

Test Procedure Development for “Blended Type” Plug-In Hybrid Vehicles

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ABSTRACT

Several plug-in hybrid electric vehicles (PHEVs) have recently been made available by conversion companies for laboratory testing. The viability of the technology must be evaluated by dynamometer benchmark testing, but because the technology is so new, existing and new test methods must first be investigated. Converted Gen 2 Toyota Prius vehicles from Hymotion, EnergyCS, and Hybrids Plus were tested at Argonne’s dynamometer facility according to general testing concepts. These vehicles all share basic attributes — all are blended type PHEVs, all use Lithium battery technology, and all deplete charge in a similar fashion (although at different rates). In a time span of one year, lessons learned from one vehicle were carried over into the next test vehicle. A minimum test method was formulated that is well suited for all these vehicles. The method was validated with two vehicles of varying charge-depleting range.

INTRODUCTION

Open collaborative work on devising a standard test procedure for hybrid electric vehicles (HEV) began in the fall of 1992. The J1711 SAE committee task force was formed initially with widespread participation from industry and government entities with the goal of addressing any and all HEV designs. At that time, it was not known what HEV design(s) would be predominant.

A first proposal was devised by 1994, and a document ready for balloting was written from 1996 to 1998. Of course, no production hybrids existed and prototypes were scarce. University-built prototypes taken from winning teams participating in the Argonne-managed U.S. Department of Energy’s “HEV Challenge” competition were volunteered to test out the procedure [1]. And every year since 1994, the competition vehicle from UC-Davis (always a PHEV) would be tested yet again by the Argonne staff, usually at the hosting industry sponsor or the U.S. EPA. However, these early PHEV concepts and prototypes were fundamentally

electric-capable vehicles with a charge-sustaining mode. Not well investigated were the new type of PHEVs that represent the design path made by the PHEV conversion companies — the Blended-Type PHEV.

Several types of objectives are satisfied by dynamometer testing of PHEVs. One is determination of the fuel economy as the basis for comparison (CAFE, label MPG, others), the second is emissions certification (EPA and CARB), and the third is technology characterizations — essentially answers to research-related questions in emissions/fuel inventory and vehicle-level technology benchmarking. At the time of publication, the committee tasked to re-issue J1711 has not finalized procedures and calculations. This paper reflects the background work performed by Argonne to support the research into finding new test methods more suited to current PHEV designs.

For conventional vehicles, emissions certification, CAFE MPG, and label fuel economy are all satisfied by the same battery of tests for a conventional vehicle. This convenience may not be available for standard PHEV dynamometer testing. Historically, emissions certification for new technology has been demonstrated as not exceeding limits for the worst-case scenario [8]. For PHEVs, this could be in either charge-depleting or charge-sustaining mode. In addition, varying initial SOC levels before a cold-start test may force the engine to start in varying situations that may also impact emissions results. These emissions issues are beyond the scope of this paper.

DEFINITIONS OF PHEV TYPES

The distinguishing characteristic of a PHEV is the ability to store electricity taken from the electrical grid by charging at home (or elsewhere) to be used for propulsion. This energy is depleted in some manner during “charge-depleting” operation after which “charge-sustaining” operation is required to continue driving. The depleting range is a consequence of the battery

energy capacity and how quickly the energy is consumed during depleting operation, and this depleting rate is limited by the maximum electric power capability of the PHEV.

In the discussion of how to apply test procedures, it helps to be specific about the type of PHEV in terms of electric propulsion power capability. Significant changes in engine operation (or lack thereof) represent the most significant hurdles in adapting 30-year-old test procedures for PHEVs originally suited for the operation of conventional vehicles. These definitions are in the context of grouping a wide array of possible PHEV designs into convenient categories useful in test procedure application. Other definitions classifying PHEVs may also be useful in describing operation for other purposes, such as customer perceptions.

