Understanding the Challenges in HEV 5-Cycle Fuel Economy Calculations Based on Dynamometer Test Data

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ABSTRACT

EPA testing methods for calculation of fuel economy label ratings, which were revised beginning in 2008, use equations that weight the contributions of fuel consumption results from multiple dynamometer tests to synthesize city and highway estimates that reflect average U.S. driving patterns. The equations incorporate effects with varying weightings into the final fuel consumption, which are explained in this thesis paper, including illustrations from testing. Some of the test results used in the computation come from individual phases within the certification driving cycles. This methodology causes additional complexities for hybrid electric vehicles, because although they are required to have charge-balanced batteries over the course of a full drive cycle, they may have net charge or discharge within the individual phases. The fundamentals of studying battery charge-balance are discussed in this paper, followed by a detailed investigation of the implications of per-phase charge correction that was undertaken through testing of a 2010 Toyota Prius at Argonne National Laboratory's vehicle dynamometer test facility. Using the charge-correction curves obtained through testing shows that phase fuel economy can be significantly skewed by natural charge imbalance, although the end effect on the fuel economy label is not as large. Finally, the characteristics of the current 5-cycle fuel economy testing method are compared to previous methods through a vehicle simulation study which shows that the magnitude of impact from mass and aerodynamic parameters vary between labeling methods and vehicle types.

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LIST OF ABBREVIATIONS

A/C	air conditioning
ANL	Argonne National Laboratory
APRF	[Argonne National Laboratory] Advanced Powertrain Research Facility
CAFE	Corporate Average Fuel Economy
CFR	Code of Federal Regulations [of the United States]
CD	charge-depleting
CS	charge-sustaining; OR cold start
EPA	United States Environmental Protection Agency
EREV	extended-range electric vehicle
EV	electric vehicle
FC	fuel consumption
FTP	Federal Test Procedure
HEV	hybrid electric vehicle
HS	hot start
HWFET	Highway Fuel Economy Test
MPG	Miles per gallon [mi/gal]
NEC	net energy change
NEDC	new European drive cycle
NHTSA	National Highway Traffic Safety Administration
PHEV	plug-in hybrid electric vehicle
SC03	the EPA SC03 or air conditioning test drive cycle
SOC	state of charge [e.g. of a battery]
THC	total hydrocarbons
UF	utility factor
UDDS	Urban Dynamometer Driving Schedule
US06	the EPA US06 (also: “aggressive” or “high speed”) drive cycle
VSP	vehicle-specific power
Vzc	Zero-crossing voltage

1. Introduction

a. Background and motivation

Since the mid 1970's, the U.S. Environmental Protection Agency (EPA) has used a system of testing passenger vehicles to verify compliance with emissions regulations and to assign vehicles a fuel economy rating. The testing methods consist of driving vehicles on a chassis dynamometer through prescribed drive cycles, which are traces of velocity vs. time. From the standpoint of determining a fuel economy rating in miles per gallon (MPG), which is the focus of this paper, there are two goals: creating a common basis for comparison between different vehicles and also giving consumers information to predict how much fuel the vehicle can be expected to use under real world driving. The repeatable drive cycles meet the first goal with ease, but the second has needed revision over time, both as a result of efforts to generally improve the comprehensiveness of the methods and also in response to changes in vehicle characteristics and driver behavior over time.

The most recent revisions to the testing methods began to be applied to 2008 model year vehicles and were fully implemented in 2011. The testing methods themselves are now much more complex, so this paper will begin with a characterization of their properties. Once the methods are understood, it becomes clear that with charge-sustaining hybrid vehicles, there is a potential for an effect on the calculation due to changes in battery charge level during the course of certain drive cycles included in the testing regime. A detailed set of tests to understand the effects of this battery charge imbalance on the EPA fuel economy rating was carried out using a 2010 Toyota Prius. Finally, a simulation study was carried out to see how certain vehicle design changes affect the fuel economy label under the current testing system as compared to prior methods.

b. Objectives

- Characterize the EPA fuel economy label calculation methods, including the relative contributions of each part to the overall fuel consumption and details on the breakdown of cycles into separate phases
- Provide information and evidence in support of the appropriate method for measuring net change in battery charge
- Use test data to determine whether phase fuel consumption is charge-sustaining
- Derive charge correction curves for separate cycle phases using test data and consider the effects of correction on per-phase fuel consumption and label fuel economy
- Investigate whether the transition to the 5-cycle fuel economy method affects the importance of certain vehicle design parameters (due to changes in cycle characteristics)

2. Characterization of EPA fuel economy calculation methods

a. Definitions: fuel economy and fuel consumption

There are two terms that must be defined prior to discussion of fuel usage in automobiles. "Fuel consumption" specifies what quantity of a fuel is used for a given distance. Typically the fuel quantity is given volumetrically, and common units to express fuel consumption are gallons per mile, gallons per 100 miles, and liters per 100 kilometers. "Fuel economy" is the inverse of fuel consumption, therefore specifying what distance is driven for a given quantity of fuel. Traditionally, vehicle fuel usage has been expressed in the U.S. as a fuel economy in miles per gallon (MPG).

This distinction between fuel economy and fuel consumption is very important when considering the difference between two values, including percentage changes. Consider the example illustrated in Figure 1, which plots a curve of corresponding points of fuel consumption vs. fuel economy. The green and red arrows depict two different 20 MPG increases, one from 20 to 40 MPG and one from 40 to 60 MPG, and the corresponding fuel consumption decreases. The MPG rating gives the illusion that these increases are of equal magnitude, but the corresponding fuel consumption decreases are not the same. In the first case, consumption is reduced by 2.5 gal/100 mi, but in the second, only 0.833 gal/100 mi are saved. Therefore, as base fuel economy increases, each additional increase in MPG represents a smaller amount of actual fuel savings. These data from the example plot are given in Table 1, along with calculations of the percent change in both fuel economy (FE) and fuel consumption (FC). The difference in the percentage changes for the given steps illustrate that large percentage increases in fuel economy do not equate to the same percentage reductions in fuel consumption.

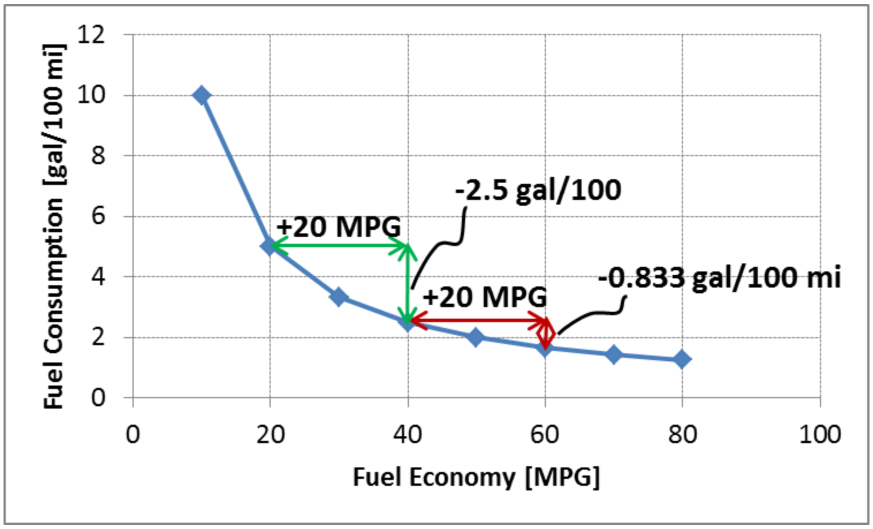

Figure 1. Comparison in fuel consumption change for two different 20 MPG increases.

Table 1. Example fuel economy and fuel consumption change calculations.

MPG step	**FE Increase**	**FC decrease [gal/100 mi]**	**% FE increase**	**% FC decrease**
20 → 40 MPG	20	2.5	100%	50%
40 → 60 MPG	20	0.833	50%	33%

This paper will consistently use the terms fuel economy and fuel consumption according the definitions given here. Any time a percentage change is calculated, it will always be given as a percentage change in fuel consumption, even if reference values are given in MPG.

b. The UDDS and HWFET cycles

The two cycles that have served as the basis for U.S. fuel economy testing have been used since 1973. These are the Urban Dynamometer Driving Schedule (UDDS), traditionally referred to as the "city" cycle, and the Highway Fuel Economy Test (HWFET). Both cycles are prescribed velocity traces which were recorded at 1 Hz from an actual vehicle driven on-road. The UDDS is based upon the LA4 route, a 12 mile driving route which was determined through trial and error testing by employees of California's Vehicle Pollution Laboratory in Los Angeles to be a fair representation of typical driving experienced on the employees' commuting routes in the mid-1960's. Using a 1969 report on typical driving patterns in Los Angeles, the recorded LA4 trace was modified so that the trip length would be 7.5 miles. Small modifications were also made to ensure that acceleration rates did not exceed the 3.3 mph/s limit of Clayton chassis dynamometers which were used in testing, thus producing the UDDS drive cycle. For 1975, the Federal Test Procedure (FTP) was created from the UDDS cycle by specifying a repeat of the first 505 of the 1369 total seconds of the procedure to capture results under warmed-up engine operation after the vehicle had been soaked with the engine off for 10 minutes [EPA FTP Review 1993 (p. 12-15)]. Therefore, the FTP became a 3-phase procedure, with phases 1 and 2 being the initial continuous UDDS driving pattern after a cold start (as after a vehicle has been parked overnight), and phase 3 being the repeat of phase 1 driving after a 10 minute soak. The FTP has been the foundation of U.S. EPA fuel economy testing ever since. The actual MPG number that is reported for the FTP comes from a harmonic weighting at 43 % of the cold start UDDS and 57 % of the hot start UDDS which is synthesized from FTP bags 2 and 3. The HWFET cycle was recorded by EPA and based on rural driving, and was added to fuel economy label reporting beginning in 1974. In the certification testing procedure for the HWFET, in contrast with the FTP, the measurement is taken on a vehicle with an engine already in a warmed-up condition, which is achieved by driving a preparation HWFET cycle immediately prior to the actual test cycle. A plot of the drive traces, along with shading to indicate which segments of the cycle belong to individual phases are shown for the UDDS in Figure 2, the FTP in Figure 3, and for the HWFET in Figure 4. Note that the phase numbers can also be referred to as "bag" numbers since exhaust gases are collected in separate emissions bags when running the tests in a dynamometer facility.

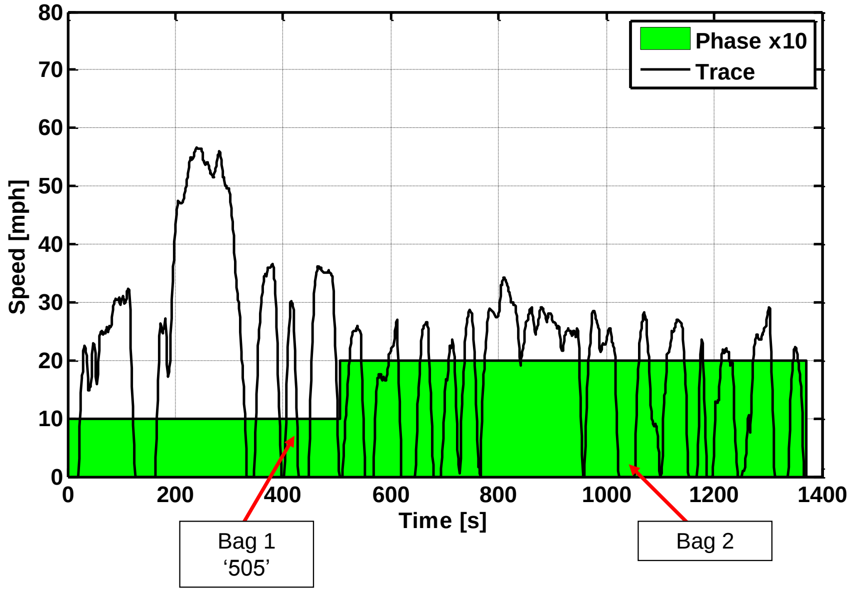

Figure 2. UDDS drive cycle and phase designations.

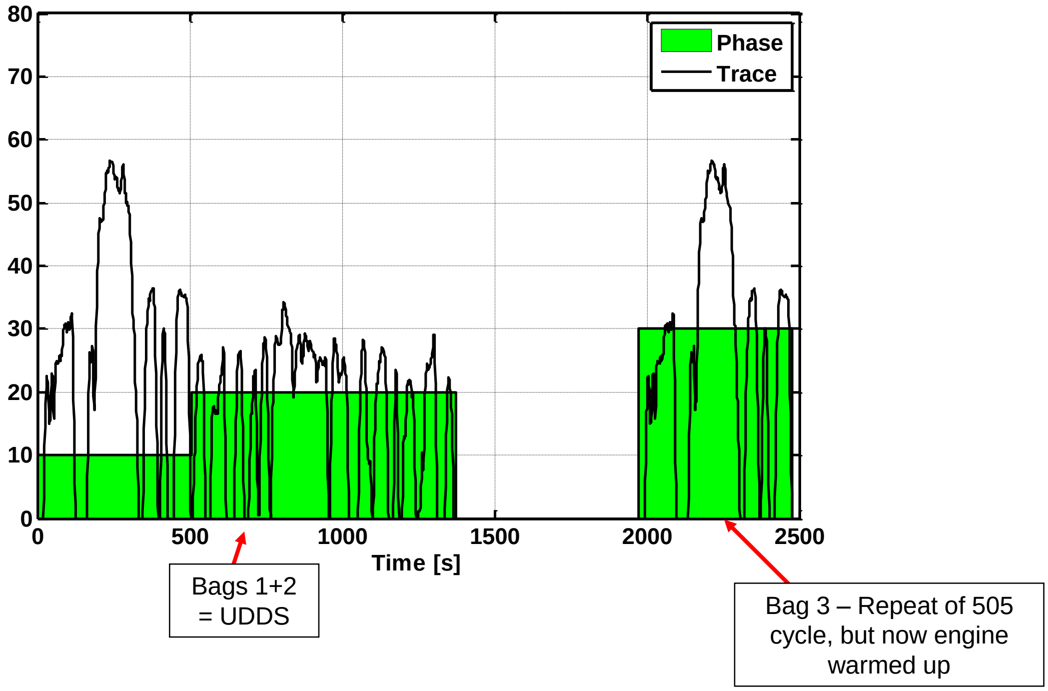

Figure 3. FTP drive trace and phase designations.

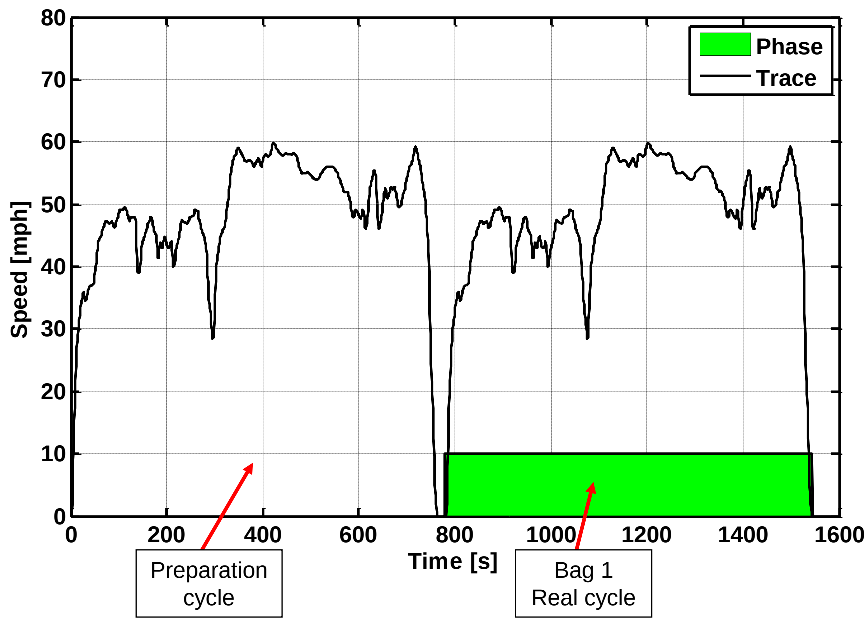

Figure 4. HWFET drive cycle trace.

c. Fuel economy labeling through the year 2007

Beginning with 1977 model year vehicles, a fuel economy labels with the values determined from the EPA testing procedures was required to be placed on new vehicles, and the EPA published a listing with the results for all vehicles in that model year. From very early on in the fuel economy labeling program, it was recognized that the observed on-road fuel economy of vehicles was not matching the estimates from the results of these dynamometer tests [Tyree 1982]. So after several years of real-world data analysis in 1984, EPA released a rule which would adjust the tested fuel economy result in miles per gallon (MPG) downward by 10 % for the FTP result and 22 % for the HWFET result to give the value used in labeling [EPA FE Labeling 2006, (p. 7)]. Although there were various changes to emissions testing rules and regulations over the years, this method for calculating the fuel economy label rating was used continuously through 2007. In later sections, this previous method of fuel economy label value calculation is sometimes referred to as “2-cycle”, in contrast with newer methods which use a total of 5 separate drive cycle tests: “5-cycle”.

d. Corporate average fuel economy (CAFE)

Alongside the requirement that manufacturers provide fuel economy labels to inform consumers about vehicle performance, the EPA methods are also used in a program managed by NHTSA that mandated each vehicle manufacturer to achieve a certain sales-weighted average fuel economy rating. The value used for a vehicle model combined the raw dynamometer results from FTP and HWFET cycles by weighting them according to a formula describing an estimated distribution of city vs. highway on-road driving in the U.S. The harmonic weighting is 55 % of the FTP result and 45 % of the HWFET result. In contrast with the results used on the 2-cycle fuel economy labels, the CAFE combined rating does not use the 10 % and 22 % downward adjustments.

In response to the criticism that the CAFE system inherently favors manufacturers that produce a higher percentage of small, lightweight vehicles instead of large cars or light trucks, the updated rules from NHTSA and EPA for 2012 and beyond specify different requirements based upon vehicle footprint, which is wheelbase times track length. In this way, larger vehicles will be allowed a lower MPG rating, so CAFE will not drive manufacturers to change the types of vehicles they produce, but will require vehicles of all sizes to make efficiency gains. The fleet MPG requirement for a particular vehicle manufacturer is therefore the sum of its sales-weighted vehicle footprint requirements [Federal Register 2010].

The important note about the CAFE requirements that is relevant to this paper is that the MPG ratings used in CAFE are still based upon the unadjusted test results from the UDDS and HWFET tests (although credits can be obtained for certain fuel-saving technologies not captured by those tests) [Csere 2011]. The MPG rating for a particular vehicle for CAFE purposes will not be the same as the fuel economy label value, which is based upon a revised system implemented in 2008. Indeed the CAFE MPG value will be much higher than the fuel economy label.

e. Trends leading to changes in fuel economy

Despite the adjustment to raw FTP and HWFET results, people recognized that fuel economy label ratings still overestimated modern real-world averages. A contributor to the broadening of the discrepancy between the two was the changes in vehicles and driving patterns over the years. Through continued technological advancement, the performance of modern vehicles far exceeds the capabilities of the vehicles that were driven when the UDDS and HWFET were recorded. Information about vehicle and fuel economy trends can be found in a report from EPA [EPA Trends 2010]. In Figure 5, which is reproduced from this report, there are very distinct trends in weight, horsepower, and acceleration (0 to 60 MPH) performance. After an initial trend of lightweighting in response to the implementation of CAFE and high fuel prices, the average passenger vehicle weight increased continuously until about 2004 due to trends in physical size as well as the addition of numerous safety and comfort features. At the same time, engine output has increased drastically. Whereas in 1975, 140 hp was the average peak rating, a 2009 model year vehicle averaged 208 hp. Likewise, and despite the weight increases, 0 to 60 MPH acceleration times dropped from upwards of 14 s to 9.7 s in model year 2009. In summary, vehicle characteristics changed in ways that would generally increase fuel consumption and increase capability for higher acceleration and comfortable high-speed cruising.

Weight, Horsepower and 0-to-60 Performance

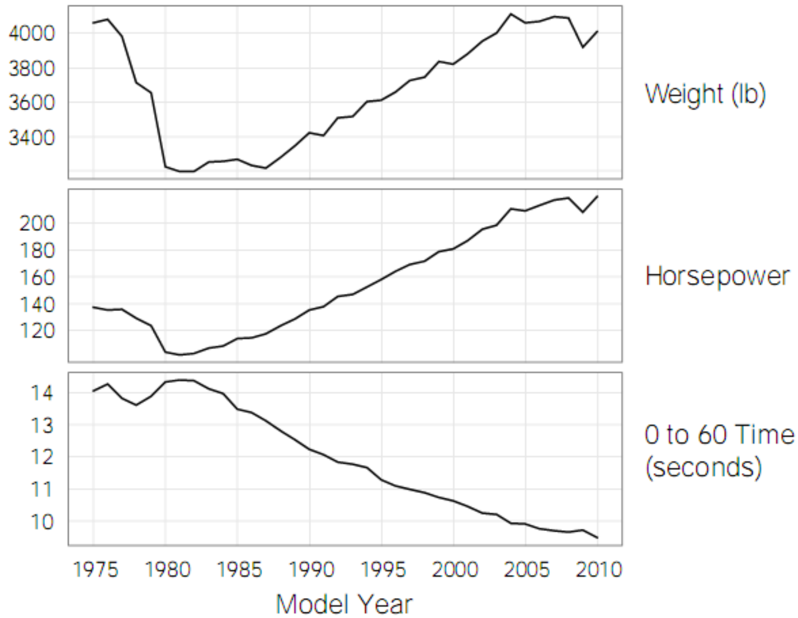

Figure 5. Vehicle weight and performance characteristics over time. [EPA Trends 2010]

As a result of these trends in vehicle characteristics, from about 1985 to 2005, the technological advancements in support of more efficient fuel use did not cause a large increase in average fleet MPG, but rather allowed continually heavier, better-equipped vehicles to maintain approximately constant fuel economy ratings. This data is shown in Figure 6 taken from the EPA report. The plot in the lower section of that figure illustrate the reason that the combined car/truck fleet MPG rating actually declined over that time period: the share of trucks increased from about 20 % in the early 1980's to 50 % by 2005. This trend also began to reverse in the latter half of the 2000s.

