HPPC test

Figure 6 below presents the battery's HPPC 10-second pulse power values as a function of depth-of-discharge. The graph shows the power values over the range of depth-of-discharge and the U.S. Advanced Battery Consortium (USABC) target goals of 45-kW discharge power and 30-kW regen power for a minimum plug-in hybrid battery. The battery test meets the USABC power goals for battery state-of-charge range of 100 to 25.0%.

Figure 7 illustrates the battery's useable energy as a function of power. The x-axis indicates a desired discharge or charge power level and the y-axis indicates the useable energy at that power. The blue, dashed horizontal line shows the USABC minimum plug-in hybrid electric vehicle energy goal in charge-depleting mode of 3.4 kWh. The blue, dashed vertical line shows the USABC minimum power assist power goal of 45 kW. The Energy CS battery's useable energy curve falls below and to the left of the intersection of the USABC energy and power goals. The maximum power that can be delivered while meeting the USABC energy goal is 44 kW at 3.4 kWh. The maximum energy that can be delivered while meeting the USABC power goal is 1.75 kWh at 45 kW. This indicates that at the time of testing, battery performance did not meet the USABC goals.

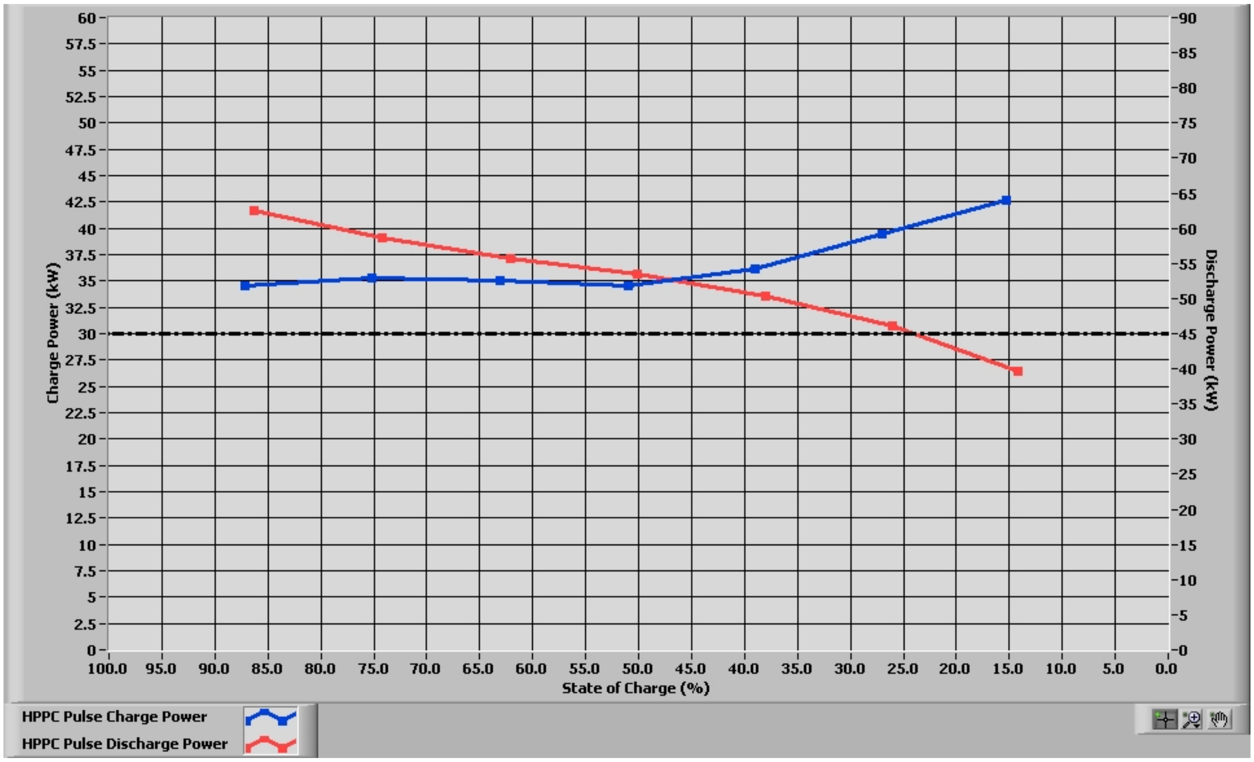

Figure 6. HPPC peak power values versus SOC

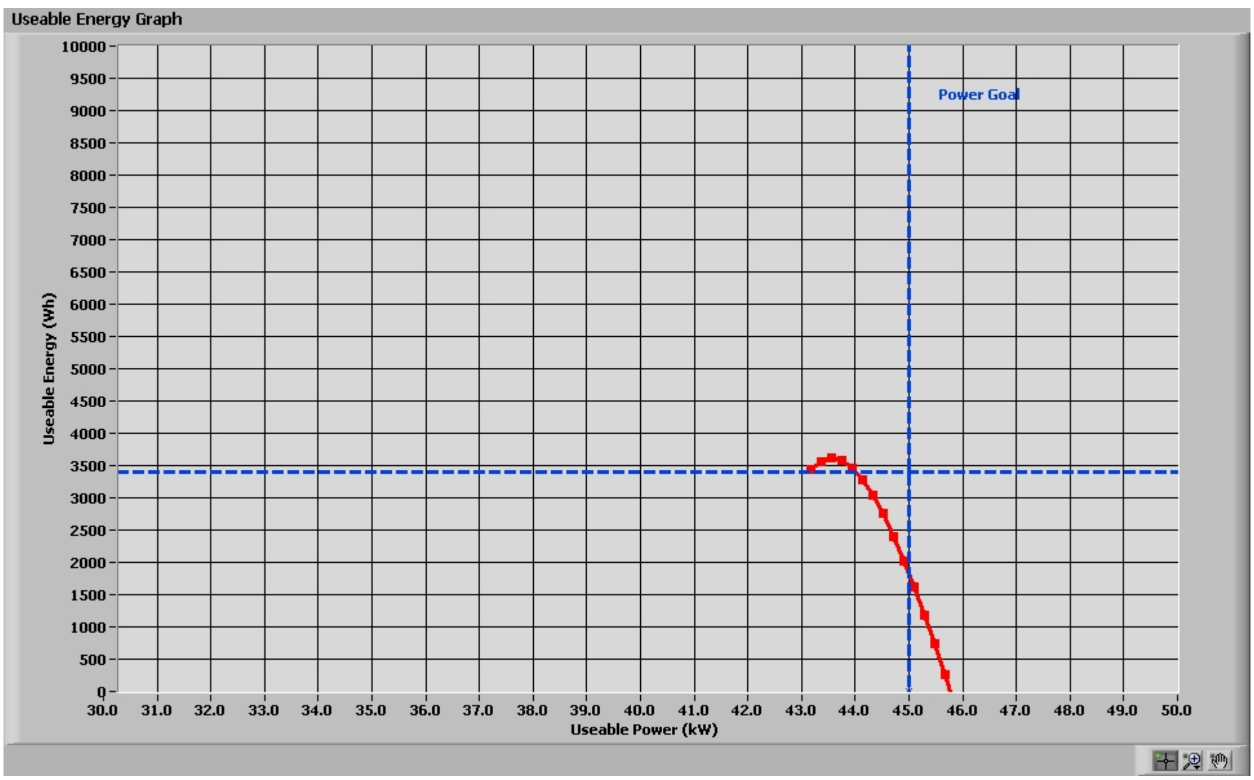

Figure 7. Useable energy versus useable power from the HPPC test

1.4 Acceleration Test Results

Results from the vehicle on-track acceleration tests at beginning of test (BOT) while the vehicle was in charge-sustaining (CS) mode and charge-depleting (CD) mode are summarized in the following table:

