Issues in Emissions Testing of Hybrid Electric Vehicles

M. Duoba, J. Anderson, H. Ng
Argonne National Laboratory

ABSTRACT

Argonne National Laboratory (ANL) has tested more than 100 prototype HEVs built by colleges and universities since 1994 and has learned that using standardized dynamometer testing procedures can be problematic. This paper addresses the issues related to HEV dynamometer testing procedures and proposes a new testing approach. The proposed ANL testing procedure is based on careful hybrid operation mode characterization that can be applied to certification and R&D. HEVs also present new emissions measurement challenges because of their potential for ultra-low emission levels and frequent engine shutdown during the test cycles.

INTRODUCTION

Applying standardized dynamometer test methods to hybrid electric vehicles (HEVs) is problematic. A recommended practice for HEV testing in the United States was developed by an SAE committee and subsequently approved in 1998. Currently, however, the HEV test procedures (standard SAE J1711) have not yet been fully demonstrated. The U.S. Environmental Protection Agency (EPA) has used the procedure "for the purposes of familiarization only and not to simulate a certification process."[1] The procedures are not widely accepted because they require considerable knowledge of the vehicle's response to the test cycles; for some HEV designs, these can be very lengthy. The California Air Resources Board (CARB) certifies vehicles according to California's emissions laws. In the early 1990s, CARB was developing its own HEV test procedure for certification; CARB has since taken the position that it will follow the SAE procedures and/or the EPA's selection of test procedures.

The HEV's reversible energy storage system was certainly not considered during the original development of standardized dynamometer test procedures. Use of the second energy system opens up essentially a second dimension in operational behavior compared with the one-dimensional world of conventional vehicles. This new dimension cannot be characterized without taking additional steps to accommodate the large design space of HEVs. HEV designs can range from battery-dominant designs to engine-dominant designs. There are obvious problems with accounting for continued use of off-board electrical energy and issues relating to the transient energy use in hybrid operation. These problems complicate the development of an accurate and representative test procedure for HEVs.[2,3]

A key problem with developing test procedures is that very few HEV designs are available for validating new test procedure concepts. Since 1994, Argonne National Laboratory (ANL) has been testing prototype HEVs at various university vehicle research competitions across the country.[4,5,6] To date, over 100 tests of college and university HEVs have been administered under the direction of ANL staff. Because of this unique experience, the Laboratory has been able to gather information about the basics of HEV testing and issues important to the successful characterization of HEVs. At ANL's Advanced Powertrain Test Facility (APTF), tests are being conducted with newly available OEM HEVs: the Japanese model Toyota Prius and the U.S. model Honda Insight. ANL continues to develop test procedures during testing of OEM and prototype HEVs.

ANL uses some of the fundamental concepts developed in current and past J1711 drafts, with a few procedures developed and validated at the annual competitions. Successful vehicle characterization can be achieved by carefully considering each vehicle's operational strategy and by manipulating the battery

DISCLAIMER

DISCLAIMER

SOC between test cycles to achieve valid battery-use trends. A sound philosophy is to characterize each individual operational mode in such a way that the elements of both the Federal Test Procedure (FTP) and Federal Highway Test can be satisfied. The main objective of test procedure design is to maintain the ability to compare mileage and emissions rates results of HEVs with those of existing conventional vehicles by satisfying the test procedure inputs.

ANL has recently commissioned the APTF, which is dedicated to testing and model validation of advanced vehicle technology. ANL uses the state-of-the-art test equipment to measure economy and emissions from engines and vehicles. The main focus is HEV powertrains and vehicles for assessment and model validation in DOE's Systems Analysis team. Recently, ANL tested the first mass-marketed HEV, the Toyota Prius. The objective of this test program is to provide systems and component data for model calibration and validation. During testing, ANL identified key issues in the area of emissions measurement systems. For example, frequent engine-on/-off operation during a test cycle can cause measurement problems. As new techniques for ultra-low emissions are being developed, the measurement community must be aware of the effects of this emerging vehicle technology.

HEV DYNAMOMETER TEST PROCEDURE ISSUES

BACKGROUND: REQUIREMENTS OF U.S. FEDERAL TEST PROCEDURE

The FTP is a standard used as the basis for EPA published fuel economy, federal emissions certification, and individual states emissions certification. The entire test procedure includes upon two dynamometer driving cycles: the Urban Dynamometer Driving Schedule (UDDS) and the Highway Fuel Economy Driving Schedule (HFEDS). The two other cycles referenced in the revised FTP (US06 and SC03) will not be addressed in this paper, but the HEV characterization process applies to all cycles.

The test for highway fuel economy includes two back-to-back HFEDS cycles. The first cycle is a warm-up for the second cycle, during which emissions data are taken and a carbon balance-based fuel economy calculation is made. The emissions certification is based upon the UDDS cycle tested twice — a first start-of-the-day UDDS test is undertaken, followed by a short 10-min rest period; a second UDDS cycle is then given. The first test is called the "cold-start" test; the second test is the "hot-start" test. The initial condition of the cold-start test is that the vehicle must rest at ambient temperature (a "cold soak") overnight (12–36 h).

The current FTP includes a small short cut that ends the hot-start test after 505 s. After this period, the vehicle is assumed to be thermally stabilized, behave in the same manner, and yield similar results as after the first 505 s of the cold-start UDDS. Because HEVs may not operate in a repeatable manner during both stabilized phases of the UDDS, SAE J1711 recommends that the hot-start UDDS cycle be driven until completion. This issue will be discussed in a later section.

