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Actual Versus Estimated Utility Factor of a Large Set of Privately Owned Chevrolet Volts

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ABSTRACT

In order to determine the overall fuel economy of a plug-in hybrid electric vehicle (PHEV), the amount of operation in charge depleting (CD) versus charge sustaining modes must be determined. Mode of operation is predominantly dependent on customer usage of the vehicle and is therefore highly variable. The utility factor (UF) concept was developed to quantify the distance a group of vehicles has traveled or may travel in CD mode. SAE J2841 presents a UF calculation method based on data collected from travel surveys of conventional vehicles. UF estimates have been used in a variety of areas, including the calculation of window sticker fuel economy, policy decisions, and vehicle design determination.

The EV Project, a plug-in electric vehicle charging infrastructure demonstration being conducted across the United States, provides the opportunity to determine the real-world UF of a large group of privately owned Chevrolet Volt extended range electric vehicles. Using data collected from Volts enrolled in The EV Project, this paper compares the real-world UF of two groups of Chevrolet Volts to estimated UF's based on J2841.

The actual observed fleet utility factors (FUF) for the MY2011/2012 and MY2013 Volt groups studied were observed to be 72% and 74%, respectively. Using the EPA CD ranges, the method prescribed by J2841 estimates a FUF of 65% and 68% for the MY2011/2012 and MY2013 Volt groups, respectively. Volt drivers achieved higher percentages of distance traveled in EV mode for two reasons. First, they had fewer long-distance travel days than drivers in the national travel survey referenced by J2841. Second, they charged more frequently than the J2841 assumption of once per day - drivers of Volts in this study averaged over 1.4 charging events per day. Although actual CD range varied widely as driving conditions varied, the average CD ranges for the two Volt groups studied matched the EPA CD range estimates, so CD range variation did not affect FUF results.

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INTRODUCTION

A plug-in hybrid electric vehicle (PHEV) is a type of hybrid electric vehicle that can use both grid electricity stored in batteries, and a liquid fuel as sources of energy. The use of grid electricity as an energy source reduces the use of conventional fuel and allows a PHEV to achieve reductions in greenhouse gas emissions, criteria emissions, and fueling costs [1]. Electrical energy is stored on-board a PHEV electrochemically in batteries, which are only able to store enough energy to drive the vehicle for a limited range. This means that a PHEV will generally operate in two modes: a charge depleting (CD) mode, in which the energy stored in the batteries will contribute to powering the vehicle, and a charge sustaining (CS) mode, in which conventional fuel provides all of the required driving energy and the net change in battery energy is zero. PHEVs that drive farther than their CD range use both CD and CS modes of driving.

Because CD mode and CS mode are fundamentally different in terms of their energy sources, it is necessary to quantify and communicate the effect of each the two modes on metrics of vehicle fueling cost, emissions, and petroleum use. To this end, the SAE J2841 standard defines the concept of utility factor (UF), a method of weighting vehicle energy consumption in both CD and CS modes. SAE J2841 uses the National Household Transportation Survey (NHTS) as a model of consumer driving to provide a real-world basis for weighting

between a vehicle's CD and CS performance. In this way, the UF allows for a PHEV's energy consumption to be modeled in a way that is representative of real-world driving [2].

The J2841 UF is a tool that is widely used in policy and academic research. However, it contains several simplifying assumptions about consumers' use of PHEVs. These include an assumption that drivers will charge their battery only once per day and start the day with a fully charged battery, an assumption that the NHTS driving patterns are representative of PHEV driving patterns, and an assumption that a PHEV's CD range can be represented as a constant value. It has been previously shown that UF calculations are sensitive to variations in driver habits and vehicle characteristics [3, 4], but in the absence of real-world vehicle data, it has been difficult to evaluate the representativeness of the J2841 utility factors.

The EV Project is a large-scale plug-in electric vehicle and charging infrastructure demonstration, in which data is collected from consumer-owned Chevrolet Volt extended range electric vehicles. The Volt is an all-electric capable PHEV, where driving done in CD mode is done solely in electric vehicle (EV) mode. Once the Volt's high voltage battery is depleted, the vehicle operates in extended range mode using a CS control strategy.

