THESIS

UNDERSTANDING FUEL CELL PLUG-IN HYBRID ELECTRIC VEHICLE USE, DESIGN, AND FUNCTIONALITY

Submitted by

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ABSTRACT

UNDERSTANDING FUEL CELL PLUG-IN HYBRID ELECTRIC VEHICLE USE, DESIGN, AND FUNCTIONALITY

The fuel cell plug-in hybrid electric vehicle (FCPHEV) has been shown to be a promising vehicle architecture in terms of cost, emissions reduction, and reducing petroleum use. It combines a high power battery pack and a small fuel cell to make a zero emissions vehicle with all of the capabilities of current consumer vehicles. Previous FCPHEV studies have projected vehicle cost, emissions, and efficiency, but little work has been performed towards understanding the use, design, and functionality of the architecture. This study presents several topics which will help to advance the state of the FCPHEV.

Plug-in hybrid vehicles, including FCPHEVs, can use two different sources of fuel depending upon how the vehicle is driven and charged. To quantify this fuel use, SAE J2841 establishes a utility factor method based upon transportation survey data that includes assumptions about vehicle use and battery charging habits. The utility factor model is an important tool for automakers, consumers, and researchers, and it is used by the EPA to determine the fuel economy of plug-in hybrid vehicles. In the Section A of this study, the utility factor model is examined and compared to data collected from over 1,400 Chevrolet Volts in order to assess its accuracy. Until now, there has been no large-scale set of vehicle data to which the model could be compared. Results show that the assumptions of the J2841 utility factor model are not representative of the driving behavior of this set of plug-in vehicles.

A hydrogen fueled vehicle requires a high pressure gaseous fuel storage and delivery system that is very different than the fueling systems of current conventional vehicles. The design and execution of the system is critical to the safety and functionality of an FCPHEV, but previous literature on hydrogen fueled vehicles covers fuel systems in little detail. Section B of this study details the considerations that one must make when designing a high pressure hydrogen fuel system and provides an example of how those considerations were met for the FCPHEV built by Colorado State University in the EcoCAR 2 competition.

The FCPHEV built for the EcoCAR 2 competition is the first of its kind to publish real-world driving data. Data taken from the vehicle during on-road testing is analyzed in Section C of this study to prove the FCPHEV concept and increase the understanding of overall system operation. The results of the driving tests demonstrate the viability of the FCPHEV and highlight its advantages over current zero emissions vehicle architectures.

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INTRODUCTION

In recent decades, the United States has been putting emphasis on reducing petroleum dependence and the environmental impact of the transportation sector. With initiatives such as the Partnership for a New Generation of Vehicles (PNGV) and the FreedomCAR and Fuel Partnership Plan, the federal government has provided funding to automakers and energy companies for the research and development of alternative fuel vehicles and infrastructure. The overall goal of these programs is to help realize a clean and sustainable transportation energy future and to increase US manufacturing capabilities of advanced vehicle technologies [1][2].

The PNGV began in 1993, and had goals to increase US manufacturing capabilities, use new vehicle technologies, and develop vehicles that could get fuel economy of 70 mpg or better. Each of the “big three” automotive companies were able to produce a 70+mpg vehicle, and they were all diesel hybrids. These vehicles were more expensive to manufacture, and at the time there was no federal requirement for highly fuel-efficient vehicles, so there was no incentive for automakers to produce them. Billions of dollars were spent developing technologies and incorporating them into a vehicle, but the vehicles would have been less affordable for consumers and manufacturers alike, so they weren’t pursued further [2]. In a similar timeframe as PNGV, Japanese automakers like Toyota and Honda had been developing similar technologies, and were successfully selling hybrid vehicles to consumers by the late 1990’s. The PNGV was defunded in 2002 and replaced with the FreedomCAR program.

FreedomCAR and Fuel Partnership, which began in 2003, put major emphasis on the development of hydrogen fuel cell technologies and hydrogen infrastructure to enable the production of affordable hydrogen fuel cell vehicles. Among the specific goals were to produce fuel cell systems able to achieve 60% peak efficiency, specific energies of 325 W/kg, and energy densities of 220 W/L at a cost of $45/kW by 2010 and have hydrogen fueling infrastructure with an energy cost equivalent to gasoline prices, assumed to be $2-3 per gallon of gasoline equivalent, by 2015 [1]. At that time, it was expected that fuel cell vehicles would be selling in the US by the thousands around 2010 and by the hundreds of thousands in today's market [3].

While a few of the FreedomCAR fuel cell goals were met and some fuel cell vehicles were developed by auto manufacturers, the fuel cell vehicle market did not take off as expected. This result was generally attributed to scarcity of hydrogen fueling infrastructure and fuel cell reliability issues [4]. In 2010, the FreedomCAR and Fuel Partnership budget was reduced greatly and emphasis was removed from hydrogen and fuel cell vehicles [5].

Over the last two decades in the United States, vehicles have become more fuel efficient [6] and hybrid electric vehicles are becoming more common, but in 2009 only five percent of household vehicles were either hybrid or used alternative fuel [7]. One of the fastest growing alternative fuels in vehicles is electricity. Electricity is available nearly everywhere, so electric charging infrastructure is not as difficult to install as that of other alternative fuels. A fully electric vehicle, or battery electric vehicle (BEV), uses only grid electricity stored in batteries. BEVs are highly efficient at converting energy from the grid into tractive force, and they are able to recover energy during drives due to regenerative braking. As a major disadvantage, BEVs generally have a limited range due to the size and cost of batteries necessary for vehicle power and energy requirements. The "refueling" of the battery systems can also take several hours, rather than a few minutes like with a conventional vehicle. In order to use advantages of both electrification and conventional vehicles (CVs), and to bridge the gap between CVs and BEVs, the plug-in hybrid electric vehicle (PHEV) was developed through cooperation of automakers, researchers, and universities.

A PHEV is a type of hybrid vehicle that can use liquid fuel as well as grid electricity as sources of energy. Using electricity from the grid allows PHEVs to achieve reductions in emissions and petroleum fuel use while increasing fuel economy [8]. PHEVs store electrical energy on-board the vehicle in batteries, which store only enough energy to drive the vehicle for a limited range. Because of this, a PHEV will generally operate in two driving modes: a charge depleting (CD) mode in which the energy stored in the batteries contributes to powering the vehicle, and charge sustaining (CS) mode, in which conventional fuel provides all required driving energy. This means there will be driving segments which will use only grid electricity, others which use only liquid fuel, and others still that use both electricity and fuel. As these vehicles become more and more prevalent in the US market, it is necessary to understand and represent their performance as precisely as possible in order to provide information to those performing advanced vehicle research as well as consumers who may be looking to buy the vehicles [4].

PHEVs represent a vehicle technology that is able to utilize current refueling infrastructure, but long-term goals like that of FreedomCAR and California Air Resource Board (CARB) initiatives are built upon the idea of non-petroleum fueled, zero emissions vehicles (ZEVs). The only vehicle fuels with ZEV potential are electricity and hydrogen. Fuel cell vehicles (FCVs) that have been developed use fuel cells as the main source of vehicle power. This requires a large fuel cell, which makes the vehicle very costly to manufacture, and the fuel cell must perform in a highly dynamic manner, which can lead to lifetime issues of the fuel cell stack. These are among the reasons fuel cell vehicles have not become common, but this has not changed the goals of CARB policies or their ZEV policies. In order to reach these goals, many believe that it will be necessary to further the development of vehicles using fuel cell technology

[8]. A fuel cell plug-in hybrid electric vehicle (FCPHEV) is a promising technology to bridge the gap between electric vehicles and fuel cell vehicles.

In much the same way that a PHEV combines internal combustion with electrification, an FCPHEV combines hydrogen fuel cells with battery electric components. A large battery pack provides all of the driving power and has the ability to drive the vehicle for a limited range on battery power only, and a fuel cell provides energy to extend the battery range to be comparable to that of a current conventional vehicle. This means the vehicle’s operation is not fully dependent on the developing hydrogen infrastructure, but it can use electricity for a large portion of its driving. Using a fuel cell as a range extender means that the fuel cell can be much smaller and operate at set operating points, greatly decreasing fuel cell cost and reducing lifetime issues.

Colorado State University has used its involvement in the EcoCAR 2 program as a means to increase the understanding of PHEVs and FCPHEVs. The EcoCAR2 project was created by the U.S. Department of Energy (DOE) and General Motors (GM) to provide a platform on which innovative vehicle technologies could be designed and built using a complete vehicle design process (VDP). Through these competitions, North American universities are able to demonstrate vehicle architectures that reduce fuel consumption, well-to-wheel (WTW) greenhouse gas (GHG) emissions, and criteria tailpipe emissions in comparison to conventional petroleum based vehicles [10]. As a participant university in the EcoCAR 2 competition, the Colorado State University Vehicle Innovation Team (CSU VIT) has designed and fully integrated a Fuel Cell extended range electric vehicle (FCPHEV) architecture into a 2013 Chevrolet Malibu.

Research Objectives

There are no FCPHEVs in production and only a few FCPHEVs have been modeled or demonstrated, so many challenges still exist. The primary references for FCPHEVs in the literature are Kordesch [11], Suppes [12], Kalhammer [13], and the EPRI FCPHEV report [8]. The existing FCPHEV literature focuses mainly on vehicle cost and emissions reduction, so there are still many questions regarding the design, performance, and utility of FCPHEVs.

Based on this understanding of the state of the art in the field, this thesis seeks to address some of the sources of uncertainty with the modeling, operation, and design of FCPHEVs. Section A of this thesis seeks to model the energy consumption and costs of PHEV operation. The source of energy a PHEV, or FCPHEV, uses at any given time is dependent upon the driving and charging habits of the driver, so modeling efforts should account for these considerations. Until recently, the actual habits of PHEV drivers were unknown, so SAE J2841 used assumptions based on existing driving surveys to estimate driving statistics. To augment the data that can be derived from these standards, data collected from more than a thousand consumer-owned Chevrolet Volts will be used to compare current PHEV driving models to the habits of PHEV owners in an effort to improve future PHEV and FCPHEV modeling efforts.

The design of an FCPHEV provides unique challenges due to the use of gaseous hydrogen as fuel. Hydrogen fueled vehicles have been developed and built by OEMs, smaller companies, and research groups, but there is little information available for systems design of these vehicles. As a part of the EcoCAR 2 project, a collegiate competition sponsored by the Department of Energy and General Motors, the team from Colorado State University converted a 2013 Chevrolet Malibu to an FCPHEV. A rigorous design process was followed when designing the custom hydrogen storage and handling system for the CSU FCPHEV using insight and collaboration from industry experts. Section B of this thesis will detail the considerations necessary to design such a system and explain how these considerations were addressed for the CSU system. It can act as a guide to constructing a safe, functional fueling system for future research efforts regarding hydrogen fueled vehicles.

Determining the utility of FCPHEVs as a consumer vehicle requires, in some form, real-world demonstration of such a vehicle. Section C of this thesis will analyze data from the FCPHEV’s functional operation at the EcoCAR 2 competition and during further driving tests. This information can be used to verify the utility of FCPHEVs as consumer vehicles and highlight their advantages over more conventional alternatively fueled vehicles.

