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Measuring and Reporting Fuel Economy of Plug-In Hybrid Electric Vehicles

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NOTICE

MEASURING AND REPORTING FUEL ECONOMY OF PLUG-IN HYBRID ELECTRIC VEHICLES[1]

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Abstract

Plug-in hybrid-electric vehicles (PHEVs) have recently emerged as a promising alternative technology to dramatically reduce fleet petroleum consumption. However, the fuel economy of many recent prototype and theoretical vehicles has varied widely and often been exaggerated in the press. PHEVs present a significant challenge as compared with conventional vehicle fuel economy reporting because they receive energy from two distinct sources and exhibit widely varying per-mile consumption, based on the drive cycle and distance driven. This paper reviews various techniques used to characterize PHEV fuel economy and discusses the relative merits, limitations, and best uses of each. This review will include a discussion of the SAE J1711 Recommended Practice issued in 1999 and will comment on how recent analysis indicates that the described procedures could be improved for reporting PHEV fuel economy. The paper highlights several critical reporting practices accurately captured by SAE J1711: use of standardized drive cycles; inclusion of charge depleting and charge sustaining operation; and using utility-factor weighting to properly combine the vehicle's operating modes using representative driving statistics. Several recommended improvements to J1711 are also discussed: separate reporting of fuel and electricity use; better determination of the vehicle's charge depleting performance; and application of a once-per-day vehicle charging assumption. As the U.S. Environmental Protection Agency (EPA) considers changes to window-sticker fuel economy test procedures, and the original issuance of SAE J1711 expires, the authors hope to stimulate the necessary discussion and contribute to adoption of consensus reporting metrics. In order for the resulting metrics to be useful, stakeholders must be able to translate the numbers into sound predictions of relative vehicle energy cost, petroleum use, and potential carbon dioxide (CO_2) production.

Keywords: Plug-in Hybrid; Grid-connected HEVs; Vehicle Performance; Energy Efficiency, Energy Consumption; Codes, Standards, Legislation, Regulations; Environmental Impact

1   Introduction

A PHEV is a hybrid-electric vehicle (HEV) with the ability to recharge its electrochemical energy storage with electricity from an off-board source (such as the electric utility grid). The vehicle can then drive in a charge-depleting mode that reduces the system's state-of-charge (SOC), thereby using

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electricity to displace petroleum fuel that would otherwise be consumed. PHEVs typically have batteries that are larger than those in HEVs so as to increase the potential for petroleum displacement.

Plug-in hybrid-electric vehicles have recently emerged as a promising alternative to displace a significant fraction of vehicle petroleum consumption with electricity. This potential derives from several factors. First, PHEVs are potentially well-matched to motorists' driving habits, particularly the distribution of miles traveled each day. Second, PHEVs can build off the success of production HEVs in the marketplace. Finally, PHEVs are very marketable in that they combine the beneficial attributes of HEVs and pure battery electric vehicles (BEVs) while simultaneously alleviating the disadvantages of each. As a result, PHEVs have the potential to come to market, penetrate the fleet, and achieve meaningful petroleum displacement relatively quickly. Few competing technologies offer this potential combined rate and timing of reduction in fleet petroleum consumption [1].

Plug-in hybrid-electric vehicles are typically characterized by a "PHEVx" notation, where "x" generally denotes the vehicle's All-Electric Range (AER) – defined as the distance in miles that a fully charged PHEV can drive on stored electricity before needing to operate its engine. The California Air Resources Board (CARB) uses the standard Urban Dynamometer Driving Schedule (UDDS) to measure the all-electric capability of PHEVs and provide a fair comparison between vehicles [2]. According to this definition, a PHEV20 can drive 20 all-electric miles (32 kilometers) on the test cycle before the first engine turn-on. However, this all-electric definition fails to account for PHEVs that might continue to operate in charge-depleting mode after the first engine turn-on.

To better capture the range of PHEV control strategies and configurations, the authors of this paper use a different definition of PHEVx that is more-appropriately related to petroleum displacement. Under this definition, a PHEV20 contains enough useable energy storage in its battery to displace 20 miles of petroleum consumption on the standard test cycle. Note that this definition is not meant to imply all-electric capability because the vehicle operation will ultimately be determined by component power ratings, the vehicle's control strategy, and the nature of the actual in-use driving cycle.

The key limitation of the PHEVx designation is that it is a *relative metric* that only describes potential petroleum displacement relative to the same vehicle operating in charge-sustaining mode. It does not provide information about absolute vehicle fuel economy. For example, a PHEV20 sedan may achieve 40 miles per gallon (mpg), or 5.9 liters per 100 kilometers (L/100 km) in charge-sustaining operation, whereas a PHEV20 SUV may only achieve 25 mpg (9.4 L/100 km), but this is not captured by the PHEVx metric. Furthermore, a fully-charged all-electric PHEV20 uses no petroleum over a 20-mile trip, leading to the impressive result of infinite miles-per-gallon (0 L/100 km) of petroleum use. Such a result is clearly helpful in marketing PHEVs, but does not provide much information about real-world potential because in reality motorists drive a variety of distances – some short, some long. An objective method is clearly needed for evaluating and reporting PHEV fuel economy, so as to avoid exaggerated claims and generate a vehicle rating that translates in some way to expectations for the real-world vehicle performance.