Table 4. Acceleration test results

	Average Discharge Power Over 10s (kW)	Energy Discharged at 1 Mile (Wh)	Capacity Discharged at 1 Mile (Ah)	Minimum Discharge Pack Voltage (V)	Minimum Discharge Cell Voltage (V)
BOT CD	22.0	284	1.31	213.3	2.96
BOT CS	22.2	279	1.27	216.2	3.00

Figures 8 and 9 show battery power versus time during the one-mile acceleration test while the vehicle was in CD and CS modes, respectively. These graphs are the basis for the power calculations over the specified time interval and the cumulative discharged energy capacity during the duration of the test. Initially, during the acceleration test, the power quickly ramps up from about 0 kW to a peak value. This initial peak power is used as a reference point for the rest of the power analysis. Ideally, the power would remain constant; however, the battery system dynamics, which may include battery control logic, cause the voltage to drop, resulting in an overall reduction in power.

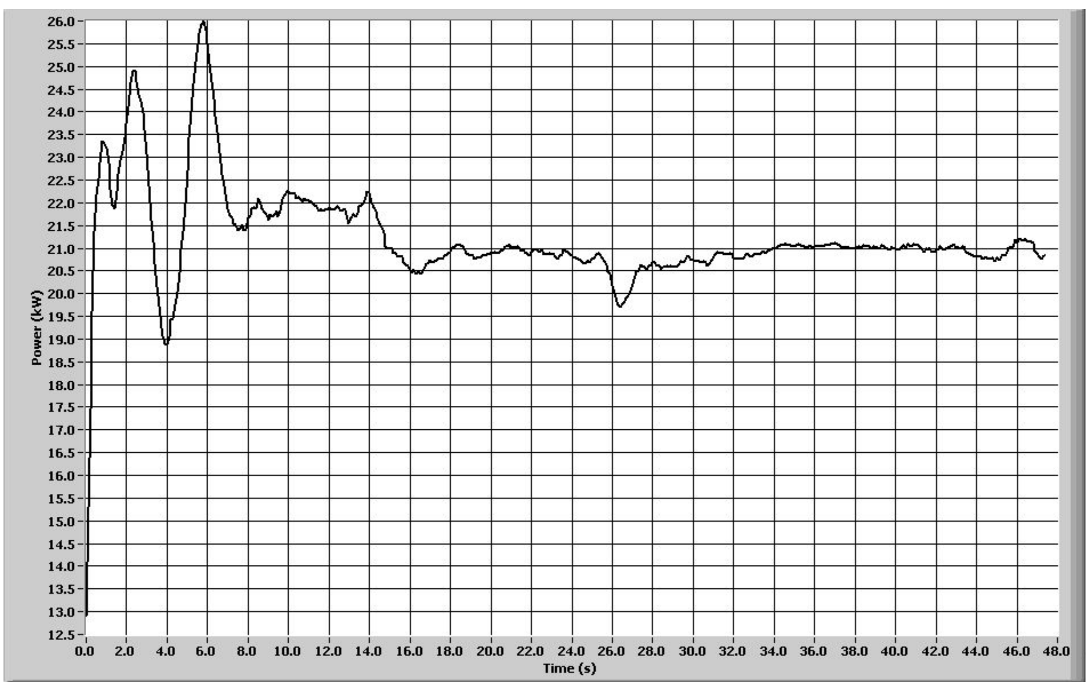

Figure 8. Battery power versus time for the acceleration test in CD mode

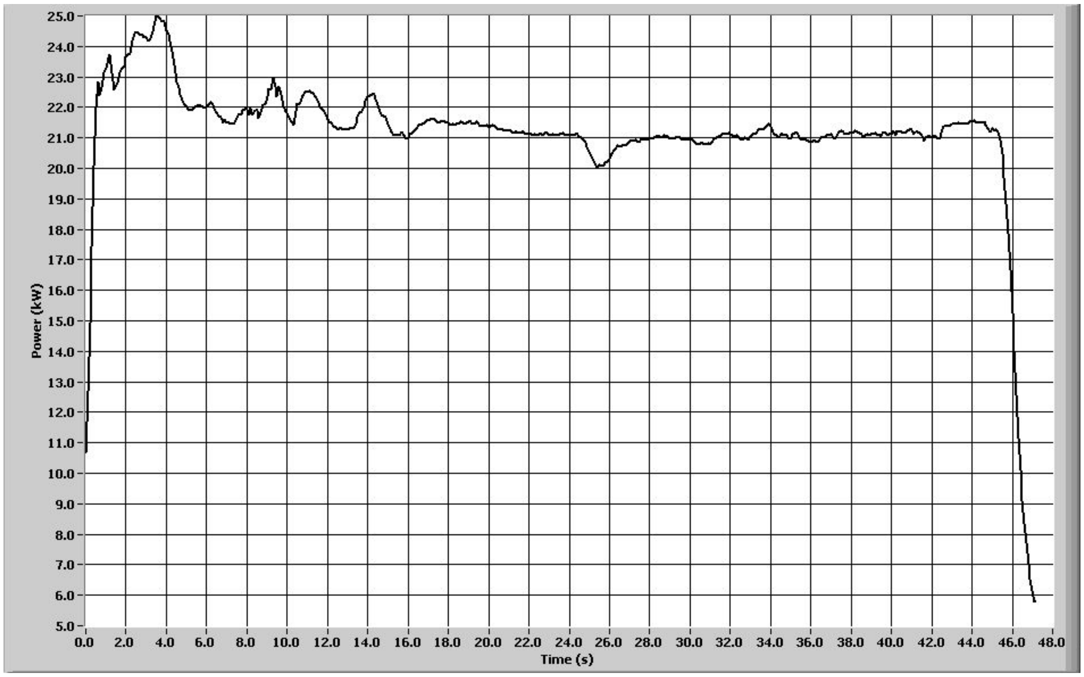

Figure 9. Battery power versus time for the acceleration test in CS mode

Figures 10 and 11 show battery voltage versus time during the one-mile acceleration test while the vehicle was in CD and CS modes, respectively. The values are analyzed, where possible, to determine the battery control module's minimum allowable voltage. Although the test may not yield a definitive minimum voltage value, it can yield 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.