A. EV Project Chevrolet Volt Utility Factor Analysis

A.1 Introduction

Plug-in hybrid electric vehicle driving takes place in one of two modes: charge depleting (CD), in which only battery power is used, and charge sustaining, in which fuel provides all of the vehicle energy. 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 [14].

The J2841 UF is a tool that is widely used in policy, academic research, and by automotive companies. It is used to determine the EPA rated fuel economy of vehicles, which is incredibly important to an automaker's CAFE rating, as well as a consumer's incentive to purchase a vehicle. However, J2841 UF contains several simplifying assumptions about consumers' use of PHEVs which could have a large impact on the accuracy of the utility factor method. 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 real-world PHEV driving patterns, and an assumption that a PHEV's CD range can be represented as a constant, deterministic value. It has been previously shown that UF calculations are sensitive to variations in driver habits and vehicle characteristics [15][16], 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, included in which is data 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 Volt data was collected for the EV project by OnStar and then sent to a database at Idaho National Laboratory. From this database, reports are generated and analysis, like this utility factor work, is performed. The flow of data through the EV Project system can be seen in . This work falls in the section labeled Technical Papers, Publications, and Presentations.

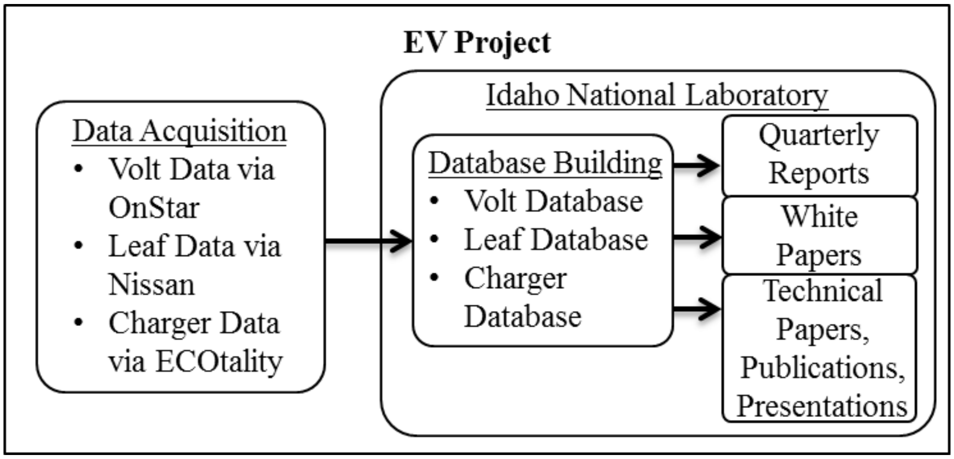

Figure 1 Structure and data flow of the EV Project

The objective of this section is to make a quantitative comparison between the J2841 UF and the UF as observed in the Chevrolet Volts enrolled in the EV Project. This will be done in an effort to determine whether the J2841 UF method adequately represents consumer PHEV driving.

A.2 Vehicle Data Set

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.

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

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.

A.3 Observed and Calculated Fleet Utility Factors

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

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%

A.4 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 in Equation 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.

Equation 1 Fleet utility factor

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

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 *FUF*s 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.

A.5 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 *FUF*s for the EV Project Volt groups are between 15% and 14% higher than the J2841 estimated *FUF*s. 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 *FUF*s 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 [14]. 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 2.

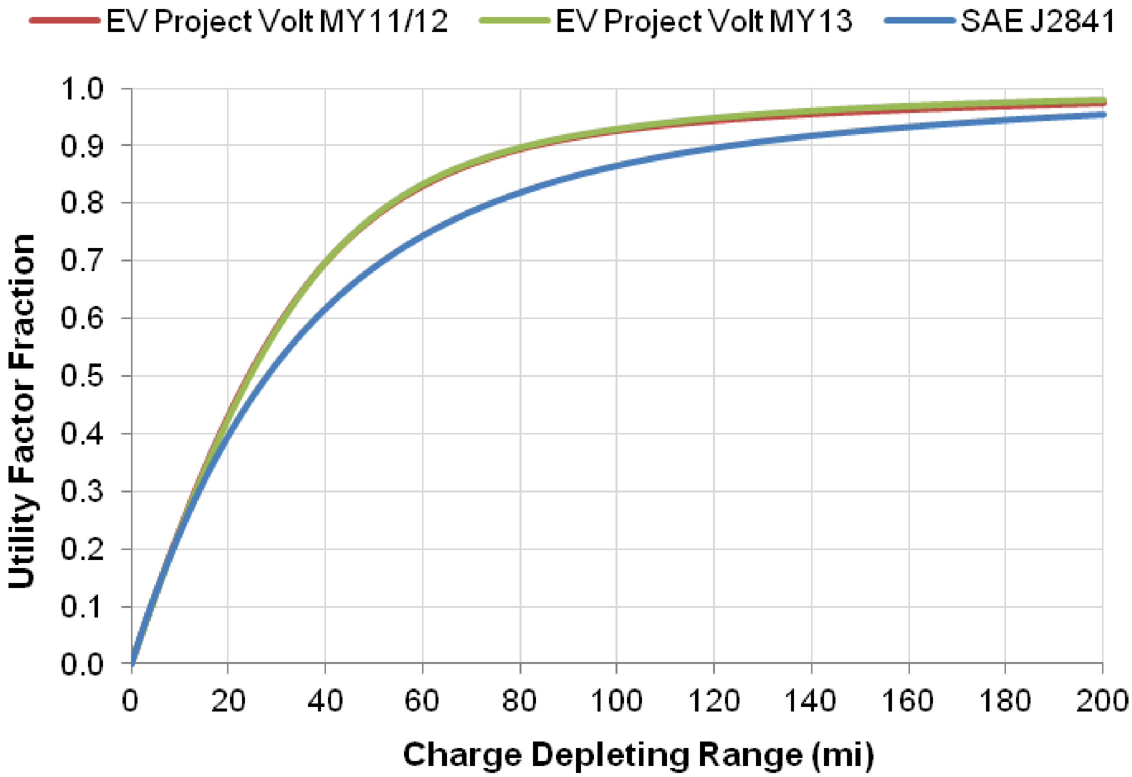

Figure 2 Utility factor curves from SAE J2841 and EV Project Volt groups

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 subset of vehicles surveyed by NHTS 2001 that are included in the J2841 calculation. The inset in Figure 2 is expanded in Figure 3 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 *FUF*s for MY2011/2012 and MY2013 Volts are 64.5% (horizontal red line) and 67.8% (horizontal green line), respectively.

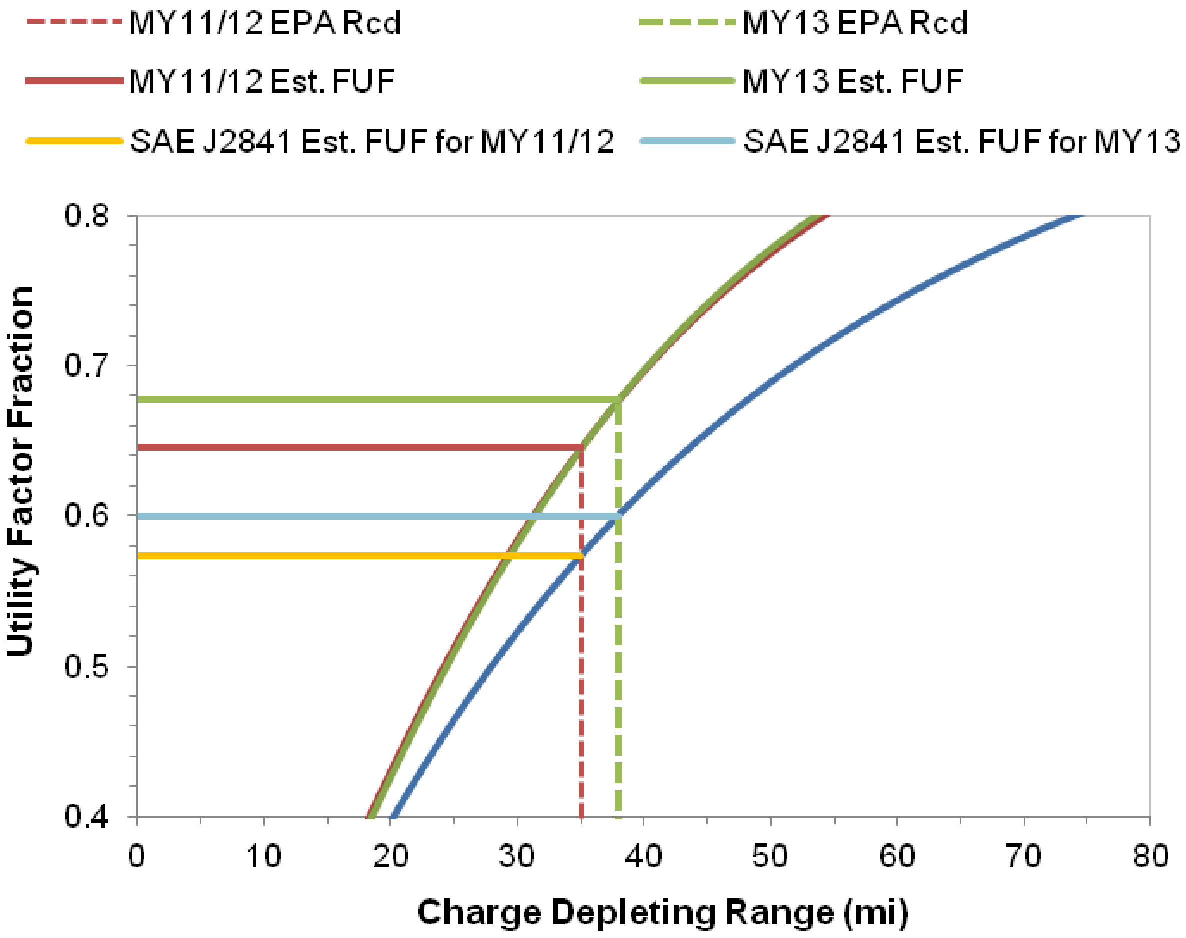

Figure 3 Estimated FUFs based on utility factor curves and EPA CD ranges

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 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 [15][16].

A.6 Comparison of Estimated Fleet Utility Factors to Actual Fleet Utility Factors

The observed *FUF*s of the Volt groups shown in Table 2 can be applied to the EV Project Volt *FUF* curves to determine the effective R_{CD} of the Volts in these two groups. This is shown in Figure 4.

Using the utility factor method, the MY2011/2012 Volt group's actual *FUF* of 72.4% corresponds to an effective daily R_{CD} 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 R_{CD} of 45 mi [72.4 km], depicted in Figure 3 by the gray horizontal solid and vertical dashed lines. The difference between the expected R_{CD}, 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.

