Journal of Power Sources 195 (2010) 5399–5408

Contents lists available at ScienceDirect

Journal of Power Sources

journal homepage: www.elsevier.com/locate/jpowsour

Analysis of plug-in hybrid electric vehicle utility factors

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ARTICLE INFO

Article history:
Received 21 January 2010
Accepted 25 February 2010
Available online 6 March 2010

Keywords:
Plug-in hybrid electric vehicles
Policy
Fuel consumption
Greenhouse gases
Economics

ABSTRACT

Plug-in hybrid electric vehicles (PHEVs) are hybrid electric vehicles that can be fueled from both conventional liquid fuels and grid electricity. To represent the total contribution of both of these fuels to the operation, energy use, and environmental impacts of PHEVs, researchers have developed the concept of the utility factor. As standardized in documents such as SAE J1711 and SAE J2841, the utility factor represents the proportion of vehicle distance travelled that can be allocated to a vehicle test condition so as to represent the real-world driving habits of a vehicle fleet. These standards must be used with care so that the results are understood within the context of the assumptions implicit in the standardized utility factors. This study analyzes and derives alternatives to the standard utility factors from the 2001 National Highway Transportation Survey, so as to understand the sensitivity of PHEV performance to assumptions regarding charging frequency, vehicle characteristics, driver characteristics, and means of defining the utility factor. Through analysis of these alternative utility factors, this study identifies areas where analysis, design, and policy development for PHEVs can be improved by alternative utility factor calculations.

1. Introduction

Plug-in hybrid electric vehicles (PHEVs) are under development by a number of automakers and researchers as a near-term means to improve the sustainability of the transportation energy sector. PHEVs can achieve reductions in vehicle fueling cost, petroleum consumption, greenhouse gas emissions, and criteria emissions by replacing conventional transportation fuels with grid electricity. In general, PHEVs store this grid electricity on board the vehicle in electrochemical storage batteries. The batteries are generally energy-limited in that they can only supply the energy to drive the vehicle for a limited distance. This limitation means that the PHEV will operate in two distinct modes: a charge-depleting mode where the stored battery energy contributes to the propulsive energy consumed by driving the vehicle, and a charge-sustaining mode, where the net energy from the battery is essentially zero [1].

A fundamental question in the design and assessment of PHEVs has been: How to evaluate and communicate the real-world effectiveness of a vehicle that has these two energy management modes? For instance, an example PHEV (using the range extending strategy [1]) may have a charge-depleting range of 12.4 mi (20 km). If the example vehicle is tested to ascertain its gasoline fuel consumption from 100% state of charge (SOC) using the Federal Test Procedure (FTP) 75 test, the vehicle will complete the test entirely in charge-depleting mode, because the FTP75 has a test distance of 11.1 mi (17.8 km), which is less than the CD range of the vehicle. This measured fuel consumption cannot be used to estimate the fuel consumption of the PHEV for an example 40 km trip since the fuel consumption of the vehicle will change between the 12th and 13th mile (20th and 21st km) of driving. By testing the fuel consumption of the PHEV in charge-sustaining mode as well, the fuel consumption of the PHEV over the 40 km trip could be estimated by weighting the charge-sustaining fuel consumption by the fraction of the trip that is completed in charge-sustaining mode and weighting the charge-depleting fuel consumption by the fraction of the trip that is completed in charge-depleting mode. The sum of weighted charge-depleting and weighted charge-sustaining fuel consumptions would estimate the fuel consumption of the vehicle for the example trip. As the trip length increases, the fuel consumption of the vehicle will change, eventually asymptotically approaching the charge-sustaining fuel consumption for trips of distances much greater than the charge-depleting range [2–4].

The Society of Automotive Engineers (SAE) has proposed a standard method (SAE J1711) [5] for testing hybrids and PHEVs that defines this weighting between charge depletion driving and charge-sustaining driving as a utility factor (UF) (SAE J2841) [6]. The general procedure for calculation of UF weighted vehicle performance is shown in Fig. 1. The UF is a ratio of the number of

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doi:10.1016/j.jpowsour.2010.02.082

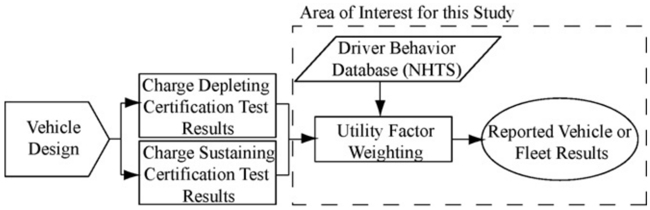

Fig. 1. Information flow diagram for calculation of utility factor weighted test results for a plug-in hybrid vehicle.

miles driven under charge-depleting mode to the total number of miles driven. The J2841 UF is derived from the driving habits of the US light-duty vehicle fleet as measured by the 2001 National Household Transportation Survey (NHTS) [7]. Although the J2841 UF has usefulness as a standardization tool, it contains assumptions about the way that consumers will use their PHEVs. Some notable assumptions implicit in the J2841 UF are: it assumes that vehicles charge only once per day, it assumes that PHEVs are driven in the same patterns as national average vehicles, it assumes that PHEV energy consumption mode changes are best characterized by a charge depletion range.

This study proposes to challenge the normative definitions of UFs so as to determine the effect of some of these assumptions on reported PHEV performance. In addition, this study will extract and present alternative UFs from the 2001 NHTS that can represent the conditions of use of PHEVs in more detail, and for important subsets of the driving population.

2. Normative utility factor definition

The 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 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}:

$$\mathrm{UF}_{\mathrm{distance}}(R_{CD}) = \frac{\sum_{k=1}^{N} \min(d(k), R_{CD})}{\sum_{k=1}^{N} d(k)}. \quad (1)$$

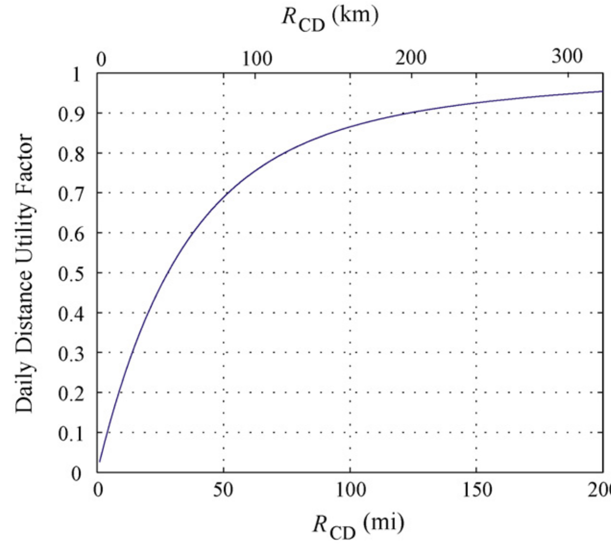

Fig. 2. J2841-type UF derived from the 2001 NHTS.

The daily distance UF from J2841 is shown in Fig. 2. Fig. 2 can be interpreted as follows. For a given R_{CD}, Fig. 2 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.

The UF can then 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:

$$\mathrm{FE}_{\mathrm{UF\ weighted}} = \frac{1}{(\mathrm{UF}/\mathrm{FE}_{CD}) + ((1-\mathrm{UF})/\mathrm{FE}_{CS})} \quad (2)$$

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

$$\mathrm{FC}_{\mathrm{UF\ weighted}} = \mathrm{UF} \cdot \mathrm{FC}_{CD} + (1-\mathrm{UF}) \cdot \mathrm{FC}_{CS} \quad (3)$$

These formulations have been used in a similar way to calculate the net effect of conditions of use on vehicle electrical energy consumption, emissions, fueling costs, battery degradation, and more.

