THESIS

CASE STUDY OF THE REAL WORLD INTEGRATION OF FUEL CELL PLUG-IN HYBRID ELECTRIC VEHICLES AND THEIR EFFECT ON HYDROGEN REFUELING LOCATIONS IN THE PUGET SOUND REGION

Submitted by

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ABSTRACT

CASE STUDY OF THE REAL WORLD INTEGRATION OF FUEL CELL PLUG-IN HYBRID ELECTRIC VEHICLES AND THEIR EFFECT ON HYDROGEN REFUELING LOCATIONS IN THE PUGET SOUND REGION

The personal vehicle transportation fleet relies heavily on non-renewable and pollutive sources of fuel, such as petroleum. However, with harsher restrictions from the Environmental Protection Agency's (EPA) Corporate Average Fuel Economy (CAFE) and California Air Resource Board's (CARB) Zero Emission Vehicle (ZEV) standards coupled with growing sales for alternative fueled vehicles, the automotive industry has begun to shift toward more renewable and clean sources of energy to power vehicles. The fuel cell plug-in hybrid electric vehicle (FCPHEV) architecture provides a unique and promising solution to decreasing the dependence of vehicles on petroleum and decreasing the amount of pollution emitted from tailpipes.

Until recently, the FCPHEV architecture had only been developed in concept cars and paper studies. However, recent studies have confirmed the capability of the FCPHEV concept in terms of its economics, environmental benefits, and real-world viability.

From this concept it becomes important to understand how daily commuters will benefit from driving a FCPHEV using real world driving data. Through the use of geographic information system (GIS) data of vehicle travel in the Puget Sound area from the National Renewable Energy Laboratory (NREL) a model of electrical and hydrogen energy consumption of a fleet of FCPHEVs can be constructed. This model can be modified to model the driving, charging and fueling habits of drivers using four different all-electric driving ranges, and using either a normal plug-in hybrid control strategy or a control strategy that focuses on highway fuel cell operation. These comparisons are used to analyze the driving habits of daily commuters while using a FCPHEV, and the effect of the FCPHEV architecture on the location of hydrogen refueling.

The results of this thesis help to define FCPHEV energy management strategies and show that the FCPHEV architecture can concentrate the location of hydrogen refueling to predictable areas and aid in the development of the hydrogen refueling infrastructure.

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1.0 INTRODUCTION

As of 2011, the transportation section of the United States was consuming 28% of the nation's energy. Of this energy consumed, 93% came from petroleum while only 3% came from renewable sources as shown in Figure 1. This is in large part due to a light-duty personal transportation vehicle fleet that averaged 23.5MPG as of 2011 [1]. However, changes in the automotive industry are visible in the growing popularity and acceptance of alternative energy vehicles. From December 2010 to April 2014 198,030 plug-in electric vehicles (PEV) have been sold in the United States. Each year since 2011 has seen greater sales than the year before it, demonstrating the growing popularity of alternative fuel vehicles in the United States [4].

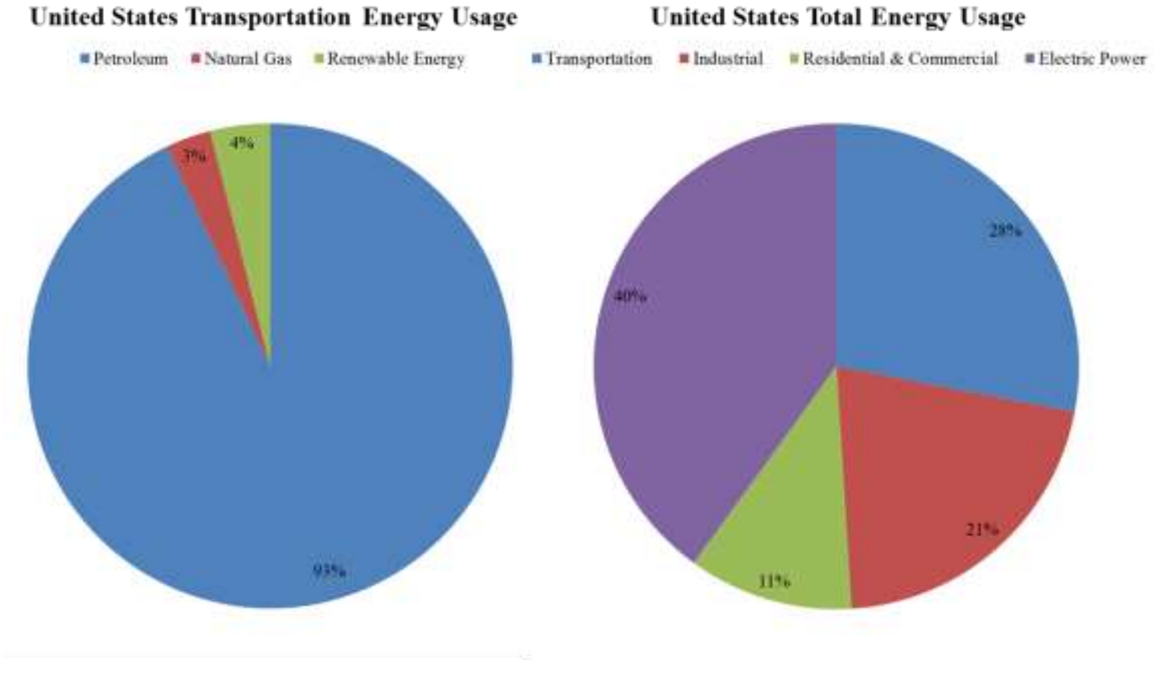

Figure 1 Energy sources used by the transportation sector in comparison to the energy consumed by other sectors of the United States.

With the combination of vehicle efficiency standards set by the Environmental Protection Agency's (EPA) Corporate Average Fuel Economy (CAFE) and California Air Resource

Board's (CARB) Zero Emission Vehicle (ZEV) protocols and the rising sales in PEV, the automotive industry has been developing new vehicle architectures to reduce both fuel consumption and emissions production to meet regulations and consumer demand [2][3][4]. The CAFE standard was developed in conjunction between the EPA and the Department of Transportation's (DOT) National Highway Traffic Safety Administration (NHTSA). The overall goals of these policies are to reduce oil consumption while addressing the risks of global climate change. By model year (MY) 2021, the CAFE standard dictates that the average fuel economy (FE) of the automotive original equipment manufacturers' (OEM) vehicle fleet must be 40.3-41MPG. According to their studies, the fuel savings garnished from a more efficient vehicle fleet will outweigh higher initial vehicle costs with a country wide fuel savings between $326 billion to $451 billion [2]. Legislation to reduce criteria pollutants such as nitrous oxides (NO_x), carbon monoxide (CO), and particulate matter (PM) has been led by CARB since its establishment in 1967. The purpose of their ZEV standard is to severely decrease the amount of harmful chemicals that emit from vehicle tailpipes. The ZEV requirement established by CARB states that automotive OEMs are to have a minimum of 16% of their transportation fleet as ZEVs by 2018 [3].

In order to meet the regulations being created by groups such as the EPA and CARB, the automotive industry has begun to design vehicle architectures that utilize alternative sources of energy. A hybrid electric vehicle (HEV) utilizes a combination of fuel and electrical energy sources to power the car while driving, as shown via a block diagram in Figure 2. The fuel energy originates from an internal combustion engine (ICE), while the electric energy flows from an electrochemical battery pack. More recently the automotive industry has been producing vehicle architectures that can utilize the more efficient and lower cost electrical energy from the electric grid. A plug-in hybrid electric vehicle (PHEV) uses both a fuel and electrical energy source much like the HEV architecture, outlined in Figure 2 [5].

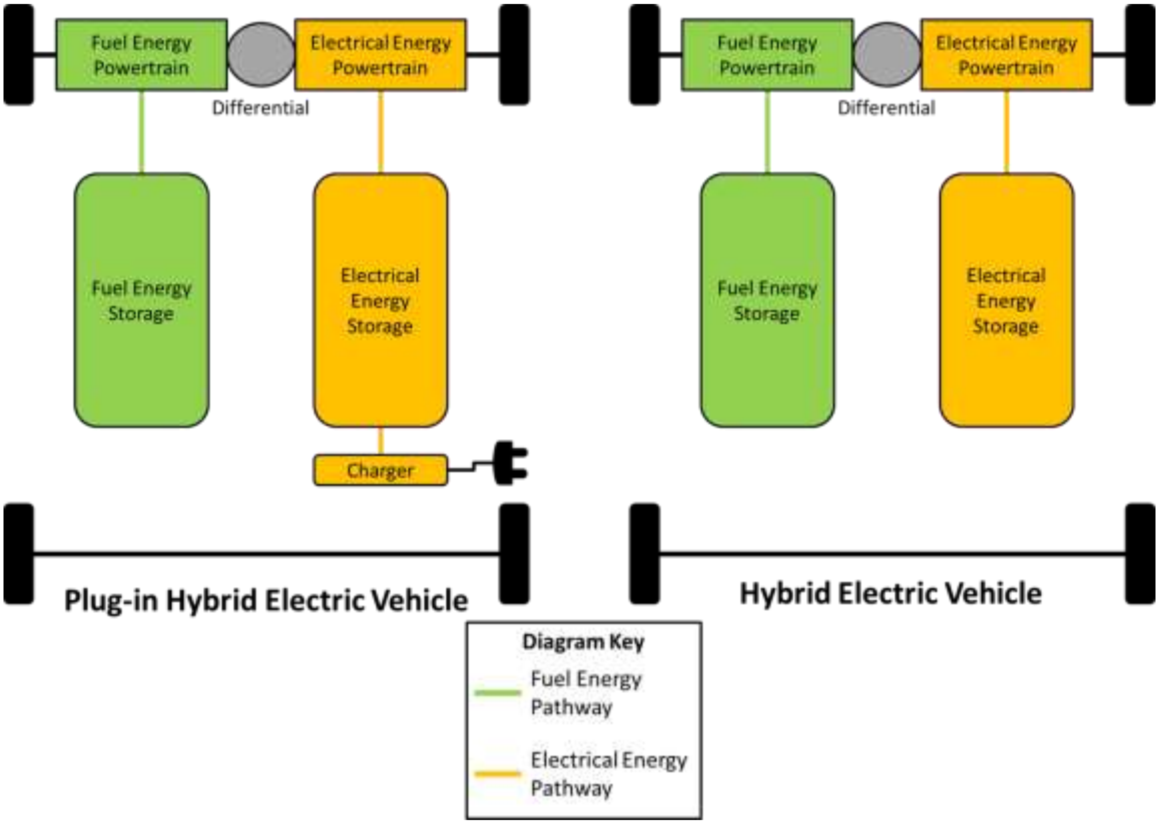

Figure 2 Example block diagrams of the Plug-in Hybrid Electric Vehicle and the Charge Sustaining Hybrid Electric Vehicle.

However, the PHEV is able to draw energy from the electrical grid through an onboard charger to recharge the electrochemical battery pack. The ability to recharge the battery pack allows the PHEV to drive a limited distance using energy only from electrochemical stored energy. This driving mode is known as an all-electric mode or charge depleting (CD) mode. In this driving mode the battery's state of charge (SOC) decreases over the driving distance as only electrical energy is used by the vehicle to power the wheels. The SOC of the battery is the remaining working capacity of the battery, which is commonly expressed as a percent of the maximum usable battery pack energy. Once the battery of the PHEV reaches a predetermined

SOC it will switch over to a charge sustaining (CS) driving mode for the rest of the drive. During CS mode, fuel energy maintains the SOC of the battery until the battery pack is recharged using electric energy from the grid. By utilizing first the electrical energy from the battery pack a PHEV is able to act as a ZEV for a set distance, thus decreasing the amount of fuel consumed and emissions produced on average by the vehicle over its lifetime [5]. In contrast, a conventional HEV operates only in the CS mode. Depending upon the architecture of the HEV, the fuel energy will either maintain the SOC of the battery or it will provide the bulk of the power to the wheels while utilizing energy form the battery pack and motor when more power is needed or to run more efficiently. In CS mode, the SOC of the battery is controlled such that it remains charge neutral during the driving time. The HEV architecture provides fuel savings and reduced emission compared to a conventional ICE vehicle, but doesn't provide the same savings as a PHEV [5].

1.1 Present State of Hydrogen Powered Vehicles

An alternative fuel that has been proposed as a possible solution to reducing vehicle emissions and oil consumption is hydrogen gas (H_2). The hydrogen fueled vehicle architectures being researched by government agencies, universities, and the automotive OEMs include conventional hydrogen ICEs, hydrogen fuel cell vehicles (FCV), and fuel cell plug-in hybrid electric vehicles (FCPHEV) [6]. Hydrogen has been used as an ICE fuel because of its wide flammability range, low ignition energy, and high flame speeds even at stoichiometric ratios [7]. Hydrogen ICEs tend to operate at lower in-cylinder temperatures, thus decreasing emission of temperature based pollutants such as NO_x. However, hydrogen combustion engines have troubles with premature ignition due to its low ignition energy, thus decreasing the efficiency of the engine. Automotive OEMs have not seriously researched the hydrogen ICE vehicle architecture since the early 2000s, but instead have switched to natural gas combustion vehicles because they provide similar fuel and emissions saving with a vastly superior fueling infrastructure [7]. In contrast to hydrogen combustion vehicles, FCVs emit zero operational pollutants because the fuel cells utilize a chemical reaction to generate electricity where the only exhaust from the process is water (H_2O). There are numerous types of fuel cells that utilize different electrolytes to produce electrical energy. For example, Figure 3 shows a diagram of a proton exchange member (PEM) fuel cell. A PEM fuel cell uses a thin polymer sheet as the electrolyte between the anode and cathode, as shown in the fuel cell diagram. First pressurized hydrogen gas (H_2) flows into the anode of the fuel cell where the electron (e^-) is stripped from the atom, ionizing the hydrogen atom. Then the direct current (DC) provided by the separated electrons travels across a load back toward the cathode. Next either pressurized or ambient oxygen is fed into the cathode where it finally combines with the hydrogen ion and electron to form water as the exhaust.

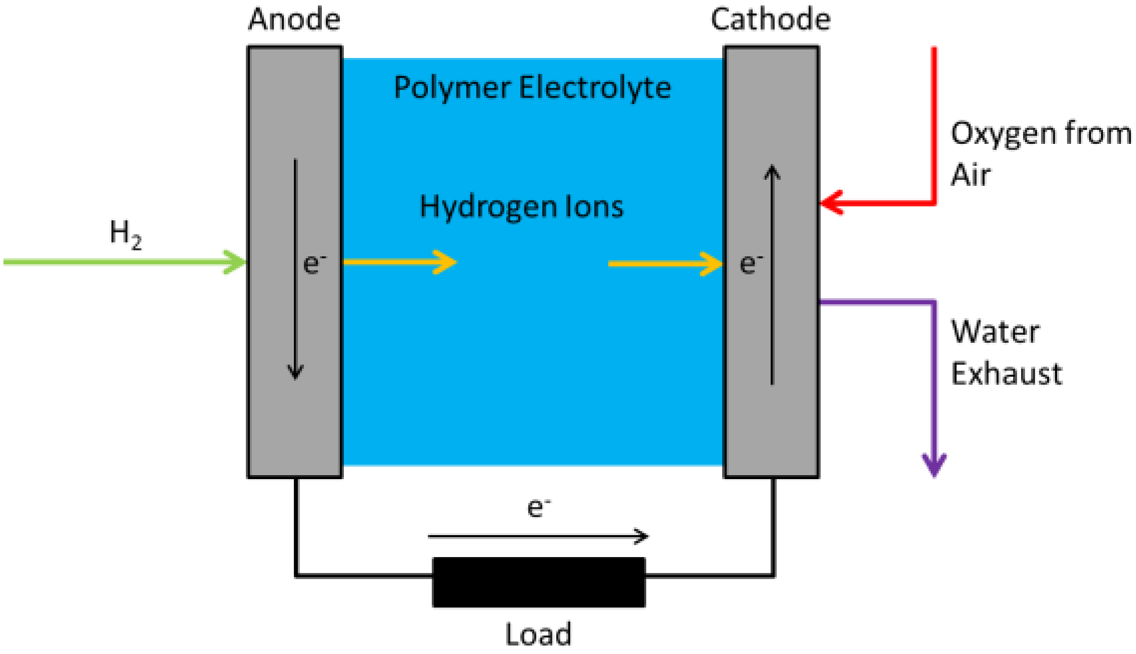

Figure 3 Diagram of an example proton exchange membrane fuel cell.

Because water is the only emission produced by the fuel cell's chemical process, FCVs are considered ZEVs because they don't produce any criteria pollutants while driving. The zero emission capabilities of FCVs have pushed numerous automakers within the last decade to begin producing their own fuel cell powered vehicles. General Motors (GM) converted 119 Chevrolet Equinox to FCVs in 2007. These FCVs were only built as demonstration vehicles, but as a whole they have been driven nearly three million miles to date with an estimated fuel savings of $552,631 [8]. Starting in 2008, Honda allowed limited three year leases of their FCX Clarity FCV with only a handful of Claritys on the road at any given time. As with the Equinox, Honda only released the Clarity as demonstration vehicle with no plans for commercialization [9]. These early FCV demonstrations were limited in their exposure to the public as neither GM nor Honda intended to fully commercialize the vehicles. However, in the last year automakers such as Toyota, Honda, and Hyundai have begun to develop and demonstrate concept FCVs at auto shows across the United States. The difference between the Toyota FCV, Honda FCEV, and Hyundai Tucson FCEV and earlier fuel cell demonstration vehicles is that these vehicles are being designed with large scale production in mind. All three of these vehicles will be available starting in 2015 [10][11][12]. The demonstration of these vehicles indicates that the automotive industry is slowly adopting the FCV architecture to adhere to the regulatory standards and provide fuel cost savings to potential customers.

There are a few potential reasons for the shift toward fuel cell powered vehicles by the automotive industry. The United States Department of Energy's (DOE) Fuel Cells Technologies Office (FCTO) has installed incentives to help FCVs become more competitive with conventional petroleum powered vehicles. The goal of some of the DOE's targets is to decrease the production cost of FCVs by decreasing the production costs of the fuel cell system [6][16].

The cost of fuel cell systems per kW in Figure 4 shows that the DOE has set a production cost target of 30$/kW by the year 2015. A study conducted by the National Renewable Energy Laboratory (NREL) in 2005 analyzed that the cost of producing the entire fuel cell system, which includes the fuel cell stacks and balance of plant components such as pumps or blowers, was 67$/kW [15]. However, as shown in Figure 4, production costs published by fuel cells companies Directed Technology Inc. and Ballard Power Systems show varying results of cost reduction in comparison with the findings of the NREL study. The published data from these two companies show that production costs are trending lower each year. Directed Technology Inc. has reported a 93% decrease in costs from 2002-2011, while Ballard Power Systems reported a 42% decrease in costs from 2002-2005 [13][14]. The reduction in costs of the fuel cell system is sensitive to larger production numbers, increases in energy density of the stacks, decreases in weight of the stacks, and prices of raw materials such as platinum [6][13][15][17].

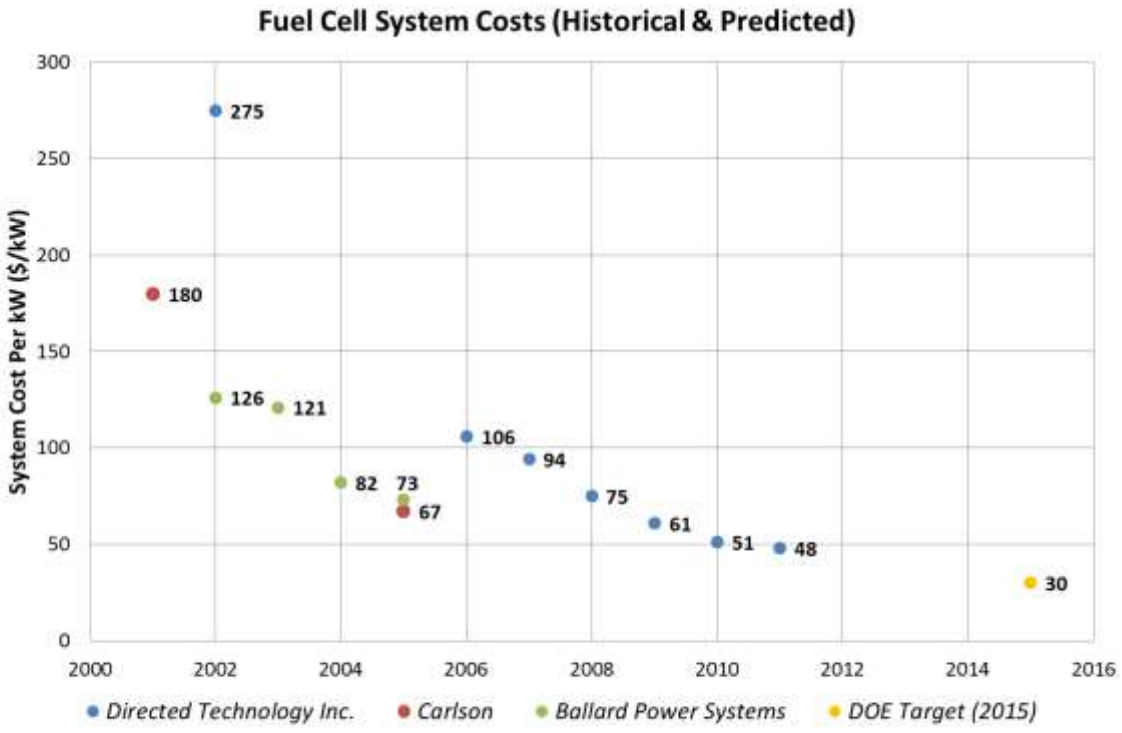

Figure 4 Fuel cell stack costs that have been demonstrated by government studies [15], published by fuel cell production companies [13][14], and the 2015 targets set by the DOE [16].