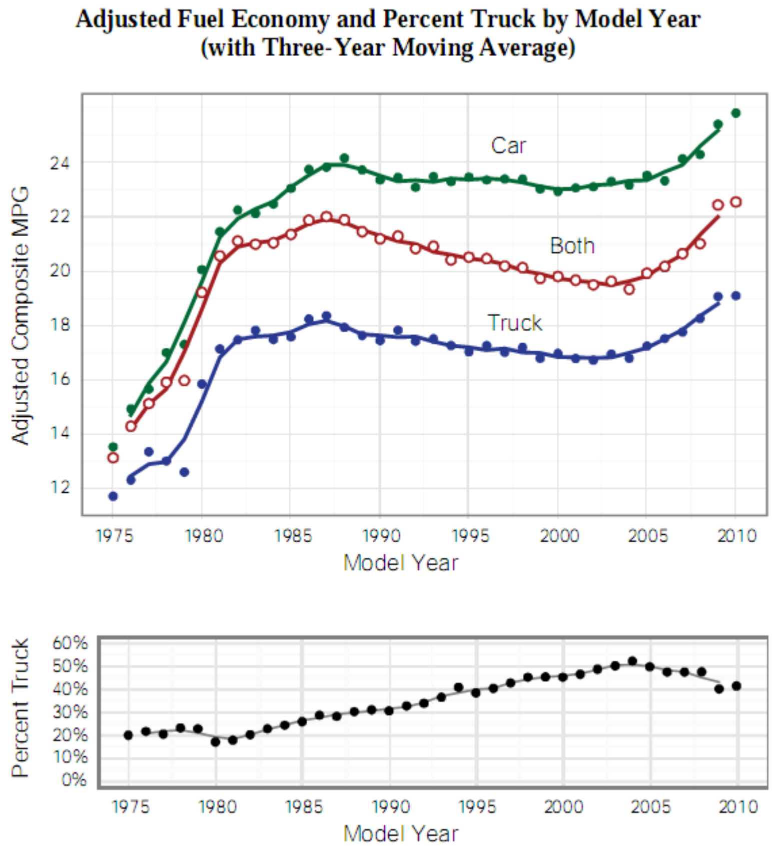

Figure 6. Adjusted combined fuel economy vs. time for cars & trucks; and percent truck in light duty vehicles. [EPA Trends 2010]

The changes in on-road fuel economy that might be expected as a result of these vehicular trends were documented in a number of data sets and studies which were considered by EPA as they began to look at revising fuel economy labeling methods. These included the Oak Ridge National Laboratory "YourMPG" program in which the general public submit their observed fuel economy, the DOE FreedomCAR test fleet study program, Strategic Visions New Vehicle Survey of recent new car purchasers, Kansas City Instrumented Vehicle Study, and estimates of on-road fuel economy by independent organizations including Consumer Reports, the American Automobile Association (AAA), and Edmunds [EPA Labeling 2006].

To provide just a few illustrative examples of the discrepancy between on-road observations and label fuel economy, Table 2 lists the average on-road fuel economy observations provided by three independent organizations as well as the corresponding average combined fuel economy ratings for those same vehicles on the 2-cycle system. Criticism of the 2-cycle labels had increased especially due to the even larger discrepancies for hybrid vehicles, which are more sensitive to drive cycle characteristics. The discrepancies for the small set of hybrid vehicles available for study in the EPA report from the independent organization data presented in the EPA rulemaking are summarized in Table 3.

Table 2. Comparison of organizations' fuel economy estimates to 2-cycle EPA label combined ratings. (data compiled from [EPA FE Labeling 2006])

Organization	**Number of Vehicles Studied**	**Avg. Observed MPG**	**2-cycle adj. label MPG**	**Discrepancy**
Consumer Reports	303	20.7	22.9	-9 %
AAA	163	21.7	22.1	-1.5 %
Edmunds	40	19	23	-14 %

Table 3. Comparison of organizations' fuel economy estimates for hybrids only to the 2-cycle EPA label ratings. (data compiled from [EPA FE Labeling 2006])

Organization	**Number of Vehicles Studied**	**Avg. Observed MPG**	**2-cycle adj. label MPG**	**Discrepancy**
Consumer Reports	4	33	41	-19 %
AAA	2	*n/a*	*n/a*	-6.6 %
Edmunds	4	*n/a*	*n/a*	-24 %

In addition to these observations of hybrid electric vehicle real-world fuel economy discrepancies, the lower robustness to drive cycle intensity was investigated and confirmed by researchers at Argonne National Laboratory [Duoba 2005]. In that study, three hybrids were compared to three conventional vehicles in fuel economy on EPA 2-cycle vs. more aggressive cycles, where the hybrids had much larger increases in fuel consumption than the conventional vehicles. They also tested the vehicles on variations of the UDDS cycle which were scaled to be more aggressive and derived a fuel consumption sensitivity factor from the trends, which showed that hybrid fuel consumption is much more sensitive to increases in cycle intensity.

f. Fuel economy labeling 2008 and later: the 5-cycle system

i. Additional cycles

In response to the differences between on-road and label fuel economy, EPA set out to alter the method of calculating the fuel economy label such that the rating would represent a true estimate of average on-road fuel economy. For the sake of easing the additional testing burden to derive this rating from laboratory testing, EPA took advantage of two additional drive cycles which had been introduced in 1996 as part of the added supplemental federal test procedure (SFTP) for exhaust emissions regulations plus the 1994 model-year requirement to certify carbon monoxide emissions on an FTP at 20 °F [Bontekoe 2005]. These cycles featured many of the additional characteristics needed to capture more real-world conditions such as higher speeds and accelerations, cold temperatures, and air conditioning use. A list of the 5 cycles (with key characteristics highlighted) is provided in Table 4 as provided in [EPA FE Labeling 2006].

Table 4. List of the 5-cycle tests and their key characteristics. [EPA FE Labeling 2006]

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

The US06 cycle involves higher rates of acceleration and higher speeds (up to 80 MPH) than the other certification cycles. It is divided into multiple phases, which are designated "city" and "highway". The US06 city phase is actually a combination of two separated segments from the overall cycle at the beginning and end which involve multiple accelerations and decelerations typical of urban driving. The US06 highway phase is a long period of nonstop driving in the middle of the cycle which resembles interstate highway driving. The drive trace and phases are shown in Figure 7.

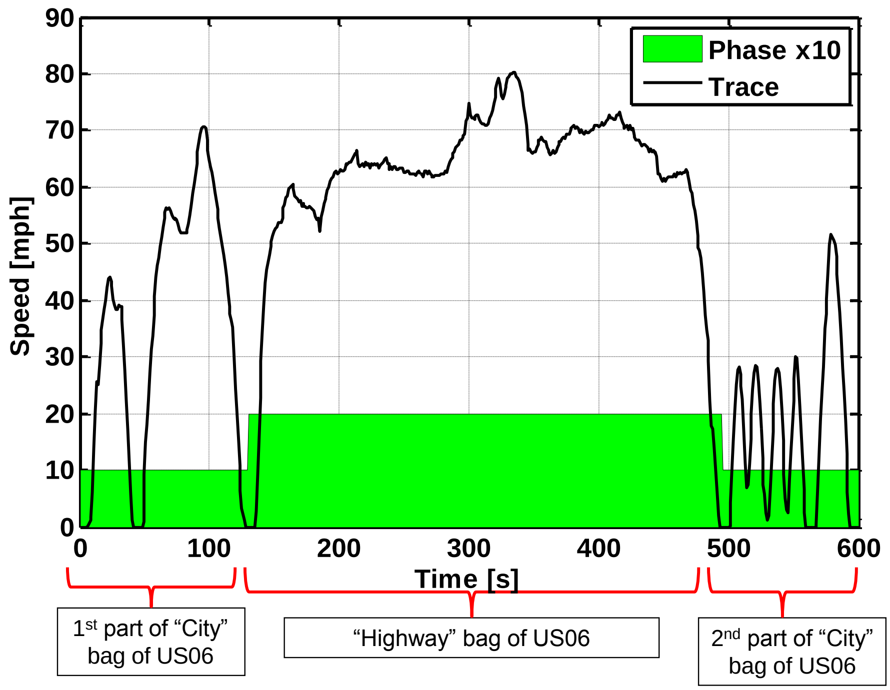

Figure 7. US06 drive cycle trace and phase designations.

The SC03 is a low speed cycle with multiple idle periods which resembles the UDDS, but is a shorter distance and has some more aggressive accelerations. However, the key feature of the cycle is that a vehicle is run with air conditioning turned on at an ambient temperature of 95 °F and with a simulated solar load. It has only 1 phase; the drive trace is shown in Figure 8. The third cycle that is added to fuel economy label testing under the 5-cycle system is the Cold CO, which is the same as an FTP except that it is performed at 20 °F (with increased road load coefficients to account for air density and rolling resistance increases) and involves some operation of the vehicle interior heater.

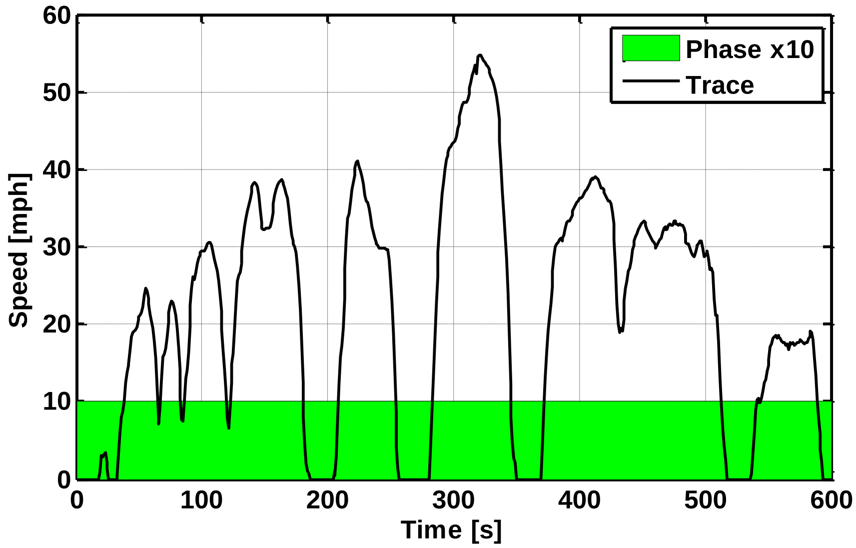

Figure 8. SC03 cycle drive trace.

ii. Calculation formula parts

The test results from the phases of each of the 5 drive cycles are input to a set of formulae to produce final city and highway fuel economy label values. These formulae can be described in five categories which are described in Table 5. Item 2 in the table, the running fuel consumption, defines a harmonic weighting of the fuel consumption results from select phases, which is illustrated graphically in Figure 9. The other quantities listed in the table are derived by extracting and manipulated certain measured effects from the tests. Item 1, start fuel consumption, uses the difference in fuel usage of the cold start and warmed-up operation on corresponding parts of the FTP tests, and then applies a factor based on average trip length so that it can be added as a function of distance to the overall fuel consumption. The effects of temperatures and A/C usage that are observed in the Cold CO and SC03 cycles are factored in through weighting factors 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.

Table 5. The parts of the 5-cycle fuel economy label calculation.

	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 9).
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.

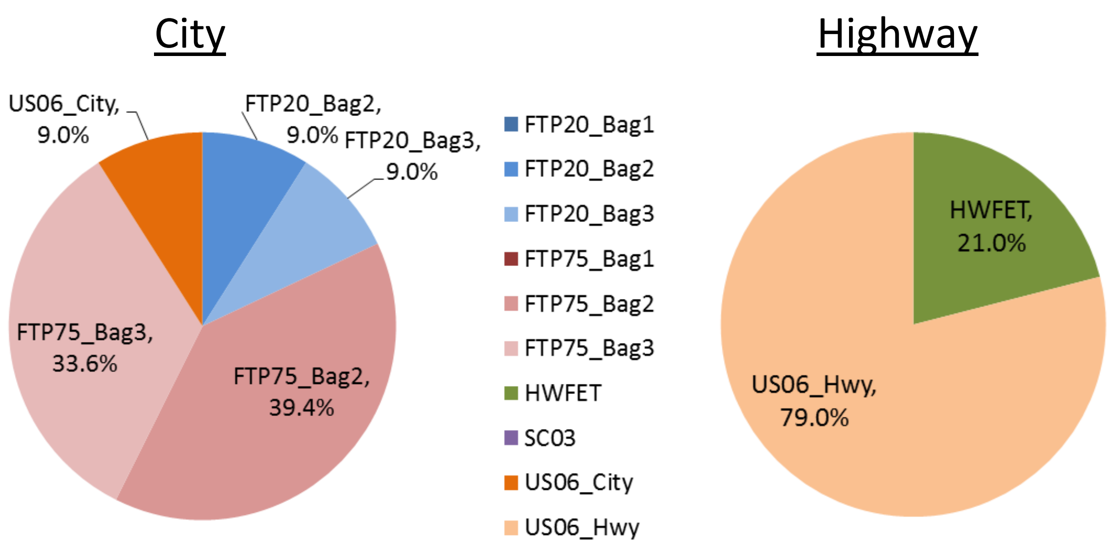

Figure 9. Fractional weighting factors for running fuel consumption only in city and highway fuel economy.

The running fuel consumption is the largest contributor to the total fuel consumption label values, and it represents the vehicle behavior under normal driving. In order to get a good representation of typical U.S. driving patterns from the certification test cycles, EPA performed a regression from the various vehicle fleet studies that correlated the distributions of acceleration vs. speed and vehicle-specific power (VSP) vs. speed to the test cycle phases. VSP is a measure of tractive power per unit mass, which is useful for generalizing the intensity of a cycle. The result of this regression study yielded the harmonic weighting coefficients that are illustrated in Figure 9, which are effectively the fraction of distance that is driven under conditions resembling that phase for aggregate city or highway driving. Note that, with the exception of the HWFET, each contributor to the running fuel consumption is an individual phase from a longer cycle.

One of the derived quantities that has a more complex derivation is the air conditioning fuel consumption. The basis from testing is the SC03 cycle. From that test, the added fuel consumption that is required for operating the air conditioning is calculated. Ideally, such a quantity would be found by simply running a drive cycle with and without the A/C operating and then taking the difference in the two measured fuel consumptions. Since the SC03 is not run without A/C as part of the certification process, an equivalent fuel consumption is computed by subtracting a weighted combination of the fuel consumption on phase 2 and phase 3 of the FTP that correlate to fuel consumption on SC03 without A/C. The weighting factors to distribute the A/C fuel consumption into the overall label value consider two factors. First, EPA used a 1992 study of vehicles in Phoenix which developed an equation defining the percentage of time that an A/C compressor will run as a function of heat index. U.S. aggregate weather conditions can then be used to create a factor predicting the average annual air conditioning "on"-time. The second factor in the equations converts this time basis information to distance, which is a function of the average speeds of the cycles.

Finally, the 5th item in Table 5 showed the 9.5% increase to fuel consumption that is applied to the end of both city and highway results to account for non-dynamometer effects. Despite having accounted for many factors formerly captured in the 22 % and 10 % fuel economy label adjustments through the addition of more cycles, the 5-cycle method still does not account for certain factors that have an adverse effect on real-world fuel economy. Table 6 lists the various factors considered by EPA; the right-hand column indicates the added effect on top of the 5-cycle label fuel economy due to each factor. The most significant factors, which were discussed in detail in [EPA Labeling 2006], include fuel quality, wind, road surface quality, and tire pressure. Although, as indicated in the table, summing the estimated effects of each non-dynamometer factor shows a 12-15 % reduction in fuel economy, EPA decided that this computation was too aggressive, and so applied a final downward adjustment to fuel consumption of 9.5 %, which for the vehicle studied in the rulemaking process led to fuel economy labels that most closely matched real-world observed fuel economy.

Table 6. List of reductions in fuel economy due to non-dynamometer effects. [EPA Labeling 2006]

Factor	Analysis for 1984 Rule	Effect Applicable to 5-Cycle Fuel Economy
Ambient temperature	-5.3%	Included
Fuel Quality	0%	-1.1 to -1.5%
Altitude	-0.1%	-0.1%
Wind	-2.3%	-6%
Road grade	-1.9%	-1.9%
Road surface	-4.2%	-1.4% to -3.2%
Road curvature	-0.1%	-0.1%
Trip length	0.8%	Included
Average vehicle speed	10.6%	Included
Cold starts	-0.7%	Included
Acceleration intensity	-11.8%	Included
Brake drag	-0.3%	-0.3%
Wheel alignment	-0.3%	-0.3%
Tire switching	-0.4%	-0.4%
Tire pressure	-3.3%	-0.5%
Vehicle load	-0.4%	-0.4%
Dynamometer loading	-2.7%	Revised test procedures may have removed most of these effects
Tire effects	-5.1%	
Weight classification	-1.0%	
Manual transmissions	-1.8%	
Power accessories, air conditioning	~0%	Air conditioning included
Sum	-30%	-12% to -15%

iii. Contributions of cycles and derived factors to FE label

Although the harmonic weighting factors on the cycles in running fuel consumption give some idea of how much each of those will contribute to overall fuel consumption, the size of the derived quantities depends entirely upon test data. The relative magnitude of the weighted cycle phase fuel consumptions and the derived effects varies depending on actual vehicle performance in the tests. To illustrate an example using test data from a 2010 Toyota Prius, the contributions are shown in pie chart form in Figure 10 for city and Figure 11 for highway. The running fuel consumption is accounted for in the colored portions of the main pie, and then the slice with start fuel consumption, A/C FC, and the non-dynamometer adjustment is broken out in detail. The running fuel consumption contributions have relative proportions similar to what would be expected based on the weighting factors in Figure 9, but with the two US06 contributions being slightly larger due to the higher intensity of that cycle. Both start and A/C fuel consumption will always be lower on highway driving, since the trip distance in highway driving is longer and the higher average speed reduces A/C demand when given on a distance basis. In both city and highway, the 9.5 % adjustment is still a major part of the non-running fuel consumption.

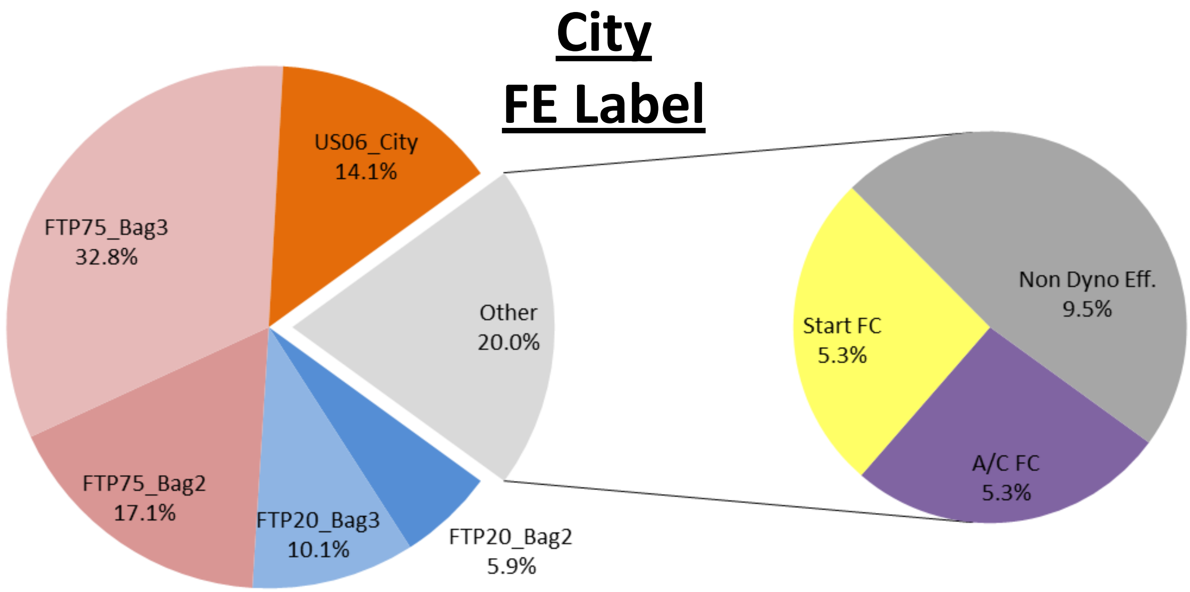

Figure 10. 2010 Toyota Prius 5-cycle City fuel consumption contributions.