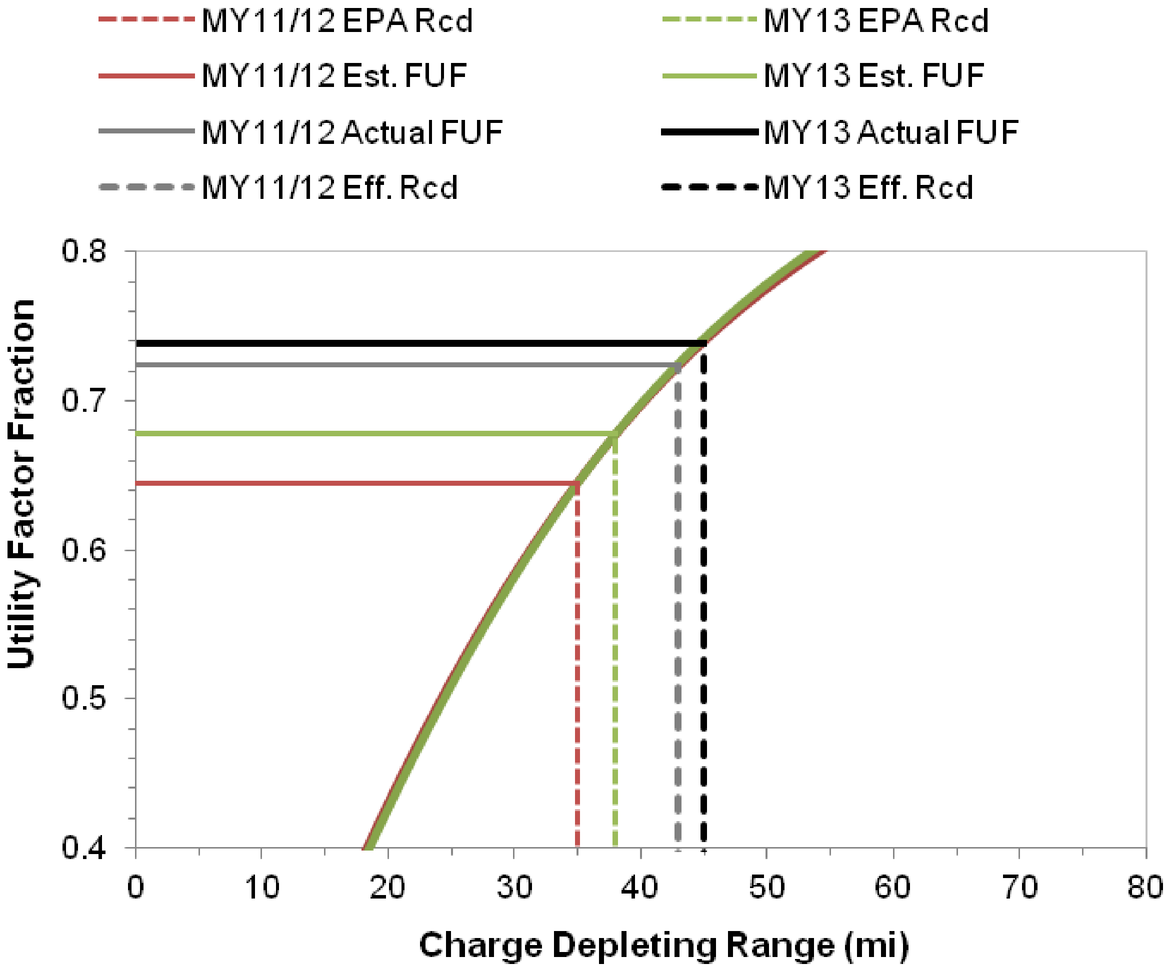

Figure 4 Observed FUFs and effective daily CD ranges for EV Project Volt groups

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 R_{CD} 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 perfect correlation between charging frequency and effective daily R_{CD}. It suffices to say that Volt drivers achieved more EV mode operation than expected due to their frequent charging.

A.7 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 5.

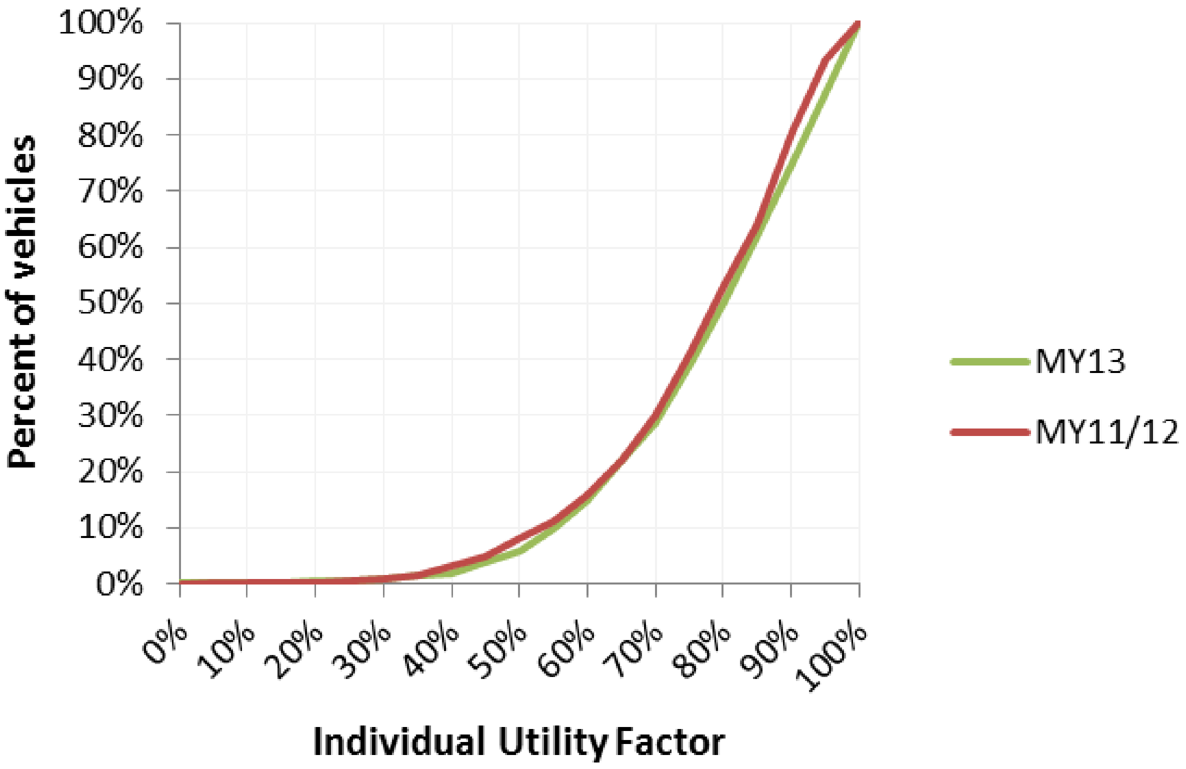

Figure 5 Cumulative distributions of observed individual vehicle UFs for EV Project Volt groups

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.

A.8 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 6.

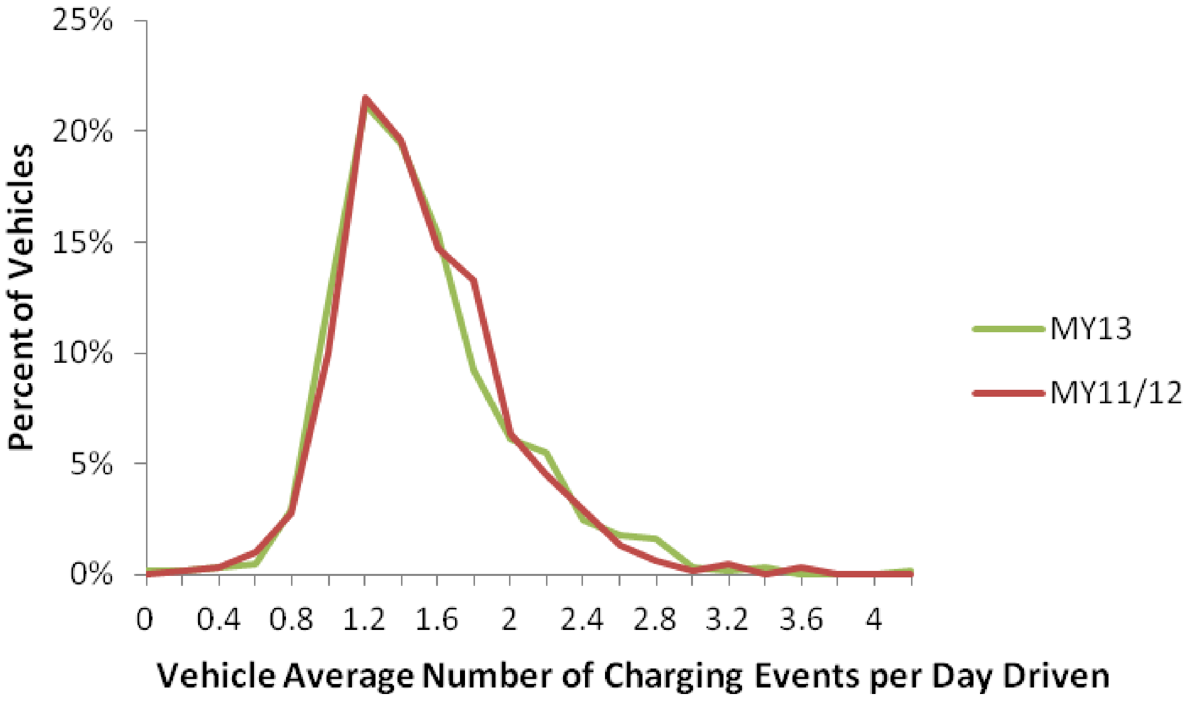

Figure 6 Distributions vehicle average number of charging events per driving day for EV Project Volt groups

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.

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

	MY 2011/2012	MY 2013
Max	3.52	4.12
Median	1.43	1.42
Mean	1.35	1.33
Min	0.12	0.00

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 R_{CD}. 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.

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.

A.9 Charge Depleting Range

J2841 considers a PHEV's R_{CD} to be a fixed value. R_{CD} 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 R_{CD} 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 7 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.

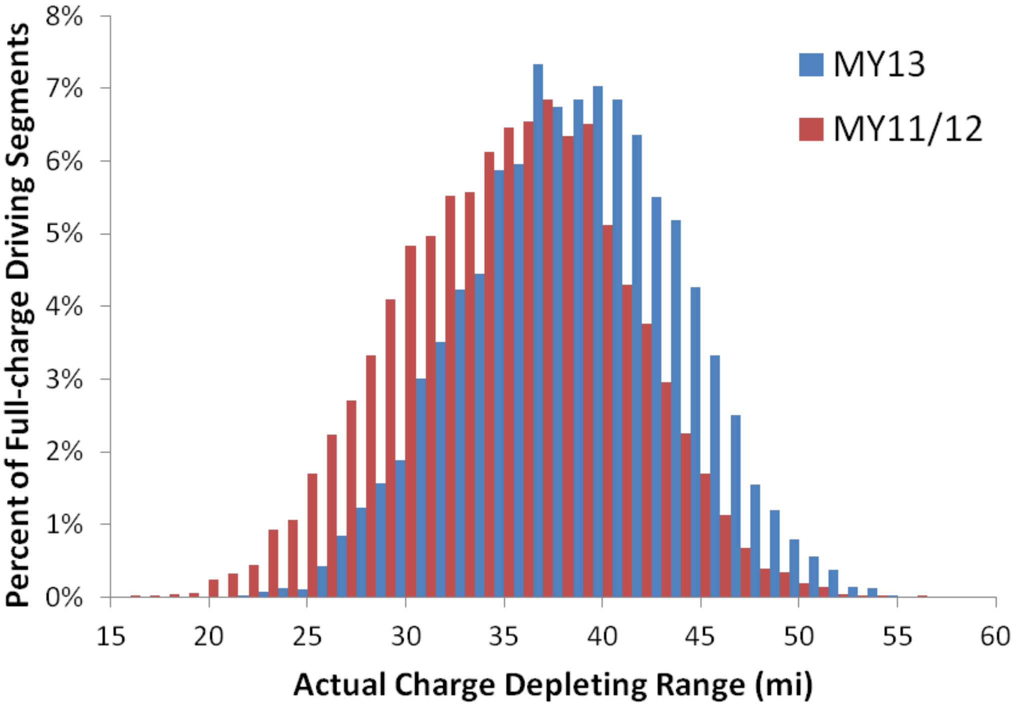

Figure 7 Distributions of actual single-charge CD range for EV Project Volt groups

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.