The reader should note that this paper will emphasize imperial units (miles and gallons for driving distance and gasoline usage, respectively) and fuel *economy* rather than *consumption* to be consistent with U.S. Government regulatory standards. Also note that, although this paper was written primarily from a fuel economy perspective (with little discussion of emissions measurement), these recommended procedures for PHEV testing and reporting are designed for suitable application to both fuel economy and emissions measurements.

2   PHEV fuel economy reporting methods

Determining a "fuel economy rating" for PHEVs presents a particular challenge as compared with other vehicle technologies because the motive power for the vehicle is derived from two distinct sources: a chemical fuel (typically gasoline) and electricity. The relative consumption of each fuel depends greatly on the duty cycle over which the PHEV operates. As with other vehicles, the type of

driving (urban, highway, high speed, etc.) is a very important factor, but more important to PHEVs is the distance driven between vehicle recharging events. In addition to appreciating the factors influencing fuel vs. electricity consumption, the presence of two energy sources presents a challenge in providing a rating comparable to vehicles using a single mile-per-gallon economy or liter-per-100 kilometers consumption value.

One approach would be to report only the fuel use of the vehicle. This method captures the petroleum consumption impact, but fails to account for the impacts and costs of the additional electricity consumption. Alternatively, the fuel and electricity use can be combined into a single metric that makes assumptions about the equivalent values of the two energy forms. One example is the commonly used energy-equivalency of gasoline and electricity (1 gallon [gal] = 33.44 kilowatt-hours [kWh]), which leads to a metric that accounts for both, but fails to account for differences in the supply-chain efficiency of each. Even if a different energy-equivalence factor is used to account for supply-chain efficiencies, it does not account for likely differences in the primary energy source for each supply chain. One megajoule of coal (for electricity) may have the same primary energy content as one megajoule of crude oil (for gasoline), but these sources are certainly quite different from an economic, environmental, and geopolitical perspective. Other examples of equivalency factors include cost-equivalency factors (e.g., 1 gal @ \$3/gal = 30 kWh @ \$0.1/kWh) and CO_2 emissions-equivalency factors. However, all metrics based on equivalency factors suffer the disadvantage of not providing useful information about net petroleum consumption impact.

Ultimately, there are a variety of stakeholder perspectives that must be addressed when devising a method for fuel economy reporting. Motorists may be primarily concerned with vehicle operating costs and therefore may want a metric that conveys the magnitude of those costs. On the other hand, policymakers and environmentalists may be primarily concerned with national petroleum impact and CO_2 production levels and may want a metric that can be extrapolated to the fleet level. Vehicle manufacturers, however, are obliged to focus on benchmarking and certification procedures and will also want a metric that is well-suited to this purpose.

The authors argue that the measurement technique ultimately selected must capture specific standardized performance aspects to accurately evaluate the tested vehicle with respect to annual operating costs, national petroleum impact, and CO_2 production. Furthermore, the testing to obtain the performance ratings must be conducted over consistent and representative standardized driving profiles, with appropriate weightings applied to account for typical driving distances and to make comparisons with other vehicle technologies possible.

3 SAE J1711 Recommended Practice

While the various reporting approaches discussed in the previous section have been used by a variety of individuals for particular applications or analyses, the most formalized PHEV reporting procedure to date appears to be contained within the Society of Automotive Engineers (SAE) J1711 *Recommended Practice for Measuring the Exhaust Emissions and Fuel Economy of Hybrid-Electric Vehicles* [3]. Originally issued in 1999, the document seeks to provide a technical foundation for reporting procedures applied to a range of HEV designs, including those with "Off-Vehicle-Charge" (OVC) capability (i.e., PHEVs). Figure 1 presents a general overview of the steps in SAE J1711 that build to determining a final fuel economy rating over a particular test cycle. The specific test cycles addressed in the document include the UDDS and the Highway Fuel Economy Test (HWFET), which the EPA use for light-duty fuel economy testing.

Non-OVC-capable conventional HEVs would only complete the steps on the left side of Figure 1, whereas PHEVs follow the steps from both sides of the figure. The Partial-Charge Test (PCT) is designed to measure the vehicle's performance in a charge-neutral hybrid operating mode, such as after a PHEV has depleted its energy storage system (ESS) to the desired charge-sustaining operating level. The Full-Charge Test (FCT) measures the vehicle's performance when the initially fully-charged ESS is permitted a net discharge through the course of the test cycle. The bottom row in

