TEST PROCEDURES AND BENCHMARKING
Blended-Type and EV-Capable Plug-In Hybrid Electric Vehicles

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Abstract

With fuel prices at all-time highs and a high visibility for “green” transportation, the plug-in hybrid electric vehicle (PHEV) has seen much renewed interest. Manufacturers have announced production of PHEVs, and the question of how they will be counted amounts essentially the question of how they will be tested. The SAE J1711 procedures issued in 1999 were designed to address PHEVs, but since that time many new ideas and notions have caused the committee to reissue the procedures to take a close look at changes to the procedures. There are distinctly different discussions for PHEVs that are based upon today’s full hybrids with larger plug-in battery packs (“blended type”) and a “range-extender” PHEV type. A full-charge test is given to a PHEV (starting at full-charge to charge-sustaining) to find the capacity and to characterize the vehicle’s operation. Driving statistics are useful in processing the full-charge test and in combining depleting with sustaining operation. Several blended-type vehicles have been tested, and many lessons were learned. A minimum test method was found that can be suitably applied to the vehicles tested thus far. Just as was the problem in mid-1990s, the lack of refined prototypes with all-electric range capability slows the rate of progress in developing a suitable procedure.

Keywords: PHEV, Testing

1 Test Procedure Background

Open collaborative work on devising a standard test procedure for hybrid electric vehicles (HEVs) began in the fall of 1992. The J1711 SAE committee taskforce was formed initially with widespread participation from industry and governmental entities with the goal of addressing all HEV designs. At that time, it was not known what HEV design(s) would be predominant. The procedure took on may draft forms [1] with the most challenging aspect being addressing the possibility of multiple driver-selectable operating modes and how to test and characterize HEVs with “externally chargeable energy storage systems” – now commonly referred to as plug-in hybrid electric vehicles (PHEVs).

The 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 from winning teams participating in the Argonne-managed U.S. Department of Energy’s (DOE’s) “HEV Challenge” competition were used to test out the procedure [2], and since 1993, the University of California, Davis has entered a PHEV in the yearly DOE competitions [3, 4]. Although the competition format did not allow organizers to apply the exact procedures in J1711, many J1711 concepts were tried, and shortcuts were applied to characterizing and comparing the PHEV to the other charge-sustaining HEV designs. SAE J1711 was approved in 1999.

The balloted version of J1711 (J1711-MAR1999) had many goals and constraints that shaped the final test concept. First, the procedure was to be all-inclusive of HEV designs and include testing and weighting of driver-selectable modes. A guiding goal, and significant challenge, was designing a procedure that, if followed with a conventional vehicle, would yield the same results; thus, hybrid-related aspects would not change the results of a conventional vehicle tested using J1711 procedures. The existing J1634 electric vehicle (EV) test procedure was used in applying a significant constraint that converted off-board electrical energy into a miles per gallon (MPG)-equivalent energy usage rate with a direct energy conversion factor of 36.66 kWh per gallon of gasoline (this value was updated to 33.44 in J1711-1999MAR).

J1711-1999 classified the HEV into different functional categories to apply specific procedures accordingly. An important aspect of the approach was the introduction of a charge-balance window that would serve to define a valid, charge-balanced test that eliminated extra testing or any correction for changes in battery state of charge (SOC) for the fuel and emissions results. Earlier drafts included SOC corrections; the final version presented them as an optional component.

Since the balloting of 1711-1999, only parts of the document have been used in certification testing. The various interpretations of the charge-tolerance concept were used by the U.S. Environmental Protection Agency (EPA) to certify production HEVs. Contained in the document is terminology that has seen widespread use. Since the Prius was released in Japan in 1997, the predominant production hybrid design has been the “charge-sustaining” design, initially marketed with television commercials and print ads proclaiming that “you never have to plug it in.” Although research into the benefits of PHEVs continued, the PHEV procedures in J1711-1999 were basically moot until interest in PHEVs were revitalized with the emergence of enthusiasm for modifying production Prius hybrids into a PHEV design [5].

All SAE standards expire after 5 years. An SAE J1711 taskforce was re-formed with a kickoff meeting held at SAE headquarters in Troy, MI, in August of 2006. For this taskforce, refined PHEV prototypes were available for testing, and representation and involvement were complete. All major original equipment manufacturers (OEMs) were involved, and there was routine attendance by engineers from EPA and California’s Air Resources Board (ARB).

2 Modifications of J1711

As the dialogue in PHEV research continued, various aspects of J1711-1999 were identified as needing modification or deletion [5, 6]. A significant new development was the demonstration of charge-depleting operation with regular use of the engine. Existing charge-sustaining hybrids can be re-tuned to use the engine less often (only at higher loads) within the capability of a charge-sustaining design. This operation has been termed “blended.” Rather than operating in an EV mode and then sustaining an HEV mode, the engine and battery are blended together during charge-depleting operation. This operation was not specifically addressed in J1711-MAR1999.

In addition to procedure omissions, certain components of the procedure were deemed worthy of significant change in the literature and in the re-formed J1711 committee. The major changes are:

- Omit references to fuel cells, as SAE J2572 specifically addresses these vehicles.
- Eliminate the requirement to be compatible with EV procedures by not converting the electric energy consumption into equivalent units of consumable fuel.
- Translate alternating current watt hours (AC Wh) into equivalent amounts of carbon dioxide (CO_2) emissions, with results including tailpipe CO_2 and inventory CO_2 emissions.
- Change the baseline assumption for a driver’s battery charge frequency from once every other day to once a day.

- Define a charge-depleting range and treat this operation in a similar manner as the EV range is treated in existing procedures.

The existing concepts that will be maintained (but perhaps slightly altered):

- Testing will characterize the charge-depleting and charge-sustaining behavior separately.
- Updated driving statistics will be the basis of weighting the depleting with sustaining results.
- EV range will be defined by the first engine start, but the equivalent EV range – a metric to describe the usable off-board energy stored on-board – may also be used for definition purposes and defining the charge-depleting range for weighting.

3 Classifying PHEVs Based on Power Levels

Given that the procedures used for testing will characterize the vehicle in the depleting and sustaining modes for each test cycle (there are as many as five cycles to satisfy the 2011EPA "5-cycle" fuel economy labeling requirement), one major focus of the J1711 taskforce has been to come up with a minimum test method specifically designed to address likely PHEV design types with the least number of test days.

The design space for PHEVs is quite varied. Before detailed discussions of procedural concepts can begin, each vehicle's behavioral characteristics must be defined. One very important parameter to acknowledge is the electric drive capability. PHEVs can be grouped according to the electric-only power capabilities compared to the various test cycle requirements. Consider the plot in Figure 1 below.

In the upper plot is the second-by-second power requirement at the wheel to drive the Urban Dynamometer Driving Schedule (UDDS) cycle for a vehicle sized to the 2004 (Gen 2) Toyota Prius. The lower plot shows the aggressive US06 cycle and a full-power acceleration observed during chassis dyno testing. Drawn across these plots are three different electric power levels shown to define significant PHEV types.

The lowest power level is shown as the "blended" mode of operation on the plot. A charge-balanced engine-on power level for the Prius is tested to be roughly 7-8 kW; however, if depletion is desired, that level can be raised to the capabilities of the electric drive system, up to 20 kW. Seen in the center plot of Figure 1 are test results from a Hymotion Prius, an aftermarket PHEV retrofit, which shows the location of the engine-on points (engine speed) during the UDDS cycles associated with ~12-15 kW at the wheel. To retain favorable emissions, the engine is on during the first "hill" of the UDDS, after which the engine is engaged for loads that approach the 12-15 kW threshold.