Table 4 Statistics describing the distributions of actual CD range

	MY 2011/2012	MY 2013
Number of full-charge driving segments	16,296	5,420
Mean segment distance, mi	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}.

A.10 Section Conclusion

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.

These findings suggest that the SAE J2841 utility factor method is not representative of actual PHEV driving, and may be underestimating the utility of PHEVs to both consumers and automakers. Using EPA fuel economy calculation methods and the results of this analysis, the utility factor weighted fuel economy rating of a 2013 Volt would increase from 64 mpge to 68 mpge. This change could have a substantial effect on Corporate Average Fuel Economy standards and consumer fueling costs, potentially making PHEVs more desirable to automakers and consumers alike.

B. VEHICLE HYDROGEN FUELING SYSTEM DESIGN CONSIDERATIONS

B.1 Introduction

Hydrogen is believed to be a promising fuel for vehicle use [3][4][8]. It has a lower heating value of 120 kJ/g, nearly three times higher than that of gasoline (44.5 kJ/kg). However, the energy density of atmospheric hydrogen is 10,050 kJ/m^3, which is 0.03% the value of liquid gasoline (31,150,000 kJ/m^3)[17]. In order for a hydrogen fueled vehicle to store enough energy, it must make use of advanced fuel storage systems to increase hydrogen density. The current state of the art for hydrogen storage is using high pressure gas cylinders. Compressed hydrogen is stored on-board the vehicle in cylinders and then must be regulated down to lower pressures to be used in the vehicle's energy conversion device, most commonly a proton exchange membrane fuel cell.

In the design of a hydrogen fueled vehicle, such as an FCPHEV, the storage and handling of compressed hydrogen is a system critical to the safety and functionality of the vehicle. SAE J2579 is a report that provides definitions for design and operation of hydrogen storage and handling systems in on-road vehicles, but it provides little information in terms of designing and executing such a system [18]. Descriptions of existing or theoretical hydrogen fueling systems are scarce in the literature, and those that exist are very general and basic [19][20][21][22]. This section will detail the design considerations for functionality and safety of the storage and handling of gaseous hydrogen as fuel in vehicles, as well as provide an example of how these considerations were met with the CSU FCPHEV, named H2eV, built for the EcoCAR 2 competition.

B.2 CSU Fuel Delivery System Overview

Creating the FCPHEV hydrogen fueling system required a rigorous design and review process with industry experts on hydrogen fueled vehicles. In order to be used in the EcoCAR 2 competition, the system had to be certified in design and execution to meet or exceed industry standards. The CSU fueling system, detailed in Figure 8, was designed, built, and functionally demonstrated in the EcoCAR 2 FCPHEV application.

In the CSU system, hydrogen is stored in the trunk of the vehicle in three separate type III storage cylinders at 5,000 psi. The outputs of each tank are connected to a single junction with the main fueling line. In this line, there are two in-line shutoff valves, one manual and one electronic, each capable of completely stopping fuel flow. Two pressure regulators decrease the pressure in the fuel line, resulting in high, medium, and low pressure sections of the system. After regulation, the gas is routed to each fuel cell, with solenoid valves controlling the inlet and outlet of hydrogen to each fuel cell stack. The system is fueled using SAE J2600 components and can be filled using communication protocol established by the California Fuel Cell Partnership. The J2600 standard receptacle is positioned behind the Malibu fuel door, and hydrogen is then routed to each of these cylinders. Each fuel tank has a check valve on its inlet to prevent flow back into the filling section. Every component in the system has a specific and necessary purpose for the successful execution of a compressed hydrogen fueling system.

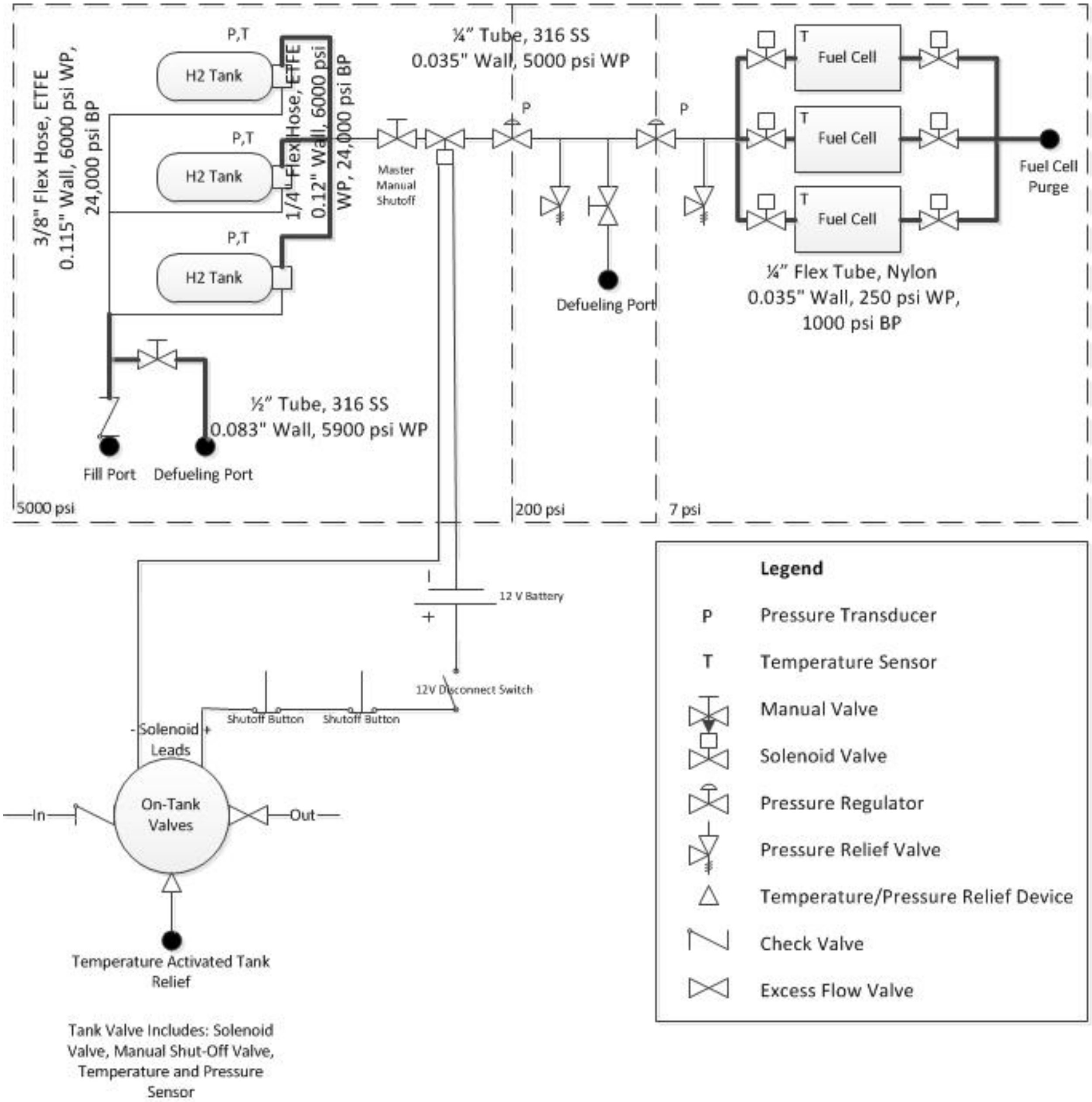

Figure 8 Schematic of CSU compressed hydrogen fuel system

B.2 Fueling System Design Requirements

Throughout the design process for the CSU hydrogen fueling system, it was determined that high pressure hydrogen fueling systems had several main requirements:

- Operational Requirements: Provide hydrogen gas to the fuel cells under a variety of operation conditions at a specific pressure and flow rate.

- Safety Requirements: Effectively respond to safety issues such as fire, overpressure, leaks, and system damage.
- Serviceability Requirements: Have the ability to assemble and disassemble any portion of the system safely.

In order to meet all of these requirements, many issues must be taken into consideration.

B.3 Operational Requirements

In any application, the main function of a fueling system is to provide fuel to an energy conversion device. In a hydrogen fueled vehicle, it is important that the hydrogen enters the device at an acceptable pressure and flow rate for optimal fuel cell operation. For the Horizon fuel cell stacks used in the FCPHEV application, hydrogen gas is required at 6.5-8 psi at a rate of 195 L/min. The pressure will differ from the regulator setpoints for several reasons, and these must be accounted for when determining optimal setpoints.

B.3.1 Regulator Effects

High pressure gas used as a fuel must reach a usable pressure through the use of pressure regulators. When regulating the pressure of a flowing gas, the delivery (downstream) pressure will depend upon the regulator’s source (upstream) pressure. When using a cylinder as a source of pressure, the pressure within the cylinder can vary widely. As the fuel from the cylinder is used, the source pressure will decrease, and the supply pressure will increase as a function of the regulator’s supply pressure effect (SPE). Every regulator has a different SPE, and datasheets will represent the effect as a percentage or a pressure per 100 psig, effectively a percentage. The SPE can be calculated using Equation 2.

Equation 2 Regulator delivery pressure increase due to supply pressure effect

$$\begin{aligned} &Delivery\ Pressure\ Increase \\ &\qquad = SPE \times (Initial\ Supply\ Pressure - Final\ Supply\ Pressure) \end{aligned}$$

In a vehicle application, the difference in supply pressure from a tank can be tens of MPa. Fuel cells often require specific delivery pressures, so measures must be taken to mitigate SPE. The issue can be solved by using two regulators in series and cascading pressure from the tanks to the fuel cells. The range of delivery pressure from the first regulator will be much smaller than that of the fuel tanks, and adding second regulator can achieve a steady and controlled delivery pressure to the fuel cells.

For the H2eV, the fuel tanks will be full at 34.5 MPa and empty at 2.8 MPa, and the fuel cells require fuel at 45 kPa to 55 kPa. There are two regulators in the system, and the resulting supply pressure effect can be seen in Figure 9.