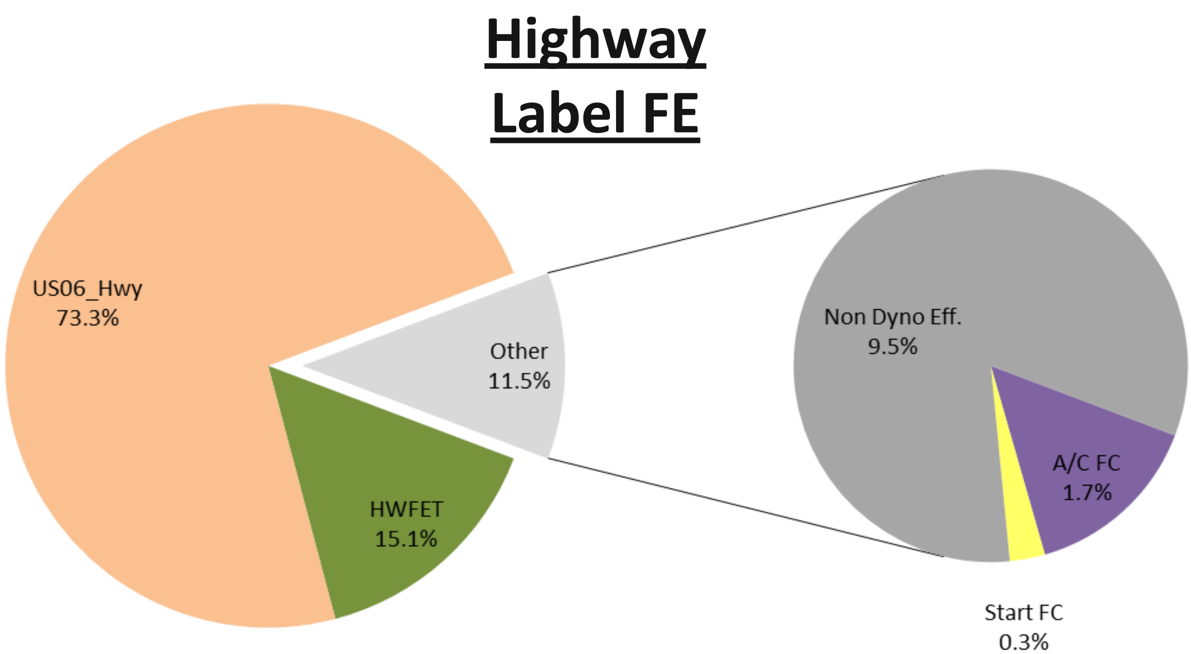

Figure 11. 2010 Toyota Prius 5-cycle Highway fuel consumption contributions.

iv. MPG-based estimate of 5-cycle from 2-cycle

In addition to the full vehicle-specific 5-cycle method described above, there is an alternative method for estimating the 5-cycle fuel economy label values. This estimation method correlates the results from the FTP and HWFET to the city and highway label, respectively. Using these so-called "MPG-based" estimation equations was an acceptable method of generating label values during the introductory phase of 5-cycle from 2008-2010. The equation is also useful for creating estimates of current 5-cycle MPG label ratings for older vehicles in the EPA database, so that, for example, consumers can compare annual fuel cost estimates for a used vs. new car. The linear fits for the MPG-based method were derived by EPA from a dataset of 615 cars from 2003-2006 model years. 14 of the vehicles were hybrids. Each vehicle had test data from all 5-cycles available, however for some, the individual phase results within a cycle had to be estimated using typical ratios of phase to overall MPG. [EPA Labeling 2006, p. 100] The figures illustrating the regression test points from the EPA report are given in Figure 12 for city and Figure 13 for highway, with the corresponding equations overlaid on the graphs. Test values for the hybrid vehicles in the database are shown by the solid points in the figures. EPA listed the standard errors of the difference between the full 5-cycle and MPG-based values as 0.5 MPG for city and 1.15 MPG for highway.

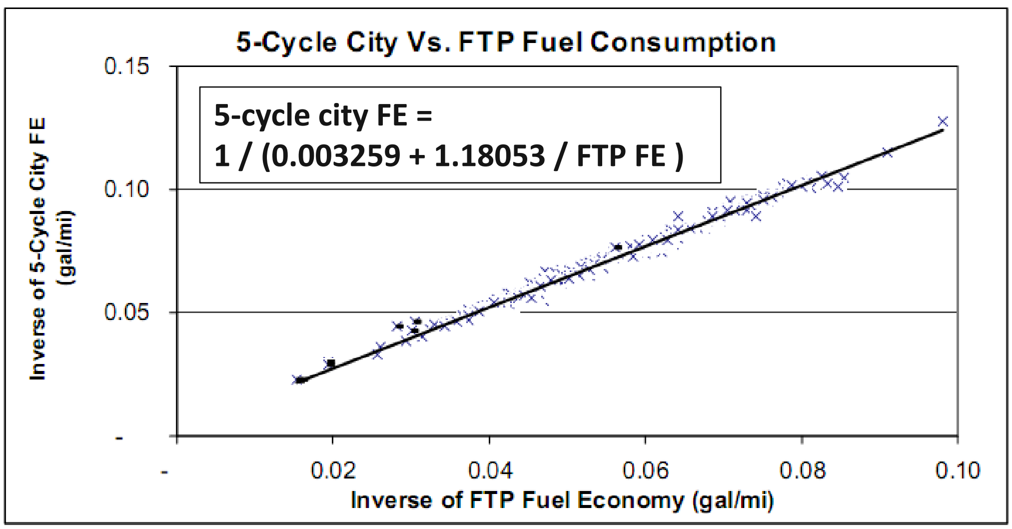

Figure 12. 5-cycle City FE vs. FTP and MPG-based city equation. [EPA Labeling 2006]

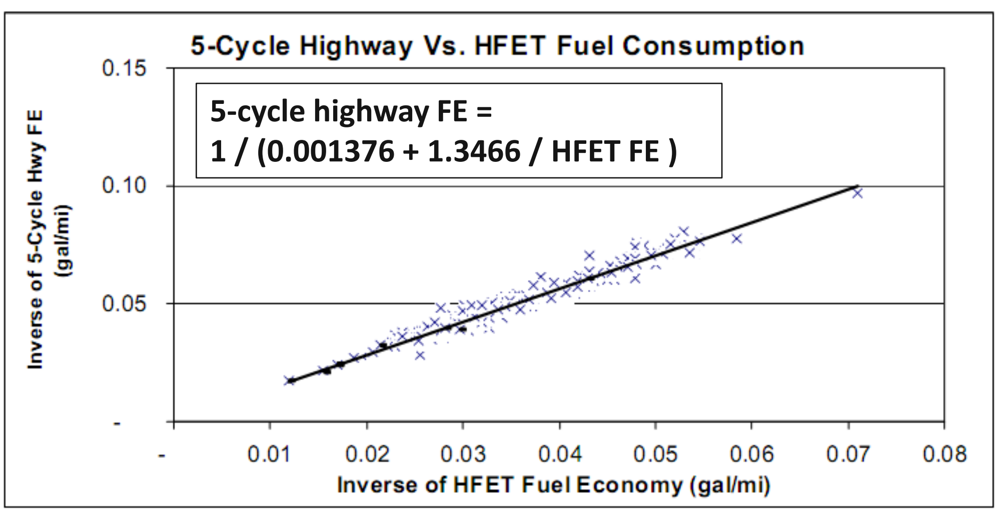

Figure 13. 5-cycle Highway FE vs. HWFET and MPG-based highway equation. [EPA Labeling 2006]

In general, beginning with 2011 model-year vehicles, the full 5-cycle method is required to be used, however certain specific vehicle configurations may still use the MPG-based estimate. The criterion for this decision is stated by EPA as follows: "For model year 2011 and after, if the five-cycle city and highway fuel economy values for an emission data vehicle group are within 4% and 5% of the mpg-based regression line, respectively, then all the vehicle configurations represented by the emission data vehicle (e.g., all vehicles within the vehicle test group) would use the mpg-based approach." [EPA Labeling 2006, p. 142] Examining the 2011 EPA Fuel Economy Guide data file reveals that only 130 of the 842 entries indicate that they are from the vehicle-specific (full 5-cycle) method or a variant, while 712 use derived, MPG-based method. The 2012 data file has a similar distribution. [fueleconomy.gov]

The MPG-based equation is useful for illustrating the larger effect of the change from 2-cycle to 5-cycle for highly efficient vehicles. Whereas under the 2-cycle system, raw FTP and HWFET fuel economies were adjusted downward by 10 % and 22 %, the MPG-based equations show that the FTP and HWFET are effectively adjusted downward by a larger percentage, which is variable with the raw MPG. This comparison is shown in Figure 14. For a high-MPG vehicle, for example, with an unadjusted FTP result of 65 MPG, the MPG-based equation reduces the fuel economy by about 28 %, vs. only 10 % under the previous methodology.

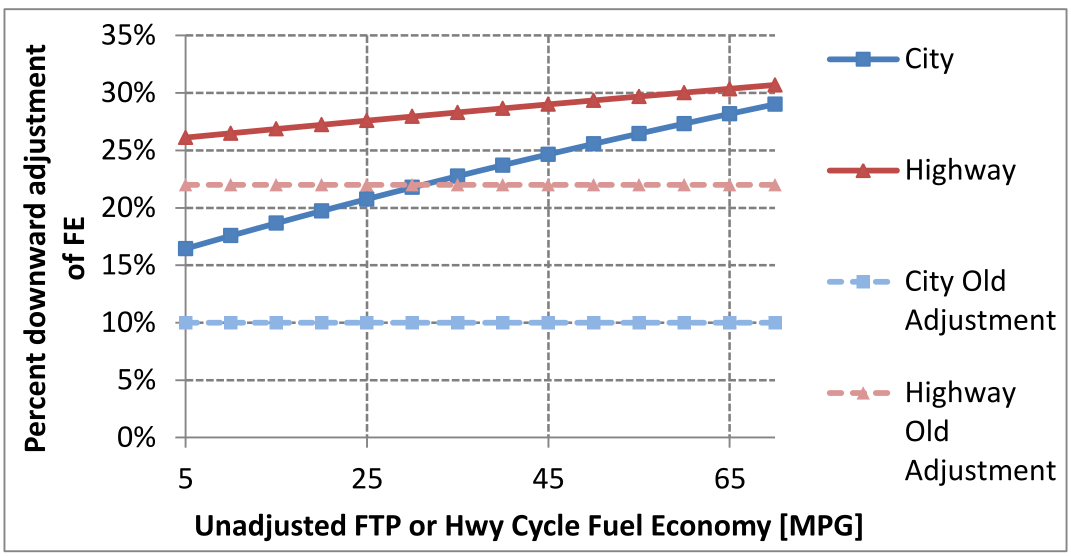

Figure 14. Comparison of effective city and highway fuel economy adjustment 2-cycle vs. MPG-based 5-cycle.

g. Fuel economy label design

The 5-cycle fuel economy calculation methods described here are used to compute city and highway fuel economy ratings which are targeted for consumer knowledge for comparing vehicles. EPA publishes the information in annual fuel economy guides and through a website, but the most prominent form of presentation of this data has been a sticker in the window of every new vehicle sold in the U.S., alongside other required information like suggested retail price and included options. The overall label is called the "Monroney", after the U.S. Senator who sponsored the Automobile Information Disclosure Act of 1958 which mandated the vehicle labeling [Simanaitis 2011]. In 2011, EPA finalized a separate rulemaking affecting the design of the physical fuel economy labels. From 2008 until this new regulation took effect, the 5-cycle fuel economy values were reported on the same label design that had previously been in use. Besides making general improvements to the presentation of information on the label, an important motivation for the update was to better define labels for electric and plug-in electric vehicles (EVs and PHEVs). An EPA-supplied sample label for a gasoline-fueled vehicle (which would include HEVs) is given in Figure 15. The most prominent number on the label is a combined city/highway fuel economy rating in MPG, which is a 55 % / 45 % city/highway weighting on a fuel consumption basis. EPA had previously considered changing the combination weightings to 43 % / 57 % city/highway, which most closely represents the distribution of aggregate U.S. driving on a distance basis, however they elected to retain the current weighting methods, which was suggested to align more closely with consumer perceptions of the amount of time spent in each driving behavior and also matches continued CAFE combination methodology [EPA Response 2006, p. 25]. Next to the combined rating, the city and highway MPG ratings are given. Below that information, the combined rating is also expressed as a fuel consumption in gallons per 100 miles. Other information including fuel costs and comparisons to other vehicles are also presented on the label.

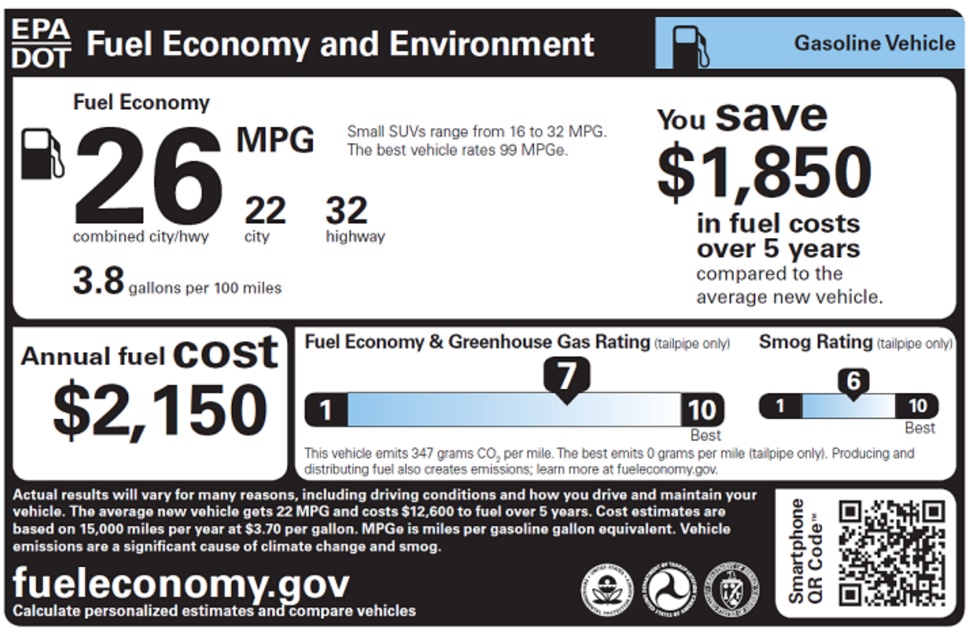

Figure 15. EPA fuel economy label sample for a gasoline vehicle. [http://fueleconomy.gov/feg/label/]

3. Literature review

There are several works that are cited in this thesis which provide key background or support on the topics of fuel economy testing for conventional and hybrid vehicles as well as charge correction. A review of the contents of these papers is provided here.

a. EPA 5-cycle fuel economy labeling technical support document (2006)

The U.S. Environmental Protection Agency (EPA) produced a comprehensive 170-page document with the supporting background information and details of the calculations for the 5-cycle fuel economy labeling method [EPA Labeling 2006]. In the first of three major sections in the report, EPA presents data from various on-road vehicle fleet studies which quantify fuel consumption under real-world driving conditions. Several of these studies also provided the detailed information about the corresponding driving conditions, such as the distribution of speeds and accelerations that the vehicles underwent, which were needed for EPA's derivations of what drive cycles to use as real-world representations. This section also summarized the fuel economy estimates created by independent organizations such as Consumer Reports, the American Automobile Association (AAA), and Edmunds. These estimates not only provide an additional benchmark on the gap between previous fuel economy label ratings and real-world observations, but they also document the frequent complaint that EPA labels for hybrids especially overestimated the fuel economy.

The largest chapter of the EPA technical support document presents the full fuel economy label calculation equations with an explanation of how the various parts were derived. That includes the topics of start fuel, the representative drive cycle mix in running FC, the effects of A/C and cold temperatures, and an adjustment for non-dynamometer factors. Each section generally presents the statistical regressions used on the collected real-world data to produce similar estimates using dynamometer test results from 5 different emissions test cycles. Sensitivities and uncertainties in the formulae are also discussed. The final chapter, which is not relevant to this thesis, considers the costs and general regulatory burden of the new method.

b. SAE J1711 standard for hybrid fuel economy testing (2010)

The Society of Automotive Engineers produces a number of surface vehicle recommended practices, or standards, on the topic of testing. Key to the experimental work undertaken in this thesis is the SAE J1711 standard, entitled "Recommended Practice for Measuring the Exhaust Emissions and Fuel Economy of Hybrid Electric Vehicles, Including Plug-in Hybrid Vehicles" [SAE J1711 2010]. The standard was first published in 1999, and the latest version from June 2010 was updated mainly to incorporate methods for testing PHEVs. The standard was developed by a committee of various stakeholders, including members of original equipment manufacturers, national labs, and other government agencies. The practices defined in this type of standard often are used by government regulators as a basis.

The most important sections of J1711 for hybrid electric vehicles relate to the considerations of battery energy in testing procedures. The standard first establishes clear terminology in the relevant areas and defines a method for measuring net battery energy change. The method involves using an off-board power analyzer to measure cumulative battery current. This value is multiplied by nominal battery voltage to become a measure of equivalent energy. The standard defines a metric for what net battery energy change is acceptable during a test to be considered charge-sustaining operation. The exact test steps and related calculations are defined for each of the EPA fuel economy / exhaust emissions dynamometer cycles with references to the related portions of the Code of Federal Regulations.

An appendix in SAE J1711 outlines a method for making corrections to fuel economy values when a charge-sustaining result is desired but not obtained directly in a single test. This method is used in the testing performed as part of this thesis.

Another large body of the standard explains how to test PHEVs, which require two phases: one to determine fuel and electric consumption under charge-depleting (CD) operation, and one under charge-sustaining (CS). In addition to giving explicit test procedures, the standard gives a method for combining these two results into a single fuel economy number by a weighting term called the utility factor (UF). The UF is assigned based on the electric range determined by testing, and it essentially gives a percentage of distance covered in CD and CS modes for aggregate fleet driving by a vehicle as a function of range.

c. Morita et. al paper comparing charge correction methods (2001)

This paper, presented at the Electric Vehicle Symposium (EVS) 18 in Berlin in 2001, discusses the impacts of charge-correction on full-cycle fuel economy results [Morita 2001]. The authors, Morita et. al, are from the Japan Automobile Research Institute. Their testing work was performed using three of the early production hybrid electric vehicles available at that time. Three methods determining fuel economy for hybrid vehicles are considered for comparison. They are:

- Continuous repeating method – cycles are driven multiple times in succession and the overall average fuel consumption is taken. This method takes advantage of the stabilization around a steady SOC that hybrids will undergo after a certain period of homogeneous driving conditions.
- Linear approximation method – fuel consumption is measured in tests with varying amounts of electric charge change, and the charge-sustaining FC is taken by linearly interpolating with respect to electric energy change to find the value at zero electric consumption.
- SAE J1711 – here refers simply to the criterion from the standard which states that a test can be considered charge-sustaining when the net change in battery energy is less than or equal to 1 % of fuel energy consumed for the cycle.

The linear approximation method from this paper is the same as a charge-correction option defined in the appendix of the latest SAE J1711 version, and it is the method that is used in testing for this thesis. The Morita paper shows the interesting phenomenon of the 1 % of fuel energy criterion that fuel economy can vary among several tests even though they are all considered CS according to the criterion. The paper gives results for the 10-15 mode Japanese cycle, the NEDC, HWFET, and UDDS. In the worst case on the UDDS and HWFET cycles, the fuel economy of one vehicle spanned a range of 96 – 104 % of the true charge-sustaining fuel economy (as determined by the linear approximation method) while remaining within the J1711 criterion.

Emissions of CO, total hydrocarbons (THC), and NOx were also measured during the testing performed by Morita et. al, and they determined that there was no correlation between electric energy change and emissions levels within the ranges observed.

d. Duoba et. al paper on robustness of fuel economy measurements (2005)

This paper presented at the Electric Vehicle Symposium 21 in 2005 provides laboratory testing support for the assertion that previous (then current) EPA methods of calculating fuel economy do not match on-road observations and that the gap is largest for hybrid vehicles [Duoba 2005]. Using two hybrids and four conventional vehicles (Toyota Prius, Honda Insight, Toyota Echo, Ford Focus, Ford Escape, Jaguar XJ8), testing was performed on a number of different cycles. First, the results from the Ford ATDS and US06 drive cycles, which are more intensive drive cycles than those used in 2-cycle EPA calculations, are compared to the EPA label values. This metric showed that hybrids had the greatest percentage reduction in fuel consumption on the US06 over the EPA values. A notable outlier was the Jaguar XJ8, which actually had lower fuel consumption on the US06 than on the EPA 2-cycle tests.

In order to quantify the "robustness" of vehicle fuel consumption to more intensive driving, Duoba et al. performed testing on UDDS cycles with varying intensity at multiples of 0.8, 1.0, 1.2, and 1.4x. The paper presents graphs showing the trend in fuel consumption for each vehicle between the scaled results. The robustness of the various vehicles is defined in terms of an "FC sensitivity factor" which is the percent change in FC divided by the cycle multiplier. The Honda Insight and Toyota Prius had sensitivity factors of 0.456 and 1.105, respectively, with the worst conventional vehicle tested, the Toyota Echo, having a factor of 0.308. The Jaguar XJ8, the most robust vehicle, had a factor of only 0.086, indicating that fuel consumption was only minorly affected by changes in cycle intensity. The paper is concluded with a more detailed calculation of the vehicle powertrain efficiencies with insight into the reasons that hybrids are generally more sensitive to driving intensity.

This paper provides a strong foundation with extensive test data to show that hybrid vehicles are generally less robust to increases in driving intensity. This fact supported the motivation for developing the 5-cycle fuel economy label calculation method and is useful in considering how the addition of certain more intensive drive cycles such as the US06 to the label value could affect hybrid powertrain design decisions.

4. The challenges of charge correction: background and motivation

a. 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 16 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 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 the fuel for vehicle propulsion. Plug-in vehicles can be recharged through grid electricity, but may also include combustion engines (in the case of PHEVs). An extended-range electric vehicle (EREV) is a PHEV which can operate with full performance in an electric-only mode.