The decreasing production costs of the fuel cell systems has allowed FCVs to become more competitive with conventional vehicles (CV) than they have at any other time in the last two decades.

1.2 Present State of the Hydrogen Refueling Infrastructure

A major sticking point in the adoption of hydrogen powered vehicles into the personal transportation fleet has always been the lack of a sufficiently sized hydrogen refueling infrastructure [6][30]. The problem inherent with the growth of alternative fueling stations, such as hydrogen stations, is the cause of said growth. Research has tried to determine whether it is the initial integration of an alternative fuel infrastructure that increases the penetration of alternative fueled vehicles into the market, or whether it is alternative fueled vehicles that create the demand for increased implementation of alternative refueling infrastructure [18]. No matter the arguments of this chicken or the egg debate, according to the United States DOE there are currently only 10 publicly available hydrogen refueling stations. All of these stations are located in either California or South Carolina [19].

Along with developing new FCVs, some automakers are also working on developing and expanding hydrogen refueling infrastructures across the world. The automaker Daimler, in collaboration with six other companies, has plans to expand the hydrogen infrastructure of Germany from its present state of 17 stations to 100 stations by 2017 and to 400 stations by 2023. The new infrastructure plan, termed the H_2 Mobility Plan, is going to locate stations across the major cities of Germany, and add stations along the major highways no further than 56mi apart. It is estimated that the 400 stations to be built by 2023 will cost $474 million [20]. Toyota has begun research into combing hydrogen refueling into urban planning. Their experimental hydrogen refueling station in Toyota City, Japan is an example of the types of station Toyota wishes to release with the development of their own FCVs [21]. While some of the major automakers are presently researching and developing the hydrogen infrastructure necessary to sustain their production of FCVs, infrastructure research is being led by government labs and academia to determine the optimal hydrogen infrastructure to support substantial penetration of hydrogen powered vehicles into the personal transportation fleet while minimizing the costs of building the said infrastructure.

The cost of installing a sufficient hydrogen refueling infrastructure is a large stumbling block in the growth of hydrogen refueling station across the country. NREL conducted a study in 2013 to estimate the cost of installing different sized hydrogen stations over the next 5 to 10 years. The study analyzed hydrogen fueling stations of different capacities that they predicted would enter into the market at different points between the present and the year 2016, as shown in Table 1. The model developed by NREL assumed that cost reductions would occur over the coming years due in large part to gained experience from increased hydrogen station installations and decreased production costs because of higher production levels. The capital cost results show that by increasing the capacity/size of the hydrogen station the cost of its construction and installation increases. However, when looking at the results based on the capital cost per station fueling capacity it can be seen that there are large reductions in cost starting with early commercial stations in 2014-2016. By the time hydrogen stations are installed with greater fueling capacities (600kg/d and 1500kg/d versus 160kg/d) there is a 69-80% reduction in capital costs per unit of station capacity. The NREL study determines that while current hydrogen refueling station costs are larger, there is a higher probability that these prices begin to trend downward in the near future [22]. As seen by the calculated daily average hydrogen fueling output and station utilization rate, the returns of a hydrogen station relies heavily upon locating the station in the area of greatest access to drivers.

Table 1 Hydrogen station fueling capacity, utilization rate, average daily output, and capital costs estimated by the NREL hydrogen station study [22].

Station Type	***Present Day (2012)***	***Early Commercial (2014-2016)***	***Greater Volume Commercial (after 2016)***	***Large Commercial Station (after 2016)***
Hydrogen Fueling Capacity (kg/day)	160	450	600	1500
Station Utilization Rate (%)	57	74	76	80
Calculated Average Output (kg/day)	91	333	456	1200
Total Capital Cost Per Station ($Million)	2.65	2.8	3.09	5.05
Capital Cost per Capacity ($1000 per kg/d)	16.57	6.22	5.15	3.37
Percent Reduction from Present Day (%)	N/A	62	69	80

Academic research has analyzed the optimal ways to determine the placement of hydrogen refueling stations to accommodate as much of the population as possible. Whether on a national, state, or regional level, academic studies have used optimization methods such as dynamic programming (DP) or mixed integer linear programming (MILP) to optimize the placement of hydrogen stations [23][24]. A majority of the research into optimizing the hydrogen infrastructure incorporates analyzing the entire hydrogen supply chain (HSC) when optimizing station placement. The HSC analyses encompass the economic analysis of the hydrogen production facilities, feedstock, storage costs, distribution chains, and refilling stations [23][24]. These detailed HSC models are good at optimizing both the hydrogen demand and supply within the given system boundaries. However, according to Agnolluci et al. these models are unable to accurately represent the behavioral dynamics of the transportation market within the bounded system, and are unable to spatially represent the hydrogen infrastructure below the national level [23].

In order to determine an ideal hydrogen infrastructure at a regional level, researchers have utilized spatial data sets [24]. Spatial data allows researchers to use the physical geometry of towns, cities, and states to construct hydrogen refueling locations. Known as the geographical information system (GIS) approach, the spatial approach allows researchers to use the area's transportation network, population density, and other characteristics of the region to determine hydrogen station locations [24]. Melendez et al. of NREL used the GIS approach to determine the consumer demand for hydrogen in several cities and regions including Denver, Salt Lake City, Chicago, and other larger metropolitan areas. Regional consumer demand for hydrogen was based on weighting different influencing factors such as household income, air quality, commute distance, registered hybrid vehicles, and several other topics. These attributes were each weighted and ranked based on the opinions of members of NREL with expertise in advanced technology vehicle deployment. Once the demand for hydrogen was calculated using the weighted factors listed above, hydrogen stations were placed using spatial data sets. The stations were strategically placed to be within 1mi of major retail shopping centers, within areas of greater estimated hydrogen demand, along major roads with high traffic, and near proposed interstate hydrogen stations such that the stations provided a wide coverage to the region's population [25]. The proposed hydrogen locations for the cities analyzed by this study had roughly 90-99% of the region's population within 10mi of a hydrogen station. However, while the study predicts the location of hydrogen stations that best fit the need of the population using socioeconomic and demographic metrics, the study does not incorporate vehicle driving or refueling behavior besides locating areas of high traffic [25]. The Institute of Transportation Studies (ITS) at the University of California Davis (UC Davis) conducted a similar study to determine the spatial demand for hydrogen in the state of Ohio. The study used US census data from the year 2000 to predict the hydrogen demand of the Ohio region in 2030. Using population growth, density, and income the study created various clusters of hydrogen demand similar to the regional demand calculated by the NREL study. The study used an estimated vehicle hydrogen use (0.6kg H_2/day/vehicle) and fuel economy (65 miles/kg) to help determine the density of hydrogen demand [26]. Using the estimated hydrogen use, population statistics, and varying values of hydrogen vehicle market penetration, the study estimated geographically specific demand clusters (kg H_2/day consumed) in Ohio and placed "hydrogen demand centers" to cover the higher density areas. The results of the ITS study indicated that at varying FCV market penetrations and demand center locations, anywhere between 47% and 74% of the hydrogen demand of Ohio could be covered [26]. Both the NREL and ITS studies are examples of population and socioeconomic characteristics being used to determine the appropriate size of hydrogen refueling infrastructure.

In their analysis on the refueling behavior of California drivers, Kitamura et al. determined it was vehicle travel characteristics like refueling location, price, work related trip, and home related trip that determined the locations where drivers consistently refueled their vehicles. The analysis of their survey suggested that drivers were more accustomed to repeatable refuelings at gasoline stations along their daily commute between home and work. They determined that neither socioeconomic nor demographic characteristics had a large correlation with driver refueling behavior. Instead, vehicle usage provided the greatest insight into understanding the refueling behavior of everyday drivers [18]. Further academic research by the ITS supports the conclusions of Kitamura et al. By analyzing different specifications to help shape future alternative fueling infrastructures, the ITS determined that a consumer’s demand for refueling was based on distance traveled on various daily trips or commutes [28][29]. In fact, analysis of the gasoline refueling patterns of Sacramento, California showed that nearly 51% of all fuel pumped at gas stations were within 1km (0.62mi) of a highway. The ITS concluded that more refueling demand occurs between the house and freeway than any other trip route, and that initial alternative fueling stations could capture large portions of the driving population at the entrances of highways [29]. These studies provide an example of vehicle behavior/development driving the integration and placement of alternative fuel infrastructures.

1.3 Review of FCPHEV Research and Architecture

FCPHEVs are one of the hydrogen fueled vehicle architectures being researched by government agencies, universities, and the automotive industry as a potential solution to meet the strict FE and emissions standards. In 2010, the Electric Power Research Institute (EPRI) conducted a study to determine the practicality of implementing FCPHEVs in comparison to battery electric vehicles (BEV), FCVs, and conventional petroleum fueled PHEVs. FCPHEVs provide an advantageous combination of hydrogen fuel cells and energy from the electrical grid to power the vehicle. The power supplied by the fuel cells help eliminate any range limitations associated with just using a battery pack to power the vehicle, and as mentioned in the previous section the fuel cells produce zero emissions maintaining the FCPHEV as a ZEV [30]. An example block diagram of the FCPHEV architecture can be seen in Figure 5. The figure shows that the electrical energy of the fuel cells is sent to the battery pack to either maintain the SOC of the battery, or help extend the range of the vehicle while driving depending on the control strategy of the vehicle. Unlike a petroleum based PHEV, the fuel cell generator does not require an additional electric motor/generator unit to convert the fuel energy to electrical energy. This helps cut the cost and weight of the FCPHEV in comparison to the conventional petroleum fueled PHEV.

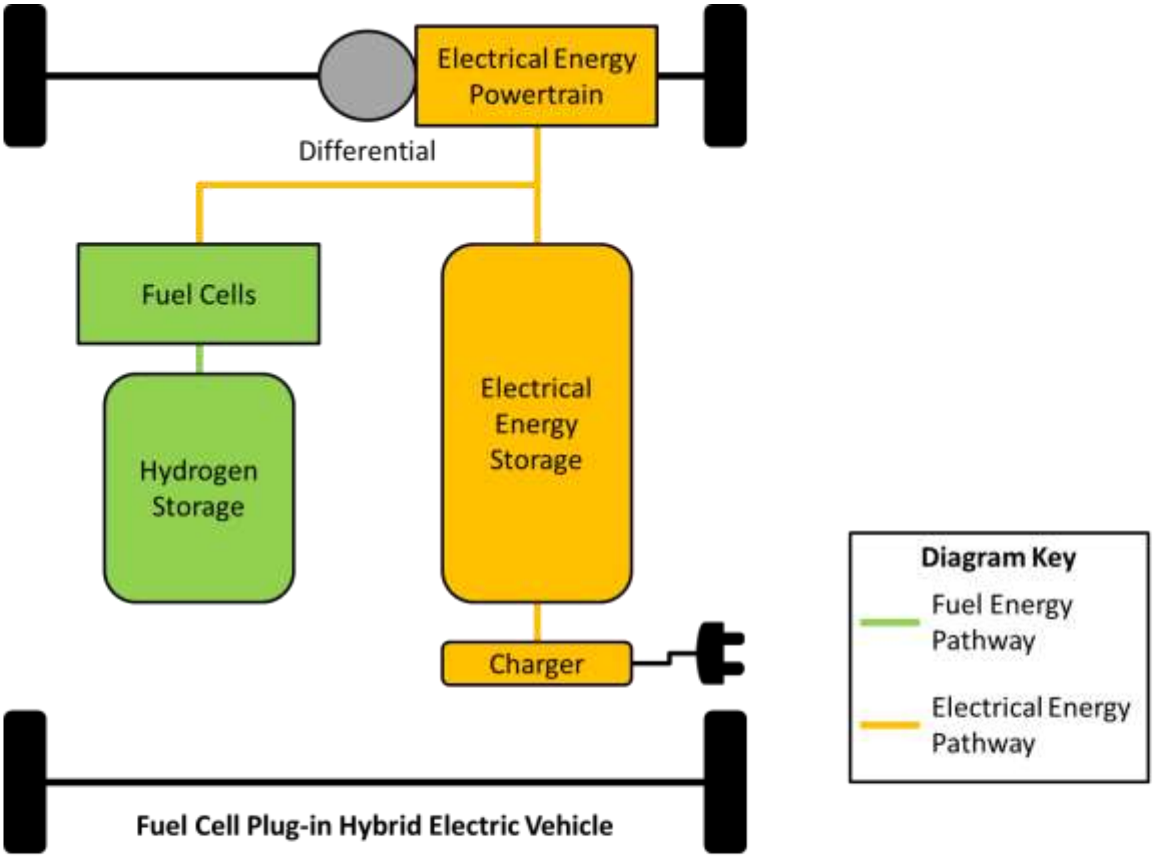

Figure 5 Example block diagram of a fuel cell plug-in hybrid electric vehicle.

There were two types of FCPHEVs analyzed in the EPRI study; a range extending FCPHEV, and a load following FCPHEV. The range extending FCPHEV utilizes the electrochemical battery pack and electric drivetrain for a specific driving distance, than turns on the fuel cells to maintain the SOC of the battery similar to the CS mode of conventional petroleum PHEVs. A load following FCPHEV allows the fuel cells to provide additional power in parallel with the battery pack to the electric motor depending upon the power required to drive the vehicle at any given time [30]. The comparison of these two FCPHEV architectures proves vital in determining an optimal architecture design that provides costs and emissions savings. A range extending FCPHEV with 55mi of all-electric range required only 20kW of fuel cell power, while a load following FCPHEV with 40mi of all-electric range required 60kW of fuel cell power. However, the range extending FCPHEV required a battery pack with 22kWh of capacity, while the load following FCPHEV required only 16kWh of battery pack storage. According to the EPRI study, by 2011 it would cost about 0.06$/mi to fuel the range extending FCPHEV, while it would cost about 0.08$/mi to operate the load following FCPHEV (in 2010 dollars). By the year 2020 both FCPHEV architectures would cost roughly 0.03-0.04$/mi to operate (in 2010 dollars). Both FCPHEV architectures provide similar greenhouse gas (GHG) emissions results. The range extending and load following FCPHEVs both produce roughly 250gCO_{2eq}/mi when using the United States electricity sources mix [30]. The comparison of these two FCPHEV architectures to conventional BEV and PHEV architectures by EPRI produced some key results. A key aspect of the study determined that by using lower power fuel cells with higher capacity battery packs, the range extending FCPHEV could maintain acceptable power (110kW) and range (300mi) levels to be comparable to other vehicle architectures. This range extending FCPHEV architecture would also provide lower operating costs and produce lower CO_{2eq} emissions similar to conventional PHEVs [30]. The study concluded the FCPHEVs could increase the acceptance of hydrogen and electricity as viable sources of energy for the personal transportation fleet.

The conclusion made by the EPRI study mirrors the results derived by the Colorado State University Vehicle Innovation Team (CSU VIT) in their design of a FCPHEV for the EcoCAR 2 vehicle design competition. By designing the components of the FCPHEV based on an inverse design process using vehicle performance metrics such as 0-60MPH acceleration time, 3.5% gradeability power requirements, vehicle range, and GHG emissions the CSU VIT was able to determine that a combination of a small powered fuel cell and large capacity battery pack would maintain performance while providing emissions and fuel savings over a conventional vehicle of similar size [31][32][33]. The prototype FCPHEV architecture designed and built by the CSU VIT, shown in Figure 6 and Figure 7, demonstrates that the concept of a FCPHEV architecture is not just a future endeavor. The electrical and hydrogen architectures shown in the two figures outline the commercially available components used by the CSU VIT to construct a FCPHEV.

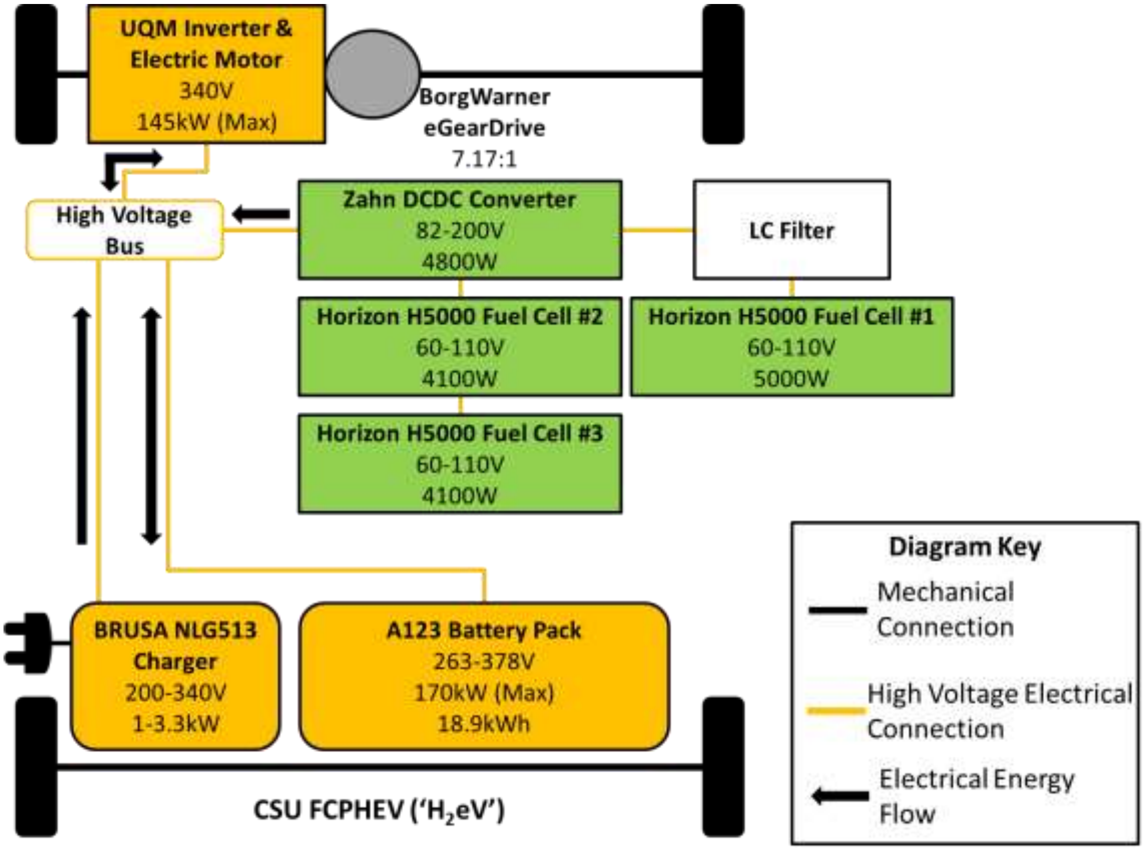

Figure 6 Electrical architecture of the FCPHEV built by Colorado State University.

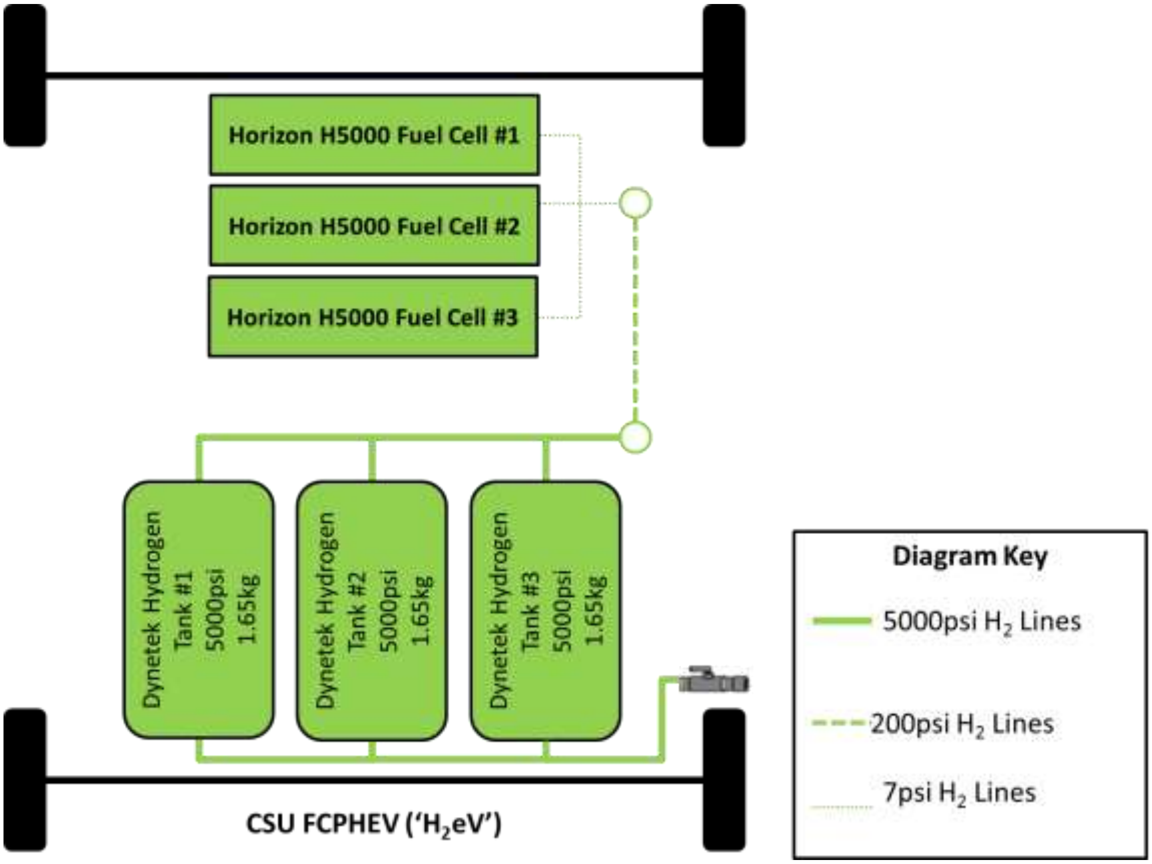

Figure 7 Hydrogen architecture of the FCPHEV built by Colorado State University.