HEV OPERATION CHALLENGES TEST PROCEDUES

Since the tests were introduced, vehicle advancements in emissions reduction and other new vehicle technologies have been accommodated by the FTP without significant changes to the procedures. However, as unattractive as it sounds, HEVs will require special treatment with changes to the test procedure to accommodate all but the mildest (small battery pack) HEV designs.

The ability of some HEVs to operate in electric only (ZEV mode) and the transient nature of operation when both the engine and electric motor work together (HEV mode) require that the conventional FTP test method be revisited.

TRANSIENT HYBRID OPERATION - Most every HEV design strategy will have inherent test variability brought about by transient energy utilization of the engine and battery pack. HEV control strategies constantly direct motor and engine output in response to road demands and battery SOC levels. This complex system is somewhat chaotic and is always changing throughout the test, causing varied results.

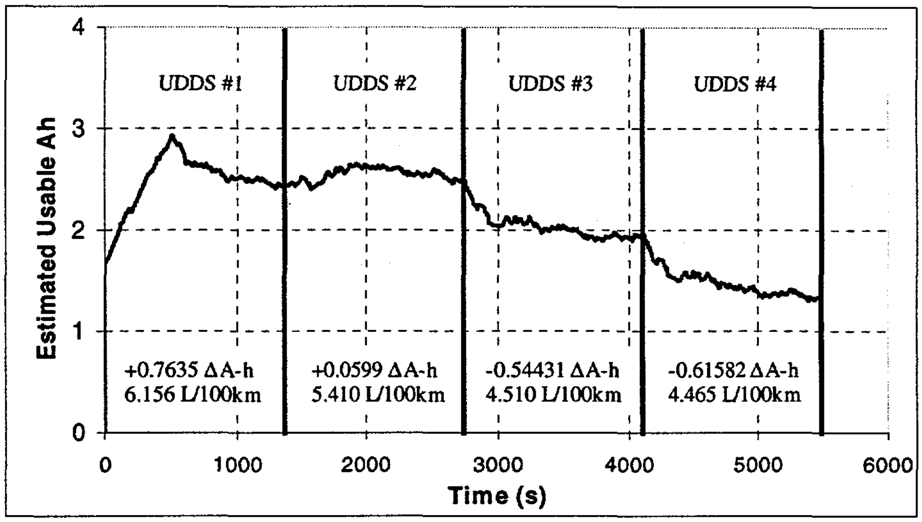

Figure 1: Test-To-Test Variation in HEV Operation (Prius)

Figure 1 shows the SOC trend and the resulting fuel usage difference for the Toyota Prius through the course of 4 consecutive UDDS cycles. The SOC in this example is constantly changing, but over time, it remains within a specific operating window. Because slight differences in electrical energy usage are found, the fuel usage result will also change. To precisely characterize the vehicle, a large number of tests can be averaged to cancel out the transient battery usage, but this requires a large number of tests.

ENGINE-ON/-OFF OPERATION - The capability of a vehicle to operate part-time in electric-only mode will create, at least in part, undefined emissions and fuel economy data in a test. Even though we can partially address this problem by separating the two vehicle operational modes (electric-only and fuel-derived operation), the capability of the engine to turn on and off any time during a test can cause anomalous test results. If the vehicle is allowed to be driven throughout the cold-start test without an engine start, the original purpose of the cold-start test is now compromised. These issues require a rethinking of the application of the FTP hot- and cold-start weighing.

HEV OPERATION THAT REQUIRES SPECIAL PROCEDURES

HEVs not only require special procedures (compared with conventional vehicles), but these procedures must be different for varying types of HEVs. Although a "one size fits all" HEV test procedure would be desirable, the diversity of HEV designs[7] and operation prevent this. Since the earliest drafts of the SAE HEV test procedure[8] and the first procedures developed by ANL used for university prototype vehicles,[9] HEV test procedures were developed with separate treatments for specific classes of HEV designs.

Design choices like the series or parallel configurations do not, by themselves, require special procedures; it is the details of the energy management strategy and other special HEV capabilities that require test classification. The two main issues that determine differences in HEV testing and reporting of results are the details of on-board charging and capability of electric-only driving.

ON-BOARD CHARGING – The fundamental characteristic separating hybrids from conventional vehicles is the fact that HEVs have on-board energy management, and this is the main reason we need to use specialized procedures. However, whether or not the charging system can keep up with the amount of energy used over time to keep the batteries charged affects how we present the final results of such an HEV test. If we always use electrical energy from the pack, we cannot report the results as if the HEV were a conventional vehicle; the net electrical energy used to drive the car must be considered.

The HEVs "charge-sustainability" depends upon the component sizing, the energy management strategy of the particular driving mode, and the driving cycle used. For our needs in vehicle testing, we will consider the test drive cycle used to make the distinction between charge sustaining (CS) and charge depleting (CD) HEV operation. For example, while driving a low-load cycle, a particular HEV may always keep the batteries charged; however, the same vehicle may always deplete during the HWFEDS cycle, and so the results of the HWFEDS cycle would require special treatment.

Without specific prior knowledge of its operation, an HEV must be tested to determine if over a given test cycle, it possesses a charge-sustaining operational mode. In addition, the tester needs to know if the vehicle is operating in a transitional or temporary mode. Certain HEV designs may indicate charge-depleting behavior, but they will reveal one or more transitional modes before reaching the final mode, which is ultimately CS or CD. For example, after a full charge, an HEV may deplete a significant amount of charge in an electric-only mode before the engine is engaged, after which the vehicle now behaves in a charge-sustaining manner. However, if in fact the HEVs is ultimately CD, there are a few responses to continued driving to the lower SOC limit of normal operation. Likely design practices include a "reduced power mode" when the average or peak power at the wheels is limited by the average or peak power of the engine. In the Prius HEV, a "turtle light" signals the driver that the vehicle is operating in a reduced power mode.

