ABSTRACT

To understand the real world conditions of use of plug-in hybrid electric vehicles, the electrical energy consumption and gasoline energy consumption must be weighted according to how often a consumer will drive fueled by each energy source. To perform this weighting The Society of Automotive Engineers Hybrid Committee has codified the concept of the utility factor in SAE J2841 - Utility Factor Definitions for Plug-In Hybrid Electric Vehicles Using Travel Survey Data. The J2841 utility factor weights the energy consumption from each energy source according to a model of US driving behavior derived statistics from the 2001 National Highway Transportation Survey, and the assumption that each vehicle begins the day trip fully charged and does not charge over the course of the day. This paper examines the sensitivity of the J2841 utility factor to more detailed models of vehicle charging behavior and proposes a utility factor model and simulation method as an alternative to J2841. This alternative utility factor aims to better represent the real-world driving and charging behavior of near-term plug-in hybrid electric vehicles.

INTRODUCTION

Plug in hybrid electric vehicles (PHEVs) are hybrid electric vehicles which can use two sources of energy (generally grid-electricity and liquid fuel) to power the motion of the vehicle. As realized in a variety of demonstration and production vehicles, PHEVs will store grid-electricity by charging electrochemical batteries. Because the distance specific costs of fueling the vehicle are lower when powered by electricity, the vehicle will preferentially drive under electric power, depleting the batteries in a charge depleting driving mode. When the batteries are depleted, the vehicle will switch to a charge sustaining mode, wherein the vehicle operates using liquid fuel as the primary energy source and no net electricity is consumed. Because the mass-specific energy (J/kg) and cost-specific energy (J/$) of liquid fuels is higher than that of electrochemical energy storage, PHEVs are generally limited in the range that they can travel in a charge depleting mode. As a result, an average day trip for a PHEV may require the use of both charge-depleting and charge sustaining modes, and travel will be powered by both grid-electricity and liquid fuels.

Characterizing the performance of PHEVs requires quantifying the performance of the vehicle in charge-depleting and charge-sustaining modes, and requires a means for understanding how often each mode is used in normal driving. The SAE J1711 standard defines the methods that are recommended to test PHEVs in both charge-depleting and charge-sustaining modes. The simplified set of outputs from the J1711 testing protocol will include 1) a charge-depleting mode electricity consumption (ACWh mile⁻¹), 2) a charge-depleting mode fuel consumption (L 100km⁻¹), and 3) a charge-sustaining mode fuel consumption (L 100km⁻¹). The means for understanding the distribution of these energy consumptions is codified in the concept of the utility factor (UF). The UF weights the consumptions in each driving mode according to their prevalence in a model of consumer behavior. This allows for the calculation of a fuel consumption which models the fuel consumption that would be realized in real-world driving.

As a standardized definition, the J2841 UF has a great deal of influence on the calculation of PHEV performance in a variety of research and policy settings. The J2841 UF (and its predecessor, the J1711-1999 UF) are present in academic studies which attempt to compare and evaluate the costs and benefits of PHEVs [1]. The J1711/J2841 UF is present in labeled fuel economy calculations [4], fleet fuel economy credit calculations, Corporate Average Fuel Economy (CAFE) regulations [5], California ZEV credit calculations [6], California Pavley GHG emissions standards, [7] and California low-carbon fuel standards [8]. Because of its pervasiveness, it is worthwhile to investigate the assumptions implicit in the J2841 UF. Previous work has shown that the UF is particularly sensitive to assumptions regarding consumer charging behavior [9].
To provide a more representative UF curve, this study generates a time-resolved and state of charge-resolved model of consumer charging behavior from the NHTS dataset. This charging behavior model allows us to propose an alternative to the J2841 UF which represents a conservative and near-term scenario for PHEV driving and charging behavior.

**NORMATIVE UTILITY FACTOR DEFINITION**

The normative J2841 UF is defined from the results of the 2001 NHTS. The NHTS is a periodic, federally-funded survey of the US population whose purpose is to gather information on daily and long distance travel. For the 2001 NHTS, 69,817 households completed the survey. Individuals are surveyed regarding their household makeup, personal demographics, vehicle characteristics, travel during an assigned travel day, and long-distance travel over a 4 week assigned travel period. The information in the NHTS can be used to analyze the driving habits of the US population.