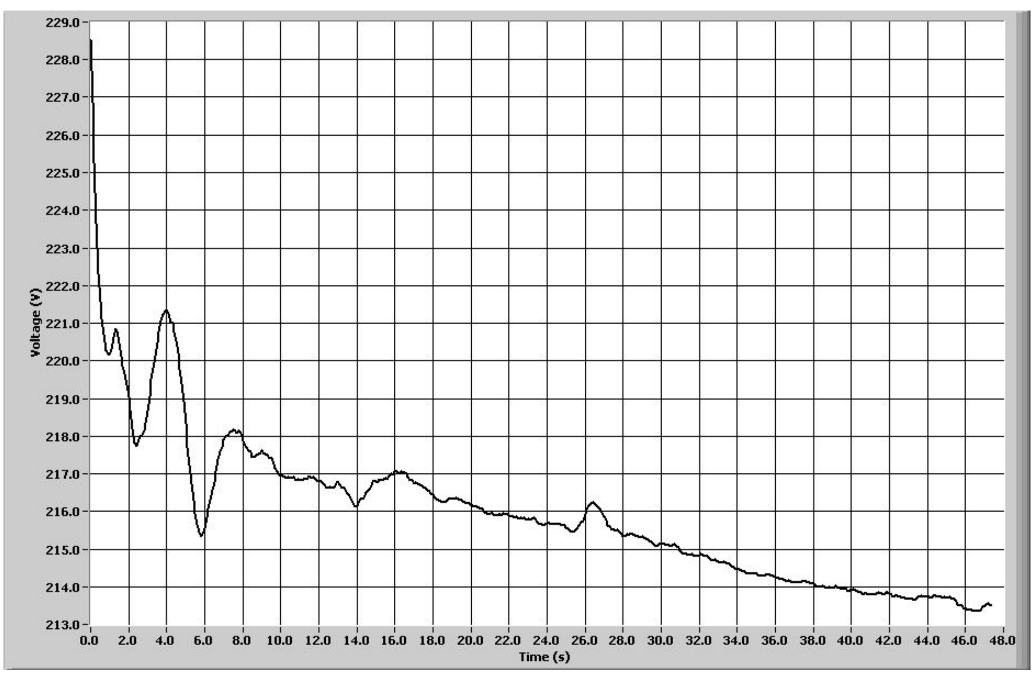

Figure 10. Battery voltage versus time for the acceleration test in CD mode

Figure 11. Battery voltage versus time for the acceleration test in CS mode

Figures 12 and 13 show the battery current versus time during the one-mile acceleration test while the vehicle was in the CD and CS modes, respectively. This graph also is the basis for determining the cumulative discharged current capacity during the test run.

