

Battery Charge Balance and Correction Issues in Hybrid Electric Vehicles for Individual Phases of Certification Dynamometer Driving Cycles as Used in EPA Fuel Economy Label Calculations

Mark Meyer

Virginia Tech / Argonne National Lab

Douglas Nelson

Virginia Tech

Henning Lohse-Busch

Argonne National Laboratory

ABSTRACT

This study undertakes an investigation of the effect of battery charge balance in hybrid electric vehicles (HEVs) on EPA fuel economy label values. EPA's updated method was fully implemented in 2011 and uses equations which weight the contributions of fuel consumption results from multiple dynamometer tests to synthesize city and highway estimates that reflect average U.S. driving patterns. For the US06 and UDDS cycles, the test results used in the computation come from individual phases within the overall certification driving cycles. This methodology causes additional complexities for hybrid vehicles, because although they are required to be charge-balanced over the course of a full drive cycle, they may have net charge or discharge within the individual phases. As a result, the fuel consumption value used in the label value calculation can be skewed.

To determine the effect of net battery energy change on fuel consumption using an example vehicle, testing was carried out on a 2010 Toyota Prius at Argonne National Laboratory's vehicle dynamometer test facility. Each phase was driven with various levels of electric charge or discharge, thereby yielding a charge correction line quantifying the tradeoff between electric and fuel consumption for that driving phase. The slopes of these lines will be compared along with discussion of the factors influencing them. The testing effort to produce this information was considerable, with at least 4 test points per driving phase, and the importance of preconditioning and vehicle preparation in ensuring valid results further extended the time investment. The collected data are used to show the effect of phase charge correction on fuel economy label values, and potential methods of implementing the corrections as well as the shortcomings thereof are discussed.

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INTRODUCTION

HYBRID VEHICLES DEFINITION AND SCOPE

With the added technology in electrified vehicles, the process of measuring fuel consumption is more complicated than what is defined by the basic testing procedures for conventional vehicles. Some automobiles even use multiple

fuel sources, including electric charging. To help define the scope of the study presented here, [Figure 1](#) graphically depicts the classification of road vehicles ranging from conventional vehicles with no propulsive electric components to the most highly electrified vehicle, a pure battery electric vehicle (BEV). Within the blue "electrified vehicle" box there are two primary categories: charge-sustaining hybrid electric vehicles (CS HEVs) and plug-ins, with fuel cell vehicles being an electrified powertrain that can partially



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overlap either of those. A CS HEV uses a combustion fuel as the sole source of external energy and uses electric components to merely assist in efficiently delivering power from that fuel for vehicle propulsion. Plug-in vehicles can be recharged through grid electricity, but may also include combustion engines (in the case of PHEVs).

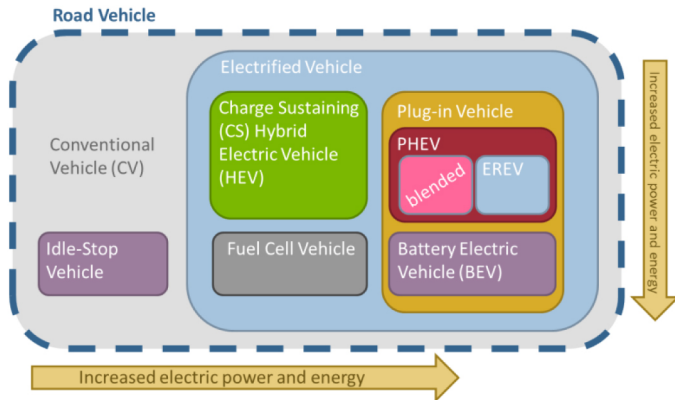


Figure 1. Vehicle classification terminology diagram.

The EPA 5-cycle fuel economy testing methods cannot be applied to certain electrified vehicles such as PHEVs and BEVs in the same form as they are for conventional vehicles, since those require extra consideration of electric charging energy or a method of combining the consumptions of these energy sources. Current provisions do exist in the EPA regulations for testing these vehicles, but they are still under further development. This paper will not consider plug-in vehicles, but will focus on CS HEVs and the challenges that exist for these vehicles in applying fuel consumption measurement methods, especially EPA 5-cycle.