Figure 1 indicates the provisions in J1711 to account for user-selectable Conventional Vehicle (CV) and Electric Vehicle (EV) operating modes. However, the test procedure discussion in this paper assumes that the PHEV is only operated in a default/hybrid operating mode. The remaining rows in the figure follow the steps through measuring the results of the PCT and FCT, applying a Utility Factor (UF) weighting to the FCT results, and then combining together the PCT and the weighted FCT results by making an assumption about how frequently the vehicle will be recharged. The remainder of this section will briefly describe each of these steps.
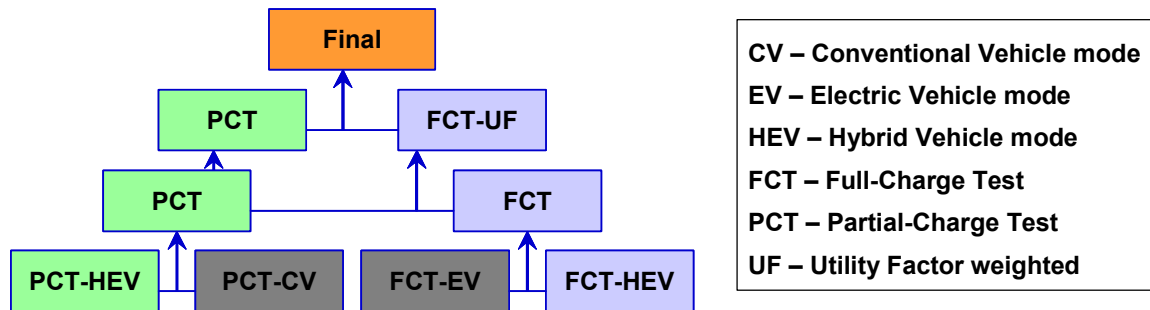

Figure 1: Overview of J1711 approach for determining "final" PHEV fuel economy for a test cycle based on Partial-Charge Test (PCT) and Full-Charge Test (FCT) results

Figure 2 illustrates an example of how the ESS SOC may vary over the course of the PCT. While the instantaneous SOC may move up and down during the test, the final SOC should return to roughly the same level as the initial SOC at the start of the test. The PCT fuel economy is calculated by the following equation, where "D" is the test distance in miles, "V_{fuel}" is the volume of fuel consumed in gallons, and "mpg_{CS}" is taken to be the charge-sustaining mile-per-gallon rating.

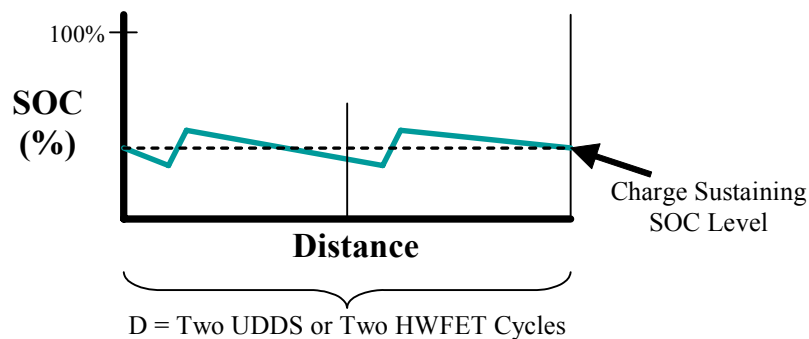$$mpg_{CS} = \frac{D}{V_{fuel}}$$

Figure 2: PCT to measure Charge-Sustaining (CS) vehicle fuel economy; illustrated with application to the UDDS or HWFET test cycles

Figure 3 provides a similar example of how SOC may vary over the course of the SAE J1711 FCT. The SOC begins the cycle at 100% and decreases as the vehicle is driven electrically. The distance traveled up until the PHEV engine turns on is recorded as the vehicle's All-Electric Range (as defined in the introduction to this paper) for the particular test cycle. Following this initial engine turn-on, the vehicle may continue operating in a Charge-Depleting (CD) mode with the engine and ESS/motor working together in a blended manner to propel the vehicle. For the two principal test cycles, the FCT is terminated after four repetitions of the UDDS or three repetitions of the HWFET. However, if the engine has not turned on at that point, the cycles continue repeating until it does turn on. At the conclusion of the test, the ESS is fully recharged using off-board electricity, and the required electrical charging energy is recorded. The following equation is used to calculate the CD mile-per-gallon rating, "mpg_{CD}," as determined by the SAE J1711 FCT. The new terms in this equation are "E_{charge}," the required electrical recharge energy in kilowatt-hours, and "$E_{gasoline}$," a constant equal to 33.44 kWh/gal

representing the energy content of a gallon of gasoline. Note that this approach converts the electrical recharge energy into an energy-equivalent volume of gasoline to add to the actual volume of fuel consumed.

$$mpg_{CD} = \frac{D}{V_{fuel} + \dfrac{E_{ch\arg e}}{E_{gasoline}}}$$
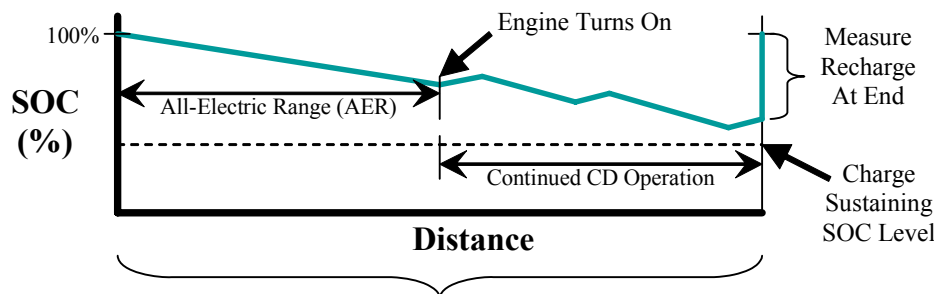
D = Four UDDS or Three HWFET Cycles (~30 miles)
(if no engine on in first 30 miles continue to run cycles until it does turn on)