The required wheel power to drive a Prius-sized vehicle was calculated for the UDDS cycle and plotted in Figure 1. Shown on the plot is the maximum electric-only propulsion power of the Gen 2 Prius of about ~20 kW at the wheel. Notice that there are several short periods in which the drive cycle requirements exceed this level, and thus the engine is required to meet the power demand. A “Blended” type PHEV is attributed to PHEVs that requires engine assistance to drive the test cycle in question. Notice the solid horizontal line of roughly 17 kW that represents the observed engine-on power levels for several retro-fitted Gen 2 Prius PHEVs [2]. This means that these Blended-type Prius PHEV retro-fits must have an engine start sometime during each test cycle. Of course, this has important implications of measuring emissions and fuel consumption.

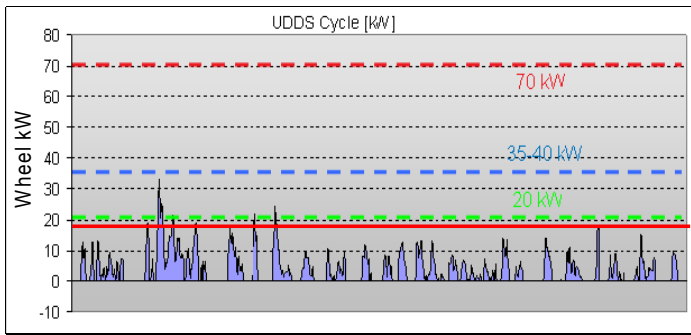


Figure 1: Wheel Power Requirements for UDDS Cycle

In Figure 2, the highly aggressive US06 cycle and test data from an actual Gen 2 Prius full power acceleration test are plotted. From the perspective of testing, a PHEV that can satisfy all 70 kW of wheel power with its electric propulsion system can initially run all the test cycles as an electric vehicle. This vehicle is defined as a “Range-Extended” EV. With full electric capability, it can be assumed that the engine will remain off until the usable battery energy is depleted. It is likely that the conditions that require engine use are related to the battery SOC, not power requirements. Of course, if the EV range is not long enough to run one cycle, the definition is not a

good fit. In this case, it would be possible to test the vehicle as a “Blended” type, even though it does not fit the power level definition.

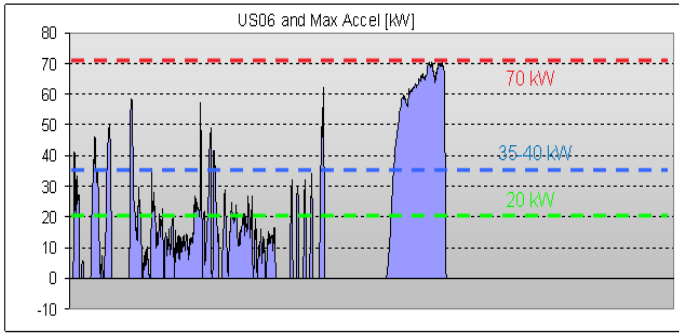


Figure 2: Wheel Power Requirements for US06 and Full Power Acceleration

In Figure 2, a line indicating a power level of 35–40 kW is high enough to allow all-electric operation on the UDDS test cycle, a metric used for credits in California’s LEV program [8]. This “Intermediate” design would allow driving on the UDDS but would start the engine for higher load cycles and, for in-use driving, could potentially cold-start the engine at a very high load (like merging onto the highway).

A general diagram relating the various definitions is shown in Figure 3. The Range-Extended EV and Intermediate PHEV types are both examples of PHEVs that are “All-Electric Range” (AER) capable. “Blended” PHEVs are also shown. It is worth restating that these definitions are cycle-specific. For example, if only the Japan 10-15 cycle is considered, the Gen 2 Prius with a larger battery could be an “Intermediate” PHEV type because the peak power demands on that cycle could alone be satisfied by the electric propulsion system.

