U.S. DEPARTMENT OF ENERGY | Energy Efficiency & Renewable Energy
VEHICLE TECHNOLOGIES PROGRAM

INL/EXT-10-19028

2007 Toyota Prius 8820 with Gen II Hymotion Prius Conversion Plug-In Hybrid Battery Test Results

Tyler Gray
Jeffrey Wishart
James Francfort

June 2010

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

ecotality NORTH AMERICA
INL Idaho National Laboratory

INL/EXT-10-19028

2007 Toyota Prius 8820 with Gen II Hymotion Prius Conversion
Plug-In Hybrid Battery Test Results

Tyler Gray[1]
Jeffrey Wishart[1]
James Francfort[2]

June 2010

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 ECOtality North America
2 Idaho National Laboratory

Disclaimers

This document highlights work sponsored by agencies of the U.S. Government. Neither the U.S. Government nor any agency thereof, nor any of its employees, makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product, or process disclosed, or represents that its use would not infringe privately owned rights. Reference herein to any specific commercial product, process, or service by trade name, trademark, manufacturer, or otherwise does not necessarily constitute or imply its endorsement, recommendation, or favoring by the U.S. Government or any agency thereof. The views and opinions of authors expressed herein do not necessarily state or reflect those of the U.S. Government or any agency thereof.

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 2007 Toyota Prius with VIN 8820 (VIN JTDKB20U577558820) was converted to a Gen II Hymotion Prius PHEV for testing. It should be noted that the same vehicle was previously converted previously to a Gen I Hymotion Prius PHEV for identical testing in the AVTA program. 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.

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

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 a second-generation Hymotion conversion of a 2007 Toyota Prius, number 8820 (VIN JTDKB20U577558820) in the battery test laboratory and during vehicle operations. The Hymotion conversion kit consists of a 5-kWh, Lithium-ion supplemental battery pack from A123 Systems. 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 and Constant Power Discharge 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 BOT and EOT Static Capacity test are provided below in Table 1.

Table 1. Static capacity test results

	Test Date	Rated Capacity (Ah)	Measured Capacity (Ah)	Measured Energy (kWh)
BOT	April 3, 2009	25.3	22.3	3.96
EOT	August 12, 2009	25.3	21.6	3.83
Difference	—	—	-0.7 (-3.1%)	-130 (-3.3%)

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

[3] Static Capacity and Constant Power Discharge 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.