Figure 3: FCT to measure Charge-Depleting (CD) fuel economy, illustrated with application to the UDDS or HWFET test cycles
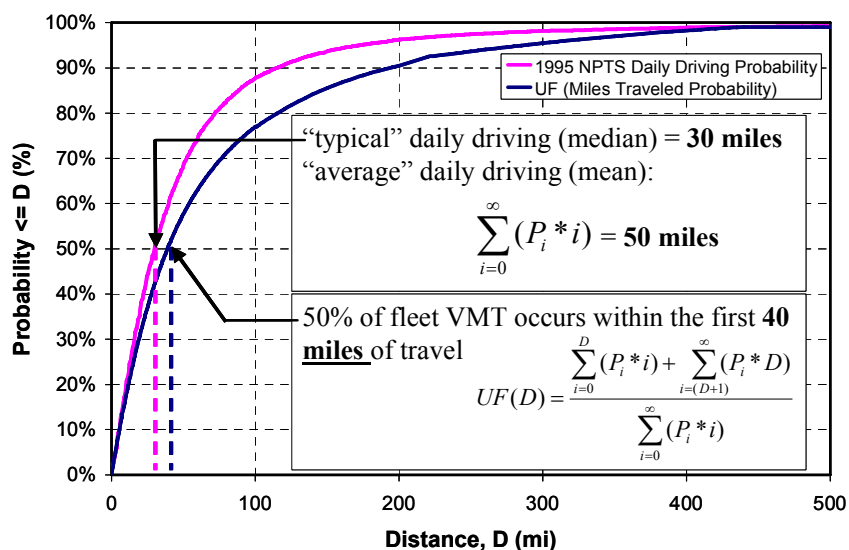

Figure 4: Illustration of Utility Factor (UF) weighting with U.S. national driving statistics

The next key step in SAE J1711 is to weight the FCT result with national driving statistics. Again, because of the focus on U.S. standards, the weighting data is taken from information on U.S. driving behavior. The purpose of the weighting is to determine on aggregate how much of a vehicle's driving is expected to occur in its CD mode vs. in its CS mode. Figure 4 demonstrates how the appropriate weighting factor is determined. The top line in the figure represents the daily driving probability distribution determined by the 1995 National Personal Transportation Survey (NPTS) conducted in the United States. For each distance, "D," given along the x-axis, the corresponding point on the y-axis indicated by the curve is the probability that a vehicle's total daily driving will be less than or equal to D. The point at which the NPTS probability curve crosses 50% is the median or "typical" daily driving distance of 30 miles. However, because longer trips consist of more driving miles, the average daily driving distance is greater – 50 miles as given by the top equation in Figure 4, where "i" is the mileage increment for driving statistics in steps of 1 mile and "P_i" is the probability that a vehicle will be driven i miles per day. The utility of a CD operating mode to the vehicle fleet must be calculated

on a miles-driven probability basis rather than a "typical vehicle" driving basis because fuel consumption is related to total driven miles, and the 50% of vehicles with daily driving distances greater than the median account for a larger portion of all driven miles. The bottom equation in Figure 4 determines utility on a miles-driven basis, including in the utility calculation all miles for vehicles with daily driving less than the CD distance, as well as the initial miles for vehicles with daily driving greater than the CD distance. The second curve shows the resulting UF calculation as a function of D. For this curve, the interpretation of the 50% probability crossing point is that 50% of fleet Vehicle Miles Traveled (VMT) occurs within the first 40 miles of daily driving.

In SAE J1711, the FCT distance used to determine mpg_{CD} is roughly 30 miles (assuming four UDDS cycles or three HWFET cycles). The UF value corresponding to this distance is 0.42, which would be used in the following equation to calculate the UF-weighted CD mile-per-gallon rating: "$mpg_{CD,UF}$."

$$mpg_{CD,UF} = \frac{1}{\dfrac{UF}{mpg_{CD}} + \dfrac{(1-UF)}{mpg_{CS}}}$$

The final step in SAE J1711 for calculating the cycle fuel economy, "mpg_{cycle}," for a PHEV is to assume the vehicle is equally likely to be driven in a UF-weighted CD mode as to be driven in a CS mode. This is similar to assuming that the vehicle is equally likely to be charged daily as to never be charged at all, or that the vehicle is charged on average once every 2 days. The equation below applies this equal probability assumption.

$$mpg_{cycle} = \frac{2}{\dfrac{1}{mpg_{CD,UF}} + \dfrac{1}{mpg_{CS}}}$$

Because the above-described approach only determines the fuel economy for specific test cycles, it is assumed that a composite PHEV fuel economy number would have to be obtained by employing the EPA's multi-cycle weighting methodology. The current-status EPA approach would be to apply a 55/45% weighted harmonic average to the results of the city/highway test cycles.

4   Important points and recommended changes to SAE J1711

The SAE J1711 Recommended Practice addresses several of the key issues necessary for properly measuring PHEV fuel economy. In particular, the document correctly recognizes that vehicle performance must be evaluated in both CD and CS operating modes, and that both fuel and net electricity consumption must be included. To account for the utility of CD operation, SAE J1711 also correctly applies a UF approach to account for the distribution of daily driving behavior that is weighted based on daily distances driven. This step is necessary to determine a PHEV fuel economy rating that is comparable on a national benefits scale to other vehicles' ratings (again assuming that national driving statistics were used to generate the UF curve).