The "range-extender" PHEV is at the other end of the EV power spectrum. This design is a fully capable EV with charge-sustaining capabilities (we are assuming that common-use PHEVs will have the engine-generator subsystem sized to sustain charge during all normal driving). Notice that the power at the wheel for the Prius was observed to be roughly 70 kW.

Between these two designs lie, for lack of a better term, the "intermediate" PHEV design. Electric power levels are high enough to propel the vehicle without engine assistance for some of the standard test cycles. But, similar to blended designs, if the driver demands more power than is available by the electric drive system, the engine will be invoked to make up the difference.

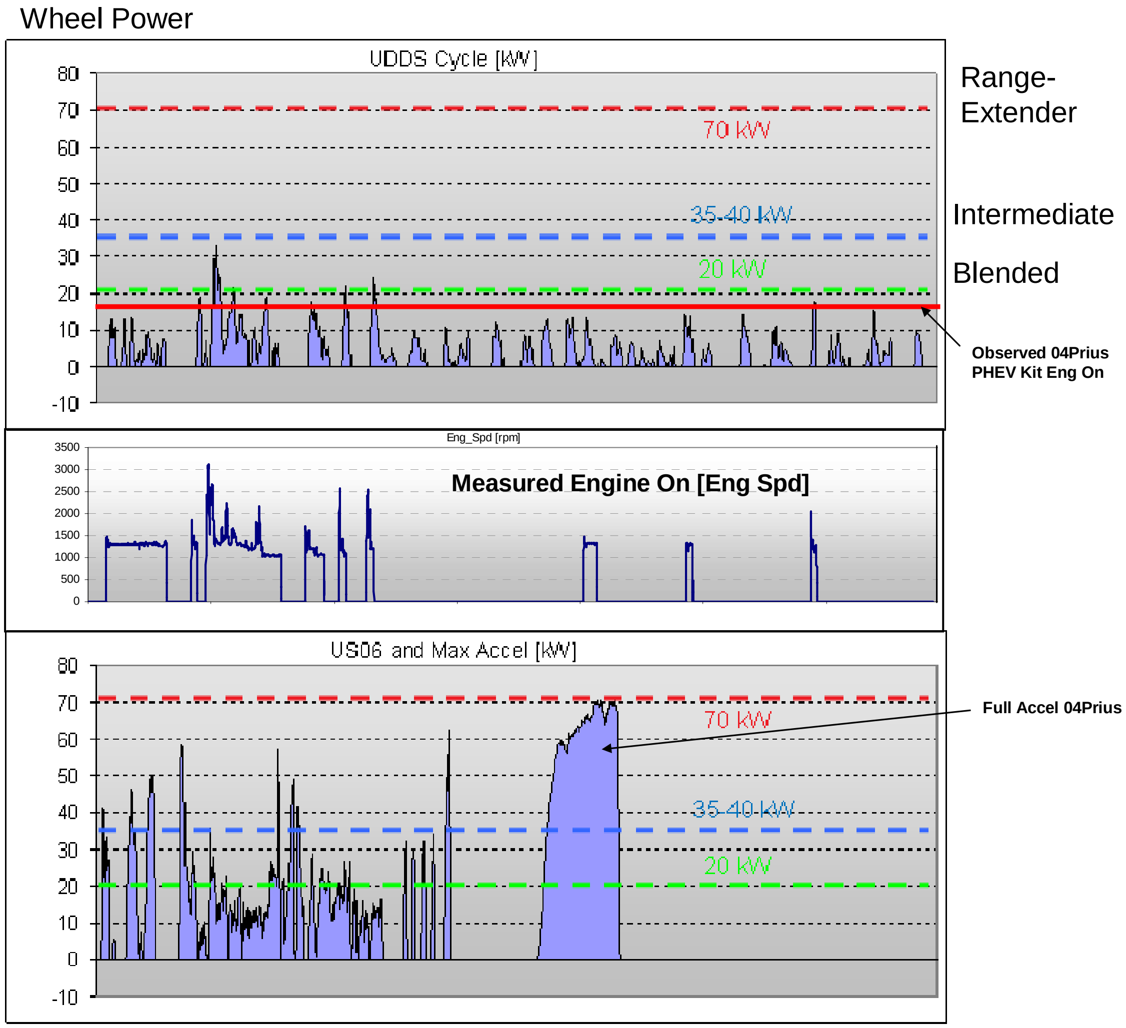

Figure 1: Wheel Power Requirements for UDDS and US06 and Maximum Acceleration

In the existing California low-emission vehicle (LEV) regulations [7], credit is given to “grid-connected hybrids” defined as “a hybrid electric vehicle that has the capacity for the battery to be recharged from an off-board source of electricity and has some all-electric range.” This range is defined as the distance driven in successive UDDS cycles. This requirement aims to promote more electrification of passenger vehicles by using EV range as a metric for defining the level of desired performance, such as emissions certification level defines the merit of a low-emissions vehicle. However, current regulations exclude blended PHEV designs.

If a credit requirement is devised as a method to quantify the degree of merit for petroleum displacement, EV range is not the most direct and inclusive measure. All of the blended-design PHEVs shown in this paper would not qualify for any credit. If, however, the argument for an EV range requirement (on the UDDS) is to avoid engine-on events for reduced emissions, the requirement falls short for two reasons:

1) There is a high likelihood of an engine start anyway because the power demand of the average driver is higher than that of the UDDS, as is evident in the drive cycles defined specifically to depict average driving (LA92 [8], ATDS [9], INRETS cycles [10]). In fact, if the engine start occurs during a high power event (e.g. on the highway), emission controls would have to be

redesigned to avoid very high emissions, a measure not likely, given this specific condition is not tested during emissions certification (e.g. highway cold-start emissions).

2) Using the same National Household Travel Survey (NHTS) [11] driving statistics data used to define utility factor, it can be calculated that less than 25% of all trips are less than 10 miles (the lowest credit level in the LEV program). Furthermore, the first cold-start of the day may not be avoided, as less than 5% of vehicles drive less than 10 miles in a day – the only scenario that avoids a cold engine start.

It is not surprising that the California ARB is considering blended mode operation for credits in the Low Emissions Vehicle Program [12].

4 Blended Charge-Depleting Operation

The principal characteristic of a PHEV is the ability to store electricity taken from the electrical grid by charging at home (or elsewhere). It follows that this energy would be depleted in some manner during driving, after which charge-sustaining operation would be required for longer distances.

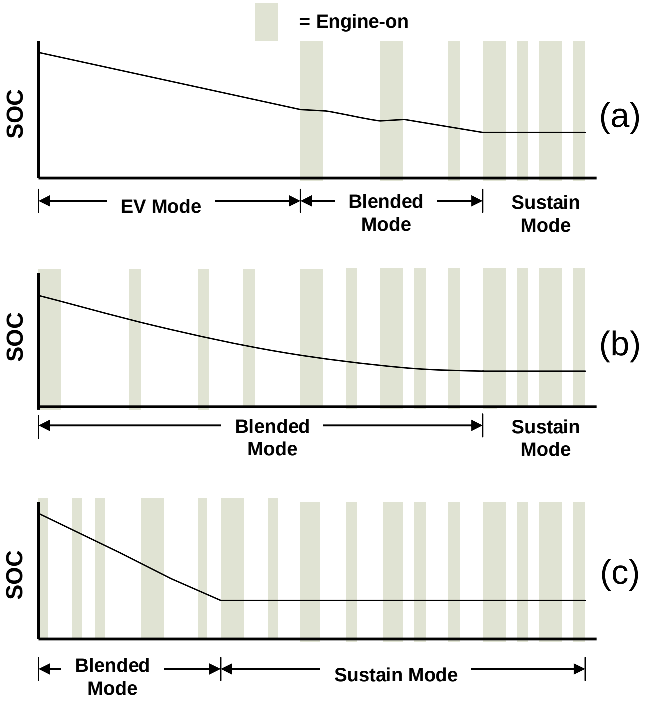

Figure 2: Diversity of Charge-Depleting Strategies

Many rates of depletion of possibly varying characteristics from all-electric to a shallow-discharge rate of the blended mode are possible, and these rates may change unexpectedly throughout depleting operation (see Figure 2). In the absence of any operational information, the safest way to capture all of this vehicle data is to run a series of cycles from a full charge until charge-sustaining operation is observed. Indeed, J1711-MAR1999 includes a "Full Charge Test" (FCT) that would run successive cycles until the engine would start (the end of charge-depleting operation).

