

Battery Evaluation for Plug-In Hybrid Electric Vehicles

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Abstract—This paper outlines the development of a battery system test regime for plug-in hybrid electric vehicles. The test regime is focused on a specific vehicle, the Plug-in Hybrid Electric Sprinter Van jointly developed by DaimlerChrysler and the Electric Power Research Institute. This paper describes an ongoing process to validate the cycle life performance of advanced batteries subjected to a PHEV duty cycle.

Plug-in hybrid electric vehicles share many component and powertrain architecture commonalities with power assist hybrid electric vehicles—but with the ability to recharge a larger energy storage system from off-board electrical power. The PHEV has unique battery requirements that often require a compromise between the high energy battery systems required by battery electric vehicles (BEV) and the high power energy storage systems used in power assist hybrid electric vehicles (HEVs). The duty cycle is generally a combination of deep and shallow discharge behavior found respectively in BEVs and HEVs and is dependent on both vehicle requirements and the energy management strategy of the hybrid powertrain.

I. INTRODUCTION

The Plug-in Hybrid Electric Sprinter Van is a light-duty commercial plug-in hybrid electric vehicle (PHEV). The PHEV Sprinter was designed with substantial all-electric operating capability and functions primarily as an electric vehicle in urban driving. The vehicle has a design range of 20 miles in the electric-only mode. The PHEV Sprinter is a parallel hybrid with a single high-power electric motor integrated between a conventional gasoline or diesel combustion engine and a five-speed automatic transmission. The electric motor produces a peak output torque of 380 Nm and peak power of 70-96 kW (final output depends upon supply voltage).

The PHEV Sprinter has three primary operational modes: (1) electric-only with the engine disengaged; (2) hybrid charge-depletion; and (3) hybrid charge-sustaining. The vehicle is designed to be charged once per day from a 3.3 kW charger, typically at the end of its daily mission. The hybrid control system manages the energy from the onboard battery system to minimize fuel consumption and emissions, discharging the battery to a minimum of 20% state-of-charge.

The cycle-life durability of available advanced chemistry batteries under this type of duty cycle is not well understood. Both nickel metal hydride (NiMH) and lithium ion (Li Ion) batteries have displayed sufficient cycle life under either straight deep discharge behavior typical of battery electric

vehicles (BEVs) or under the higher frequency shallow discharge behavior seen in power assist hybrid electric vehicles (HEVs).

This paper describes the initial stages of developing a test regime to accurately simulate the duty cycle of a typical PHEV—first applying it to the specific example of the PHEV Sprinter. The overall process is envisioned to have at least three steps:

1. Verify sufficient battery durability and performance for the PHEV Sprinter vehicle development program.
2. Develop a generalized test procedure applicable to a broader variety of vehicles with different levels of performance and energy capacity
3. Interface with existing battery testing organizations to develop a more widely accepted, standardized test procedure for PHEV battery systems

II. INITIAL BATTERY CANDIDATES

The first group of Sprinter PHEV prototypes will test two different battery candidates, one NiMH and one Li Ion. In addition to the laboratory testing outlined in this document, both battery technologies will be evaluated as part of the Sprinter demonstration program.

A. Nickel Metal Hydride Battery System

The first battery system for the PHEV Sprinter concept is based on the VARTA NP40 NiMH battery system (Table I). VARTA uses a module, air-cooled design packaging blocks of 32-40 cells connected together in series to form the entire pack. The blocks are easily replaceable, and each has an independently controlled cooling fan.

The VARTA battery system for the Sprinter will consist of 280 cells (seven 40-cell blocks) at a nominal voltage of 350 volts. The pack energy capacity is 14.0 kWh with peak power of 80 kW.

VARTA NiMH batteries have been independently tested to 5000 deep cycles to 80% depth-of-discharge (DOD). VARTA has provided a warranty on the prototype cells for between 2000 to 4000 deep cycles, depending on operating temperature. VARTA provides an integrated battery monitoring system (BMS) that tracks pack health and provides instantaneous operating data (available energy and power, battery state-of-charge, etc) via CANbus to the hybrid controller.