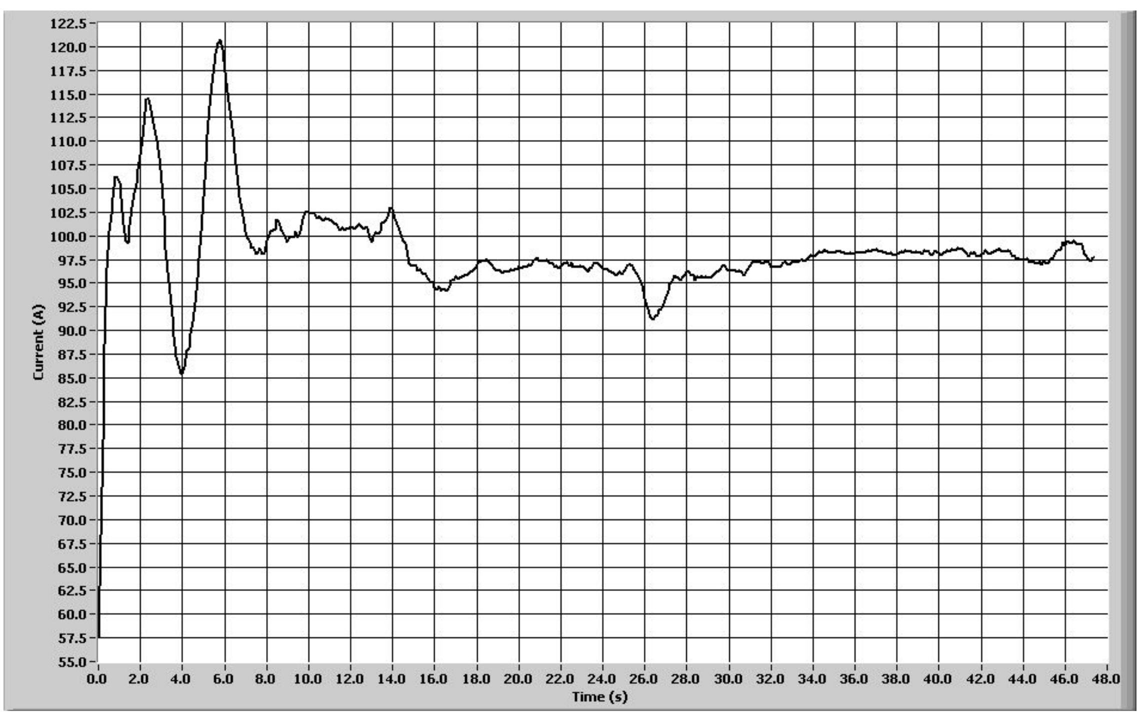

Figure 12. Battery current versus time for the acceleration test in CD mode

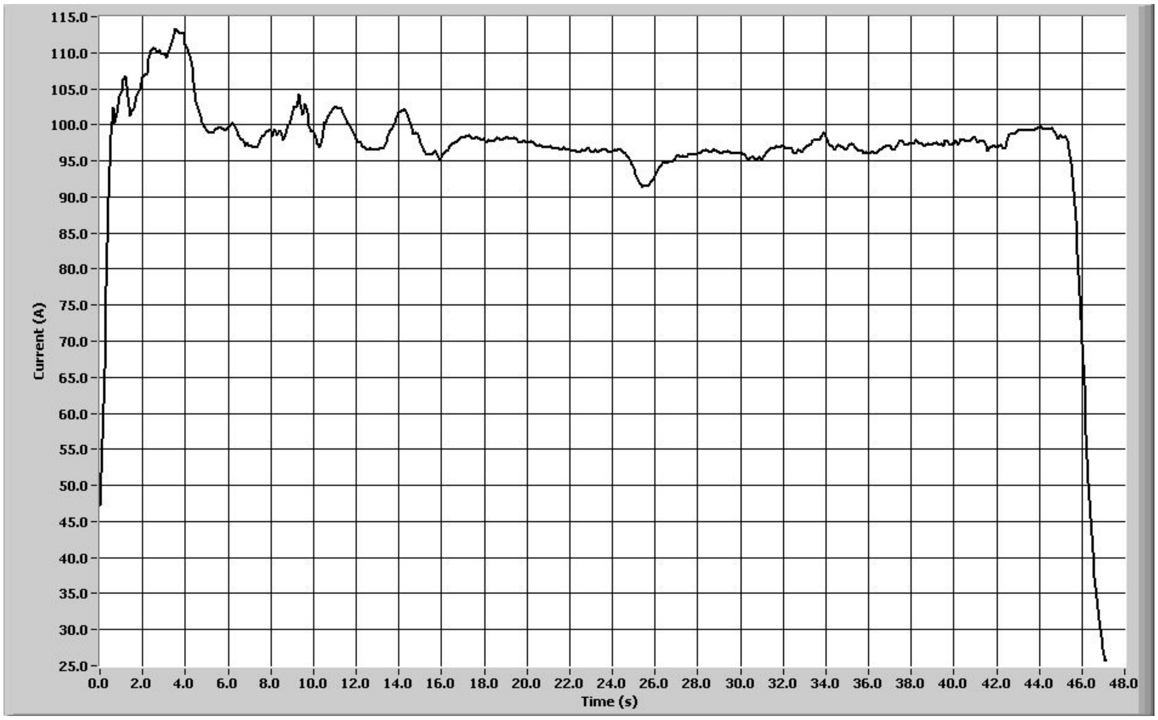

Figure 13. Battery power versus time for the acceleration test in CS mode

1.5 Fuel Economy Testing Results

Results of battery testing conducted while the vehicle was driven on a dynamometer on the Urban Dynamometer Drive Schedule[5] (UDDS) at BOT are provided in Table 4. The fuel economy for CD and CS modes were 64 mpg and 45 mpg, respectively.

Table 5. Battery performance results during dynamometer testing

Mode	Peak Discharge Power (kW)	Peak Regenerative Power (kW)	Measured Discharge Capacity (Ah)	Measured Regenerative Capacity (Ah)	Discharge / Charge Ratio	Maximum Charge Pack Voltage (V)	Maximum Charge Cell Voltage (V)	Minimum Discharge Pack Voltage (V)	Minimum Discharge Cell Voltage (V)
CD	29.0	20.9	15.5	15.4	1.0	249.6	3.47	220.0	3.06
CS	28.5	25.9	9.42	9.22	1.0	250.6	3.48	219.2	3.04

Figures 14 and 18 illustrate the vehicle motive power histogram throughout one of the tested drive schedules for the CD and CS modes, respectively. Motive power is a calculated value that represents instantaneous, theoretical, positive wheel power required to complete the urban drive cycle. The x-axis of the bar graph represents the center point of a particular power level. For example, the first bar graph with a power of 2 represents all power values between 1 and 3 kW (lower boundary is inclusive and upper boundary is non-inclusive). The corresponding y-value at this power level is the percent time at this particular power band throughout the entire drive cycle (regeneration power and zero power non-inclusive). Time at battery discharge power is shown beside the distribution of vehicle's motive power to indicate the proportion of motive power coming from the battery. While efficiency losses between the

[5] The Urban Dynamometer Drive Schedule was performed as defined by the Environmental Protection Agency. The definition of the Urban Dynamometer Drive Schedule can be found at http://www.epa.gov/nvfel/methods/uddsdds.gif.

battery and the wheels are not considered, it is apparent that the majority of motive power to complete the urban drive cycle is supplied by the battery.

Figures 15 and 19 illustrate the vehicle regenerative braking power histogram throughout one of the tested urban drive cycles for the CD and CS modes, respectively. Regenerative braking power is a calculated value that represents the theoretical negative wheel power required to decelerate the vehicle on the urban drive cycle. Figures 15 and 19 compare the distributions of available braking power and actual battery charge power. The overall shapes of the distributions indicate that the battery captures a substantial fraction of the vehicle’s power available during braking.

Figures 16 and 20 are pie charts showing the sources of regenerative energy throughout the urban drive cycle for the CD and CS modes, respectively. Ideal charging refers to regenerative braking during deceleration where the deceleration force is in excess of the vehicle drag forces. On a non-hybrid vehicle, this would require the brakes to be pressed and excess energy would be converted to heat at the brakes. In a hybrid vehicle, a portion of this excess energy can be captured and stored for later use. Because this charge method is capturing energy that is normally lost, the charge event is considered ideal. The second charging type is called non-ideal because the vehicle charges the battery through use of the internal combustion engine and generator. This can happen during acceleration, cruising, or deceleration when excess engine load is available or when the battery’s state of charge has dropped below a minimum level. This is non-ideal because the internal combustion engine charges the battery. In some cases, this can be beneficial for overall fuel economy by maintaining optimum load on the engine to increase efficiency; however, it is still considered non-ideal because gasoline is used to charge the batteries.

Figures 17 and 21 are pie graphs that show the percent of vehicle regeneration energy captured in the battery for the CD and CS modes, respectively. By calculating total vehicle energy available at the wheels during an ideal charge event and performing a direct comparison of energy into the battery, the percent energy into the battery can be calculated. In addition, system losses can be determined as the difference between energy available from the vehicle and energy into the battery. Although each component of loss cannot be determined, the total system loss can be measured by this method. Also, it should be noted that this calculation does not take into account losses at the battery due to charge inefficiency. This measurement is merely a calculation of how efficiently the vehicle charging mechanism is able to capture regeneration energy during an ideal charge event. [6]

[6] Results shown in Figures 13 and 14 do not consider the case when non-ideal engine charging occurs during a regenerative braking event. The impact of this case during the UDDS test is assumed to be negligible.