To exercise the calculation of UF weighted vehicle performance, we consider an example gasoline powered PHEV whose characteristics are listed in Table 1 [8]. The vehicle is assumed to use a range extending charge depletion strategy, meaning that the vehicle's engine will not start when the vehicle is operating in charge depletion mode [1]. With test results to describe the vehicle behavior during both charge-depleting and charge-sustaining modes, we can calculate the J2841 UF weighted fuel consumption and electricity consumption. The J2841 UF at a R_{CD} of 42 mi (68 km) is 0.635. Using (3) and a all-electric charge depletion mode such that $\mathrm{FC}_{CD} = 0$, $\mathrm{FC}_{\mathrm{UF\ weighted}}$ is equal to 142 mpg (1.66 L $(100\ \mathrm{km})^{-1}$). To calculate

Table 1
Characteristics of an example PHEV.

Vehicle characteristic	Value
Charge-sustaining fuel consumption (FC_{CS})	51.7 mpg (4.55 L $(100\ \mathrm{km})^{-1}$)
Charge-sustaining electricity consumption (EC_{CS})	0
Charge-depleting fuel consumption (FC_{CD})	0
Charge-depleting electricity consumption (EC_{CD})	282 AC Wh mi^{-1} (175 AC Wh km^{-1})
Charge-depleting range (R_{CD})	42 mi (68 km)
Battery energy capacity	10 DC kWh requiring 11.75 AC kWh to charge

the UF weighted electricity consumption, we must replace FC_{CD} with EC_{CD} and replace FC_{CS} with $EC_{CS} = 0$ in (3). The UF weighted electricity consumption for our example vehicle is 242 AC Wh mi^{-1} (150 AC Wh km^{-1}).

2.1. The utility factor in practice

Conceptually, the UF has three primary purposes in the design and analysis of PHEVs. For each one of these purposes the standard J2841 UF cannot capture details of the function of PHEVs.

The first purpose of the UF is as a communicative tool. The UF weighted fuel consumption describes and communicates the fuel consumption characteristics of a pre-designed single vehicle or fleet of PHEVs. The UF allows for the tested performance of the vehicle in two PHEV operating modes be translated to a single number that represents performance under real-world conditions [4,9,10]. For example, J1711-1999 uses the UF to define the "sticker fuel economy" that will communicate to consumers their expected fuel economy for a PHEV. Using the UF weighted fuel economy allows for the communication of expected fuel consumption without having to simultaneously communicate a charge-depleting fuel economy, a charge-depleting range, and a charge-sustaining fuel economy [11]. When the normative UF is used in this way, the consumer is assumed to have all the characteristics of an expected US driver. No allowance is made for circumstances that may alter the expected performance of the vehicle including charger availability, driving type, daily commuting distance, and user-selectable modes, as is common in "Green-Zone" type PHEVs [1,12].

Second, the UF has been used to describe the performance of a single PHEV engaged in multiple trips. For this case, the UF serves as a means to statistically sample a number of driving days to calculate the lifetime driving conditions of a single vehicle. A variety of studies have used the UF [9,13–15] (or UF simplifications [16,17]) to calculate a PHEV's lifetime energy use and lifetime cost savings to a consumer. When the normative UF is used for these calculations, the driving patterns of the PHEV are represented using the driving patterns of US light-duty vehicles, the usage of the vehicle is assumed to not change with time, and the vehicle performance is not affected by aging or degradation.

Finally, the UF has been used to describe the performance of a fleet of PHEVs. In this case, the UF serves as a statistical sample of fleet-wide or nationwide driving habits [4,18–21]. This usage of the NHTS-derived UF corresponds more closely to the intent of the NHTS as a nationwide sample of the driving habits of the US vehicle fleet. Some possible confounding factors to this use of the UF are: (1) PHEVs may not be driven for the same distances nor may they adhere to the same driving patterns as the US light-duty vehicle fleet and (2) the charging frequency of vehicle fleets may be difficult to quantify.

3. Alternative utility factor definitions

For any of these purposes, it is important to understand the sensitivity of the reported results to the methods that are used to define the UF. In the following sections, we will examine alternative definitions of the UF and assess the sensitivity of the UF and UF weighted energy consumption to some of the assumptions embedded in the NHTS and in standard UF calculations. For each alternative UF presented in this study, coefficients and equations required to use the UF in practice are presented in Appendix A.

3.1. UF sensitivity to consumer battery charging behavior

One of the most discussed assumptions in the SAE standard UFs is the assumption regarding PHEV charging frequency [4,9,22]. The 1999 J1711 calculates a daily distance UF using the assumption that the vehicle is as likely to begin the day with a fully charged battery as it is to begin the travel day with an empty battery [7]. This assumption has been difficult to justify in practice, and is to be replaced in J2841 by the assumption that the vehicle begins each travel day fully charged. The J2841 procedure for calculating UF implicitly assumes that each PHEV is charged to full capacity only at home every night. To determine the sensitivity of the UF to these assumptions we can derive alternative UFs that incorporate other assumptions regarding charging frequency and location for PHEV drivers.

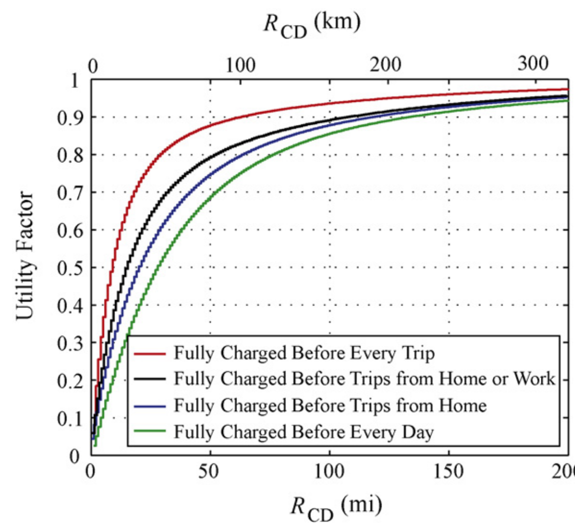

Fig. 3. Comparison of distance utility factors (UF) for the US weighted NHTS vehicle fleet as a function of PHEV charge-depleting range (R_{CD}). The UF increases significantly with increased charger infiltration.

For example, the logical upper boundary of vehicle charging frequency (and therefore of distance UF) is defined by the condition where every vehicle recharges to full battery capacity after each trip segment. This scenario assumes that charging is ubiquitous and that the rate of charging is such that the vehicle can fully recharge at each stop. Whereas the J2841 UF is a daily distance UF, this scenario defines a trip distance UF. The NHTS dataset can be used to derive this trip distance UF by assuming that the vehicle is fully recharged at the end of each surveyed trip segment. Each personal trip segment (indexed by j) that is performed with a household vehicle (TRPHHVEH(j) = 1), where person of interest is the driver (WHODROVE(j) = PERSONID(j)), and where the trip segment is performed with a light-duty vehicle (TRPTRANS(j) > 0 and TRPTRANS(j) < 5) is included in the calculation. All results are weighted to be representative of the US national vehicle fleet using the 50% completed weightings. This NHTS trip distance UF bounds the maximum feasible UF that might be expected in real-world driving and is plotted in Fig. 3.

A more near-term feasible scenario might be one where drivers recharge both at home and at work. In this case, the NHTS personal trip segments are combined into trip chains (indexed by i) that might include stops at a grocery, school, work, and home. Each trip chain that ends at the household home (WHYTRIP(i) = 1) or at work (WHYTRIP(i) = 11 or WHYTRIP(i) = 12) or at the end of the travel day is classified as a trip. For instance, a daily travel file that includes stops at a grocery, school, work, and home would be split into two trip chains, one between home and work and a second between work and home. A travel file that makes no stops at work or home but ends out of town is a single trip chain. The trip-chain distance UF that results from these calculations is plotted in Fig. 3. As might be expected, decreasing the number of times that the vehicle is charged decreases the number of trips that are performed in charge-depleting mode, reducing the UF for a given vehicle or R_{CD}.