B. Lithium Ion Battery System

The second battery system is based on the SAFT VL 41 M cylindrical cell Li Ion battery (Table I). The VL M is a medium power design that balances energy and power density. It is packaged in six-cell, liquid-cooled modules. The Sprinter battery system consists of 102 cells (17 modules) at a nominal voltage of 367 volts. Total pack energy is 15.1 kWh with peak power of 100 kW.

TABLE I
PACK LEVEL BATTERY SPECIFICATIONS

Manufacturer	SAFT	VARTA Autobatterie GmbH
Battery Chemistry	Lithium Ion	Nickel Metal Hydride
No. of Cells	102	280
Nominal Voltage (VDC)	367	350
Cell Capacity (Ahr)	41	40
Energy Capacity (kWh)	15.1	14.0
Peak Power (kW)	100	80
Package	6-cell module	40-cell block (2 modules)
Block Dimensions (mm)		507x354x290
Total System Weight (kg)	180	352
Cooling	Liquid	Air BMS-controlled individual electric fans
Battery Monitoring	SAFT BMC with voltage, current, and temperature sensing	VARTA BMS 5.P with voltage, current and temperature sensing
Charger	3.3 kW Conductive 208-240 VAC Input	3.3 kW Conductive 208-240 VAC Input



Fig. 1. VARTA 4-cell, plastic-case, 40 amp-hour NiMH module (below) and Modular Pack System (above).

III. BATTERY TEST DEVELOPMENT

A. Objectives

The immediate and primary goal of the battery test regime is to:

1. Verify achievement of a minimum deep cycle and calendar lifetime for the traction battery in the PHEV application before production of the Sprinter vehicle.
2. The secondary goals of battery testing are:
3. Provide credible estimates of the ultimate deep cycle life (or calendar life, if shorter) of the PHEV Sprinter traction battery in representative PHEV applications.
4. Verify the battery life data provided by the suppliers of the batteries tested.
5. Provide data to battery suppliers and /the academic/ community about the impact of the PHEV duty cycle on battery life.
6. Provide data to the regulatory and automobile OEMs on the capabilities of state-of-the-art batteries to meet the performance and life requirements for PHEV applications.

To meet the goals stated above, the battery testing profile:

1. Is derived from dynamic vehicle-level simulation of “real-world” driving cycles.
2. Uses drive cycles that replicate the urban driving conditions likely to be the most demanding to batteries. These driving cycles include conditions of low vehicle

speed, high acceleration and charge-sustaining HEV mode driving at low battery SOC. It is anticipated that the PHEV Sprinter will enter service in a primarily urban driving environment.

3. Uses a combination of both HEV and ZEV driving modes to represent greater than 50% of statistical daily trips.
4. Uses charging profiles suggested by the battery manufacturers as compatible with long battery life (within the constraint of charging times that are likely to be available in “real life” PHEV operations).
5. Accelerates testing sufficiently to achieve the primary and many of the secondary objectives before the beginning of series production of PHEV Sprinters.

B. Dynamic Vehicle Simulation

A dynamic simulation of the fuel economy, performance and control system of the PHEV Sprinter has been constructed to study the characteristics of the PHEV Sprinter. This simulation is constructed within the MATLAB/Simulink programming environment, and uses some components of the PNGV Systems Analysis Toolkit (PSAT). PSAT is a platform for the development and simulation of the vehicle system and can model system dynamics, control algorithms, vehicle energy consumption and component-level thermodynamics.

The simulation is made up of a network of components that interact with one another through exchanges of effort and flow and through analog and digital control signals. The battery system component is based on a linear internal resistance model that uses data provided by the battery manufacturer.

The vehicle simulation uses the same modes of control and energy management as the PHEV Sprinter vehicle. Energy management control for the PHEV Sprinter simulation is divided into two modes of operation: Charge Depleting (CD) Mode and Charge Sustaining (CS) Mode. For the development of the battery test profile, it is assumed that CD mode is an electric only driving mode (ZEV mode).