4.1 Basic Testing Methods

In the absence of any existing experience testing blended-type PHEVs, the first tests applied to the first-generation Hymotion Prius were a basic application of a FCT for each test cycle. In the case of the UDDS, the soak period was maintained with a single bag sampled, followed by a purge and an "adjustment" (calibration) performed once between tests (not before and after each bag, as specified in the U.S. *Code of Federal Regulations* (CFR). By doing this, the soak time between UDDS cycles could be maintained at 10-11 min, within the limits of the Federal Test Procedure (FTP).

For the U.S. highway test, conventional test procedures include a "prep" cycle before the sampled cycle. Highway cycle pairs were tested back-to-back with about 15-20 min between cycle pairs. One unique aspect of the Hymotion design is the ability of the operator to shut off the plug-in battery at any SOC level and run the vehicle in a charge-sustaining mode. This switch was used in initial testing for the first highway cycle prep at the start of the highway FCT.

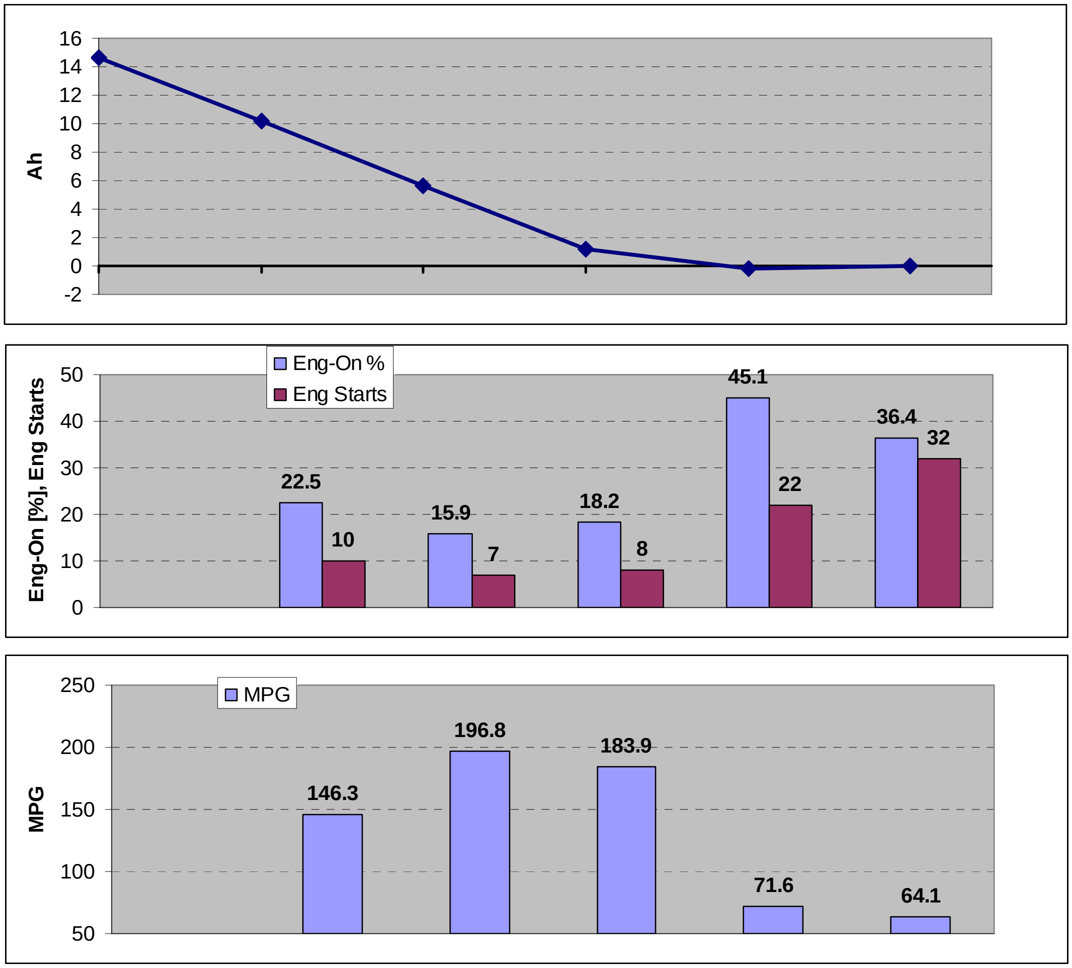

Figure 3: Gen 1 Hymotion UDDS FCT Results

4.2 Analyzing Fuel and Electrical Consumption Results

Because two energy sources are being consumed during the repeated cycles, it was found that expressing this data on a two-dimensional plot was useful in the analysis. The graph is essentially a "SOC-Correction Plot" familiar to those in the field of HEV testing (Figure 4). The trend line of the individual test results points intersect the *x*-axis at the point where all of the energy comes from the consumable fuel. New to this graph for PHEVs are data that approach the other axis. For blended-mode operation, the trend can be extrapolated out to a theoretical EV consumption rate.

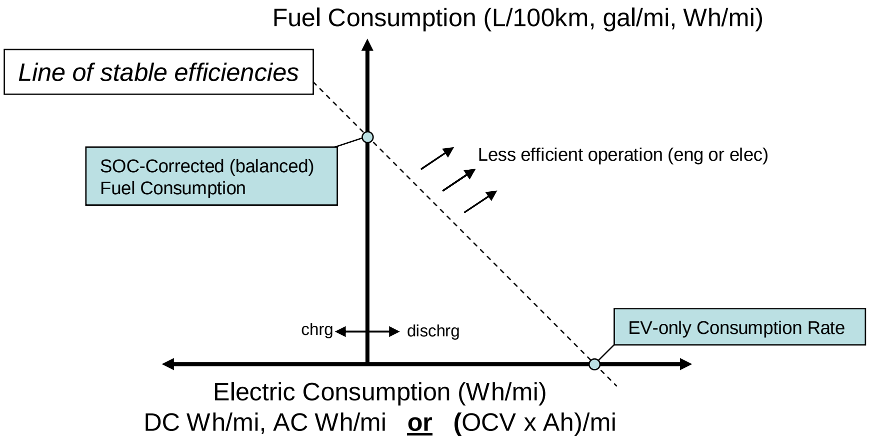

Figure 4: Expressing PHEV Energy Consumption on a Two-Dimensional Plot

As seen in Figure 4, a straight line that intersects both points of interest depicts a line of constant power converter efficiencies for electric and the engine. Data points below that line would mean that efficiencies are improved; above the line means that efficiencies are lowered.