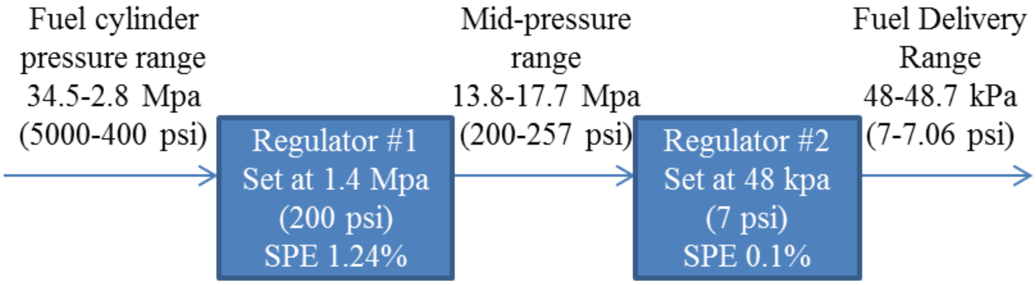

Figure 9 Pressure ranges due to supply pressure effect in FCPHEV fueling system. Regulators are labeled with their set pressure and rated SPE

Using two regulators, the effective SPE from tank to fuel cell is approximately 0.0012% and easily meets the fuel cell input pressure requirements.

The output pressure of a regulator will also be affected by the volume of gas flowing through the regulator. Increasing the flow rate of the regulated fluid will decrease the output pressure. To determine the flow effects, regulator datasheets will include flow curves that show the outlet pressure at different inlet pressures for various flow rates. Considerations must be made for the specific regulators being used on a case-by-case basis. In the case of the regulators specified for the H2eV, the flow curves indicate that delivery pressure will vary by less than 7 kpa (1 psi) during high power operating conditions (195 Lpm).

B.3.2 Pipe Flow Considerations

In a hydrogen-fueled vehicle, there will generally be a large volume of gas flowing through the system tubing. As with all fluid flow problems, there will be pressure drop within the tubing and componentry throughout the fueling system. The pressure drop within a pressure system can be calculated using an equation such as the Darcy-Weisbach equation, seen in Equation 3. In this equation, f_d refers to the Darcy friction factor, L is the length of the system, D is the pipe diameter, K_L is the sum of the minor loss coefficients, ρ is the fluid density, and $\bar{V}$ is the average fluid velocity.

Equation 3 Darcy-Weisbach equation of pressure drop due to pipe friction and minor losses

$$\Delta P = \left(f_d \cdot \frac{L}{D} + K_L\right) \cdot \frac{\rho \bar{V}^2}{2}$$

The majority of the CSU system is made up of ¼” stainless steel tubing and this tubing runs from the tanks in the trunk to the fuel cells in the engine compartment. At maximum power, each fuel cell stack will use 65 liters of hydrogen gas per minute, for a total of 195 Lpm flowing through the fueling system. Using these parameters, it was calculated that the pressure drop across the entire fueling system due to pipe friction and minor losses is 76.2 kPa, or 11 psi.

Due to the fact that pipe flow losses are highly dependent upon pipe length, it was determined that the low pressure regulator should be placed as close to the fuel cell inlets as possible. This will ensure that the pressure at which hydrogen enters the fuel cell will be as close as possible to the final regulation pressure. The short distance between the regulator outlet and the fuel cell inlets will result in a drop of less than 1 psi.

B.3.3 Hydrogen Tank Cycling

In an application using multiple high pressure storage tanks, it may be advisable to cycle tank opening and closing such that only one tank is open at any time, as this may reduce the severity of certain safety issues. For instance, if the system was damaged downstream of the tank outlets and a leak occurred, the reservoir that may be drained would be one-third the volume as if all tanks were open.

In the CSU system, the three tanks are cycled at ten second intervals. For every 30 seconds of fuel cell operation, each tank will be open for ten of those seconds. Over the course of the vehicle's operation each tank will provide a similar amount of hydrogen, and the cycling of fuel tanks will not result in large tank-to-tank pressure differentials.

B.4 Safety Considerations

B.4.1 Hydrogen Flammability

Similarly to all common vehicle fuels, hydrogen is flammable, and can burn or detonate in air under certain conditions. Just as with all flammable fuels, certain safety measures must be included in the design of vehicles using those fuels. Its flammability and explosion limits in air are much wider than those of gasoline vapor or natural gas, as seen in Table 5.

Table 5 Flammability and explosion limits of vehicle fuels in air [23]

	Hydrogen	Gasoline Vapor	Natural Gas
Flammability limit	4-74%	1.4-7.6%	5.3-15%
Explosion limit	18.3-59%	1.1-3.3%	5.7-14%

At the same time, hydrogen gas is extremely light and diffuses rapidly in air, rising at approximately 20 m/s (45 mph) [23]. Because of this, it is difficult for hydrogen gas to be ignitable unless its ability to rise is impeded and a volume collects in a confined space. For this reason, any hydrogen fueled vehicle should be designed such that any release of fuel, whether through pressure relief mechanisms or due to system damage, will achieve the results with the lowest possible level of danger.

B.4.2 Fuel Flow Stoppage Capability

A hydrogen fueled vehicle should have the capability to stop fuel flow at any time during vehicle operation. If the vehicle safety systems detect a dangerous situation, such as a crash or hydrogen leak, the flow of hydrogen to the fuel cells should be stopped immediately. For this reason, a normally closed solenoid valve should be placed in the main fuel line as close to the tank outlets as possible. It should only be given power when the vehicle is on and all of the safety systems detect normal operation.

The CSU fuel system has a high pressure solenoid valve on the main fueling line, and it is capable of stopping all fuel flow. Flow can be stopped manually or passively through the vehicles electronic safety network, which includes emergency stop buttons and an inertial switch that will trigger if the vehicle is in an accident. If the emergency stop buttons are pressed or the inertial switch senses a crash, the solenoid will close immediately, as will the solenoid valves on each hydrogen tank. The vehicle controller also monitors certain readings, such as hydrogen leak sensor output, to determine whether the vehicle is safe to run. If any of the monitored signals go outside what is determined to be their safe threshold, the solenoid valves will close and fuel flow will stop.

B.4.3 Overpressure Safety Concerns

There are safety issues present any time a design includes high pressure gas storage. In a hydrogen fueled vehicle, there are typically one or more high pressure storage tanks made of a liner of polymer or aluminum wrapped in carbon fiber composite, and a system which regulates the pressure and flow of gas to the fuel cell. Both the tanks and the rest of the system have separate issues that must be addressed regarding overpressure.

High pressure storage tanks are the source of pressure in the entire system, and overpressure of these tanks in a vehicle is usually due to increasing the temperature of the tank and contained gas from a fire. If pressure is not relieved from a tank that is being heated by a fire, it may damage the tank causing rupture and uncontrolled gas release. To avoid this situation, high pressure storage vessels are fitted with pressure relief devices (PRDs) in the vessel’s valve. A PRD for a hydrogen tank in a vehicle is temperature operated, so when the tank valve reaches a certain temperature, the PRD will open and exhaust the entire contents of the tank. The flow rate of this release can be extremely high, up to 200 g/sec of hydrogen flow according to one manufacturer, and thus the exhaust tubing must be sized to accommodate this flow. The exhaust tubing should be short with as few bends as possible to avoid issues due to the high flow rate and output the gas in the safest location possible. It is preferable to exhaust outside the body of the vehicle, but this is not always achievable depending upon the tank orientation within the vehicle.

In the CSU design, each cylinder has a built-in pressure PRD that will exhaust the cylinder contents if the valve reaches a temperature of 103 degrees C. The valves are located near the foremost portion of the vehicle trunk, and it was not feasible to route the PRD exhaust lines outside the body, so they exhaust below the vehicle towards the ground.

In the rest of the fueling system, there are several sections at different pressures. The storage tanks provide pressure for the system and regulators decrease the pressure throughout the lines. If one of the regulators were to fail, the downstream components may see pressure higher than designed and result in component damage. To mitigate an overpressure event in the fuel lines, each lower-pressure section should include a passive method of relieving pressure, usually a pressure relief valve. When a pressure relief valve experiences pressure higher than a set pressure, it will exhaust gas in the line until the pressure drops below the set pressure. Again, the exhausted hydrogen should be routed to a safe location.

In-line pressure relief is achieved in the CSU system with two pressure relief valves. The mid-pressure relief valve is set at the maximum inlet pressure of the low pressure regulator, and the low pressure relief valve is set slightly higher than the fuel cell inlet requirements. The outlets of these valves are routed such that they exhaust outside the body of the vehicle so no hydrogen pooling of exhausted hydrogen can occur.

B.4.4 Issues Due to System Damage

As with all high pressure systems, it is possible for a leak to occur due to a loose connection or component damage. It is impossible to make every part of a vehicle immune to hydrogen pooling, so it is important that such an event could be detected. For this reason, the vehicle should have a sensor network that has the ability to detect hydrogen gas. The sensors should be capable of detecting quantities of hydrogen gas well below the flammability limit so detection occurs before a dangerous situation is present. They should be placed in locations where pooling would be most likely, such as the uppermost portions of vehicle compartments.

The CSU FCPHEV uses six gas sensors placed throughout the vehicle, with two each in the uppermost portion of the trunk space, passenger compartment, and engine compartment. They are programmed to detect low levels of hydrogen gas and have warning and alarm outputs at 2000 ppm and 4000 ppm, respectively. In the case of a warning-level hydrogen detection, the vehicle will provide the driver with a visual LED warning light and provide and audible warning tone. If an alarm state is entered, an alarm LED will be lit and the audible tone will change. In addition, the flow of hydrogen will be stopped, fuel cell operation will cease, and the vehicle will enter a limited power “limp” mode so a safe location can be reached prior to exiting the vehicle.

In the case of more severe damage, such as a fuel line rupture, an uncontrolled release of gas could occur. In such a situation, the potential exists for a large gas release prior to detection from the sensor network, so an excess flow valve should be included in the system to immediately stop such a release. An excess flow valve is a mechanical device with a piston that will limit fuel flow if the downstream pressure suddenly decreases. If the line integrity is restored, the pressure equalizes on both sides of the device, and the valve will reset to allow unimpeded flow. The FCPHEV system includes excess flow valves attached directly to the output of each storage cylinder. With this placement, any uncontrolled flow in the system will trigger the valve and restrict flow.

B.4.5 Hydrogen Embrittlement

Certain materials have been shown to be negatively affected by prolonged contact with hydrogen gas. Generally, these materials lose ductility and strength, and in some cases will crack to due hydrogen diffusing into the material [24]. For this reason, the entirety of the fueling system must be composed of materials that are not susceptible to hydrogen embrittlement. The majority of the CSU system is composed of 316 stainless steel, an alloy that is known to be hydrogen compatible and is widely used in hydrogen service [25]. Other hydrogen compatible materials used include brass and polymers such as nitrile and PTFE [24].

B.6 Serviceability Requirements

B.6.1 System Defueling

It may be necessary throughout the life of the vehicle to perform maintenance to any portion of the fueling system. This can include removing any portion of the system, and for this reason it must be possible to defuel any section of the system, as it can be dangerous to open a pressurized line in anything but a controlled manner.

