Challenges for the Vehicle Tester in Characterizing Hybrid Electric Vehicles

Michael Duoba
Center for Transportation Research
Argonne National Laboratory
9700 South Cass Ave., Bldg. 362
Argonne, IL 60439

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ABSTRACT

Many problems are associated with applying test methods, like the Federal Test Procedure (FTP), for HEVs. Although there has been considerable progress recently in the area of HEV test procedure development, many challenges are still unsolved. A major hurdle to overcoming the challenges of developing HEV test procedures is the lack of HEV designs available for vehicle testing. Argonne National Laboratory has tested hybrid electric vehicles (HEVs) built by about 50 colleges and universities from 1994 to 1997 in annual vehicle engineering competitions sponsored in part by the U.S. Department of Energy (DOE). From this experience, the Laboratory has gathered information about the basics of HEV testing and issues important to successful characterization of HEVs. A collaboration between ANL and the Society of Automotive Engineer's (SAE) HEV Test Procedure Task Force has helped guide the development of test protocols for their proposed procedures (draft SAE J1711) and test methods suited for DOE vehicle competitions. HEVs use an electrical energy storage device, which requires that HEV testing include more time and effort to deal with the effects of transient energy storage as the vehicle is operating in HEV mode. HEV operation with electric-only capability can be characterized by correcting the HEV mode data using results from electric-only operation. HEVs without electric-only capability require multiple tests conducted to form data correlations that enable the tester to find the result that corresponds to a zero net change in SOC. HEVs that operate with a net depletion of charge cannot be corrected for battery SOC and are characterized with emissions and fuel consumption results coupled with the electrical energy usage rate.

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INTRODUCTION

For decades, researchers have been studying the Hybrid Electric Vehicle (HEV) as a means for increased efficiency and lower emissions in passenger vehicles. The enabling technologies for electric propulsion (such as high-power electronics and energy storage) have been developed sufficiently to bring electric vehicles (EVs) to the market in the last couple of years. Many key EV technologies are applicable to HEVs, thus accelerating HEV development. Within the next few years, production HEVs will likely be sold in the United States and overseas.

Any new vehicle technology must be evaluated by applying appropriate test procedures to accurately measure and quantify its fuel efficiency and emissions for certification purposes and for engineering evaluations and comparisons. The merits of new HEV technology must be fully understood to justify development and production.

Whereas conventional vehicles and EVs draw upon only one source of energy, an HEV has two on-board energy sources from which motive power is provided. The format and structure of the original Federal Test Procedure (FTP) was designed as an attempt to characterize on-road vehicle operation. The assumptions associated with short-cuts used in the FTP, although effective for conventional vehicles, are not necessarily compatible with the complexity of HEV operation and do not allow HEVs to be accurately characterized.

Standardize test protocols must be modified and reconfigured to accommodate HEV designs. Developing these new HEV test procedures is an underestimated problem that will have an enormous impact how we the engineering community and regulatory agencies assess these potentially prevalent vehicles of the future.

BACKGROUND

The oil shock of the 1970s spawned interest in HEV technology as a means to combat our nation's oil dependency by building a higher mileage vehicle. In the 1980s interest in HEVs continued as a means to meet air pollution reduction goals, and a variety of HEVs were built and evaluated;[1,2,3] however, no domestic manufacturer showed interest in producing HEVs. In 1990, when the California Air Resources Board (CARB) adopted its Low Emissions Vehicle regulations[4], they were interested in HEVs, but the limited availability of these vehicles halted the development of comprehensive test procedures. The test procedure CARB[5] adopted was more or less a standard FTP dynamometer test operated at worst-case conditions of the HEV, during which the engine is working its hardest.