ELECTRIC-ONLY CAPABILITY – The second HEV design distinction that affects the application of HEV test procedures is electric-only capability. Again, like charge-sustainability, this criterion is based on its performance over a particular test cycle. If, during the test cycle, the vehicle can be driven a whole test cycle without running the engine, then we will need to find a new way to test the vehicle and to express the results. If the vehicle used energy that was charged on-board, then it is possible to formulate a procedure to express fuel-only derived energy efficiency and emissions results.

However, an HEV may not run an entire cycle on only electricity, but complications arise when the engine starts very late in a cycle. The cold-/hot-start FTP emissions results of standardized procedures can be corrupted. The more electric-only operation utilized by an HEV, the more attention is required to the application of test procedures. However, if we treat this combined operation as a single CS mode of operation, then like any other operational mode, repeated tests should make it possible to characterize the mode.

CHARACTERIZING OPERATIONAL MODES

To fully characterize an HEV, each operational mode must be characterized. Today's conventional vehicles really only possess one operational mode; this mode is what is characterized by the standardized procedures (with the exception of some vehicles that have "sport or economy" mode selection for control of shifting schedules). The FTP cold-/hot-start weighing is designed as a scheme to characterize a single mode of operation under two different initial conditions to arrive at an aggregate emissions rate over the course of a few daily trips. HEVs, on the other hand, not only may possess an array of operational modes, but they may alternate among them as directed by a sophisticated passive control strategy.

The ANL HEV testing approach that can be applied to certification and for research purposes is based upon careful hybrid mode characterization. Accommodating HEVs in the FTP is accomplished by satisfying the procedural calculation inputs so that test anomalies due to HEV behavior can be avoided. Highly dynamic HEV modes must be addressed by using multiple tests with varying initial conditions so that the multiple tests can be made into one characteristic mode result.

If the vehicle's control system is toggling between different sets of operational rules, or is continually correcting its rule base (say for proper energy management) over the course of *single test cycle*, then these short operational modes cannot be characterized individually and can only be tested as part of a single mode. As with any single mode, multiple tests may be required to achieve a satisfactory characterization. Using multiple tests is one of the fundamental proposed additions to the standardized procedures. Combining multiple test results into a single result is achieved by using the concept of "SOC corrections.[2]"

MODE CHARECTERIZATION WITH SOC CORRECTIONS - SOC corrections are a way to combine repeated test results to arrive at the "zero ΔSOC condition." If we were to test a CS HEV over many cycles, the contribution of the electrical energy stored and released becomes insignificant, and the characterized mode is based solely on the average engine fuel economy and emissions. SOC corrections allow us to find the "zero ΔSOC condition" with a manageable number of test cycles.

To characterize a single CS mode, the SOC must be tracked in order to calculate the ΔSOC = zero result. Measured ΔAh is used as a surrogate for ΔSOC in SOC corrections (this is discussed in more detail later in the paper). Figure 2 shows various hot-stabilized UDDS cycles of the Toyota Prius on a plot with respect to ΔSOC. The y-intercept value is the SOC-corrected result for this operational mode. The cold-start urban cycle can be SOC corrected in the same manner. The minimum number of test results needed for a regression line is two, although more precision is gained by more results.

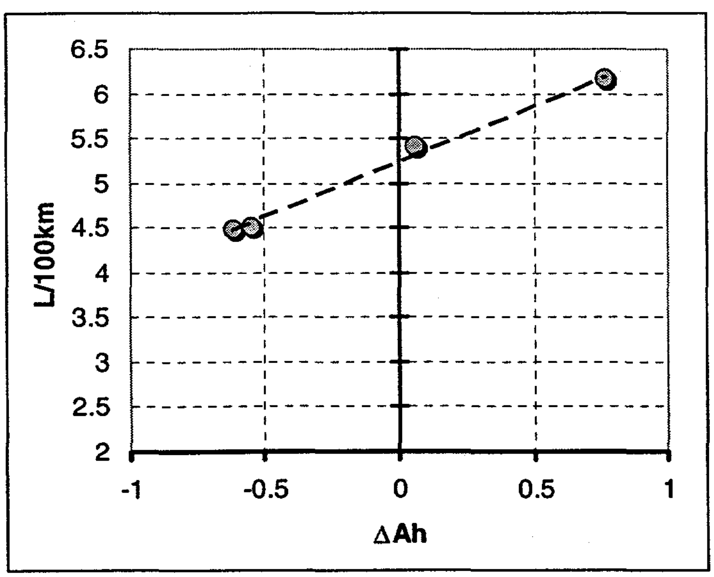

Figure 2: ANL-Test Prius Hot-Start UDDS Tests on SOC Correction Graph

Developed by ANL, the "Added ZEV Miles"[10] is another method used in applying SOC corrections for HEV competitions. The discharge rate (Ah per unit distance) of an complete electric-only cycle test is applied to a charge-gaining HEV mode test result to calculate the ΔSOC = 0 result. The HEV mode test must charge sustain; the calculations effectively add zero fuel use and emissions distance to correct the on-board charging amount back to zero (see Figure 3).