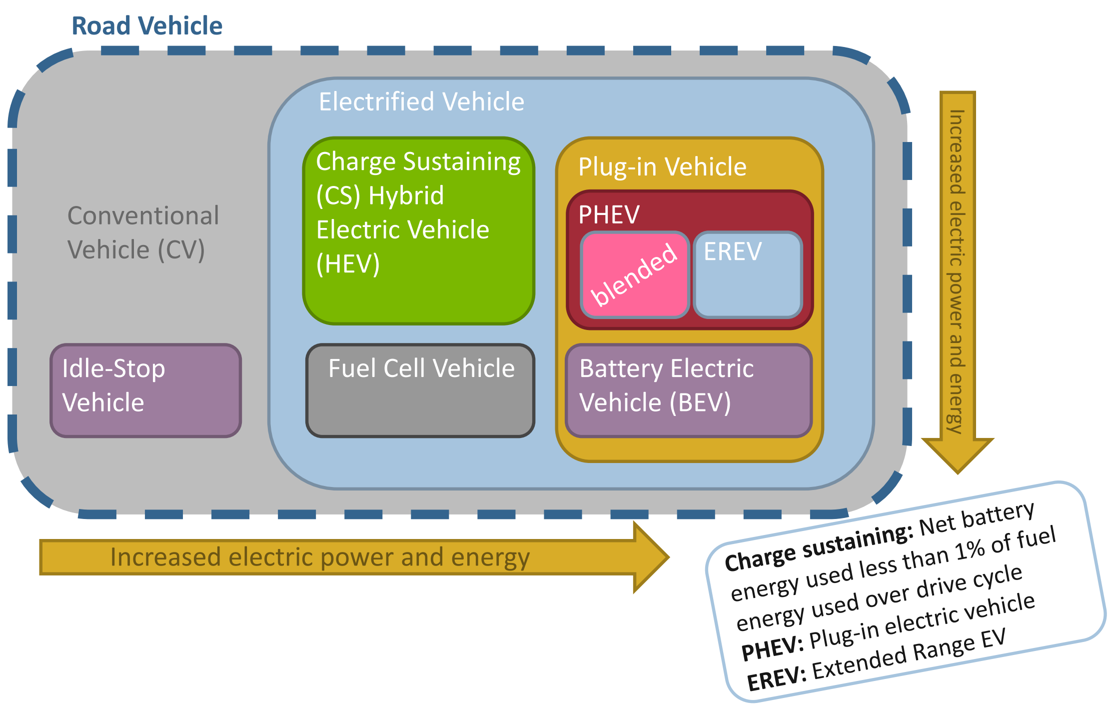

Figure 16. Vehicle classification terminology diagram.

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 consumption 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.

b. 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 [SAE J1711 2010]. (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.

There is also an inherent possibility for variation in fuel consumption results 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 [Morita 2001]. Using example data from testing of a 2010 Toyota Prius described in later sections, Figure 17 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. 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.

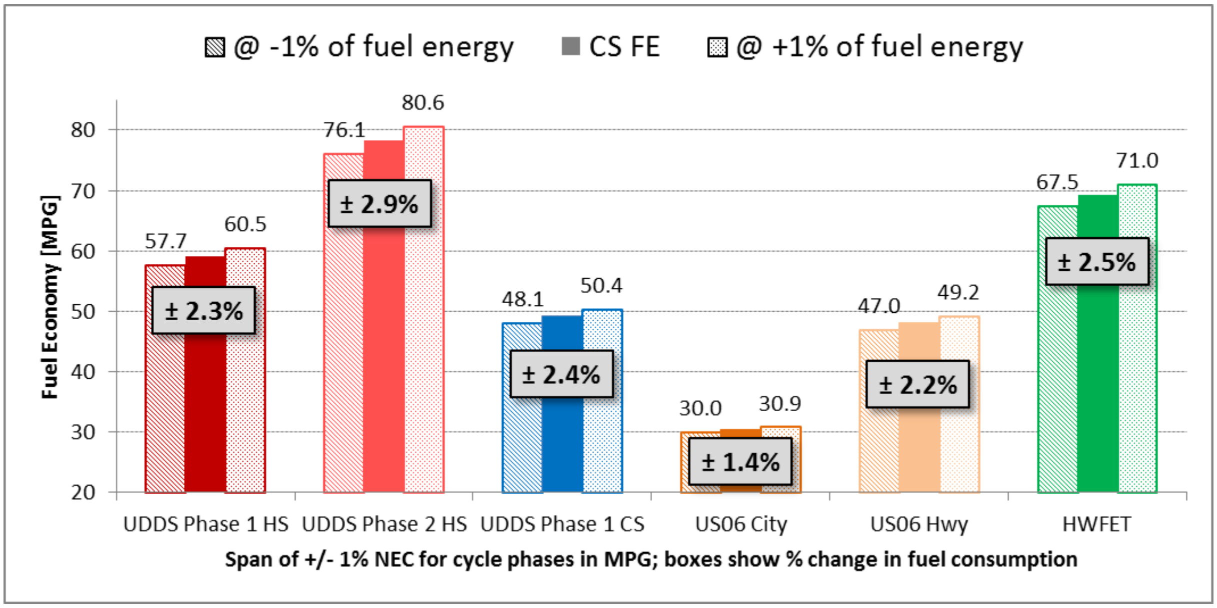

Figure 17. Range of MPG within ± 1 % NEC on each cycle phase.

c. The challenge of charge balancing and need for correction

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 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 electric energy consumption up to +/- 5 % of fuel energy (and to consider any result within +/- 1 % of fuel energy as charge-sustaining). Situations with much larger electric energy swings, such as in a blended PHEV on a CD cycle, should not be corrected according to this method of linearly interpolating the charge correction behavior. In order to have a correction line of appropriate accuracy, the standard requires at least 4 test points for its definition, with 2 each within the 1-5 % window for charging and discharging electric behavior. Figure 18 is an illustration from the standard showing the requirement. Here, an example is also shown where a new test point is then corrected using the derived slope. For this Toyota Prius study, the Regression Correction Method was used, whereby the charge sustaining fuel consumption was simply taken to be the intercept of the regression line. A final item to note on the diagram is a criterion that the fuel consumption on any test points used to compute the regression must not exceed a 5% deviation from the value predicted by the resulting regression line. In other words, gross outliers should be deleted from the regression computation.

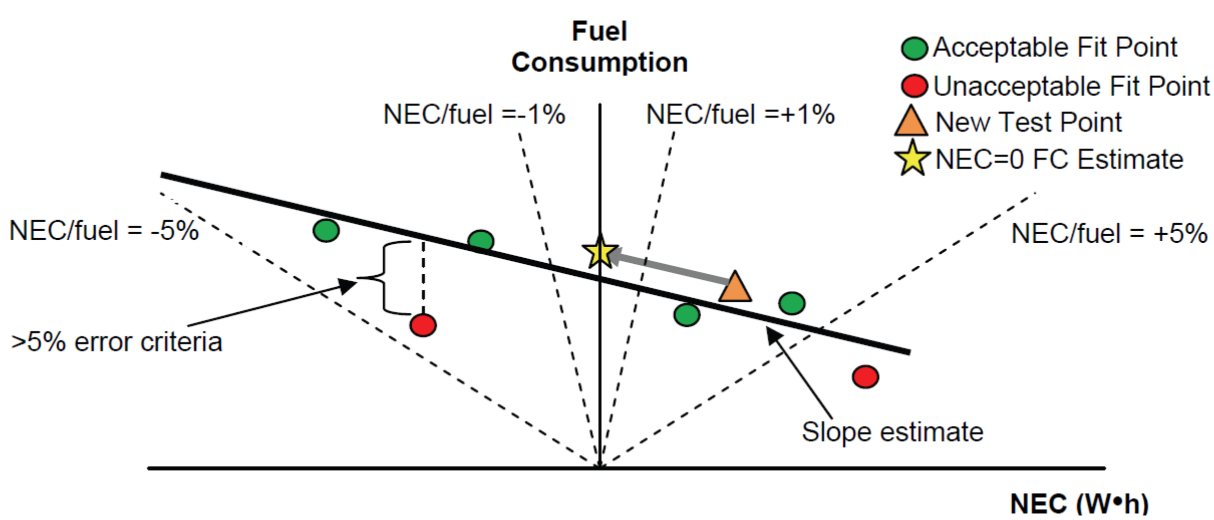

Figure 18. SAE J1711 Slope NEC Correction Method Illustration for a sample cycle. [SAE J1711 2010]

d. Measuring battery energy change

Computing the NEC requires accurate measurements of both the fuel consumption and the net electric energy consumption from a battery. Fuel consumption measurements are highly standardized by certification bodies, and are typically determined using a carbon balance methodology whereby the captured carbon gases from the exhaust are measured to determine the amount of the fuel of known properties that was burned in producing them. Fuel consumption may also be monitored directly by a fuel scale which meters flow through the vehicle fuel supply lines. In addition to being used to express volumetric fuel consumption (e.g. as L/100 km or gal/100 mi), the heating value of the liquid fuel is used to convert the mass of fuel consumed on a cycle into an energy quantity. These methods of measuring the consumed fuel are well-established.

For keeping track of battery energy, however, not all methods produce the same result. The fundamental issue is that the internal losses of a battery and the variance of terminal voltage with the load current cause the total energy in and out of the electric terminals of the battery to not be conserved. In other words, it takes more energy to recharge a battery to a particular state of charge than was output in the course of discharging from that state. The level of electrical charge of a battery most closely correlates with the capability to output a certain amount of cumulative current flow. SAE J1711 acknowledges this fact by defining the net electric energy change as the cumulative current in Amp-hours, converted to energy units by multiplying by a representative system voltage.

There are differing methods for determining the system voltage to be applied for a test result, including simple averaging over time, using a spec nominal voltage for the observed SOC range from battery test data, or interpolating a voltage at zero current from the collected data points. SAE J1711 opts for wording in support of using battery specifications, calling V_{system} the "nominal propulsion battery voltage associated with the SOC in CS operation," and noting, "This value should be supplied by the manufacturer" (sect. 3.3.3, p. 10). The test operators must therefore determine a representative SOC level of the battery during the test and have adequately detailed battery specifications to obtain voltage under this condition. Although not explicitly addressed in the standard, this specification can also be a function of temperature, which would need to be considered to match test conditions.

The convention used by engineers at ANL's APRF is to regress a zero-crossing voltage, V_{zc}, out of test data, which is necessary when detailed battery test data are not available and also to take into account the effects of temperature and varying SOC level. The method essentially finds an open-circuit voltage by looking at every point of current and voltage recorded during a test (including both positive and negative current flows), and linearly interpolates to find what the voltage would be at zero current flow. Figure 19 shows an example of this fit from a drive cycle. The dashed lines on the plot show contours of constant power for reference.

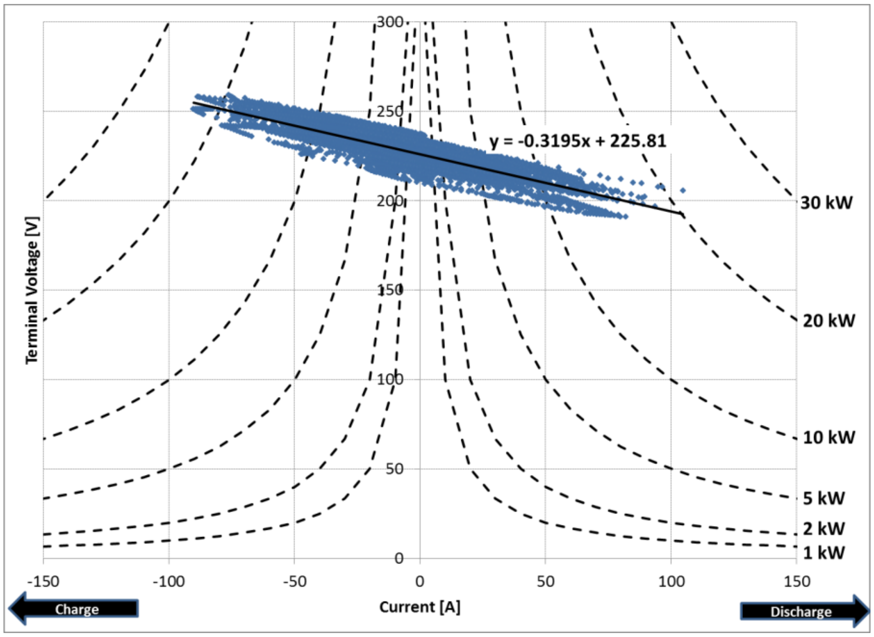

Figure 19. Sample zero-crossing battery voltage regression plot from a test of the 2010 Toyota Prius.

The difference between methods for computing battery energy change is illustrated over the course of a UDDS test of the Prius in Figure 20. There are 3 battery-related quantities plotted over time: the reported SOC from the onboard diagnostic system, integrated power, and integrated current times zero-crossing voltage. The solid blue line based upon integrated current corresponds with the battery SOC shown with red points, since both quantities attempt to indicate the true change in available charge in the battery. (The sign convention of the energy metrics is flipped for this plot such that increasing stored battery energy matches increasing SOC). This UDDS cycle was charge sustaining, and so both the SOC and the integrated current times voltage return to their starting points. However, the dashed blue line showing integrated power indicates 60 Wh above the starting point. This energy is actually dissipated in battery losses and is not available as charge anymore. These internal battery losses mean that integrated power at the battery terminals is not conserved over the course of battery usage, even when the battery is returned to the same charge level. The plot shown here helps to illustrate and confirm the distinction between battery integrated power output and NEC, which should be based upon the Amp-hour change measured at the terminals.

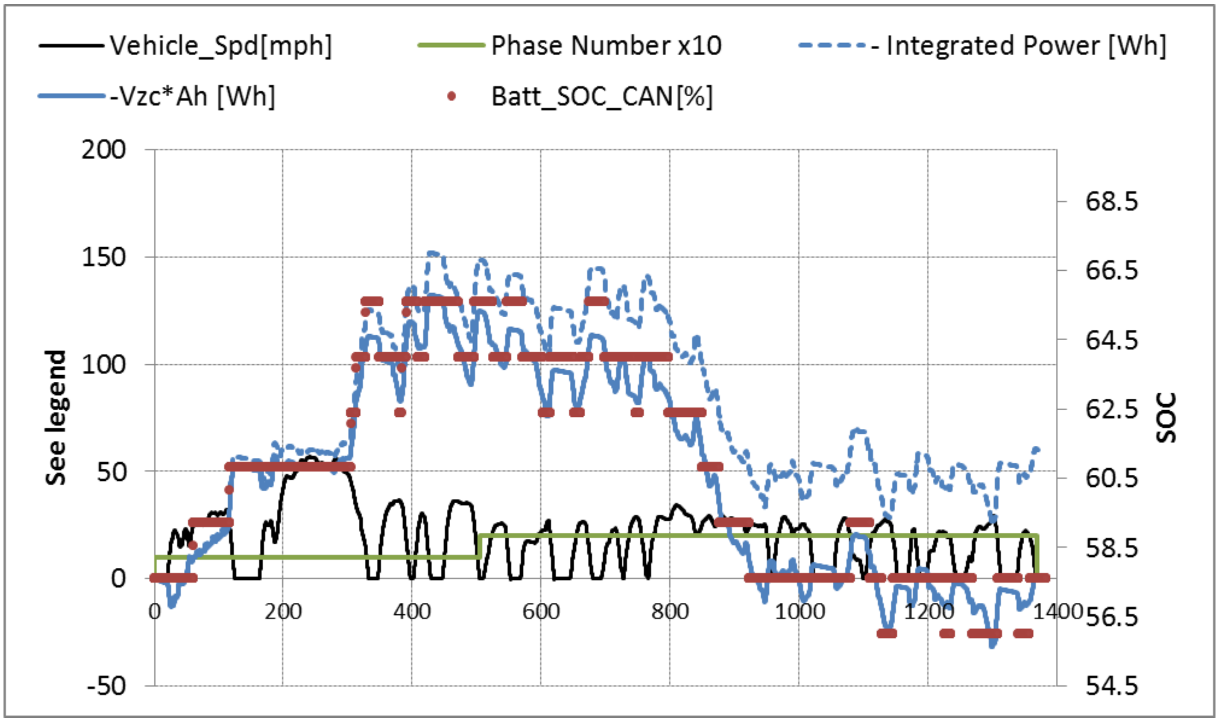

Figure 20. Plot of the Prius battery energy changes over a CS UDDS.

To reiterate, the goal of NEC correction is to determine the fuel energy associated with a particular delta in battery charge. Consider the example points shown in Figure 21, where the abscissa shows integrated current. For an HEV, the assumption is that a vehicle moves from CS to point A due to excessive engine charging. So, the desired electric energy quantity to be used in a charge-correction plot is the electric energy input to the battery in the course of charging it by 0.5 Ah. At point B, we may assume that too little engine charging occurred, so the FC would need to be increased proportional to the amount of electric energy required to charge the battery by 0.5 Ah, exactly as in point A.

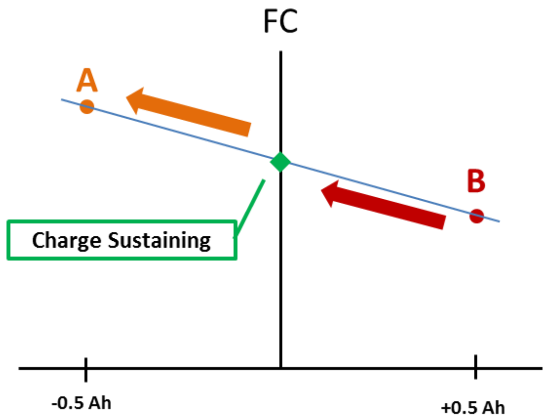

Figure 21. Illustration of equal Ah charge and discharge for 2 example tests.

Therefore, the ideal voltage value to use in the calculation would be a representation of the battery terminal voltage under typical engine-driven *charging* current levels for a particular drive cycle and SOC level. Using a nominal or open circuit voltage under the same conditions is a simplification thereof which can be practically implemented during testing. Within the narrow allowed band of charge correctability, as long as a consistent method of using nominal or zero-crossing voltage is used, the CS intercept of the charge correction line would not be greatly affected. In fact, it could even be proposed to simply use Ah as the electric units. However, there are two downsides to this method. First of all, electric energy has a greater physical linkage to fuel energy, since it comes as a result of engine energy output. More importantly though, expressing electric *energy* change enables the comparison of charge-correction slopes across multiple drive cycles with differing intensities, SOC levels, etc. These important and relevant factors are not taken into account if Ah units are used.

5. Experiment to derive charge correction for all phases and the effect on the fuel economy label

a. State of charge issue on 5-cycle phases

Although overall cycle fuel economy measurements (and likewise valid emissions testing results) can typically be obtained directly under CS operation, the EPA fuel economy label calculations that are currently in effect weight the fuel consumption values from individual phases (i.e. emissions bags) of the UDDS and US06 cycles. Therefore, the fuel economy label value will be affected by nonzero NEC over the individual phases. To illustrate the relationship between electric and fuel consumption for a vehicle, a typical figure plots fuel consumption on the ordinate axis vs. electric consumption on the abscissa. Figure 22 is a plot of this type, showing cold and hot start urban cycles and the US06 for a 2010 (3rd generation) Toyota Prius HEV. This data was derived from baseline testing of the vehicle on full-length certification cycles. For single tests where the overall result was CS, it is shown here that the individual phases of those cycles can have significant amounts of electric charge or discharge. In effect, the plot shows the natural behavior of the vehicle control strategy in terms of how it distributes the tradeoff between fuel and electric energy between different phases of a single drive cycle test. For example, on a UDDS cycle, phase 2 consists of lower speed driving where the Prius operates under electric-only propulsion for much of the time. This behavior is reflected in the 30 Wh/mi electric consumption that occurs on the overall CS cycle. Many of the phase points shown in Figure 22 fall at or beyond the 5 % of fuel energy limit for correctability, which is marked on the plot by the outer set of thin dashed lines.

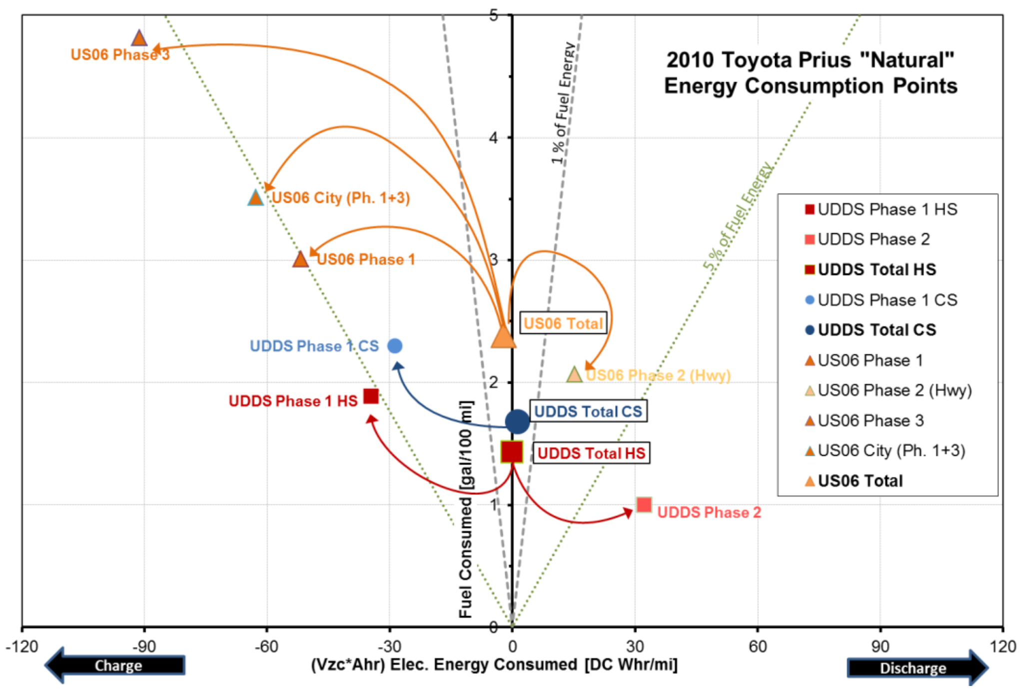

Figure 22. Toyota Prius Urban and US06 energy consumption by phase on overall charge sustaining cycles.

The EPA 5-cycle equations do have one specific provision for hybrid vehicle testing: hybrids are required to repeat the warmed up phase of the UDDS as part of the FTP at 75 °F. In other words, for hybrids, the FTP becomes a 4-phase procedure which is two full UDDS cycles. The equations therefore are slightly altered to include that 4^{th} phase rather than assuming it would be the same as phase 2 during the cold-start UDDS. The rationale was that hybrids do not warm to a steady, predictable operation as quickly as conventional vehicles. Another variation is allowed, where only 2 emissions bags are collected: one for each full UDDS. There is a version of the 5-cycle equations which uses this data to compute both start fuel and running fuel consumption, which would mitigate the effects of charge-imbalance within the two phases of each UDDS. However, the Cold CO test (FTP at 20 °F) is always a 3-phase test, for both conventional and hybrid vehicles, so the charge imbalance issues would be acute for that test. For this paper, in considering effects of phase NEC and correction, no distinction is made between phase 2 and phase 4 of an FTP, since both are effectively tested as phase 2 of a UDDS cycle.