THE EPA 5-CYCLE FUEL ECONOMY CALCULATION METHOD

With implementation beginning in 2008 and fully in place in 2011, EPA introduced updated regulations on the methods for determining the values used in vehicle fuel economy labels. Previously, city and highway ratings came from dynamometer testing on the Federal Test Procedure (FTP) and the Highway Fuel Economy Test (HWFET). The measured fuel economy on each of these cycles was adjusted downward by 10 % and 22 %, respectively, to produce a rating that was closer to real-world observations. As vehicle performance capabilities and driving patterns changed over the years, EPA set out to revise the labeling calculation system to make up for continued differences between certification fuel economy ratings and real-world measurements. The new system uses dynamometer testing from a total of 5 cycles, all of which were already in use for emissions certification procedures, and synthesizes these individual measurements into city and highway label ratings [1]. Table 1 lists these cycles and highlights key parameters.

Table 1. The 5 drive cycles used in EPA fuel economy label calculations [1].

Test	Driving	Ambient Temp.	Engine Condition at Start	Extra Accessories
FTP	Low Speed	75 °F (24 °C)	Cold and hot	None
HWFET	Mid-Speed	75 °F (24 °C)	Hot	None
US06	Aggressive; low and high speed	75 °F (24 °C)	Hot	None
SC03	Low Speed*	95 °F (35 °C)	Hot	A/C on
Cold FTP	Low Speed	20 °F (-7 °C)	Cold and hot	None*

*Notes not in original EPA table: SC03 max speed 58 MPH (93 km/h) could be considered mid-speed; Cold FTP uses heater accessory.

The US06 and the FTP test cycles are subdivided into phases, from which fuel consumption measurements are also recorded. These phases are also sometimes referred to as “bag” numbers, since exhaust gases are collected in separate emissions bags when running the tests in a dynamometer facility. For the US06, a “City” phase consisting of multiple acceleration and deceleration modes is merged from the beginning and ending portions of the test (specifically, seconds 0-130 and 495-596), and the long continuous driving pattern between those is designated as the “Highway” phase. The FTP is a procedure based upon the Urban Dynamometer Driving Schedule (UDDS). The UDDS has 2 phases, the first being commonly referred to as the “505” since it lasts that many seconds. A traditional FTP consists of a cold start UDDS, a 10 minute soak, then a repeat of the 505 (i.e. phase 3 of the overall FTP procedure). What would be the 4th phase of the FTP is normally omitted because it is assumed to be the same as the warmed-up phase 2. For hybrids, the 4th phase of the FTP at 75 °F (24 °C) is required to be driven. For the purposes of this study, we will not distinguish between phase 2 and phase 4 of the FTP. Any difference in net electric consumption that would typically be observed between these two phases will not matter in the derivation of the charge-correction line, since starting SOC is controlled in each test. There can be thermal differences as well, but these are already affected by the experimental procedure described later, and in fact, anecdotal evidence from monitoring engine oil temperatures of conventional vehicles in the testing facility suggests that thermal difference between phases 2 and 4 may not be significantly greater for this hybrid than they would be for a conventional vehicle if they were required to drive phase 4.

There is a variant on the FTP allowed by EPA for hybrid vehicles in which the results from each of two full UDDS cycles are used in computing the 5-cycle fuel consumption rather than 4 separate bag measurements. This option eliminates the problem of phase-imbalance within each UDDS cycle that is illustrated in this paper. However, this

alternative method is *not* allowed for the FTP at 20 °F (−7 °C) which must be tested using 3 phases for both hybrid and conventional vehicles.

EPA created a method for weighting results from the phases of each drive cycle to give an overall distribution of speeds and accelerations that matched data extracted from several fleet studies. They also use information from the results to incorporate weighted effects of temperatures and A/C use which consider the occurrence of these conditions in aggregate U.S. driving. Once a final increase of 9.5 % to account for non-dynamometer affects is applied to the fuel consumption, the label has been designed to represent a true U.S. average on-road fuel consumption for either city or highway driving. To incorporate all these effects, the 5-cycle calculation formulae are divided into 5 parts, which are described in [Table 2](#). Item 2 in the table, the running fuel consumption, defines a harmonic weighting of cycle fuel consumption results, which is illustrated graphically in [Figure 2](#). Further details about the 5-cycle method including the exact formulae are documented by EPA [1].