The objective of this paper is to make a quantitative comparison between the J2841 UF and the UF as observed in the Chevrolet Volts enrolled in the EV Project.

DESCRIPTION OF THE EV PROJECT DATA SET AND METHODS

The data set analyzed in this paper comes from 1,405 privately owned Volts based in 18 metropolitan areas across the United States. Owners of these Volts were PHEV early adopters who chose to participate in The EV Project and consented to allow their vehicle usage to be monitored by OnStar as a term of their participation. Data parameters were collected from their vehicles wirelessly via OnStar, such as total distance driven, distance driven in EV mode, and battery state of charge. These parameters were logged each time the vehicle was turned on and off. Data analyzed in this paper were collected from October 2012 through June 2013 and include over 9 million miles (14.5 million km) of driving.

Vehicles were split into two groups by model year, because the 2013 model year (MY) Volt has a higher CD range than previous model years. Table 1 describes the characteristics of the data set used in this study.

Many of the MY2013 vehicles were enrolled in The EV Project after the start of the study period, which explains why this group produced fewer driving days and driving and charging events.

Table 1. Description of EV Project Volt data set being studied

MY	Number (%) of vehicles	Number (%) of vehicle driving days	Total distance driven – mi [km] (%)	Number (%) of charging events
2011/ 2012	787 (56%)	160,035 (70%)	6,477,419 [10,424,415] (70%)	232,120 (70%)
2013	618 (44%)	68,709 (30%)	2,827,140 [4,549,849] (30%)	98,199 (30%)
Total	1,405	228,744	9,304,559 [14,974,265]	330,319

COMPARISON OF OBSERVED AND CALCULATED FLEET UTILITY FACTORS

EV Project Fleet Observed Utility Factor

The observed utility factor of a vehicle fleet is simply calculated as the ratio of the distance driven by all vehicles in CD mode to the total distance driven by all vehicles. The observed utility factor of the two groups of Volts in the EV Project Volt data set is calculated in Table 2. EV Project Chevrolet Volts operated in EV mode for nearly three quarters of their driving distance.

Table 2. Observed utility factor of Volt groups

MY	Total distance driven – mi [km]	Distance driven in EV mode – mi [km]	Percent of distance driven in EV mode
2011/ 2012	6,477,419 [10,424,415]	4,689,022 [7,546,264]	72.4%
2013	2,827,140 [4,549,849]	2,088,496 [3,361,115]	73.9%

This observed utility factor can be compared to the estimated utility factor as calculated per J2841.

J2841 Fleet Utility Factor

The J2841 Fleet Utility Factor (FUF) is defined as the statistical probability that an average vehicle in the US will be driven less than or equal to a certain CD range (R_{CD}) on a particular day. For a given fleet of vehicles, the equation for the FUF is defined as follows:

$$FUF(R_{CD}) = \frac{\sum_{k=1}^{N} \min\left(d(k), R_{CD}\right)}{\sum_{k=1}^{N} d(k)} \quad (1)$$

where *k* represents a single vehicle driving day, *d(k)* is the distance that vehicle traveled in that day, and *N* is the total number of vehicle driving days in the data set. The J2841 FUF

is constructed using travel behavior extracted from the NHTS 2001, a federally funded survey of US households' travel habits.

The US Environmental Protection Agency (EPA) R_{CD} estimates for the MY2011/2012 and MY2013 Volt are 35 mi (56.3 km) and 38 mi (61.2 km), respectively. The J2841 FUF equation using NHTS data gives estimated FUFs for MY2011/2012 and MY2013 Volt of 57% and 60%, respectively. This suggests that 57% of the distance driven by MY2011/2012 Volts and 60% of the distance driven by MY2013 Volts would be in EV mode, according to the J2841 estimation method.

Comparison of Fleet Utility Factor Curves

The first observation that can be made in comparing the observed and J2841 utility factors is that they are not equal. The observed FUFs for the EV Project Volt groups are between 15% and 14% higher than the J2841 estimated FUFs. Three possible causes for the discrepancy between the calculated value of the J2841 FUF and the observed value of the EV Project FUF were investigated. These sources are the difference in driving habits between EV Project drivers and NHTS drivers, the difference in charging habits between EV Project drivers and J2841 assumptions, and the variability between the EPA-rated R_{CD} and the observed R_{CD} of EV Project drivers. To assess the relative importance of these possible sources of discrepancy, each of their impacts on the FUF will be examined in turn.

