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Hybrid and plug-in hybrid electric vehicle performance testing by the US Department of Energy Advanced Vehicle Testing Activity

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Abstract

The Advanced Vehicle Testing Activity (AVTA), part of the U.S. Department of Energy's FreedomCAR and Vehicle Technologies Program, has conducted testing of advanced technology vehicles since August 1995 in support of the AVTA goal to provide benchmark data for technology modeling, and vehicle development programs. The AVTA has tested full size electric vehicles, urban electric vehicles, neighborhood electric vehicles, and hydrogen internal combustion engine powered vehicles. Currently, the AVTA is conducting baseline performance, battery benchmark and fleet tests of hybrid electric vehicles (HEV) and plug-in hybrid electric vehicles (PHEV). Testing has included all HEVs produced by major automotive manufacturers and spans over 2.5 million test miles. Testing is currently incorporating PHEVs from four different vehicle converters. The results of all testing are posted on the AVTA web page maintained by the Idaho National Laboratory.

Keywords: Hybrid electric vehicle; Fuel economy testing; Plug-in hybrid electric vehicle

1. Introduction

The Advanced Vehicle Testing Activity (AVTA), part of the U.S. Department of Energy's FreedomCAR and Vehicle Technologies Program, has conducted testing of advanced technology vehicles since August 1995 in support of the AVTA goal to provide benchmark data for technology modeling, and vehicle development programs. The AVTA has tested full size electric vehicles, urban electric vehicles, neighborhood electric vehicles, and hydrogen internal combustion engine powered vehicles. Currently, the AVTA is conducting significant tests of hybrid electric vehicles (HEV) and plug-in hybrid electric vehicles (PHEV). Results of these tests characterize performance of both the vehicle and the vehicle battery.

All automotive manufacturers are currently offering HEVs or have made announcements of future HEV products. There is great interest in HEVs as an emerging technology, with PHEVs currently the subject of modeling and testing to determine their potential for energy savings and petroleum use reduction. AVTA test results provide vital data on the performance and durability of both HEVs and PHEVs, as well as specific performance data to support modeling of vehicle performance. AVTA testing activities are conducted by the Idaho National Laboratory; through its testing partner, Electric Transportation Applications, located in Phoenix, Arizona. Testing has included all HEVs produced by major automotive manufacturers over a span of 2.48 million miles and is currently beginning testing of PHEV offerings from four different vehicle converters using three different hybrid batteries. Results of all testing are posted on the AVTA web page maintained by the Idaho National Laboratory [1].

2. HEV testing

The AVTA uses three testing methods to evaluate HEVs. Baseline Performance Testing evaluates vehicles using a series of detailed test procedures on a closed-track and chassis dynamometer. Testing occurs over a 6-week period, typically using new vehicles. Fleet Testing places HEVs in commercial fleets where 160,000 miles of fuel use, repairs, maintenance, and life-cycle costs (including insurance and depreciation costs) are collected for each vehicle. Fleet Testing provides a real-world element to the testing process by placing new HEVs in operat-

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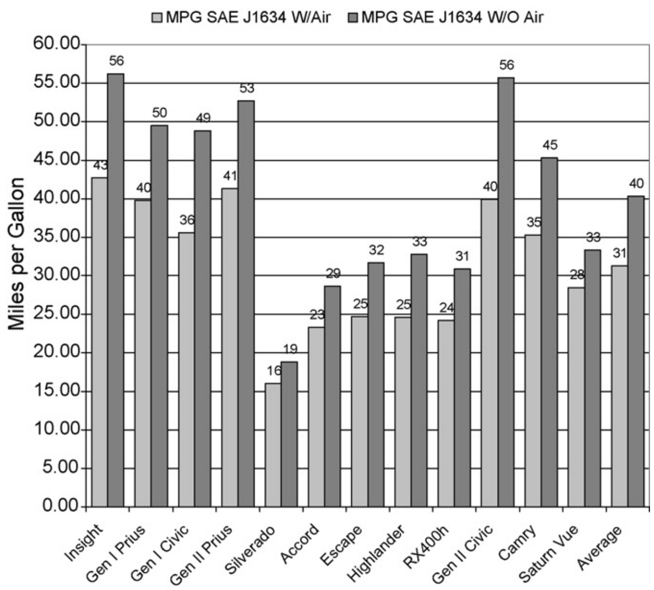

Fig. 1. Baseline performance HEV fuel economy with and without air conditioning operational.