There are also several aspects of SAE J1711 that the authors recommend modifying. Three of the most important changes include keeping fuel and electricity consumption separated, better determining the CD operating distance for UF weighting, and changing the charging frequency assumption from once every other day to once daily. The remainder of this section will discuss each of these recommendations in more detail and provide an example of their relative impact.

4.1   Recommendation 1: Report electricity separately

As discussed in section 2 of this paper, the energy equivalence method of treating electricity consumption as if it were gasoline does not support the needs of stakeholders that use the vehicle's fuel economy rating. A more useful approach to that currently suggested by SAE J1711 would be to

present a fuel economy and electricity consumption rating for the vehicle (such as providing a watt-hour-per-mile (Wh/mi) value in addition to the mile per gallon number). When combined with a distance driven over a period of time (that is representative of the typical daily distance distribution), these two numbers would provide an estimate of the volume of fuel used and the electrical charging energy that went into the vehicle over that operating period. A stakeholder who knew a baseline vehicle's fuel consumption and the production mix of a certain region's electrical utility could then take these separate fuel and electrical energy values to determine petroleum and CO_2 impact. For the benefit of consumers who are typically most interested in their vehicle's total energy cost (including fuel and electricity use), this rating approach could also consider average gasoline and electricity prices along with a typical annual driving distance to estimate a representative energy cost comparable from vehicle to vehicle.

Table 1 provides an example of the impact this revision to J1711 would have on two hypothetical PHEVs. The assumptions used to generate the annual energy cost estimates for all the tables in this paper were fuel and electricity costs of \$2.50/gal and \$0.09/kWh, respectively, and an annual driving distance of 15,000 miles (a typical annual VMT for U.S. drivers). Note also that all of the annual cost estimates are for illustration purposes only, as they are extrapolated from hypothetical test results over one cycle only. As the results in Table 1 illustrate, this change (to report electricity separately) does not by itself produce a large change in the energy cost estimate, but it does provide more accurate and useful information about the distribution of energy use between gasoline and electricity.

Table 1: Example impact of Recommendation 1 – reporting electricity separately*

Example PHEVs	PHEV5	PHEV30
PCT Results	50 mpg	50 mpg
FCT Results	30 mi, 0.5 gal, 1.2 kWh	30 mi, 0.15 gal, 5 kWh
J1711	51.1 mpg, **\$733/yr**	55.9 mpg, **\$671/yr**
J1711 Recommendation 1	51.8 mpg, 8.4 Wh/mi **\$735/yr**	59.3 mpg, 35.0 Wh/mi **\$679/yr**

*Assumes \$2.50/gal fuel, \$0.09/kWh electricity and 15,000 miles/year

4.2 Recommendation 2: Determination of utility factor (UF) weighting distance

A second recommended change to the existing J1711 reporting procedure would be to improve determination of the CD operating distance for UF weighting. Figure 5 provides an example of the SOC profile during the UDDS FCT (as described in Figure 3) for the two example PHEV5 and PHEV30 vehicles in order to demonstrate how the existing procedure could be improved. For both example vehicles, the engine turns on during the first four cycle repetitions, so the existing procedure calls for ending the test after completing the fourth cycle and measuring the recharge energy required. As the figure shows for the PHEV5 vehicle, the ESS SOC drops quickly during the first half of the initial UDDS cycle, and continues to drop at a somewhat slower rate once it begins operating in a blended (engine plus ESS/motor) mode. From partway through the second cycle until the end of the fourth cycle, the PHEV5 operates in a CS mode. For the PHEV30, the ESS discharges during all-electric vehicle operation through the first three cycles, and then continues to discharge at a slower rate during the fourth cycle as the vehicle operates in a blended mode. By the end of the fourth cycle when the existing SAE J1711 approach calls for completing the test, the ESS has not yet reached its CS SOC level. By holding the FCT to the fixed length of four-cycles, the existing J1711 approach actually averages together roughly 50% CD operation and 50% CS operation to obtain the "CD rating" for the PHEV5, and it also does not credit the PHEV30 for its continued CD operation beyond the end of the fourth cycle (instead assuming the CS rating applies to all cycles after the first four).

Instead of fixing the FCT length, the authors recommend ending the FCT after completing the cycle during which the CS SOC is reached. In a practical implementation, this would mean tracking the total Ampere-hour (Ah) discharge from the vehicle ESS and calculating when the manufacturer's CS