Surveys of PHEV drivers suggest that the driver's home is perhaps the most common charging location because of the availability of a garage, the availability of electricity, and the simple cost structure [11]. Fig. 3 shows the trip-chain distance UF for the NHTS trip chains that end at home (WHYTRIP(i) = 1) or at the end of the travel day. This UF assumes that the vehicle recharges at home (and at the end of the day's trip). As before, reducing the availability of charging reduces the UF for a given vehicle or R_{CD}.

The J2841 UF assumes that the vehicle is before every day, and is plotted in Fig. 3 for comparison. Comparison of these UFs shows that the UF is quite sensitive to the number of times the vehicle charges in a day. For our example PHEV (with R_{CD} = 42 mi (68 km)), the UF will vary between 0.857 and 0.635 among these charging scenarios. These UFs lead to a gasoline consumption (assuming that marginal electricity is 0% petroleum) of 361 mpg (0.65 L $(100\,\text{km})^{-1}$) for the ubiquitous charging scenario and 146 mpg (1.61 L $(100\,\text{km})^{-1}$) for the daily charging scenario. There is no global consensus as to what a correct number might be because the number of times that a PHEV can charge in a day is dependent on the penetration of charging infrastructure, which will vary as a function of geography, policy, and time. Still, the high sensitivity of the UF to the charging assumptions suggests that researchers must take care to define the conditions under which they are applying the UF.

3.2. UF sensitivity to vehicle characteristics

The J2841 UF is based on the sample of the US population that is present in the NHTS dataset. This sample is selected and then weighted to be representative of the US population as a whole. Analyses of the NHTS have shown that the driving behavior of vehicles differs as a function of the vehicle's age, mileage, and fuel economy. To determine the sensitivity of the UF to these parameters we can derive alternative UFs that show the differences between the conditions of use of new and old vehicles, of passenger cars and light-duty trucks, or of high fuel economy vehicles and low fuel economy vehicles. These considerations are of interest because researchers have used the UF to determine the environmental impact of a fleet of PHEVs using a fleet averaged UF representing the driving patterns of a fleet average vehicle [9]. Instead, PHEVs introduced to the vehicle fleet may be driven differently than the average vehicle because they are high fuel economy vehicles, because PHEVs will most likely be introduced as a particular model (as opposed to a fleet-wide multi-model introduction), because they are new vehicles, and because they will most likely be purchased by consumers who drive a larger annual distance (so as to fully realize the benefits of lower PHEV operating costs).

3.2.1. UF sensitivity to vehicle fuel economy

First, the NHTS can be used to determine the sensitivity of a vehicle fleet's UF to the fleet fuel economy. The NHTS includes a fuel economy estimate (EIADMPG(m)) for a proportion of the vehicles (indexed by m) in the survey. This fuel economy estimate in the NHTS dataset is derived by cross-linking the vehicle make, model, year, and vehicle type recorded in the NHTS VEHICLE database with the National Highway Transportation Safety Administration (NHTSA) Corporate Average Fuel Economy (CAFE) Database. The NHTS VEHICLE database contains the unadjusted US Environmental Protection Agency (EPA) combined fuel economy for that vehicle make and model. The NHTS applies a discount factor to the EPA combined fuel economy to estimate the real-world fuel economy of each vehicle (EIADMPG(m), n = 33,388). To calculate the sensitivity of the UF to the fuel economy of the vehicle, the NHTS dataset was divided into a high fuel economy fleet (EIADMPG(m) ≥ 25.9 mpg (9.1 L $(100\,\text{km})^{-1}$), n = 4138) and a very high fuel economy fleet (EIADMPG(m) ≥ 38.6 mpg (6.1 L $(100\,\text{km})^{-1}$), n = 117). The dividing line between the fleets is the average fuel consumption of the NHTS fleet plus a single standard deviation of fuel consumption and plus two standard deviations of fuel consumption. The NHTS VEHICLE database must then be cross-linked to the NHTS DAYTRIP database to connect each vehicle to the trips that it drives. Each daily trip (indexed by k) that is performed with a household vehicle (TRPHHVEH(k) = 1), where person of interest is the driver (WHODROVE(k) = PERSONID(k)), and where the trip segment is performed with a light-duty vehicle (TRPTRANS(k) > 0 and TRPTRANS(k) < 5) is included in the calculation. The daily distance UF for all subsets of the fleet is calculated assuming that every vehicle is charged before each day.

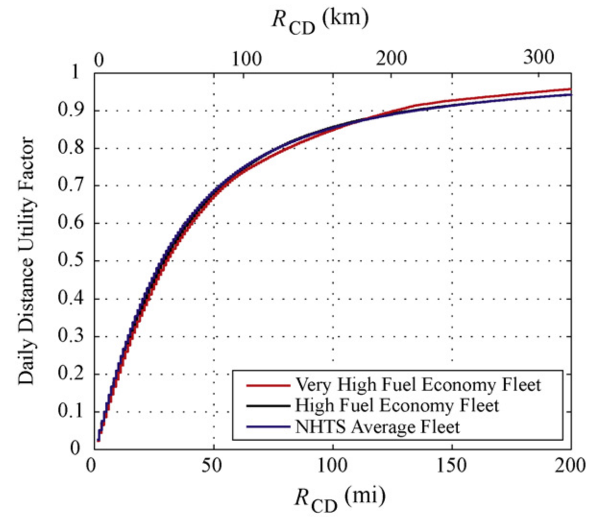

Fig. 4. Comparison of daily distance utility factors (UF) for the US weighted NHTS vehicle fleet as a function of PHEV charge-depleting range (R_{CD}). The vehicle fleet is split by vehicle fuel economy into average, high fuel economy and very high fuel economy fleets.

Fig. 4 shows the comparison between the UF of the high fuel economy NHTS fleet, the UF of the very high fuel economy NHTS fleet, and the UF of the entire NHTS fleet. The UF for the high fuel economy fleet is nearly indistinguishable from the UF of average fleet. The very high fuel economy fleet does differ in that the UF of the very high fuel economy vehicles are very slightly lower than the UF of the average fleet. The maximum difference between the UF of the high fuel economy fleet and the UF of the average fleet is 0.014 at R_{CD} = 19 mi (30.5 km). The maximum difference between the UF of the very high fuel economy fleet and the UF of the average fleet is 0.03 at R_{CD} = 27 mi (43.5 km). For our example vehicle, we might assume that it would be driven with the driving patterns of a very high fuel economy vehicle. Using the fleet average UF instead of the very high fuel economy UF would lead to an underestimation of fuel consumption by 6.8%. The relative insensitivity of the UF to driving patterns associated with high vehicle fuel economy suggests that only very high fuel economy vehicles are driven in a substantially different daily pattern than average fuel economy vehicles.

3.2.2. UF sensitivity to vehicle model type

Next, we can use the NHTS to determine whether different vehicle types (passenger cars versus SUVs, vans, and light-duty trucks) are driven differently and whether these differences will affect the UF of a PHEV. As before, each daily trip (indexed by k) that is performed with a household vehicle (TRPHHVEH(k) = 1), where person of interest is the driver (WHODROVE(k) = PERSONID(k)), and where the trip segment is performed with a light-duty vehicle (TRPTRANS(k) > 0 and TRPTRANS(k) < 5) is included in the calculation.

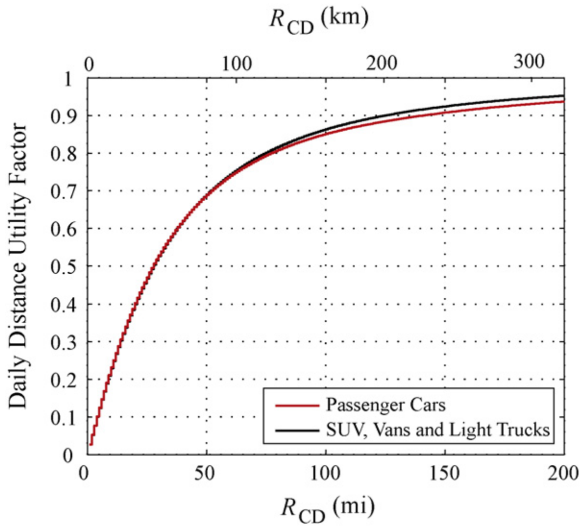

Fig. 5. Comparison of daily distance utility factors (UF) for the US weighted NHTS vehicle fleet as a function of PHEV charge-depleting range (R_{CD}). The vehicle fleet is split by vehicle type into cars and SUVs, vans and light trucks.