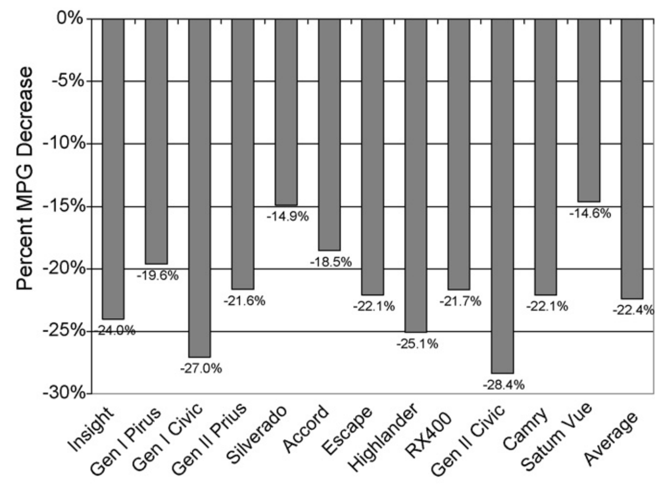

Fig. 2. Percentage decrease in Baseline Performance Testing fuel economy when testing is conducted with air conditioning operational.

ing fleets using procedural guidance to establish their operating mission. Vehicles are operated for as much as 8000 miles per month and data is collected from vehicle operation over the vehicles operating life. Typically, two vehicles of a given model are tested, with one vehicle subjected to Baseline Performance Testing and both vehicles subjected to 160,000 miles of Fleet Testing. Battery Benchmark Testing evaluates hybrid battery performance early in vehicle life and again after accumulating 160,000 miles of fleet operation.

2.1. Baseline Performance Testing

Baseline Performance Testing is conducted using the AVTA's HEV Vehicle Specification [2] and 22 HEV testing procedures [3] covering the testing process from required minimum vehicle specifications, through vehicle receipt, quality control, and testing methods which measure vehicle performance (acceleration times, top speed, handling, braking, gradeability, and fuel economy). Fuel economy is measured using a four-wheel chassis dynamometer operating on the Urban Dynamometer Driving Schedule (1372 s duration) and Highway Fuel Economy Test Schedule (764 s duration) defined in the Society of Automotive Engineers (SAE) recommended standard SAE J1634—Electric Vehicle Energy Consumption and Range Test Procedure [4].

To date, Baseline Performance Testing has been completed on 11 HEV models; the first and second generation (Gen I and Gen II) Toyota Prius, Honda Insight, first and second generation (Gen I and Gen II) Honda Civic, Honda Accord, Chevrolet Silverado (2 wheel drive), Ford Escape (2 wheel drive), Toyota Highlander, Lexus RX400h and Saturn VUE. Fig. 1 presents fuel economy for HEVs tested by the AVTA both with and without air conditioning operational. Fig. 2 shows the percentage decrease in fuel economy for these same HEVs with air conditioning operational.

Comparison of Baseline Performance Testing results for fuel economy with and without air conditioning operational reveals a significant decrease in fuel economy with the use of air conditioning. Because HEVs operate very efficiently, the energy required to operate air conditioning is a large percentage of the overall energy consumed by vehicle operation. The largest decrease recorded was 15.8 mpg for the Gen II Civic. The smallest decrease recorded was 2.8 mpg for the Silverado. The Gen II Civic had the greatest percentage fuel economy decrease (28.4%) when the air conditioning was on during the SAE J1634 tests. The average decrease in fuel economy due to use of the air conditioning during the SAE J1634 testing was 22.4%.