In the CSU fueling system, there are two sections which require defueling capability. These two sections are the main fueling line, in which all of the regulation occurs, and in the line used for filling, between the SAE J2600 receptacle and the fuel cylinders. In each section, a tee fitting was used to add a branch to the line onto which a manual valve was attached. When opened, these valves could exhaust all of the fuel within the lines, and fuel tanks if necessary, to allow for safe disassembly of any part of the system.

In some instances, it may be difficult to account for all possible scenarios in which the fuel line must be defueled. For example, if a component stops working it may isolate a section of the system from defueling capabilities. It may not be necessary or possible to design for every potential situation. The CSU team ran into such a situation during the year two competition of the EcoCAR 2 project. The solenoid valve in the main fuel line became stuck closed and stopped functioning during the competition. The defueling valve is downstream of the solenoid, so there was a section of fuel line between the solenoid and the tank outputs that could not be defueled to facilitate solenoid replacement. The downstream section was defueled in designed fashion and the master manual shutoff valve was closed, leaving a small portion of the system requiring defueling. The upstream fitting of the solenoid valve was loosened very slowly, and the small amount of trapped hydrogen was slowly released. This allowed the solenoid to be safely removed and the system to be reassembled.

B.6.2 System Assembly and Disassembly

To enable the installation and removal of the hydrogen storage tanks, all connections to the fuel cylinder need to be made with flexible tubing. With three different connections to each tank, attaching rigid tubing to each connection would be impossible. In the CSU system, all connections to the cylinders are made with ETFE tubing specially made for hydrogen service.

All other connections throughout the system are made with double ferrule compression fittings, JIC fittings, or pipe thread. Using these fittings allows all portions of the system to be easily disassembled and reassembled. It was determined during assembly and leak testing that it is much more difficult to achieve leak free connections with pipe threaded fittings, so it would be advisable to avoid these if possible.

B.7 Section Conclusion

The design of a high pressure hydrogen fueling system is a complex task. Hydrogen fueled vehicles have been designed and demonstrated by automotive companies and research groups, however, there exists no literature on the fueling systems of these vehicles. In order to create a system that will be functional and operate safely, there are numerous design considerations must be made. These include regulator effects, flow calculations, high pressure gas safety, flammable gas safety, overpressure mitigation, and system serviceability. As a part of the EcoCAR 2 competition, the CSU VIT designed and built an FCPHEV fueled by gaseous hydrogen. The system was designed using the considerations outlined in this section and provides a functional demonstration of the considerations in action.

C. FCPHEV PERFORMANCE ANALYSIS

C.1 Introduction

During the first stages of the EcoCAR 2 competition, the CSU VIT conducted a breadth of design experiments and established optimized architectural characteristics of an FCPHEV to achieve the highest score in the EcoCAR 2 competition. Simulations of a modeled FCPHEV were optimized to minimize energy consumption and emissions production while still meeting common consumer expectations for vehicle driving performance [26]. Based on these simulations, over Year One and Year Two of the EcoCAR 2 competition, the CSU VIT designed and integrated the FCPHEV architecture into the 2013 Chevrolet Malibu. The FCPHEV architecture demonstration built by the CSU VIT represents a potential alternative to conventional and hybrid petroleum vehicles. It is the first ever FCPHEV to function successfully and provide published operation data. This paper will provide analysis of the FCPHEV fuel cell system during vehicle operation in order to highlight the advantages the architecture can provide. For the analysis in this section, the data presented has been logged from the vehicle CAN bus during test track and on-road driving.

C.2 System Architecture

The H_2eV is an all-electric drive vehicle that uses a single electric motor for tractive force. A UQM Powerphase 145 kW electric motor and BorgWarner eGeardrive with 7.17:1 reduction are located in the bottom of the under-hood compartment. The motor can provide up to 400 N-m of torque and is limited to 8000 rpm.

The main power source for the vehicle is an 18.9 kWh/177 kW A123 7x15s3p battery pack. This battery pack is more than capable of meeting the maximum power requirements of the

UQM motor. The battery pack is located under the rear seats and protrudes into the passenger cabin where the rear middle seat would be in a stock 2013 Chevrolet Malibu. This battery placement requires a portion of the vehicle's unibody structure to be removed. A custom structural carbon fiber battery enclosure was manufactured to contain the battery pack and maintain the strength specifications from the stock vehicle. The battery pack is rechargeable through a BRUSA NLG 513 on-board charger. This charger uses the Society of Automotive Engineers (SAE) J1772 protocol and can provide up to 3.3 kW of DC power to the battery pack from either a Level 1 (120 VAC) or Level 2 (240 VAC) electric vehicle supply equipment (EVSE).

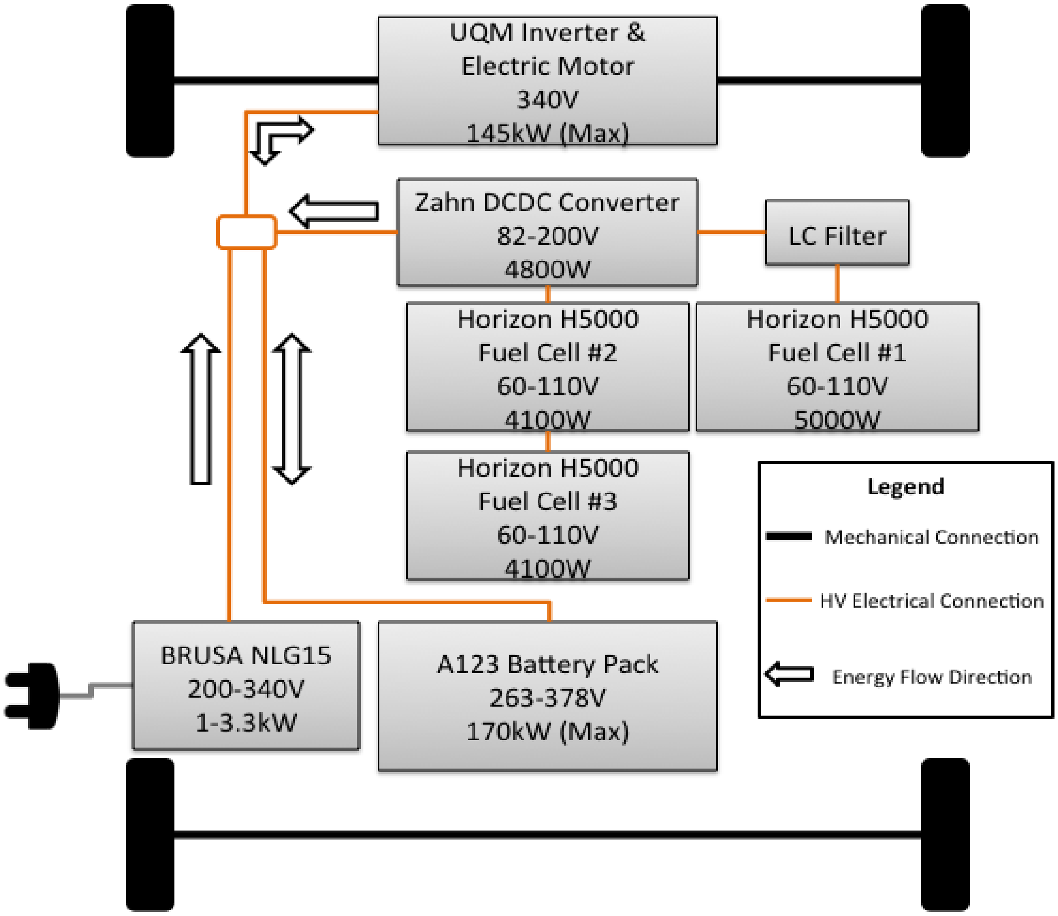

Figure 10. Diagram of the primary electrical energy connections and interactions of the H_2eV systems. The arrows symbolize the potential energy pathways during normal vehicle operation. Component sizing and locations are not to scale.

Using battery power alone, the range of the H_2eV would be limited to around 50 miles. To increasing drivable distance the fuel cell system provides the high voltage bus with supplemental power. Three Horizon H5000 fuel cells are used in the vehicle, which produce a maximum power of 5 kW each, for a potential output of 15 kW. The Horizon fuel cells are self-humidifying and self-cooling, and they use an ambient pressure cathode that requires minimal air handling. Air is pulled through the fuel cell stack via several 24 V fans. This results in low balance of plant losses. Another intriguing aspect of the Horizon fuel cells is that their highest efficiency operating point (~45%) corresponds closely to their highest output power operating point (~70A at ~72V). This means that the fuel cells can be commanded to output a large amount of power into the battery, while still maintaining high hydrogen conversion efficiency. As shown in energy flow diagram in Figure 10, a novel strategy is used to match the voltage of the fuel cells to that of the high voltage (HV) bus. One of the fuel cell stacks (fuel cell #1) is connected to a Zahn CH25090 DC/DC converter, and the output of the DC/DC converter is connected in series with the other two fuel cell stacks (fuel cells #2 and #3). During vehicle operation, the fuel cells are able to maintain a near-constant voltage and output current because the DC/DC converter regulates its voltage to match the fuel cell system voltage to the HV bus voltage. This configuration limits the fuel cell system operation from 15 kW to 8-13 kW (depending on battery voltage), but can achieve high efficiency energy transfer as the DC/DC converter losses (80-85% efficiency) are only applied to fuel cell #1. Unlike some FCV, this strategy does not require a custom high power, high voltage DC/DC converter, which greatly reduces vehicle build cost.

Gaseous hydrogen is stored on board the vehicle in Type III Dynetek storage cylinders. There are three cylinders located in the trunk of the vehicle and each store 1.65 kg of hydrogen at 5000 psi for a total of 4.95 kg. Hydrogen is delivered to the fuel cells through a custom hydrogen delivery system based off of SAE J2579 best practices. The system uses two-stage regulation to go from 5000 psi at the tank to 7 psi at the fuel cell inlet with the intermediate step at approximately 200 psi. The hydrogen tanks are filled according to the SAE J2601 standard, including the capability to perform communication fills.

C.3 Fuel Cell System Testing

In the following sections, data collected during H_2eV driving events will be presented and analyzed in order to show the operation of the fuel cell system. Data taken during the EcoCAR 2 competition and during additional on-road testing will be analyzed and demonstrated to show the capabilities and functionality of the H_2eV FCPHEV prototype.

C.3.1 EcoCAR 2 Competition Testing

The fuel cell system seen in Figure 10 was designed to operate at steady state, regardless of vehicle driving conditions as stated earlier. Any variation in the battery current due to driving loads will result in a change in voltage on the high voltage bus, and this voltage must be matched at all times by the output of the fuel cell system. The DC/DC converter has the ability to instantaneously handle these voltage changes, so the fuel cells are not required to dynamically change operation points with varied road load. The power output of the fuel cell system is controlled through a current request to the DC/DC converter. Theoretically, at any current request value, there will be a single equilibrium point of system operation (between battery voltage, fuel cell voltage, and DC/DC), and operation should be irrespective of vehicle driving conditions.