The first step in this comparison is to understand the effect of the difference in driving habits between EV Project drivers and NHTS drivers. To calculate this effect, the FUFs were calculated for the two EV Project Volt groups using equation (1) and compared to the curve fit of the NHTS FUF curve given in the appendix of J2841 [2]. The EV Project Volt curves assume the J2841-type charging schedule and the EPA-rated R_{CD} for each Volt. No filtering was applied to the EV Project Volt driving data. The FUF curves are plotted in Figure 1.

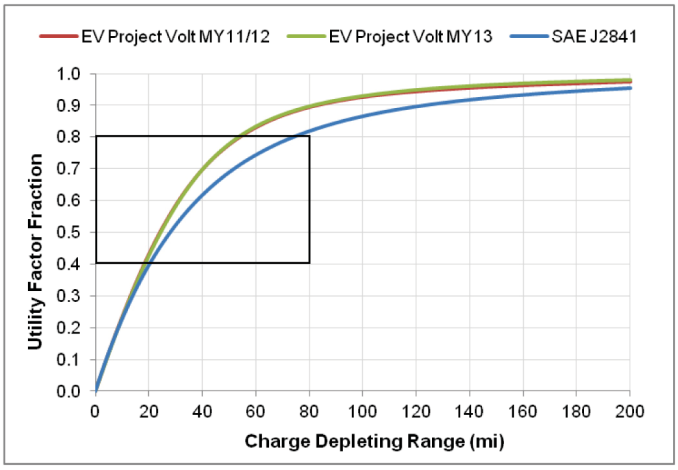

Figure 1. Utility factor curves from SAE J2841 and EV Project Volt groups

The FUF curves of the two Volt groups are nearly identical to each other and are higher than the J2841 curve, indicating that the EV Project Volts had fewer long distance travel days than the vehicles surveyed by NHTS 2001. The inset in Figure 1 is expanded in Figure 2 to depict how the estimated FUF is calculated. This is done by intersecting the Volt's CD range with the FUF curves. Using the FUF curves derived from EV Project data, the estimated FUFs for MY2011/2012 and MY2013 Volts are 64.5% (horizontal red line) and 67.8% (horizontal green line), respectively.

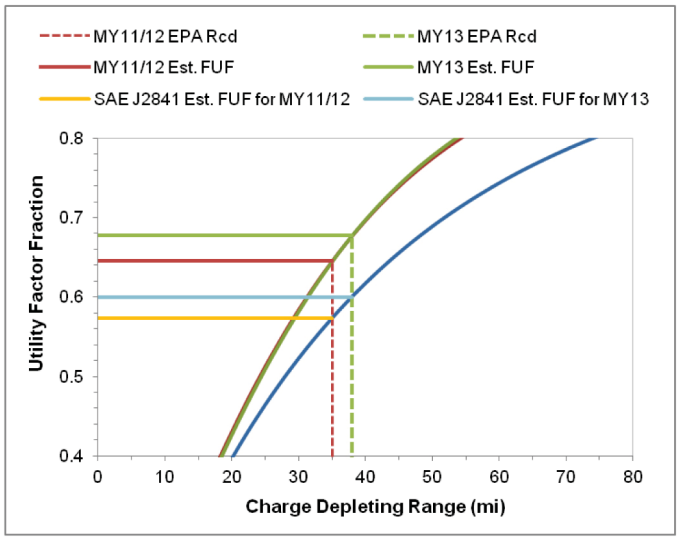

Figure 2. Estimated FUFs based on utility factor curves and EPA CD ranges

The difference in the estimated FUF results - the vertical separation between the two pairs of horizontal lines in Figure 2 - is due to differences in the distribution of daily vehicle distance traveled by the vehicles in the NHTS and EV Project Volt data sets. EV Project participants drove their vehicles less distance per day in the study period than the NHTS sample set referenced by J2841. There are a number of possible reasons for this difference. EV Project Volt owners are PHEV early adopters who use their vehicles for personal use. NHTS 2001 data used by J2841 come from survey responses of owners of a wide variety of vehicle types, including passenger cars, SUVs, and light trucks. A relatively small number of households surveyed owned a hybrid electric vehicle, but none owned PHEVs. Differences in size, utility, and efficiency of vehicles in the US market have been demonstrated to lead to different vehicle usage. Differences between NHTS results and daily driving practices of PHEV drivers have been explored further in other works [3, 4].