The demonstration of this vehicle by CSU provides proof that the engineering required to build a FCPHEV is attainable using present technology. Further investigation into its role in every day driving is necessary to prove the benefits of the vehicle architecture.

1.4 Research Questions

Based on this understanding of the field, we can compose two primary questions of interest in understanding the relationship between the FCPHEV and the hydrogen infrastructure. First, we can seek to understand the effect that FCPHEV control strategy has on the number and types of fueling events, and on the quantities of either hydrogen or electricity used to power the FCPHEV. The following research questions were developed to help guide research into the fueling characteristics of the FCPHEV in real world applications.

1. How does the utilization of the electrical and hydrogen fueling pathways change with changes in the vehicle design of the FCPHEV?
    a. Do changes in the vehicle's all-electric range change the energy economy and energy sources of the FCPHEV?
    b. Do changes in the vehicle's energy management control strategy change the energy economy and energy sources of the FCPHEV?

To answer these questions this thesis will introduce methods used to calculate the utility of the hydrogen and electrical energy storage systems of the FCPHEV. These methods will be used to evaluate the real world fuel consumption across a large data set of vehicles and vehicle trips. The analysis will be conducted across multiple all-electric ranges, as well as being compared for two different energy management control strategies.

A second research question was composed to guide research into whether the FCPHEV can reduce the requirement for the hydrogen refueling infrastructure.

2. What is the effect of the FCPHEV architecture on the location and quantity of required hydrogen refueling infrastructure?
    a. Does this requirement for hydrogen infrastructure change based on the all-electric range of the FCPHEV?
    b. Is there an energy management control strategy that centralizes the FCPHEV's hydrogen refueling needs?

The results of the first research question will allow the analysis of the thesis to determine the exact locations that the FCPHEV will need to refuel the hydrogen storage tanks during the trips of each vehicle in the database used for this study. Calculations will be outlined that locate the exact longitude and latitude of each hydrogen refueling instance for each of the all-electric ranges and control strategies used in this thesis. The geographical position the refueling infrastructure will then be compared to better understand the impact of varying all-electric ranges and control strategies.

2.0 METHODS

The following sections detail the methods used to answer the research questions posed by this thesis. The data set, programming scripts, and calculations used in this analysis will be reviewed as it pertains to understanding the energy consumption behavior of a FCPHEV fleet, and how the hydrogen refueling needs the vehicle fleet change with the incorporation of the FCPHEV architecture.

2.1 FCPHEV Fleet Energy Consumption Analysis

The development of a FCPHEV prototype at CSU has developed our understanding of the real world integration challenges of such a vehicle [31][32]. Research conducted by CSU determined it is important to try and understand the proportion of hydrogen and battery energy used by the FCPHEV when integrated into a person's daily commute. The following section details the data and processes used to determine the energy consumption behavior of the FCPHEV.

2.1.1 Utility Factor

The concept of Utility Factor (UF) was created in order to quantify the actual fuel consumption or FE of a PHEV. This means that both the engine generator and battery energy consumption must be weighted appropriately, depending upon the way in which the PHEV is driven [34][35]. In general, UF is a ratio of miles driven in an all-electric mode over the total miles driven by the particular vehicle. The Society of Automotive Engineers (SAE) standard J2841 was created alongside the HEV testing method standards of SAE J1711 to define the metrics that would be used to calculate the UF of a PHEV. J2841 uses the mileage-based fleet transportation survey data from the National Household Transportation Survey (NHTS). The NHTS is a federally funded survey constructed to determine the household makeup, personal demographics, vehicle characteristics, daily travel distances, and long term travel distances over a four week study. In the 2001 NHTS, roughly 69,817 households participated in the survey. The UF analysis of SAE J2841 is used with the following assumptions:

1. A constant all-electric range is used for the vehicles of the NHTS no matter a particular vehicle's driving behavior.
2. Each vehicle begins each day with a fully charged battery pack.
3. Charging of the battery pack occurs at the end of each day, at home.

The UF calculated by the J2841 standard is based on a daily driving distance of the vehicles that participated in the NHTS survey [36]. The daily distance UF of a PHEV can be calculated using a given travel day (k), the daily distance of the vehicle ($d(k)$), and the all-electric range of the PHEV (R_{CD}). The daily distance UF is calculated using the ratio of the all-electric range over the daily distance ($R_{CD}/d(k)$) for instances when the daily driving distance is less than the all-electric range of the PHEV ($d(k) < R_{CD}$). The UF is 1.0 when the daily driving distance is greater than the CD range ($d(k) > R_{CD}$). For a vehicle driven over a given amount of travel days (N), Equation 1 is used.

Equation 1 Daily distance Utility Factor calculations as defined by the SAE standard J2841.

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

The daily distance UF equation reports the fraction of daily distances in the NHTS that are driven using only electrical energy from the battery pack. An example of daily distance UFs calculated for vehicles with different yearly mileage accumulations can be seen in Figure 8. For example, a PHEV with a 40mi all-electric CD range would have a UF of ~0.65 for vehicles with small annual mileage accumulation, a UF of ~0.73 for vehicles with large annual mileage accumulations, and a UF of ~0.7 for all vehicles no matter the annual driving distance.

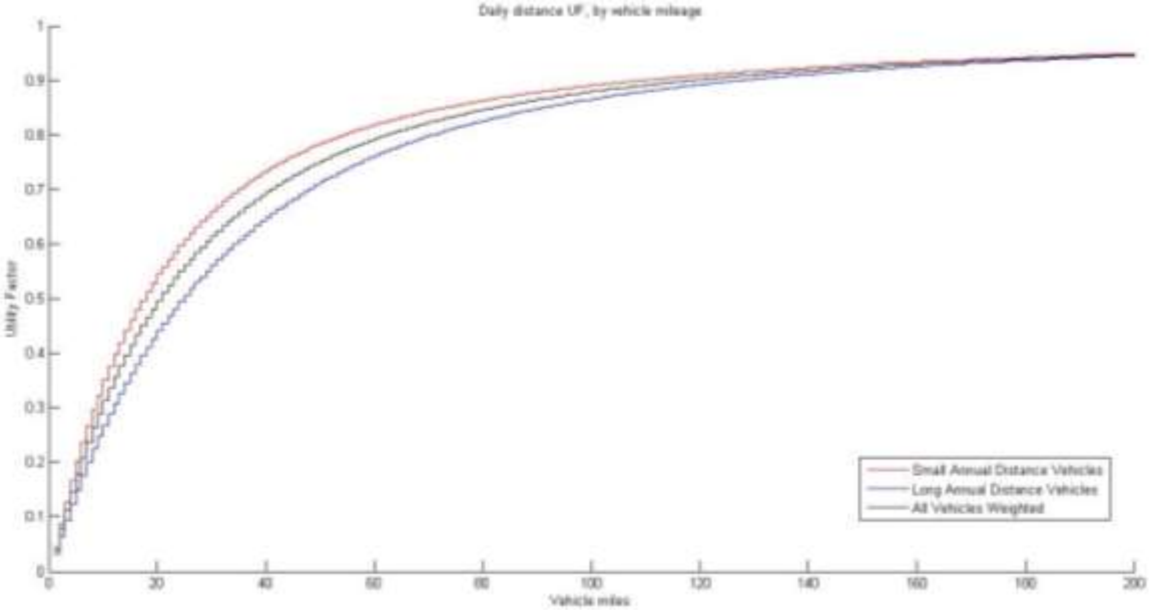

Figure 8 Example of a daily driving distance Utility Factor curve.

The daily distance UF is the current standard used by the automotive OEMs to report the number of all-electric miles and combined FE PHEVs can achieve on a full charge.

2.1.2 FCPHEV Utility Factor

Instead of calculating the daily distance UF of the FCPHEV from sample trips, this analysis calculates a UF based on the distance driven in either all-electric or CS mode by a vehicle over an entire year using an experimentally gathered set of driving data from NREL. The analysis will look at the total distance driven, all-electric distance driven, and fuel cell fueled CS distance driven by a given vehicle over year of driving. From these driving distances the amount of hydrogen fuel consumed and the refuelings required over the course of the year will also be calculated. Two control strategies were used for the analysis of the FCPHEV architecture. The first control strategy, which will be known as the '*PHEV-X control strategy*', uses all of the available battery energy for driving before it turns on the fuel cells for CS operation. This is the prototypical control strategy used by commercially available PHEVs [5]. The second control strategy, which will be referred to as the '*H2 Highway control strategy*', uses battery energy to power the vehicle in urban driving environments while using the hydrogen fuel cells to charge sustain during highway driving. For the H2 Highway control strategy, if the vehicle runs out of electrical battery energy during city driving the fuel cells will turn on for CS operation the rest of the trip. As with the daily distance UF calculations for SAE J2841, there are assumptions that were made when calculating the UF and energy use of the FCPHEV:

1. The FCPHEV begins each day of travel with 100% SOC corresponding to the assumption that the vehicle has a home recharging station, and it is used for overnight charging.
2. Charging of the HV battery pack only occurs at the household of the vehicle at the end of each day. Workplace and midday home charging was not considered in this thesis.
3. The CS hydrogen FE (mi/kg) used by the PHEV-X and H2 Highway Control Strategies are constant for each vehicle no matter the driving behavior of the vehicle. No consideration is made for the speed dependency, slope dependency, or temperature dependency of fuel cell operation or hydrogen consumption
4. The all-electric range of the FCPHEV is constant and doesn't vary based on the driving behavior of each vehicle. No consideration is made for the speed dependency, slope dependency, or temperature dependency of battery operation or energy efficiency.
5. The FCPHEV uses all of the gas stored in the hydrogen tanks before refueling with hydrogen.

Each control strategy was implemented in the model with all-electric ranges of 10mi, 20mi, 30mi, and 40mi. The CS hydrogen fuel consumption for each of the EV ranges was taken from a light-duty vehicle fuel consumption study conducted by ANL's Energy Systems Division. In this study ANL simulated the hydrogen fuel consumption of four PHEV EV ranges at different vehicle classes/weights. The analysis of this thesis uses the hydrogen fuel consumption for a 2010 medium sized vehicle (966kg glider weight), shown in Table 2 [38]. The urban CS FE was taken from FCPHEV simulations on the urban dynamometer drive schedule (UDDS), and the CS FE was taken from FCPHEV simulations on the highway fuel economy driving schedule (HWFET). The size of the hydrogen storage of the FCPHEV was based on the tanks used by the CSU FCPHEV prototype (Figure 7). A full hydrogen storage tank for this analysis holds 4.95kg (*TANK_CAP*) of hydrogen gas.

Table 2 Hydrogen fuel economies for a medium sized (996kg) FCPHEV with different all-electric ranges [38].

All-Electric Range [mi (km)]	UDDS CS FE [mi (km)/kg]	HWFET CS FE [mi (km)/kg]	Combined CS FE [mi (km)/kg]
10 (16)	54.35 (87.47)	58.82 (94.66)	55.69 (89.62)
20 (32)	53.62 (86.29)	56.82 (91.44)	55.01 (88.53)
30 (48)	52.91 (85.15)	55.55 (89.40)	53.98 (86.87)
40 (64)	52.36 (84.26)	54.88 (88.32)	53.28 (85.75)

While the UF calculations outlined by SAE J2841 utilize the NHTS data set, the FCPHEV UF calculations require a data set that provides geographical positioning data which allows for the analysis of vehicle travel behavior. NREL maintains a large database of detailed transportation survey data from numerous cities and projects across the United States. The data sets provided by the Transportation Secure Data Center (TSDC) provides similar vehicle trip characteristics as the NHTS data set, but in addition it provides the geographical location data of the vehicle for all of the recorded trips through the use of global positioning systems (GPS) recording [37]. From the TSDC the Puget Sound Regional Council (PSRC) Traffic Choices Study from 2004 to 2006 was chosen as the data set to be used for the analysis in this thesis.

Figure 9 General map of the Puget Sound, Washington area.

The PSRC data set provides a good combination of urban and highway vehicle travel for the participating surveyors within the Puget Sound area shown in Figure 9. The purpose of the PSRC survey was to monitor the use of toll roads by daily commuters in and out of the cities within the Puget Sound region. The number of households, vehicles, and trips surveyed for the PSRC database can be seen in Table 3. The PSRC data set encompasses trips of varying distance (1-250mi) and destinations (work, home, store, etc.). The GPS recorded location data at intervals of 0.1-0.2mi throughout the vehicle’s trip. The vehicles of the PSRC database were studied for different time periods. This means that some vehicles have less than a year of trip data, while some vehicles have more than a year of trip data. Because this thesis is analyzing the real world utility of the FCPHEV over a fleet of vehicles, the results of each vehicle need was normalized to a year of driving when calculating UF and energy consumption results.

Table 3 Details of the scope of vehicles and trips studied in the PSRC travel survey.

PSRC Database Details	
Houses	254
Vehicles	377
Total Trips	689,000

The PSRC data set is accessed through the Structural Query Language (SQL), which is a programming language used to manage and query large sets of data. There are five SQL schemas, or top level organized groups, within the PSRC data set that outline different specifications of the travel study, but for this analysis the ‘normal’ schema was primarily used for vehicle trip data and the ‘census’ schema was used for the GPS location of the Washington’s major highways. Within the ‘normal’ schema there are six data tables labeled ‘trips’, ‘tours’, ‘points’, ‘census’, ‘households’, and ‘vehicles’. For this analysis the data contained within the ‘trips’ and ‘points’ data tables were used to calculate the UF and energy use of the FCPHEV fleet. Of the data held within these two tables, the variables listed in Table 4 were extracted. Of the six variables three correspond to the identification of trips (trip_id), households (hhid), and vehicles (vehicle_id) while the other three variables correspond to the number of miles driven on city and county roads (road_mi), the number of miles driven on state and interstate highways (highway_mi), and the date of each of the vehicle’s trip (trip_start_date).

Table 4 Variable names, units, and descriptions of the variables used from the PSRC data set.

PSRC Variable	Units	Description
hhid	N/A	Individual household ID for each house of the PSRC travel survey
trip_id	N/A	Individual trip ID for each of the trips driven by a an individual vehicle of the PSRC travel survey
vehicle_id	N/A	Individual ID for each of the vehicle's associated with a specific household
road_mi	mi	The distance of each trip associated with travel along a county or country road
highway_mi	mi	The distance of each trip associated with travel along a state or interstate highway
trip_start_date	YYYY/MM/DD HH:MM:SS	The starting date associated with a specific trip ID, vehicle ID, and household ID

In order to determine the distance traveled by each vehicle on each trip and on each day, the data needed to be filtered based on the household, vehicle, and trip IDs. The scripts used for these filters and calculations were written in the Python programming language. Python is an open-source high-level programming language that provides a good platform for object-oriented and functional programming. For this analysis, custom Python scripts were written. Figure 10 shows a block diagram of the Python code created to use SQL queries to filter the required data from the PSRC database. The diagram shows that each of the household IDs (hhid) were used to collect the trip IDs (trip_id) associated with the particular household.

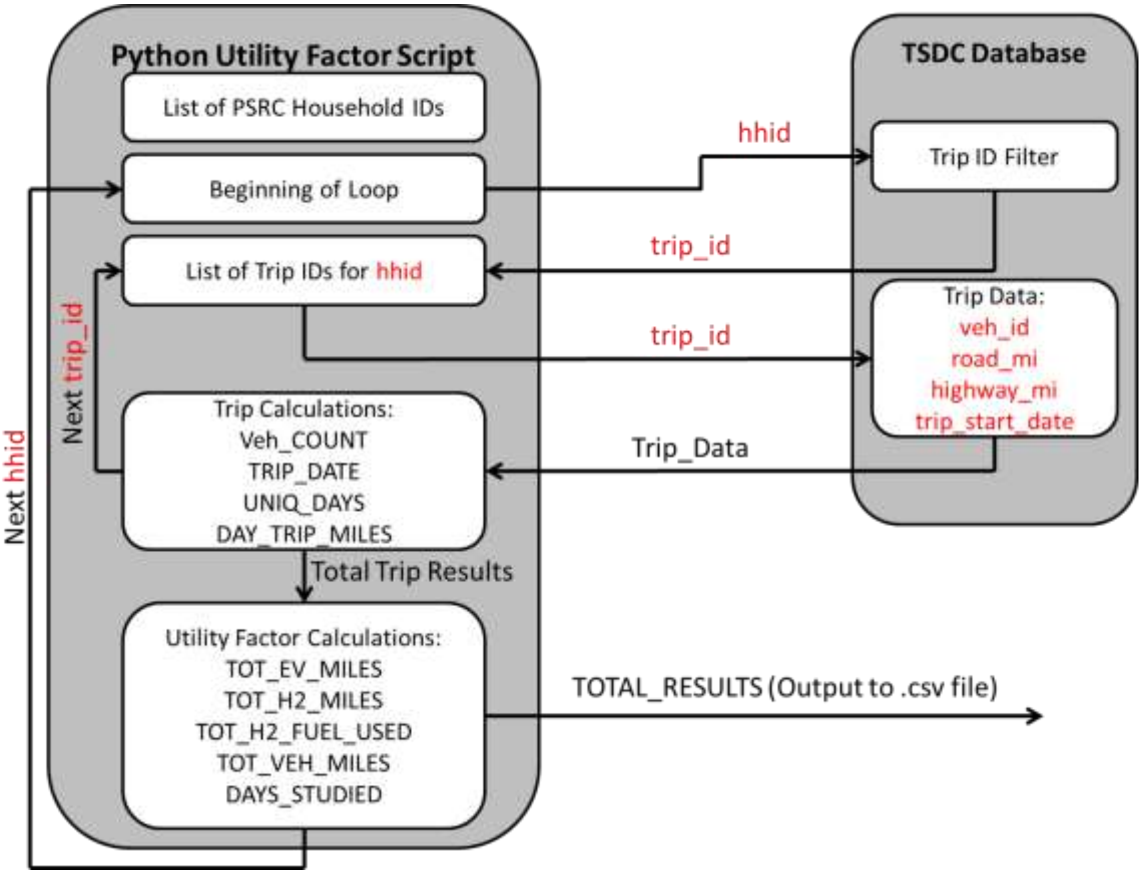

Figure 10 Block diagram of the looped script that is used to calculate the alternative UF of the FCPHEV when using the PHEV-X control strategy.

These trips were only passed back and stored in the Python script if they had an average trip driving speed less than 80MPH, as it was determined that some trips existed where the data was not collected properly and were indicated by unlikely high average trip vehicle speeds and distances. Each of the trip IDs filtered from the PSRC database were sent back as a new SQL queries to retrieve the miles traveled on urban and highway roads as well as the date of the trip. In order to determine if a specific GPS point within a vehicle's trip was driven on a highway or urban road, the SQL function 'ST_DWithin' was used to determine if the vehicle GPS travel point was within less than a tenth of a mile of the geographical position of the highway or roadway as shown in Figure 8. This function was used for each GPS point within each trip of the data set.