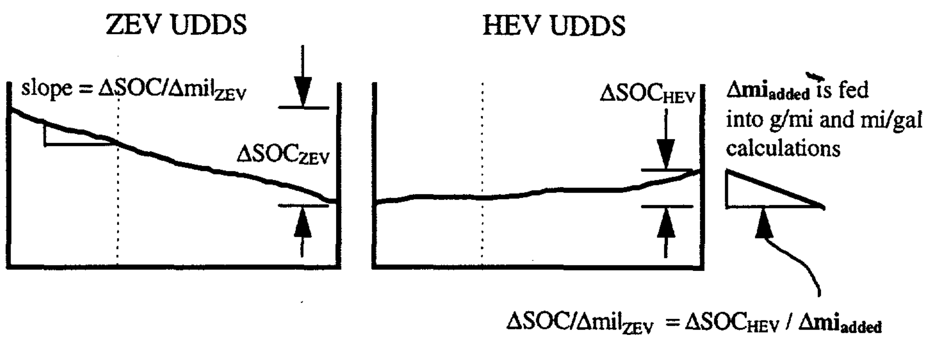

Figure 3: Added ZEV Miles Method for SOC Corrections

SOC CONDITIONING – For the SOC correction regression line to pass through the y-intercept, one test result must gain charge and the other deplete. This may not always happen with any given set of tests. Sometimes, the battery needs to be conditioned to a desired initial SOC. Conditioning is easiest to do on a motoring electric dynamometer. To deplete before a test, the vehicle can either be run in a manually selected electric-only mode or be run with a few hard accelerations, during which significant power assist is expected. For maximum effect, regenerative braking should be disabled to avoid recharging the energy that is taken during acceleration.

To accumulate charge, the dynamometer should be run in speed control mode at a low speed, and regenerative braking should be used to boost the SOC. During charge-sustaining operation, if one test is at the allowable upper SOC limit and the other is at the lower limit, both results must appear on opposite sides of the SOC correction regression line.

The biggest difficulty in performing SOC conditioning is simultaneously satisfying the other initial test conditions — namely, the prescribed soak conditions before tests. SOC conditioning can be performed the night before, then placed in cold soak. However, the 10-min rest period between the cold-start and hot-start urban tests prescribe no vehicle operation at all. Therefore, SOC conditioning could be performed, but it would compromise the soak conditions by keeping the tires and bearings warm and the fans and coolant systems running during the soak period. Yet, if the engine is not operated, small-battery HEVs only take a couple of minutes to adjust the SOC. For the purposes of research, this may not significantly alter the end results. To solve the hot-start initial SOC problem, the vehicle can be run over several hot-start UDDS (separated by the 10-min soak period) until both +ΔSOC and –ΔSOC results are obtained.

The Federal Highway procedure prescribes a complete warm-up Federal Highway cycle immediately preceding the test highway cycle. The initial SOC of the warm-up cycle can be set; however, the tester has no control over the initial SOC of the cycle of the second cycle if the cycles are immediately back to back. Again, multiple tests may need to be given until +ΔSOC and –ΔSOC data are gathered.

AVOIDING SOC CORRECTIONS – If, however, the initial SOC condition can be set so that the ending SOC is equal to the initial SOC over a particular cycle, a single test would suffice for the "zero ΔSOC result." This is the approach described in SAE J1711.[11] Eliminating the requirement of multiple tests is certainly an attractive feature for vehicle testers. The procedure specifies a minimum tolerance of ΔAh for a valid test. Unfortunately, the existing requirement to keep within a 3% test-to-test variability compounds the difficulty to generate valid certification results. This approach can be demonstrated conceptually and in computer simulations, but it has yet to be demonstrated satisfactorily in practice with battery packs at least as large as those used in the Toyota Prius.

A vehicle's control strategy may direct somewhat reproducible operation in response to the initial test SOC. However, battery SOC cannot be directly measured; the inferred SOC may be corrected slightly during a test (or, at times, abruptly change, as in the Prius), causing an unintended SOC deviation. If the battery computer has lost its certainty in its current SOC value, the battery management system may decide to reset itself or actively reach both SOC "bump points" during the test; in this condition, the SOC and Ah will not track well. The basic problem is that vehicle control strategy bases its decisions on the value from the SOC algorithm, and the procedure defines corrections based upon the ΔAh measured. More in-use experience is needed to prove that using a single test can be a robust approach without producing an abundance of "invalid" test results.

For example, in Figure 4, the battery computer's claimed SOC is plotted along with the estimated absolute Ah based upon ΔAh measurements. When the vehicle is restarted, the battery computer has decided to change its SOC estimation at the beginning of the last two UDDS tests. Thus, the control strategy will allow net discharging during these cycles.