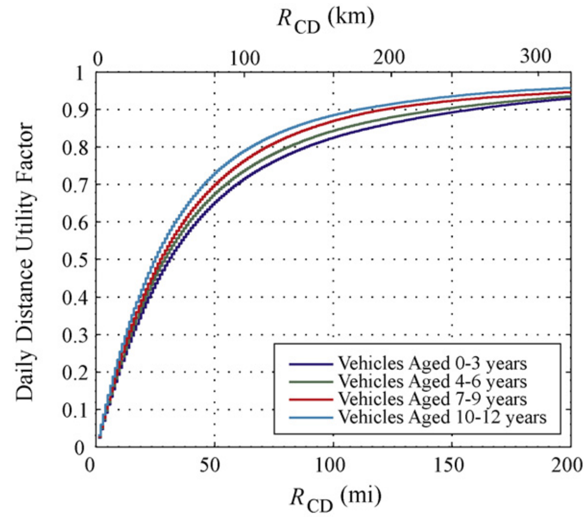

Fig. 6. Comparison of daily distance utility factors (UF) for the US weighted NHTS vehicle fleet as a function of PHEV charge-depleting range (R_{CD}). The vehicle fleet is split by vehicle age.

This subset of the NHTS trip segments is divided into a subset of trips that are taken in passenger cars (TRPTRANS(k) = 1) and a subset of trips that are taken in SUVs, vans, or light-duty trucks ((TRPTRANS(k) = 2)|(TRPTRANS(k) = 3)|(TRPTRANS(k) = 4)). The daily distance UF for these two fleet subsets is calculated assuming that every vehicle is charged before each day.

Fig. 5 shows the comparison of the UF for the two vehicle types. The differences between the daily distance driving patterns of a US average passenger car and the US average SUV, van, and light-duty truck are almost negligible. The only distinguishable difference in the UFs shows that passenger cars drive more long trips relative to the other light-duty vehicles, as evidenced by their lower UF at high values of R_{CD}. For our example PHEV, we might assume that it is a passenger car. Calculating its gasoline consumption using a fleet average UF instead of the passenger car-specific UF would lead to an underestimation of gasoline consumption of 2.1%. The insensitivity of the UF to the makeup of the vehicle fleets suggests that the daily mileage driving patterns of drivers is not a strong function of the type of vehicle that they are driving.

3.2.3. UF sensitivity to vehicle age

The next vehicle characteristic that we will examine for its effect on the UF is vehicle age. It is understood that as PHEVs age, their usage patterns will change. The NHTS dataset can be used to quantify the effect of vehicle age on the driving patterns that determine the UF for a vehicle fleet. The NHTS VEHICLE database includes the age of each vehicle (VEH_AGE(m)) in each household in the dataset. The vehicles in the NHTS fleet that are less than 13 years old are divided into fleet subsets according to their age (0–3 years old, n = 26,238; 4–6 years old, n = 21,759; 7–9 years old, n = 17,624; 10–12 years old, n = 11,696). To determine which vehicles are to be used to calculate the UF, the VEHICLE database must again be cross-linked to the DAYTRIP database to connect each vehicle to the trips that it drives. As before, each daily trip (indexed by k) that is performed with a household vehicle (TRPHHVEH(k) = 1), where person of interest is the driver (WHODROVE(k) = PERSONID(k)), and where the trip segment is performed with a light-duty vehicle (TRPTRANS(k) > 0 and TRPTRANS(k) < 5) is included in the calculation. The daily distance UFs for these four fleet subsets are calculated assuming that every vehicle is charged before each day.

Fig. 6 shows the daily mileage UF for the NHTS fleet as a function of vehicle age. As vehicles age, the distance that they are driven on days that they take a trip changes. As the vehicles get older, they take shorter trips, as evidenced by the higher UF of the more aged vehicles. The maximum difference between the UF of a new vehicle and the UF of a vehicle in the oldest subset is 0.074 at a R_{CD} of 50 mi (80.5 km). Our example PHEV, which we will assume is 0 years old, has a daily distance UF of 0.616. Calculating the petroleum consumption of the example vehicle using the fleet average UF instead of our age-relevant UF leads to an underestimation of petroleum consumption of 6.7%. These results show that the UF of PHEVs will change with their age due to changes in the driving patterns of ageing vehicles, and that the change in UF with vehicle age can have a significant effect on the modeled vehicle performance.

3.2.4. UF sensitivity to vehicle annual distance travelled

Finally, we can examine the sensitivity of UF to the distance that a PHEV is driven in a year. In aggregate vehicles with higher annual distance travelled will perform more long distance trips. The NHTS dataset can be used to quantify the effect of vehicle annual distance travelled on the driving patterns that determine the UF for a vehicle fleet. The NHTS VEHICLE database provides a number of estimates of the annual distance travelled by the surveyed vehicles, but the estimate entitled ANNUALZD contains the fewest number of outliers. ANNUALZD is an estimate of the annual distance travelled that is compiled by asking the survey participants to report their vehicle's odometer two times approximately 60 days apart. The dates and values of the odometer recordings are used to estimate annual distance traveled for each household vehicles. The standard error calculated by the NHTS for ANNUALZD is not used in this study. The vehicles in the NHTS VEHICLE database which provided odometer readings are placed into four bins according to the distance that they driven in a year (1–5000 mi y^{-1}, 0–8046 km y^{-1}), n = 3188; 5001–10,000 mi y^{-1} (8048–16,093 km y^{-1}), n = 5383; 10,001–15,000 mi y^{-1} (16,095–24,140 km y^{-1}), n = 4682; 15,001–20,000 mi y^{-1} (24,141–32,187 km y^{-1}), n = 2793. The methods for determining which trips are used to calculate UF is the same as in the previous section.

Fig. 7 shows that the UF does indeed change as a function of the annual distance traveled by the vehicle. Vehicles that travel a further distance in a year take longer trips and have a lower UF than vehicles that drive less. For the example vehicle with a charge-depleting range of 42 mi (68 km), the UF varies between 0.627 for the longest distance bin, and 0.761 for the shortest distance bin.

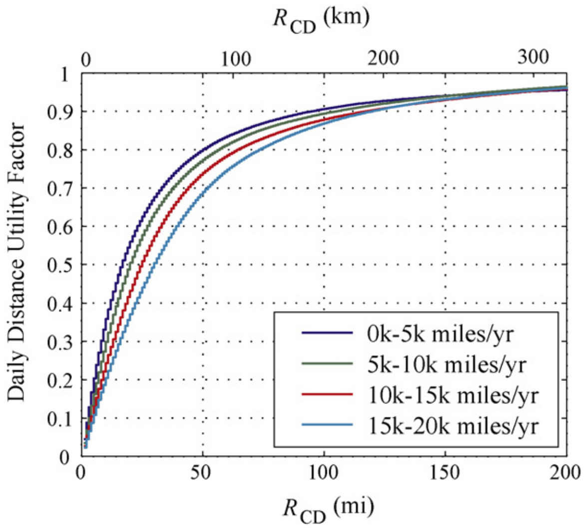

Fig. 7. Comparison of daily distance utility factors (UF) for the US weighted NHTS vehicle fleet as a function of PHEV charge-depleting range (RCD). The UF decreases significantly with increased annual distance driven.