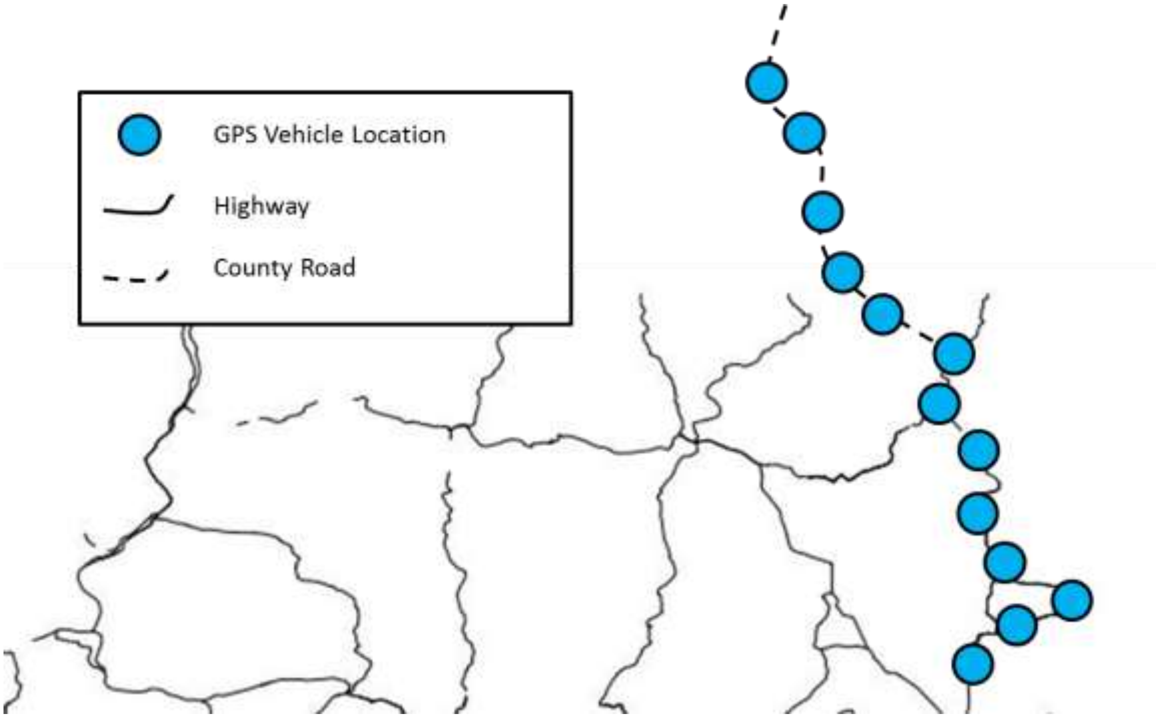

Figure 11 Example of the ST_DWithin function used to determine the road of travel of the vehicle.

To validate the accuracy of the GPS location script, sample trips were plotted in geographical mapping software and the GPS points located on urban and highway roads were physically counted and compared to the results of the Python script. The classification of miles traveled in urban and highway areas was important in comparing the effect of the two different vehicle control strategies used in this analysis. This set of data was then passed through the rest of the Python script to calculate the variables required to analyze the UF and energy consumption of the FCPHEV, shown in Table 5. The user-created variables in Table 5 were calculated for all 377 vehicles in the data set, but only the variables based on results from the entire survey were saved to a '.csv' file at the end of one household ID processing loop.

Table 5 Variables used to calculate the alternative UF for FCPHEV in the Python Script.

Python Script Variable	Units	Description
VEH_COUNT	N/A	List of the number of vehicles within each household
TRIP_DATE	YYYY/MM/DD	Date of the given trip
UNIQ_DAYS	YYYY/MM/DD	Filtered list of each day a trip was taken by a vehicle of the household
DAY_TRIP_MILES	mi	Total number of miles driven on all of the trips of a given day
TOT_EV_MILES	mi	Total miles driven using only energy from the battery pack
TOT_H2_MILES	mi	All miles driven CS with the fuel cells
TOT_H2_FUEL_USED	kg	Total amount of hydrogen consumed by the fuel cell system
TOT_VEH_MILES	mi	Total miles driven by the vehicle over the course of the study
DAYS_STUDIED	N/A	Number of days the vehicle was studied for the PSRC survey

The variables listed in Table 5 were calculated for the PHEV-X control strategy and H2 Highway control strategy, and for all four all-electric driving ranges. With the travel survey data collected from the PSRC database and the fuel cell hydrogen fuel consumption results from the ANL study, the behavior of the two FCPHEV control strategies and four all-electric ranges were analyzed and compared based on the following calculations and variables:

- Yearly all-electric miles traveled per year per vehicle $\left(\frac{TOT\_EV\_MILES}{DAYS\_STUDIED} * \frac{365\ days}{year}\right)$
- Hydrogen CS miles driven per vehicle per year $\left(\frac{TOT\_H2\_MILES}{DAYS\_STUDIED} * \frac{365\ days}{year}\right)$

- FCPHEV fleet UF $\left(\frac{TOT\_EV\_MILES}{TOT\_VEH\_MILES}\right)$
- Hydrogen fuel consumed per vehicle per year $\left(\frac{TOT\_H2\_FUEL\_USED}{DAYS\_STUDIED} * \frac{365days}{year}\right)$,
- Number of refills needed per vehicle per year $\left(\frac{TOT\_H2\_FUEL\_USED}{TANK\_CAP} * \frac{1}{DAYS\_STUDIED} * \frac{365days}{year}\right)$.
- Total number of hydrogen refueling for the PSRC vehicle fleet using a particular control strategy and all-electric range.

2.2 Hydrogen Filling Station GIS Analysis

The present hydrogen refueling infrastructure is very small in comparison to the large petroleum refueling infrastructure already in place [28][29]. Previous studies have simulated the future placement of hydrogen refueling stations based on socioeconomic and demographic metrics, indicating that the implementation of a hydrogen refueling infrastructure will increase the demand for hydrogen powered vehicles [25][26]. In this thesis driver behavior from the PSRC database will be used to determine the areas of refueling need which can be used to implement a hydrogen refueling infrastructure. Some studies have hypothesized that FCPHEVs can concentrate the areas where drivers will need to refuel their storage tanks and allow for the concentration of hydrogen infrastructure development in areas of known hydrogen refueling needs. Hydrogen refueling refers to each instance a vehicle uses all of the hydrogen gas stored on board and would need to refill the tanks before continuing the trip. The following section details the analysis used to locate every hydrogen refueling required by all 377 vehicles of the PSRC fleet.

To test this theory and answer research question 2, this thesis will construct a simulation that can enable the modeling of each hydrogen refueling event for the PSRC vehicle fleet. The

Python script used to collect vehicle data from the PSRC database in the previous section was incorporated into the Python script used to locate the points on each vehicle's daily commute where they will need to refuel their hydrogen storage tanks. The hydrogen refueling analysis used the same hydrogen fuel consumption, all-electric range, and hydrogen storage capacity specifications used in the previous section. In addition to the variables used in Table 5, new variables used and produced as results by the refueling Python script can be seen in Table 6.

Table 6 Variables used by the hydrogen refueling location Python script.

Python Refueling Location Variable	Units	Description
EV_MILES	mi	Accumulated all-electric miles driven by the vehicle over the course of the study
H2_MILES	mi	Accumulated hydrogen supported CS miles driven by the vehicle over the course of the study
H2_FUEL	kg	Accumulated hydrogen consumed by the vehicle over the course of the study
H2_REFIL_TRIP_ID	N/A	Trip ID associated with a trip that requires refueling
REFIL_TRIP_DIST	mi	Total distance traveled on the a trip of the vehicle that requires a hydrogen refueling
REFIL_TRIP_H2_FUEL	kg	Total amount of hydrogen gas consumed by the FCPHEV on the refueling trip
REFIL_H2_MILE_CONS	kg/mi	Hydrogen fuel consumption on the refueling trip
REFIL_H2_FUEL_TO_EMPTY	kg	Amount of hydrogen until the storage tank is empty
REFIL_MILES_TO_REFIL	mi	Amount of miles into the refueling trip until the hydrogen storage tanks are empty

In order to determine the exact trip and mile into the trip that a vehicle will need to refuel the all-electric (EV_MILES), hydrogen supported CS (H2_MILES), and total distance traveled by the vehicle were summed sequentially over the course of the travel study. Once the EV and hydrogen supported distances were calculated for each vehicle trip and day of travel, the amount of hydrogen fuel (H2_FUEL) used each trip and day was accumulated over the length of the study. From the total hydrogen used by a particular vehicle over the study period, the number of refuelings was calculated. This number was used to find the instances where the hydrogen used on a specific trip (H2_REFIL_TRIP_ID) reached/exceeded a multiple (based on the number of total refuelings) of the hydrogen tank capacity. With trip IDs for all of the instances where the vehicle will need to refuel, the approximate GPS location within the trip was calculated.

First, the total distance traveled on a given refueling trip was determined using Equation 2. Next the amount of hydrogen consumed by the fuel cells over the course of the trip was calculated using Equation 3. From the distance of the trip and the amount of hydrogen consumed, the hydrogen fuel consumption per unit distance was calculated using Equation 4. To determine the location of the trip's hydrogen refueling, the amount of hydrogen remaining in the tanks at the beginning of the trip was determined. Equation 5 uses the capacity of the FCPHEV's hydrogen tanks, multiplied by the number of refills up to the current refill, and subtracts the amount of hydrogen used thus far. From the remaining hydrogen within the tanks and the estimated hydrogen consumption of the trip, the distance through the trip that the FCPHEV will need to refuel the hydrogen tanks was calculated in Equation 6.

Equation 2 Calculating the total miles on the trip with a hydrogen refueling event.

$$REFIL\_TRIP\_DIST \ = VEH\_TRIP\_MILES[k] - VEH\_TRIP\_MILES[k-1]$$

Equation 3 Calculation of the amount of hydrogen fuel consumed on the trip with a refueling event.

$$REFIL\_TRIP\_H2\_FUEL \ = H2\_USED[k] - H2\_USED[k-1]$$

Equation 4 Estimate of the amount of hydrogen fuel being consumed per mile on the trip with a refueling event.

$$REFIL\_TRIP\_H2\_MI\_CONS \ = \frac{REFIL\_TRIP\_H2\_FUEL}{REFIL\_TRIP\_DIST}$$

Equation 5 Calculating the amount of hydrogen gas within the storage tank at the beginning of the trip.

$$REFIL\_TRIP\_H2\_FUEL\_TO\_EMPTY \ = m * TANK\_CAP \ - \ H2\_USED[k-1]$$

Equation 6 Calculating the distance into the trip where a hydrogen refueling event will occur.

$$REFIL\_TRIP\_MILES\_TO\_REFIL \ = \frac{REFIL\_TRIP\_H2\_FUEL\_TO\_EMPTY}{REFIL\_TRIP\_H2\_MI\_CONS}$$

Equation 2 through Equation 6 were calculated for each trip ID associated with a hydrogen refueling for all 377 vehicles of the PSRC data set. A graphical representation of the refueling location process can be seen in Table 11.

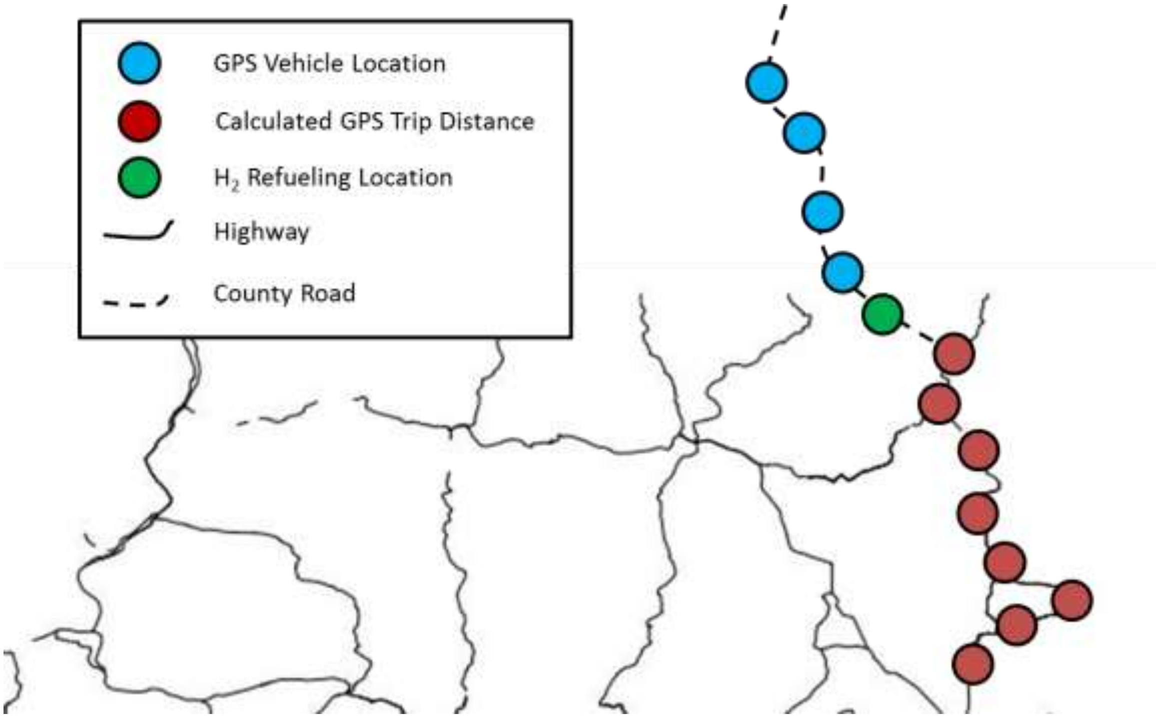

Figure 12 Representation of the process used to determine the location of hydrogen refueling.

These equations were used for each of the vehicles in the PSRC data set. The refueling location Python script, shown in Figure 13, uses SQL queries to the PSRC database along with the trip calculations developed in section 2.1.2 FCPHEV Utility Factor to determine the latitude and longitude coordinates of each vehicle's hydrogen refueling. The results of the Python script refueling locations was validated by physically calculating the amount of hydrogen used by a few sample vehicles using an Excel spread sheet. The urban and highway distance traveled and trip ID were placed in the spread sheet to calculate the consumption of hydrogen over a single trip, then for each day of the vehicle's travel, and over the course of the study. Each time the hydrogen used by the sample vehicle exceeded a multiple of the hydrogen tank capacity, the associated trip ID was recorded. All the hydrogen refueling trip IDs calculated by the Excel spread sheet were compared to the trip ID results of the Python script for each of the sample vehicles.

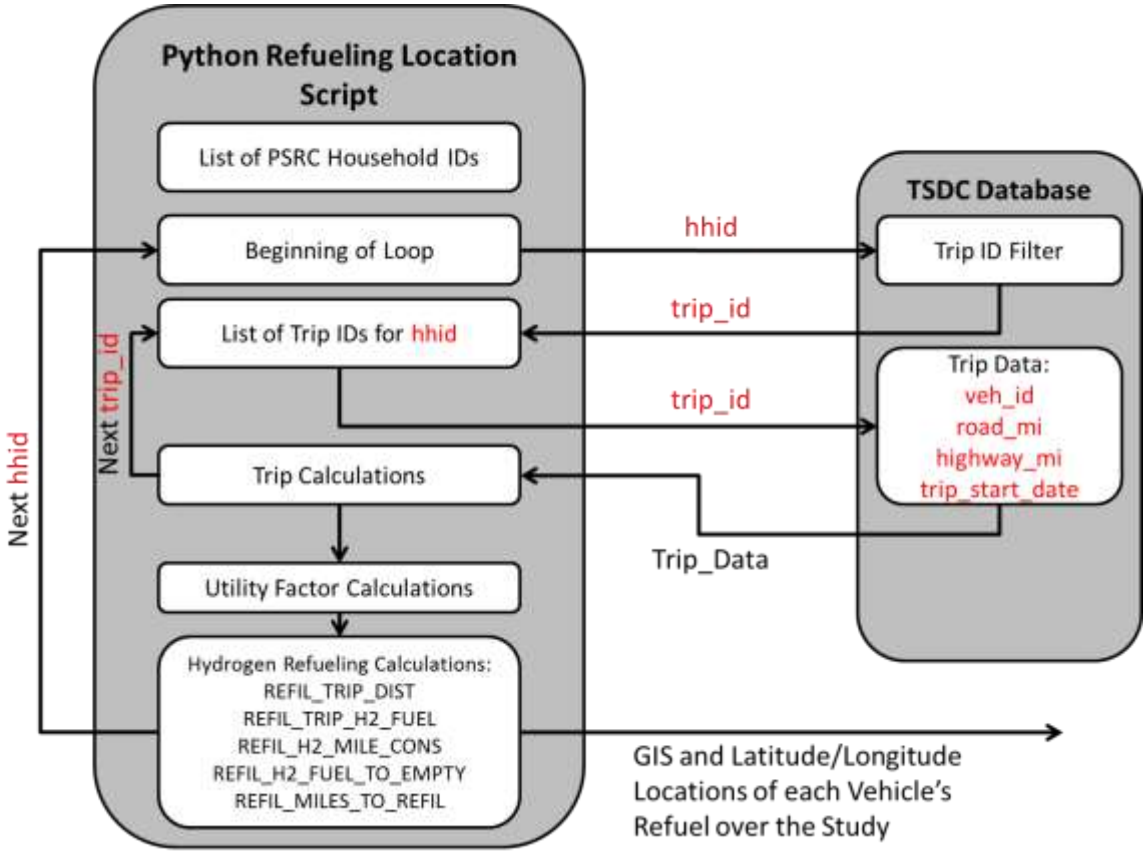

Figure 13 Block diagram of the Python script used to determine the refueling locations for each vehicle of the PSRC database.

The list of hydrogen refueling location results was exported to a .csv file to be plotted. The Quantum Geographic Information Systems (QGIS) software was used to plot the exact hydrogen refueling location for each vehicle of the PSRC data set. QGIS is a geographic mapping software that uses multiple map projection layers for road, city, and other user specified objects. The QGIS software was used to map the major highway networks within the state of Washington as a base layer for the refueling location coordinates. Figure 14 shows an example map of the major highway network of Washington, with specific latitude and longitude locations of hydrogen refuelings in green. In accordance with the rules of the TSDC, to secure the safety of the location of the participants of the PSRC travel survey, the locations of the households within the data set will not be shown on any of the QGIS produced maps in this thesis.

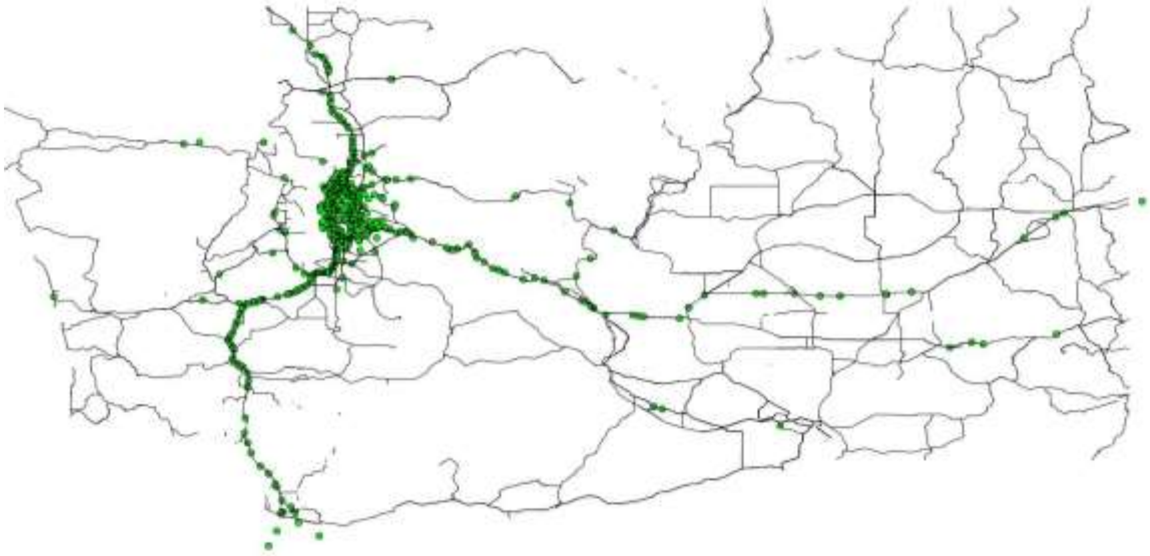

Figure 14 Example QGIS map of the state of Washington.

For a metric of comparison between the control strategies and vehicle designs, this analysis will determine the number of hydrogen refueling events that occur on the highway in comparison to the total number of refuelings for the particular control strategy and all-electric range. This analysis will provide a better understanding of the utility provided by either the PHEV-X or H2 Highway control strategy in helping concentrate the construction of the hydrogen refueling infrastructure. To determine if a refueling location is located on a highway, the QGIS function '*Buffer*' was used to create the same buffer around the highways that was used for the trip road/highway distance analysis earlier. Points that lie within the buffer, as shown in Figure 15, are counted using the '*Spatial Query*' function of QGIS to determine if the latitude/longitude point of the refueling location intersects with the buffer zone of the highway system. The '*Spatial Query*' function sums the number of points located within the highway buffer region in comparison to the total number of hydrogen refuelings for the entire PSRC vehicle fleet.