Due to the unconventional configuration of the CSU VIT’s fuel cells and DC/DC converter, it is important to test whether the configuration will work as designed. Initial testing at the EcoCAR 2 Year Two final competition proved the utility of the concept. Actual vehicle data collected from a portion of the EcoCAR 2 Emissions and Energy Consumption (E&EC) drive cycle can be seen in Figure 11. The E&EC drive cycle tested at the Year Two final competition encompassed heavy acceleration and high speed driving conditions. In essence, this drive cycle example shows the ability of the fuel cells to operate consistently during high intensity driving. Due to time constraints leading up to and during the competition, very little testing of the system was performed before the Year Two evaluation, so fuel cell operation and control strategy were not yet optimized. At the competition, a simple proportional control was used to ramp the DC/DC current request based on the voltages of the three fuel cells. If any of the three fuel cells fell below a minimum voltage, the controller would decrease the current request of the fuel cells to compensate accordingly. During the final competition, current of the fuel cell (fuel cell #1) loading the DC/DC converter was limited at 35 A within the controller to mitigate potential failures that may be observed under high load conditions.

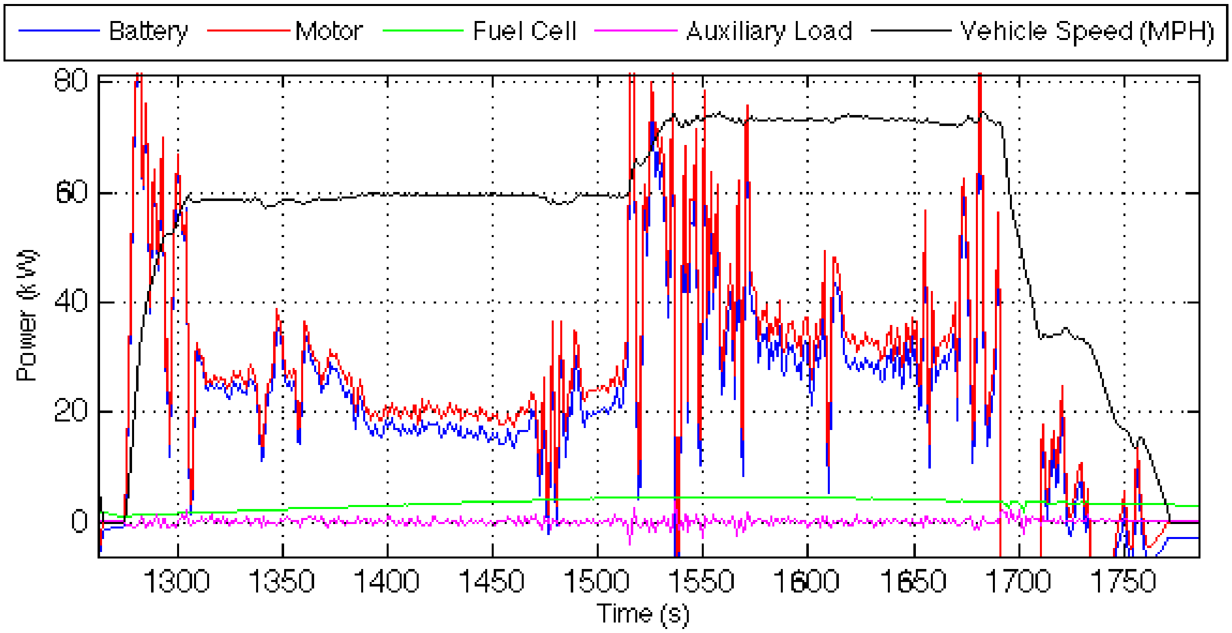

Figure 11. Portion of the E&EC drive cycle. Figure illustrates the constant output power of the fuel cells while the battery and motor fluctuate power in order to match the road loads of the vehicle.

Throughout the section of drive cycle in Figure 11, the operation of all three fuel cells is quite constant. The battery operation, however, is far from constant. The fluctuations observed in battery voltage are successfully isolated from the fuel cell operation. It can also be observed in Figure 11 that the battery power requirement is offset from the motor power by the fuel cells and auxiliary loads.

Figure 4 shows additional details (current and voltage) about the fuel cells' operation over same portion of the drive cycle (as in Figure 11). Through the acceleration and constant speed portions, the current produced by the fuel cells ramps up at the rate determined in the proportional controller. As the fuel cell voltage dropped to its minimum voltage set in the controller, the current request was decreased, this occurs in Figure 12 just prior to the 1600-second mark. The oversimplified proportional controller is unable to recover from this decrease, and never again reaches the current limit within this section of driving.

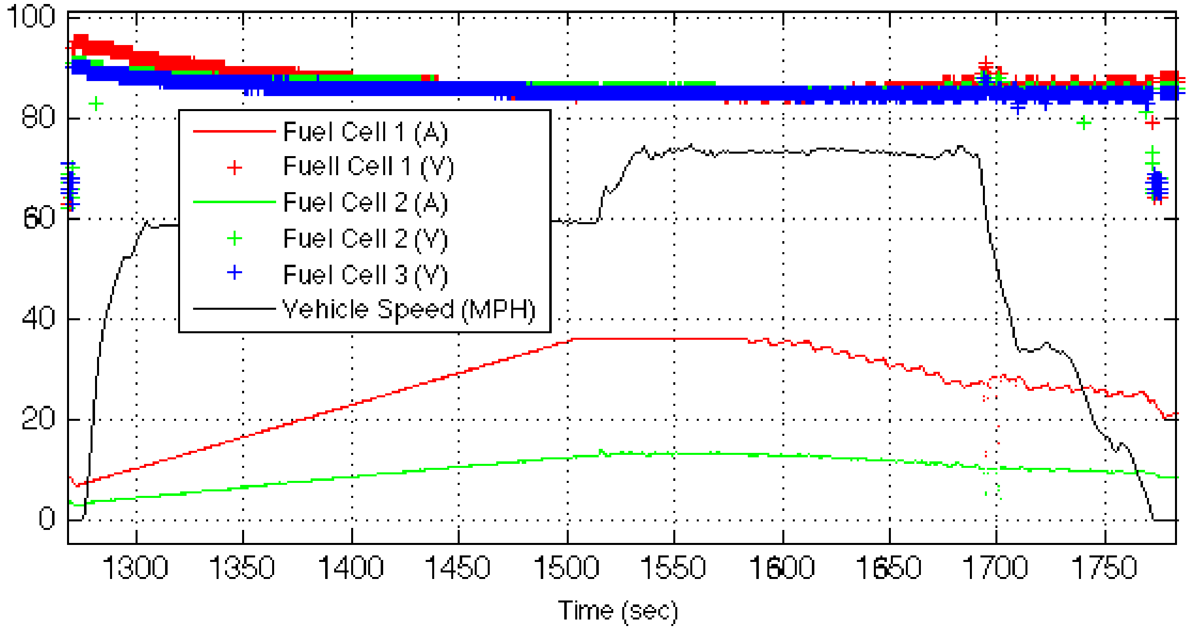

Figure 12. Plot of the fuel cells' voltage and current during a portion of the E&EC drive cycles.

As soon as the vehicle comes to a stop, the voltage of each fuel cell drops very low and the current decreases quickly as specified by the controller. Throughout the drive cycle, a similar pattern was observed. Fuel cell current was steadily increasing during driving and decreasing as soon as the vehicle stopped moving. It was determined that an error in the fuel cell controller was failing to turn on the fuel cell fans, so when the car was not moving, the fuel cells were not getting sufficient oxygen replacement.

As observed in this section, under high load driving conditions the H_2eV exhibits a blended charge depleting energy management strategy, as designed. The fuel cell system is able to provide a consistent power output that reduces the battery depletion rate, and therefore extends the total available zero emission driving range.

C.3.2 Additional On-Road Testing

The vehicle was driven around the CSU campus in the town of Fort Collins to further analyze the functionality of the FCPHEV architecture. The velocity profile of the on-road testing shown in Figure 13, is similar to the stop-and-go driving style of the urban dynamometer driving schedule (UDDS). Despite a lack of intensive acceleration during the drive cycle, this cycle does show the ability of the fuel cells to maintain their current and voltage during numerous driving conditions. During the E&EC testing at the final competition, the fuel cells were unable to maintain their energy output when the vehicle was stopped. The lack of air flow into the fuel cells while the vehicle was stopped affected the working health of the fuel cells. Therefore, the fuel cell fan speeds were increased for on-road testing, which pulled more air through the fuel cells while the vehicle was stopped and alleviated the issues seen during the E&EC testing. As with the E&EC drive cycle testing, the DCDC loaded fuel cell #1 was limited to an output current of 35A. This limited the current output of fuel cells #2 and #3 to 11-12A.

The fuel cells were allowed to ramp up to a steady state before driving. This was done to ensure that the behavior of the fuel cells at their maximum output could be analyzed. The fuel cells were able to output 4kW of power on average during the drive cycle.

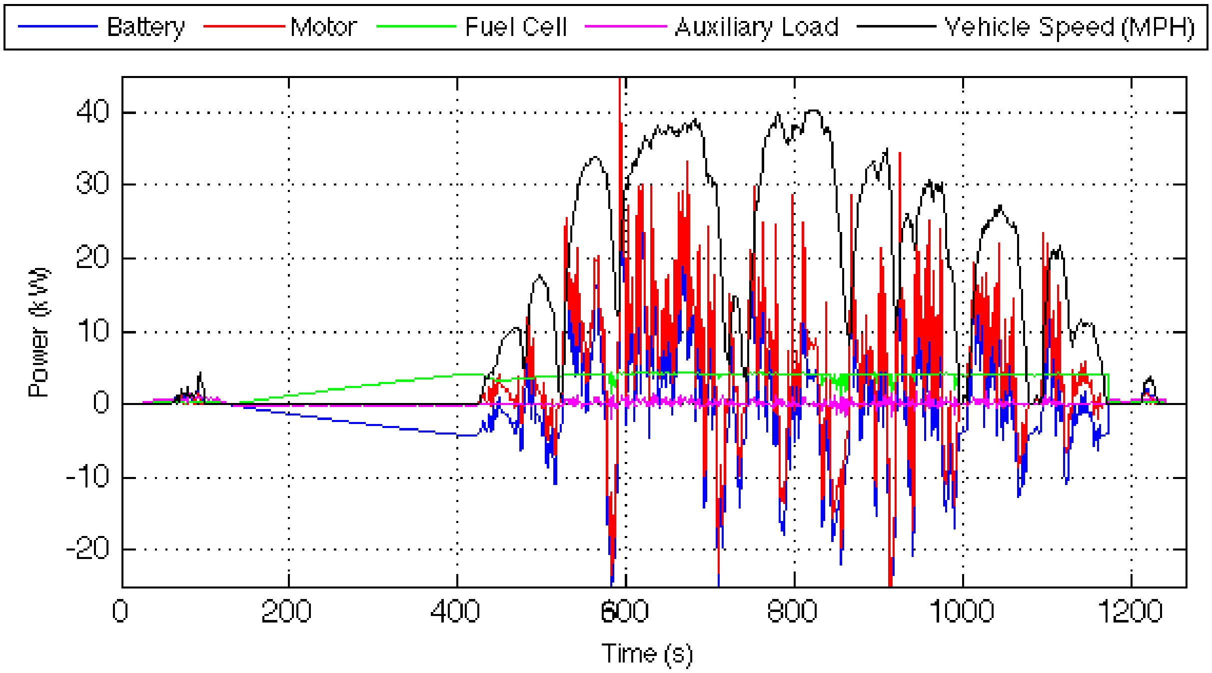

Figure 13. Instantaneous power of the battery, motor, and fuel cell systems over the course of the Fort Collins town drive cycle test.