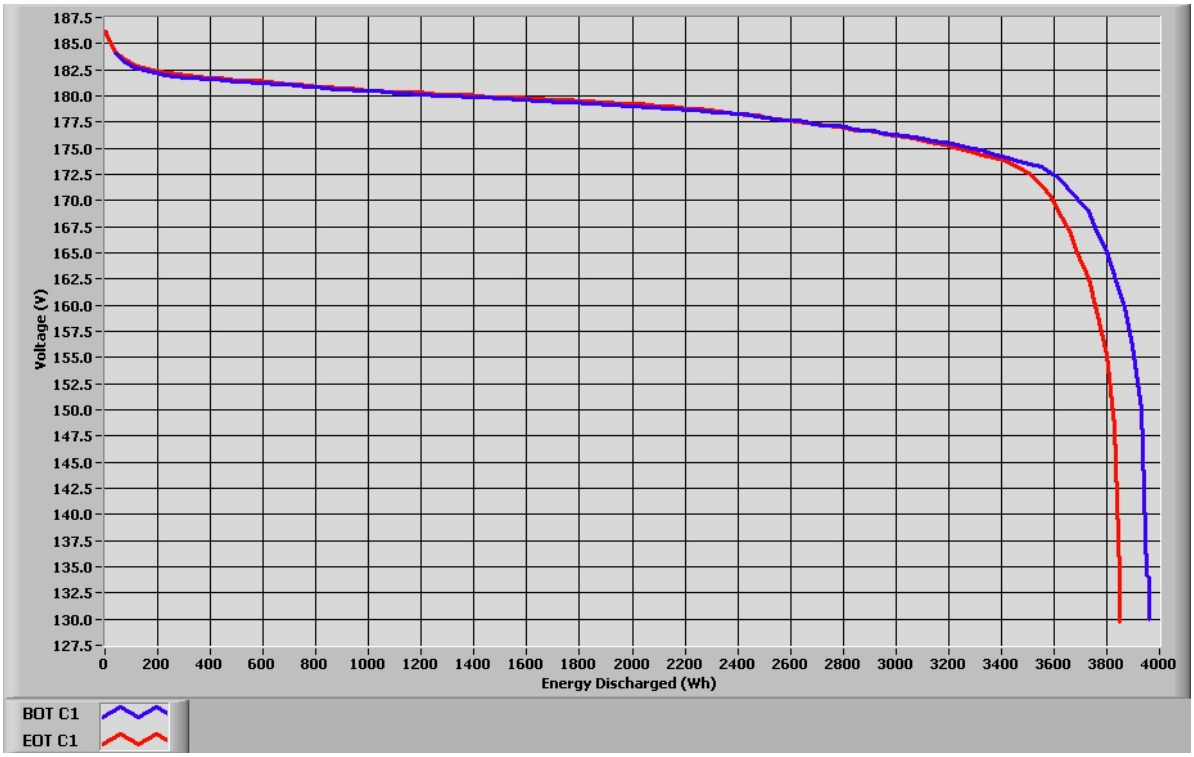

Figure 1. Voltage versus energy discharged during Static Capacity test

1.2 Constant Power Discharge Test Results

Results from the laboratory BOT and EOT Constant Power Discharge test are provided in Table 2. Results of both tests were 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 (minutes)
BOT	22.6	3.89	26.8
EOT	21.6	3.74	25.7
Difference	-1.0 (-4.4%)	-0.15 (-3.9%)	-1.1

1.3 Hybrid Pulse Power Characterization Test Results

A HPPC test was not performed for this plug-in battery pack because it is a supplemental pack that is connected in parallel to the manufacturer-designed, nickel-metal hydride (NiMH),hybrid electric vehicle battery pack. The supplemental pack assists the original equipment nickel-metal hydride pack by delivering extra power to the system and allowing the vehicle to perform longer in all-electric or power-assist modes. This particular pack does not accept any charge from the vehicle during normal operation; therefore, the HPPC test is not relevant for this battery pack.

1.4 Acceleration Test Results

Results from the vehicle on-track acceleration tests at BOT are shown in Table 3.

Table 3. 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*	22.7	186	0.93	197.2	3.52

* All values represent only Hymotion conversion pack performance.

Figure 2 below shows the combined power of both battery packs in the converted vehicle versus time during the one-mile acceleration test. This graph is the basis for 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, battery system dynamics, which may include battery control logic, cause the voltage to drop, resulting in an overall reduction in power.

Figure 2. Battery power versus time during acceleration test

Figure 3 shows the battery system voltage versus time during the one-mile acceleration test. The values are analyzed, where possible, to determine the battery control module's minimum allowable voltage. This graph also shows the impact of the vehicle power electronics or the battery controller on the voltage response.

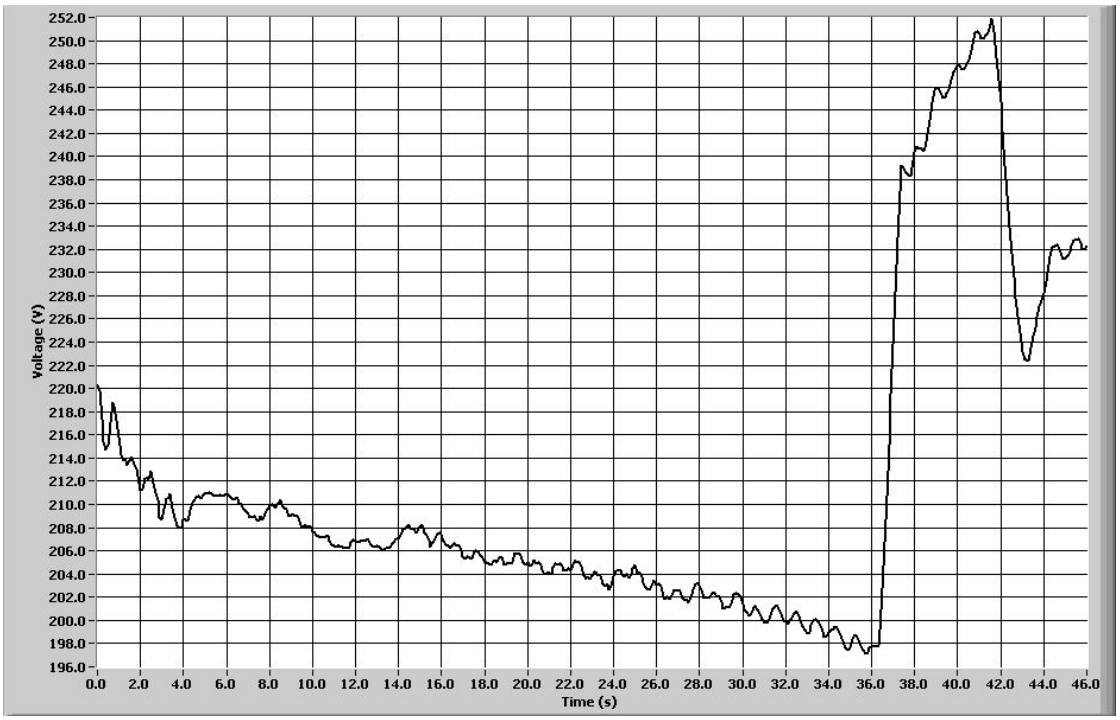

Figure 3. Battery voltage versus time during acceleration test

Figure 4 shows the combined current from both battery packs in the converted vehicle versus time during the one-mile acceleration test. This graph also is the basis for determining the cumulative discharged current capacity during the test run.