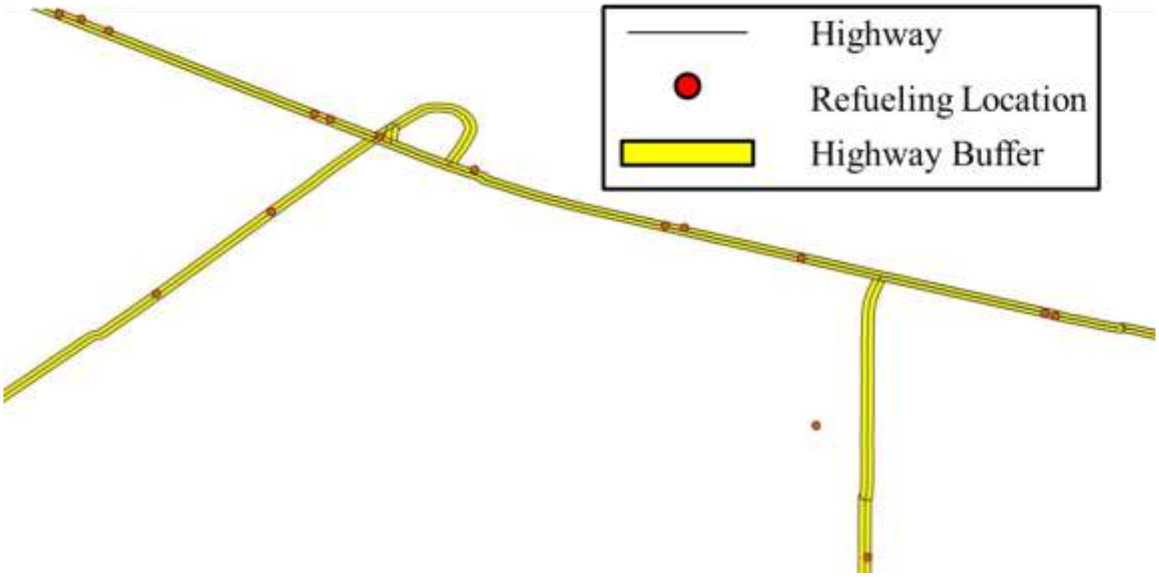

Figure 15 Example of road buffer zone created to determine the density of refueling events on the highway.

3.0 RESULTS AND DISCUSSION

The following section presents the simulations results that answer the research questions posed in this thesis. For the discussion in the following sections the FCPHEV will be categorized by the all-electric range and control strategy as follows:

- *FCPHEV-X*: This nomenclature will be used to describe the FCPHEV that uses the conventional PHEV-X energy management control strategy. The '*X*' will be replaced with the all-electric range of the vehicle in question.
- *FCPHEVH2-X*: This nomenclature will be used to identify the FCPHEVs that utilize the H2 Highway control strategy. Just as before, the '*X*' will be replaced with the all-electric range of the vehicle being discussed.

3.1 FCPHEV Fleet Energy Consumption Analysis

The developed Python code was used to analyze the driving habits of the FCPHEV using both the PHEV-X and H2 Highway control strategies. Each control strategy was also used for the four different all-electric vehicle ranges discussed in Table 2. The results given in this section will be organized based on all-electric range and control strategy. The vehicle fleet results for all-electric distance, hydrogen supported CS distance, hydrogen gas consumed, and number of refueling were normalized to a year of driving to better compare the two control strategies and judge variation of vehicle usage from driver to driver within the data set.

Table 7 shows the all-electric and hydrogen supported CS distance driven by the vehicles of the PSRC database using the PHEV-X control strategy. The table shows that as the all-electric range of the FCPHEV increases, on average the distance driven using only the battery pack increases while the distance driven using the fuel cells decreases. This result mirrors previous UF analysis of PHEVs, which show that larger battery packs with larger all-electric ranges will allow drivers to drive more trips using just the battery [34][35]. The normalized fleet results show that each vehicle of the fleet drives at least some distance using the fuel cells, but there are some vehicles when driving the FCPHEV-40 that never use more than one refueling of the stored hydrogen.

Table 7 All-electric and hydrogen CS miles results for the PHEV-X control strategy.

All-Electric Range [mi (km)]	Max EV Travel [mi (km)/year]	Min EV Travel [mi (km)/year]	Avg EV Travel [mi (km)/year]	Max H2 Travel [mi (km)/year]	Min H2 Travel [mi (km)/year]	Avg H2 Travel [mi (km)/year]
10 (16)	3637 (5854)	543 (875)	2878 (4632)	18505 (29781)	286 (460)	6538 (10522)
20 (32)	7138 (11489)	667 (1074)	5102 (8211)	15354 (24710)	57 (92)	4547 (7318)
30 (48)	10425 (16778)	730 (1175)	6666 (10728)	12701 (20440)	11 (18)	3104 (4995)
40 (64)	13754 (22133)	740 (1192)	7696 (12385)	10653 (17144)	2 (3)	2114 (3402)

The vehicle fleet results in Table 7 show a large distribution between the maximum and minimum for the all-electric and hydrogen supported CS distance traveled. The FCPHEV-40 has a distribution of 13014mi/year for all-electric travel, while the FCPHEV-10 fleet result has a distribution of 3093mi/year. As might be expected, the distance traveled using hydrogen showed a higher distribution for the FCPHEV-10 (18220mi/year) than the FCPHEV-40 (10651mi/year).

Because the PSRC data set encompasses such a variety of trip distances, and driver types, the results of the yearly hydrogen consumption of the FCPHEV fleet must take into consideration the stochastic nature of its distribution. Figure 16 provides a visualization of the distributions of all-electric and CS miles for each of the all-electric ranges and for each driver in the PSRC data set. Regardless of the large diversity of driving styles and distances within the PSRC vehicle fleet, the averages of the all-electric miles shows a 63% decrease in all-electric travel as the range of the battery pack decreases from 40mi to 10mi. Subsequently, the average hydrogen supported CS travel results in Figure 17 shows a 68% decrease in the number of miles driven using the fuel cells from FCPHEV-10 to FCPHEV-40.

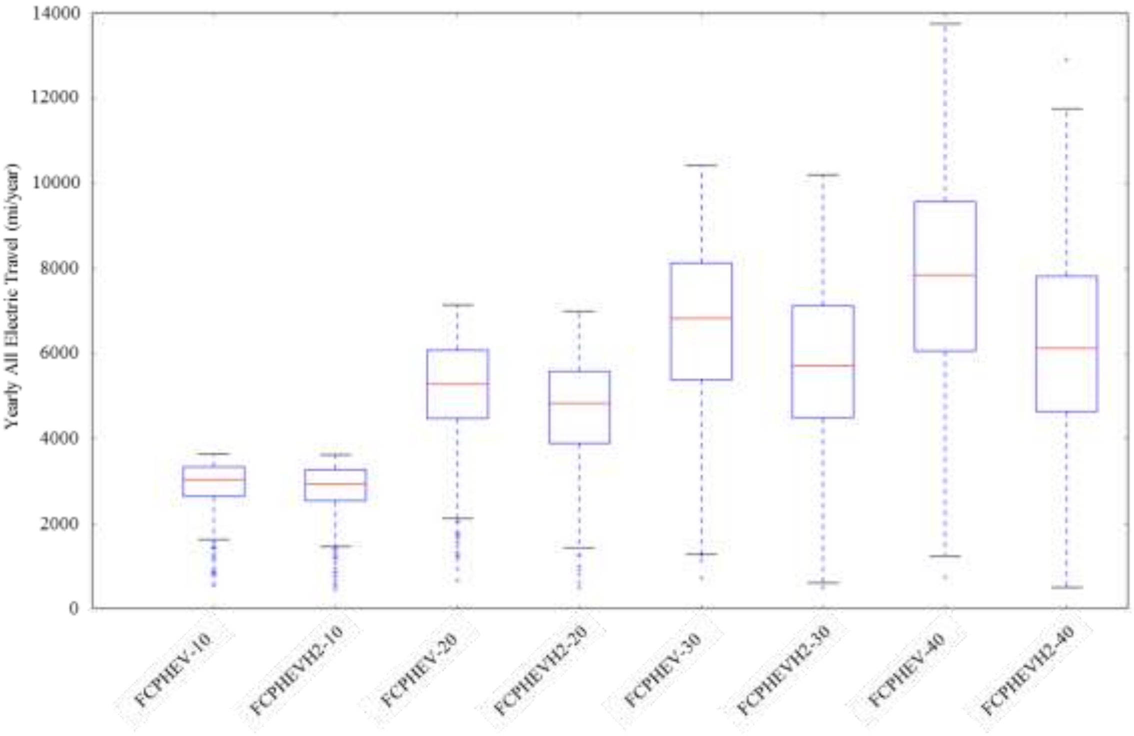

Figure 16 Box plots of the all-electric miles driven by the PSRC vehicles for both control strategies and all four all-electric ranges.

Mirroring the results presented for the PHEV-X control strategy, Table 8 shows the all-electric and CS miles driven by the PSRC vehicle fleet using the H2 Highway control strategy. Similar to the PHEV-X control strategy, the FCPHEV drives more miles all-electric on average as the all-electric range increases. The H2 Highway control strategy FCPHEVs have higher minimum CS miles traveled than the PHEV-X control strategy FCPHEVs due to the control strategy differences.

Table 8 All-electric and hydrogen supported CS miles results for the H2 Highway control strategy.

All-Electric Range [mi (km)]	Max EV Travel [mi (km)/year]	Min EV Travel [mi (km)/year]	Avg EV Travel [mi (km)/year]	Max H2 Travel [mi (km)/year]	Min H2 Travel [mi (km)/year]	Avg H2 Travel [mi (km)/year]
10 (16)	3618 (5823)	460 (740)	2794 (4496)	24410 (39284)	211 (340)	7133 (11479)
20 (32)	6991 (11251)	499 (803)	4648 (7480)	22051 (35488)	144 (232)	5278 (8494)
30 (48)	10195 (16407)	505 (813)	5688 (9154)	20209 (32523)	84 (135)	4240 (6829)
40 (64)	12912 (20780)	505 (813)	6244 (10049)	18893 (30405)	69 (111)	3683 (5927)

The fleet results of the H2 Highway control strategy show the same types of distribution as the PHEV-X control strategy results. The difference between the maximum and minimum all-electric travel for the FCPHEVH2-40 was 12407mi/year, while the difference between the maximum and minimum for the FCPHEVH2-40 was only 3157mi/year. The distribution of CS travel results for the FCPHEVH2-40 was 15210mi/year, while the distribution of results for the FCPHEVH2-10 was 17277mi/year. For both control strategies the distribution of all-electric travel is similar, meaning the vehicles of Puget Sound are using the battery pack similarly no matter the energy management strategy. However, the distribution of CS hydrogen miles differs based on the principle that the H2 Highway control strategy FCPHEVs driving the most hydrogen based miles are driving a majority of those miles on the highway. On average the FCPHEVH2-10 drives 53% less all-electric miles per year than the FCPHEV-40, while the FCPHEVH2-40 drives 48% less hydrogen CS miles per year than the FCPHEVH2-10.

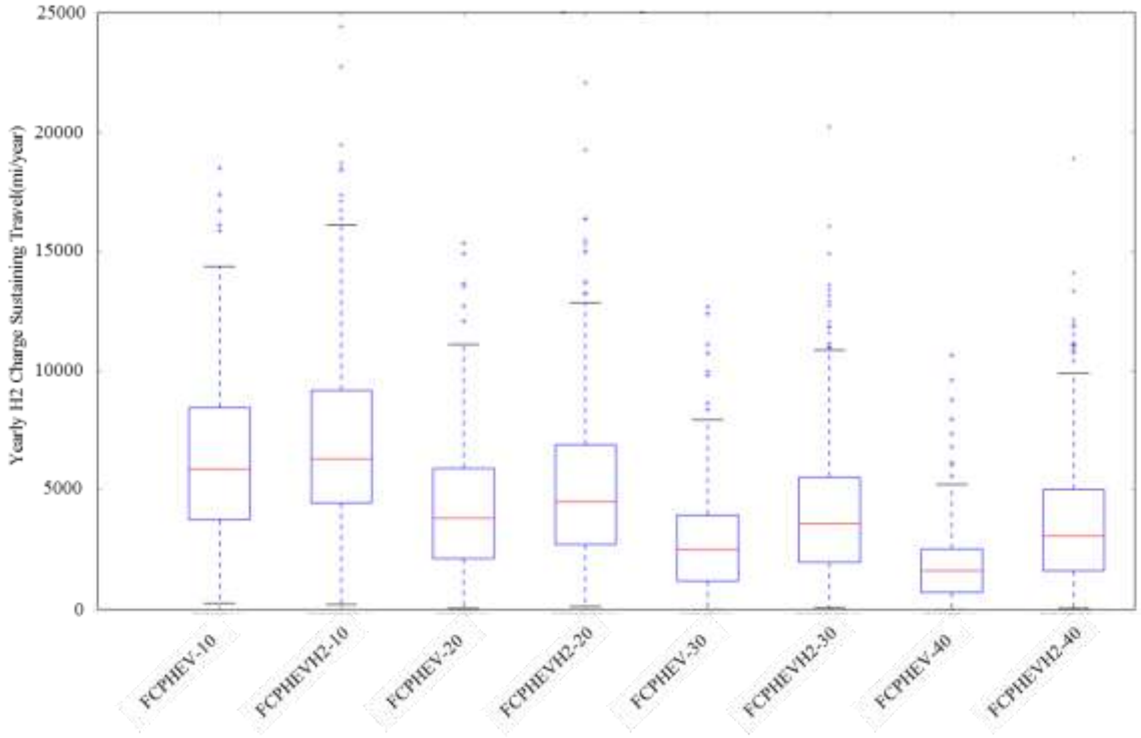

Figure 17 Box plots of the CS miles driven by the vehicles of the PSRC database for both control strategies and for each of the four all-electric miles.

The plots in Figure 16 and Figure 17 shows a clear difference in the average number of all-electric and CS miles driven by the FCPHEV using either control strategy. To further explore this difference a UF analysis will be used. The UF analysis outlined in SAE J2841 uses the fraction of daily travels that could be driven only using the HV battery pack. For this FCPHEV analysis, the ratio of average all-electric miles driven to the average total miles driven by the PSRC vehicles over one year was calculated. Figure 18 shows the UF for all four all-electric ranges and each control strategy. As shown by the earlier results, the larger the range of the battery pack the larger the percentage of miles the driver will use only the battery pack to drive the vehicle. The FCPHEV-40 has a UF of 84.49% while the FCPHEVH2-40 has a UF of 62.9%.

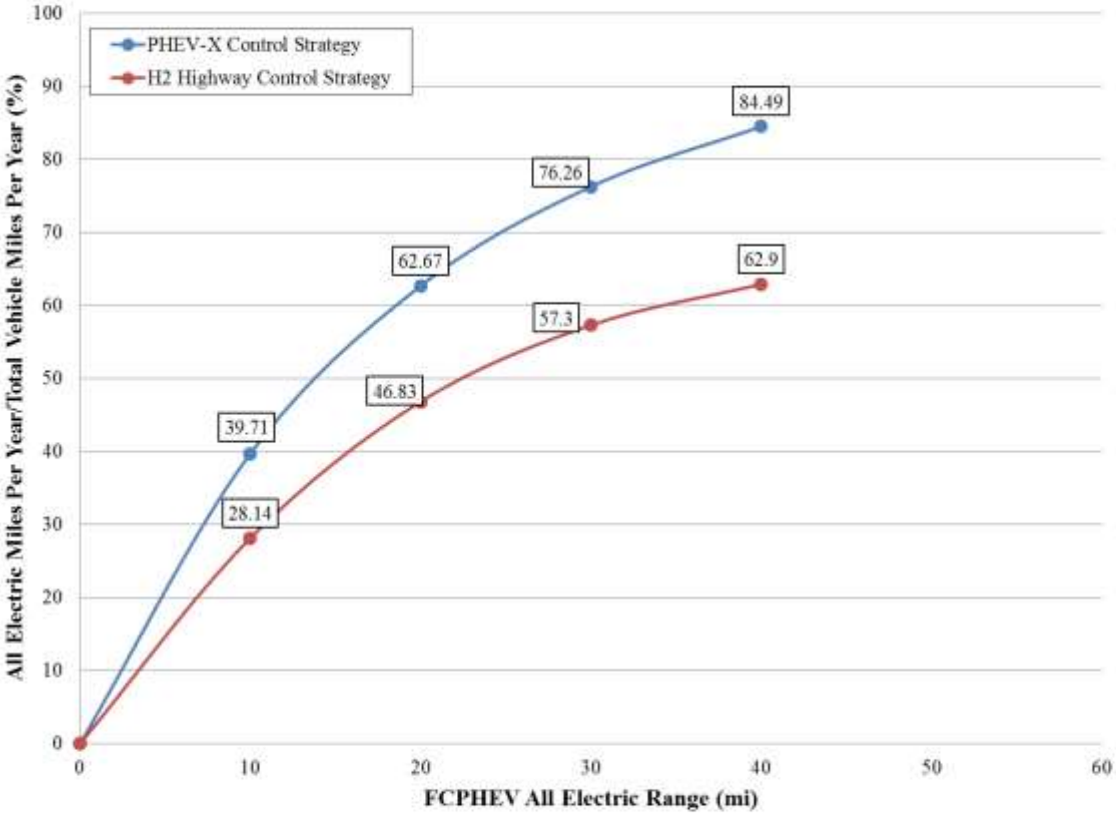

Figure 18 Ratio of miles drive all-electric to the total miles driven for each control strategy.

With 40mi of all-electric range, FCPHEV drivers in the Puget Sound area were driving over 20% more of their travel using only the battery pack when using the conventional PHEV-X control strategy. The gap between the UFs of the two control strategies begins to shrink as the size of the FCPHEV's battery becomes smaller. With an all-electric range of 10mi, the FCPHEV-10 has a UF of 39.71% while the FCPHEVH2-10 has a UF of 28.14%. While the UF curves in Figure 18 show that the PHEV-X control strategy will inevitably provide more fuel savings benefits over the H2 Highway control strategy, it is interesting to point out that both control strategies have UF curves that follow the general outline of the daily distance UF curves calculated by SAE J2841 (Figure 8). While these results might not be surprising with a conventional PHEV-X control strategy, it is interesting that even though the H2 Highway control strategy is mandating that the fuel cells turn on as soon as the vehicle is driving along a highway the PSRC vehicle fleet is still using the battery pack to drive the vehicle with similar trends to the conventional PHEV-X control strategy.

The amount of hydrogen consumed and the number of refueling required by the FCPHEV using the PHEV-X control strategy over the course of the study are outlined in Table 9. For all four all-electric ranges there was at least one vehicle in the fleet that did not use more than the capacity of one tank fill up (4.95kg). As a whole, the vehicle fleet used less hydrogen fuel on average as the all-electric range increased, thus limiting the number of times the FCPHEV needed to refuel over the course of the study.

Table 9 Hydrogen fuel consumed over the study period by the FCPHEV using the PHEV-X control strategy.

All-Electric Range [mi (km)]	Max H2 Fuel Consumed (kg)	Min H2 Fuel Consumed (kg)	Avg H2 Fuel Consumed (kg)	Max H2 Fuelings (#)	Min H2 Fuelings (#)	Avg H2 Fuelings (#)
10 (16)	457	4	132	92	0	26
20 (32)	396	1	92	79	0	18
30 (48)	340	0	63	68	0	12
40 (64)	297	0	44	59	0	8

The amount of hydrogen gas consumed by the PSRC vehicle fleet using the H2 Highway control strategy can be seen in Table 10. The FCPHEV uses more hydrogen on average across all four of the all-electric ranges due to the fuel cells being turned on during highway travel. However, even with the PSRC vehicle fleet using more hydrogen, there are still some cars within the study that still travel a majority of their miles using only the battery pack of the FCPHEV, helping reinforce the UF results seen in Figure 18. As the battery range decreases toward 10mi, the two control strategies on average consume the same amount of hydrogen with the FCPHEV-10 using 131.94kg and the FCPHEVH2-10 using 132.36kg over the course of the study.

Table 10 Hydrogen fuel consumed over the study period by the FCPHEV using the H2 Highway control strategy.

All-Electric Range [mi (km)]	Max H2 Fuel Consumed (kg)	Min H2 Fuel Consumed (kg)	Avg H2 Fuel Consumed (kg)	Max H2 Fuelings (#)	Min H2 Fuelings (#)	Avg H2 Fuelings (#)
10 (16)	450	4	132	90	0	26
20 (32)	416	3	99	83	0	20
30 (48)	387	2	81	78	0	16
40 (64)	365	1	70	73	0	14

If the number of refuelings is normalized to a year of driving, as was done for the all-electric and CS travel, it can be seen in Table 11 that on average the FCPHEVH2s have to refuel their vehicles more when the electric range is 30mi or 40mi. However, at the lower all-electric ranges (10mi and 20mi) the average number of hydrogen refuelings begins to converge for the two control strategies.

Table 11 Number of hydrogen tank refuelings over a year period for both FCPHEV control strategies.