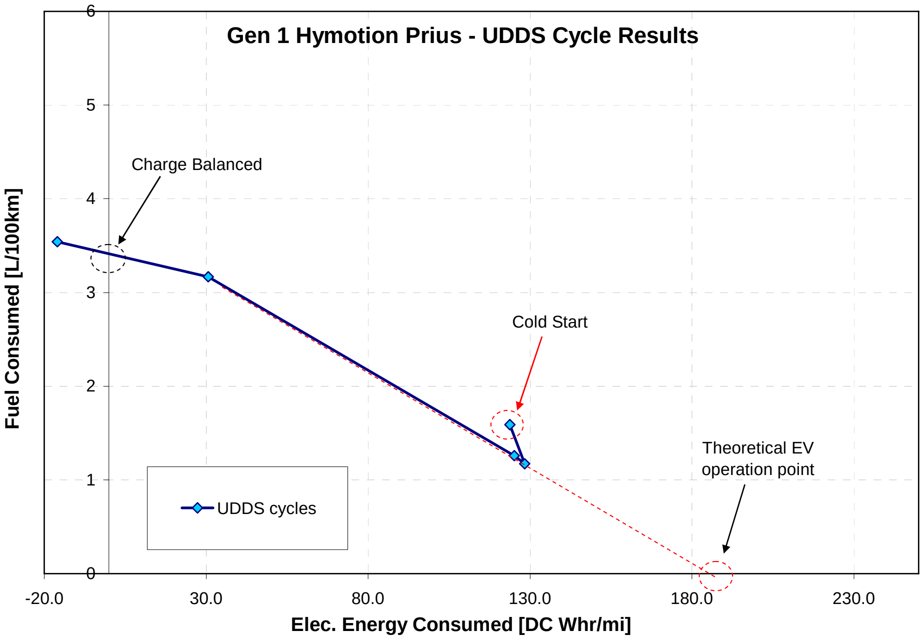

Figure 5: Gen 1 Hymotion Prius UDDS FCT Results on Two-Dimensional Plot

In Figure 5, FCT test data on the UDDS cycle are plotted. Notice the cold-start result has lower efficiencies because of increased losses and thermal warm-up strategies consume more fuel than the hot-start UDDS cycles.

4.3 Weighting Depleting with Sustaining Operation: Utility Factors

If the desire is to combine depleting with sustaining operation for a final result, a common approach is to first define a mileage-weighted probability curve (MWP), or Utility Factor (UF), and use the vehicle's depleting distance to find the fraction of expected depleting vs. sustaining operation in nationwide use. The 2001 NHTS data was processed and depicted in Figure 6 below.

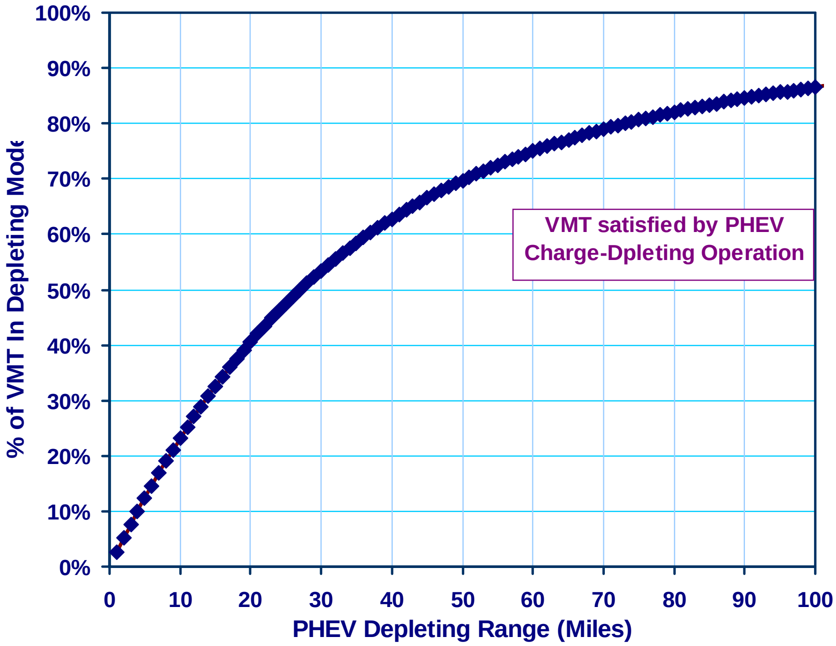

Figure 6: NHTS Data Processed to Express Mileage-Weighted Probability of Charge-Depleting Operation

This data allows a means to combine the depleting and sustaining operation together to form a single consumption result. The MWP data was first used to combine EV operation with sustaining operation, but the calculations hold true for blended operation by applying the fractional percentages to both the fuel and electrical consumption results of depleting operation.

This is, of course, a fleet-wide estimate. The caution from EPA that "your mileage may vary" takes on a whole new meaning if your driving style and especially your daily driving distances can change your fuel economy by a factor of 2-3. The changes are remarkably distorted when a range-extender PHEV is considered. Consider the specifications of the GM Volt concept PHEV; your mileage may vary – from 50 MPG (driving long distances, or you forgot to charge) to infinity (no fuel consumed makes an undefined MPG level).

4.4 Developing Minimum Test Methods

It was found in testing blended PHEVs from aftermarket converter companies that there may be little reason to depart from a set of basic assumptions concerning bended-type PHEV operation, even though the conceivable design space for charge-depleting energy management strategies is quite large. Refer back to Figure 5, the Hymotion data; two hot-start data points are clustered together during depleting operation because the operating strategy is essentially unchanged for those tests. The next result on the operation line represents the transition from depleting to sustaining. Assumptions of this simple operation allow simplification and shortening of the FCT. The assumptions for a simplified approach are:

1) Battery: Throughout the depleting SOC window, the energy storage system will perform with little variation; thus, the performance and constraints affecting operation will also be stable. (One exception is the amount of regenerative braking that can be accepted by lithium batteries at SOC levels approaching 100% because of peak cell voltage level limitations.)
2) Controls: For a given cycle, the control parameters will be fixed according to a desired depleting scheme and maintain these parameters until a particular SOC is achieved, at which point, the strategy switches to a stable charge-sustaining strategy.
3) Calculations: Each cycle's depleting range can be accurately estimated, given the usable depletable capacity of the battery and the respective depletion rate of each test cycle result.

At least one FCT must be run in order to define the usable capacity of the vehicle and apply it to UF calculations for all of the cycles tested. The currently available aftermarket kits have a depleting range greater than 40 miles. This means that the depleting range is long enough for the "4-bag" FTP (UDDS×2 = 15 miles) followed by the highway test (HWFET×2 = 20 miles). The range will be depleted by running highway tests (HWFET×2) until there is no longer any net energy observed coming from the battery system. This minimum test method FCT is depicted in Figure 7 below. In the figure, "U" indicates the UDDS cycle, and "H" is the highway cycle.

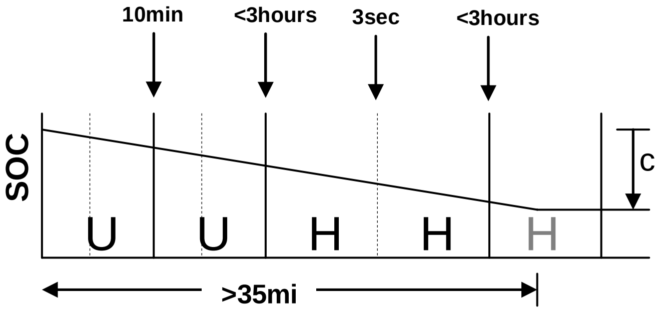

Figure 7: Blended-Type PHEV Minimum Test Method "Full Charge Test"

However, if the charge-depleting range is shorter than 35 miles, then the testing must accommodate charging in order to have representative depleting test results. Figure 8 shows examples of various charge-depleting range test sequences. One possibility shown is to do away with the highway prep cycle, which is valid if we can assume that the vehicle warm-up conditions are uncertain and not steady-state during depleting operation. And if the depleting range is so short that by the end of the test the vehicle is sustaining, then a single test is essentially a FCT; thus, no short-cut procedure is possible or needed.