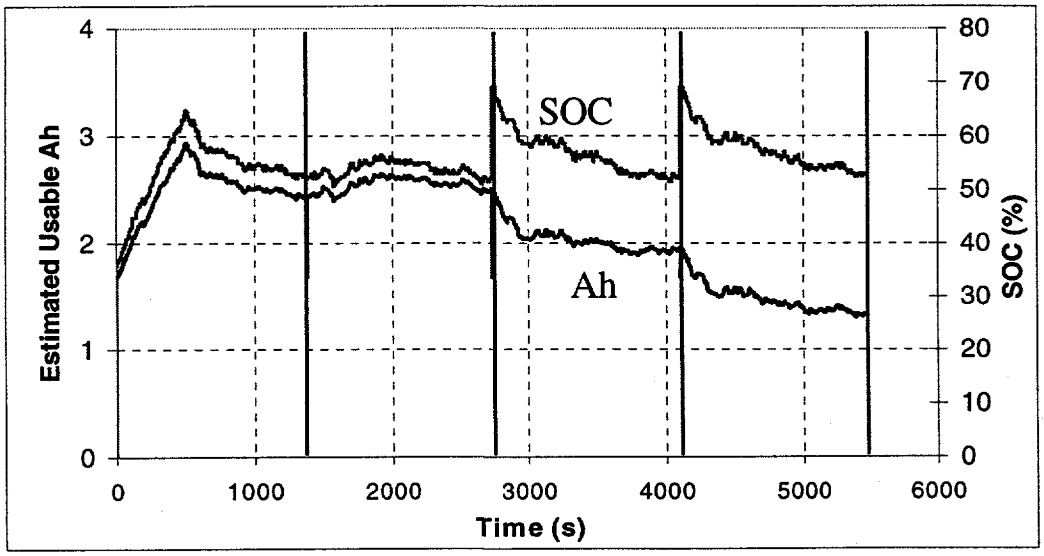

Figure 4: In-Practice Comparison of SOC and Ah

An ANL suggestion to use a single test, ΔSOC=0 method is requiring the manufacturer to demonstrate a statistical SOC correction slope (or curve) for testers to use for slight corrections of a single test. A different SOC correction function is needed for each type of test; cold-start data cannot be used to correct hot-start tests. If this approach is used, a wider SOC tolerance can be implemented in the test procedure to avoid numerous invalid tests.[12] Errors using statistical SOC correction data should be much smaller than the expected test-to-test variability of typical dynamometer results. More testing is needed to demonstrate this approach.

SATISFYING EXISTING PROCEDURES USING MODE CHARACTERIZATION

For HEVs like the Prius with a single normal CS operational mode, the vehicle testing basically involves characterizing this CS mode for all the elements required for the FTP and Highway test. The cold-start UDDS and the hot-start UDDS are characterized separately first, and then the hot/cold weighting can be applied. Test characterization and SOC corrections must be made before any post-processing calculations are performed; otherwise, results will get distorted.

The recommendation in J1711 that an HEV FTP test should be a 4-bag test with the entire hot-start UDDS carried out past the "505" cycle to completion has merit. However, an argument can be made that one could fully characterize just the "505" cycle with SOC corrections (or use SOC correction substitute methods) and follow the current 3-bag FTP method. Currently, ANL is looking into how much possible discrepancy there is between using a 3-bag and a 4-bag test.

If both the hot-start and cold-start UDDS tests are used, then there is essentially no need to sample a total of 4 bags. Entire UDDS tests can be sampled into one bag. The hot and cold weighting would be changed from Equation 1 to Equation 2. However, the sample rates and total bag volume must be checked to avoid over inflating and bursting sample bags. One possible side benefit to using a single bag is helping mitigate the problems of measuring the very small emissions rates in the hot-stabilized phase; the higher expected engine start emissions in bag 1 and 3 will elevate overall bag emissions concentrations.

Eq. 1: $Y_{wm} = 0.43 * [(Y_{ct} + Y_s) / (D_{ct} + D_s)] + 0.57 * [(Y_{ht} + Y_s) / (D_{ht} + D_s)]$ ref [13]

Eq. 2: $Y_{wm} = 0.43 * [(Y_{UDDS1}) / (D_{UDDS1})] + 0.57 * [(Y_{UDDS2}) / (D_{UDDS2})]$ ref [6]

Y	- grams emissions
D	- driving distance in cycle
ct	- cold-start test, bag 1 & bag 2
ht	- hot-start test, bag 3
s	- stabilized bag, bag 2
UDDS1	- cold-start UDDS
UDDS2	- hot-start UDDS

ACCOMMODATING CD TRANSITIONAL MODES - For HEVs with CD transitional modes, the vehicle characterization needs to make assumptions that are well beyond the scope of the original FTP procedures. For example, a battery-dominant HEV can, and may, operate over the life of the vehicle in three modes: (1) electric-only operation, (2) battery charge-depleting hybrid operation, and (3) battery charge-sustaining operation. When and how often the modes are used during the life of the vehicle should determine the overall characterization of the vehicle.

SAE J1711 takes the approach of annualizing the transient mode behavior relying on in-use driver statistics to weigh different operational modes. If we know how often the vehicle is using the transitional modes (based upon distance driven and recharging frequency), then these modes can be weighted appropriately. National Personal Transportation Survey (1990 NPTS) data[14] include a distribution of daily vehicle miles traveled. These data can tell us statistically how much driving the public does in a single day. It is assumed that the vehicle is recharged at the end of the day (overnight). The J1711 further assumes that not all vehicles will charge every night, but a frequency distribution will describe how often charging will occur. In the absence of in-use data, the distribution chosen is an average rate of 50% overnight recharge. To accommodate this approach, the testing must not only characterize each transitional mode, but also must find the duration of these modes.

Consider a CS HEV with significant electric-only range. The vehicle's transitional electric-only operation is shown in Figure 5, with the SOC dropping to target point when the CS HEV mode is engaged. Superimposed are the NPTS statistics about the daily vehicle miles traveled. In this case, a statistical amount of in-use miles will be driven in electric-only mode by using off-board energy.