The possibility of using a full US06 instead of the separate city and highway bags is presented parenthetically in the technical support document but not a currently permitted alternative under the regulations. Using a regression to full US06 cycles resulted in the US06 being eliminated from the city calculation and being 75% on the highway, with HWFET making up the balance. Using this alternative formulation, the average city MPG increased, but the average highway fuel economy was 2 MPG lower for both hybrids and conventional vehicles [EPA Labeling 2006, p. 132]. This result is expected considering the highly dynamic portions of the US06 that would be included in the highway calculation.

EPA did also briefly acknowledge HEV charge-balance issues in response to questions from a vehicle manufacturer about whether charge-correction methods would be allowed. They reiterated that vehicles should be re-tested if they do not meet charge balance criteria on full cycles and said, "We would be willing to evaluate such a proposal to allow data validation by applying battery SOC corrections to fuel economy results, in addition to the existing provision for a discretionary re-test." [EPA Response 2006, section 6.5] The possibility that correction could be done a per-phase basis was not addressed explicitly, nor were concerns about the effects of phase NEC on the fuel economy label calculations.

The bottom line is that per-phase results are the currently sanctioned method for calculating the fuel economy label, so a judgment about potential changes to regulations would depend upon the degree to which charge-balance issues may exist. Addressing this issue is the motivation behind the charge-correction experiment described here.

b. Experimental setup

In order to provide a fair and valid fuel consumption metric in the computation of EPA label values, the NEC of individual phases should be considered. A set of experiments was performed to obtain measurements at a variety of fuel and electric consumption points to create charge correction lines for each phase of the multi-phase cycles used in the fuel economy label calculation. A report on this testing work and results are documented in an upcoming (2012) SAE paper in addition to within this thesis document [Meyer 2012].

Testing took place at Argonne National Laboratory's 2WD chassis dynamometer lab. The vehicle is shown as set up in the facility in Figure 23. Fuel consumption was measured using a fuel scale which records instantaneous and integrated flow through the vehicle onboard fuel supply line. Battery measurements were recorded by a Hioki power analyzer. The vehicle had been modified to include a wire loop from the high-voltage battery where a current clamp could be affixed. This Toyota Prius has been highly instrumented, including a torque sensor at the output of the engine before the hybrid transmission, numerous thermocouples to monitor engine fluids, exhaust, and the battery, plus an ability to read data from the vehicle's CAN bus and service scan tool.

Figure 23. 2010 Toyota Prius test vehicle on the ANL 2WD chassis dynamometer.

The charge or discharge behavior was forced by adjusting the battery SOC before each test. To decrease the starting SOC, the battery was discharged by selecting the driver-accessible EV mode button and driving the vehicle at low speed on a simulated grade. To charge the battery prior to a test, the chassis dynamometer was motored at constant speed (e.g. 20 MPH) with the vehicle in drive while the driver lightly applied the brake pedal to capture regenerative braking energy.

Aside from the issue of artificially preconditioning the battery to produce the desired test result points, it was important to prepare the vehicle for each measured test as closely as possible to the method that would be employed during certification testing. The preparation steps are specified by the EPA and recorded in the Code of Federal Regulations (CFR) title 40 parts 86 and 600 [CFR40 2010]. A brief description of the preparation that would occur before each cycle phase is shown in Table 7. The required preconditioning cycles ensure that fuel consumption will be measured at a consistent vehicle thermal state. It was also discovered during the course of preliminary testing that a vehicle may be sensitive to recent cycling of the ignition or key switch. For example, driving phase 2 of the UDDS immediately after switching on the key of the vehicle may cause different engine behavior than if the vehicle has been powered on for a period of time, even if important thermal measures such as engine oil and coolant are at similar levels. Due to the many parameters that may be considered by the complex control strategies in modern HEVs, there are a larger set of factors that can possibly influence the fuel consumption result than for conventional vehicles.

Table 7. Cycle preconditioning guidelines.

Cycle Phase	**Prep / preconditioning actions**	**Key on/off preceding test ?**
UDDS Phase 1 Hot Start (HS)	Vehicle is warm as after a full UDDS, then a 10 minute soak directly precedes the measured test	**Off**
UDDS Phase 2	Vehicle should have driven UDDS Phase 1 immediately prior	**On**
UDDS Phase 1 Cold Start (CS)	Vehicle has soaked for 12-36 hours with key off; so any SOC adjustment is done prior to soak period	**Off**
US06 City	Preceded by a US06 prep cycle and 1-2 minutes of idle	**On**
US06 Hwy	Preceded by a US06 prep cycle plus the first city driving mode	**On**
HWFET	Preceded by a HWFET prep cycle and 17 seconds of idle	**On**

For this study, a set of tests was also run to show charge correction on the HWFET cycle as a comparison to the phases of US06 and UDDS. One comment to note in terms of the future practicality of finding charge correction lines for individual phases: in order to obtain 4 points per line on each phase from a multiphase cycle used in the fuel economy labeling, at least *32 tests* would be required! That would be 4 tests each from: (a) Phase 1 and (b) Phase 2 of a cold start UDDS, (c) Phase 1 of a hot start UDDS (if we assume that phase 2 hot start is the same as phase 2 after a cold start), (d) US06 city section, (e) US06 highway section, and then each of the UDDS tests a,b, and c performed at 20 °F. In this study, facilities were not available to do cold temperature testing, so 20 tests would have been the minimum required.

In reality, more tests than that may be required since it is difficult to predict the initial battery SOC required to get a test point with a desired electric charge or discharge value. In fact, it is only possible to do so as a result of test experience or a thorough understanding of the particular vehicle's control strategy. These points are not the same between different cycles, either. For example, an initial SOC of 50 % may cause the vehicle to charge at 20 Wh/mi on the highway cycle, but result in a charge rate of 60 Wh/mi in UDDS phase 1 driving. In actual testing, the results of 31 tests were used for UDDS and US06 phases, plus 4 HWFET tests and 6 tests which were discarded from early testing where the effects of a key-off event were not yet understood. Each test required proper vehicle warmup or preparation, which also adds time, although some tests can serve as preparations for each other if the test facility supports cycling the measurement equipment (e.g. completing data processing after each test) quickly enough.

c. Results

The end result of the testing efforts was the charge correction lines shown in Figure 24. (Full tabulated results with the value represented by each data point can be found in Appendix A). Each point is one test of that phase, and a linear best fit is drawn through all of these tests. The original data point extracted from the full charge sustaining cycle is shown for each phase by the unfilled point, for reference. Most lines have a good distribution of points on both the charge and discharge sides according to the guidelines of SAE J1711. The most notable exception is the US06 city phase, where it was nearly impossible to force the vehicle to charge deplete. Typically, the vehicle could be forced to this behavior by charging the battery to a very high state, such that the vehicle would use extra EV mode or electric assist.

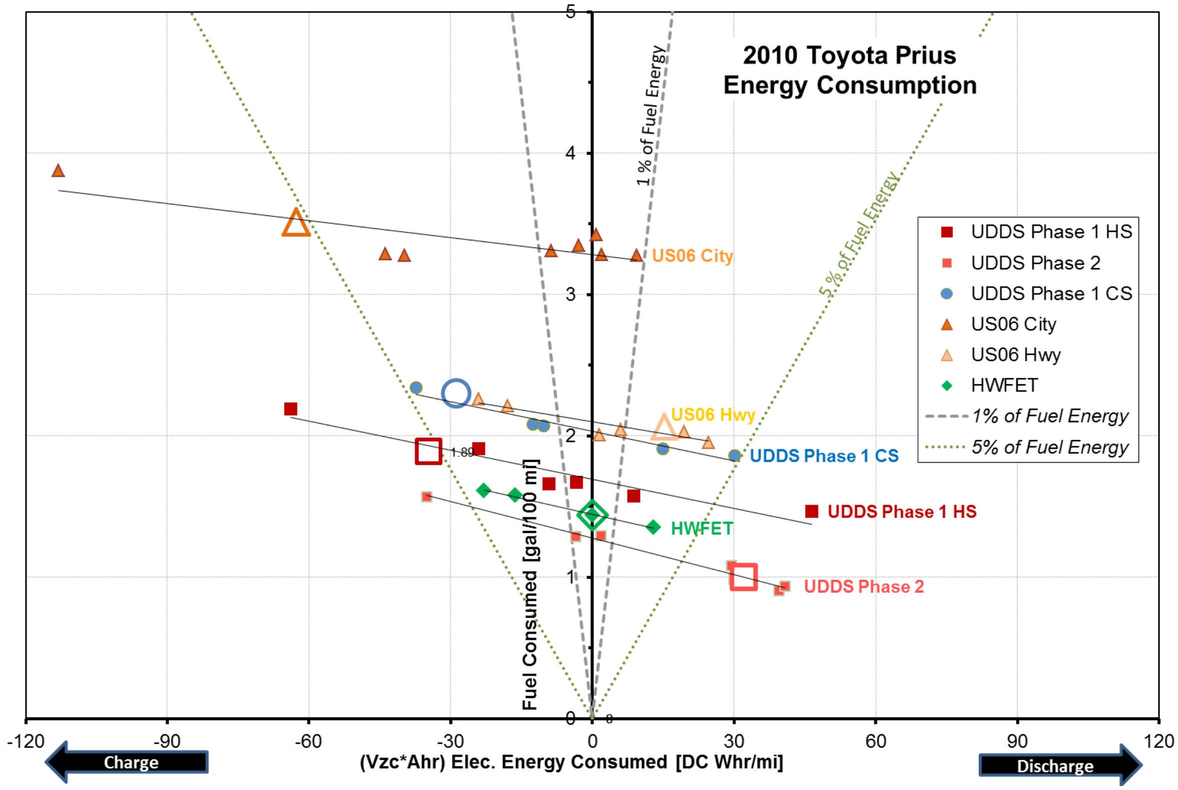

Figure 24. Toyota Prius energy consumption for a variety of test points on each cycle phase, showing the linear regression.

The linear regressions through each phase's energy consumption points are quantified in Table 8. The units of slope on the graph are change in fuel consumption in gal/100 mi per change in electric consumption in Wh/mi. If the slope is inverted and fuel volume is converted to energy using the lower heating value, the resulting value effectively gives a marginal charging efficiency, excluding battery losses. Note that some charge energy comes from regenerative braking, meaning that the energy flow path may not have simply been direct engine charging. When looking at the slopes in this form, the outlier of the US06 City is most interesting, since the value is 75% (the slope has a negative sign due to the convention of electric *discharge* being positive). The number may seem unrealistically high – that it would suggest very little fuel usage to gain additional electric energy. However, the reason for the skew is that for this cycle phase, the difference in electric energy change for each test point was primarily caused by limitations on regenerative braking. Therefore, moving to more negative electric consumption (i.e. charging) merely recovers otherwise wasted braking energy, thus having little effect on fuel usage. Some of the details of these kind of vehicle behavior changes are discussed later. Continuing through the data table, the third data column is the intercept of the linear regression, which is taken to be the true charge-sustaining fuel consumption. That value is then shown in MPG and contrasted with the MPG result from the uncorrected phase value taken from an overall CS cycle. The final column is the percent error in fuel consumption between the uncorrected and corrected phases.

Table 8. Charge correction data regression summary.

Cycle	Raw Slope [gal/100 mi per Wh/mi]	Inverse Unitless Slope [Elec Energy / Fuel Energy]	Intercept [gal/100 mi]	*Corrected* Phase MPG	Phase MPG of CS cycle	% Error from CS FC
UDDS Phase 1 Hot Start (HS)	-0.00687	-0.436	1.69	59.1	53.1	11%
UDDS Phase 2	-0.00858	-0.349	1.28	78.3	100.1	-22%
UDDS Phase 1 Cold Start (CS)	-0.00694	-0.431	2.03	49.2	43.5	13%
US06 City	-0.00399	-0.751	3.28	30.5	28.5	7%
US06 Hwy	-0.00660	-0.454	2.08	48.1	48.4	-1%
HWFET	-0.00743	-0.403	1.45	69.2	69.4	0%

Charge correction tests were not run for full UDDS or full US06 cycles, but such an effort would produce different results than doing the individual phases. In fact, combining the intercept NEC=0 fuel economies of phases 1 and 2 of the UDDS does not result in the same fuel economy value as the charge sustaining single test. This fact can partially be expected due to scatter/variability in the data, but also because the transfer between electric and fuel energy does not occur within the one bag (according to its correction curve) but throughout the entire cycle.

The regression lines fit the data well for most cycles, with R-squared falling between 0.91 and 0.99 for every phase except the US06 city, for which R-squared is only 0.67. Some of the provisions in the SAE J1711 standard such as the 5 % NEC limit for charge-correction and the requirement of at least 4 points per correction line help to improve the accuracy of the charge-correction derivation. A relatively small part of any inaccuracy in the measurements taken in this testing is due to instrument uncertainty. The fuel consumption measurement equipment, the power analyzer used to monitor battery energy, and the dynamometer distance measurement are much more accurate than the inherent variability in testing due to vehicle conditioning or driver error. Indeed, these potential factors affecting test repeatability were more exaggerated in this investigation than under normal certification testing due to the unconventional preparatory steps required for testing subsections of larger cycles with battery preconditioning. A rule of thumb used by engineers in the APRF testing facility is that fuel consumption measurements in chassis dynamometer drive cycle testing are accurate to within 2 % of the true value, although the effort to quantify this overall test accuracy more precisely is still ongoing.

d. Additional analysis of vehicle behavior changes at varying charge or discharge points

In order to apply the charge correction slopes to fuel consumption results, it is assumed that the slope gives a tradeoff in the fuel energy required to produce a certain battery charge delta. The test results show that for some phases, this assumption does not match the reality of what changes take place at different test points. On the HWFET, the changes are simple. Due to power split speed limitations, the engine runs for nearly the entire test, so the vehicle will apply additional engine loading as needed to charge the battery, or will blend electric assist to deplete.

i. UDDS Phase 2

A case which is slightly different is the UDDS Phase 2. Here, the default Prius behavior includes a significant amount of EV operation during low speed driving. If the battery starts in a more depleted state, the engine will run for longer time while recharging. This behavior is illustrated in Figure 25, which shows bar graphs of engine-on time for each driving mode (i.e. “hill”, or section of movement beginning and ending with a stop, as illustrated with the overlaid drive trace). There are 3 different tests shown, progressing from (1) an extreme charge case through (2) charge-sustaining and to (3) high discharge. In Test 1, the engine runs for much longer than in the other cases. Also noteworthy is that the differences mostly disappear after the first 6 modes of phase 2, so the vehicle has already stabilized at its target SOC before the end of the test.

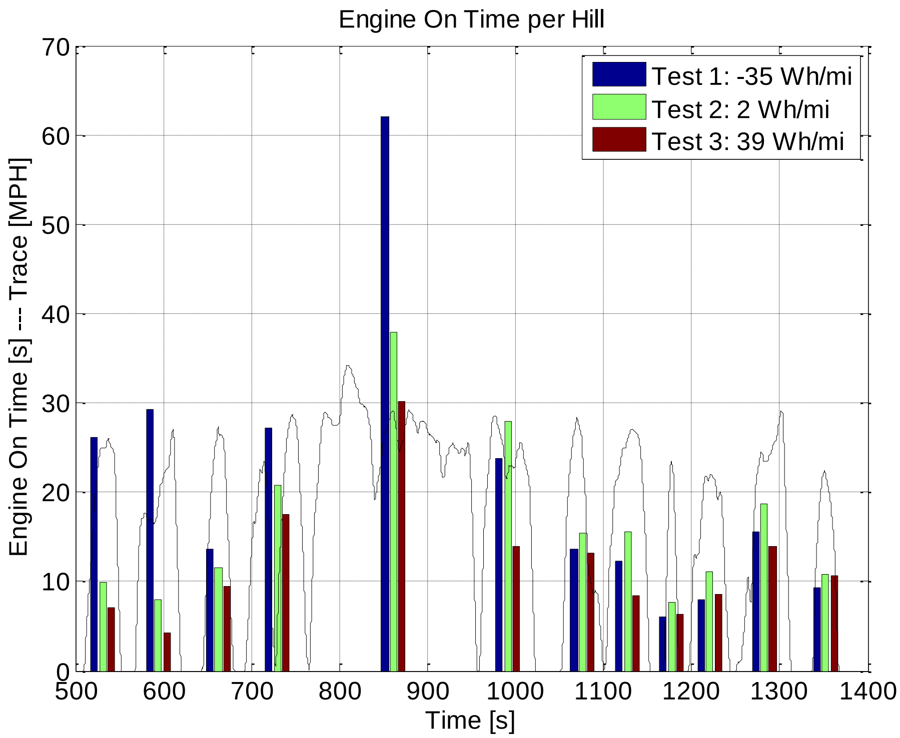

Figure 25. Engine-on time for each mode of UDDS phase 2 in 3 different tests.

Figure 26 shows the engine's energy output (determined by integrating power at the engine torque sensor) for each hill of the same set of UDDS phase 2 tests. The pattern of changes between tests is similar to the engine-on time plot, showing that the engine essentially runs at a constant power level and adjusts for charging needs primarily by running for more or less time. Finally, to show how the behavior of the vehicle's electric components are affected, Figure 27 depicts integrated battery charge flows by hill, separated into positive and negative directions. Both charge and discharge behaviors are affected in the course of achieving overall net charge or discharge on the cycle. For example, looking at the first hill of the UDDS phase 2, in Test 1 there is more battery charging than in the other tests (primarily from engine generation) and less battery discharging (due to less EV or electric assist type behavior). So, the changes that take place are certainly more complex than for highway driving, due to effects on electric propulsion modes, but changes in overall electric consumption still affect fuel consumption by using the engine for varying degrees of propulsion and charging, which is compatible with the assumptions of a charge-correction line.

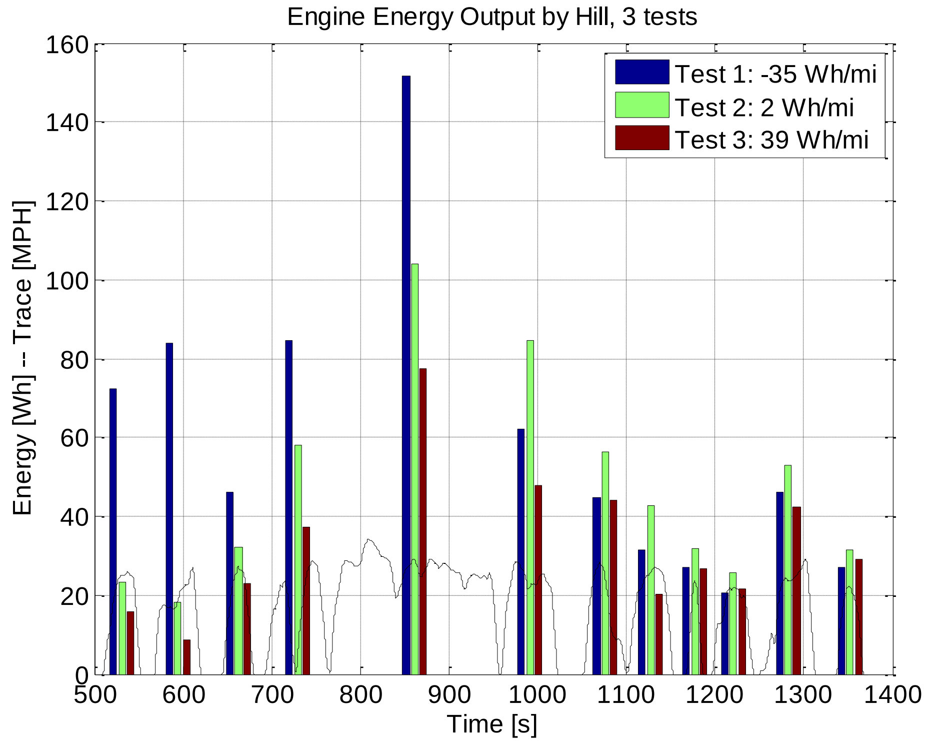

Figure 26. Engine energy output for each mode of UDDS phase 2 in 3 different tests.

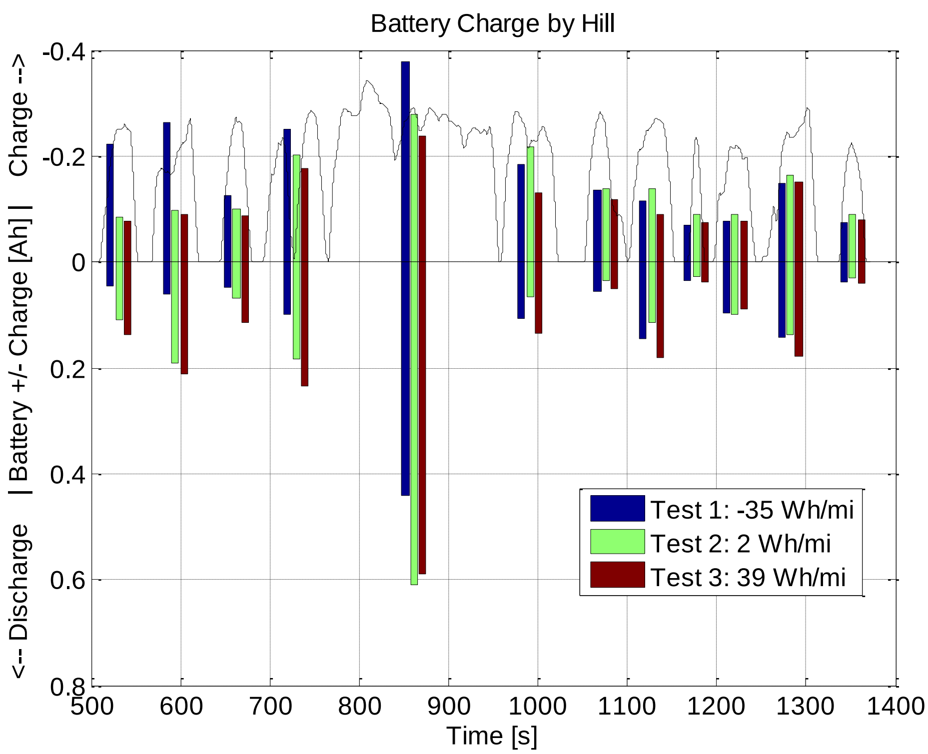

Figure 27. Integrated battery current by hill, separated into positive and negative flows.

ii. US06 City

The US06 city cycle had a much flatter charge correction curve than the UDDS phase 2, and taking a look at the details of the vehicle behavior for this cycle shows the reasons why. As was done with the prior analysis, there are 3 tests compared on the plots, ranging from high levels of charge, to the largest discharge. For the US06 city, the vehicle could not be made to discharge overall. To begin with, the engine-on time per hill for this cycle is roughly the same across the three tests regardless of the NEC, as shown in Figure 28. Likewise, the energy output, shown in Figure 29, is also relatively similar across the various tests. Because of the aggressive accelerations in the US06 city cycle, the Prius needs to use the engine in order to meet the demands of the trace, regardless of whether the control strategy is targeting charge or discharge.