4.5 Charge-Depleting Rate

In blended operation, the depletion rate can be widely varied, so what is the relationship between the depletion rate, testing procedures, and results processing? With the same size battery, rapid depletion rates have high fuel economy with short depleting distances; slow depletion rates will have lower fuel economy, but with longer depleting distances. If we maintain our earlier assumptions of constant energy conversion efficiencies, on any very long trip, either depletion rate scenario will end up consuming identical amounts of fuel. However, for days with short total distances traveled, the battery may be left with energy in the pack, thus "wasting" fuel in that day. Under these assumptions, depleting as fast as possible is clearly the best choice.

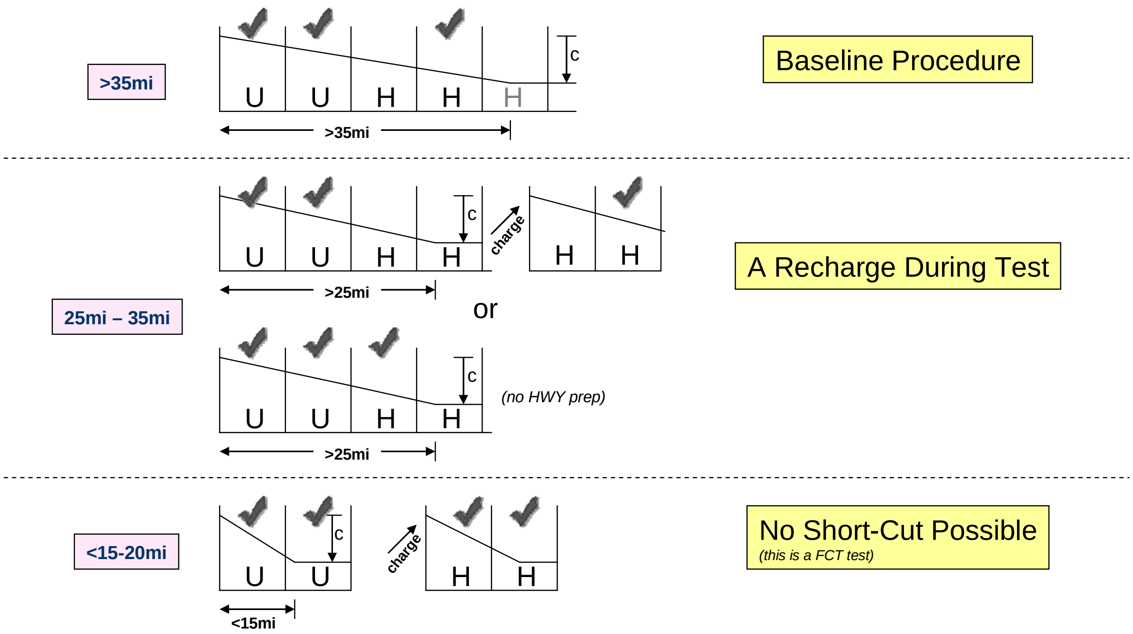

Figure 8: Variations of the UDDS/HWY FCT Based on Depleting Range

In reality, the above assumptions are too simplified. Engine efficiency is not constant; it is dependent upon engine load levels, so there is merit in studying differences in depletion rate with the overall trip fuel economy and the UF-weighted final result (while considering variations in operating engine efficiency).

There are two fundamental parameters to the energy management that will affect the depletion rate: (1) engine-on load, and (2) once the engine is on, the engine power compared to the load power demands. These relationships are described in more detail for several charge-sustaining HEVs in SAE 2007-01-0291 [13]. For the sake of this analysis, consider a Prius-sized series HEV with the same engine power vs. efficiency curve. The charge-sustaining engine-on load point is somewhere around 7 kW. If the engine-on power level is raised, the vehicle will deplete charge. It will deplete even faster if the engine is unloaded, but that would sacrifice engine efficiency, so for this comparison, we will run the engine at the required load level for driving ("load-following" control strategy) and vary the depletion rate with the engine-on level. Other attributes of the vehicle are shown in Table 1.

Table 1: Specifications of PHEV for Depleting Distance Analysis

Vehicle Weight/Size	2004 Prius, 1,474 kg
Configuration	Series HEV
Engine/Generator	53 kW, same efficiency
Battery	5k Wh usable

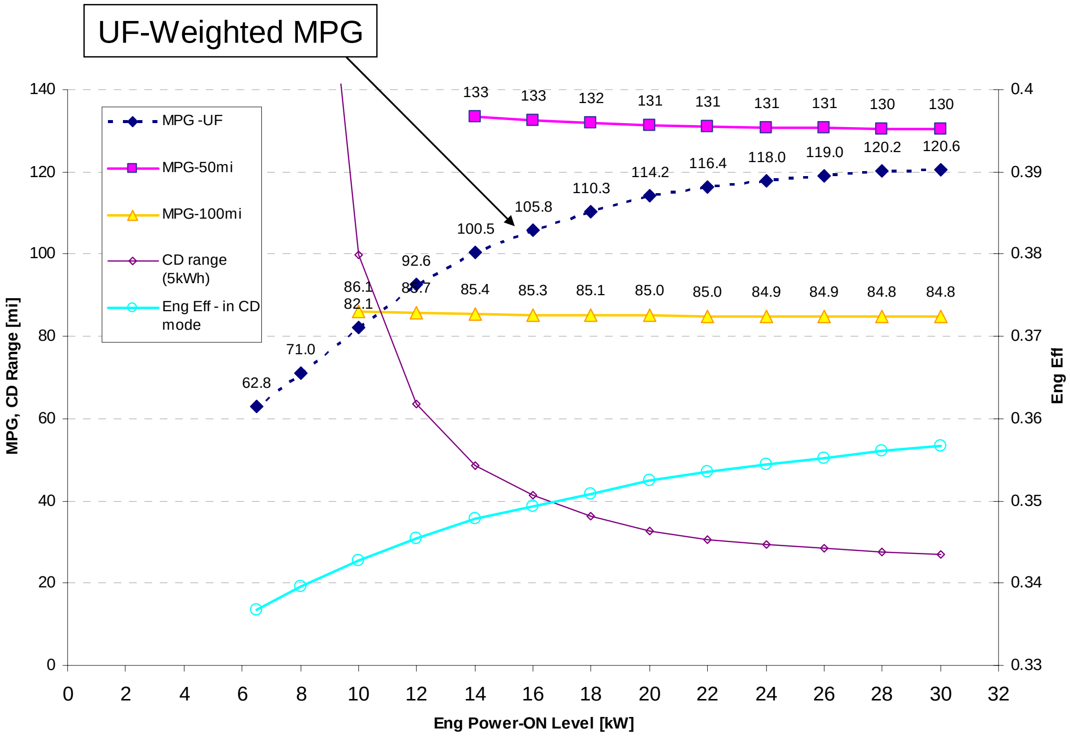

Figure 9: Comparison of Depleting Rates, Trip Lengths, and UF-Weighted Combined Results

The engine-on load was varied to control the depleting rate. This controlling parameter is shown in Figure 9 on the *x*-axis. The associated variations in depleting distance (charge-depleting [CD] range) and UF-weighted fuel economy are shown.