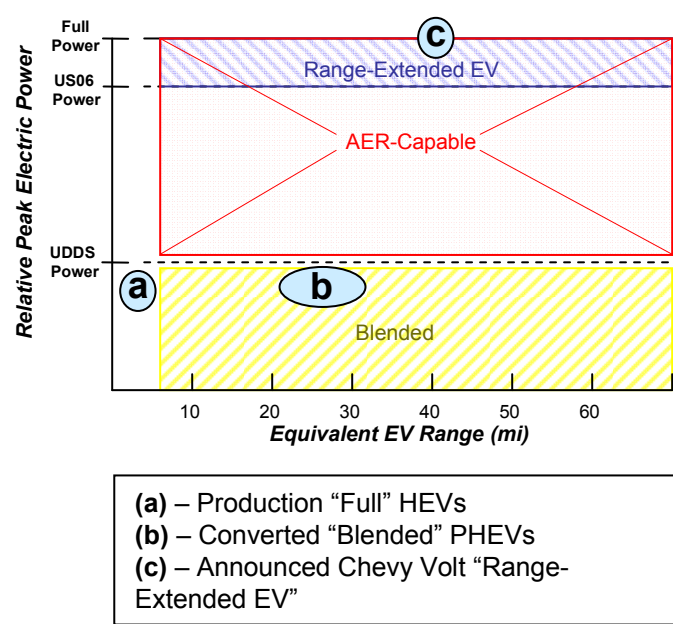


Figure 3: PHEV Definitions

TESTING PHEVS

Part of the renewed interest in PHEVs comes from the successful demonstration of vehicles produced by a cottage industry of aftermarket plug-in hybrid converters. Existing “full” hybrid designs are converted into charge-depleting PHEVs by replacing the stock battery or adding an extra battery to the stock battery. Novel controls over the vehicle’s communication network force the vehicle to deplete net charge and achieve over 100 MPG (fuel only) [2] while in depleting mode.

The converted “full” hybrids still have the same electric propulsion power and speed limitations, and so the vehicles cannot drive in EV mode at high power levels or at higher vehicle speeds. If driven mildly, the aftermarket kits have enough energy (from 3 to 9 usable kWh observed) to drive electric-only for a respectable 20–40 miles; however, the drive cycles used in (U.S.) testing require speeds and loads that are too high for the current production hybrids to complete without engine assistance for a few brief moments. Given that they all operate within the powertrain constraints of the original charge-sustaining hybrids, these vehicles are Blended-type PHEVs.

In 2006, there was an immediate need for DOE to evaluate the newly available PHEV retrofit vehicles to assess their technology. At the time, only the SAE J1711 and the California Air Resources Board procedures existed. Neither of these procedures specifically addressed the blended PHEV operation. To get an understanding of these vehicles and how they operate, the most basic concepts from J1711 were applied by characterizing the charge-depleting and charge-sustaining operation with adaptations of the “Full-Charge Test” and the “Partial-Charge Test” from J1711 [1].

FULL CHARGE TEST (FCT) – One fundamental approach to evaluating the depleting operation of a PHEV for a given cycle is to charge the battery up to “full” and run a full charge test (FCT). This is essentially the drive cycle in question run repeatedly until charge-sustaining behavior is observed.

This may sound easy, but in practice, running successive cycles poses new problems to solve. How are initial test conditions set and valid prep conditions satisfied for each test cycle? Can these conditions remain compatible with current procedures? Is the test equipment even capable of running repeated test cycles? For this paper, the scope was limited to the issues testing the Federal Test Procedure’s (FTP’s) UDDS and Highway cycles. Note that for model year 2011, EPA has specified new and much more comprehensive calculations to determine the EPA “label” mileage ratings that include results from the SC03, cold CO FTP, and the US06 tests [3].