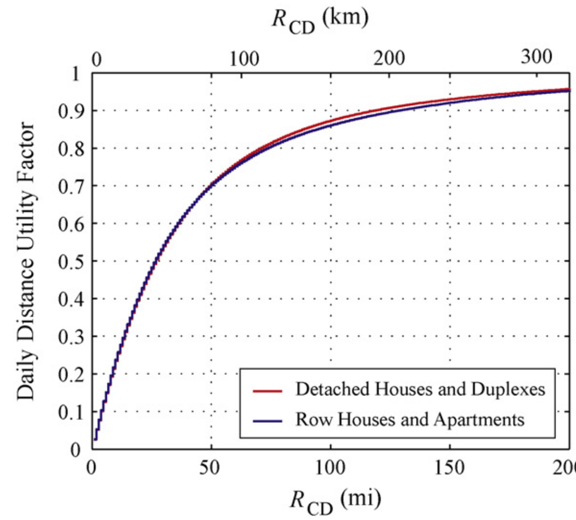

Fig. 8. Comparison of daily distance utility factors (UF) for the US weighted NHTS vehicle fleet as a function of PHEV charge-depleting range (RCD). The vehicle fleet is split according to the housing type of the vehicle owner.

These results suggest that the fuel consumption (or fuel savings relative to a conventional car) of a PHEV can be highly dependent on the rate at which the vehicle is driven. Consider two identical PHEVs one of which drives 100,000 mi (160,934 km) in 13.3 years at 7500 mi y^{-1} (12,070 km y^{-1}), the other of which drives 100,000 mi (160,934 km) in 8 years at 12,500 mi y^{-1} (20,117 km y^{-1}). Without making any allowances for other factors including the different speeds of driving that might be required, the 12,500 mi y^{-1} (20,117 km y^{-1}) vehicle would use 16% more fuel per unit distance than the 7500 mi y^{-1} (12,070 km y^{-1}) vehicle due solely to the difference in energy sources as expressed through the UF.

3.3. UF sensitivity to driver characteristics

Having now examined ways in which the vehicle characteristics can be correlated with changes in the UF, we can also examine how the characteristics of the driver affect the vehicle's UF.

Because of the sensitivity of PHEV operating costs to charging frequency (as demonstrated above), researchers have hypothesized that PHEVs may only have high value to vehicle owners who have personal parking spaces in front of their homes or in a garage [11,21]. The personal parking space allows the PHEV owner to park in the same location each evening and have electrical and billing infrastructure already installed to enable daily vehicle charging. Because of the benefits of PHEVs may be most realizable by vehicle owners who have access to a personal parking space, PHEVs may be disproportionally owned by people who live in single-family detached houses, duplexes, or mobile homes. We can use the DAYTRIP database to test how different the driving patterns of drivers who live in single-family detached houses, duplexes or mobile homes (HOMETYPE(k) = 1|HOMETYPE(k) = 2|HOMETYPE(k) = 5) are from those who live in apartments, townhouses and dormitories (HOMETYPE(k) = 3|HOMETYPE(k) = 4|HOMETYPE(k) = 6). The methods for determining which trips are used to calculate UF is the same as in the previous section.

Fig. 8 shows the UFs for the two groups of drivers. The drivers whose housing types may be particularly amenable for charging a PHEV (single-family detached houses, duplexes or mobile homes) drive very similarly to the NHTS average drivers. For our example PHEV, the UFs of the NHTS fleet and the UF of the fleet of vehicles whose households live in single-family detached houses, duplexes or mobile homes differs only by 0.3% for a difference in fuel consumption of less than 0.4%.

3.4. UF sensitivity to its definition as a function of charge-depleting range

As defined so far, the concept of the UF is based on the ratio of the charge depletion range of a vehicle to the distance that it travels on a particular trip or set of trips. This method quantifies the utility of a vehicle in terms of distance travelled. Of course, other methods of quantifying the utility of a vehicle could be proposed which might be able to provide new functions for the UF. Here we will propose the definition of an UF based on the energy consumed by the vehicle as opposed to the distance travelled by the vehicle. For a single PHEV, calculating the daily energy UF is a matter of simply multiplying the abscissa of the daily mileage UF by the charge-depleting energy consumption ($FC_{CD} + EC_{CD}$) of the vehicle. The daily energy UF of our example plug-in hybrid vehicle is shown in Fig. 7. Note that the daily energy UF of this vehicle at the capacity of its 10 DC kWh battery pack is equal to the daily distance UF of the same vehicle at its charge-depleting range R_{CD} = 42 mi (42 mi = 11.75 AC kWh/0.282 AC kWh mi^{-1}).

To define this daily energy UF for a fleet of PHEVs, we can again poll the NHTS DAYTRIP dataset to find the energy consumed by each vehicle in a fleet over each surveyed trip that the fleet vehicles take. For this example, we will represent the US average passenger car fleet by excluding the surveyed vans, light-duty trucks and SUVs. As before, each personal trip segment (indexed by j) that is performed with a household vehicle (TRPHHVEH(k) = 1), where the person of interest is the driver (WHODROVE(k) = PERSONID(k)), and where the trip segment is performed with a light-duty car (TRPTRANS(k) = 1) is included in the calculation. All cars in the fleet are assumed to begin each day fully charged. The gasoline energy consumption of each car is found by cross-linking the NHTS VEHICLE database to the NHTS DAYTRIP database to find the fuel economy estimate (EIADMPG(m)) for each vehicle. The electrical energy consumption of each trip, $e(k)$, is calculated from the fuel economy estimate and the distance travelled based on an equivalency of 14.61 AC kWh gal^{-1} (3.86 AC kWh L^{-1}) [8]. This equivalency between DC electrical energy and gasoline energy is derived from dynamometer testing of a variety of PHEVs and differs from the 82.05 AC kWh gal^{-1} (21.68 AC kWh L^{-1}) recommended by the US

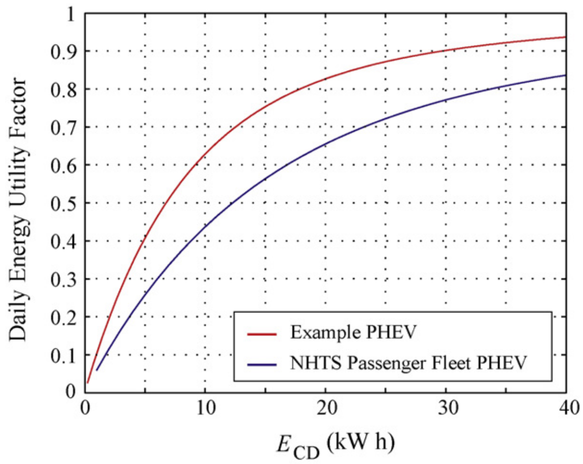

Fig. 9. Comparison of daily energy utility factors (UF) for the US weighted NHTS vehicle fleet and for the example PHEV as a function of battery charge depletion energy (E_{CD}).

Department of Energy (USDOE) in that engine energy conversion efficiencies are not included in the USDOE equivalency [23].

For N travel days, a daily energy UF can be calculated as a function of the charge depletion energy carried on board the vehicle, E_{CD}, and the amount of energy consumed on the vehicle trip, $e(k)$ (from both electrical or petroleum sources). This particular calculation assumes that the vehicles will operate as range extending PHEVs, where the vehicle operates entirely without the engine until the battery is depleted.

$$\mathrm{UF_{energy}}(E_{CD}) = \frac{\sum_{k=1}^{N} \min(e(k), E_{CD})}{\sum_{k=1}^{N} e(k)} \quad (4)$$

For the NHTS weighted car fleet, the energy UF is shown in Fig. 9. This graph can be interpreted as follows. For this NHTS fleet, installation of the battery capacity along the abscissa, with no corresponding changes in vehicle sizes, charge-sustaining fuel economy, or driving conditions will result in a fleet-wide UF that can be read from the ordinate. For example, a fleet with the same fuel economy composition and driving patterns as the US car fleet with a PHEV battery capacity of 20 DC kWh would have a daily energy UF of 0.66. This daily energy UF can be used with (1)–(4) to calculate the equivalent fuel consumption of the fleet. It is notable that the daily energy UF for the weighted car fleet is lower than the daily energy UF of the example PHEV. This occurs because the energy economy of the US car fleet is lower than that of the example PHEV.