The results of this analysis show that, when considering the UF-weighted fuel economy, depleting faster will have a higher fuel economy result. However, if you are taking a particular trip longer than any of the depleting distances, the remaining driving will run the engine at the lower charge-balanced engine-on load. The differences in engine efficiency during charge-depleting operation are also shown in the graph.

Two trip distances were considered: 50 miles and 100 miles. The associated fuel economy for the whole trip was plotted for each charge-depleting distance (shown in diamonds). The highest fuel economy is found when the depleting range matches the trip length; the improvement is apparent, but marginal. So in the absence of any knowledge of trip length, the controls should aim to deplete at a maximum reasonable rate. However, if trip lengths are known to be longer, then slight improvements to the trip fuel economy can be appreciated with slower depletion rates.

The best on-road energy management strategy would be to arrive back home just as the usable battery capacity is finally depleted. If a vehicle is equipped with a global positioning system (GPS), the destination information and total trip length can be fed to the control strategy for improved fuel economy. If the destination is not known, a theoretical round-trip distance can be calculated from any location on the trip compared to the distance to drive back home. For this strategy, as the vehicle is driven farther from home, the depletion rate could be reduced to match the longer anticipated driving distance. Note, regulators would have to be assured that any adaptive strategy would not be detrimental to fuel consumption or tailpipe emissions.

The power-split hybrid powertrains in current charge-sustaining hybrids do have engine-off limitations, and thus cannot always stay off for low-load demands. Thus, the interaction of engine efficiency and depletion rate becomes more complex [6]. It would be expected that the design objectives of production PHEVs will minimize this problem much as in the description of the prototype Prius PHEVs announced by Toyota [14].

5 All-Electric Capable PHEV Operation

Much literature assessing the impacts of PHEVs consider a range-extender hybrid with an associated all-electric range [15]. It is easy to see the benefits of this operation for fuel economy and emissions reduction. References to PHEV20 or PHEV60 in the literature refer to differences in all-electric range (20 and 60 miles, respectively) associated with different relative-sized battery packs. The car behaves like an EV for the specified range (20 and 60), then switches to sustaining operation. This simple model is used to forecast future oil savings and is the basis for variable LEV emission credits based upon the EV range. However, in reality, the design space for PHEVs with an all-electric capability can be a little more complex. A vehicle may have a blended mode for some time before completely sustaining operation. Certainly if the vehicle's electric propulsion system was designed only for the UDDS, then higher power demands would result in an engine start, and thus technically the end of its EV range. Figure 10 is a generic representation of a possible scenario for a FCT.

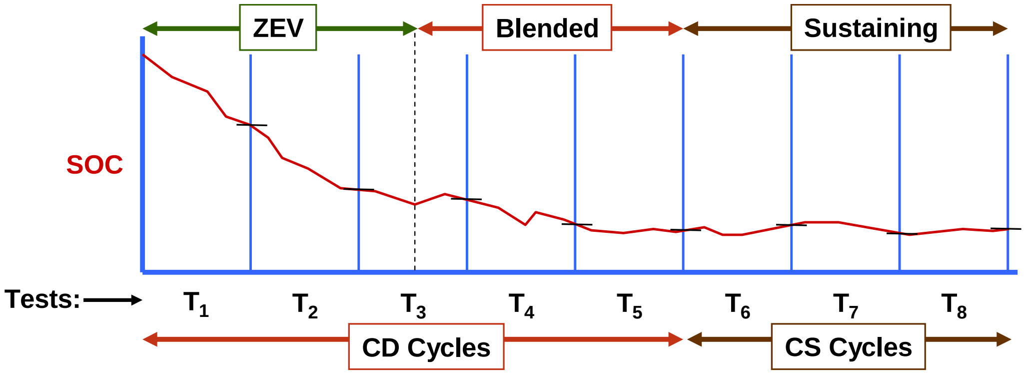

Figure 10: A Possible All-Electric Range Capable PHEV Operating over a FCT

From this scenario, the strict definition of EV range is simply the total distance traveled to the point of first engine start. To credit off-board energy use but put in terms of EV range, an equation for equivalent EV range was developed by comparing the sustaining fuel consumption to the blended-mode fuel consumption and finding a displaced EV distance. Using the scenario in Figure 10, the equation for equivalent all-electric range corresponds to Equation 1.

$$\text{P-HEV}x\text{ Equivalent} = \underbrace{\left(1 - \frac{1/\text{MPG}_{CD}}{1/\text{MPG}_{CS}}\right)}_{\text{(PDF)}} \times \underbrace{\text{Miles}_{CD}}_{\text{(Charge Depleting Distance)}} \qquad \text{Equation 1.}$$

In the equation, PDF stands for Petroleum Displacement Factor in percentage (from 0% – sustaining, to 100% – full EV operation), which indicates the amount of propulsion energy that is displaced by the battery system. It also indicates the rapidity of the depletion rate. MPG_{CD} and MPG_{CS} are the charge-depleting and charge-sustaining fuel economy, respectively. The charge-depleting fuel economy includes all of the fuel consumed in the charge-depleting cycles and the depleting range that is associated with the end of the last depleting cycle. The equation is applicable to blended and all-electric range (AER)-capable PHEVs. The equation is also helpful in defining a precise depleting range for which there may be no distinct transition point from depleting to sustaining behavior in the data.

5.1 Applying UF to Multiple Operation Modes

The plug-in hybrid equivalent all-electric range “PHEVx” can used in the utility factor analysis, or another approach may be used to count each cycle’s results more precisely using the same UF data. If the charge-depleting operation were sufficiently complex, a method of assigning each charge-depleting cycle with a specific UF fraction could be employed. Consider Figure 11 and the application of UF parts for each charge-depleting cycle. Regardless of the depletion method or trend, individual weighting factors can be applied to a FCT that results in earlier cycles weighted the most and later cycles weighted the least.

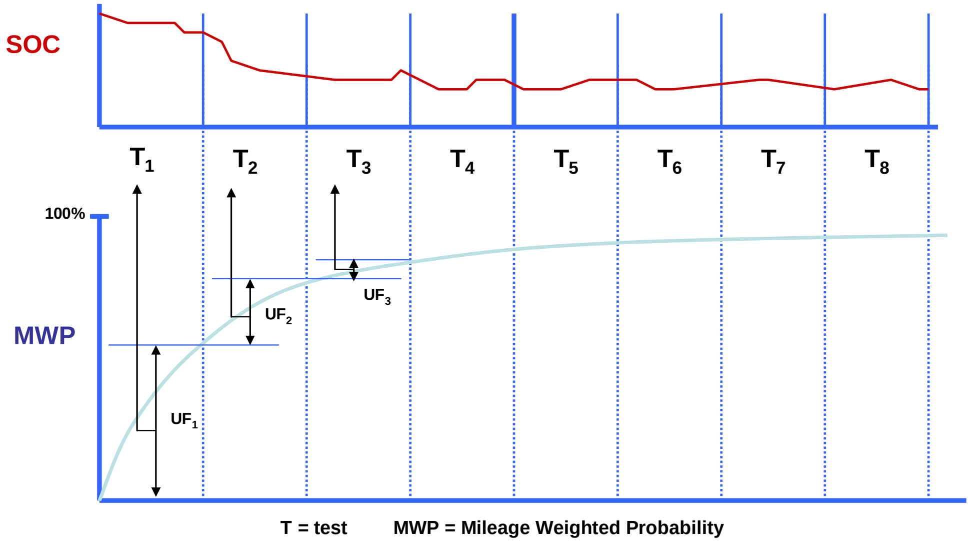

Figure 11: Assigning UF Fractions to Each Depleting Test Result

The associated equations with this approach are shown in Equations 2 and 3. The result captures all operation from depleting to sustaining and wraps the results together into one result of fuel consumption and electrical consumption.