2.2. Fleet Testing

As of 1 February 2007, the 31 HEVs operated by the AVTA in Fleet Testing (Table 1) have accumulated 2.48 million test miles with cumulative fleet operating fuel economies (Fig. 3) ranging from 17.7 mpg for the Chevrolet Silverado HEV to 45.2 mpg for

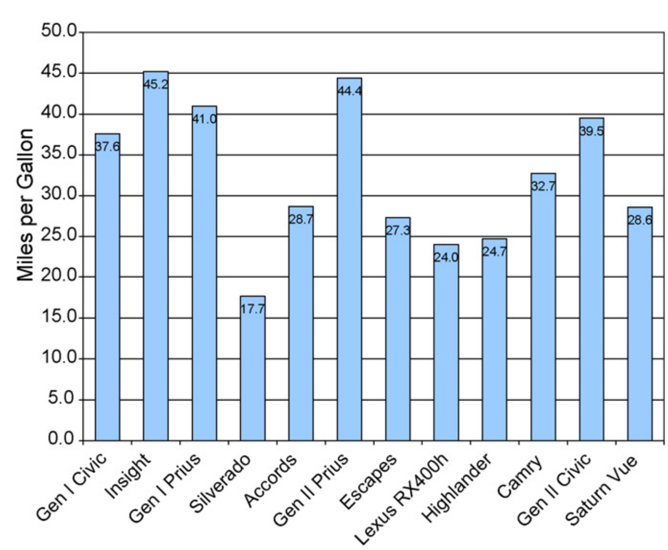

Fig. 3. Cumulative fuel economy by HEV model.

Table 1
Number of vehicles by vehicle model, and the testing status and miles per gallon for the HEVs in Fleet Testing

Vehicles in test	Model and year	Testing status	Cumulative fuel economy (mpg)
6	2001 Honda Insight	Complete	45.2
6	2002 Toyota Prius	Complete	41.0
4	2003 Honda Civics	Complete	37.6
2	2004 Toyota Prius	Ongoing	44.4
2	2004 Chevrolet Silverado	Ongoing	17.7
2	2005 Honda Accord	Ongoing	28.7
2	2005 Ford Escape	Ongoing	27.3
2	Toyota Highlander	Ongoing	24.7
2	Saturn VUE	Ongoing	28.6
3	Lexus 400h	Ongoing	24.0
2	Toyota Camry	Ongoing	32.7
2	Honda Civic	Ongoing	39.5

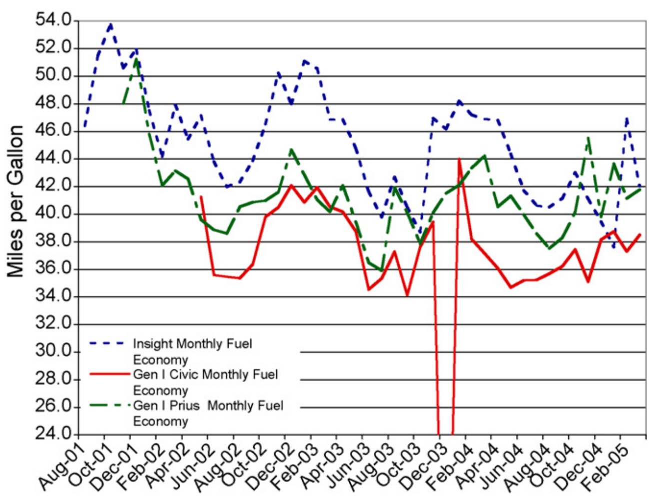

Fig. 4. Monthly Fleet Testing fuel economy test results.

the Honda Insight. When viewed on a monthly basis (Fig. 4), the three HEV models (Civic, Insight and Gen I Prius) with the most test miles show seasonal variations in fuel economies of greater than 10% (Fig. 5) and as high as 11.5% for the Civic. The "Hot 3 Months" shown in Fig. 5 are June, July and August with average high temperatures of 103 °F and lows of 77 °F (heavy expected air conditioning use). The "Cool 3 Months" shown in Fig. 5 are December, January and February with average high temperatures of 66 °F and lows of 45 °F (little expected air conditioning use).

In addition to higher energy use in the "Hot 3 Months" due to air conditioning use, decreased charge acceptance has been observed as a result of high battery temperatures in the nickel metal hydride batteries used in all HEVs tested by the AVTA.