Comparison of Estimated Fleet Utility Factors to Actual Fleet Utility Factors

The observed FUFs of the Volt groups shown in Table 2 can be applied to the EV Project Volt FUF curves to determine the effective CD range of the Volts in these two groups. This is shown in Figure 3.

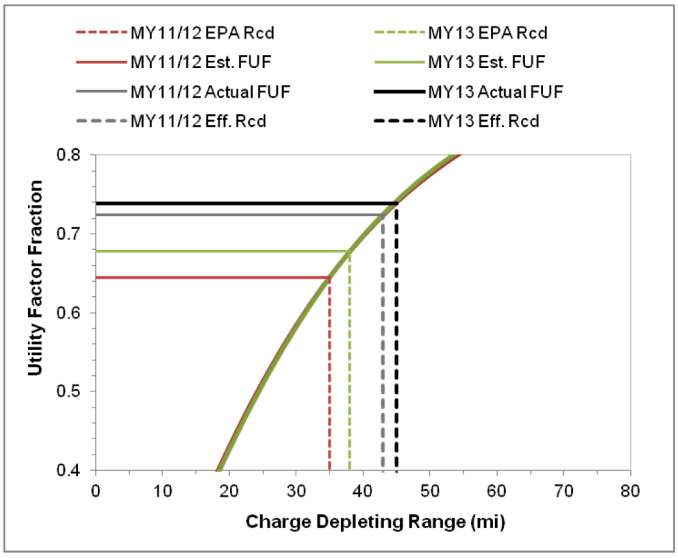

Figure 3. Observed FUFs and effective daily CD ranges for EV Project Volt groups

Using the utility factor method, the MY2011/2012 Volt group's actual FUF of 72.4% corresponds to an effective daily CD range of 43 mi [69.2 km]. This is depicted in Figure 3 by the black horizontal solid and vertical dashed lines. The MY2013 Volt group's actual FUF of 73.9% corresponds to an effective daily CD range of 45 mi [72.4 km], depicted in Figure 3 by the gray horizontal solid and vertical dashed lines.

The difference between the expected CD range, or the distance the Volt can travel in EV mode when starting with a fully charged battery (without respect to time), versus the effective *daily* CD range is a function of charging frequency. Recall that J2841 assumes vehicles are charged, on average, once per day and vehicles start each day with a full battery. Therefore, any time drivers charge their vehicles between trips during the day, the effective daily CD range is increased. EV Project data show that drivers frequently exceeded the assumed charging behavior of once per day: the average number of charging events in the study period was 1.45 and 1.43 for the MY2011/2012 and MY2013 Volt groups, respectively. Naturally, not every charge resulted in a completely full battery, and drivers occasionally started a day without a completely full battery, so there is not a linear correlation between charging frequency and effective daily CD range. It suffices to say that Volt drivers achieved more EV mode operation than expected due to frequent charging.

UTILITY FACTORS FOR INDIVIDUAL VEHICLES

In addition to quantifying the fleet utility factor for all vehicles in each EV project Volt group, utility factors were observed for each individual vehicle in each group. The cumulative distributions of UFs for both model year groups can be seen in Figure 4.

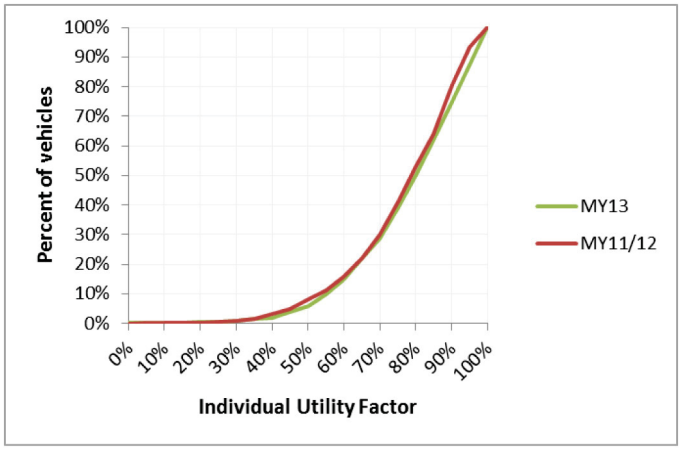

Figure 4. Cumulative distributions of observed individual vehicle UFs for EV Project Volt groups