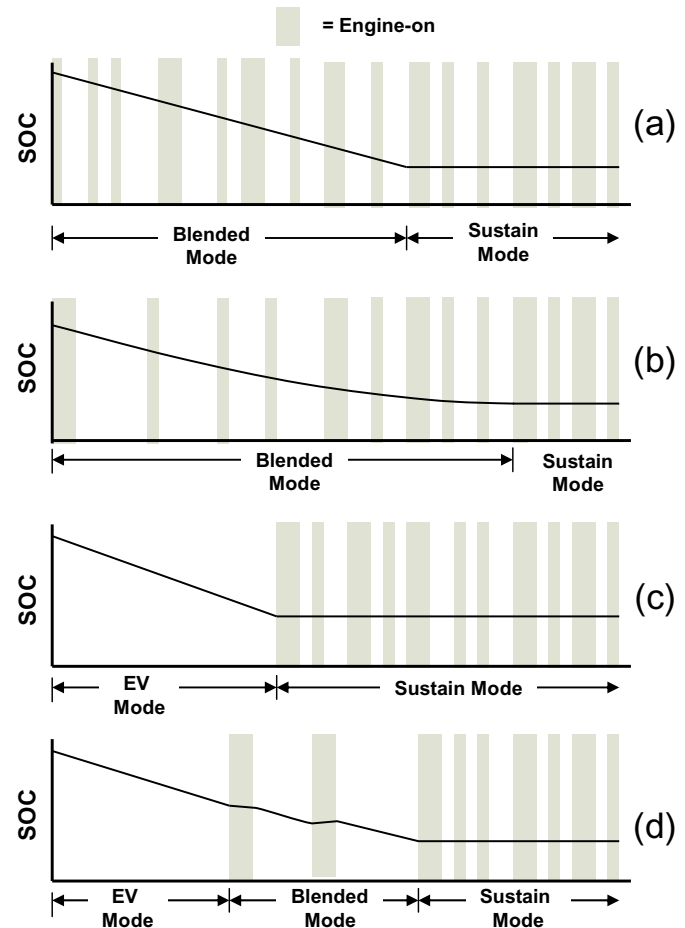


Figure 4: Variations of PHEV Depleting Operation

The objective of the FCT is to capture all charge-depleting operation for a specific test cycle. Figure 4 shows possible basic operational possibilities of a PHEV during its depleting mode. Depleting operation includes any blended modes or electric-only operation. Plot (a) represents the blended-mode PHEV that maintains a constant discharge rate until the depleting SOC limit is achieved. Plot (b) is also a blended type, but with a varying depletion rate. Plot (c) is an AER-Capable PHEV that upon engine-start is immediately in sustaining mode. The most complex is shown in plot (d) where all three basic operational characteristics (EV mode, blended operation, and sustaining operation) are depicted. As will be shown later, the PHEV depicted in (a) may be much easier to test because the depleting mode can be characterized more easily.

One practical consideration for any FCT is the termination criteria – how does the tester know when to terminate a test? Test termination can occur after the last depleting cycle has concluded, but that is not known unless the vehicle has a “charge-sustaining indicator” to alert the tester that sustaining mode is activated. Without direct knowledge of the vehicle mode, testing can continue until a charge-balanced cycle is observed. SAE J1711-1999 has a charge-tolerance that defined a charge-balanced cycle as the net change in stored battery energy to be less than 1% of the fuel energy consumption. Compared to a large PHEV battery pack, this tolerance may be quite small, and the charge-

sustaining mode may be in operation for one or more cycles before such a tolerance is met. This tolerance could be relaxed for PHEVs transitioning to sustaining mode if the objective is only to terminate after depleting operation. If a vehicle is charge-sustaining, but the energy swings are large, then it would be likely that a cycle will gain charge, and thus the tester would be sure that the vehicle is in charge-sustaining mode. These termination criteria would have to be determined during testing such that any calculations must occur in immediate test post processing in order to act between test cycles during the FCT – another added requirement for PHEV testing.