2.3. Battery Benchmark Testing—initial

An objective of AVTA testing is to determine whether HEV traction batteries will maintain nominal vehicle performance throughout the life of the vehicle. As of 1 February 2007, only one traction battery pack has failed in the AVTA's hybrid electric test vehicles (2.48 million total test miles). A Honda Insight with 72,000 miles failed both the battery control module and traction battery pack. Both the control module and battery pack were replaced under the manufacturer's warranty. The cause of the pack failure is not known. However, it is speculated that the

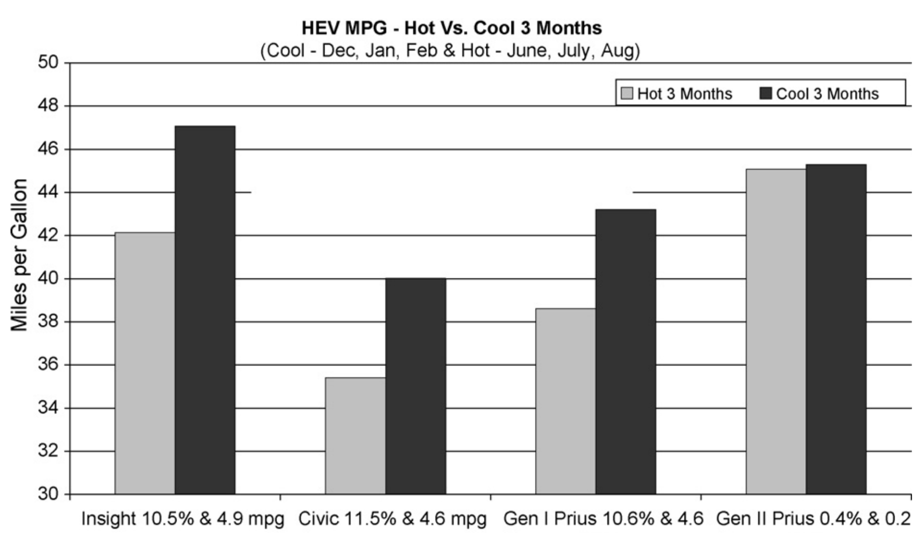

Fig. 5. Seasonal variations in fuel economy for HEVs operating in Arizona.

Table 2
AVTA HEV test battery types

Batteries tested	Model and year	Battery manufacturer	Battery type
6	2001 Honda Insight	Panasonic	NiMH
6	2002 Toyota Prius	Panasonic	NiMH
4	2003 Honda Civics	Panasonic	NiMH
2	2004 Toyota Prius	Panasonic	NiMH
2	2004 Chevrolet Silverado	Panasonic	VRLA
2	2005 Honda Accord	Sanyo	NiMH
2	2005 Ford Escape	Sanyo	NiMH
2	Toyota Highlander	Panasonic	NiMH
2	Saturn VUE	Cobasys	NiMH
3	Lexus 400h	Panasonic	NiMH
2	Toyota Camry	Panasonic	NiMH
2	Honda Civic	Panasonic	NiMH

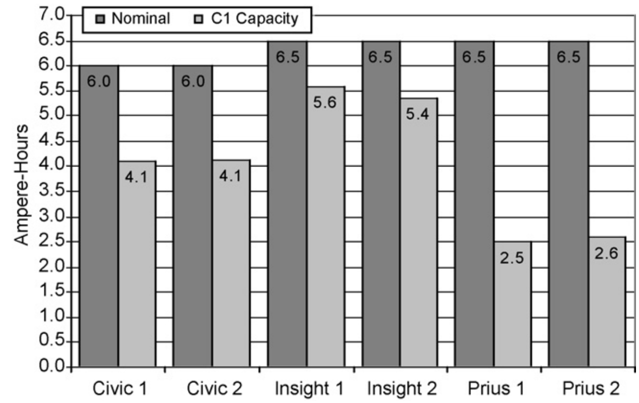

Fig. 6. HEV end-of-life static capacity test results.

battery pack failure was caused by the battery control module failure.

In an effort to develop a quantitative metric to evaluate battery performance, the first HEVs tested by the AVTA in fleet operation (two Gen I Prius, two Insights and two Civics) to reach 160,000 miles were tested to characterize the effects of high mileage on the ability of traction battery packs to meet vehicle power demands. Each 160,000-mile HEV was subjected to traction battery pack Static Capacity and Hybrid Pulse Power Characterization (HPPC) testing to simulate peak power demands during vehicle operation. Other than manufacturer's recommended maintenance and preparation requirements for each test procedure, none of the vehicles or their traction battery packs were specially prepared for any of the tests.