All-Electric Range [mi (km)]	Max H2 Fuelings (#/year)	Min H2 Fuelings (#/year)	Avg H2 Fuelings (#/year)
PHEV-X Control Strategy			
10 (16)	87	0	25
20 (32)	75	0	17
30 (48)	65	0	11
40 (64)	56	0	7
H2 Highway Control Strategy			
10 (16)	86	0	25
20 (32)	79	0	18
30 (48)	74	0	15
40 (64)	69	0	13

While the results in Table 11 shows that there is a small difference in the number of average yearly hydrogen refuelings for both control strategies, these numbers only represent the average expected of each vehicle within the PSRC data set. Table 12 shows the total number of hydrogen refuelings required by the entire PSRC vehicle fleet over the course of the study. Per vehicle the two control strategies show similar refueling numbers, but when looking at the entire fleet it can be seen that the FCPHEVH2 fleet refuels nearly twice as much for all the electric ranges for the 40mi, 30mi, and 20mi FCPHEVs. However, for the 10mi FCPHEVs the H2 Highway control strategy has the PSRC vehicle fleet refueling two and a half more times than their PHEV-X control strategy counter parts. Included in Table 12 is the number of refuelings for a conventional FCV, which has zero miles of all-electric ranges, and behaves much like a conventional vehicle. The refuelings results show that regardless the size of the battery pack, and for both control strategies, a FCPHEV allows the driver to substantially decrease the number of times they need to refuel the storage tank of their vehicle.

Table 12 Total number of refuelings for the entire PSRC vehicle fleet for each all-electric range and control strategy.

All-Electric Range [mi (km)]	Total H2 Refuelings (#)	Highway Refuelings (#)	Highway/Total Refuelings (%)
PHEV-X Control Strategy			
10 (16)	7953	4377	55.04%
20 (32)	5717	3380	59.12%
30 (48)	3921	2439	62.20%
40 (64)	2693	1741	64.65%
H2 Highway Control Strategy			
10 (16)	19825	7972	40.21%
20 (32)	11663	5467	46.87%
30 (48)	7744	4304	55.58%
40 (64)	5953	3682	61.85%
Fuel Cell Vehicle			
0	39395	13695	34.76%

3.1.1 FCPHEV Fleet Energy Consumption Analysis Summary

Research question 1 asked how the utilization of the electrical and hydrogen fueling pathways change with changes in the vehicle design of the FCPHEV. By answering the following two sub questions of research question 1, this analysis provided a better understanding of the energy consumption characteristics of a FCPHEV fleet:

- Do changes in the vehicle’s all-electric range change the energy economy and energy sources of the FCPHEV?
    - The results of this section showed that for both the PHEV-X and H2 Highway control strategies, the FCPHEV utilized electrical and hydrogen energy differently as the all-electric driving range changed. On average the FCPHEV-40 traveled 7696mi/year in all-electric mode and 2114mi/year in CS mode, while on average the FCPHEV-10 traveled 2878mi/year in all-electric mode and 6538mi/year in CS mode. On the other hand, on average the FCPHEVH2-40 traveled 6244mi/year in all-electric mode and 3683mi/year in CS mode, while on average the FCPHEVH2-10 traveled 2794mi/year in all-electric mode and 7133mi/year in CS mode. Across both control strategies, the FCPHEVs with larger all-electric ranges provided more benefit to the consumer by driving the majority of the yearly travel all-electric (Figure 18) and reducing the number of times drivers will need to refill the hydrogen tanks (Table 11).
- Do changes in the vehicle’s energy management control strategy change the energy economy and energy sources of the FCPHEV?
    - The FCPHEV UF analysis showed that a FCPHEV with a longer all-electric range provided the most utility for driver for both control strategies, but the comparison across control strategies showed a difference in benefits when using the PHEV-X control strategy over the H2 Highway control strategy. The FCPHEV-40 had a UF of 84.49% while the FCPHVEH2-40 had a UF of 62.9%, congruently the FCPHEV-10 had a UF of 39.71% while the FCPHEVH2-10 had a UF of 28.14%. These UF results show that the PHEV-X control strategy allowed drivers of the

PSRC vehicle fleet to travel on more of their trips using just energy from the battery pack than the same vehicles using the H2 Highway control strategy. In fact, the FCPHEVH2-40 vehicle fleet required 3260 more hydrogen refuelings than the FCPHEV-40, showing that the PHEV-X control strategy provides more fuel savings than the H2 Highway control strategy. These comparisons proved that a FCPHEV using a conventional PHEV-X control strategy provides more utilization of battery energy and more fuel cost savings than a FCPHEV using the H2 Highway control strategy.

3.2 Hydrogen Filling Station GIS Analysis

Next the effect of FCPHEVs on the location of hydrogen refuelings is analyzed. The total refueling results for both control strategies in Table 12 shows a large difference in the total number of refuelings between the two control strategies. From this difference this analysis will now look at the locations of these refuelings, and how their concentration may affect the location of the hydrogen refueling infrastructure.

Using the methods outlined in 2.2 Hydrogen Filling Station GIS Analysis, every refueling location was determined for all of the vehicles within the PSRC fleet for each of control strategies and all four battery ranges. The refueling locations of each control strategy will be compared across the four all-electric ranges, but first the refueling locations of a FCV will be looked at. With zero all-electric range, the FCV represents the worst case refueling scenario. It will behave much like a conventional petroleum ICE vehicle, and will represent how the drivers of Puget Sound utilized the roadways without the assistance of a battery pack with some all-electric range. The refueling locations of the FCV are located along the major highways, but they are also dispersed in urban and suburban areas across the state of Washington and the Puget

Sound area as shown in Figure 19. Because the FCV fleet required more refuelings than either the PHEV-X or the H2 Highway control strategies (Table 12), the density and number of hydrogen refuelings is greater in the FCV fleet than it is in the PHEV fleets.

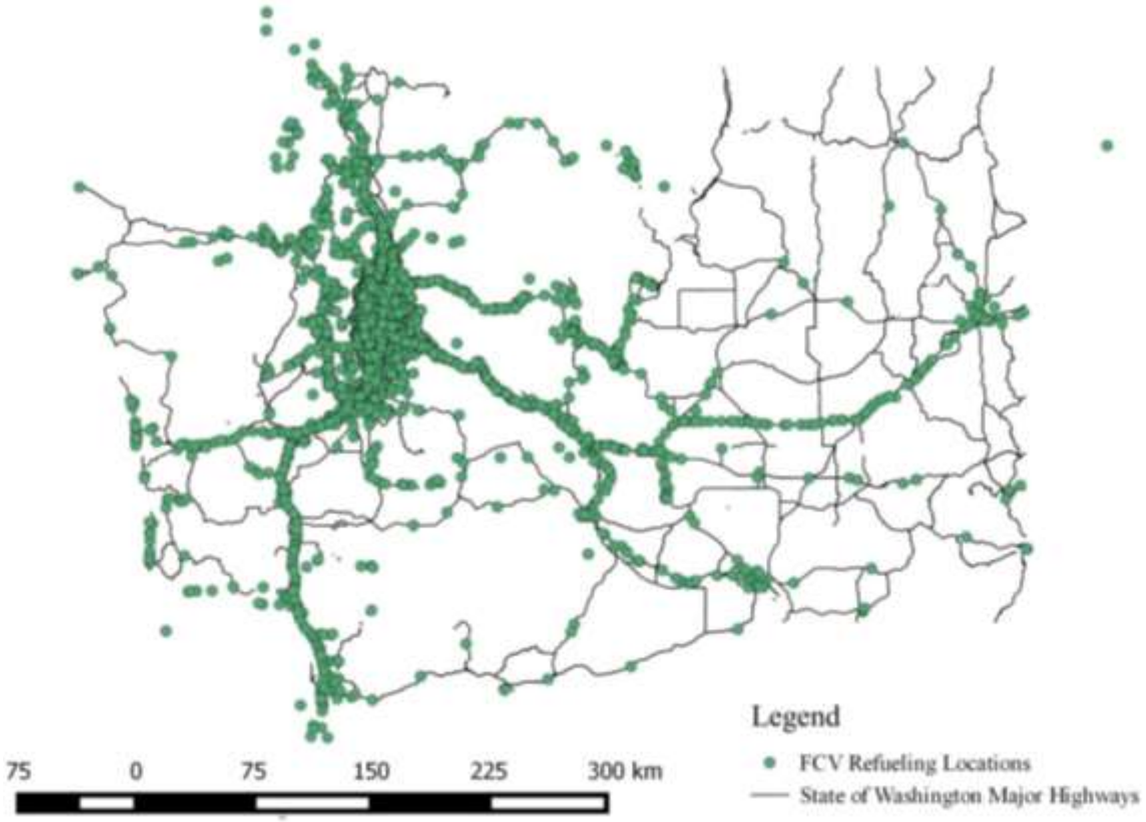

Figure 19 Statewide refueling locations for the FCV, using the FE numbers from the FCPHEV-10.

The refueling locations plotted on top of a map of the major highways in the state of Washington for the PHEV-X control strategy are mapped in Figure 20, and the refueling locations for the H2 Highway control strategy are mapped in Figure 21. From this statewide view of the hydrogen refueling locations for both control strategies, and all four all-electric ranges, there are a few observations that should be noted:

- All eight refueling location maps show that a large number of the hydrogen refueling events occur around the metropolitan regions of the Puget Sound area. From this map it seems as if the density of urban center refueling locations increase as the all-electric range decreases for both control strategies. This point will be further investigated later in this section.

- Long trips in and out of the Puget Sound area occur along Washington’s major highways regardless of the all-electric range or control strategy of the FCPHEV. The only visual difference in refueling locations between the control strategies and all-electric ranges is the density of hydrogen refuelings located along these major highways.

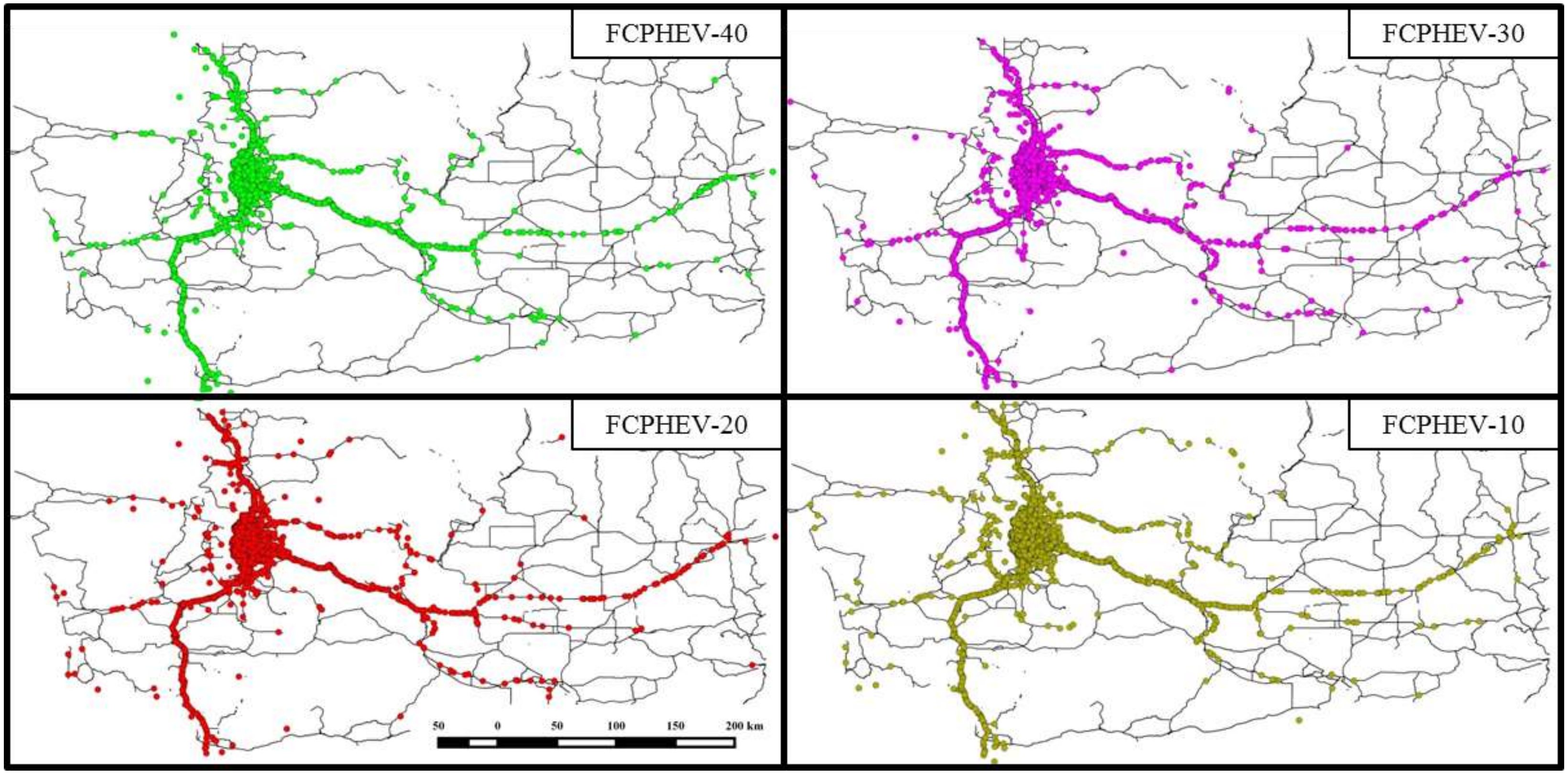

Figure 20 Statewide view of the hydrogen refueling events for all four all-electric ranges for the PHEV-X control strategy.

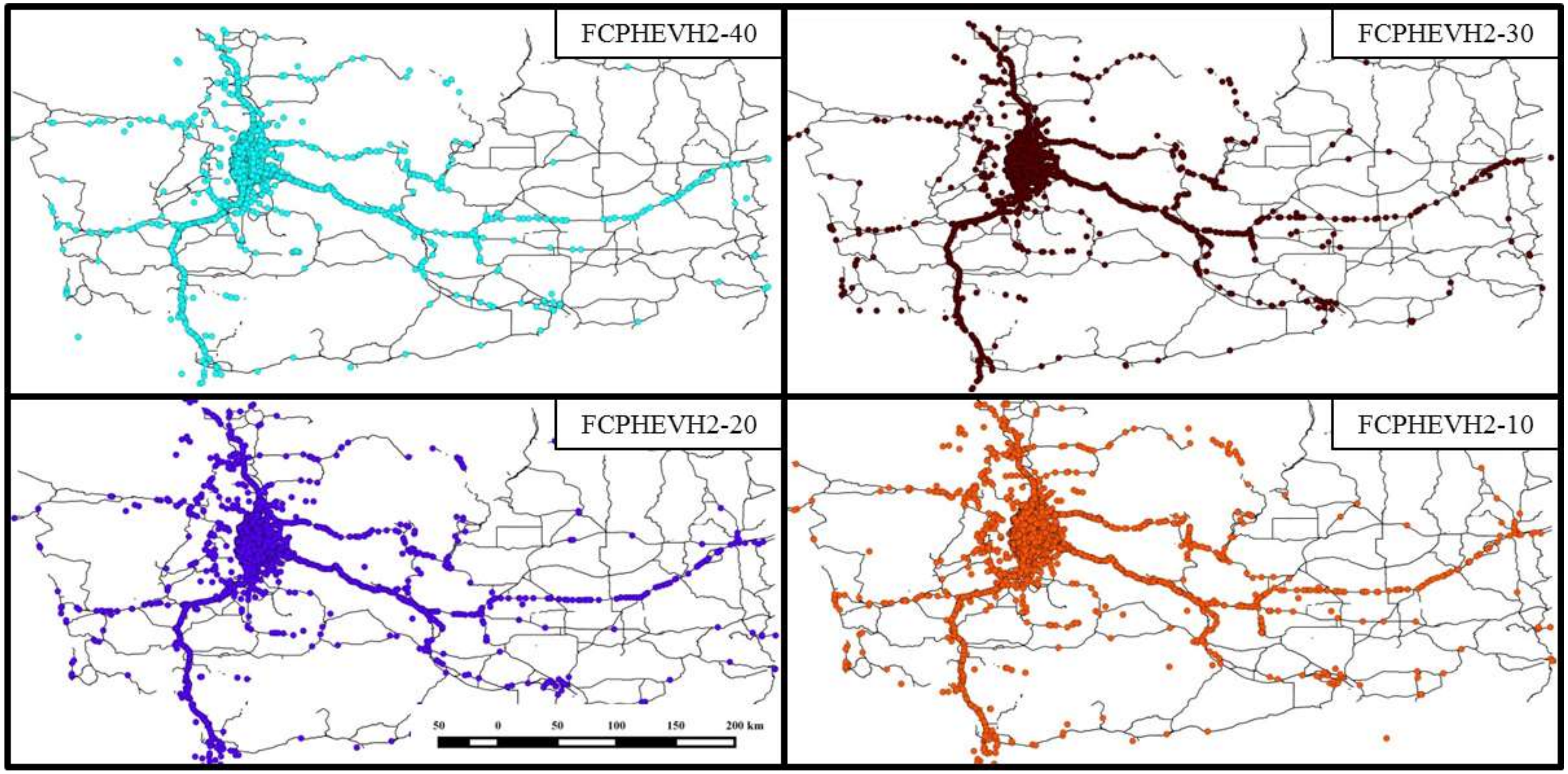

Figure 21 Statewide view of the refueling events for all four all-electric ranges for the H2 Highway control strategy.

The qualitative mapping of the refueling locations for both control strategies in Figure 20 and Figure 21 showed that besides the vehicles that are taking long distance trips on the major highways, the majority of refueling events take place around the more densely populated areas of Puget Sound. It can be determined from the trip data that the majority of vehicles within the studied PSRC fleet commuted to the city frequently for work or other activities. Therefore, the next mappings will look more closely at the concentration of hydrogen refuelings around the cities and highway in the Puget Sound area. When zoomed in on the Puget Sound area, as shown in Figure 22, the variation in refueling locations becomes more evident. The map of the FCPHEV-40 and FCPHEVH2-40 vehicle fleet refueling shows a variation of highway and urban refueling locations. Layered on top of each other, it can be seen that both control strategies have large concentrations of refuelings along the toll roads and highways that run through the Puget Sound area, but the FCPHEVH2-40 vehicle fleet requires more refuelings thus the density of their refuelings is larger on these roadways than the FCPHEV-40 fleet. The map also shows more refueling events located in urban areas than seen on the statewide maps. While both control strategies generate urban refueling events, the map shows that the H2 Highway control strategy generates a larger and more dispersed cluster of refueling locations in the Puget Sound urban areas.

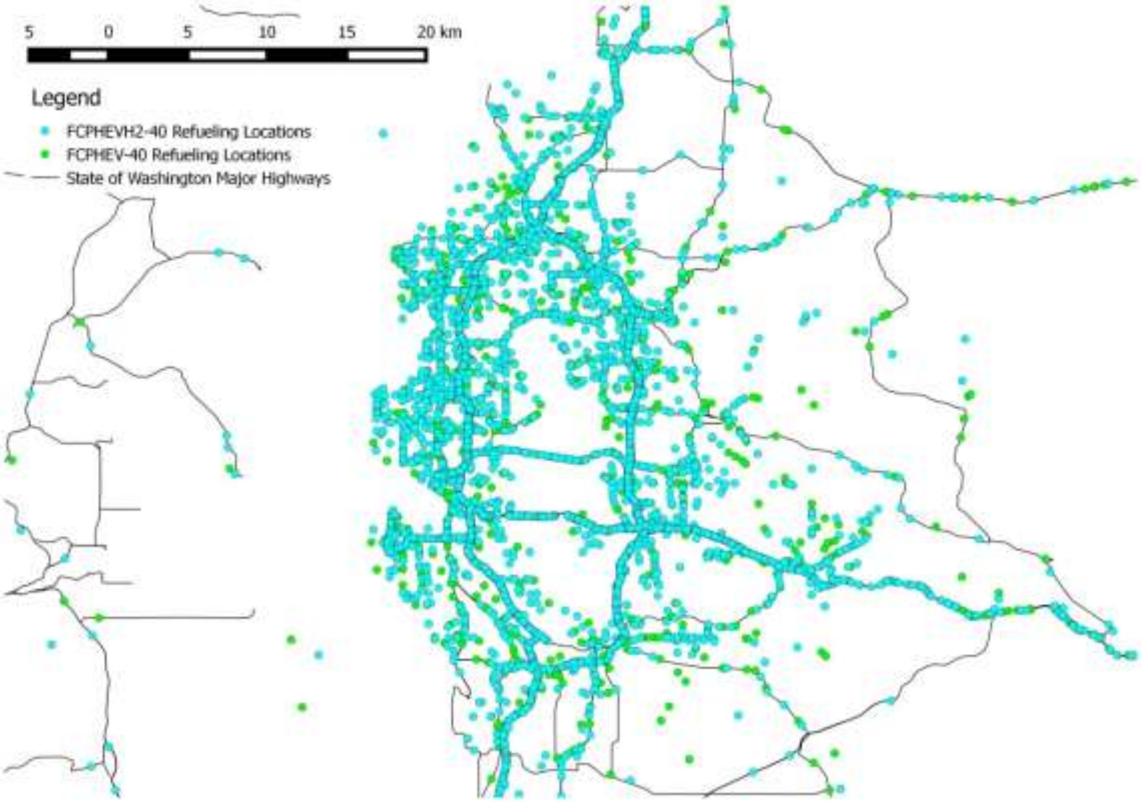

Figure 22 Map of the refueling locations for both control strategies with 40mi all-electric range.