C. Drive Cycle Specification

A portion of the INRETS URB1 vehicle test cycle (see Fig. 2 for its key characteristics) is used to define the battery power profile. The INRETS URB1 cycle was chosen because it represents “real-world” driving, being derived from measurements of the speed of actual vehicles engaged in urban driving.

The final 181.5 seconds of the INRETS URB1 drive cycle is used as the basis of the battery test cycle for both charge depleting and charge sustaining modes. The section of the INRETS URB1 cycle to be used is the period between 528.5 and 710 seconds, as shown in Fig. 3 and Table II. This section of the drive cycle was chosen for four reasons:

The period of the section of the INRETS URB1 cycle is 181.5 seconds. Southern California Edison EV Technical Center test engineers have suggested that the time period of the battery test cycle be around 200 seconds. A 181.5 second test period allows for repetition of the cycle roughly 27 times

during the charge depleting section of the test profile.

Division of the battery test profile into small segments causes less variation in the energy throughput from the battery under test in charge depletion mode.

Peak accelerations and peak battery power demands are well distributed within the drive cycle sample. There are 3 events in the CD test cycle where the battery power demand is greater than or equal to 80% of the peak battery power demand. Again, distribution of the peak battery power demand events within the cycle causes less cycle-to-cycle variation in the battery testing.

The drive cycle includes stop/start sections at the beginning and end of the cycle, so repetition of the drive cycles does not cause a discontinuity in vehicle speed or battery power demand.

The energy consumption over this portion of the cycle is comparable to the vehicle energy consumption over the entire cycle, as shown in Table II.

D. Battery Test Cycle Specification

A profile of the battery power used by the vehicle can be derived by using this section of the INRETS URB1 drive cycle as an input to the dynamic vehicle simulation. For the charge depleting battery mode test profile, the vehicle simulation is programmed to use only battery energy to drive the vehicle (ZEV mode). For the charge sustaining battery mode test profile, the vehicle simulation is programmed to maintain the battery SOC over the course of the battery test cycle. The output of the dynamic simulation is a trace of battery power demand as a function of time, sampled at 100 Hz.

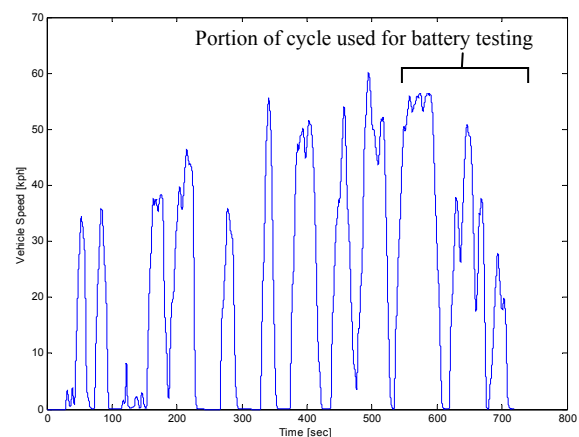


Fig. 2. Full INRETS URB1 Vehicle Test Cycle.

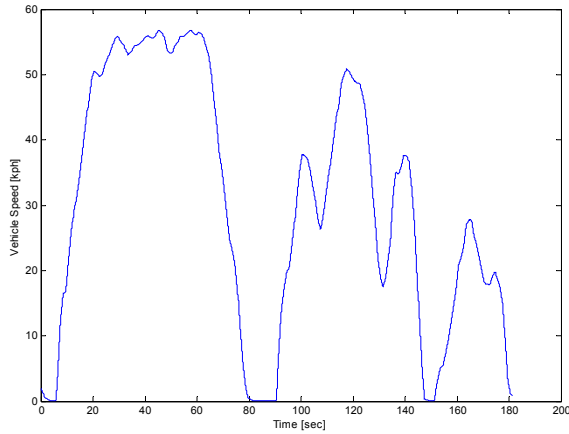


Fig. 3. Sample of INRETS URB1 Cycle used for Battery Testing.