The traction battery pack capacity of each HEV was characterized in accordance with AVTA test procedure ETA-HTP14—Evaluation of Hybrid Electric Vehicle Battery Packs [5], for static capacity and hybrid pulse power characterization. To ensure consistency, all testing was performed in a temperature-controlled environment and with identical test protocol. All batteries tested were nickel metal hydride, with nominal characteristics as shown in Table 2.

To determine battery pack static capacity, the battery pack of each end-of-life HEV was fully charged using the battery manufacturer's recommended charging procedures. After the full charge and an 8-h rest period to allow for cell stabilization, the battery pack was discharged at its nominal C1 discharge rate until the average cell voltage was 1.00 V per cell. This procedure was repeated until the results of three consecutive discharge cycles yielded a capacity that did not vary more than 3% between three consecutive tests.

Results of static capacity testing at end-of-life showed significant reductions from nominal battery capacity as shown in Fig. 6. The two Honda Civics showed an average 31.7% reduction in battery pack capacity, the two Insights an average 15.8% reduction in battery pack capacity, and the two first generation Toyota Prius an average 61.0% reduction in battery pack capacity.

HPPC testing was performed to determine the state-of-charge (SOC) at which the battery pack could no longer provide the discharge pulses demanded by the vehicle during operation, or accept the charge pulses available during regenerative braking. To determine an appropriate magnitude for the charge and discharge pulses, peak power demand data from the SAE J1634 drive cycle (the same cycle upon which fuel economy data is obtained) conducted during Baseline Performance Testing for each vehicle type was examined. Using this data, the highest 0.5% battery pack charge current data was averaged to provide a charge pulse current value for HPPC testing. Similarly, the highest 0.5% discharge current data was averaged to provide a discharge pulse current value for HPPC testing. Using these values, the battery pack was subjected to a 10 s pulse discharge and a 10 s pulse charge at each percent SOC level, starting at 90% and decrementing at 10% nominal SOC intervals. Between each charge/discharge pulse, the battery pack was discharged at its nominal C1 rate to reach the next 10% SOC interval. Testing was terminated when the battery pack voltage during the C1 discharges between pulses reached an average of 0.8 V per cell or the battery pack voltage during the charge pulse reached an average of 1.8 V per cell.

Results of HPPC testing suggest a qualitative measure of the capability (range of working capacity) of each end-of-life HEV battery pack to meet a short-term, high-load demand that is representative of a typical drive cycle. The SOC step at which an HPPC test discharge pulse was limited and the corresponding percent SOC at termination are displayed in Table 3. The lower the percentage SOC, the greater the battery's capability to meet vehicle power demands. All batteries tested were capable of absorbing charge pulses without reaching their voltage limit. Therefore it is reasonable to conclude that the battery's ability to absorb energy from regenerative braking was not degraded

Table 3
HEV end-of-life HPPC test results

HEV test vehicle	Discharge pulse limit (SOC)	Charge pulse (A)/(C)	Discharge pulse (A)/(C)
Civic 1	30%	71.6/11.9	−68.4/−11.4
Civic 2	50%	71.6/11.9	−68.4/−11.4
Insight 1	10%	78.7/12.1	−65.7/−10.1
Insight 2	10%	78.7/12.1	−65.7/−10.1
Prius 1	60%	53.4/8.2	−78.9/−12.1
Prius 2	10%	53.4/8.2	−78.9/−12.1