SOC level was reached, or determining when the net ESS Ah change either increases or remains within a tolerance during all or most of one cycle. (The latter approach could result in one full cycle of CS operation included at the end of the FCT, so the following steps could be adjusted accordingly in order to set the UF-weighting distance to only include cycles in which CD operation occurred.) Assuming that it could be determined when the CS operating level was reached, the end of the cycle during which this occurred would be used as the distance, D, in the UF-weighting, and the recharge energy would be measured at this point. As Figure 5 illustrates, the modified FCT would be completed after two cycles for the PHEV5 vehicle and the recharge energy would remain basically the same. For the PHEV30 vehicle, the modified FCT would be extended to seven total cycles and the recharge energy would be greater (accurately reflecting the energy required to return the vehicle from a CS SOC state to fully-charged).
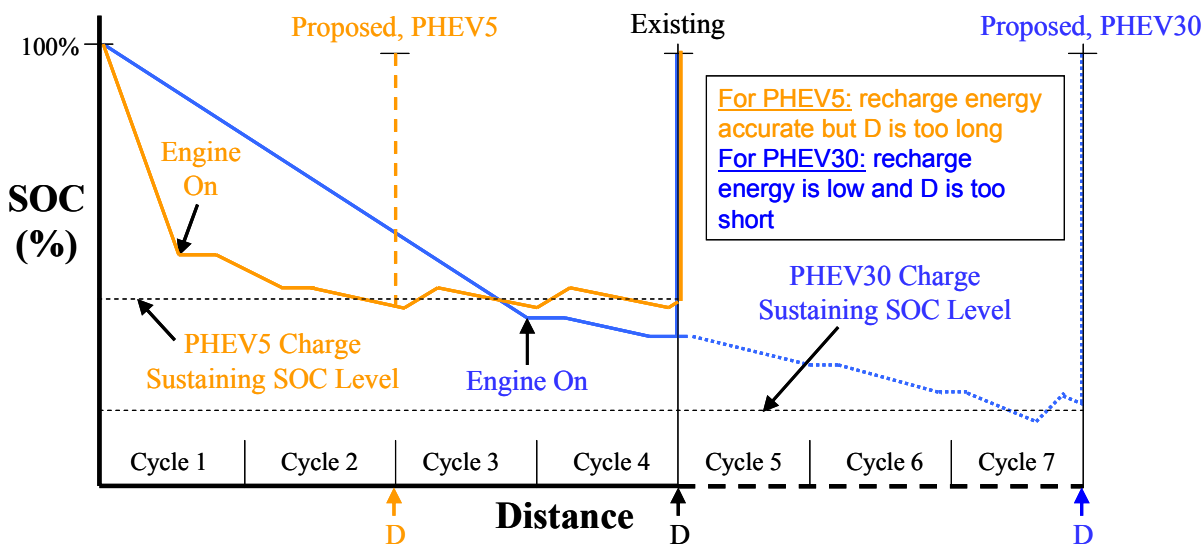

Figure 5: Hypothetical FCT SOC profiles for two example PHEVs over a UDDS cycle test

Table 2 presents an example of the impact this change might have on estimated energy use and cost. The table compares the result of just modifying J1711 with the separate electricity reporting recommendation to the result of using J1711 with separate electricity reporting and a modified FCT to more accurately determine the UF weighting distance. The result of the change is minor for the PHEV5 vehicle, but is noticeable for the PHEV30 vehicle – producing a 5% decrease in the annual energy cost estimate. The impact of the change should be largest for vehicles with a large ESS, for which the existing procedure potentially misses many miles of continued CD operation between the end of the FCT and when the vehicle actually begins CS operation.

Table 2: Example impact of Recommendation 2 – determining UF weighting distance*

Example PHEVs	PHEV5	PHEV30
PCT Results	50 mpg	50 mpg
Original FCT Results	30 mi, 0.5 gal, 1.2 kWh	30 mi, 0.15 gal, 5 kWh
Revised FCT Results	15 mi, 0.2 gal, 1.2 kWh	52.5 mi, 0.3 gal, 7.2 kWh
J1711 Recommendation 1	51.8 mpg, 8.4 Wh/mi, **$735/yr**	59.3 mpg, 35.0 Wh/mi, **$679/yr**
J1711 Recommendations 1&2	52.1 mpg, 9.6 Wh/mi, **$733/yr**	63.3 mpg, 40.5 Wh/mi, **$647/yr**

*Assumes $2.50/gal fuel, $0.09/kWh electricity and 15,000 miles/year

Note that to ensure CS operation follows completion of the FCT, the FCT and PCT could be combined into one single procedure to first measure CD operation and then subsequent CS operation. However, the authors anticipate that comprehensive emissions measurement will still necessitate completion of a

cold-start PCT, and so do not suggest moving away from two separate tests. Note also that the procedure for determining the UF weighting distance implicitly assumes that the average mpg and Wh/mile values can be uniformly applied over the vehicle's driving up to distance, "D." In reality, the vehicle will likely consume more electricity and less fuel early on in the cycles, and will shift to consuming more fuel and less electricity as it approaches the distance, "D." A worthwhile approach to consider for capturing this effect would be to segment the utility factor in whole-cycle increments in order to weight the fuel and electricity use over each individual cycle for determining the total representative energy use estimate. However, the authors do not recommend this more complicated approach because the uncertainty introduced through necessary estimation of the recharge energy required for each cycle could easily offset the improved accuracy over a uniform CD operation assumption. In addition, the uncertainties in the data used to generate the UF curve could be amplified and inadvertently propagated when assigning individual weightings to each incremental cycle segment distance.