TABLE II
CHARACTERISTICS OF INRETS URB1 AND SAMPLED INRETS URB1 DRIVE CYCLES

	INRETS URB1 Drive Cycle	Sampled Drive Cycle	Units
Length of Cycle	719	181.5	[sec]
Simulated Distance Traveled	4.19	1.54	[km]
ZEV Energy Consumption	311	279	[Wh/km]
ZEV Average Power Consumption	6.5	8.5	[kW]

The sampling period for input to the battery testing machinery is approximately 2 seconds to reflect the capabilities of a variety of test equipment models. The simulation output must be filtered to meet the requirements of the battery testing machinery, while maintaining as many of the features of the original battery power demand as is possible. To maintain the relevant features of the PHEV battery power traces, the output data from the dynamic simulation is manually filtered, sampled at variable frequency and reconstituted with a zeroth order hold. Fig. 4 shows a close-up view of a portion of the filtered and unfiltered battery test cycle. This figure shows that manual filtering of the battery power demand data can preserve the battery power transients due to vehicle acceleration/regeneration and engine on/off control, but cannot preserve the transients that are due to shifting (~5Hz) or PI speed controller dynamics (~1Hz).

The battery power demand is expressed in terms of battery pack output power for 280 NiMH cells or 102 Li Ion cells. Actual battery testing will most likely be done at the module or sub-pack level, so power demand levels must be adjusted accordingly.

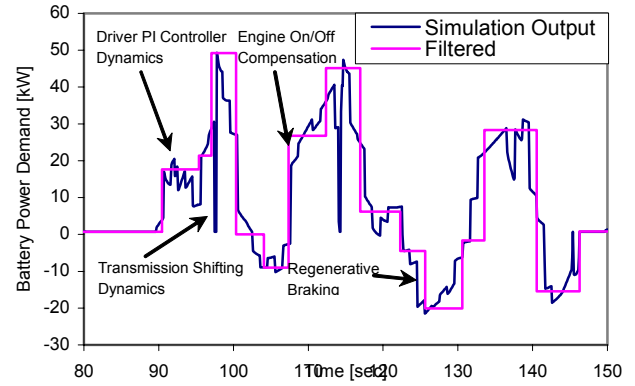


Fig. 4. Enlargement of Filtered and Unfiltered Battery Test Cycle.

Comparisons of the battery power output from the simulation and the filtered, resampled battery test cycle are presented in Fig. 5 and Fig. 6. Fig. 7 shows the histograms of the filtered battery test profile period. From the histograms and Table III, it is clear that the sample period varies between 2 and 14 seconds and that there are roughly 50 samples for each battery test cycle.

Over the course of the charge sustaining cycle, the testing will either slightly charge or slightly discharge the battery, depending on inaccuracies in the modeling, changes in the internal resistance of the batteries, etc. The proposed charge-sustaining battery test cycle should serve as the basis of the actual battery test cycle, but may be adjusted to compensate for any charging or discharging that may occur during charge sustaining testing.

E. Charge Depletion/Charge Sustaining Mode Proportioning

The number of CD (ZEV) cycles is determined by the capacity of the battery under test and the fraction of battery capacity that is discharged per cycle. In the proposed test cycle, the initially fully charged battery is discharged until 20% SOC is reached. After reaching 20% SOC, the battery is operated in the charge sustaining battery test cycle.

In principle, the number of charge sustaining battery test cycles (that is, the length of the charge-sustaining time period) could be selected as desired. However, because that number will impact battery life, its selection as part of the test profile must be governed by the requirement that the overall profile represent battery operation in typical urban PHEV driving.