$$\mathbf{MPG} = \frac{1}{\sum_{i=1}^{maxCD} UF_i\,(1/MPG_{CD})_i \;+\; (1-\sum_{i=1}^{maxCD} UF_i)(1/\,MPG_{CS})} \qquad \text{Equation 2.}$$

$$\mathbf{AC\ Wh/mi} = \sum_{i=1} UF_i\,(AC\ Wh/mi_{CD})_i \;+\; (1-\sum_{i=1}^{maxCD} UF_i)(AC\ Wh/mi_{CS}) \qquad \text{Equation 3.}$$

5.2 Challenges in Emissions Testing AER Capable PHEVs

The biggest challenge in applying test procedures to an AER capable PHEV is dealing with legacy emissions weighing schemes. The FTP for HEVs consists of an overnight soak with two UDDS cycles with a 10 min soak period in between. The first test is weighted as 43% and the hot-start UDDS, 57%. This weighting scheme originates as a simplified way to represent a day with multiple trips that either took place after only a short period of time (going to the store and returning quickly) or after a much longer time (after a whole day’s work, 8+ hours). In a PHEV FCT with AER capability, we essentially have too much information to weight using the familiar 43%/57% cold/hot split and only one test cycle for a start after the long soak period, which is likely in EV mode.

The solutions to applying a standard test procedure for AER-capable PHEVs are not fully developed, but at this time are leaning toward different procedures for emissions and fuel consumption measurement focusing on the different objectives of each. Emissions certification will likely follow “worst case” scenarios; thus, if a person never plugs in the PHEV and runs it like a conventional hybrid, there would be no discount for zero-emissions driving. Thus, the focus of the emissions testing is identifying all of the emissions modes and testing them separately. The fuel economy testing will encompass an accurate characterization of depleting and sustaining operations and weight them according to the UF for the range.

Based upon testing and conversations with battery companies and OEM developers, it is likely that the transition from depleting and sustaining will be short and perhaps not long enough to warrant separate characterizations. Thus, for a AER capable PHEV, the equivalent EV range will be suitable for applying the UF. For blended-type PHEVs, the calculated (extrapolated) depleting range is suitable for weighting the depleting with the sustaining results.

6 Charging Data

The data collected during testing is from the direct current (DC) bus going into and out of the drive inverters. The results that are reported should be related to the system energy consumption, i.e., the AC kWh consumption rate. There are losses and irreversibilities that occur between the DC consumption point and the AC charging energy. For a given vehicle system, changes in battery SOC – even for a single cycle – must be related back to the recharging process, expressed in AC kWh.

Especially for lithium-ion (Li-ion) batteries, integrated ampere hours (Ah) track well with SOC, so the charging data can be processed to provide this transformation of integrated Ah and the associated AC recharge energy. The charging data from several Prius retrofit vehicles with Li-ion batteries were analyzed, and it was found that Ah as a good proxy for SOC can provide a look-up for AC kWh used in charging. Consider Figure 12, where a single test has a starting and engine Ah. This data could be used to find the starting and ending AC kWh energy levels. In fact, the data in this case is so close to linear that using a single proportional coefficient would only incur a very small error compared to the actual charging curve.

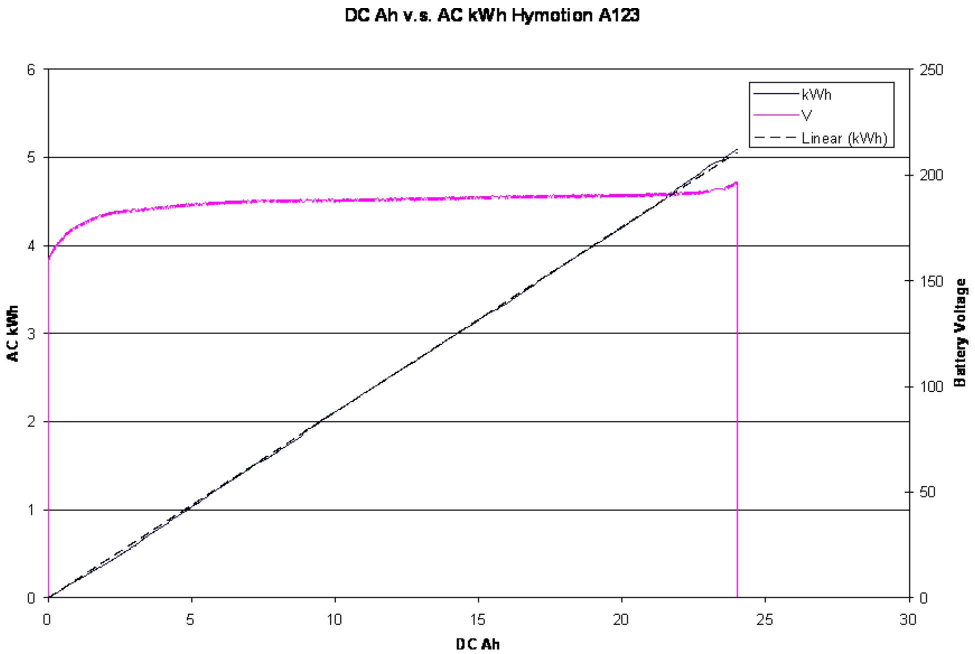

Figure 12: Charging Data Used to Calculate AC kWh Charging Energy

7 Facility and Instrumentation for PHEV Testing

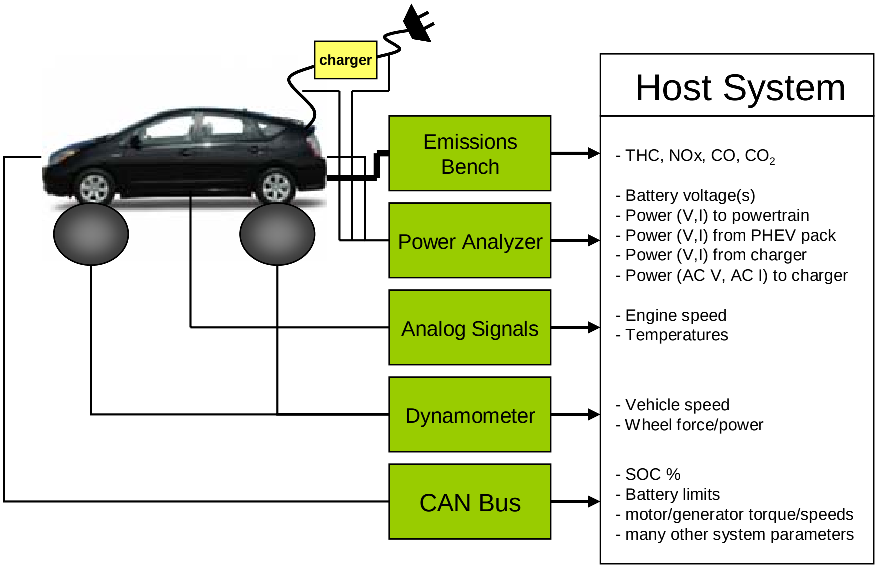

Figure 13: PHEV Instrumentation in Test Facility

Testing PHEVs is not much more difficult than testing production charge-sustaining HEVs. Argonne's facility Host system integrates the data from the emissions bench, power analyzer, data acquisition system, dynamometer, and CAN bus. The system collects all these parameters at 10Hz (can go faster, if required). The power analyzer used is the Hioki 3193 with all 6 channels populated with high-voltage current/voltage modules. In the case of Hymotion Prius testing, at a minimum, there is a node for the total system, the PHEV battery, the charger output, and the charger input (AC).