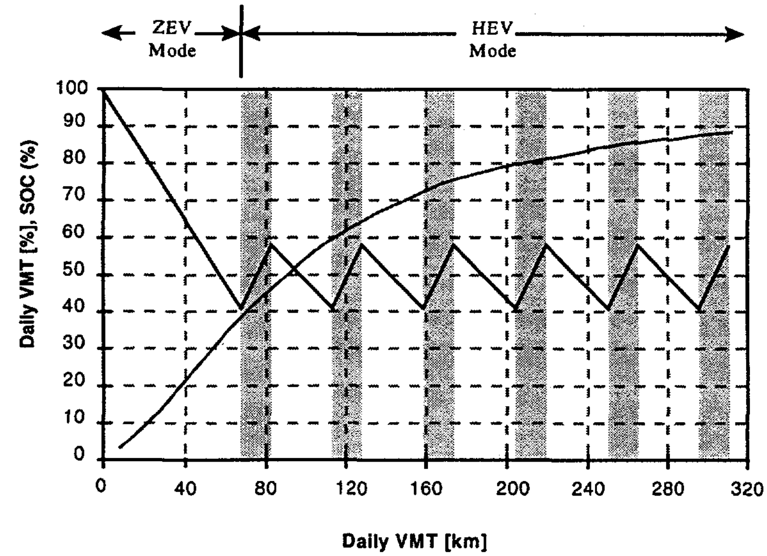

Figure 5: National Personal Transportation Survey Data (1990 NPTS) and an Electric-Only Capable HEV

How off-board energy is treated for energy use and emissions should be a subject for regulators and can be controversial. Movements behind mandates and regulations can change, but the procedure should be developed to remain constant. The off-board electricity should be left separate from fuel and emissions test data — afterwards, regulation incentives and government mandates can be applied. The test procedure itself should not be written with built-in incentives for electric-only operation (such as combining electric-only with hybrid operation). The electric vehicle (EV) procedure SAE J1634 uses electrical energy on a 1:1 energy basis with consumable fuel energy. Results of the procedure give EVs a fuel economy well over 100 MPG. The precedence of the EV procedure should not lead HEV test developers to treat off-board electricity as if it were consumable fuel. Procedures should report the data separately.[15]

MEASUREMENT CHALLENGES OF HEVS

In addition to procedure development challenges, HEVs also pose potentially problematic issues with test measurements. With battery SOC becoming a new critical measurement affecting the final results, how these measurements are taken will become very significant. New low-emissions vehicles are pushing the limits of current measurement systems by using a constant volume sampler. HEVs present new emissions measurement challenges with their potential for ultra-low emissions and frequent engine shutdown events during the test cycle.

MEASURING SOC

Battery SOC is never directly measured; it can only be inferred with other measurements. SOC is a measure of what is left in the battery and can only be found by discharging the pack and measuring this available quantity of charge. However, for the purposes of dynamometer testing calculations, it is the change in SOC during a test. As mentioned earlier, integrated ampere-hours measurement during a given cycle is used for SOC corrections. Future vehicle testing may include provisions for the test lab to attach an inductive current sensor in an accessible location of the traction battery conductors. The conductor cables in OEM vehicles are typically internally shielded, but for essentially DC current measurements taken during the test, the shielding will not interfere with the inductive measurements.

The other option is to require the vehicle to have a precision shunt resistor in the battery conductors. The resistance of the shunt can be measured for accuracy, and the voltage measured across the resistor can give accurate current signals. However, isolation and accuracy under high amplification are necessary for good results.

The on-board algorithms for SOC should not be used for SOC correction calculations, but they are useful when the tester needs to determine the high or low SOC test conditions. Battery conditioning should be based upon on-board SOC indication; the control strategy response is based upon this reading. Current procedures do not rely upon measurements or signals that originate from the vehicle, so it is likely that future certification measurements will follow this precedence by making the ΔSOC measurements the responsibility of the test lab.

MEASURING EMISSIONS

Automakers, major test labs, and measurement system suppliers are very interested in the methodology to measure ultra-clean emissions, as evident by the number of recent papers published describing improvements and replacements to the current methods.[16,17,18,19,20] The existing constant volume sampling (CVS) method measures pollutant concentrations of room air (background) mixed with the all the exhaust at a fixed total flow. The background pollutants are then subtracted from the measured emissions to obtain the exhaust emissions. However, there are obvious problems when the vehicle emits exhaust pollutants on the order of the background amounts – this is the main limitation of diluting exhaust with large volumes of background air.

An alternative is the "mini-dilution" method, which involves diluting only a small fraction of the entire exhaust with an ultra-pure inert gas (because it is impractical to dilute the entire exhaust). Whereas the problems associated with background pollutants are eliminated, new uncertainties arise in converting the concentration measurements into total mass measurements. Current mini-dilution systems use either CO_2 concentrations from a CVS or a direct exhaust flow measurement to calculate the total mass emissions. Both the CVS and mini-dilution systems have unique limitations that do not entirely solve the challenge of accurate ultra-low exhaust measurements.

The limitations in the current CVS method become magnified by an HEV that has the ability to shut the engine down for significant portions of the cycle. The CVS system will continue to draw background air and further dilute the exhaust sample being taken in the bag. If an HEV has a large enough battery pack, or has partial electric-only capability, a particular bag of the test may have no emissions.

The use of mini-diluter systems addresses one problem but creates another, especially for the case of repeated engine-on/-off behavior in HEVs. The strength of the CVS system is the fact there are far fewer uncertainties in the collection of the exhaust because all of the exhaust is being diluted, and the constant sampling from the entire diluted exhaust will not miss transient behavior. The mini-diluter system emulates CVS operation by continuously keeping the exhaust sample proportional to the exhaust flow rate during a test. This makes transient response of this system critical to overall accuracy of the collected totals. The mini-diluter system validation process is progressing to address such problems, but as we might expect, the process includes only conventional vehicles that do not shut down the engine repeatedly during a cycle.

The Prius vehicle tested by ANL demonstrated that during a single FTP cycle, the engine can shut down 36 times. Each time the engine shuts down, the system must provide a rapid and accurate response to prevent small errors from adding into significant errors throughout the cycle. During decelerations and at a stop, the Prius engine will completely stop; at other times, the engine will keep spinning but will not be producing any power. Both of these conditions were found to be problematic using mini-dilution modal sampling during the Prius engine shutdown events.