For this test, the number of charge sustaining battery test cycles is determined by subtracting the mileage covered in the charge-depleting battery mode test cycle from the expected average daily mileage of a Sprinter van. The initial assumption is to select the number of charge sustaining battery test cycles such that the total battery charge profile yields a simulated mileage of 50 miles. Roughly two-thirds (~68%) of all vans covered in the 1997 Vehicle Inventory and Use Survey drive less than 50 miles per day [1]. To reach a total of 50 miles per battery test cycle, the 24 charge depleting

cycles are combined with 28 charge sustaining cycles for a total of 50 miles and 2.6 hours of urban driving.

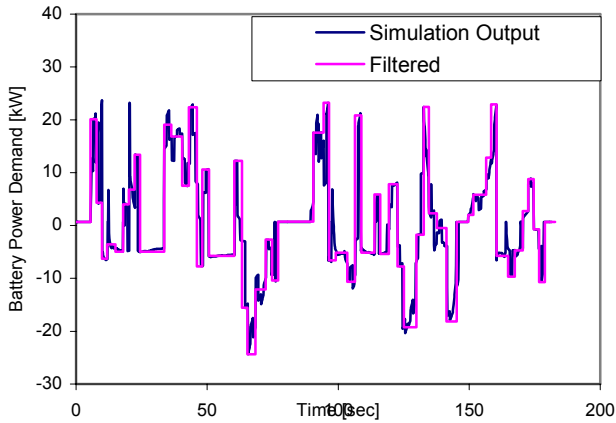


Fig. 5. Charge-sustaining Simulation Output and Filtered Battery Test Cycle.

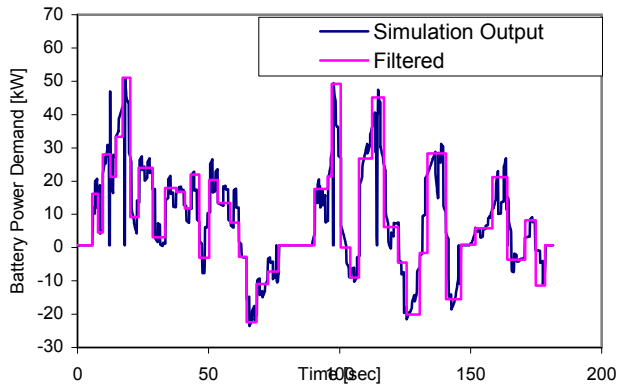


Fig. 6. Charge-depleting Simulation Output and Filtered Battery Test Cycle.

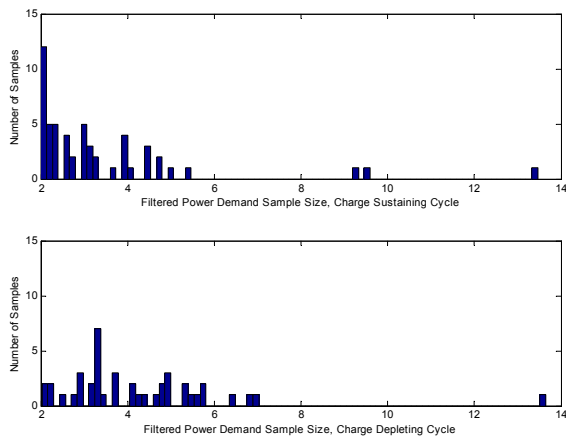


Fig. 7. Histogram of Sample Size for Filtered Battery Test Cycle.

F. Charging Profile

The charge sustaining mode battery cycle test is followed by the battery charging profile. The specification of the battery charging profile is guided by the requirement that the charging rate be as fast as possible while still being compatible with the battery supplier recommendations for maintaining battery life. The battery system should be charged as quickly as is feasible to reduce the charge/discharge cycle period and to increase the rate of battery cycling.