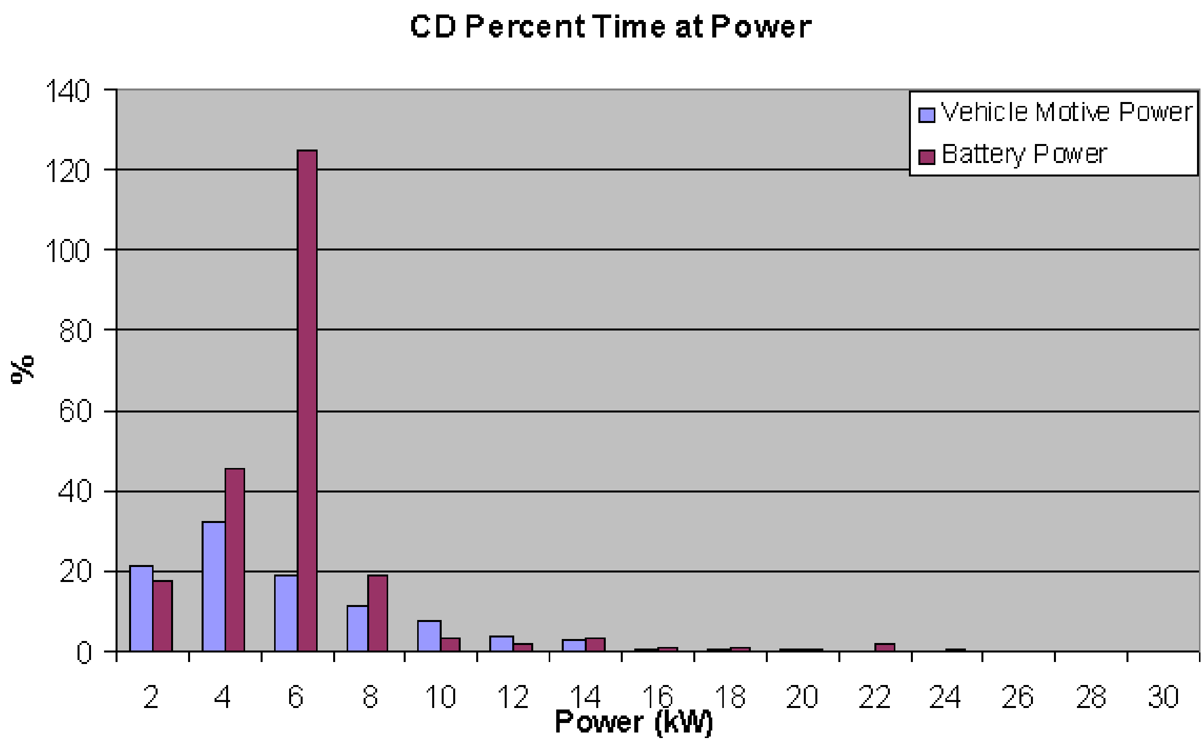

Figure 14. Percentage of time histogram at different motive power levels for the UDDS in CD mode

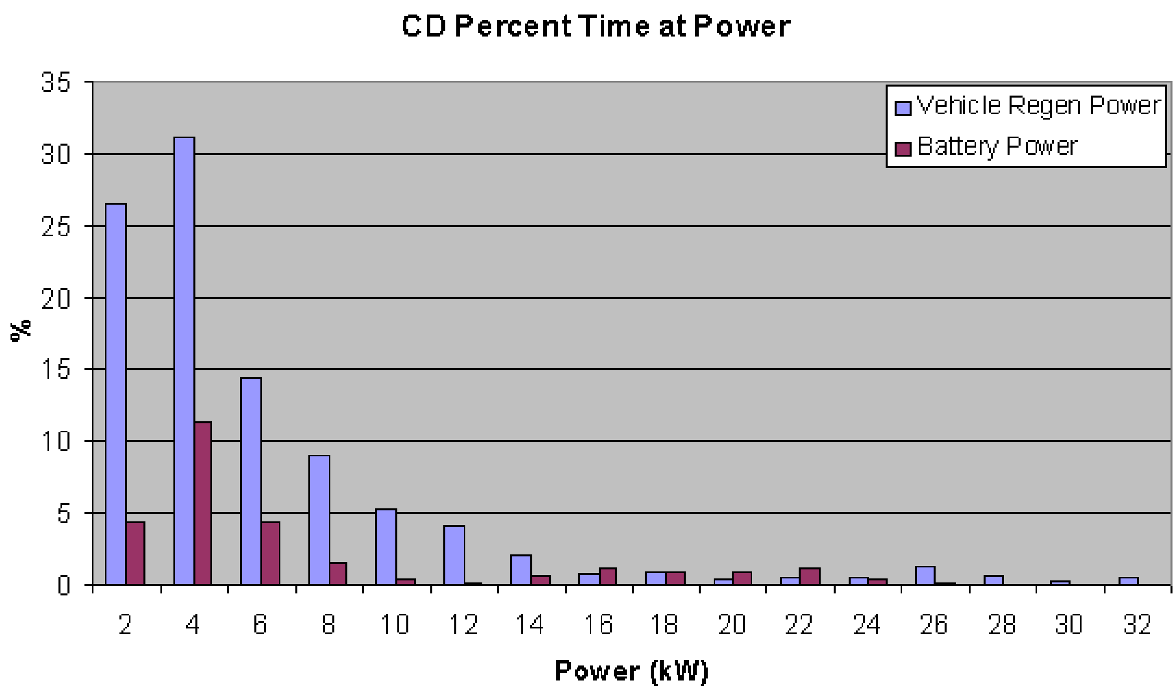

Figure 15. Percentage of time histogram at different regen/battery charge power levels for the UDDS in CD mode