Over the segment of the on-road testing in Figure 13, it can be seen that fuel cell systems maintains a 4kW output when the vehicle is accelerating and decelerating. Small fluctuation events are seen during the times when the vehicle is recharging the battery pack through regenerative braking. The influx of power from the motor into the battery subsequently increases the voltage of the high voltage bus. This causes a small rippling effect in the DCDC and fuel cell system voltage (+/- 4V) and power (+/- 1kW) output. However, the fuel cell system returns to steady state after the initial vehicle deceleration.

Figure 14 shows the integrated energy of the FCPHEV components over the same interval.

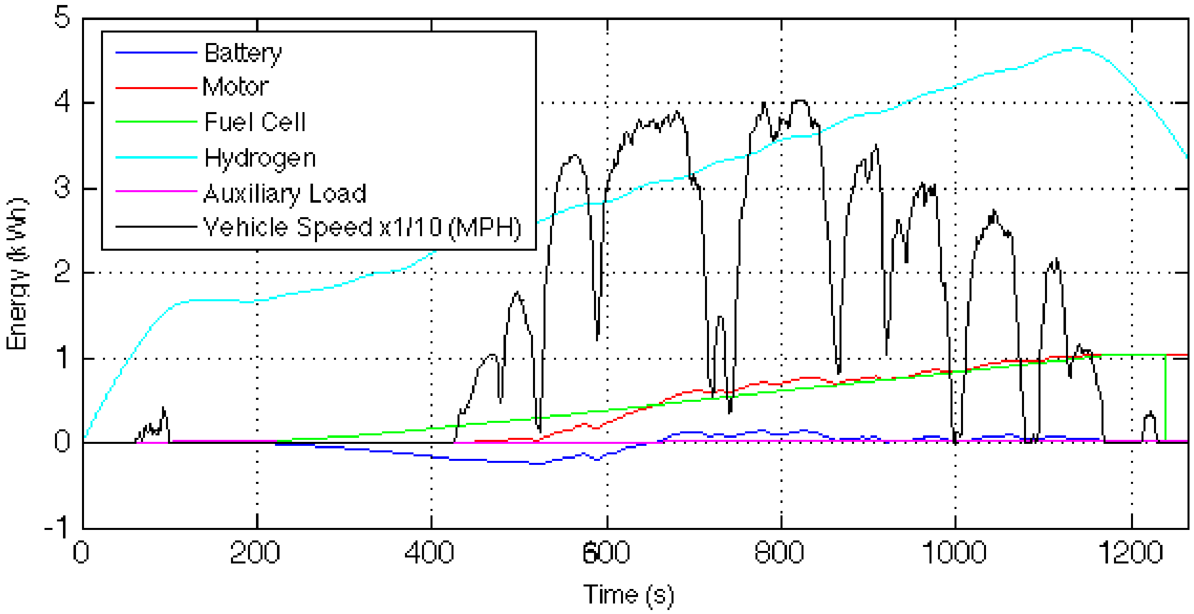

Figure 14. Total energy of the different FCPHEV systems including the battery, motor, fuel cells, and hydrogen chemical energy.

In addition to confirming the fuel cells are able to offset the battery energy during low intensity driving, it is important to analyze the operational characteristics of the fuel cells. As observed earlier, it is important to provide additional air to the fuel cells when the vehicle is traveling at low speeds, or when it is stopped. Figure 15 shows the operating points of each of the fuel cells during the CSU campus drive schedule. The black line represents the ideal operating line for all three fuel cells. This curve is based on data provided by the fuel cell manufacturer. Figure 7 shows that fuel cell #1 was successfully limited to 35A as requested by the controller, and that it followed the ideal operating line. However, while the other two fuel cells were limited to 11-12A, they are still operating below the ideal operation line. The discrepancy between the operation of fuel cells #1 and #2 and ideal operation may be attributed to insufficient airflow.

The fuel cells are placed in the H_2eV such that fuel cell #1 receives air through the front grill, and this air subsequently travels through fuel cell #2 and then fuel cell #3. In this way, the amount of oxygen received by fuel cells #2 and #3 may be less than sufficient to operate along the ideal line. A similar issue was seen in earlier testing at the EcoCAR 2 competition. Recall from Figure 12 that during E&EC testing, all of the fuel cells were operating at approximately 85V, much lower than the operation seen in Figure 15 during similar loading conditions. The ~10V difference in operating points between the two driving tests may be attributed to air flow, as there were issues with fuel cell fan operation during E&EC testing. The air being provided by the fans in the second test allows the fuel cells to operate in a healthier region, especially fuel cell #1. Fuel cell #1 is being supplied with the most air of the three fuel cells, and is operating along its ideal operating line. Thus, if more air is provided to fuel cells #2 and #3, it is predicted that their operational patterns will more closely follow that of fuel cell #1.

The multiple operating points that fall far below the ideal operating line for all three fuel cells in Figure 15 occur when the vehicle is performing regenerative braking. Potential solutions for this issue are being investigated and will be evaluated through future testing.

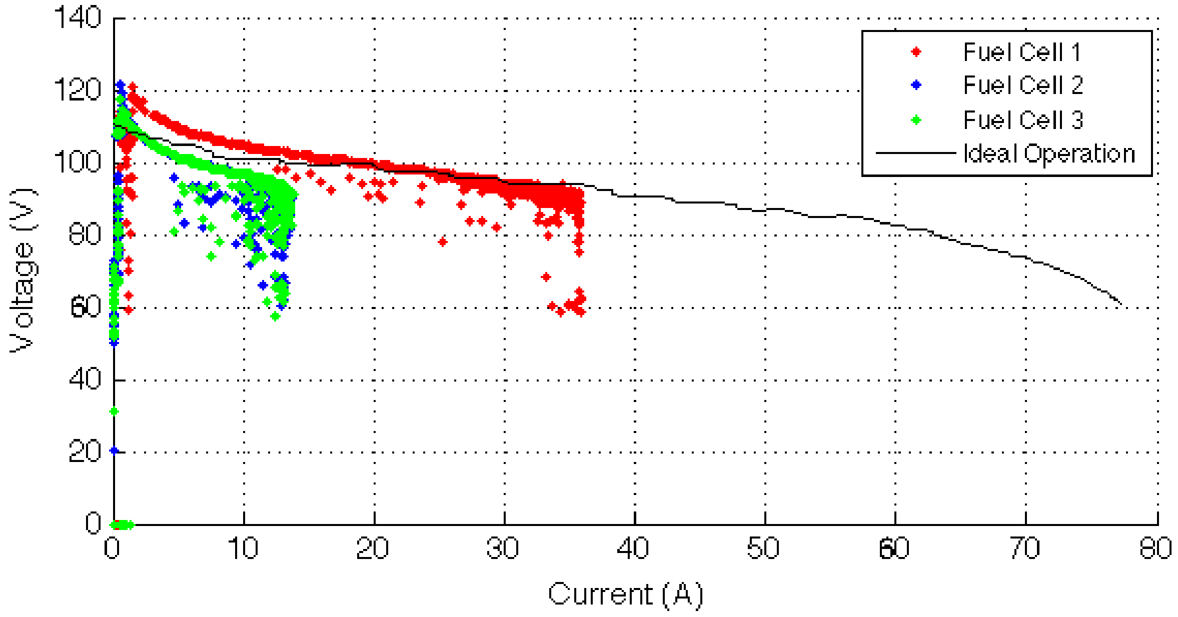

Figure 15. Plot of the operational points of all three fuel cells in the H_2eV during the Fort Collins town drive cycle. The fuel cell numbers correspond to their configuration from Figure 10.

To further prove the utility of the range extending operation of the fuel cells, the amount of energy used, or produced, by each of the major drivetrain components of the H_2eV FCERV were analyzed. Over the driving portion of the on-road testing in Fort Collins (429-1173 seconds) the motor consumed an average of 220 Wh/mi of electrical energy. This is approximately the amount of energy needed to overcome the road loads of the vehicle during the driving test. During this time span, the battery only depleted 8 Wh/mi of electrical energy, while the fuel cells produced 212 Wh/mi of electrical energy. These numbers validate the ability of the fuel cells to provide enough energy to the battery during low intensity driving to maintain the battery's SOC. Over the driving portion of this test 2.3 kWh of hydrogen gas was converted by the fuel cells to produce 0.83 kWh of electrical energy. This equates to 35.9% conversion efficiency, which rivals the maximum efficiencies of many internal combustion engines.

C.4 Section Conclusion

The H_2eV FCPHEV designed and built by the CSU VIT for the EcoCAR 2 competition has been successfully demonstrated. This demonstration has provided data highlighting the advantages FCPHEVs can provide over more traditional alternatively fueled vehicles. Significant downsizing of the fuel cell system and a novel approach to DC/DC converter integration have shown as-designed operating characteristics and provide an opportunity to greatly decrease production cost as compared to current fuel cell vehicles. It was demonstrated during both high load and low load testing that the fuel cell and DC/DC converter combination was able to match voltage of the battery, while still allowing the fuel cells to efficiently operate at constant power output. Through testing and refinement the H_2eV is expected to further highlight the many advantages possible for personal transportation from hydrogen fuel cell plug-in hybrid vehicles.

CONCLUSION

The fuel cell plug-in hybrid electric vehicle is one that has shown promise as a way to decrease petroleum use and emissions of the personal transportation sector. FCPHEVs would be zero emissions vehicles, just like BEVs and FCVs, but without the range limitations of BEVs or the lifetime issues of current FCVs. It is believed that the FCPHEV could be a stepping stone from current BEVs to the FCVs of the future, allowing time for hydrogen infrastructure to become more available. FCPHEV literature is relatively scarce, so this thesis provided information and analysis regarding their use, design, and performance in order to advance the knowledge in the state of the field.

Consumer driving and charging habits of plug-in hybrid electric vehicles from the EV Project, a large scale data collection effort, were compared to the current SAE J2841 UF model which uses assumptions made prior to PHEV data availability. It was determined that the current method substantially underestimated the utility of current PHEVs due to differences between real data and the assumed values of daily driving distance, charging frequency, and charge depleting range. These differences are notable due to the fact that J2841 is used to determine EPA fuel economy of PHEVs and is a decision making tool for automakers looking to build advanced vehicles, both of which have extremely high monetary implications. For this reason, further action should be taken to refine the UF method in order to better represent PHEV usage.

The design considerations for an on-board hydrogen storage system for a hydrogen fueled vehicle were detailed and an example was provided using the CSU FCPHEV built for the EcoCAR 2 competition. All of the functional and safety considerations required for a safe, reliable system were specified.

During the EcoCAR 2 project, the FCPHEV built by CSU provided real-world driving data. This data showed the advantages of the FCPHEV over other ZEVs and proved the FCPHEV concept. The downsized fuel cell was able to provide constant power to the battery pack, offsetting the required battery power in order to increase the battery range. This will reduce cost when compared to current FCVs and eliminate fuel cell lifetime issues due to dynamic operation.

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