Figure 5 shows a portion of the urban drive cycle when the engine shuts down three times. During engine shutdown, the calculated g/s emissions never reach zero. The g/s calculation is a function of the measured concentration and calculated exhaust flow rate. This off-site testing facility used the CO_2 tracer method for calculating exhaust flow; this graph shows that while the engine is spinning under no load, there are HC emissions measured. From these data, we see concentrations of HC present in the exhaust, after the engine stops rotating, but we cannot be certain if this is measurement lag or actual emissions HC emissions sampled from the exhaust pipe. However, the calculated g/s emissions should be zero if the exhaust measurement is zero. In the dynamometer system used, the exhaust calculation was either not capable or not allowed to reach zero — a "floor" of 56.6 cubic feet per minute was used in for mass emissions during engine shut-down.

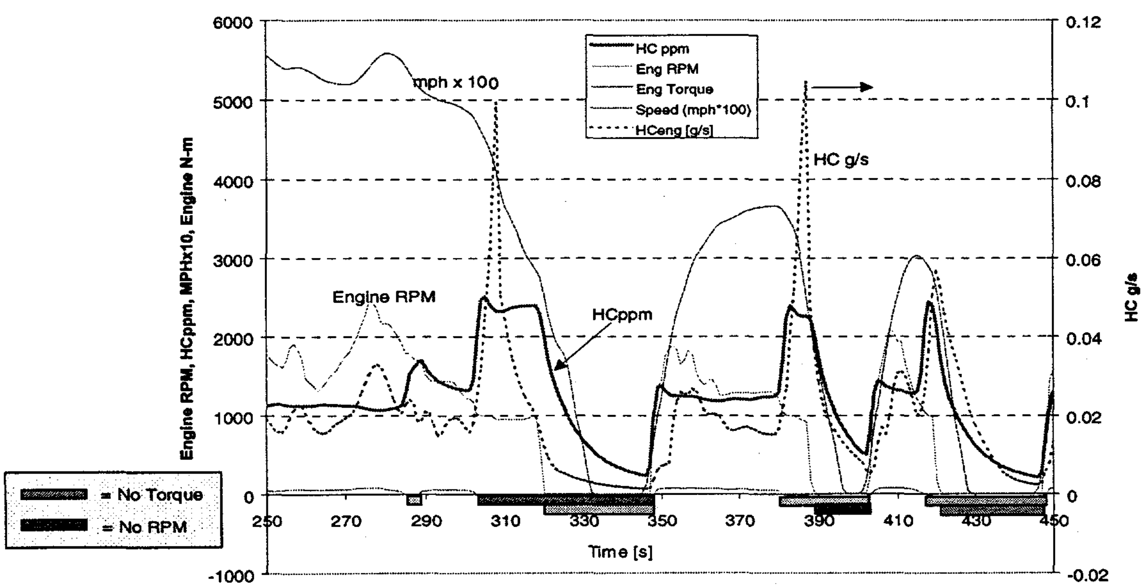

Figure 5: Transient Emissions Data Using Mini-Dilution Modal System

Figure 6 shows the same portion of the test cycle but with ANL test equipment (including fast-response emissions analyzers and a raw emissions bench). Using this test equipment revealed the same problems as those encountered in the bench tests, namely that zero emissions are not measured easily during engine shutdown. Where the engine is spinning but there is no torque, HC emissions are measured by both systems; this appears to be a true phenomenon. On the other hand, the fast-response equipment shows a much faster response and does, in fact, find no HC emissions in the exhaust pipe after an engine shutdown event. Meanwhile, the bench cannot respond fast enough to measure zero emissions during this period. Emissions systems of the future must be able to react to periodic zero emissions states; these conditions will be commonplace in HEV designs.

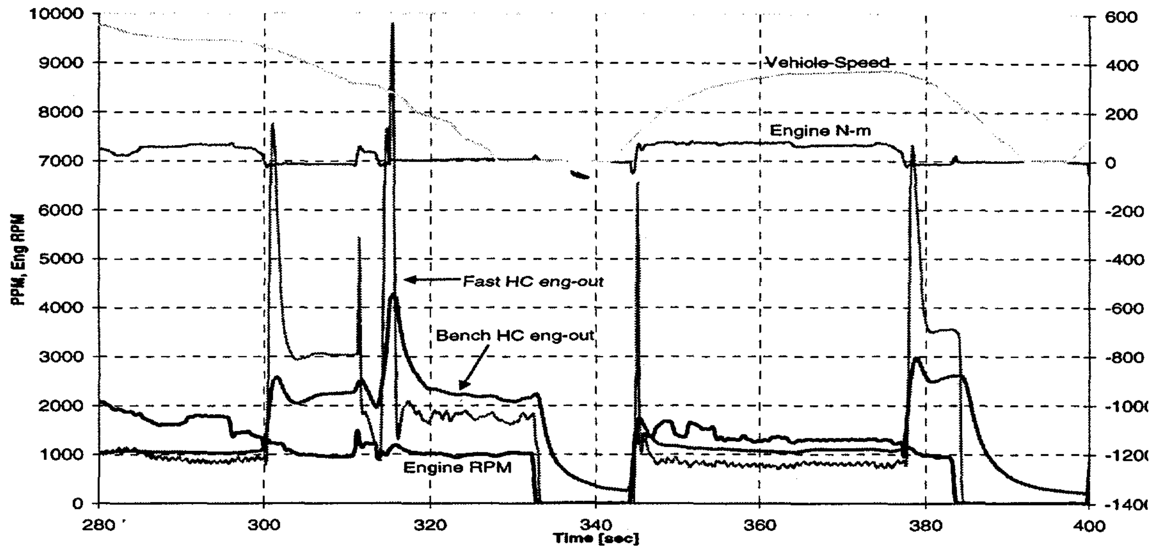

Figure 6: Fast Response Emissions Measurements of Engine Shutdown Events

CONCLUSIONS

HEV technology is moving from the research stage to production schedules as evident by two new OEM HEVs for sale in model year 2000. In addition, nearly every major manufacturer has announced their plan to introduce HEVs within the next five years. Standard test procedures for certification testing and development for conventional vehicles have proven to be problematic for HEVs. The vehicle tester must be acclimated to the new challenges that have emerged with the prospect of a large number of HEVs introduced into the fleet.