Table 2. 5-cycle fuel economy calculation parts

	Part	Description/Notes
1	Start fuel	Computed from difference in cold and hot start FTP test fuel consumptions at both 75 and 20 °F
2	Running fuel at 75 °F without A/C	Harmonically weights FC results from cycles (see Figure 2).
3	Effect of A/C	Compares SC03 fuel consumption to a comparably-weighted section of the FTP to find A/C fuel consumption
4	Effect of cold ambient temperatures	Incorporated into running fuel and start fuel through Cold FTP result
5	Adjustment for non-dynamometer effects	Increases final fuel consumption by 9.5 % to account for real-world factors not captured in dynamometer testing, e.g. fuel quality, tire pressure, wind, etc.

The important thing to note from the design of the 5-cycle fuel economy calculation method is that it weights fuel consumption results from individual phases of FTP and US06 cycles and also calculates certain derived quantities like start fuel or A/C fuel consumption based upon these phase results. This fact will present a potential issue concerning battery charge balance in hybrid vehicles.

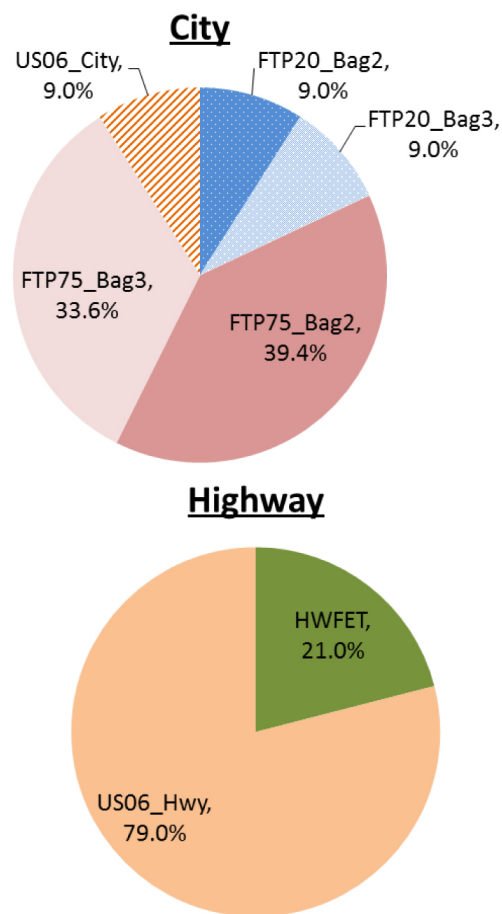


Figure 2. Fractional weighting factors for running fuel consumption only in city and highway fuel economy.

CHARGE SUSTAINING OPERATION CONDITION

When testing hybrid electric vehicles on certification dynamometer cycles, the net energy change (NEC) of the energy storage system (e.g. battery) must be monitored in addition to the liquid fuel consumption. The goal when measuring charge-sustaining (CS) fuel consumption is to have an NEC = 0 for a drive cycle. If the NEC condition is perfectly fulfilled, it means that at the end of a test, the state of charge of the battery has returned to the same level it was in at the beginning of the test. This criterion is important because a net consumption of electric energy from the battery to drive the vehicle with the electric motor would typically cause a reduction in liquid fuel consumption, and likewise, a net recharge of the battery would have required extra fuel. In the long run during real world driving, a hybrid vehicle that is not “plug-in” or externally recharged must operate in a charge-sustaining condition since it has to manage its own battery level using energy from the combustion fuel. Even plug-in hybrid electric vehicle (PHEV) test procedures must include a charge-sustaining test to define operational performance once the battery has been depleted.

To ensure that the fuel consumption test result on a hybrid vehicle represents a valid charge-sustaining operation result, the SAE J1711 standard sets a boundary criterion for the NEC of an energy storage system with the stated goal of obtaining a fuel consumption measurement that is within 3 % of the vehicle's "true representative fuel consumption" for the charge sustaining test [2]. (Here, only batteries are considered, but the requirement also exists for other energy storage systems like capacitors or flywheels.) The NEC of the battery is given as a percentage of the total fuel energy consumed on a full cycle. The net change in electric energy of the battery is computed by monitoring the cumulative current flow at the battery terminals and multiplying this quantity by a representative system voltage. To be considered CS operation, an NEC of less than 1 % of fuel energy is required. This requirement and certain other provisions defined in the SAE J1711 recommended practice are not necessarily included in federal regulations as defined by the EPA, but they do represent industry-standard practice. SAE J1711 seeks to define procedures in harmony with existing regulations, but EPA is not required to adopt these additional provisions.