The distributions for each group show that 95% of vehicles drove over half of their distance traveled in EV mode. About half of vehicles had UFs greater than 80%. It is also important to note the variability of UF from vehicle to vehicle. The percentage of distance driven in EV mode varied from 0% to 100%. This implies there were significant differences in the usage of Volts from driver to driver. A key difference was charging frequency.

Charging Frequency

The average number of charge events per driving day was calculated for each vehicle. The distribution of vehicle average charging frequency can be seen in Figure 5.

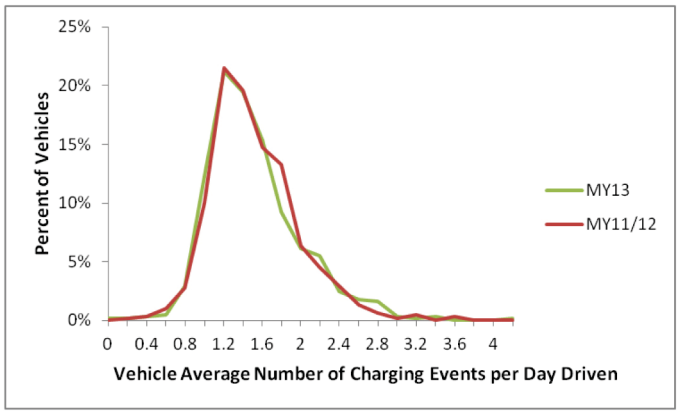

Figure 5. Distributions vehicle average number of charging events per driving day for EV Project Volt groups

It is evident that the once-per-day charging assumption does not accurately capture the charging behavior of vast majority of vehicles in the EV Project data set. Descriptive statistics for the distributions in Figure 5 are given in Table 3.

Those who averaged more than 1 charging event per day could have potentially realized significantly higher driving distances in EV mode each day, compared to their vehicle's single-charge CD range. At the same time, there were some

vehicles which were rarely charged and which consequently experienced drastically less EV mode driving than may have been expected.

Table 3. Statistics describing the distributions of individual vehicle average charging frequency

	MY2011/ 2012	MY2013
Max	3.52	4.12
Median	1.43	1.42
Mean	1.35	1.33
Min	0.12	0.00

All EV Project Volt drivers had the opportunity to charge at home. In order to be eligible for participation in The EV Project, participants were required to have a garage or dedicated parking spot at their residence, where a 240-volt level 2 charging unit was installed. In each of the EV Project regions, public charging stations were also installed. However, these stations were made available for use by the general public and EV Project participants were not given financial discounts for the use of these stations (if a fee for use was charged). EV Project participants also had the option of using non-EV Project public charging equipment or standard 120-volt outlets, where available.

Charge Depleting Range

J2841 considers a PHEV's CD range to be a fixed value. CD range for an individual vehicle varies due to a number of factors, including driving style, vehicle performance mode selection, route type, temperature, and the use of climate control and other auxiliary systems. Figure 6 shows the distribution of actual CD range of the two Volt groups observed in the study period. These were determined by querying the distance driven in EV mode in each trip or set of trips between consecutive charging events, where the vehicle started with a fully-charged battery and ended with its battery at 0% indicated state of charge. These are referred to as full-charge driving segments. The number of full-charge driving segments each vehicle contributed to the distributions in Figure 6 varied, based on how often each vehicle was charged to 100% state of charge and then driven to full depletion prior to the next charge.

Full-charge driving segments between consecutive charging events were not filtered based on conditions so that the effect of varying driving conditions would be included. For example, the CD range observed from a full-charge driving segment during which a vehicle was driven aggressively in “sport” mode in urban stop-and-go traffic is included alongside the CD range achieved during gentle driving in “normal” mode on a rural state highway. This and other factors result in wide variation in the distributions of CD range. The mean shift between the MY2011/2012 and MY 2013 groups is expected due to the increased capability of the MY2013 Volt. Table 4 provides descriptive statistics for these distributions.