4.3   Recommendation 3: Changing the charging frequency assumption

The third recommended change to SAE J1711 is fairly simple but can have a large impact on reported energy consumption and cost. As described in section 3, the current approach averages together the UF-weighted CD result (which is intended to approximate once daily charging) and the CS result (which represents no charging). Because no reliable national data exists to predict how often PHEV drivers will plug in their vehicles, the original J1711 task force selected this equal weighting between "plug-in" and "non-plug-in" operation as a placeholder for combining the effects of these two operating modes. However, in the absence of conclusive data to capture expected charging frequency for PHEVs, the authors of this paper assert that once-per-day charging (represented by the UF-weighed CD result) is a better placeholder for combining CD and CS operation. This is because in addition to charging the vehicle either zero or one time per day, the PHEV driver could charge the vehicle multiple times per day (known as "opportunity charging") whenever parked at a home, work, or other location that had a charging outlet.

Especially during the early years of their introduction into the market, there will likely be a large price increment between a conventional or hybrid and a comparable PHEV. In order to recover some of this initial expense, there will be a large economic incentive for PHEV drivers to take advantage of the significantly lower energy cost to operate the vehicle on electricity rather than on gasoline alone. The relatively small early market penetration levels should also require fairly little utility control over vehicle charging to avoid exacerbating peak daytime electricity demand. This would permit PHEV drivers to act on the incentive to opportunity charge several times daily. Even so, until solid data sets become available to support an average charging frequency assumption greater than once daily (or between 0-1 times per day), once daily charging provides a reasonable placeholder for this frequency assumption. Because of the economic incentive to charge, especially in the initial years of PHEV adoption and test procedure application, this once per day assumption should provide a more accurate placeholder than a once every other day assumption.

Table 3: Example impact of Recommendation 3 – changing the charging frequency assumption*

Example PHEVs	PHEV5	PHEV30
PCT Results	50 mpg	50 mpg
Revised FCT Results	15 mi, 0.2 gal, 1.2 kWh	52.5 mi, 0.3 gal, 7.2 kWh
J1711 Recommendations 1&2	52.1 mpg, 9.6 Wh/mi, **$733/yr**	63.3 mpg, 40.5 Wh/mi, **$647/yr**
J1711 Recommendations 1,2&3	54.3 mpg, 19.2 Wh/mi, **$716/yr**	86.4 mpg, 80.9 Wh/mi, **$543/yr**

*Assumes $2.50/gal fuel, $0.09/kWh electricity and 15,000 miles/year

Table 3 provides the final example results highlighting the impact of adding this third recommended change to the first two. For both example vehicles, the final change causes the reported fuel economy

to increase at the expense of a higher per-mile electricity consumption rating, but ultimately provides an overall reduction in the estimated annual energy cost. The observed impact is again much greater for the PHEV30 with its larger ESS – resulting in a 16% reduction in the annual energy cost estimate.

4.4   Additional discussion

There are two significant open issues not addressed in SAE J1711 that this document does not examine in detail. The first is the correlation between driving type and driving distance. The current-status UF weighting approach implicitly assumes that the daily distance distribution of the driving represented by a particular test cycle matches the average distribution given by national (U.S.) driving statistics. For instance, with the current two-cycle city and highway EPA approach, the same national driving statistics would determine the combined CD and CS weighting for the UDDS (city driving) and for the HWFET (highway driving) before merging these values into a composite rating (by applying the 55/45% weighting of city/highway driving). This set UF weighting approach for each cycle neglects the fact that shorter city trips are likely to make up a larger fraction of CD operating miles, and longer highway trips are likely to make up a larger fraction of CS operating miles.

If future travel surveys can begin to capture the variation of driving type by daily driving distance, then a unique UF curve could be selected for each cycle. In the mean time, it once again seems most appropriate to maintain application of the uniform UF curve to each cycle evaluated. The EPA's proposed move to a five-cycle procedure [4] will present additional challenges, not the least of which is a dramatically increased burden of up to ten tests in order to complete the PCT and FCT for each cycle. An official revision to J1711 should consider the new procedure EPA officially adopts and balance decisions to improve accuracy with those to avoid excessive testing complexity and cost.

The second challenging issue that will require further examination is how to apply EPA in-use fuel economy adjustment factors to a PHEV. The EPA introduced these adjustment factors in 1984 in an effort to quantify observed reductions in real-world fuel economy below certification cycle test results due to effects such as more aggressive driving and use of accessories (especially air conditioning). This adjustment approach is still in use today, although continued overestimation of in-use fuel economy has prompted the EPA to now consider more dramatic procedure revisions. The current methodology reduces the UDDS and HWFET test results by 10 and 22 percent, respectively, to determine the city and highway fuel economy estimates. However, the same methodology cannot be used to adjust a PHEV's UF-weighted fuel economy and electricity consumption results because the effects that the adjustment factors are supposed to represent (such as more aggressive driving) would be observed prior to performing the UF weighting of CD and CS operation. Specifically, the adjusted cycle could impact the PCT and FCT mile per gallon and watt-hour per mile results, as well as the CD distance used for UF weighting.