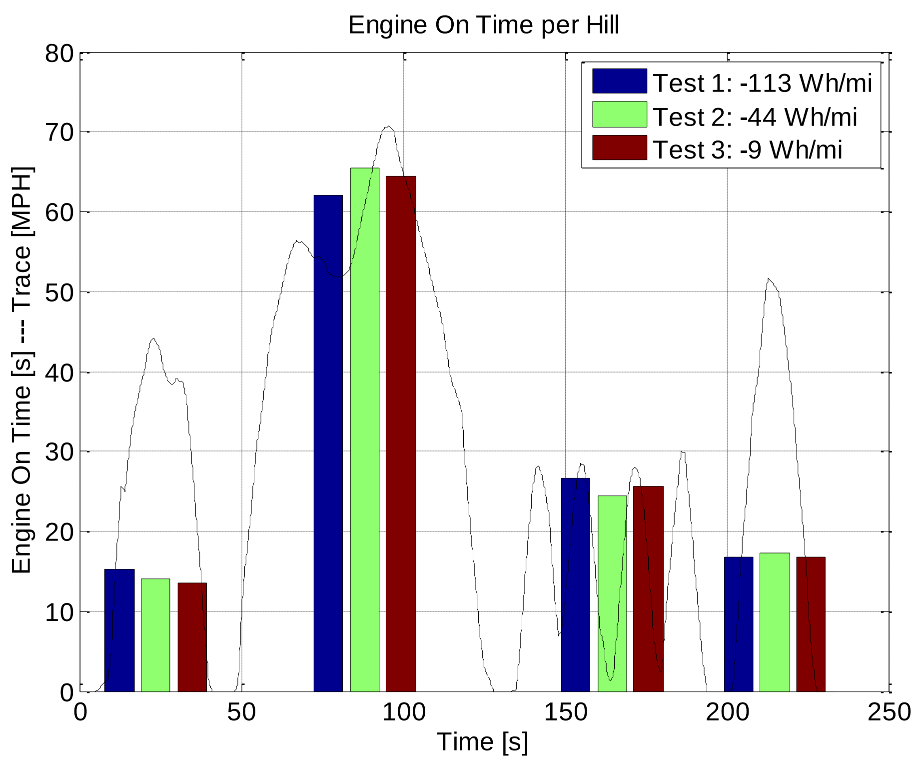

Figure 28. Engine-on time per hill for 3 US06 city tests.

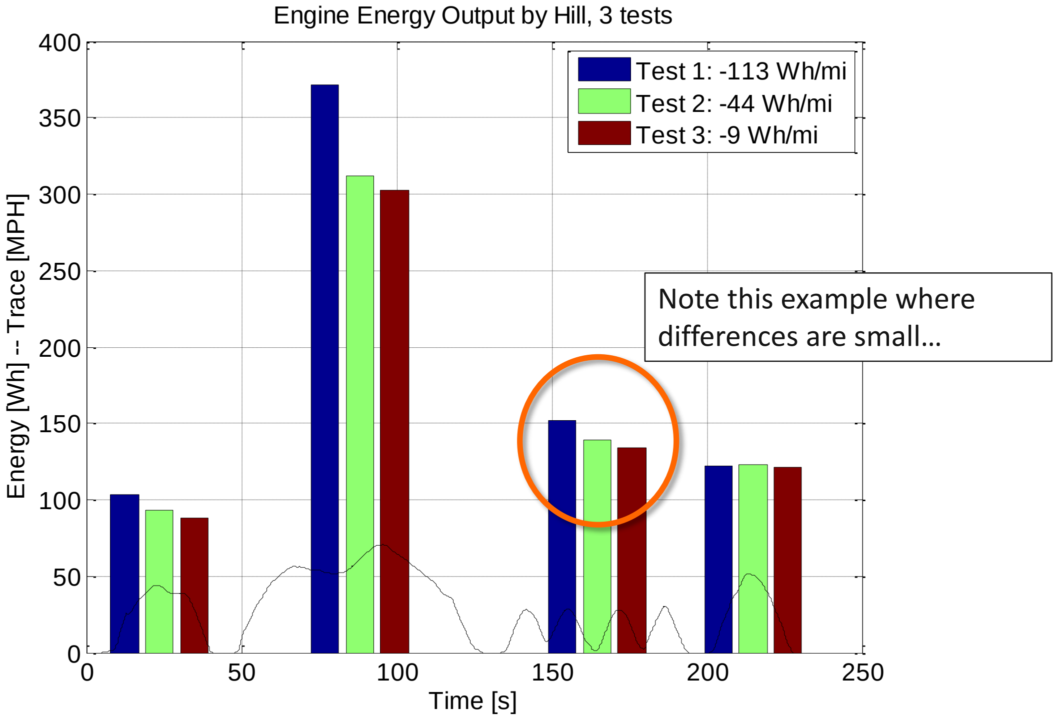

Figure 29. Engine energy output per hill for 3 US06 city tests.

If the engine energy output is similar across tests, there must be another explanation for the differences in NEC. The circled driving mode in Figure 29 is an example that will illustrate a source of the difference. Although the engine energy output is similar across the 3 tests on this section, there is a sharper difference in the battery charge increases occurring on that section, as shown in Figure 30. The amounts of charge depletion are circled in that figure as well, and they are not nearly as varying as in the UDDS phase 2 example, meaning that the levels of electric assist are similar across the board. What this information illustrates is that the biggest contributor to the difference in net charge on the cycle is the amount of regenerative braking capture.

The typical way to force the Prius to discharge as much as possible on a test was to start with the battery fully charged at the controller-regulated limit of approximately 80 % SOC. Since the vehicle does not use significant electric assist or EV on this aggressive driving cycle, the battery remains highly-charged and will not use regenerative braking since it is full. A series of tests was performed to try to force CS behavior by driving repeated US06 city cycle in a row. In this case, regenerative braking is still limited, here because the vehicle de-rates battery charging in response to intense average current loads and the resulting battery temperature increase.

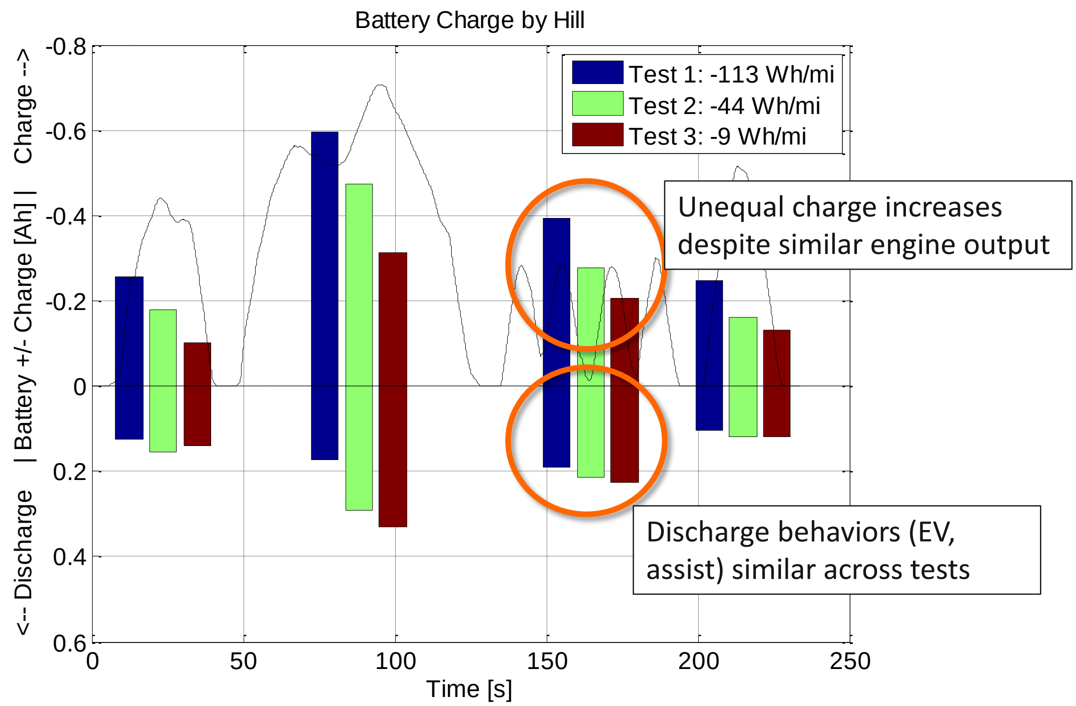

Figure 30. Battery charge and discharge by hill for 3 US06 city tests.

These observations of the vehicle behavior show why the charge correction line is very flat for US06 city. Moving to higher levels of electric charging does not have a large effect on fuel consumption, because otherwise wasted braking energy is merely being allowed into the battery. This fact does not fit with the assumption of how a charge correction slope will be used. During a full US06 cycle, the electric energy that is recovered by regenerative braking on the city sections (so with a low "cost" in terms of fuel) is then depleted on the highway portion. The vehicle does not trade off fuel and electric energy exclusively within the city portion, but that is the process that is represented by the charge correction slope. These complex factors that define the fuel-electric energy tradeoff when deriving charge correction lines for short separate cycle phases should be taken into consideration when evaluating the practicality of applying the corrections to fuel consumption results.

e. Effect of charge correction on fuel economy label value

The final quantity of interest in this study is the fuel economy label number (city and highway) and how it may be affected by charge correction or the lack thereof. EPA's 5-cycle calculation takes as inputs the fuel economy results from all phases of the involved cycles. The US06 and UDDS cycles have multiple phases and were therefore the focus of testing. The label value can be calculated using inputs from these phases in both uncorrected and charge-corrected form. Although the Cold CO test would also be vulnerable to charge-correction sensitivities, electric consumption data was not available for these tests. As a very rough approximation based upon results from previous testing of thermal effects on full UDDS cycle fuel consumption for a power split hybrid vehicle, the Cold CO fuel consumption is set as 33% higher for each phase than for the FTP with equal percent changes between uncorrected and charge corrected values as for the FTP. Also at the time testing was carried out, there were no facilities available for providing a solar load during the SC03 test, so the fuel consumption result from this test was obtained from a third party which had independently carried out testing of the same vehicle model.

The final label values derived using the EPA 5-cycle weightings are shown in Table 9 based upon both the corrected and uncorrected cycle phase data. The actual percent change in fuel consumption as a result of applying the correction is shown in the 3rd column of data, and it is small in both cases. This was surprising given the more significant differences observed on individual phases, but the weightings given to each of those in the label calculation reduce the influence of some of those. However, for additional insight into this result, the 4th column shows the percent difference in only the harmonically-weighted phase fuel consumption results that make up the so-called Running FC, without the adjustment for air conditioning. The notable quantity here is the 2 percent increase in Running FC for the city calculation. What that means is that the 2nd component in the overall label computation: the Start FC, actually decreases and therefore partially offsets that increase in Running FC to give only a 0.6 % increase overall. In fact, the Start FC decreases by 18 %, but it is a much smaller portion of the overall fuel consumption than the Running FC, especially for the highway. Since the Start FC is based upon the difference in fuel consumption between the cold start and hot start UDDS/Cold CO, this result makes sense because the cold start phase 1 does not charge as much as the hot start phase 1 (see the large unfilled marker points in Figure 24). Once they are brought to an equal electric consumption basis (charge sustaining), the difference between the hot and cold fuel consumptions has increased.

Table 9. Fuel economy label value using uncorrected and corrected phase results.

5-cycle label for:	**Uncorrected MPG**	**Corrected MPG**	**% diff in FC**	**% diff in Running FC only**	**% diff in Start FC only**
City	47.1	46.8	+0.6 %	+2.0 %	-18.1 %
Highway	45.4	45.2	+0.4 %	+0.6 %	-18.1 %

f. Charge balance in composite driving vs. per-phase

Although it has been shown here that all phases used in the EPA label calculations *can* be corrected to zero NEC, that does not answer the question of whether doing so is a good idea. From a practical standpoint, this study has shown that there are certainly issues with the huge test load required to derive charge correction data. But another point to consider is whether forcing hybrids to CS operation on short phases is an appropriate representation of how they should be expected to run in the real world. The EPA's method in developing the 5-cycle label calculations was to replicate the distribution of driving speeds, accelerations, and environmental conditions in real, average U.S. driving. If the desired distribution of driving behaviors were captured in a single overall city or highway drive cycle rather than pieced together from various phase results, a hybrid would be able to trade off electric and fuel energy freely within the entire cycle as long as it were charge-sustaining overall. This strategy of shifting operating points to maximize overall engine efficiency is one of the fundamental bases for fuel consumption reduction in hybrids. If the labeling method assumes that city driving consists of a mix of UDDS-like and US06(city)-like operation, the hybrid should be required to be charge-balanced on that overall operation, but should not be expected to charge-balance on all sections of driving, such as the aggressive US06 city which is only a small portion of overall urban driving. A tight SOC balance requirement on a particular driving phase may lead to less efficient hybrid powertrain operation. Another potential complication, mentioned earlier, is that the NEC for some phases may not fall within the ±5 % limit for correctability, so the simple linear fit between fuel consumption points may not be an accurate assumption.

Given EPA's reasons for using existing certification drive cycles to synthesize the fuel economy label result, how could the NEC behavior across the full 5-cycle city or highway result be quantified aside from correcting each phase? One possibility is to weight the phase electric consumption according to the same equations that weight the fuel consumption results. Since the equations effectively weight the % of overall driving distance covered under each of the cycle phases' conditions, it would be possible to weight electric consumption behavior on each phase according to the same method. Using ANL's 2010 Toyota Prius test data, this measure is shown in Table 10 both as a percentage of fuel energy and in net Wh/mi. In addition to a result from using full 5-cycle equations (the "overall" column), the table also shows the result from the simple harmonic weighting of cycle results referred to in the EPA procedure as "running fuel consumption" without any adjustments for air conditioning use or start fuel. Note that since detailed electric data from Cold CO testing were not available, the electric consumption for those cycles was taken to be the same as on the standard FTP.

Table 10. 2010 Toyota Prius weighted 5-cycle net electric consumption as % of fuel energy and in Wh/mi.

	Overall 5-cycle FC		Running FC only	
City	-0.59 %	-4.2 Wh/mi	-1.16 %	-6.6 Wh/mi
Highway	2.07 %	15.2 Wh/mi	2.02 %	13.1 Wh/mi

The table shows that using the electric consumption results associated with the uncorrected phase fuel consumption data for this vehicle in the 5-cycle label calculations yields a net charge for the city result and net discharge for the highway result. The highway fuel consumption would therefore not be considered charge-sustaining, since NEC exceeds 1% of fuel energy.

If it were required that a vehicle have < 1 % NEC on overall highway driving, it would present a serious control strategy design challenge. A control strategy will eventually adapt to CS on a continuous cycle, even if only because the battery reaches charge or discharge limits. To design a way of producing zero NEC on the 5-cycle weightings would be an extreme challenge. The net discharge on the highway comes entirely from the US06 highway cycle, which in the overall dynamometer test cycle is preceded by city driving behavior that causes the vehicle to charge up. The vehicle could not easily be expected to have a control strategy which would alter this behavior by somehow knowing that it was distributing “city” cycle charging into “highway” cycle discharging. So, although the idea of requiring charge balance for weighted overall 5-cycle city and overall highway driving would be fair and most fitting to real-world operation, it could be challenging to design for because the results come from areas of non-contiguous control strategy operation.

g. Conclusion

The EPA fuel economy label values are computed by equations which synthesize results extracted from individual phases of drive cycles, including the UDDS and US06. For hybrid electric vehicles, although charge-sustaining over the entire cycle, the fuel consumption result for a phase may be significantly affected if it is not within the allowable NEC range, as was shown by testing of the 2010 Toyota Prius as an example. For the Prius, the electric consumption on individual phases of CS UDDS and US06 cycles fell outside of the 1 % NEC limit and was near the 5 % charge-correction limit in most cases. According to the SAE J1711 testing standard, these changes in NEC are significant, and on a per-phase basis, the impact on fuel consumption was as high as 22 % (UDDS Phase 2). To address this error, with a large effort of additional testing, it is possible to develop a charge-correction line for each of the phases, but there can be issues with the actual meaning of the charge-correction slope in intense cycles like the US06. In this example, the effect of applying charge correction to each phase to the final label number was less than 1 %, but the effect of charge-imbalance on derived quantities such as start fuel consumption could lead to major skew in certain elements in the 5-cycle rating. The effects for hybrid vehicles other than the single model tested here could also vary. Finally, a concept for alternatively checking whether the total fuel economy rating is charge-sustaining was discussed, but like the idea to charge correct every phase result, it presents hurdles for practical implementation.

6. Effect of vehicle design changes in 5-cycle vs. previous fuel economy label

a. Introduction and motivation

If a vehicle manufacturer wants to improve a product with a competitive fuel economy label rating, they would be interested in the details of how certain vehicle technology improvements would have an effect. Under previous fuel economy labeling methods, it was purely the performance on UDDS and HWFET cycles that would have an effect on the MPG rating and thus relatively straightforward to design a vehicle for good fuel economy. For example, it can be seen that certain hybrid vehicles have electric motors sized to capture the maximum braking power on the UDDS cycle. Under the EPA 5-cycle system, however, predicting the end result of vehicle parameter changes is more complicated. And, since the characteristics of the composite 5-cycle driving are different than a single UDDS or single HWFET, one might speculate that the effect of specific vehicle parameter changes on the fuel economy label may not be the same under the new system.

Note that vehicle design is not simply a matter of optimizing a particular performance aspect, such as fuel economy label ratings. Indeed, even in the realm of fuel economy, manufacturers are also concerned with meeting Corporate Average Fuel Economy (CAFE) requirements, which are still based on the UDDS and HWFET cycles, but also give special credits for particular technologies such as environmentally-friendly air conditioning refrigerants or active grill shutters [Csere 2011]. Additionally, there are emissions regulations which may drive design features like higher fueling rates during warmup idling to reduce pollutant levels that actually have a negative effect on fuel economy. Finally, manufacturers consider consumer expectations for vehicle performance and comfort.

Nevertheless, fuel economy label ratings are a competitive and important area where auto makers do indeed face competition. A most visible example is in the compact car segment where several companies' advertising campaigns have emphasized vehicles which achieve a highway fuel economy rating of 40 MPG. Often the ratings come from special high fuel economy versions of a model with features like active grill shutters and low rolling resistance tires. The company can use the headline ratings from those models to get consumer attention for the vehicle line. Example vehicles with advertising campaigns featuring their 40+ MPG fuel economy rating are the Ford Fiesta and Focus, Hyundai (4 models), the Honda Civic, and GM's Cruze [Evarts 2011]. In trying to reach a round, benchmark number like 40 MPG, the precise characteristics of the 5-cycle highway fuel economy calculation method are very important. For example, a manufacturer may consider what effect a certain aerodynamic improvement would have on the highway fuel economy label rating.

The EPA fuel economy label ratings are used in advertising not only because they provide a good estimate of on-road fuel economy, but because federal law mandates that any manufacturer claim of "city" or "highway" fuel economy must be the rating determined by EPA label procedures [CFR16 2011]. These regulations are overseen by the Federal Trade Commission to prevent deceptive advertising practices. This mandate also helps support one goal of EPA fuel economy labeling rules: to provide a common basis for comparison of vehicle performance. Because of this rule, manufacturer interest in maximizing EPA fuel economy estimates as an advertising feature is further strengthened.

b. Simulation study setup

To investigate how these vehicle parameter changes affect the 5-cycle fuel economy label versus the previous method, a simulation study was run using the Autonomie software developed by Argonne National Laboratory [Autonomie 2011]. Autonomie is a full-vehicle simulation software package which uses detailed mathematical models of vehicle powertrain components to determine performance on a variety of drive cycles. For this study, two vehicles are simulated on each phase required for 5-cycle individually, and the results are substituted into the EPA equations in a separate spreadsheet to compute the 5-cycle and 2-cycle city and highway fuel economy ratings. One vehicle is a midsize conventional and the other is a power-split hybrid. For the hybrid vehicle, the phases were simulated iteratively until a charge-sustaining result was produced. Running each phase individually rather than extracting results from full cycles simplifies the simulation procedure. Since the simulation does not model engine warmup, it is not important to run the phases as part of full cycles.

For this simulation, a number of simplifying assumptions have to be made. The cold start penalty is taken to be a 10 % increase in fuel consumption on UDDS Phase 1 only. The only change to the UDDS results for the cold temperature test is to increase the engine start penalty to 15 % FC increase. Effects such as increased road load due to the cold temperature (a function of increased air density and also tire mechanics) as well as the accessory load from heater operation were not simulated. Finally the air conditioning load is simulated as a constant power load on the vehicle: electric for the hybrid and mechanical for the conventional. The 6 distinct cycle phases and any special assumptions are listed in Table 11.