The UF that is conventionally used and is derived in J2841 is a national daily distance utility factor, meaning that it is a statistical probability that a US geographically averaged vehicle will be driven less than or equal to its $R_{CD}$ during a particular driving day. To construct this UF, the distance travelled by each household automobile during the assigned travel day can be extracted from the NHTS dataset. For a single travel day ($k$) covering a daily distance ($d(k)$), the daily distance UF of a PHEV can be calculated as the ratio of the charge depleting range to the distance travelled ($R_{CD}/d(k)$) if $d(k) < R_{CD}$, and 1.0 if $d(k) > R_{CD}$. For $N$ travel days, a composite UF can be calculated as a function of $R_{CD}$:

$$U_{F_{distance}}(R_{CD}) = \frac{\sum_{k=1}^{N} \min(d(k), R_{CD})}{\sum_{k=1}^{N} d(k)}$$ (1)

The daily distance UF from J2841 is shown in Figure 1. Figure 1 can be interpreted as follows. For a given $R_{CD}$, Figure 1 defines a daily distance UF. The daily distance UF is the fraction of miles travelled in the NHTS fleet where the vehicle has travelled a shorter distance since the start of the day than the given $R_{CD}$. For PHEVs, the daily distance UF can be assumed to represent the fraction of miles in the NHTS fleet that are travelled in charge depletion mode.

![Figure 1 - J2841-type UF derived from the 2001 NHTS](image)
METHODS

The alternative UF is defined from the results of the 2009 NHTS. The 2009 NHTS contains the surveyed driving habits of 150,147 households. Information in the 2009 NHTS is similar to the contents of the 2001 NHTS. The behavior of each participant is weighted using day trip, full sample weightings (the J2841 UF is unweighted).

In order to incorporate a more detailed model of consumer charging behavior, the alternative UF simulates the time-resolved state of charge of every vehicle in the NHTS. The NHTS data is organized into trip chains, the length of which depends on the locations of charging infrastructure. For this study, we will confine the charging locations to only the household home (WHYTRIP(i)=1). For instance, a daily travel file that includes morning stops at a grocery, and then back home, then to work, and home again would be split into two trip chains, one morning trip to and from home and and another trip to and from home. A travel file that makes no stops at home but ends out of town is a single trip chain.

The charging simulation is initialized at the beginning of the travel day with 100% SOC (an assumption consistent with the J2841 UF calculation). If the first trip chain distance \( R_{trip} \) is less than the vehicle’s \( R_{CD} \), then the entire trip will be performed in charge depleting mode and the SOC at the end of the trip chain will proportional to the ratio of \( R_{trip} \) to \( R_{CD} \). If the first trip chain is longer than the vehicle’s \( R_{CD} \), then the end of the trip will be performed under charge sustaining mode and the vehicle will end the trip at the minimum SOC. When the trip chain ends, the vehicle has arrived at home and will immediately begin charging. The rate of charging for this study is assumed to be 1.44ACkW level 1 charging, with an 85% assumed charger efficiency. The charging algorithm charges at a rate of 1.44ACkW until 100% SOC is reached or the charging is interrupted by the next trip chain. This simulation allows the vehicle to be recharged multiple times over the course of the travel day, which means that the total miles driven under charge depleting mode during the travel day \( d_{CD} \) can be greater than \( R_{CD} \). For all \( N \) travel days in the NHTS, the daily distance UF can be calculated as:

\[
UF_{distance}(R_{CD}) = \frac{\sum_{k=1}^{N} d_{CD}(k)}{\sum_{k=1}^{N} d(k)}
\]  

(2)

Figure 2 shows an example of the results of this simulation for a sample vehicle with an \( R_{CD} = 20 \) miles. This vehicle makes two trips chains on the NHTS sample day which end at home: one trip of 23 miles, and one trip of 18 miles. The two stops at home over the course of this day lead to two charging events. The first charging event occurs between trips and is not able to fully recharge the battery in the 3 hours between trips. The second charging event occurs after the vehicle returns home for the day. The vehicle ends the simulation when the SOC reaches 100% at 4am the next day. Only the single surveyed travel day is simulated for each vehicle.