One possible approach to apply the EPA adjustment factors to a PHEV would be to reduce the PCT fuel economy in the same manner as would be done for a conventional vehicle, and determine the resulting increase in fuel volume consumed over a CS distance equal to the original (UF weighting) FCT distance. The UF weighting distance for the FCT would then be assumed to remain the same, with the calculated volume of fuel added into the FCT fuel economy result. An alternate approach would be to apply the adjustment factor to the PCT and FCT fuel economy and electricity consumption results, as well as to the CD distance (resulting in a reduced distance to use with the UF weighting curve). Further analysis will be required to determine the validity of either of these approaches. Fortunately, either method would maintain some applicability to the anticipated EPA procedure changes, as the EPA proposal retains a downward adjustment of measured fuel economy results to account for effects impossible to incorporate in laboratory dynamometer testing [4].

5   Summary and conclusions

In its present form, the SAE J1711 recommended practice provides useful guidelines for consistent reporting of hybrid vehicle fuel economy across a range of vehicle types. Through application to standard drive cycles and weighting the utility of CD PHEV operation (based on national fleet statistics), J1711 provides a more objective comparison of PHEV performance to that of conventional and HEVs than do other less formalized rating approaches. J1711 nonetheless requires some revision to fully satisfy the needs of stakeholders using the fuel economy rating, and to further improve its accuracy in reporting PHEV performance. Table 4 summarizes the example impacts for the three major recommended changes described in this paper.

Table 4: Summary of example impacts for recommended changes to SAE J1711*

Example PHEVs	PHEV5	PHEV30
J1711 original result	**51.1 mpg, $733/yr**	**55.9 mpg, $671/yr**
+ Keep electricity separate	51.8 mpg, 8.4 Wh/mi, $735/yr	59.3 mpg, 35.0 Wh/mi, $679/yr
+ Better capture CD distance	52.1 mpg, 9.6 Wh/mi, $733/yr	63.3 mpg, 40.5 Wh/mi, $647/yr
+ Assume once daily charging (**New final result**)	**54.3 mpg**, 19.2 Wh/mi, **$716/yr**	**86.4 mpg**, 80.9 Wh/mi, **$543/yr**

*Assumes 50 mpg PCT, $2.50/gal fuel, $0.09/kWh electricity and 15,000 miles/year

The new results for the modified reporting approach provide a more accurate estimate of the petroleum savings each of these vehicles could provide, which was understated by the original J1711 result. Specifically, the petroleum consumption estimate is reduced by 6% for the PHEV5 and by 35% for the PHEV30. The new results also provide an estimate of the electricity consumption per mile that a typical user could expect the vehicle to achieve. From this more accurate description distinguishing fuel from electricity use, and assuming once daily charging, the results demonstrate a 2% reduction in the annual energy cost estimate for the PHEV5 and a 19% reduction in the annual energy cost estimate for the PHEV30 relative to the original J1711 result. The magnitude of the improved estimates for petroleum use and energy cost are greater for longer distance rated PHEVs because of the potential offered by their larger energy storage systems.

It is in the best interest of all those evaluating the potential benefits of PHEVs to be able to objectively evaluate the technology relative to other vehicles. It should likewise be in the best interest of PHEV advocates to establish and follow consensus PHEV reporting procedures to avoid accusations of providing unfounded "hype" for the technology.   In particular, the adopted procedures should characterize PHEV performance over a representative range of driving conditions, including proper weighting of typical vehicle daily driving distances. A discussion of accurate and objective PHEV fuel economy reporting is particularly important in the present context of increasing technical interest in PHEVs, expiration of the original issuance of SAE J1711 and EPA's proposal to change the agency's conventional vehicle test procedures. It is the authors' hope that the issues raised in this paper help stimulate the necessary discussion and contribute to adoption of consensus reporting metrics. As discussed in this paper, for the resulting metrics to be useful, stakeholders must be able to translate the numbers into sound predictions of relative vehicle energy cost, petroleum use, and potential carbon dioxide (CO_2) production.

Acknowledgement

List of symbols and acronyms

AER – all-electric range
CARB – California Air Resources Board
CO_2 – carbon dioxide
CV – conventional vehicle
DOE – U.S. Department of Energy
$E_{gasoline}$ – gasoline energy content (33.44 kWh/gal)
EPA – U.S. Environmental Protection Agency
FCT – Full-Charge Test
HWFET – Highway Fuel Economy Test
mpg_X – mile-per-gallon rating in mode X
NPTS – National Personal Transportation Survey
PHEV – plug-in hybrid electric vehicle
SAE – Society of Automotive Engineers
UDDS – Urban Dynamometer Driving Schedule
V_{fuel} – fuel volume consumed [gallons]

BEV – battery electric vehicle
CD – charge depleting
CS – charge sustaining
D – distance [miles]
E_{charge} – electrical recharge energy
ESS – energy storage system
EV – electric vehicle
HEV – hybrid electric vehicle
i – mileage increment for driving statistics
OVC – off-vehicle charge
PCT – Partial-Charge Test
P_i – probability i miles driven in a day
SOC – state of charge (of the ESS)
UF – Utility Factor
VMT – vehicle miles traveled

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[4] Environmental Protection Agency, *Fuel Economy Labeling of Motor Vehicles: Revisions to Improve Calculation of Fuel Economy Estimates*, 40 CFR Parts 86, 600, EPA: Notice of Proposed Rulemaking, EPA-HQ-OAR-2005-0169.

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