As the all-electric range of the FCPHEV decreases toward 10mi, the density of refueling locations around the Puget Sound area begins to increase. As shown in Figure 23, the refueling locations for the FCPHEV-10 and FCPHEVH2-10 fleets are more densely located around the major toll ways and urban areas than the refueling locations of the FCPHEV-40 and FCPHEVH2-40 fleets in Figure 22. In comparing the refueling locations of the FCPHEV-10 and FCPHEVH2-10, the map shows that the FCPHEVH2-10 has a wider cluster of refueling events in the urban areas of Puget Sound than the FCPHEV-10. With two and half times more refuelings for the entire fleet, the FCPHEVH2-10 seems to not be concentrating these refuelings on the highway systems but instead expanding them throughout the Puget Sound area.

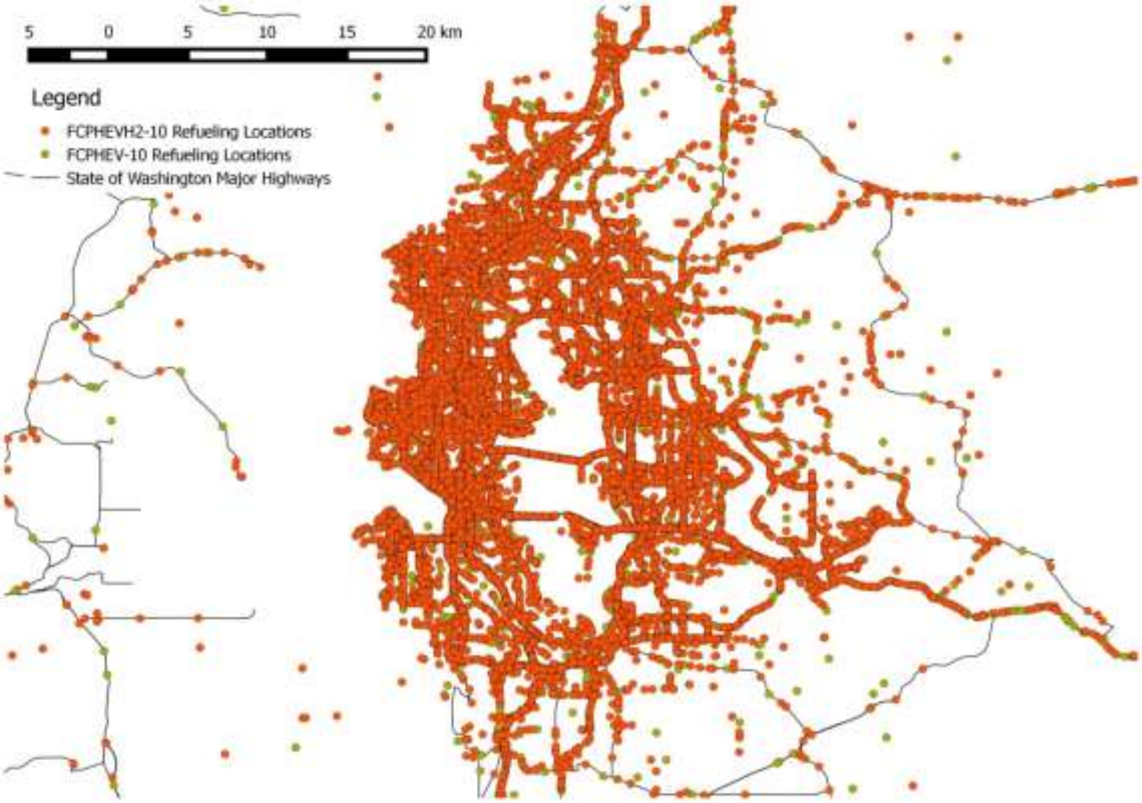

Figure 23 Map of the refueling locations for both control strategies with 10mi all-electric range.

In order to better compare the concentration of hydrogen refueling for both control strategies the number of refuelings on the highway were calculated using the buffer method described in 2.2 Hydrogen Filling Station GIS Analysis. From this method, Figure 24 shows the percentage of hydrogen refueling locations that occurred within the highway system in comparison to the total number of refuelings for the entire FCPHEV fleet. The results show that with 40mi of all-electric range the PHEV-X and the H2 Highway control strategies concentrate 61-65% of their refueling locations to Washington's highway system. However, as the all-electric range of the FCPHEV decreases the inclusion of hydrogen refuelings in the highway system decreases quite differently between the two control strategies. For the H2 Highway control strategy the number of refuelings that are located on highways decreases from 61.85% for the FCPHEVH2-40 all the way to 40.21% for the FCPHEVH2-10. For the same stretch the

FCPHEV-40 has 64.65% of the hydrogen refuelings located on the highway, while the FCPHEV-10 has 55.04% of the fleet's refuelings on the highway. The difference of 30mi of all-electric range only decreases the number of refuelings on the highway by 9.61% for the PHEV-X control strategy, while the same decrease in all-electric range created a decrease in highway refuelings by 21.64% for the H2 Highway control strategy.

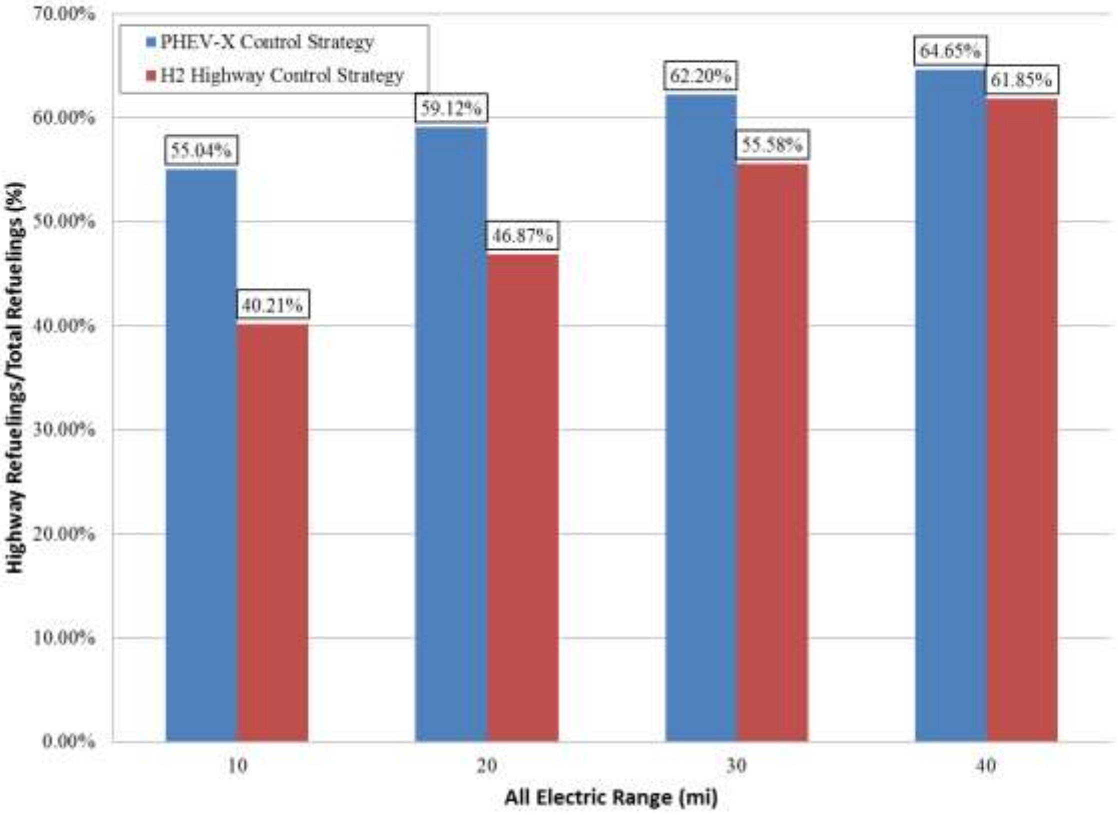

Figure 24 Percentage of hydrogen refuelings on the highway.

From the overall refueling results, it should be noted the vehicles of the PSRC had 34.76% of their refuelings occur on the highway while driving the FCV. Because the FCV behaves much like a conventional ICE vehicle (no electric range) this percentage is indicative of the normal driving behavior of the commuters in the Puget Sound area, which means that a majority of their driving occurs in urban and suburban areas.

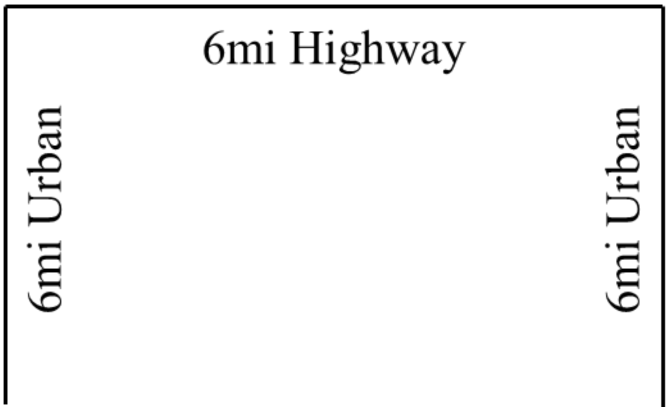

Figure 25 Sample trip representing the driving behavior of the Puget Sound area.

By studying an example trip that has 2/3 urban driving and 1/3 highway driving, the probability of a FCPHEV needing to refuel on either the highway or an urban/suburban road can be estimated. A trip with 6mi on urban roads, then 6mi on the highway, and then 6mi on urban roads would be an example of such a hypothetical 2/3 urban driving trip, shown in Figure 25. In this instance, the probability of a FCPHEV-10 needing to refuel on the highway would be 1.5:1, and the probability of a FCPHEVH2-10 needing to refuel on the highway would be 2:1. This example trip supports the results of the simulations above determined that vehicles using the PHEV-X control strategy have a better chance of running out of hydrogen on the highway than the same vehicles using the H2 Highway control strategy.

3.2.1 Hydrogen Filling Station GIS Analysis Summary

The purpose of research question 2 was to determine if the FCPHEV had any effect on the location and quantity of hydrogen refuelings of a vehicle fleet. The research question was answered by answering to sub questions that posed the effect of the vehicle architecture and control strategy on the location and quantity of hydrogen refuelings:

- Does this requirement for hydrogen infrastructure change based on the all-electric range of the FCPHEV?

    - The results of the hydrogen refueling analysis shows that hydrogen refuelings are concentrated to the highway more for FCPHEV fleets with large all-electric ranges, no matter the energy management control strategy. The FCPHEV-40 fleet had 64.65% of their hydrogen refuelings on the highway, while the FCPHEV-10 fleet had 55.04% of their hydrogen refuelings on the highway. In similar fashion, the FCPHEVH2-40 fleet had 61.85% of its hydrogen refuelings on the highway, while the FCPHEVH2-10 fleet had 40.21% of its hydrogen refuelings on the highway. In all FCPHEV simulation cases, the hydrogen refuelings were concentrated more on the highways than the number of refuelings for a conventional FCV.
- Is there an energy management control strategy that centralizes the FCPHEV's hydrogen refueling needs?
    - The percentage of highway hydrogen refuelings for both control strategies showed that the H2 Highway control strategy did not concentrate the number of hydrogen refuelings to the highway as much as the PHEV-X control strategy did. For 40mi of all-electric range, both control strategies had nearly 65% of their refuelings on the highway, but for 10mi of all electric range the FCPHEV-10 was above 50% in highway refuelings while the FCPHEVH2-10 was closer to 40%. To better understand why the PHEV-X control strategy was refueling more often on the highway, the probability of running out of hydrogen on the highway was calculated for both control strategies. On a sample day of driving for a vehicle in the PSRC fleet the PHEV-X control strategy had a probability of 1:1 of running

out of hydrogen on the highway, while the H2 Highway control strategy had a probability of 2.25:1 of running out of hydrogen on the highway.

4.0 CONCLUSIONS

This thesis analyzed the real world operation of the FCPHEV architecture using location specific vehicle trip data in the Puget Sound area from NREL's TSDC. A simulated FCPHEV fleet was studied using two energy management control strategies (PHEV-X and H2 Highway) and four all-electric driving ranges (10mi, 20mi, 30mi, and 40mi). The analysis was conducted to determine the driving behavior and energy utilization of the FCPHEV fleet, as well as the effect of the FCPHEV architecture on the location and density of hydrogen refueling needs.

The yearly results for the FCPHEV showed a larger usage of the battery pack by the PHEV-X control strategy for all-electric ranges of 20mi, 30mi, and 40mi than the H2 Highway control strategy vehicles. The behavior of the two FCPHEV control strategies began to converge when both vehicle fleets had an all-electric range of 10mi. However, the UF analysis of the two control strategies showed that that conventional PHEV-X control strategy drove a higher percentage of all-electric miles over an entire year than the H2 Highway control strategy. Even at the lowest all-electric range (10mi) the PHEV-X control strategy vehicle fleet drove 11.57% more all-electric miles. A FCPHEV-40 provides nearly 22% more all-electric miles than the FCPHEVH2-40 while also needing to refill the hydrogen storage tanks only half as many times as the FCPHEVH2-40. The FCPHEVs using the PHEV-X control strategy also provided huge refueling savings when compared to the number of refuelings of a conventional FCV. The FCPHEV-10 requires only 20.19% of the refuelings the FCV requires, and the FCPHEV-40 needs only 6.84% of the total refuelings that the FCV needed over the survey period.

The hydrogen refueling locations found for both the PHEV-X and H2 Highway control strategies showed that a large portion of the refuelings occurred on the highways of Washington.

As the electric range of the FCPHEV decreased, and the number of refuelings subsequently increased, the location of the hydrogen refuelings became more dispersed into the urban areas of Puget Sound. By looking at the percentage of hydrogen refuelings located on the highway in comparison to the total number of refuelings required by the PSRC fleet, the results showed that no matter the all-electric range the PHEV-X control strategy had more refuelings on the highway than the H2 Highway control strategy. In comparison to the percentage of FCV refuelings on the highway, the FCPHEV-40 runs out of fuel on the highway 29.89% more than the FCV. Therefore, a control strategy that tries to centralize fuel cell utilization to the highway system doesn’t provide added benefit when locating hydrogen refueling stations. In fact the FCPHEV-40 provides higher concentrations of highway refuelings over both the H2 Highway control strategy and a conventional FCV.

The integration of the FCPHEV architecture into the daily commute of the vehicles of the Puget Sound travel survey shows that it can handle the majority of driver’s trips with the all-electric range of the battery pack. Even with a conventional PHEV-X control strategy, the higher concentration of highway refueling needs would allow for the building of a hydrogen infrastructure to be more centered on the highway system even within the more densely populated areas of Puget Sound. This result demonstrates that this technology can facilitate the integration of the hydrogen highway refueling infrastructure, and that it is not necessary to wait for the infrastructure to be built in order to begin production of hydrogen based vehicles. While the results of this thesis are sensitive to the regional characteristics of the Puget Sound area, the analysis of the integration of the FCPHEV architecture into daily commutes in other major metropolitan areas could demonstrate that the FCPHEV provide similar driving and infrastructure benefits.