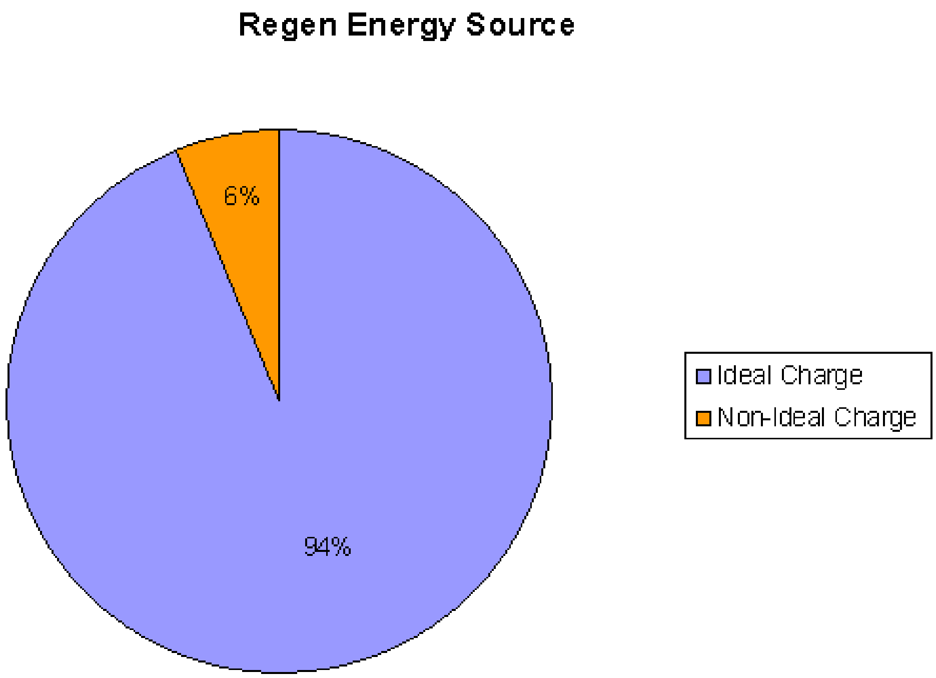

Figure 16. Source of regenerative energy comparison in CD mode

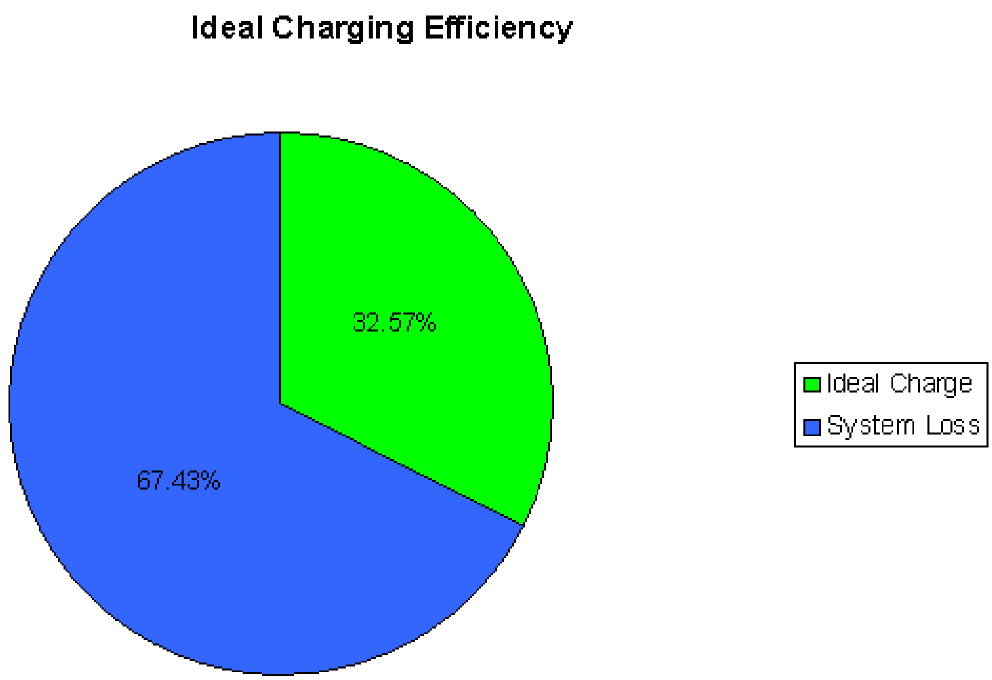

Figure 17. Destination of ideal regenerative energy in CD mode

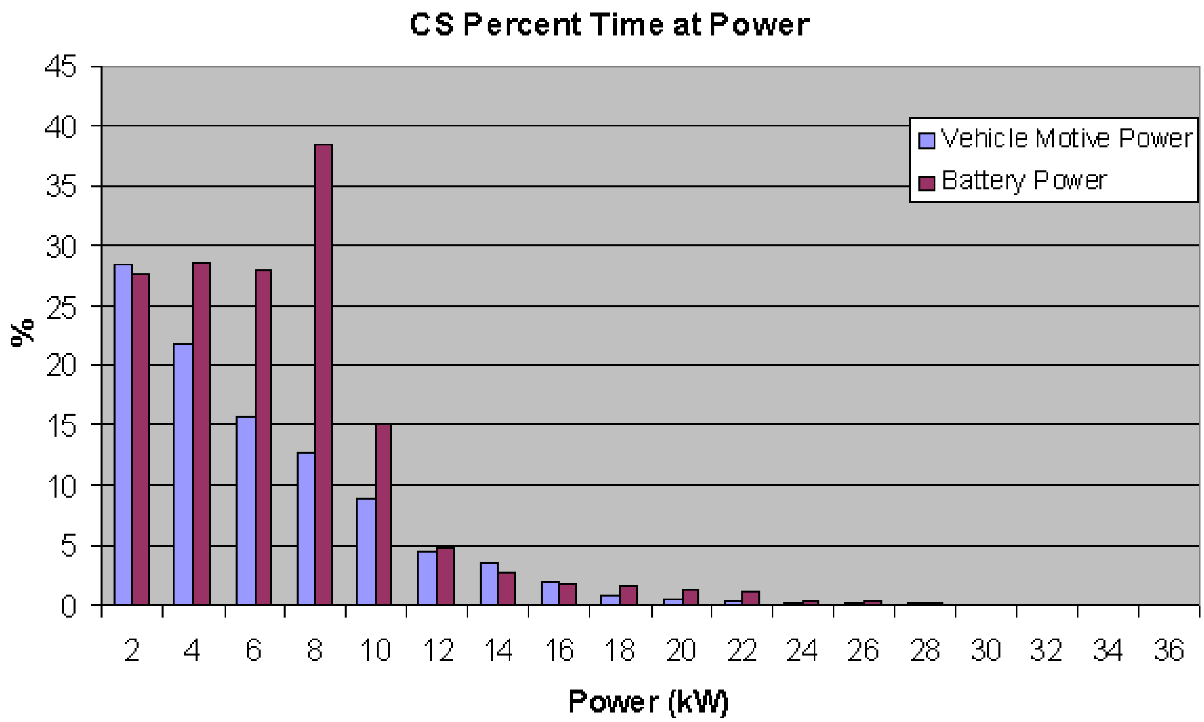