In 1992, GM presented a proposal to the Environmental Protection Agency (EPA) for test procedures specially suited for HEVs. GM observed that, "Neither the best-case nor the worst-case tests alone are sufficient. A fair characterization requires at least two extremes and a rational scheme for weighting them[6]" Also in 1992, a paper by INEL described a test procedure[7] that recommends testing HEV operation until a full charge/discharge cycle is observed and terminating the test at the same battery state-of-charge (SOC) as the test started (more discussion about testing concepts will be given in the body of the paper). In also in 1992, the Society of Automotive Engineers (SAE) assembled the Hybrid-Electric Vehicle Test Procedure Task Force consisting of representatives from industry, the national laboratories, the U.S. EPA, and other interested parties to formulate a standard practice for testing HEVs. SAE's test procedure is draft J1711[8] and has been a living document undergoing several significant revisions over the past few years. In 1993, the U.S. Department of Energy (DOE) signed five-year contracts with Ford and GM (Chrysler has since joined the DOE HEV program) to cost share the development of a production HEV for the mass market, thus underscoring a real need for a standardized test procedure.

Although we have seen HEV development efforts grow over the years, few HEVs have been available for testing. Studying HEV test procedure using only one or two prototypes would overlook many HEVs that represent a considerably large variety of possible designs. CARB has been experimenting with a prototype HEV from Mitsubishi, but this experience is limited to only a particular type of HEV, which was reflected in CARB's earlier procedures (however, in 1996, CARB staff informally expressed interest in using the SAE J1711 procedure when it is completed).

Since 1988, DOE, through Argonne National Laboratory (ANL) has been partnering with the major domestic automobile manufacturers to showcase the engineering efforts of the best colleges and universities in North America through Advanced Vehicle Technology Competitions (AVTC). Since that time, there have been five competitions[†] in which over 50 HEVs have been tested and evaluated. Competition events covering design and performance characteristics have included dynamometer testing for emissions and fuel economy by using HEV test procedure concepts. Testing a wide selection of HEV designs has been an excellent opportunity to learn about and develop hybrid test procedures. The information in this paper is based primarily on information gathered during the competitions.

HEV OPERATION

HEVs posses very elaborate drivetrains and potentially operate in entirely new and complex ways. In fact, these new operational capabilities have often confused discussions regarding the application of HEVs to the national fleet because usually the definitions used and the assumptions made about hybrid vehicles are too loose. Some HEVs operate most of the time like an electric vehicle (zero emissions vehicle, or ZEV) and use the engine to remedy the range limitations of the battery pack that charges while the vehicle is in storage. Some HEV designs may never be plugged in; although they are refueled like a conventional vehicle, they use an HEV drivetrain as a means to achieve new degrees of optimization for high energy efficiency and low emissions. In spite of all these differences, what these vehicles do have in common is an energy storage device (EDS): either a battery, ultracapacitor, or flywheel, that can store and release energy throughout operation in the HEV mode. This technology presents new challenges in vehicle testing and characterization.