Table 11. List of simulated cycle phases and additional notes.

UDDS Phase 1	Simulated FC increased by 10 % for cold start at 75 °F; 15 % for cold start at 20 °F
UDDS Phase 2	
HWFET	
SC03	A/C load: 2 kW electric (hybrid) or 1.5 kW mechanical (conventional)
US06 City	The two sections from the US06 comprising this cycle were merged into one continuous drive
US06 Highway	

The two parameters investigated through simulation are mass and aerodynamic drag. For each of the two vehicles, a baseline case is run, followed by one case with a significant aerodynamic drag change, and another with a significant mass change. The parameters are listed in Table 12. For the later comparisons between a pair of mass cases or a pair of drag coefficient cases, it is not important which one is the baseline; the results will be given as a reduction in fuel consumption due to the improvement of the chassis parameter. To quantify these parameters changes as improvements, Table 13 shows them in percentage terms.

Table 12. Vehicle parameters list.

Vehicle	**Baseline**	**Change C_D Case**	**Change Mass Case**
Midsize conventional	1700 kg 0.3 C_D	0.25	1525 kg
Power split hybrid	1475 kg 0.25 C_D	0.3	1325 kg

Table 13. Vehicle parameter changes listed in terms of percentage reductions.

Vehicle	**C_D Reduction**	**Mass Redcution**
Midsize conventional	0.30 → 0.25 *16.7 %*	1700 →1525 kg 175 kg = *10.3 %*
Power split hybrid	0.30 → 0.25 *16.7 %*	1475 →1325 kg 150 kg = *10.2 %*

c. Simulation results & analysis

To give a frame of reference for the importance of individual phases, pie charts are used to show the percent contribution of each weighted phase and derived fuel consumption quantity to the overall 5-cycle city and highway fuel consumptions. Note that the air conditioning fuel consumption and start fuel consumption are purely functions of the aforementioned assumptions used for the simulations. The baseline city and highway fuel consumptions for the conventional vehicle are shown in Figure 31 and Figure 32, respectively. This information is presented for the hybrid vehicle in Figure 33 and Figure 34. The corresponding 5-cycle fuel economy label value is listed on each plot, as well as a note of the result from just the running fuel consumption without the air conditioning adjustment. These “Running FC only” values correspond to the weighted cycle phases on the main pie excluding “other”. Full tabulated results from the simulation study can be found in Appendix B. Both vehicles have similar relative contributions from the components of the fuel consumption rating, with the city being dominated by the UDDS phases comprising the FTP and the highway dominated by the US06 highway cycle.

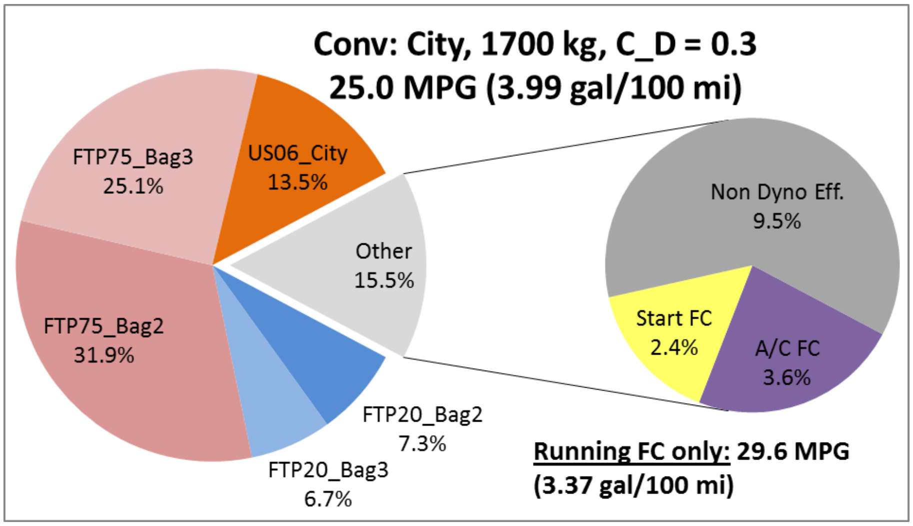

Figure 31. Conventional vehicle baseline simulation city fuel consumption breakdown.

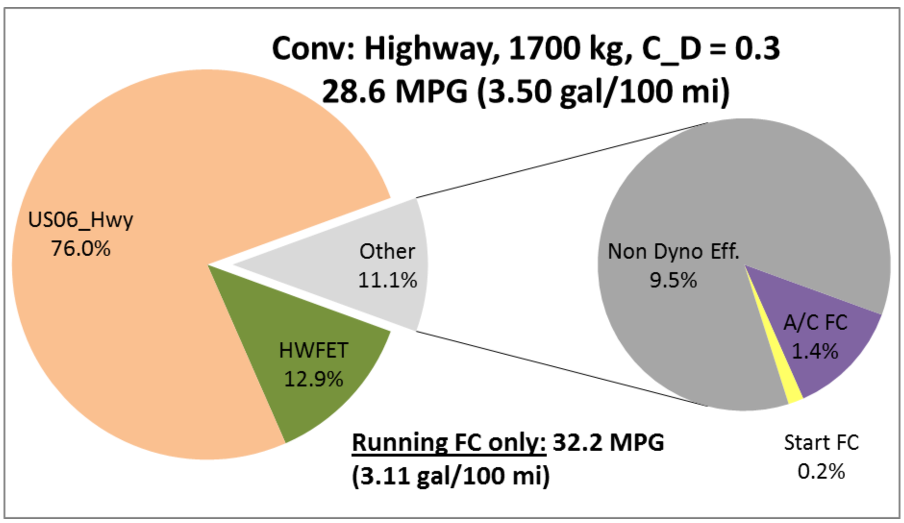

Figure 32. Conventional vehicle baseline simulation highway fuel consumption breakdown.

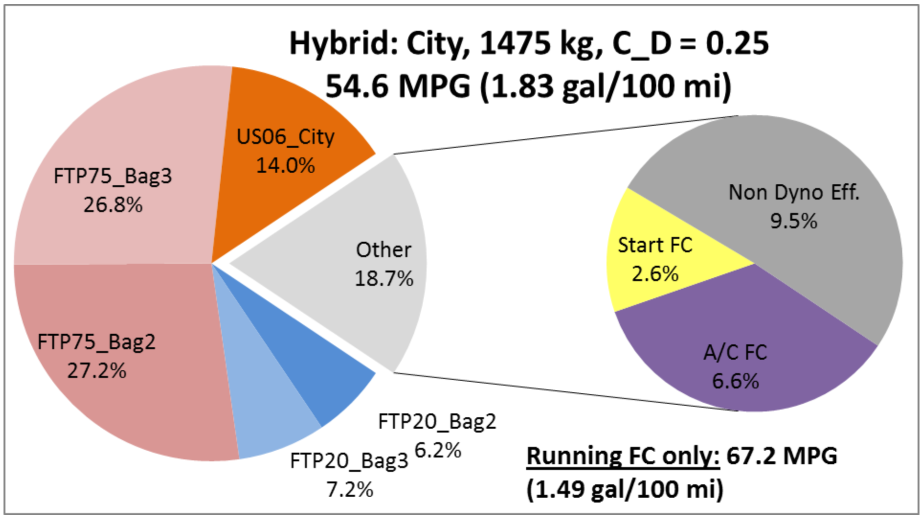

Figure 33. Hybrid vehicle baseline simulation city fuel consumption breakdown.

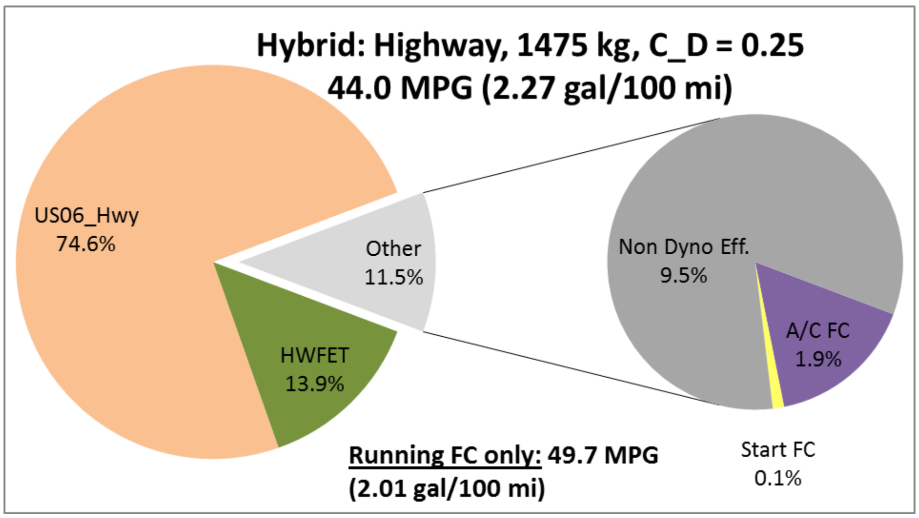

Figure 34. Hybrid vehicle baseline simulation highway fuel consumption breakdown.

i. Mass reduction effects

The computed fuel economies from the simulation results in the mass reduction comparison study are shown in Table 14. Both the hybrid and conventional vehicle are shown separately, with the high and low mass cases given along with the equivalent percent reduction in fuel consumption due to the lightweighting. Since the primary goal of this study is to compare the outcome of the parameter changes on the 5-cycle method vs. previous labeling methods, the table shows the actual 5-cycle label, the "old" 2-cycle adjusted sticker value, as well as the 2008 MPG-based estimate of 5-cycle which uses FTP and HWFET results. Interestingly, the 2008 estimates deviate from the actual 5-cycle FE by several MPG in every case except the conventional city rating. Although some deviation is expected and observed in the real world as well, (especially for hybrids), this calculation is also sensitive to simulation assumptions and simplifications.

Looking at the difference in improvements on 2-cycle vs. 5-cycle, the fuel consumption savings are similar in percentage terms. For example, the improvement in the city rating is roughly 6 % for the conventional vehicle and 7 % for the hybrid regardless of whether the fuel consumption is computed according to 5-cycle or the previous label method. Although there is not a stark contrast in the absolute size of these reduction percentages, the effects of lightweighting are consistently higher on 5-cycle than on 2-cycle, with the increased savings ranging from 0.3 to 0.5 percentage points.

Table 14. Simulated 5-cycle fuel economy results [MPG] and % FC reduction due to mass decreases.

	Conventional Vehicle			Hybrid		
	1700 kg FE [MPG]	**1525 kg FE [MPG]**	**% FC Reduction**	**1475 kg FE [MPG]**	**1325 kg FE [MPG]**	**% FC Reduction**
5-cyc. City	25.0	26.7	6.2%	54.6	58.8	7.1%
2008 Est. City	24.6	25.9	5.2%	50.9	54.0	5.7%
2-cyc. City Sticker	28.4	30.1	5.7%	64.9	69.6	6.8%
5-cyc. Hwy	28.6	30.1	5.0%	44.0	45.6	3.6%
2008 Est. Hwy	33.3	34.8	4.4%	46.7	48.1	2.9%
2-cyc. Hwy Sticker	36.6	38.4	4.6%	52.4	54.1	3.1%

Another way of looking at the benefits of lightweighting is to consider the absolute amount of fuel saved in terms of fuel consumption in gal/mi. The stacked bar charts of Figure 35 and Figure 36 sum the weighted contributions of each part of the 5-cycle and 2-cycle methods to the total reduction in fuel consumption as a result of the mass reduction. For the 2 cycle bar, the weighted hot and cold start FTP result is lumped into a single contributor. In both highway and city 2-cycle bars, there is a contributing portion from the label adjustment that is also shown. Since the computed MPG was reduced by 10 % (city) and 22 % (highway) to give the final fuel economy label value in the 2-cycle system, this effective additional fuel consumption is reduced whenever the base fuel consumption is reduced.

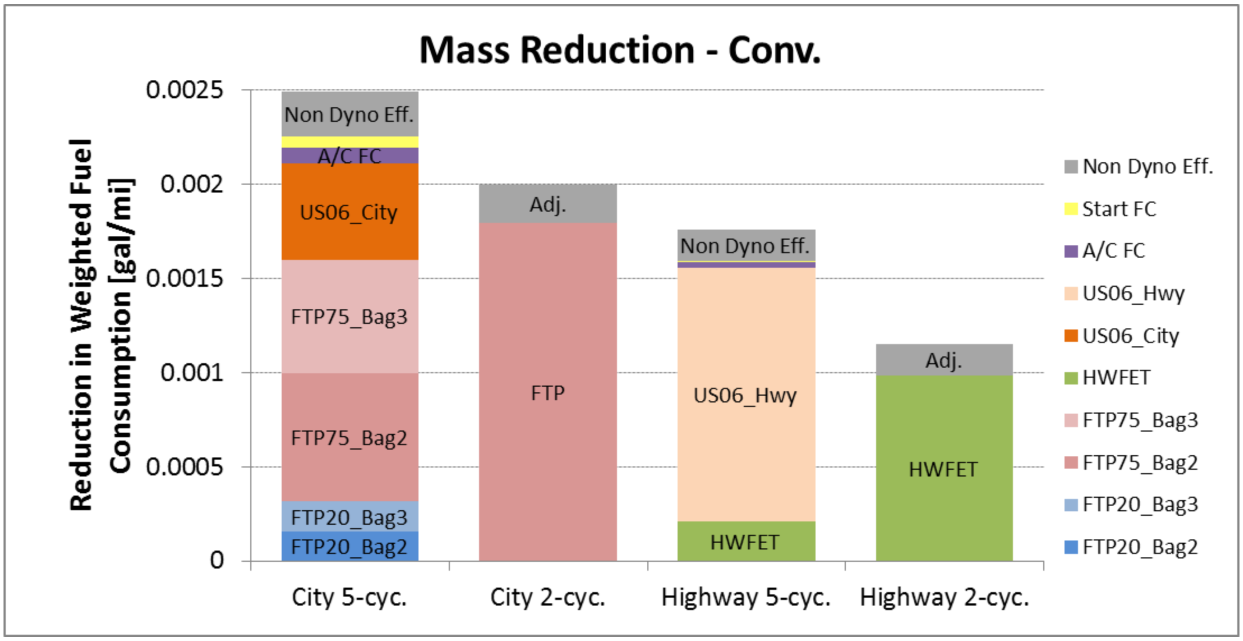

Figure 35. Contributions to fuel consumption savings due to mass reduction – conventional vehicle.

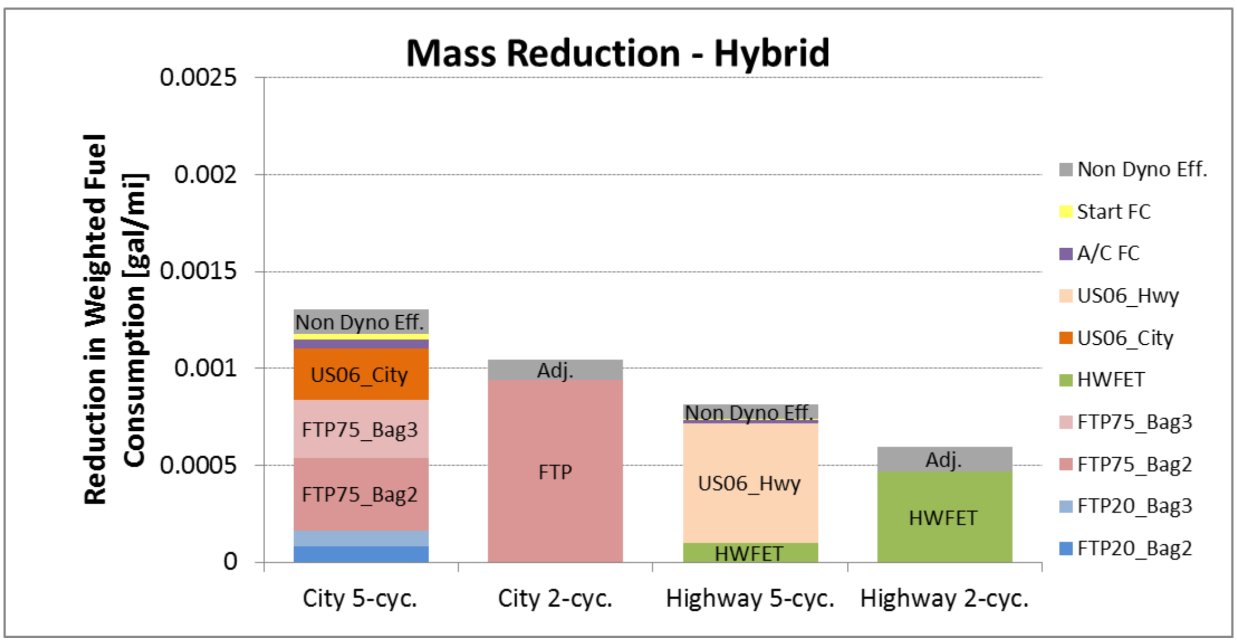

Figure 36. Contributions to fuel consumption savings due to mass reduction – hybrid vehicle.

Whereas the effects of lightweighting looked similar in 5-cycle and 2-cycle when first presented in percentage terms, the difference in the potential fuel consumption savings can be seen more distinctly. As shown in the graphs, both the hybrid and the conventional vehicle achieve a greater fuel savings in 5-cycle city and highway ratings than on 2-cycle. A particular aspect of the 5-cycle method stands out in this comparison – the US06 city cycle. For the conventional vehicle, the pie graph of baseline contributions to city fuel consumption that was shown in Figure 31 showed that the US06 city accounted for only 13.5 % versus the FTP phases at 25-30 % each. However, the stacked bar graph of Figure 35 illustrates that the US06 city contribution is reduced by roughly the same amount as the two FTP phases. This result is expected, given that the US06 has much higher acceleration levels and therefore mass-dependent inertial energy use.

Although the mass parameter changes to the conventional and hybrid vehicle are not perfectly comparable to each other (they are the same in percentage terms but different in absolute value), the stacked bar graphs of the amount of fuel saved in city driving do show that the hybrid vehicle does not benefit as much from lightweighting as a conventional. The reason is that a portion of the additional propulsive inertia energy required to move the increased mass is recaptured in regenerative braking and reused to propel the vehicle. This effect appears in both 2-cycle and 5-cycle city calculations.

ii. Aerodynamic improvement effects

The results of the aerodynamic improvement study will now be presented in the same way as the mass reduction study. The simulated fuel economy label ratings and the equivalent percentage reduction in fuel economy are shown in Table 15. One immediately apparent fact is that the vehicle aerodynamic improvement has very little effect in the city rating of the conventional vehicle. Even for the hybrid, the savings is still much smaller than in the highway FE label, but it is higher than for the conventional. One explanation for the increased benefit of aerodynamics in the city on a hybrid is that lower aerodynamic drag leaves more of the vehicle inertial energy available for regenerative braking capture during decelerations, thus reducing future fuel consumption. In a conventional vehicle, the reduction in aero drag would cause the resulting deceleration demand to be met by increased friction braking, which does not have an effect on fuel economy. In this case, the aero improvements are only useful during propelling.

Under highway driving, aerodynamic drag is a key source of energy loss, and the resulting impact on fuel consumption due to improvements on both the hybrid and conventional vehicles reflects this fact. On 5-cycle highway, the simulated 16.7 % decrease in the drag coefficient led to decreases in fuel consumption in the range of 7 % for both vehicles. Due to the significantly higher speeds on the US06 highway than the HWFET, aerodynamic improvements are expected to have greater benefit on 5-cycle than on 2-cycle. In percentage terms, that is indeed the case for both vehicles, but the difference between the two is small on the hybrid.

Table 15. Simulated 5-cycle fuel economy results [MPG] and % FC reduction due to aerodynamic drag reduction.

	Conventional Vehicle			Hybrid		
	C_D = 0.30 FE [MPG]	**C_D = 0.25 FE [MPG]**	**% FC Reduction**	**C_D = 0.30 FE [MPG]**	**C_D = 0.25 FE [MPG]**	**% FC Reduction**
5-cyc. City	25.0	25.5	1.6%	52.5	54.6	3.8%
2008 Est. City	24.6	24.9	1.5%	48.9	50.9	4.0%
2-cyc. City Sticker	28.4	28.9	1.7%	61.8	64.9	4.8%
5-cyc. Hwy	28.6	30.7	7.0%	40.6	44.0	7.7%
2008 Est. Hwy	33.3	35.3	5.6%	43.4	46.7	6.9%
2-cyc. Hwy Sticker	36.6	38.9	5.8%	48.5	52.4	7.4%

The plot summing phase contributions to fuel savings on 2-cycle vs. 5-cycle for the conventional vehicle is shown in Figure 37 and for the hybrid in Figure 38. Again, the aerodynamic improvements are much less helpful in city driving, with the savings on 5-cycle and 2-cycle being roughly equal given the similar average speed in both cases. For highway fuel consumption, the 5-cycle savings are much higher than on 2-cycle.