Figure 18. Percentage of time at motive power levels for the UDDS in CS mode

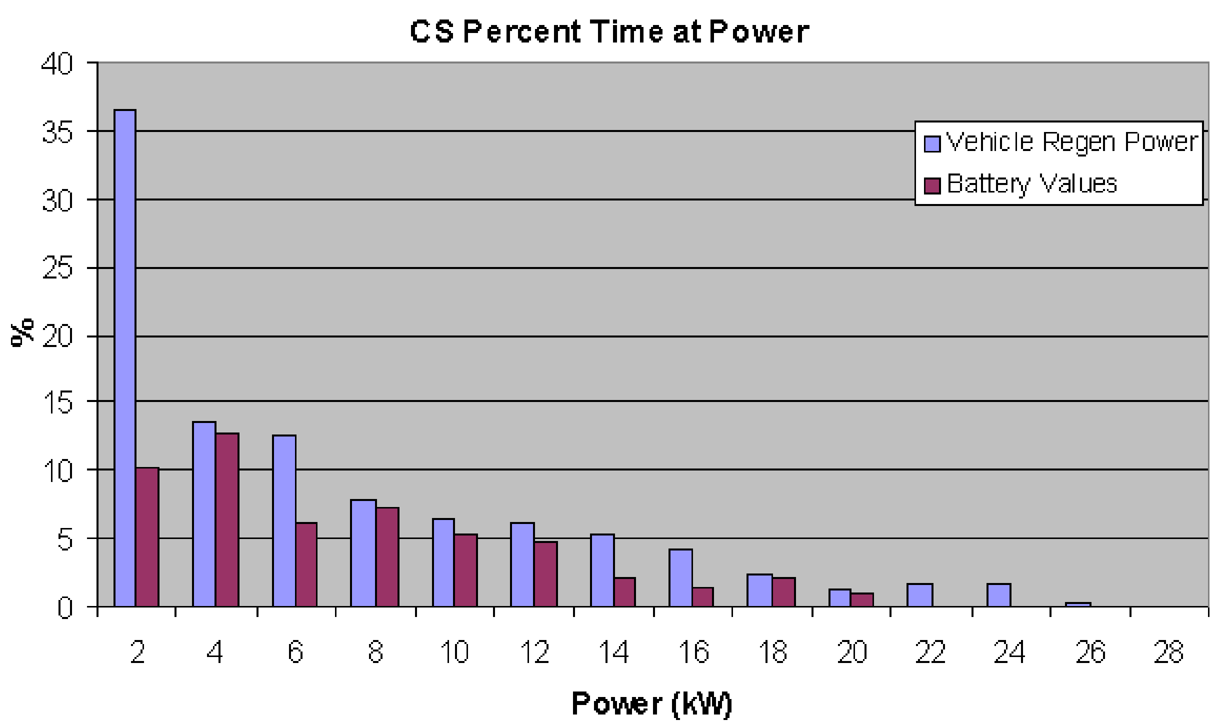

Figure 19. Percentage of time histogram at different regen/battery charge power levels for the UDDS in CS mode