The level of difficulty in defining the transition from depleting and sustaining is a good reason for the OEMs to design in their system a depleting/sustaining indicator (either in the instrumentation panel or available on the service scan tool) that can be monitored by the tester to help easily determine when to terminate the test. The FCT objective is only focused on the depleting behavior, without the indicator – it would not be clear to the tester that charge-sustaining mode has begun and more cycles in a FCT would have to be run.

UDDS FCT – The FTP for conventional vehicles is a truncated version of a test with two UDDS cycles. Typical hybrid vehicle testing includes running the second UDDS cycle to its conclusion (rather than terminating the test after the first 505 seconds). The prep conditions for the test include running a UDDS cycle and then soaking the vehicle in ambient test conditions for 12 to 36 hours. The second UDDS cycle is run after a short 10-minute soak on the dynamometer. Difference in operation from the two cycles can be quite significant – especially when we consider the transient nature of engine-on/off decisions made by the controls related to warm-up and differences in SOC.

The most straightforward interpretation of a FCT for the UDDS is:

- Deplete to sustaining mode
- Run a UDDS prep cycle
- Charge battery while soaking overnight (12–36 h)
- Run UDDS cycle (“cold-start”)
- 10-minute soak
- Run UDDS cycle (“hot-start”)
- Repeat 10-minute soak and UDDS cycles until charge-depleting operation is exhausted

An important practical consideration for the UDDS FCT is the issue of how long it takes to finish sampling the bags, purge the bags, calibrate the analyzers, and reinitialize the next test. Most test facilities cannot perform these tasks in 10 minutes unless a significant rewriting of the test cell control software automates and optimizes each step. Anecdotally, only half of the test engineers participating in the reissue of J1711 think that this is possible with new software and their existing system hardware.

Problem Weighting Cold/hot UDDS FCT – With the new FCT testing paradigm, we are presented with a problem: there is simply too much information to apply the FTP cold/hot weighting equations without significant reworking. According to EPA certification procedures, the generic equation for weighting emissions and fuel consumption (where Y is the result needed to be weighted) is shown below in Equation 1.

$$Y_{h/c_weighted} = (0.43) \frac{Y_{cold}}{mi_{cold}} + (0.57) \frac{Y_{hot}}{mi_{hot}} \quad \text{Eq. 1}$$

Certainly for a Blended-type PHEV, the first UDDS in the FCT will be the cold start, but should that cycle alone carry the 43% weighting for the rest of the entire series of tests? It must in order to be comparable to decades-old standard test procedures. The original reason for weighting the two urban cycles was to represent a daily scenario with several trips taken per day – some cold-start, some warm and hot-start. It is not expected that the first start of the day would represent 43% of the daily mileage. On any given day with several trips, one is the day's first cold start and others start after short and possibly very long soak periods. The early architects of the FTP used 43% cold-start weighting to represent all cold starts for an entire day and 57% hot-start weighting to represent trips taken with very little rest time.

What this means for our PHEV FCT is that the first cold-start may not well represent all of the potential cold-starts of a given day. One idea that was considered (but later discarded) for J1711 [5] was a series of four UDDS cycles with a 3-hour soak taken between the second and third cycle as a means to mimic the cold/hot weighting percentages with a four-trip scenario with equal weighting applied to all four cycles.

Charge-Balanced UDDS Test – In the existing J1711, the term “Partial-Charge Test” is used to describe this procedure. However, the authors prefer to make reference to this test as the “Charge-Balanced” or “Charge-Sustaining” tests because it is more descriptive of the test objectives.

The charge-balanced UDDS tests can be conveniently performed the day after the FCT tests. The test procedure follows:

- Run a UDDS prep cycle (while in sustaining mode)
- Soak over night (12 to 36 h)
- Run UDDS cycle (“cold-start”)
- 10-minute soak
- Run UDDS cycle (“hot-start”)

Another variation practiced at Argonne for benchmarking is running a third UDDS test to make sure that there exists good charge-balanced test results to analyze. There is only one chance for the cold-start UDDS, but either hot-start test represents a valid charge-sustaining hot-start test.



Documents

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