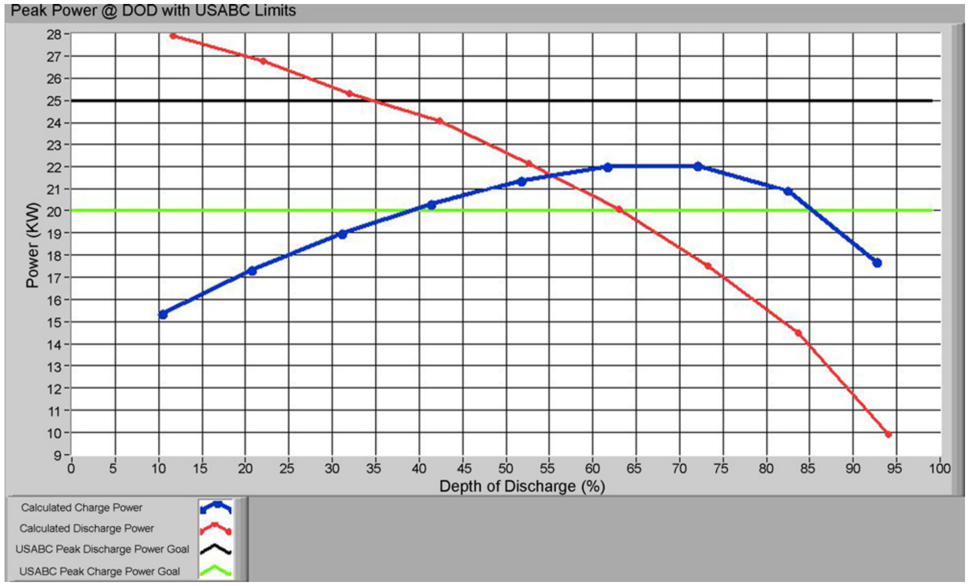

Fig. 7. Typical HEV battery available charge and discharge power as a function of SOC with USABC charge and discharge power goals noted.

by 160,000 miles of Fleet Testing. Also displayed in Table 3 are the pulse charge and pulse discharge currents used in the HPPC testing and the corresponding current value divided by the battery's nominal 1-h discharge rate.

2.4. Battery Benchmark Testing—current

Using lessons learned from Battery Benchmark Testing of first generation HEVs, AVTA test requirements for HEV battery testing have been revised to incorporate testing when the vehicle is new as well as a test at the completion of Fleet Testing (160,000 miles). Additionally, test procedures have been revised to conform to the FreedomCAR Battery Test Manual For Power-Assist Hybrid Electric Vehicles [6]. Specifically, the HPPC test has been modified to calculate battery pack available energy. Changes include the use of a 5 C charge and discharge pulse, rather than pulses determined by vehicle demand. From the results of the HPPC, battery internal resistance is calculated and used to determine peak charge and discharge power capability of the battery pack at various states-of-charge as shown in Fig. 7.

Using this method, the area under the charge and discharge curves (available energy) can be compared for a new battery pack and that same battery pack after accumulating 160,000 miles.

3. PHEV testing

Continuing the trend of testing vehicles that introduce new technologies, the AVTA has initiated the testing of plug-in hybrid electric vehicles (PHEV). The AVTA is currently testing PHEV conversions of a Toyota Prius by HyMotion and Energy CS, conversion of a Honda Civic by HyMotion and conversions of a Ford Escape by HyMotion and Electrovaya. These vehicles utilize lithium batteries manufactured by A123 Systems, Valence Technology, Inc. and Electrovaya.

To govern the conduct of PHEV testing, a set of highly repeatable test procedures have been developed [7]. These procedures follow closely the methods developed for testing HEVs discussed above and include Baseline Performance Test Procedures, Accelerated Test Procedures, Fleet Test Procedures and Battery Benchmark Testing. Due to the flexibility in PHEV design, control strategy and fuel source (i.e., liquid or gaseous fuel and/or electricity), the AVTA test procedures utilize the following definitions to ensure unambiguous results:

Electric operating mode—Propulsion and accessories powered by the electric drive and onboard electric energy storage (i.e., engine off).
Hybrid operating mode—Propulsion and accessories powered by the electric drive and/or engine, encompassing all power sharing/blending strategies.
Charge-depleting strategy (hybrid)—Operation in hybrid mode with a net decrease in battery state-of-charge (SOC).
Charge-sustaining strategy (hybrid)—Operation in hybrid mode with a relatively constant battery state-of-charge.
All-electric range (AER)—Distance traveled in electric mode (engine off) on standard driving cycles.
Charge-depleting range (CDR)—Distance traveled in hybrid mode with a charge-depleting strategy until the vehicle transitions to the charge-sustaining strategy.
Electric consumption—Electrical energy consumed in electric or hybrid mode.
Liquid or gaseous consumption—Liquid (e.g., gasoline or diesel) or gaseous (e.g., CNG) consumed on standard driving cycles.
Fuel economy—Distance traveled per unit of total fuel consumed (electric, liquid and/or gaseous) on standard drive cycles.