Performing this simulation for every vehicle in the 2009 NHTS allows for the calculation of an alternative UF.
RESULTS

A comparison between the J2841 UF and the proposed alternative UF is presented in Figure 3. The alternative UF is higher than the J2841 UF for values of $R_{CD}$ under 65 mi (105 km) because the alternative UF captures the effect of mid-day charging on the charge depleting range of PHEVs. The effect of this midday charging is greatest at lower $R_{CD}$. The difference decreases with $R_{CD}$ because the fraction of the battery that can be recharged using the 1.44 ACkW connection decreases with increasing battery size. For the alternative UF, the value of the UF would be increased with increased charging availability and increased charging power.

At higher $R_{CD}$, the effect of the midday charging decreases and the differences between the 2001 unweighted NHTS sample (used for J2841) and the 2009 weighted sample (used for the alternative UF) becomes more evident. For $R_{CD}$ greater than 65 mi (105 km), the alternative UF is lower than the J2841 UF because of the differences between the contents and treatment of the two datasets.
These UFs can be used to estimate the conditions of use of the PHEV fleet during mixed charge-depleting and charge-sustaining driving. For an example, the utility factor weighted fuel economy (i.e. km L$^{-1}$) of a PHEV fleet over a certain drive cycle can be calculated as:

$$FE_{UF\text{weighted}} = \frac{1}{UF + \left(1 - UF\right) \cdot FE_{CS}}$$  \hspace{1cm} (3)

The utility factor weighted fuel consumption (i.e. L km$^{-1}$) of a PHEV fleet over a certain drive cycle can be calculated as:

$$FC_{UF\text{weighted}} = UF \cdot FC_{CD} + \left(1 - UF\right) \cdot FC_{CS}$$  \hspace{1cm} (4)

For a simple example to show the sensitivity of PHEV performance to the differences between the J2841 UF and the alternative UF, we will use the PHEV 20 model presented in [10]. At this vehicle’s $R_{CD}$ of 23 mi, the alternative UF is 9.4% greater than the J2841 UF. This translates into a petroleum consumption reduction of 8% that would be realized by the use of the alternative UF.

**DISCUSSION**

The UF concept is under continuous scrutiny and development [11] and this proposed alternative to the J2841 UF does not purport to end that productive and ongoing process. Instead, this alternative UF attempts to capture several principals that can guide the application of the UF to PHEV policy and research problems.

First, the alternative UF more fully incorporates the understanding that the primary charging location for PHEVs will be at home, but that charging need not be confined to overnight. Consumer acceptance studies have found that future-buyers and early-adopters of PHEV will be homeowners [12-13]. All production PHEVs will be provided with a standard 120V, 12A charger so 1.44kW represents the charging power that will be available to every PHEV owner at home. Although the alternative UF is sensitive to the effect of drivers forgetting to plug in their vehicles, drivers in the alternative UF plug their vehicles in more often than those in the J2841 UF and with less energy throughput per charging event. This makes the alternative UF less sensitive to a fraction of forgotten charging events than is the J2841 UF.

Second, the alternative UF is intrinsically conservative because it is based on a conservative near-term scenario. Relative to the conditions under which the alternative UF is calculated, the UF will be increased by increases in charging infrastructure availability,
charging infrastructure power, changes in driving habits with vehicle age [7]. All of these are likely future developments which are not included in the alternative UF calculation.

Finally, the alternative UF uses the day trip, full sample weightings of the NHTS to achieve minimally biased results. The sample weightings statistically adjust the NHTS for non-responses, geographical under-coverage and multiple telephones in a household. Because the J1711 UF is calculated without weightings, the habits of US drivers may be misrepresented where the NHTS national sample is not representative of the US as a whole.

CONCLUSIONS

This study has proposed and demonstrated alternative UFs which can represent the conditions of use of near-term available PHEVs and their charging infrastructure. The goal of this investigation into the construction and sensitivity of the UF is to provide more accurate information to researchers regarding the actual conditions of use of PHEVs. The development and use of alternatives to the J2841 UF will allow for the utility, consumption, costs and benefits of PHEVs to be assessed with more fidelity.

REFERENCES


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