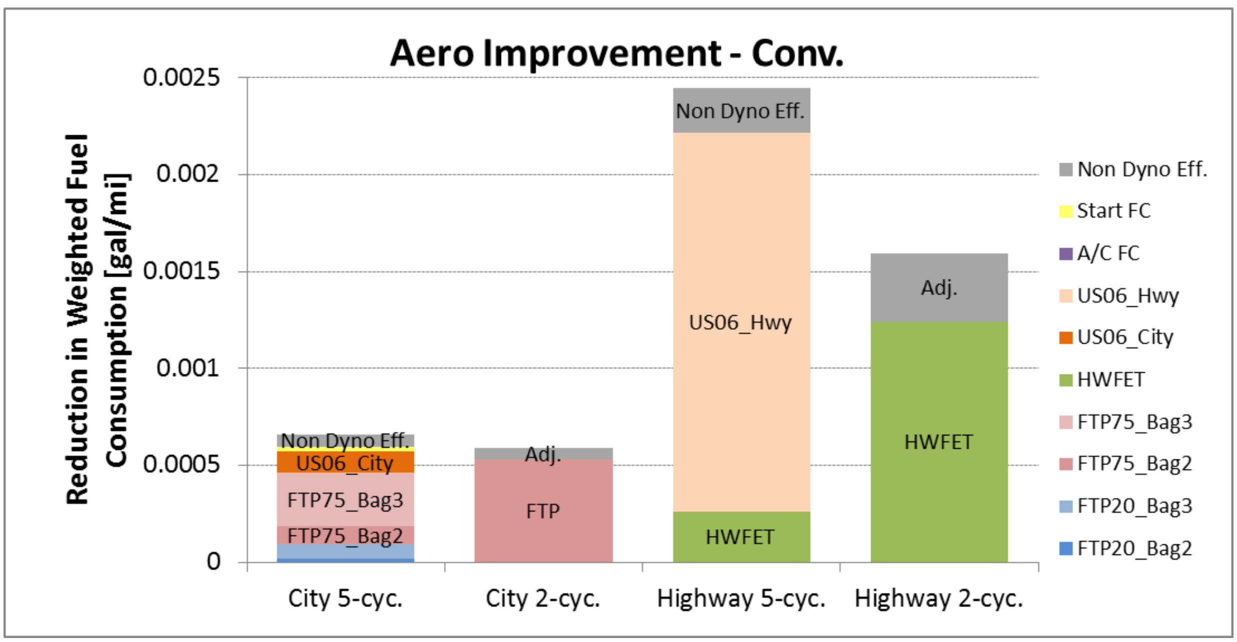

Figure 37. Contributions to fuel consumption savings due to aero improvement – conventional vehicle.

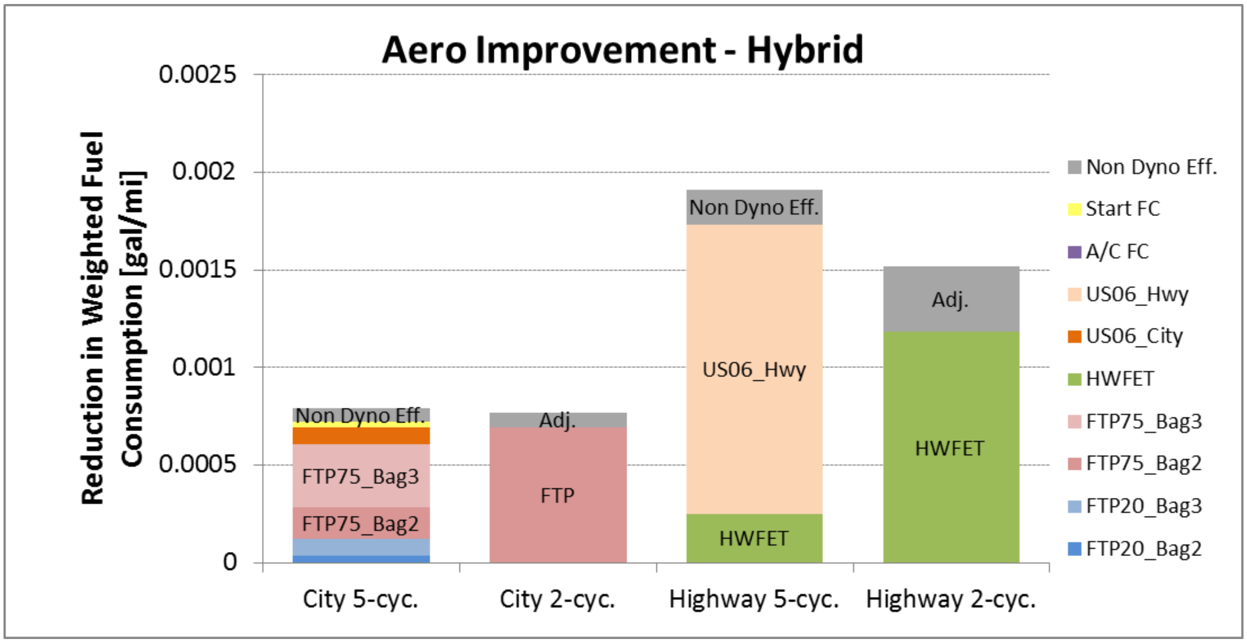

Figure 38. Contributions to fuel consumption savings due to aero improvement – hybrid vehicle.

In summary, the simulation study shows that both mass reduction and aerodynamic drag reduction yield a benefit to the label fuel consumption that is similar in percentage terms on both 2-cycle and 5-cycle. In absolute fuel savings, for example as measured in a gal/mi reduction, there are greater gains to the 5-cycle label than to the 2-cycle label value for both parameters and both vehicles. The biggest contrast in percentage savings between the two fuel consumption computation methods is for the conventional vehicle in highway driving, where the gain on 5-cycle was 1.2 percentage points higher than on 2-cycle. In general, hybrids have less to gain from lightweighting than do conventional vehicles, but they can make better use of aerodynamic improvements on highly dynamic cycles.

This simulation study does not attempt to investigate the effects of charge-correction on the results. To streamline the generation of results, each phase was simulated separately and forced to be charge-sustaining for the hybrid. If the simulations had been run according to certification testing procedures, where full cycles are charge-sustaining but not necessarily individual phases, the results could have been different. No attempt was made to verify whether the difference between these methods in simulation was similar to the results found on the 2010 Prius charge correction testing study.

For vehicle manufacturers seeking to maximize fuel economy label ratings, in the case of the two midsize vehicle examples simulated here, the simulation shows that the 2-cycle method may provide a good predictor of the expected percentage savings in fuel consumption due to chassis parameter changes such as mass or aerodynamic drag properties. Given the low cost of performing full-vehicle simulations with modern software and computers, running a full 5-cycle simulation may be just as easy, but as in the case of this study, that would rely upon a thorough knowledge of thermal and accessory effects that are present in 5-cycle testing but more difficult to simulate. In fact, many of the parameters that are accounted for in 5-cycle that were not tested in 2-cycle (such as air conditioning efficiency or cold-temperature performance), which could therefore be expected to be significant sources of potential fuel economy label improvement, were not considered in this study. For example, a more efficient air conditioning system would have had zero gain in 2-cycle fuel economy label ratings but would indeed have an effect in 5-cycle.

7. Conclusion and outlook

With the goal of providing useful information to consumers for comparing the fuel economy of automobiles, the U.S. Environmental Protection Agency (EPA) has regulated a system of calculating city and highway label ratings based upon test data since the 1970's. The oldest dynamometer driving cycles used in certification testing are the UDDS and HWFET, which represent relatively mild city and highway driving, respectively. Previously, simple adjustment factors were applied to the measured fuel economy results to bring the fuel economy label value closer to observed real-world values. However, due to changes in vehicles and driving patterns over time and lack of consideration of certain on-road effects, the gap remained unacceptably high. The most recent changes to the test methodology, which began phase-in in 2008, attempt to produce a fuel economy label value that comes from driving conditions that are close to average on-road observations. This rating is synthesized from the results on 5 separate drive cycles (divided into as many as 11 total phases). The three additions to the fuel economy method which were all previously in use for emission certification are the FTP at 20 °F (also known as "Cold CO" test), the SC03 air conditioning cycle, and the US06 high speed/aggressive driving cycle. In contrast with the simple 2-cycle system, the new method uses a complex set of equations to transform the raw data taken from individual phases of the various drive cycles into one comprehensive estimate for city and highway driving. Certain contributions to the final fuel consumption have greater importance than others, as can be seen by looking at the calculation method in detail as was done in Chapter 2 of this thesis.

Chapter 4 discusses the general testing procedures for considering battery energy change, including several possible metrics, which are required for HEV testing. As a result of the synthesis of results from individual drive cycle phases, the battery energy changes that occur in the course of each drive cycle phase will affect the fuel economy label results. Testing of the 2010 Toyota Prius shows that significant battery energy changes can occur on individual phases even when the overall cycle is charge-sustaining and that these changes do affect the fuel economy result for each phase. Developing charge correction lines for every phase is a laborious task which may not always produce results that match assumptions about charge-correction, therefore it is unlikely to be practical for use in certification testing of every hybrid vehicle. Although the fuel economy of individual phases did change significantly as a result of charge correction, the overall fuel economy label for this example case changed to a lesser degree. The derived quantities such as start fuel and air conditioning fuel consumption can be skewed by nonzero battery net energy change (NEC) on the phases in those calculations as well. The experimental work that was performed as part of this thesis and is described in Chapter 5 meets the objective of revealing the effects of charge imbalance on fuel economy label values.

As manufacturers consider how to maximize vehicle label fuel economy for the sake of drawing consumers to their models, the details of the test procedures are important to understanding effects of parameter changes. The 5-cycle method incorporates measures of previously-ignored factors like cold temperatures, air conditioning, and aggressive driving. Hybrid electric vehicles can be more sensitive to some of these factors than conventional vehicles, as had been observed in the various on-road studies considered by EPA when developing the 5-cycle method. In the simulation study presented in Chapter 6, hybrid and conventional vehicles are shown to respond differently to mass and aerodynamic parameter changes and that the relative effects of these parameters are different on 5-cycle than they were under the 2-cycle system. The added complexity of the 5-cycle method and the effect on hybrids that was demonstrated in earlier chapters is therefore shown to be both relevant and significant given the prominence of fuel economy labeling in the marketing of new automobiles.

A body of additional work related to this topic remains to be done. There is currently no regulatory mandate to consider the effect on fuel economy of per-phase charge imbalance, and it is unknown how these effects may compare on other vehicles than the power-split hybrid tested in this thesis. Generally, it would be expected that hybrids with greater electric powertrain capabilities and more capable batteries would have the potential for greater, more rapid changes in battery energy. In the future, EPA may need to create a rule to explicitly address these concerns and standardize a method for dealing with them. The charge imbalance issues on UDDS phases could be mitigated by mandating the exclusive use of the alternative 1-bag UDDS 5-cycle equations, including expansion of this requirement to the cold temperature FTP test which currently allows only the first phase to be repeated after warmup. The US06 is the most difficult phase to deal with because of the extreme nature of the US06 city and the fact that the cycle affects both city and highway fuel economy label inputs. The charge-balance benefit of only using a full US06 in the highway equations would need to be weighed against the probable increase to highway FC that would result from that method.

Although the test effort of developing charge-correction lines for every phase is impractical for normal certification procedures, in yet another concept for addressing charge-imbalance, EPA could consider allowing for development of a single charge-correction slope for a vehicle from a representative cycle, such as the HWFET, which could then be applied to each phase result. A significant body of development work would be required to determine whether the resulting improvement to the fairness of the fuel economy rating offsets potential sources of inaccuracy in a simplified charge-correction method like this one.

An even more complex decision facing regulators is the finalization of rules regarding fuel economy of other advanced technology vehicles such as battery electric vehicles (EVs) and plug-in hybrid electric vehicles (PHEVs). These vehicles already require much longer test procedures by needing to repeat cycles until a battery is depleted (at least to a degree to make extrapolations). The industry-standard test methods for PHEVs are also addressed in the Society of Automotive Engineers (SAE) J1711 standard that is referenced in this thesis for testing of hybrid electric vehicles like the Toyota Prius. A standard for EVs is defined in the SAE J1634 recommended practice. As of 2011, the fuel economy labels for EVs and PHEVs are calculated using some form of the MPG-based estimation equation, which was not specifically designed to work with these types of vehicles. Future testing work will need to consider how EVs and

PHEVs respond to full 5-cycle testing procedures. It has not been demonstrated with test data whether the MPG-based estimate for EVs actually produces results similar to the full 5-cycle method. The testing burden is automatically doubled for PHEVs since they have to be tested in both charge-depleting (CD) and charge-sustaining (CS) modes. That is, electric and fuel consumption are determined for operation where the battery is being depleted, and then fuel consumption is measured under operation once the battery has been fully depleted. Certain PHEVs, such as those with range-extending series generators, can have control strategies (e.g. engine optimum operation) that allow the battery to charge and discharge in a wide range, which could make measurement of true CS fuel economy even more challenging. EPA has aspects of a method from the SAE J1711 standard which computes overall fuel economy for PHEVs using a weighting called "utility factor" (UF) which is related to the all-electric CD range of a vehicle. The range on which the UF is based does not come from the 5-cycle label consumption, so another research area considers potential effects on fuel economy ratings of different methods for determining electric range of plug-in hybrids.

REFERENCES

[Autonomie 2011] Autonomie, "Math-based plug-and-play software for automotive system design". <http://www.autonomie.net>. Accessed 11/1/2011.

[Bontekoe 2005] Bontekoe, Eldert and Richard A. Rykowski. *Vehicle Fuel Economy Labeling and The Effect of Cold Temperature, Air-Conditioning Usage and Aggressive Driving on Fuel Economy*. U.S. EPA Office of Transportation Air Quality. August 12, 2005.

[CFR40 2010] Electronic Code of Federal Regulations, 2010 edition. Title 40—Protection of Environment, Subparts 80 and 600. <http://www.gpo.gov/fdsys/browse/collectionCfr.action?collectionCode=CFR>. Accessed 9/14/2011.

[CFR16 2011] Electronic Code of Federal Regulations, 2011 edition. Title 16 – Commercial Practices, Subpart 259. *Guide Concerning Fuel Economy Advertising for New Automobiles.* <http://www.gpo.gov/fdsys/pkg/CFR-2011-title16-vol1/pdf/CFR-2011-title16-vol1-part259.pdf>. Accessed 10/26/2011.

[Csere 2011] Csere, Csaba. "The CAFE Numbers Game". *Car and Driver*, Nov. 2011, p. 19-20.

[Duoba 2005] Duoba, Michael; Henning Lohse-Busch; Theodore Bohn. *Investigating Vehicle Fuel Economy Robustness of Conventional and Hybrid Electric Vehicles.* Electric Vehicle Symposium (EVS) 21, Monte Carlo, April 2-6, 2005.

[EPA FE Labeling 2006] U.S. Environmental Protection Agency. *Final Technical Support Document – Fuel Economy Labeling of Motor Vehicle Revisions to Improve Calculation of Fuel Economy Estimates*. Dec. 2006. <http://epa.gov/fueleconomy/420r06017.pdf>. Accessed 9/15/2011.

[EPA Response 2006] U.S. Environmental Protection Agency. *Response to Comments: Fuel Economy Labeling of Motor Vehicles.* Dec. 2006. EPA Report: EPA420-R-06-016. <http://www.epa.gov/fueleconomy/420r06016.pdf>. Accessed 10/20/2011.

[EPA FTP Review 1993] U.S. Environmental Protection Agency. *Federal Test Procedure Review Project: Preliminary Technical Report*. May 1992. <http://www.epa.gov/oms/regs/ld-hwy/ftp-rev/ftp-tech.pdf>. Accessed 10/14/2011.

[EPA Trends 2010] U.S. Environmental Protection Agency. *Light-Duty Automotive Technology, Carbon Dioxide Emissions, and Fuel Economy Trends: 1975 Through 2010.* Nov. 2010. <http://www.epa.gov/oms/cert/mpg/fetrends/420r10023.pdf>. Accessed 10/13/2011.

[Evarts 2011] Evarts, Eric. “Is 40 MPG the new 30? Reading between the ad lines.” *Consumer Reports [online]*. Jun. 16, 2011. < http://news.consumerreports.org/cars/2011/06/is-40-mpg-the-new-30-reading-between-the-ad-lines-cruze-focus-fiesta-civic-fuel-economy.html>. Accessed 10/6/2011.

[Federal Register 2010] Federal Register, May 7, 2010. Part II: Environmental Protection Agency; Department of Transportation. *Light-Duty Vehicle Greenhouse Gas Emission Standards and Corporate Average Fuel Economy Standards; Final Rule.* <http://www.nhtsa.gov/staticfiles/rulemaking/pdf/cafe/CAFE-GHG_MY_2012-2016_Final_Rule_FR.pdf>. Accessed 10/14/2011.

[Fueleconomy.gov] www.fueleconomy.gov. “Download Fuel Economy Data”. <http://www.fueleconomy.gov/feg/download.shtml>. Accessed 10/20/2011.

[Meyer 2012] Meyer, Mark; Henning Lohse-Busch; Doug Nelson. *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.* SAE paper number [not yet assigned]. SAE World Congress, April 24-26, 2012.

[Morita 2001] Morita, Kenji et al. *Fuel Economy and Exhaust Emissions Test Procedure for Hybrid Electric Vehicles – Comparison of Continuous Repeating Mode, Linear Approximation and SAE J1711*. Electric Vehicle Symposium 18, Berlin, 2001.

[SAE J1711 2010] SAE J1711 *Recommended Practice for Measuring the Exhaust Emissions and Fuel Economy of Hybrid-Electric Vehicles, Including Plug-in Hybrid Vehicles*. Revised June, 2010.

[Simanaitis 2011] Simanaitis, Dennis. “Monroney Reading, Self-Taught – Technical Report.” *Road & Track*. February 11, 2011. < http://www.roadandtrack.com/auto-news/tech/monroney-reading-self-taught>. Accessed 10/26/2011.

[Tyree 1982] Tyree, Clifford D. *History and Description of the EPA Motor Vehicle Fuel Economy Program.* EPA Technical Report No. EPA-AA-CPSB-82-02. Sept. 1982.

APPENDIX A: VEHICLE TESTING RESULTS

The tables in this appendix list the fuel economy and net electric consumption results for the testing on which the charge correction study was based. The regressions are illustrated in Figure 24. The testing was performed at Argonne National Laboratory.

Table 16. UDDS and US06 city phase results.

Internal Test Number	Phase Test #	Phase	MPG	Vzc*Ah [Wh/mi]
71103014	1	UDDS ph1 CS	48.1	-12.6
71103018	2	UDDS ph1 CS	53.7	30.1
71103024	3	UDDS ph1 CS	48.3	-10.4
71104010	4	UDDS ph1 CS	52.3	14.9
71104015	5	UDDS ph1 CS	42.8	-37.4
71103015	1	UDDS ph1 HS	68.2	46.4
71103019	2	UDDS ph1 HS	45.7	-63.9
71103021	3	UDDS ph1 HS	60.2	-9.1
71104008	4	UDDS ph1 HS	59.8	-3.4
71104011	5	UDDS ph1 HS	52.4	-24.1
71104013	6	UDDS ph1 HS	63.6	8.8
71103018	1	UDDS ph2	77.2	1.9
71103019	2	UDDS ph2	110.6	39.4
71103024	3	UDDS ph2	106.9	40.7
71104009	4	UDDS ph2	101.3	29.9
71104010	5	UDDS ph2	92.6	29.5
71104012	6	UDDS ph2	77.5	-3.6
71104014	7	UDDS ph2	63.8	-35.1
71103017	1	US06 City	29.2	0.8
71103029	2	US06 City	30.4	-43.8
61006020	3	US06 City	28.5	-62.7
71104007	4	US06 City	30.5	-39.8
71104016	5	US06 City	25.8	-113.0
71104018	6	US06 City	30.2	-8.8
71104018	7	US06 City	29.9	-2.9
71104018	8	US06 City	30.5	9.5
71104018	9	US06 City	30.5	2.0

Table 17. US06 highway and HWFET phase results.

Internal Test Number	Phase Test #	Phase	MPG	Vzc*Ah [Wh/mi]
71103022	1	US06 Hwy	49.9	1.4
71103023	2	US06 Hwy	44.2	-24.1
71104005	3	US06 Hwy	49	6.1
71104006	4	US06 Hwy	45.3	-17.9
71104019	5	US06 Hwy	51.3	24.6
61006020	6	US06 Hwy	48.4	15.2
61009008	7	US06 Hwy	49.3	19.5
71103026	1	HWFET	74.1	13.0
71103027	2	HWFET	62.1	-23.0
71104004	3	HWFET	63.3	-16.4
61102006	4	HWFET	69.4	0.1

APPENDIX B: AUTONOMIE SIMULATION STUDY RESULTS

The following tables list the results from each phase and each vehicle configuration that was simulated.

Power-split hybrid results (note: C_D = 0.25 in both mass cases, and mass = 1475 kg in the C_D result)

Table 18. Power-split hybrid simulation results.

	SC03	HWFET	US06 City	US06_HWY	UDDS Phase 1 only	UDDS phase 2 only
Cycle distance [mi]	*3.58*	*10.26*	*1.77*	*6.2*	*3.59*	*3.86*
Mass 1475 kg FE [MPG]	44.99	67.13	35.3	46.87	68.55	79.16
Mass 1325 kg FE [MPG]	47.66	69.3	39.37	48.65	73.06	85.53
C_D = 0.3 FE [MPG]	44.37	62.19	34.17	43.11	64.34	76.65

Table 19. Power-split hybrid 5-cycle label values based on simulation results.

	5-cycle City Fuel Economy [MPG]	5-cycle Highway Fuel Economy [MPG]
Mass 1475 kg FE [MPG]	54.6	44.0
Mass 1325 kg FE [MPG]	58.8	45.6
C_D = 0.3 FE [MPG]	52.5	40.6

Conventional midsize vehicle results (note: C_D = 0.30 in both mass cases, and mass = 1700 kg in the C_D result)

Table 20. Conventional vehicle simulation results.

	SC03	HWFET	US06 City	US06_HWY	UDDS Phase 1 only	UDDS phase 2 only
Cycle distance [mi]	*3.58*	*10.26*	*1.77*	*6.2*	*3.59*	*3.86*
Mass 1700 kg FE [MPG]	24.55	46.98	16.7	29.91	33.6	30.9
Mass 1525 kg FE [MPG]	26.05	49.26	18.45	31.51	35.75	32.65
C_D = 0.25 FE [MPG]	24.89	49.89	17.05	32.28	34.54	31.13

Table 21. Conventional vehicle 5-cycle label values based on simulation results.

	5-cycle City Fuel Economy [MPG]	5-cycle Highway Fuel Economy [MPG]
Mass 1700 kg FE [MPG]	25.0	28.6
Mass 1525 kg FE [MPG]	26.7	30.1
C_D = 0.25 FE [MPG]	25.5	30.7