Table 4
HEV Accelerated Testing urban and highway test cycles

Cycle distance (miles)	Urban loops per cycle	Highway loops per cycle	Charge time (h)	Cycle repetitions (N)	Total cycle distance (miles)	Cumulative distance (miles)
10	1	0	4	60	600	600
20	1	1	8	30	600	1200
40	4	0	12	5	200	1400
40	2	2	12	5	200	1600
40	0	4	12	5	200	1800
60	2	4	12	10	600	2400
80	2	6	12	8	640	3040
100	2	8	12	6	600	3640
200	2	18	12	3	600	4240
Total	1740	2500	984	132	4.240	4240
Average	41%	59%	7.5	32.1		

The AVTA procedures for PHEV testing have been developed to specifically address testing in these various operating modes and are unique to PHEVs.

3.1. *Baseline Performance Test Procedures*

Baseline Performance Testing is conducted in each available vehicle-operating mode. When operation in an electric operating mode is possible, testing is conducted beginning at 100% SOC and 50% SOC to determine if performance degrades with battery SOC. As with HEV testing, PHEV drive-cycle dynamometer testing includes the Urban Dynamometer Driving Schedule and Highway Fuel Economy Test Schedule. However fuel economy and electric consumption are determined with the vehicle operating in both charge-depleting and charge-sustaining modes. Dynamometer testing is conducted at the Advanced Powertrain Test Facility of Argonne National Laboratory outside Chicago, Illinois. Test results are presented in test reports, summarized for wide dissemination in one-page data sheets and presented on the AVTA web page maintained by the Idaho National Laboratory [1].

3.2. *Accelerated Test Procedures*

Accelerated Testing rapidly provides performance and reliability data for PHEVs by using dedicated drivers to drive PHEVs on fixed routes in and around Phoenix, Arizona. This allows the accumulation of fuel economy data for trips of diverse lengths. As PHEV fuel economy and electric consumption vary significantly by trip length, PHEVs are tested using test cycles of varying length. Each test cycles is composed of a different number of repetitions of fixed urban and highway test routes (loops). These loops, each 10 miles long, are combined into test cycles varying in distance from 10 to 200 miles, as shown in Table 4. Test cycles are repeated to obtain approximately 600 test miles for each cycle distance. Test vehicles are charged between test cycles for the minimum times shown in Fig. 4. At a minimum, fuel consumption, maintenance requirements and operating anomalies are recorded for each test cycle.

3.3. *Fleet Test Procedures*

During Fleet Testing, PHEVs are monitored as they operate in commercial and government vehicle fleets. Operating mission selection is carefully performed to maximize the benefits associated with the performance characteristics of PHEVs. The PHEVs are operated, by one or more fleet drivers, for 2 years and 24,000 miles. Data is collected for fuel use, maintenance costs and vehicle reliability. Selected PHEVs are equipped with a data acquisition system designed specifically to collect supplemental operating data from vehicles during Fleet Testing.

3.4. *Battery Benchmark Testing*

Batteries in PHEV duty typically begin operation at full (or nearly full) charge. Over the vehicles charge-depleting range or all-electric range, the battery is discharged until it reaches an SOC at which it is maintained in charge-sustaining mode by operation of the hybrid power source, typically an internal combustion engine. As a result, the PHEV battery is subject to both shallow cycling typical of HEVs as well a deep discharges typical of battery electric vehicles (BEV). To test PHEV batteries under these conditions the FreedomCAR Battery Test Manual For Power-Assist Hybrid Electric Vehicles [6] is under revision to include both charge-depleting and charge-sustaining tests. Once approved, these procedures will become the bases for AVTA testing of PHEV batteries.

4. Discussion and conclusions

AVTA testing has demonstrated through nearly 2.5 million mile of testing that HEVs have reached maturity in both performance and reliability. Battery test results from first generation HEVs accumulating 160,000 miles of fleet operation demonstrate that, while significant degradation in battery capacity was observed, the batteries remained capable of meeting vehicle power demands and absorbing power from regenerative braking, allowing performance to remain unchanged over the operating life of the HEV.

Quantifying PHEV performance in the various operating modes available presents a significant testing challenge. Developing a battery to operate successfully in these various operating modes represents an even greater challenge. Testing conducted by the AVTA using converted PHEVs and eventually using original equipment manufacturer PHEVs will evolve to provide an ongoing metric to quantify the success of PHEVs.

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