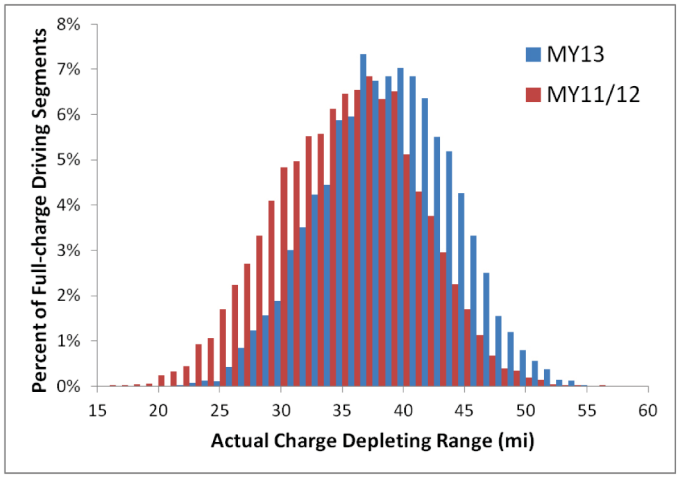

Figure 6. Distributions of actual single-charge CD range for EV Project Volt groups

Table 4. Statistics describing the distributions of actual CD range

	MY2011/ 2012	MY2013
Number of full-charge driving segments	16,296	5,420
Mean	34.7	38.3
Standard deviation	5.7	5.3

Average CD ranges for these vehicles match the EPA range estimates. This supports the assumption that for aggregate calculations using large data sets, such as calculating FUF using national travel survey data, R_{CD} can be assumed to be a single value. However, when analyzing the potential for EV mode driving of individual vehicles or small vehicle sets, an analysis method must be used that accounts for variation in R_{CD}.

SUMMARY/CONCLUSIONS

The EV Project, a large plug-in electric vehicle and charging infrastructure demonstration, provided an opportunity to study the real-world driving of Chevrolet Volt extended range electric vehicles. Data collected from 1,405 privately-owned Volts from October 2012 through June 2013 were examined to determine the fleet utility factor, or overall percentage of distance traveled in EV mode, of these vehicles over the study period. These results were compared to utility factors estimates calculated by the method defined in SAE J2841.

EV Project Volts were assigned to two groups, based on model year. The actual observed FUFs for the MY2011/2012 and MY2013 Volt groups studied were observed to be 72% and 74%, respectively. Using the EPA CD ranges, the method prescribed by J2841 estimates a utility factor of 65% and 68% for the MY2011/2012 and MY2013 Volt groups, respectively. Volt drivers achieved higher percentages of distance traveled in EV mode because their driving habits differed from the NHTS drivers and their charging habits differed from J2841

assumed behavior. EV Project Volts in this study had fewer long distance travel days than the vehicles surveyed by NHTS 2001. This is represented by the FUF curves for the MY2011/2012 and MY2013 Volt groups, which were higher than the curve given in SAE J2841. Also, most EV Project Volt drivers consistently charged more frequently than once per day. This led to an overall average charging frequency of over 1.4 charging events per day for the two Volt groups.

Individual vehicle utility factors varied widely for the Volts studied. Although most vehicles had high UFs - 95% of vehicles drove over half their distance in EV mode and 50% of vehicles drove 80% or more of their distance in EV mode - utility factors ranged from 0% to 100%. This variation was largely due to variation in charging frequency and actual CD range. Care should be taken to incorporate this variation into calculations when estimating utility factors for individual vehicles or subsets of vehicles.

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DISCLAIMERS

Chevrolet Volt owners participating in The EV Project have given explicit written consent to allow data to be collected from their vehicles.

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DEFINITIONS/ABBREVIATIONS

EV - Electric vehicle

PHEV - Plug-in hybrid electric vehicle

MY - Model year

UF - Utility factor

FUF - Fleet utility factor

CD - Charge depleting

CS - Charge sustaining

R_{CD} - Charge depleting range