Figure 4. Battery current versus time during acceleration test

1.5 Fuel Economy Test Results

Results of battery and fuel economy testing conducted on a dynamometer during the Urban Dynamometer Drive Schedule[5] (UDDS) drive schedule at BOT are shown in Table 4.

Table 4. Dynamometer battery testing results

Peak Discharge Power (kW)	Measured Discharge Capacity (Ah)	Minimum Discharge Pack Voltage (V)	Minimum Discharge Cell Voltage (V)
10.8	22.8	177	3.16

1.6 On-Road Accelerated Test Results

The per-cycle and cumulative fuel economy for on-road accelerated testing are shown below in Table 5. The leftmost column refers to the number of miles between vehicle recharges. As the distance between charges goes up, the electricity used decreases, as does the fuel economy. A drop in fuel economy is seen in the first two 40-mile cycles. Upon investigation, it was determined that this was due to an increase of driver aggressiveness, rather than degradation in battery or vehicle performance. Those cycles were repeated with a mild driving style, with a resulting fuel economy of over 90 mpg per cycle.

Table 5. Results of on-road accelerated testing

Cycle (mi)	Urban (10 mi)	Highway (10 mi)	Charge (hr)	Reps (N)	Total (mi)	Electricity AC kWh	Gasoline	
							Gals	mpg
10	1	0	4	60	600	111.43	5.205	117.6
20	1	1	8	30	600	124.50	8.105	80.1
40	4	0	12	15	600	71.28	9.8	62.1
40	2	2	12	15	600	64.36	9.70	64.3
40	2	2	12	15	600	75.14	6.20	99.8
40	0	4	12	15	600	75.18	6.10	103.3
60	2	4	12	10	600	33.38	10.54	58.8
80	2	6	12	8	640	41.38	10.71	61.8
100	2	8	12	6	600	26.48	10.91	56.5
200	2	18	12	3	600	16.01	10.41	57.7
Total	**2,340**	**3,100**	**1,404**	**167**	**6,040**	**Weighted Average**		**76.8**

[5] 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.

2 CONCLUSIONS

The 2007 Toyota Prius 8820 converted to a Gen II Hymotion Prius PHEV experienced a 3.1% and 3.9% degradation in static capacity and constant power discharge capability, respectively. The result of the EOT Constant Power Discharge test (3.74 kWh) was above the U.S. Department of Energy's available energy performance goal for charge-depleting operation of 3.4 kWh. These results are an improvement on the Gen I Hymotion Prius PHEV tested previously.

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 #: JTDKB20U577558820	Battery Manufacturer: A123 Systems Generation: 2nd Battery Type: Li-Ion Number of Cells: 616 Nominal Cell Voltage: 3.3 V Nominal System Voltage: 185 V Nominal Pack Energy: 4.7 kWh
Beginning-of-Test Vehicle Baseline Performance Test Results[c]	
Acceleration Test	**Fuel Economy Test**
Peak Discharge Power @ 10 seconds[c]: 22.7 kW Energy Discharged @ 1 mile[d]: 186 Wh Capacity Discharged @ 1 mile[d]: 0.93 Ah Minimum Discharge System Voltage: 197.2 VDC	Peak Discharge Power: 10.8 kW Peak Charge Power: NA Measured Capacity Discharged[e]: 22.8 Ah Measured Capacity Regenerated: NA Battery Discharge/Charge Ratio: NA Maximum Charge Pack Voltage: 177.0 VDC Maximum Charge Cell Voltage: 3.16 Vpc Minimum Discharge Pack Voltage: 0 VDC Minimum Discharge Cell Voltage: 0 Vpc
Battery Beginning-of-Test Laboratory Test Results	
Hybrid Pulse Power Characterization Test	**Static Capacity Test**
NA	Measured Average Capacity: 22.3 Ah Measured Average Energy Capacity: 3.96 Wh Date of Test: April 4, 2009
Constant Power Discharge Test	
Ahr Discharged: 22.6 Ah kWh Discharged: 3.89 kWh Time to Fully Discharge: 26.8 minutes	
Battery End-of-Test Laboratory Test Results	
Constant Power Discharge Test	**Static Capacity Test**
Ahr Discharged: 21.6 Ah kWh Discharged: 3.74 kWh Time to Fully Discharge: 25.7 minutes	Measured Average Capacity: 21.6 Ah Measured Average Energy Capacity: 3.83 Wh Date of Test: August 12, 2009

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. System voltage refers to the Hymotion battery pack connected in parallel through a dc/dc converter to the stock Prius battery pack.

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