The battery system must be monitored to compensate for test-to-test variability caused by transient energy utilization. This requirement may force test laboratories to install additional instrumentation. The test time and the number of days it will take to test HEVs will likely be longer than those for conventional vehicles. Manufacturers may need to provide additional information for the tester, including the type of HEV, the kinds of test that are needed, and the expected operation under initial SOC conditions. The proposed ANL HEV testing methods is based on careful hybrid mode characterization that can be applied to certification and R&D.

The emissions measurement community is working hard to develop systems that can repeatably measure newly produced SULEV vehicles. This community must include on/off engine operation in the development and validation process. If this kind of vehicle operation is ignored in the near term, development may be interrupted in the future when HEVs represent a significant volume of vehicle sales.

ACKNOWLEDEMENTS

The work for this paper was supported by the U.S. Department of Energy, Assistant Secretary for Energy Efficiency and Renewable Energy through the Office of Advanced Automotive Technologies, under contract W-31-109-ENG-380.

REFERENCES

[1] Hellman, Karl, "Evaluation of a Toyota Hybrid System (THS)," Technical Report EPA420-R-98-006.

[2] California Air Resources Board, "Proposed Amendments to the Low-Emission Vehicle Regulations to Add an Equivalent Zero-Emissions Vehicle (EZEV) Standard and Allow Credit for Hybrid-Electric Vehicles," Appendix D: Discussions of Hybrid Electric Vehicle Testing Issues, July 1995.

[3] Burke, A., "Development Of Test Procedures For Hybrid/Electric Vehicles," DOE/ID - 10385-Rev., July 1992.

[4] Duoba, M.; Quong, S.; LeBlanc, N.; Larsen, R., "Testing Hybrid Electric Vehicle Emission and Fuel Economy at the 1994 DOE/SAE Hybrid Electric Vehicle Challenge," SAE 950177, 1995.

[5] Duoba, M.; Larsen, R., "HEV Dynamometer Testing with State-of-Charge Corrections in the 1995 HEV Challenge," SAE 960740, 1996.

[6] Duoba, M.; Larsen, R.; Buitrago, C., "Investigation of practical HEV test procedures with prototypes from the 1997 FutureCar Challenge," SAE 981080, 1998.

[7] Duoba, M.; Larsen, R.; LeBlanc, N., "Design Diversity of HEVs with Example Vehicles from HEV Competitions," SAE 960736, 1996.

[8] SAE, "Recommended Practice for Measuring the Exhaust Emissions, Fuel Economy, Electrical Energy Consumption, and All-Electric Range of Hybrid Electric Vehicles – SAE J1711," Dated 5-23-94.

[9] Duoba, M.; Quong, S.; LeBlanc, N.; Larsen, R., "Testing Hybrid Electric Vehicle Emission and Fuel Economy at the 1994 DOE/SAE Hybrid Electric Vehicle Challenge," SAE 950177, 1995.

[10] Ibid.

[11] SAE, "Recommended Practice for Measuring the Exhaust Emissions and Fuel Economy Hybrid-Electric Vehicles – SAE J1711," September 18, 1998.

[12] Duoba, M.; Svestka C., "FutureTruck 200 Rules and Regulations, E-8 Dynamometer Testing Events, E-8.2.3 SOC Correction Methods," http://www.futuretruck.org/pdfs/rules3.pdf, April 25, 2000.

[13] Code of Federal Regulations, 40 Part 86, Environmental Protection Agency

[14] U.S. Department of Transportation and Federal Highway Administration, 1990 National Personal Transportation Survey, http://www-cta.ornl.gov/npts, 1990.

[15] CEN /TC 301, "Electrically propelled road vehicles, Part 2: Thermal Electric Hybrid Vehicles."

[16] Silvis, W. and R. Chase, "Proportional Ambient Sampling: A CVS Improvement for ULEV and Lean Engine Operation," SAE 1999-01-0154, SAE Congress March 1-4, 1999.

[17] Silvis, W., et al., "A CFV Mini-dilution Sampling System for Vehicle Exhaust Emissions Measurement," SAE 1999-01-0151, SAE Congress March 1-4, 1999.

[18] Guenther, M., et al., "Improved Bag Mini-diluter Sampling System for Ultra-Low Level Vehicle Exhaust Emissions," SAE 2000-01-0792, SAE Congress March 1-4, 1999.

[19] Nagy, D., et al., "Evaluation of the Bag Mini-Diluter and Direct Vehicle Exhaust Volume System for Low Level Emissions Measurement," SAE 2000-01-0793, SAE Congress March 1-4, 2000.

[20] Schiefer, E., et al., "Study of Interferences for ULEV-CVS Measurement, Related to the Complete Measuring System; Discussion of Error Sources, Cross-Sensitivity and Absorption," SAE 2000-01-0796, SAE Congress March 1-4, 2000.