TABLE III
ADDITIONAL INFORMATION ABOUT SAMPLED BATTERY TEST CYCLES

	Charge Depleting (ZEV)	Charge Sustaining (CSHEV)	Units
Number of Samples	44	55	[-]
Number of Samples of less than 2 sec period	0	0	[-]
Smallest Sample Period	2.04	2.01	[sec]
Assumed Battery In/Out Energetic Efficiency	N/A	93.1%	$[E_{out}/E_{in}]$
Peak Output Power Filtered/Simulated	51.0/52.6	23.3/23.7	[kW]
Peak Regenerative Power Filtered/Simulated	-22.4/-23.5	-24.4/-24.4	[kW]

On the basis of the preliminary information provided by the battery manufacturers, we propose that the VARTA NiMH batteries (in pack form) be charged at a constant 5.28kW continuously until 100% SOC is reached. 5.28kW represents a 6.6kW charger operating at 80% efficiency. We propose that the Saft Li Ion batteries be charged using Saft's recommended charging algorithm. The peak charging power for this algorithm is 5.04kW. These proposed algorithms take 2.5hrs and 3.6hrs respectively for the NiMH and Li Ion packs. If battery charging algorithms exist that are of shorter duration, but are recommended by the battery manufacturer to not reduce battery life, those algorithms may be substituted for those proposed here.

G. Battery Test Profile Specification

The Battery Test Profile is constructed by assembling the charge-depleting battery test cycles, the charge-sustaining battery test profiles and the charging profile into a single discharge/charge cycle. The Battery Test Profile lasts 5.1 hours for the NiMH battery and 6.3 hours for the Li Ion battery, as shown in Table IV. With roughly an hour allowed for chemical and thermal stabilization of the battery, four battery charge/discharge cycles per day can be accomplished for the NiMH battery and more than 3 charge/discharge cycles per day for the Li Ion battery.

A plot of the composite battery test profile for the NiMH pack is presented in Fig. 8. Red vertical lines mark the

transition between charge-depleting, charge-sustaining, and charging regimes and the end of test condition.

TABLE IV
SUMMARY OF KEY BATTERY PROFILE CHARACTERISTICS

	NiMH Battery Test Profile	Li Ion Battery Test Profile	Units
Number of Cycles of CD Batt. Test	25.1	25.1	[-]
Time of CD Batt. Test Cycling	1.3	1.3	[hrs]
Energy Consumed in CD Batt. Test Cycling	10.4	10.8	[kWh]
Number of Cycles of CS Batt. Test	27	27	[-]
Time of CS Batt. Test Cycling	1.4	1.4	[hrs]
Energy Consumed in CS Batt. Test Cycling	~0	~0	[kWh]
Charging Time	2.5	3.6	[hrs]
Total Batt. Test Profile Time	5.1	6.3	[hrs]

IV. REFERENCES

[1] 1997 Economic Census, Vehicle Inventory and Use Survey, p. 3, 6
 [2] USABC Electric Vehicle Battery Test Procedures Manual, Rev. 2, p. 9.
 [3] PNGV Battery Test Manual, Rev. 3, p. 4.

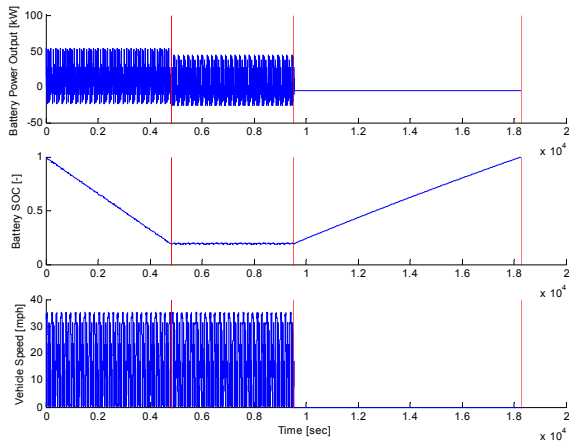


Fig. 8. Composite Battery Charge/Discharge Profile for VARTA NiMH Pack.

H. Battery Characterization Tests

The battery will periodically undergo a standard series of battery characterization tests to track the state of health of the battery as it ages. The following proposed characterization tests are to be performed on a monthly basis:

1. USABC Peak Power Test [2]
2. Hybrid Pulse Power Characterization Test [3]