This change in UF definition does not affect the “normal” uses of UF (note that the UF of the example PHEV at E_{CD} = 10 DC kWh is 0.64, which is equal to the daily distance J2841 UF at R_{CD} = 42 mi (68 km)), and would add new capabilities. For instance, the energy UF may be more applicable to fuel consumption calculations where the platform of vehicle (compact car, light-duty truck, or SUV) that would be subjected to the UF calculation is unknown. The energy UF incorporates information about both the NHTS fleet driving habits and the NHTS vehicle energy consumption into a single number. The capabilities of the energy UF are discussed in detail in Section 4.

4. Discussion

4.1. Example communicative use of alternative UFs

The primary reasons for communicating the energy consumption of a vehicle to consumers are: (1) to communicate the expected personal and societal costs of driving the vehicle. Personal costs are communicated through metrics such as fuel economy and the estimated fuel cost, and societal costs are communicated through metrics such as CO_2 emissions.

To calculate the labeled fueling cost of a new vehicle for model year 2008, the USEPA calculates the annual fueling cost assuming a gasoline cost of $2.80 per gallon, and an annual mileage of 15,000 mi y^{-1} (24,140 km y^{-1}). Using our example PHEV with 42 mi (68 km) of electric range, we can calculate that the J1711 daily mileage UF is 0.64. At d_{year} = 15,000 mi y^{-1} (24,140 km y^{-1}), we can calculate the UF weighted average annual cost to this fleet assuming a gasoline cost of $2.80 gal^{-1} (US$0.74 L^{-1}) and electricity costs of US$0.11 AC kW^{-1} h^{-1}.

$$C_{\mathrm{UF\ weighted}} = d_{\mathrm{year}}(\mathrm{UF_{distance}} \cdot \mathrm{FC_{CD}} \cdot C_{\mathrm{elec.}} + (1 - \mathrm{UF_{distance}}) \cdot \mathrm{FC_{CS}} \cdot C_{\mathrm{gasoline}}) \quad (5)$$

The J1711 UF weighted cost to drive our example PHEV with an R_{CD} of 42 mi (68 km), for 15,000 mi y^{-1} (24,140 km y^{-1}) is US$591 y^{-1}.

This study has shown that the UF of PHEVs changes as a function of their annual distance driven, therefore using the J1711 daily mileage UF to calculate an equivalent fuel economy fuel cost results in an inconsistent set of assumptions. The J1711 UF is based on the expected driving patterns for a NHTS fleet average vehicle, but a vehicle that drives 15,000 mi y^{-1} (24,140 km y^{-1}) is in the 69th percentile of NHTS vehicles in terms of annual distance travelled. Of course, the NHTS can be used to construct the UF to represent the driving habits of people who drive ~15,000 mi y^{-1} (24,140 km y^{-1}), and whose vehicles are less than 4 years old. NHTS drivers who drive 15,000 ± 1000 mi y^{-1} (24,140 ± 1609 km y^{-1}), have an alternative UF of 0.60 (n = 750) resulting in a yearly fuel cost of US$605 y^{-1}. Although the alternative UF makes only a 2.3% difference in terms of calculated annual costs, it is more internally consistent with the EPA's assumptions of a vehicle with an annual distance travelled of 15,000 mi y^{-1} (24,140 km y^{-1}).

The J2841 UF represents the expected driving patterns of the NHTS fleet. As such, communications of PHEV performance which use the J2841 UF to represent the costs or fuel consumption of vehicles may be misestimating the fuel consumption and costs of PHEVs where a representation of the expected driving patterns of other fleets is called for.

4.2. Example multiple-trip use of alternative UFs

To calculate the lifetime energy consumption or lifetime costs of a PHEV, researchers have used the UF to represent the driving characteristics of PHEV drivers so that we allocate energy consumption or costs from charge-depleting operation and charge-sustaining operation according to how often they are encountered in real-world driving. The lifetime cost is of interest to PHEV researchers because it can be the basis of a model of a consumer's willingness to pay an upfront price premium for longer term savings through reduced fueling cost. To date, researchers who model the lifetime costs of PHEV have taken a number of terms into account. These cost models have included the incremental purchase price of the PHEV, the depreciation of the PHEV hardware due to the finite lifetime of the vehicle, reduced mileage driven with increasing vehicle age, and fueling price changes, but no analyses have considered the change in vehicle driving patterns that occurs with aging of the vehicle as expressed through the UF.

The results of this study allow us to model the way that UF changes with vehicle age. When PHEVs are new, their UF is lower than the UF of the average NHTS vehicle. As the PHEVs age, they drive fewer miles per year and they drive shorter distances per day, increasing their UF as they age. This relationship has already been shown in Fig. 6.

In this example calculation, we will model an economic comparison of our example PHEV to a conventional hybrid electric vehicle for the period 2012–2024. For the baseline scenario, retail prices and maintenance costs for both vehicles are from ANL Base Case Mid-sized cars, where the costs of our example PHEV42 are the average of the costs of the PHEV20 and the PHEV60 [9]. All costs are represented in US$2010 using a constant inflation rate of 3.8%. Vehicle purchases are modeled using a 48 month automobile loan with 4.99% interest rate and a 10% down payment. Colorado state taxes (6.7%) and license fees (1.5%) are applied. Both vehicle resale values are depreciated at 13.8% annually to approximate the depreciation rate of the 3rd generation Toyota Prius. The prices of gasoline and residential electricity are derived from EIA estimates [24]. A discount rate of 6% is used to discount future costs and earnings. Vehicle annual distance travelled as a function of vehicle age is derived from the NHTS [25].

We can use the NHTS to calculate the effect of changing vehicle usage on the present value of a PHEV's cost of ownership. Our example PHEV has a NHTS national weighted, light-duty vehicle, daily mileage UF of 0.64. If we model the change in UF as a function of time, the same example PHEV has a UF that varies between 0.591 at the bin between years 0 and 3, and 0.668 at the bin between years 10 and 12. Using this model, we can calculate how much time it will take for the initial investment in the incremental costs of a PHEV to be paid back. The PHEV with constant UF takes 10.2 years to reach economic parity to the conventional HEV. The PHEV with time varying UF takes 10.8 years to reach economic parity to the conventional HEV. Details of the cost of ownership calculation are presented in Appendix A. Although the differences between the calculations are slight, it is important to include the time varying UF as it is a parameter of the economic calculation that increases with time of ownership.

4.3. Example multiple-vehicle use of alternative UFs

Finally, the UF can be used to evaluate the performance of fleets of PHEVs, which represents the original intention of the NHTS UF calculation. For a multiple-vehicle example of the use of the alternative UFs, we will consider the multiple-vehicle use of the energy UF.

In studies of PHEV performance and environmental impacts, PHEVs are classified by their R_{CD} regardless of the vehicle type. Work by EPRI and others have shown that it is more likely that the incremental costs of batteries will limit the R_{CD} that can be designed into larger vehicles. In other words, the multi-thousand dollar price increment of a 10 kWh battery may be all that is tolerable in any light-duty vehicle regardless of vehicle type or size. The energy UF can be a useful tool to understand the effect of battery size on a diverse fleet of vehicles as shown by the following example.

Consider a regulator who would like to understand how much to subsidize the purchase of PHEV battery packs so as to monetize the greenhouse gas (GHG) emissions benefits of PHEVs. Because of the diversity of vehicles in the regulated fleet (from subcompacts to SUVs), a subsidy to battery purchase does not buy a definite increment in charge-depleting range; over the diversity of vehicles in the vehicle fleet a battery subsidy is perhaps more closely related to an increment in charge depletion *energy*. By defining the UF as an energy ratio (the ratio of the charge-depleting energy consumed by the vehicle to the energy that it consumes on a particular trip) as opposed to a distance ratio, then the petroleum displacement of a battery subsidy can be quantified across a diverse vehicle fleet [21]. If this fleet-wide calculation was performed using the conventional daily distance UF, the regulator would have to assume a set of vehicle types, a proportion of their representation in the fleet, and their conditions of use, but the daily energy UF can be constructed to intrinsically represent the entire fleet of vehicles and performing under their surveyed conditions of use.