Testing is usually conducted in the two-wheel-drive (2WD) mode. From a previous study [16], it was concluded that the Prius's (and a few other production HEVs') regenerative braking system did not behave significantly different when operated in the 2WD or four-wheel-drive (4WD) mode. Regenerative braking would be affected if the foundation brakes were blended in a parallel manner where progressively more baking needed to be commanded in the 2WD case than in the 4WD case. Because it is the manufacturer's desire to utilize regenerative braking as much as possible, the braking systems are designed in a series manner; thus, regenerative braking is always maximized during testing.

8 Results of PHEV Testing

Several PHEVs have been tested in Argonne's Advanced Powertrain Research Facility's chassis dynamometer test cell. With the exception of a Renault Kangoo EV-range extender [6], all have been Prius vehicles retrofitted with either a second battery pack or a complete replacement of the stock battery system. The results of testing are shown in Table 2 below. The fuel and electrical consumption are representative numbers without the effects of cold starts (long rest period beforehand).

Table 2: Argonne Blended PHEV Prius Test Results to Date

	Depleting UDDS Fuel Economy		Electric Consumption	CD Range	Usable Energy	Pertoluem Displacement	Sustaining UDDS Fuel Economy
	MPG	L/100km	DC Wh/mi	mi	kWh	Factor [%]	MPG
Hymotion Gen 1	178	1.32	126	24	2.9	63%	66
Hymotion Gen 2*	160	1.47	129	25	3.1	63%	59
EnergyCS	139	1.69	131	34	4.5	55%	63

	Depleting HWY Fuel Economy		Electric Consumption	CD Range	Usable Energy	Pertoluem Displacement	Sustaining HWY Fuel Economy
	MPG	L/100km	DC Wh/mi	mi	kWh	Factor [%]	
Hymotion Gen 1	122	1.93	98	33	3.2	48%	63
Hymotion Gen 2*	101	2.33	113	31	3.4	46%	55
EnergyCS	103	2.28	103	50	4.9	44%	58

* Gen 2 Hymotion control software bug limited usable energy from a possible 4.5kWh to 3kWh.

Note that the Gen 2 Hymotion Prius had a larger usable capacity than the controls allowed to operate. The second round of testing a similarly equipped vehicle showed roughly 4 usable DC kWh of energy used in an FCT.

The differences in cold-start fuel usage and hot/cold weighting significantly impact the overall "final result." Currently these nuances are being decided by the J1711 committee, and future testing will include running a minimum test method and post-processing as a demonstration of the procedure.

9 Conclusions

In the end, the test procedure should be comprehensive enough to handle any type of conceived PHEV design. The authors recommend that if it is found possible to employ a much-shortened procedure sequence that will satisfy stakeholder needs, then this should be an integral part of the overall procedures. There are essentially two distinct components of a procedure. The first is the testing procedures themselves that define how the data are taken. The second involves how these data are processed to come up with final results. It is imperative that test procedures are found that will accommodate any stakeholder's need to find particular desired test outcomes. That is, if in the future a stakeholder has interpreted PHEV performance in a new way, the test results should include enough information to carry out this calculation. This may prove difficult because initial test conditions of SOC and soak times directly affect the test outcome. If these conditions are assumed to be different, then the results would not be complete enough for the post-processing.

In general, there are many stakeholders requiring results from emissions and fuel consumption (economy) testing for road vehicles. The results from the testing must be suitable for calculating emissions for certification, to be used by the EPA for fuel economy labeling, which would be used to track corporate average fuel economy (CAFE) levels and to determine parameters that are needed for any government mandate or merit system. In Figure 14, a possible scenario for testing PHEVs is laid out. Either a minimum test method or a long, comprehensive procedure is conducted that includes depleting and sustaining emissions and fuel consumption and charging procedures. The prescribed instrumentation will provide outputs available to all stakeholders.

One remaining question is whether a procedure-developing committee can provide an all-inclusive set of equations that properly satisfy all stakeholder needs. Emissions certification of unusual vehicle technology usually follows a "worst-case" test scenario; thus, no discounting will be given for EV operation. However, the test procedure goal may be to provide representative predictions of emissions. Also, in analyzing the new EPA labeling equations, it has become apparent that these complex equations are valid only for conventional vehicles. The assumptions of start and running fuel consumption are not compatible with the notion that a hybrid stores and releases energy throughout a charge-balanced cycle. Furthermore, in the case of PHEVs – especially AER capable PHEVs – the equations are a complete mismatch. If somehow the label fuel economy equations were rewritten as to not make assumptions for start fuel consumption and to not divide cycles into parts, it may be possible calculate a label fuel consumption based upon a complete set of PHEV results from the five test cycles.

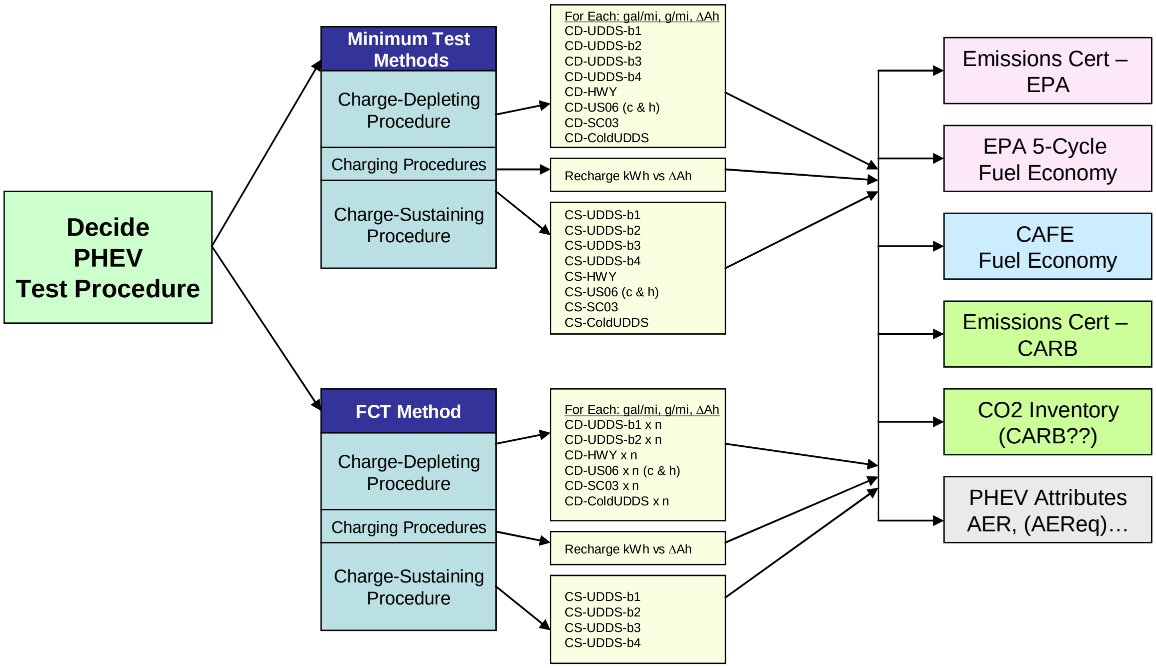

Figure 14: Generic Flow of PHEV Test Procedure and Post-Processing Outcomes

10 Acknowledgments

The authors of this paper would like to gratefully acknowledge the sponsorship of Ed Wall, Program Manager, and Tien Duong, Team Leader, Vehicle Technologies, Office of FreedomCAR and Vehicle Technologies, U.S. Department of Energy. Also, thanks to the many participants in the SAE J1711 subcommittee for their participation and guidance in this effort.

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