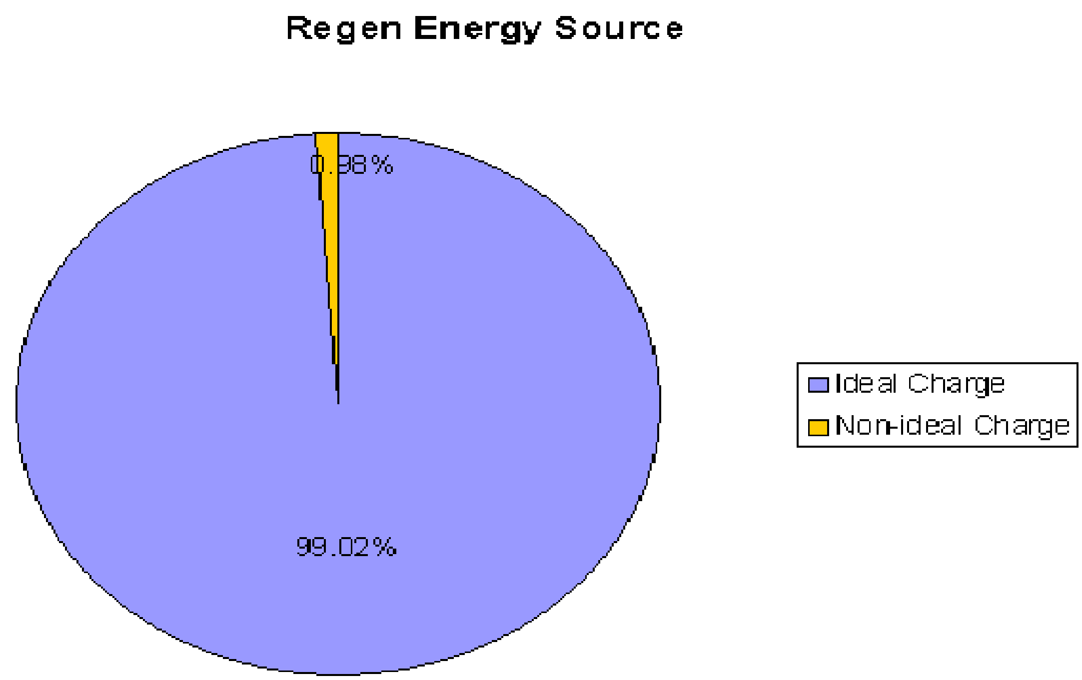

Figure 20. Source of regenerative energy comparison in CS mode

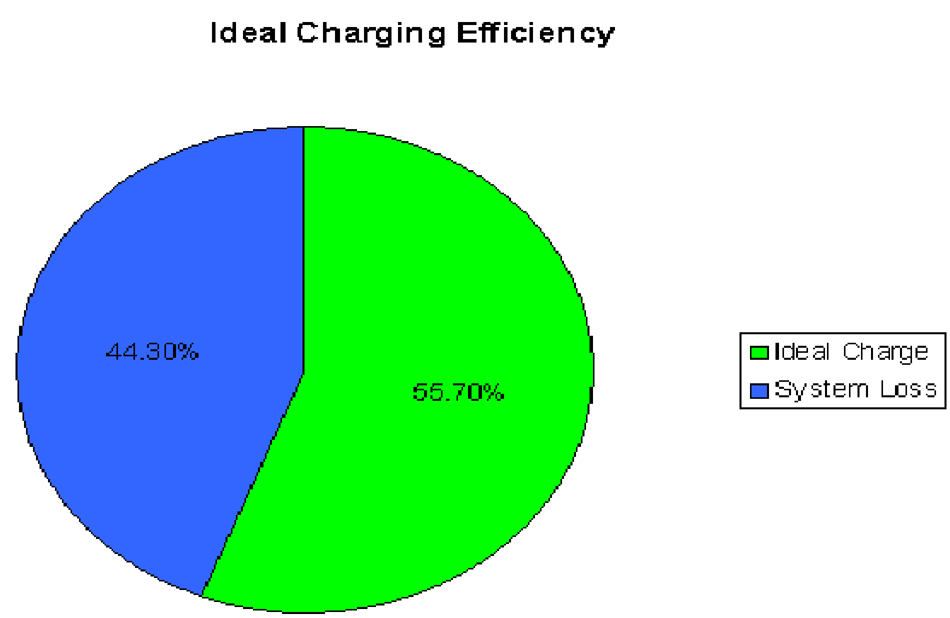

Figure 21. Destination of ideal regenerative energy in CS mode

1.6 On-Road Accelerated Testing Results

The per-cycle and cumulative fuel economy for on-road accelerated testing are shown below in Table 5. Low fuel economy during the 40-mile cycles was found to be due to excessively low voltage in a small number of cells. Therefore, although it was not quantified in the laboratory testing, the Energy CS battery pack was found to experience degradation during the 5,400 mile on-road accelerated testing, which was significant enough to affect vehicle performance.

Table 6. On-road accelerated testing results

Cycle (mi)	Urban (10 mi)	Highway (10 mi)	Charge (hr)	Reps (N)	Total (mi)	Electricity kWh	Gasoline	
							Gals	mpg
10	1	0	4	60	600	115.58	4.78	128.1
20	1	1	8	30	600	86.21	7.95	77.9
40	4	0	12	15	600	25.00	14.29	42.7
40	2	2	12	5	600	31.52	11.05	56.1
40	0	4	12	5	600	32.44	11.36	55.5
60	2	4	12	10	600	65.00	5.90	103.7
80	2	6	12	8	640	39.04	10.09	65.8
100	2	8	12	6	600	22.67	8.81	70.8
200	2	18	12	3	600	12.98	10.46	57.8
Total	**2,340**	**2,500**	**984**	**147**	**5,440**	**Weighted Average**		**73.1**

2 CONCLUSIONS

The 2008 Toyota Prius 8820 converted to an Energy CS Prius PHEV experienced a degradation in battery performance during the accelerated on-road testing. However, the amount of degradation was not quantified and was not obvious from the on-road results. A BOT test was not conducted, so a comparison with the beginning state of the battery was not possible. The result of the EOT constant power discharge test (8.38 kWh) was below the U.S. Department of Energy's available energy performance goal for charge-depleting operation of 3.4 kWh. However, the results of the HPPC test indicated that the battery did not meet the USABC's goals for useable energy at a given amount of power (3.4 kWh at 45 kW).

APPENDIX A – Vehicle Specifications and Test Results Summary

Vehicle Specifications	Battery Specifications
Manufacturer: Toyota Model: Prius Year: 2007 Number of Motors[a]: 1 Front Motor Power Rating[b]: 50 kW VIN #: JTDKB20U767508841	Battery Manufacturer: Valence Technology Generation: 1st Battery Type: Li-Ion Number of Cells: 2376 Nominal Cell Voltage: 3.2 V Nominal System Voltage: 230 V Nominal Pack Energy: 10 kWh
Beginning-of-Test Vehicle Baseline Performance Test Results[c]	
Acceleration Test	**Fuel Economy Test (CD/CS)**
Peak Discharge Power @ 10 seconds[c]: 22.0/22.2 kW Peak Discharge Power @ 1 second[c]: 24.3/24.3 kW Energy Discharged @ 1 mile[d]: 284/279 Whs Capacity Discharged @ 1 mile[d]: 1.31/1.27 Ah Minimum Discharge Pack Voltage: 231.3/216.2 VDC Minimum Discharge Cell Voltage: 3.21/3.00 V	Peak Discharge Power: 29.0/29.0 kW Peak Charge Power: 20.9/25.9 kW Measured Capacity Discharged[e]: 15.5/9.22 Ah Measured Capacity Regenerated[e]: 15.4/9.42 Ah Battery Discharge/Charge Ratio[f]: 1.0/1.0 Maximum Charge Pack Voltage: 249.6/250.61 VDC Maximum Charge Cell Voltage: 3.48 Vpc Minimum Discharge Pack Voltage: 220.0/219.2 VDC Minimum Discharge Cell Voltage: 3.06/3.04 Vpc
Battery End-of-Test Laboratory Test Results	
Hybrid Pulse Power Characterization Test	**Static Capacity Test**
Peak Pulse Discharge Power @ 10 seconds[g]: 53.4 kW Peak Pulse Discharge Power @ 1 second[g]: 51.7 kW Peak Pulse Charge Power @ 10 seconds[g]: 34.6 kW Peak Pulse Charge Power @ 1 seconds[g]: 47.9 kW Maximum Cell Charge Voltage: 3.6 V Minimum Cell Discharge Voltage: 2.5 V	Measured Average Capacity: 37.1 Ah Measured Average Energy Capacity: 8.36 kWh Date of Test: April 22, 2009 **Constant Power Discharge Test** Ah Discharged: 37.0 Ah kWh Discharged: 8.38 kWh Time to Fully Discharge: 50 minutes

Analysis Notes:

a. Motor refers to any motor capable of supplying traction power.

b Motor power rating refers to the manufacturer's peak power rating for the motor(s) supplying traction power.

c The peak power at a specified duration is the average power value over a specified interval beginning at the measured maximum power of the pulse.

d The capacity\energy value is defined as the net value over a 1-mile, full-throttle, acceleration test.

e. Cumulative capacity measurement over two hot start urban drive cycles and two hot start highway drive cycles.

f. 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.

g. Calculated value based on selected battery voltage limits and at 50% state of charge.

Ah = amp-hour	VDC = volt direct current
kW = kilowatt	Vpc = volt per cell
kWh = kilowatt-hour	Wh = Watt-hour