To perform this calculation, we can assume that the regulated vehicle fleet is equivalent in makeup to the NHTS light-duty vehicle fleet (TRPTRANS(k) > 0 and TRPTRANS(k) < 5). To calculate the expected value of GHG emissions for the NHTS fleet, we use ANL GREET 1.8c to calculate the well-to-wheels GHG intensity of gasoline ($I_{\text{gasoline}} = 11.053$ kg-$CO_{2\text{-eq}}$ gal^{-1}, 2.63 kg-$CO_{2\text{-eq}}$ L^{-1}) and of marginal electricity ($I_{\text{elec.}} = 0.481$ kg-$CO_{2\text{-eq}}$ AC kW^{-1} h^{-1}).

$$C_{\text{UF weighted}} = d_{\text{year}}(\text{UF}_{\text{distance}} \cdot \text{FC}_{\text{CD}} \cdot C_{\text{elec.}} + (1 - \text{UF}_{\text{distance}}) \cdot \text{FC}_{\text{CS}} \cdot C_{\text{gasoline}}) \quad (6)$$

For this example, we can calculate the monetized value of the GHG emissions benefits from the installation of 20 kWh of batteries into two different vehicle classes. The expected value of the fuel economy for the NHTS passenger vehicle fleet is 28.3 mpg (8.3 L (100 km)$^{-1}$), so that the expected lifetime (150,000 mi (241,400 km)) GHG emissions of a passenger vehicle is 58.6 tons $CO_{2\text{-eq}}$. The $\text{UF}_{\text{energy}}$ for a 20 kWh battery in the passenger vehicle class is 0.66, resulting in an expected lifetime GHG emissions of 41.1 tons $CO_{2\text{-eq}}$ per vehicle. The value of the GHG emissions reductions due to 20 kWh of batteries in the passenger vehicle fleet sums to $873 per vehicle, assuming a value of CO_2-eq reductions of $50 ton^{-1}. This potential subsidy is less than the incremental costs of the 20 DC kWh battery. These GHG emissions benefits are purely due to the electrification of vehicle energy. For comparison, the value of the GHG emissions in the NHTS Van/SUV/light-duty truck fleet with the addition of 20 kWh of batteries is $948 over the 150,000 miles lifetime of the vehicle. This analysis suggests that at large battery pack sizes, the value of large battery packs in terms of emissions reductions is higher in less-efficient vehicle fleets.

The energy UF allows for the investigation of the effects of vehicle electrification in terms of battery size instead of charge depletion range. In effect, the energy UF disaggregates the battery sizing for PHEVs from the vehicle design, which can provide value to large-scale policy and decision making processes.

5. Conclusions

The standard daily distance UF is only one option among many for calculating the effects that driving habits have on the fuel economy of PHEVs. This study has proposed and demonstrated alternative UFs which can represent the conditions of use of more detailed subsets of the NHTS fleet. Analysis of the NHTS shows that the UF is very sensitive to assumptions regarding consumer battery charging behavior, vehicle age, and vehicle annual distance driven. In contrast, UF is shown to be insensitive to vehicle class, vehicle fuel economy, and driver characteristics. The utility of these alternative UFs is shown by example wherein the consistency and accuracy of PHEV consumption, economics and policy are improved with alternative UF calculations.

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 daily distance UF will allow for the utility, consumption, costs and benefits of PHEVs to be assessed with more fidelity.

Appendix A.

Tables A.1–A.4 .

Table A.1
Conventional HEV lifetime cost of ownership model.

Year of ownership	Annual VMT	Annual fuel cost	Annual purchase expenditures	Trade-in value after each year	Annual maintenance costs	Total cost of ownership after each year
	14,800	$(864.42)	$(11,101.80)	$26,044.08	$(784.73)	$(8726.87)
2	14,600	$(900.12)	$(7652.83)	$22,686.96	$(740.31)	$(14,037.24)
3	14,550	$(944.25)	$(7219.65)	$19,762.59	$(698.40)	$(18,483.92)
4	14,350	$(980.94)	$(6810.99)	$17,215.16	$(658.87)	$(22,142.14)
5	13,900	$(983.25)	–	$14,996.11	$(621.58)	$(25,966.02)
6	13,350	$(979.00)	–	$13,063.09	$(586.39)	$(29,464.43)
7	12,800	$(963.59)	–	$11,379.24	$(553.20)	$(32,665.07)
8	12,450	$(958.78)	–	$9912.44	$(521.89)	$(35,612.54)
9	12,150	$(951.45)	–	$8634.71	$(492.35)	$(38,334.06)
10	11,717	$(922.59)	–	$7521.69	$(464.48)	$(40,834.15)
11	11,150	$(885.20)	–	$6552.13	$(438.19)	$(43,127.09)
12	10,583	$(844.79)	–	$5707.55	$(413.38)	$(45,229.85)
13	10,130	$(808.61)	–	$4971.84	$(389.98)	$(47,164.15)

Table A.2
PHEV lifetime cost of ownership model with constant UF.

Year of ownership	UF	Annual VMT	Annual fuel cost	Annual purchase expenditures	Trade-in value after each year	Annual maintenance costs	Total cost of ownership after each year
1	0.64	14,800	$(632.46)	$(12,853.05)	$30,153.03	$(681.27)	$(9506.99)
2	0.64	14,600	$(643.43)	$(8859.96)	$26,266.27	$(642.70)	$(15,042.10)
3	0.64	14,550	$(658.22)	$(8358.45)	$22,880.51	$(606.33)	$(19,553.11)
4	0.64	14,350	$(667.84)	$(7885.33)	$19,931.18	$(572.01)	$(23,129.86)
5	0.64	13,900	$(656.24)	–	$17,362.03	$(539.63)	$(26,894.89)
6	0.64	13,350	$(636.66)	–	$15,124.04	$(509.08)	$(30,278.61)
7	0.64	12,800	$(621.37)	–	$13,174.53	$(480.27)	$(33,329.76)
8	0.64	12,450	$(614.38)	–	$11,476.32	$(453.08)	$(36,095.44)
9	0.64	12,150	$(606.73)	–	$9997.00	$(427.44)	$(38,608.91)
10	0.64	11,717	$(586.62)	–	$8708.38	$(403.24)	$(40,887.40)
11	0.64	11,150	$(561.73)	–	$7585.86	$(380.42)	$(42,952.07)
12	0.64	10,583	$(536.55)	–	$6608.03	$(358.88)	$(44,825.33)
13	0.64	10,130	$(516.55)	–	$5756.25	$(338.57)	$(46,532.23)

Table A.3
PHEV lifetime cost of ownership model with time varying UF.

Year of ownership	UF	Annual VMT	Annual fuel cost	Annual purchase expenditures	Trade-in value after each year	Annual maintenance costs	Total cost of ownership after each year
1	0.572	14,800	$(657.10)	$(12,853.05)	$30,153.03	$(681.27)	$(9531.64)
2	0.5805	14,600	$(667.29)	$(8859.96)	$26,266.27	$(642.70)	$(15,090.61)
3	0.589	14,550	$(681.01)	$(8358.45)	$22,880.51	$(606.33)	$(19,624.41)
4	0.5975	14,350	$(688.63)	$(7885.33)	$19,931.18	$(572.01)	$(23,221.96)
5	0.606	13,900	$(673.61)	–	$17,362.03	$(539.63)	$(27,004.36)
6	0.6145	13,350	$(650.30)	–	$15,124.04	$(509.08)	$(30,401.72)
7	0.623	12,800	$(630.46)	–	$13,174.53	$(480.27)	$(33,461.96)
8	0.6315	12,450	$(618.95)	–	$11,476.32	$(453.08)	$(36,232.21)
9	0.64	12,150	$(606.73)	–	$9997.00	$(427.44)	$(38,745.68)
10	0.6485	11,717	$(582.16)	–	$8708.38	$(403.24)	$(41,019.71)
11	0.657	11,150	$(553.14)	–	$7585.86	$(380.42)	$(43,075.79)
12	0.6655	10,583	$(524.27)	–	$6608.03	$(358.88)	$(44,936.76)
13	0.674	10,130	$(501.03)	–	$5756.25	$(338.57)	$(46,628.15)

Table A.4
UF curve fit coefficients C_i.