It is important to note the inherent variation in fuel consumption results that is possible even within the NEC limit. Morita et al. noted fuel economy values distributed between 96 % and 104 % of the linearly approximated value on several cycles using early generation hybrid vehicles [3]. Using data from the testing described later in this paper, Figure 3 shows the range of fuel economy results on various drive cycle phases for the extreme ends of the allowed NEC for CS operation. Note that in the figure, the abbreviations CS and HS refer to hot start and cold start cycles.

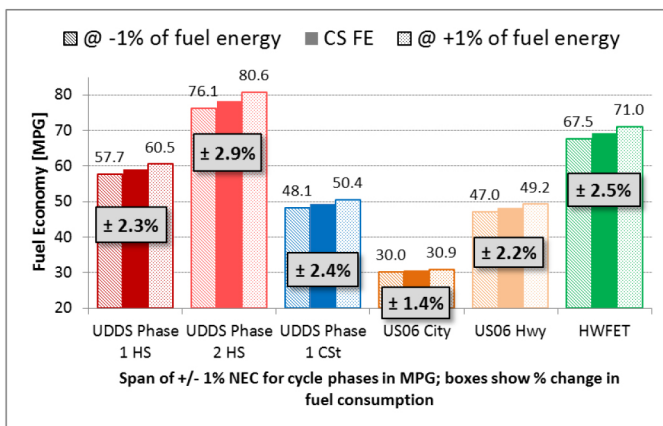


Figure 3. Range of MPG within ± 1 % NEC on each cycle phase.

The different span in MPG ranges for various phases is a function of both the charge correction slope (described later) and the nonlinearity of fuel economy. The grey boxes on the set of bars for each phase show the percent change in fuel consumption at the CS NEC limits. The range in fuel consumption for all phases falls within the SAE J1711 goal of

± 3 % of CS FC. Of course, there are other contributors to the scatter in measured FC that would cause additional variance at each electric consumption point, so these ranges shown do not guarantee that *any* FC measured at the 1 % NEC limit will be within 3 % of the true CS FC value.

CHARGE CORRECTION AND THE ISSUE OF SEPARATE BAG DATA IN LABEL FUEL ECONOMY CALCULATION

Achieving a zero NEC, charge-balanced result on a drive cycle does not occur without some amount of effort. Hybrid vehicle manufacturers have to design control strategies that will settle at charge-sustaining behavior under a variety of driving conditions. The battery charge should stabilize under long highway cruises as well as under sustained stop and go city traffic. Typically, there will be some period of time during which the control strategy allows transient behavior before CS operation occurs. During dynamometer certification testing, this issue is somewhat mitigated by preparation ("prep") cycles. That is, before driving the cycle on which measured fuel consumption is recorded, that same cycle or a similar one is driven immediately beforehand to bring the vehicle to an appropriate thermal condition. Typically, the vehicle control strategy has also adjusted to a repeatable charge-sustaining operation by the end of the prep cycle.

If a hybrid does not achieve less than 1 % NEC tolerance on a single cycle, SAE J1711 suggests a provision whereby multiple cycles can be driven in a row until there is a set of contiguous cycles over which charge balance is achieved. The fuel consumption result would then be computed using the quantity of fuel over the entire driving distance of those cycles in sum. This method isn't practical for the cold-start UDDS cycle, since the vehicle would need to soak for 12 hours between each run. It is also not useful when the fuel consumption measurement is needed from individual sections of one continuous test, for example with the urban and extra-urban sections of the NEDC, or when taking individual phase results for EPA label calculations.

If it is not possible to get CS results, another alternative is to employ a charge correction method, whereby the nonzero electric energy consumption is equated to an amount of fuel energy that the specific vehicle is known to use or save in exchange for electric energy. The measured fuel consumption is then increased or decreased by an amount that compensates for the electric energy usage. Appendix C of SAE J1711 defines an allowable NEC correction methodology. The procedure involves deriving the regression line indicating fuel consumption versus net electric energy consumption, the slope of which is used in adjusting the result of a charge-unbalanced cycle, or whose intercept at zero electric energy consumption is simply taken as the CS fuel consumption. The recommended practice here is to only allow correction for