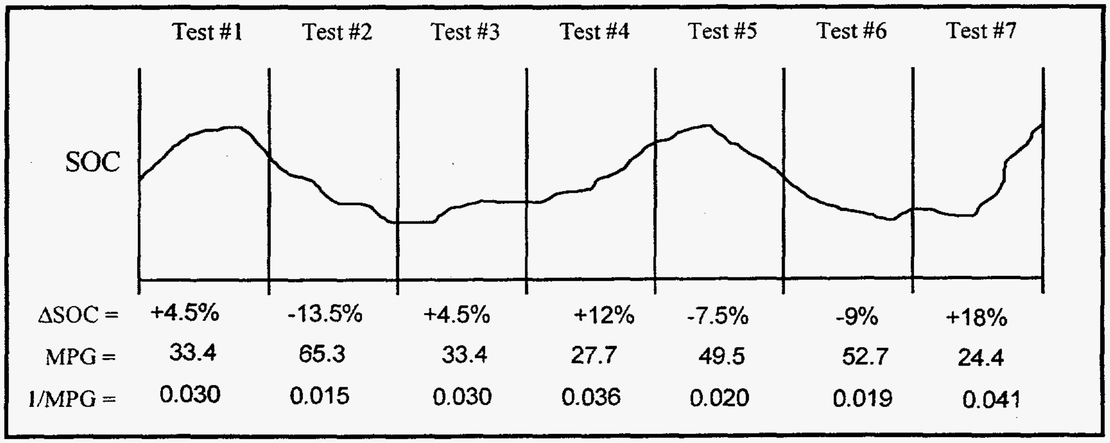

Figure 1: Test-to-Test Variation in HEV Operation

† 1994 and 1995 HEV Challenge, 1995 DOE Advanced Student Hybrid (DASH) Challenge, 1996 American Tour de Sol, 1996 FutureCar Challenge.

A series of test results from conventional vehicles would more or less show the same data with some expected scatter. In contrast, hybrid operation yields markedly different results from test to test; the results vary because of effects of transient energy storage plus, perhaps, a host of other possible parameters unique to HEV operation. Figure 1 illustrates this point.

This simplified example shows the results of a series of HEV tests while the vehicle is in the HEV mode. The SOC in this example is changing constantly, but over time it remains within an operational window. Energy taken from the ESD for propulsion power during some tests supplement fuel energy usage, which results in high MPG. Because of this operation, each individual test can only capture a small segment of the entire vehicle operation that we are trying to characterize.

Classifying HEV Designs

A lengthy (but worthwhile) discussion of HEV types and design categories is beyond the scope of this paper (see Ref. 9), but the types of HEVs that affect testing will be explored here.

Discussions of HEV designs usually begin with an explanation of the two fundamental design configurations: series and parallel. Each configuration may be more conducive to a particular operating scheme, but in reality, the configuration of the HEV (series or parallel) has no bearing on vehicle testing, outside of such issues as testing a 4-wheel-drive HEV on a 2-wheel-drive dynamometer. The vehicle configuration can be more or less "black-boxed," and the focus of our interest in testing lies in two fundamental operational distinctions:

1. Can the vehicle operate in its hybrid mode indefinitely without discharging the battery?

2. Does the vehicle have the capability to operate in electric-only mode for a significant amount of time (distance)?

Question (1) relates to "charge-sustaining" or "charge-depleting" operation as defined in draft versions of SAE J1711. If an HEV cannot maintain charge, then fuel economy and emissions cannot be defined in terms of fuel energy alone. Aside from the issue of on- and off-board charging, an off-board-charging HEV may still be capable of maintaining charge, but it uses off-board energy for ZEV operation. No matter how an HEV is evaluated, vehicles that use off-board electrical energy must be treated differently than vehicles that derive their electrical energy from on-board charging. This "apples-to-oranges" comparison is important, but beyond the scope of this paper.

Question (2) address the problem with applying an emissions and fuel economy test to a vehicle that, during some of its operation, does not use fuel or emit pollution. If, for example, an HEV's engine is invoked at the end of a cycle or not at all during a particular test, the resulting data may prove unrepresentative.

A popular vision of HEVs is that they all have electric-only capability. Although it may be possible to use the electric motor by itself to drive the vehicle, the motor may be sized too small for practical driving speeds, or the vehicle control strategy may never employ electric-only operation. Some HEV designs always have the engine on throughout their operation. Moreover, an HEV operating with the engine on all the time does not necessarily designate the vehicle as having the ability to do all of its electrical charging on-board. We can conclude that these two design distinctions are independent, which means that we can express the possibilities in a 2-by-2 matrix, as shown in Figure 2.

The matrix shows graphs in each category box that describe the operation of the possible vehicle designs expressed in SOC vs. distance plots. The graphs are useful in showing different operational modes and tracking the energy in and out of the battery. The shaded sections of the graph indicate engine operation, the unshaded regions show ZEV-mode operation. Again, the discussion of these HEV design types does not require information about drivetrain configuration (series or parallel).

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