Description	C_1	C_2	C_3	C_4	C_5	C_6
Daily distance UF for vehicles with odometers reading less than 150,000 miles	11.113	2.1538	−137.36	518.84	−849.7	537.53
Daily distance UF for vehicles with odometers reading greater than 150,000 miles	9.5203	−2.786	−12.472	−24.853	183.37	−214.58
Daily distance UF for vehicles with estimated fuel economies of 25.9–38.6 mpg	10.20591	6.9347213	−123.42	414.261	−664.565	434.415
Daily distance UF for vehicles with estimated fuel economies of greater than 38.6 mpg	8.304653	40.555465	−470.091	1909.93	−3426.85	2258.99
Daily distance UF for passenger cars	10.937	0.32931	−97.292	332.8	−489.38	282.47
Daily distance UF for trucks, vans and SUVs	10.686	−3.7497	−93.818	379.84	−630.37	394.49
Daily distance UF for vehicles 0–3 years old	9.800	1.2788	−111.95	416.17	−655.31	396.23
Daily distance UF for vehicles 4–6 years old	10.25	5.1572	−159.59	615.87	−1041.8	674.45
Daily distance UF for vehicles 7–9 years old	10.852	0.93554	−104.55	381.75	−635.53	414.02
Daily distance UF for vehicles 10–12 years old	12.131	−5.4956	−44.807	52.19	166.24	−261.57
Daily distance UF for vehicles which drive 0–5000 miles per year	19.239	−63.435	86.289	193.44	−781.99	699

Table A.4 (*Continued*)

Description	C_1	C_2	C_3	C_4	C_5	C_6
Daily distance UF for vehicles which drive 5000–10,000 miles per year	14.313	7.132	−379.58	1718.5	−3167.9	2142.6
Daily distance UF for vehicles which drive 10,000–15,000 miles per year	10.351	40.441	−476.62	1717.8	−2748	1663.4
Daily distance UF for vehicles which drive 15,000–20,000 miles per year	8.6352	20.587	−166.98	378.63	−288.3	−3.4802
Daily distance UF for the NHTS fleet	10.52	−7.28	−26.37	79.08	−77.36	26.07
Distance UF for the NHTS fleet charged before every trip	39.775	−358.82	2064.4	−6613	10,766	−6902.8
Distance UF for the NHTS fleet charged before every trip from home	15.745	−59.216	206.36	−526.49	788.51	−491.53
Distance UF for the NHTS fleet charged before every trip from home and work	21.651	−115.9	423.67	−903.05	1026.9	−479.02
Daily energy UF for the NHTS fleet	24.625	−67.897	5.1443	176.89	−65.818	39.613

Utility factor curves can be calculated using the following equation where x has units of miles (for distance UFs) or (kWh for energy UFs) [6]: $\mathrm{UF}(x) = 1 - \exp\left[-\left(\sum_{i=1}^{6} C_i \cdot \left(\frac{x}{400}\right)^i\right)\right]$.

References

[1] T.H. Bradley, A.A. Frank, Renew Sustain. Energ. Rev. 13 (2009) 115–128.
[2] J.S. Reuyl, P.J. Schuurmans, Policy implications of hybrid-electric vehicles, Report prepared for the National Renewable Energy Laboratory by NEVCOR Inc., available at: http://www.nevcor.com/images/Policy_Implications.pdf.
[3] A.F. Burke, G.E. Smith, SAE 810265 (1981).
[4] M. Duoba, R.W. Carlson, J. Wu, Electric Vehicle Symposium, vol. 23, 2008.
[5] Society of Automotive Engineers, Recommended Practice for Measuring the Exhaust Emissions and Fuel Economy of Hybrid-Electric Vehicles, Hybrid Committee, 1999, J1711.
[6] Society of Automotive Engineers, Utility Factor Definitions for Plug-In Hybrid Electric Vehicles Using 2001 U.S. DOT National Household Travel Survey Data, Hybrid Committee, 2009, J2841.
[7] National Highway Transportation Survey, http://nhts.ornl.gov/.
[8] R. Carlson, et al., SAE 2007-01-0283 (2007).
[9] Electric Power Research Institute, Comparing the Benefits and Impacts of Hybrid Electric Vehicle Options, Palo Alto, California, 2001, 1000349.
[10] T. Markel, Plug-In 2008 Conference & Exposition, San Jose, CA, July, 2008.
[11] J. Axsen, K.S. Kurani, The Early U.S. Market for PHEVs: Anticipating consumer awareness, recharge potential, design priorities and energy impacts, Institute of Transportation Studies, University of California, Davis, Research Report UCD-ITS-RR-08-22, 2008.
[12] R. Graham, T.H. Bradley, M. Duvall, Electric Vehicle Symposium, vol. 20, Long Beach, California, November 15–19, 2003.
[13] A.A. Frank, Battery Dominant Hybrid Electric Vehicle Systems Development and Evaluation, South Coast Air Quality Management District, Diamond Bar, California, 2002, 01022.
[14] A. Simpson, 22nd International Battery, Hybrid and Fuel Cell Electric Vehicle Symposium and Exposition (EVS-22), Yokohama, Japan, October 23–28, 2006.
[15] D.M. Lemoine, D.M. Kammen, A.E. Farrell, Environ. Res. Lett. 3 (2008) 014003.
[16] M. Kintner-Meyer, K. Schneider, R. Pratt, Impacts Assessment of Plug-in Hybrid Vehicles on Electric Utilities and Regional US Power Grids, Part 1: Technical Analysis, Pacific Northwest National Laboratory, 2006.
[17] M.J. Scott, et al., Impacts Assessment of Plug-in Hybrid Vehicles on Electrical Utilities and Regional US Power Grids, Part 2: Economic Assessment, Pacific Northwest National Laboratory, 2006.
[18] P. Denholm, W. Short, An evaluation of utility system impacts and benefits of optimally dispatched plug-in hybrid electric vehicles, National Renewable Energy Laboratory Technical Report, 2006, NREL/TP-620-40293.
[19] C.W. King, M.E. Webber, Environ. Sci. Technol. 42 (12) (2008) 4305–4311.
[20] Electric Power Research Institute, Environmental Assessment of Plug-in Hybrid Electric Vehicles, Palo Alto, California, 2007, 1015325.
[21] A. Vyas, et al., Electric Vehicle Symposium, vol. 23, Anaheim, CA, December 4–7, 2007.
[22] S. Letendre, R. Watts, M. Cross, Plug-in Hybrid Vehicles and the Vermont Grid: A Scoping Analysis, UVM Transportation Center, Burlington, 2008, available at: http://www.spinnovation.com/sn/Presentation/Plug-In_Hybrid_Electric_Vehicles_and_the_Vermont_Grid_-.pdf.
[23] USEPA, Electric and Hybrid Vehicle Research, Development and Demonstration Program; Petroleum-Equivalent Fuel Economy Calculation, 2000 (Federal Register: June 12, vol.65, number 113, pp. 36985–36992), available at: http://www.epa.gov/EPA-IMPACT/2000/June/Day-12/i14446.htm.
[24] Energy Information Administration, Official Energy Statistics from the U.S. Government, U.S. Data Projections, Forecasts & Analyses and Projections of Energy Information, 2009, Report #: DOE/EIA-0383 http://www.eia.doe.gov/oiaf/forecasting.html.
[25] EIA Household Vehicles Energy Use: Latest Data and Trends, http://www.eia.doe.gov/emeu/rtecs/nhts_survey/2001/.