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6.0 APPENDIX

6.1 Fleet Energy Consumption Python Script

```
""" HouseHold_PSRC_Database_Query_v3.py
Author: Jake Bucher
Latest Revision: 4/11/14
"""
import time
import psycopg2
import numpy as np
import csv
TIME_START = time.time()
## COLLECTING HOUSEHOLD IDS TO PASS THROUGH DAY TRIP MILE CALCULATOR
HH_MULT_ID = [
    "00048",
     ]
TOTAL_RESULTS = [[0 for col in range(14)] for row in range(len(HH_MULT_ID)+1)]
TOTAL_RESULTS[0] = [
    'Household ID',
    'Veh1: All Electric Travel (mi)',
    'Veh1: H2 Supported Travel (mi)',
    'Veh1: H2 Fuel Consumed (kg)',
    'Veh1: FC Starts (#)',
    'Veh2: All Electric Travel (mi)',
    'Veh2: H2 Supported Travel (mi)',
    'Veh2: H2 Fuel Consumed (kg)',
    'Veh2: FC Starts (#)',
    'Veh3: All Electric Travel (mi)',
    'Veh3: H2 Supported Travel (mi)',
    'Veh3: H2 Fuel Consumed (kg)',
    'Veh3: FC Starts (#)',
    'Number of Days Studied (#)'
    ]
```

```
for h in range(0,len(HH_MULT_ID)):

    ## CLEARING ALL IMPORTANT ARRAYS
#     del TRIP_ID[:]
#     del VEH_ID[:]
#     del TRIP_DATE[:]
#     del UNIQ_DAYS[:]
#     del DAY_TRIP_MILES[:]
#     del EV_MILES[:]
#     del H2_MILES[:]
#     del H2_FUEL_USED[:]
#     del FC_STARTS[:]
    ## DATABASE CONNECTION
    # Database connection information
    db = ""             #Puget Sound database
    us = ""       #NREL issued database username
    pw = ""       #NREL issued database password
    ho = ""        #Host address of tsdc database
    pt = ""            #Host port of tsdc database
    # Connection to database
    conn = psycopg2.connect(host = ho, port = pt, database = db, user = us, password = pw)
    cur  = conn.cursor()
    ## HOUSEHOLD ID DATABASE QUERY
    # Declaring array to store the Trip IDs from Household ID query
    TRIP_ID = [[0 for col in range(1)] for row in range(3500)] #Matrix size made large to accomodate the number of trips for each household
    # Declaring Household ID for SQL database query
    HH_ID = HH_MULT_ID[h]
    HH_QUERY = """
    TRUNCATE TABLE House_ID_1;
    DROP TABLE House_ID_1;
    CREATE TABLE House_ID_1
    (Trip_ID varchar(50)
    );
    INSERT INTO House_ID_1(
```

```
Trip_ID

)

SELECT trips.trip_id

FROM normal.trips

WHERE trips.hhid = %s AND trips.average_trip_speed_nrel < 80

ORDER BY trips.trip_id;

SELECT *

FROM House_ID_1

"""

# Passing query to PSRC database

cur.execute(HH_QUERY,(HH_ID,))

(temp) = cur.fetchall()

TRIP_ID = temp #Automatically adjust TRIP_ID array size to match array size from database output

length = len(TRIP_ID) #length of TRIP_ID array

# Declaring matrix for database query outputs

TRIP_MILES = [[0 for col in range(6)] for row in range(length+1)] #Matrix size dependant on number of Trip IDs to be passed, and the six outputs of the SQL function

# Adding column names/identifiers to RESULTS matrix

TRIP_MILES[0] = ("Trip ID",

        "Vehicle ID",

        "Total Travel (mi)",

        "Road Travel(mi)",

        "Highway Travel(mi)",

        "Trip Date (YYYY/MM/DD HH:MM:SS)")

## DECLARING DATABASE QUERY

QUERY = """

DROP FUNCTION Road_Calc(varchar);

CREATE OR REPLACE FUNCTION Road_Calc (New_Trip_ID varchar (40))

RETURNS SETOF RECORD AS

$$

DECLARE

TRIP_ID varchar(40);

VEH_ID varchar(15);

Total_mi double precision;
```

```
    Road_mi double precision;
    Highway_mi double precision;
    --Day_Week integer;
    Trip_Start_Date varchar(20);
    --Trip_End_Date varchar(20);
    --Trip_To_Home boolean;
    --Trip_From_Home boolean;
    --Trip_To_Work boolean;
    --Trip_From_Work boolean;
    SQL_RESULTS RECORD;
    BEGIN
    TRIP_ID := New_Trip_ID;
    VEH_ID := (SELECT trips.vehicle_id FROM normal.trips WHERE trips.trip_id = New_Trip_ID);
    Total_mi := (SELECT trips.bktp_mt_total FROM normal.trips WHERE trips.trip_ID = New_Trip_ID);
    Road_mi := (SELECT SUM(points.calc_miles_duration) FROM normal.points, census.roads_2010 WHERE points.trip_id = New_Trip_ID AND ST_DWithin(roads_2010.geom,points.geom,38) AND roads_2010.rttyp = 'M');
    Highway_mi := (SELECT SUM(points.calc_miles_duration) FROM normal.points, census.roads_2010 WHERE points.trip_id = New_Trip_ID AND ST_DWithin(roads_2010.geom,points.geom,38) AND roads_2010.rttyp = 'I');
    --Day_Week := (SELECT trips.day_of_week FROM normal.trips WHERE trips.trip_id = New_Trip_ID);
    Trip_Start_Date := (SELECT trips.bktp_start_date FROM normal.trips WHERE trips.trip_id = New_Trip_ID);
    --Trip_End_Date := (SELECT trips.bktp_end_date FROM normal.trips WHERE trips.trip_id = New_Trip_ID);
    --Trip_To_Home := (SELECT trips.to_home FROM normal.trips WHERE trips.trip_id = New_Trip_ID);
    --Trip_From_Home := (SELECT trips.from_home FROM normal.trips WHERE trips.trip_id = New_Trip_ID);
    --Trip_To_Work := (SELECT trips.to_work FROM normal.trips WHERE trips.trip_id = New_Trip_ID);
    --Trip_From_Work := (SELECT trips.from_work FROM normal.trips WHERE trips.trip_id = New_Trip_ID);
    SELECT  TRIP_ID,
        VEH_ID,
        Total_mi,
        Road_mi,
        Highway_mi,
        --Day_Week,
        Trip_Start_Date
        --Trip_End_Date,
        --Trip_To_Home,
        --Trip_From_Home,
```

```
    --Trip_To_Work,
    --Trip_From_Work
    INTO SQL_RESULTS
    ORDER BY VEH_ID;

RETURN NEXT SQL_RESULTS;
END;
$$
LANGUAGE 'plpgsql' VOLATILE;
SELECT *
FROM Road_Calc(%s)
AS (TRIP_ID varchar(40),
   VEH_ID varchar(15),
   Total_mi double precision,
   Road_mi double precision,
   Highway_mi double precision,
   --Day_Week integer,
   Trip_Start_Date varchar(20));
   --Trip_End_Date varchar(20),
   --Trip_To_Home boolean,
   --Trip_From_Home boolean,
   --Trip_To_Work boolean,
   --Trip_From_Work boolean);
"""
## PASSING QUERY TO PSRC DATABASE
for i in range(1,length+1):
   cur.execute(QUERY,(TRIP_ID[i-1],))
   (temp,) = cur.fetchall()
   TRIP_MILES[i] = temp
## CLOSING CONNECTION TO DATABASE
cur.close()     #Closing cursor
conn.close()    #Closing connection
## DETERMINING NUMBER OF VEHICLES WITHIN THE HOUSEHOLD ID
VEH_COUNT = [[0 for col in range(1)] for row in range(length)]
```

```
VEH = [[0 for col in range(1)] for row in range(length)]

VEH = [row[1] for row in TRIP_MILES] # Selecting vehicle ID column from 'TRIP_MILES' matrix

VEH = sorted(VEH) # Sorting the vehicles numerically

for i in range(1,length+1):

    if VEH[i][0] == VEH[i-1][0]:

        VEH_COUNT[i-1][0] = 0

    else:

        VEH_COUNT[i-1][0] = 1

VEH_COUNT = reduce(lambda x, y: x+y, VEH_COUNT)

NUM_VEHICLES = sum(VEH_COUNT) + 1 # Number of vehicles per household. +1 added for the initial vehicle in the count

VEH_ID = [[0 for col in range(1)] for row in range(NUM_VEHICLES)]

for i in range(1,NUM_VEHICLES+1):

    I = str(i)

    VEH_ID[i-1][0] = HH_ID + '_0' + I


## CONVERTING TRIP DATA MATRIX TO NUMPY ARRAY AND REMOVING 'NONE' INDECIES

TRIP_MILES = np.array([TRIP_MILES])

TRIP_MILES = np.where(TRIP_MILES == np.array(None),0,TRIP_MILES)

## CONVERTING TRIP DATA MATRIX BACK TO PYTHON LIST

TRIP_MILES = np.squeeze(np.asarray(TRIP_MILES))

## COLLECTING DAY OF TRAVEL FOR EACH TRIP

TRIP_DATE = [row[5] for row in TRIP_MILES]

TRIP_DATE = [i.split(' ',1)[0] for i in TRIP_DATE]

UNIQ_DAYS = [[0 for col in range(1)] for row in range(len(TRIP_DATE))]  #Creating array for all of the days of travel for the household


for i in range(1,len(TRIP_DATE)):

    if TRIP_DATE[i-1] == TRIP_DATE[i]:

        UNIQ_DAYS[i] = 0

    elif TRIP_DATE[i-1] != TRIP_DATE[i]:

        UNIQ_DAYS[i] = TRIP_DATE[i]

del UNIQ_DAYS[0]

UNIQ_DAYS = filter(lambda a: a != 0, UNIQ_DAYS)

## CALCULATING TOTAL MILES PER DAY FOR EACH VEHICLE
```

```
DAY_TRIP_MILES = [[0 for col in range(NUM_VEHICLES)] for row in range(len(UNIQ_DAYS))]  #Creating array for the total miles traveled each day by each vehicle of the household

for i in range(0,NUM_VEHICLES):
    for j in range(0,len(UNIQ_DAYS)):
        for k in range(1,length+1):
            if TRIP_MILES[k][1] == VEH_ID[i][0] and TRIP_DATE[k] == UNIQ_DAYS[j]:
                DAY_TRIP_MILES[j][i] = DAY_TRIP_MILES[j][i] + TRIP_MILES[k][3] + TRIP_MILES[k][4]
            else:
                DAY_TRIP_MILES[j][i] = DAY_TRIP_MILES[j][i] + 0


## UTILITY FACTOR CALCULATIONS FOR FCPHEV
# 10mi all electric range
#EV_RANGE = 10      # (mi) All electric range
#FE = 55.696        # (mi/kg) Fuel Economy
# 20mi all electric range
#EV_RANGE = 20      # (mi) All electric range
#FE = 55.011        # (mi/kg) Fuel Economy
# 30mi all electric range
#EV_RANGE = 30      # (mi) All electric range
#FE = 53.985        # (mi/kg) Fuel Economy
# 40mi all electric range
EV_RANGE = 40      # (mi) All electric range
FE = 53.288        # (mi/kg) Fuel Economy


# Declaring arrays for calculations
EV_MILES = [[0 for col in range(NUM_VEHICLES)] for row in range(len(DAY_TRIP_MILES))]      # (mi)
H2_MILES = [[0 for col in range(NUM_VEHICLES)] for row in range(len(DAY_TRIP_MILES))]      # (mi)
H2_FUEL_USED = [[0 for col in range(NUM_VEHICLES)] for row in range(len(DAY_TRIP_MILES))]   # (kg)
FC_STARTS = [[0 for col in range(NUM_VEHICLES)] for row in range(len(DAY_TRIP_MILES))]     # (num)
TOT_EV_MILES = [[0 for col in range(NUM_VEHICLES)] for row in range(1)]
TOT_H2_MILES = [[0 for col in range(NUM_VEHICLES)] for row in range(1)]
TOT_VEH_MILES = [[0 for col in range(NUM_VEHICLES)] for row in range(1)]
PER_EV_MILES = [[0 for col in range(NUM_VEHICLES)] for row in range(1)]
TOT_H2_FUEL_USED = [[0 for col in range(NUM_VEHICLES)] for row in range(1)]
```

```
TOT_FC_STARTS = [[0 for col in range(NUM_VEHICLES)] for row in range(1)]

# Calculating all EV miles, H2 miles, H2 gas consumed, and number of FC starts for each trip of each vehicle of the household

for j in range(0,NUM_VEHICLES):

    for i in range(0,len(DAY_TRIP_MILES)):

        if DAY_TRIP_MILES[i][j] <= EV_RANGE:

            EV_MILES[i][j] = DAY_TRIP_MILES[i][j]

            H2_MILES[i][j] = 0

            H2_FUEL_USED[i][j] = 0

            FC_STARTS[i][j] = 0

        elif DAY_TRIP_MILES[i][j] > EV_RANGE:

            EV_MILES[i][j] = EV_RANGE

            H2_MILES[i][j] = DAY_TRIP_MILES[i][j] - EV_RANGE

            H2_FUEL_USED[i][j] = H2_MILES[i][j]/FE

            FC_STARTS[i][j] = 1

        else:

            EV_MILES[i-1][j] = 0

            H2_MILES[i-1][j] = 0

            H2_FUEL_USED[i-1][j] = 0

            FC_STARTS[i-1][j] = 0

# Calculating total EV miles, H2 miles, H2 used, and FC starts for each vehicle of household

for i in range(0,NUM_VEHICLES):

    TOT_EV_MILES[0][i] = sum([row[i] for row in EV_MILES])

    TOT_H2_MILES[0][i] = sum([row[i] for row in H2_MILES])

    TOT_H2_FUEL_USED[0][i] = sum([row[i] for row in H2_FUEL_USED])

    TOT_FC_STARTS[0][i] = sum([row[i] for row in FC_STARTS])

    TOT_VEH_MILES[0][i] = TOT_EV_MILES[0][i] + TOT_H2_MILES[0][i]

    if TOT_VEH_MILES[0][i] > 0:

        PER_EV_MILES[0][i] = TOT_EV_MILES[0][i]/TOT_VEH_MILES[0][i]

    else:

        PER_EV_MILES[0][i] = 0


## OUTPUT DATA TO TEXT FILE


TOTAL_RESULTS[h+1][0] = HH_ID
```

```
        TOTAL_RESULTS[h+1][13] = len(UNIQ_DAYS)


        if NUM_VEHICLES == 1:
            TOTAL_RESULTS[h+1][1] = TOT_EV_MILES[0][0]
            TOTAL_RESULTS[h+1][2] = TOT_H2_MILES[0][0]
            TOTAL_RESULTS[h+1][3] = TOT_H2_FUEL_USED[0][0]
            TOTAL_RESULTS[h+1][4] = TOT_FC_STARTS[0][0]
        elif NUM_VEHICLES == 2:
            TOTAL_RESULTS[h+1][1] = TOT_EV_MILES[0][0]
            TOTAL_RESULTS[h+1][2] = TOT_H2_MILES[0][0]
            TOTAL_RESULTS[h+1][3] = TOT_H2_FUEL_USED[0][0]
            TOTAL_RESULTS[h+1][4] = TOT_FC_STARTS[0][0]
            TOTAL_RESULTS[h+1][5] = TOT_EV_MILES[0][1]
            TOTAL_RESULTS[h+1][6] = TOT_H2_MILES[0][1]
            TOTAL_RESULTS[h+1][7] = TOT_H2_FUEL_USED[0][1]
            TOTAL_RESULTS[h+1][8] = TOT_FC_STARTS[0][1]
        elif NUM_VEHICLES == 3:
            TOTAL_RESULTS[h+1][1] = TOT_EV_MILES[0][0]
            TOTAL_RESULTS[h+1][2] = TOT_H2_MILES[0][0]
            TOTAL_RESULTS[h+1][3] = TOT_H2_FUEL_USED[0][0]
            TOTAL_RESULTS[h+1][4] = TOT_FC_STARTS[0][0]
            TOTAL_RESULTS[h+1][5] = TOT_EV_MILES[0][1]
            TOTAL_RESULTS[h+1][6] = TOT_H2_MILES[0][1]
            TOTAL_RESULTS[h+1][7] = TOT_H2_FUEL_USED[0][1]
            TOTAL_RESULTS[h+1][8] = TOT_FC_STARTS[0][1]
            TOTAL_RESULTS[h+1][9] = TOT_FC_STARTS[0][2]
            TOTAL_RESULTS[h+1][10] = TOT_EV_MILES[0][2]
            TOTAL_RESULTS[h+1][11] = TOT_H2_MILES[0][2]
            TOTAL_RESULTS[h+1][12] = TOT_H2_FUEL_USED[0][2]
        with open('Output.csv', 'wb') as csvfile:
            a = csv.writer(csvfile, delimiter = ',')
            a.writerows(TOTAL_RESULTS)


TIME_END = time.time()
```

```
print "Script Execution Time:"
print TIME_END-TIME_START
```

6.2 Hydrogen Filling Station GIS Analysis Python Script

```
"""GIS_LAT_LONG_REFUELING_LOCATION_CH_CONT_STRAT_v1.py
Assuming vehicle using City/Highway Control Strategy
Author: Jake Bucher
Latest Revision: 5/1/14
"""
import time
import psycopg2
import numpy as np
import csv
import math
TIME_START = time.time()
## HOUSEHOLD ID
HH_MULT_ID = [
    "00048",
    ]
FINAL_RESULTS = [[0 for col in range(2)] for row in range(1)] #Declaring list to store the results of each household query
FINAL_RESULTS[0] = [
    'Veh1: Latitude',
    'Veh1: Longitude',
    'Veh2: Latitude',
    'Veh2: Longitude',
    ]
for h in range(0,len(HH_MULT_ID)):
    ## DATABASE CONNECTION
    # Database connection information
    db = ""            #Puget Sound database
    us = ""      #NREL issued database username
    pw = ""      #NREL issued database password
    ho = ""       #Host address of tsdc database
    pt = ""           #Host port of tsdc database
        # Connection to database
```

```
conn = psycopg2.connect(host = ho, port = pt, database = db, user = us, password = pw)
cur  = conn.cursor()
## HOUSEHOLD ID DATABASE QUERY
# Declaring array to store the Trip IDs from Household ID query
TRIP_ID = [[0 for col in range(1)] for row in range(3500)] #Matrix size made large to accomodate the number of trips for each household
# Declaring Household ID for SQL database query
HH_ID = HH_MULT_ID[h]
HH_QUERY = """
TRUNCATE TABLE House_ID_1;
DROP TABLE House_ID_1;
CREATE TABLE House_ID_1
(Trip_ID varchar(50)
);
INSERT INTO House_ID_1(
Trip_ID
)
SELECT trips.trip_id
FROM normal.trips
WHERE trips.hhid = %s AND trips.average_trip_speed_nrel < 80
ORDER BY trips.trip_id;
SELECT *
FROM House_ID_1
"""
# Passing query to PSRC database
cur.execute(HH_QUERY,(HH_ID,))
(temp) = cur.fetchall()
TRIP_ID = temp #Automatically adjust TRIP_ID array size to match array size from database output
length = len(TRIP_ID) #length of TRIP_ID array

# Declaring matrix for database query outputs
TRIP_MILES = [[0 for col in range(6)] for row in range(length+1)] #Matrix size dependant on number of Trip IDs to be passed, and the six outputs of the SQL function
# Adding column names/identifiers to RESULTS matrix
TRIP_MILES[0] = ("Trip ID",
```

```
        "Vehicle ID",
        "Total Travel (mi)",
        "Road Travel(mi)",
        "Highway Travel(mi)",
        "Trip Date (YYYY/MM/DD HH:MM:SS)")
## DECLARING DATABASE QUERY
QUERY = """
DROP FUNCTION Road_Calc(varchar);
CREATE OR REPLACE FUNCTION Road_Calc (New_Trip_ID varchar (40))
RETURNS SETOF RECORD AS
$$
DECLARE
TRIP_ID varchar(40);
VEH_ID varchar(15);
Total_mi double precision;
Road_mi double precision;
Highway_mi double precision;
--Day_Week integer;
Trip_Start_Date varchar(20);
--Trip_End_Date varchar(20);
--Trip_To_Home boolean;
--Trip_From_Home boolean;
--Trip_To_Work boolean;
--Trip_From_Work boolean;
SQL_RESULTS RECORD;
BEGIN
TRIP_ID := New_Trip_ID;
VEH_ID := (SELECT trips.vehicle_id FROM normal.trips WHERE trips.trip_id = New_Trip_ID);
Total_mi := (SELECT trips.bktp_mt_total FROM normal.trips WHERE trips.trip_ID = New_Trip_ID);
Road_mi := (SELECT SUM(points.calc_miles_duration) FROM normal.points, census.roads_2010 WHERE points.trip_id = New_Trip_ID AND ST_DWithin(roads_2010.geom,points.geom,38) AND roads_2010.rttyp = 'M');
Highway_mi := (SELECT SUM(points.calc_miles_duration) FROM normal.points, census.roads_2010 WHERE points.trip_id = New_Trip_ID AND ST_DWithin(roads_2010.geom,points.geom,38) AND roads_2010.rttyp = 'I');
--Day_Week := (SELECT trips.day_of_week FROM normal.trips WHERE trips.trip_id = New_Trip_ID);
Trip_Start_Date := (SELECT trips.bktp_start_date FROM normal.trips WHERE trips.trip_id = New_Trip_ID);
```

```
--Trip_End_Date := (SELECT trips.bktp_end_date FROM normal.trips WHERE trips.trip_id = New_Trip_ID);
--Trip_To_Home := (SELECT trips.to_home FROM normal.trips WHERE trips.trip_id = New_Trip_ID);
--Trip_From_Home := (SELECT trips.from_home FROM normal.trips WHERE trips.trip_id = New_Trip_ID);
--Trip_To_Work := (SELECT trips.to_work FROM normal.trips WHERE trips.trip_id = New_Trip_ID);
--Trip_From_Work := (SELECT trips.from_work FROM normal.trips WHERE trips.trip_id = New_Trip_ID);
SELECT  TRIP_ID,
        VEH_ID,
        Total_mi,
        Road_mi,
        Highway_mi,
        --Day_Week,
        Trip_Start_Date
        --Trip_End_Date,
        --Trip_To_Home,
        --Trip_From_Home,
        --Trip_To_Work,
        --Trip_From_Work
        INTO SQL_RESULTS
        ORDER BY VEH_ID;
RETURN NEXT SQL_RESULTS;
END;
$$
LANGUAGE 'plpgsql' VOLATILE;
SELECT *
FROM Road_Calc(%s)
AS (TRIP_ID varchar(40),
    VEH_ID varchar(15),
    Total_mi double precision,
    Road_mi double precision,
    Highway_mi double precision,
    --Day_Week integer,
    Trip_Start_Date varchar(20));
    --Trip_End_Date varchar(20),
    --Trip_To_Home boolean,
```

```
    --Trip_From_Home boolean,
    --Trip_To_Work boolean,
    --Trip_From_Work boolean);
"""
## PASSING QUERY TO PSRC DATABASE
for i in range(1,length+1):
    cur.execute(QUERY,(TRIP_ID[i-1],))
    (temp,) = cur.fetchall()
    TRIP_MILES[i] = temp
## DETERMINING NUMBER OF VEHICLES WITHIN THE HOUSEHOLD ID
VEH_COUNT = [[0 for col in range(1)] for row in range(length)]
VEH = [[0 for col in range(1)] for row in range(length)]
VEH = [row[1] for row in TRIP_MILES] # Selecting vehicle ID column from 'TRIP_MILES' matrix
VEH = sorted(VEH) # Sorting the vehicles numerically
for i in range(1,length+1):
    if VEH[i][0] == VEH[i-1][0]:
        VEH_COUNT[i-1][0] = 0
    else:
        VEH_COUNT[i-1][0] = 1
VEH_COUNT = reduce(lambda x, y: x+y, VEH_COUNT)
NUM_VEHICLES = sum(VEH_COUNT) + 1 # Number of vehicles per household. +1 added for the initial vehicle in the count
VEH_ID = [[0 for col in range(1)] for row in range(NUM_VEHICLES)]
for i in range(1,NUM_VEHICLES+1):
    I = str(i)
    VEH_ID[i-1][0] = HH_ID + '_0' + I

## CONVERTING TRIP DATA MATRIX TO NUMPY ARRAY AND REMOVING 'NONE' INDECIES
TRIP_MILES = np.array([TRIP_MILES])
TRIP_MILES = np.where(TRIP_MILES == np.array(None),0,TRIP_MILES)
## CONVERTING TRIP DATA MATRIX BACK TO PYTHON LIST
TRIP_MILES = np.squeeze(np.asarray(TRIP_MILES))
## COLLECTING DAY OF TRAVEL FOR EACH TRIP
TRIP_DATE = [row[5] for row in TRIP_MILES]
TRIP_DATE = [i.split(' ',1)[0] for i in TRIP_DATE]
```

```
UNIQ_DAYS = [[0 for col in range(1)] for row in range(len(TRIP_DATE))]  #Creating array for all of the days of travel for the household
for i in range(1,len(TRIP_DATE)):
    if TRIP_DATE[i-1] == TRIP_DATE[i]:
        UNIQ_DAYS[i] = 0
    elif TRIP_DATE[i-1] != TRIP_DATE[i]:
        UNIQ_DAYS[i] = TRIP_DATE[i]
del UNIQ_DAYS[0]
UNIQ_DAYS = filter(lambda a: a != 0, UNIQ_DAYS)
## DECLARING LISTS FOR CALCULATIONS
VEH_TRIP_CITY_MILES = [[0 for col in range(NUM_VEHICLES)] for row in range(length+1)]
VEH_TRIP_HWY_MILES = [[0 for col in range(NUM_VEHICLES)] for row in range(length+1)]
VEH_TRIP_TOT_MILES = [[0 for col in range(NUM_VEHICLES)] for row in range(length+1)]
TOTAL_MILES = [[0 for col in range(NUM_VEHICLES)] for row in range(length+1)]
EV_MILES = [[0 for col in range(NUM_VEHICLES)] for row in range(length+1)]
H2_MILES = [[0 for col in range(NUM_VEHICLES)] for row in range(length+1)]
H2_FUEL = [[0 for col in range(NUM_VEHICLES)] for row in range(length+1)]
## UTILITY FACTOR CALCULATIONS FOR FCPHEV W/ 40mi ALL ELECTRIC RANGE & 65mi/kg FUEL ECONOMY
# 10mi all electric range
EV_RANGE = 0        # (mi) All electric range
CITY_FE = 54.35       # (mi/kg) UDDS Fuel Economy
HWY_FE = 58.82        # (mi/kg) HWFET Fuel Economy
# 20mi all electric range
#EV_RANGE = 20        # (mi) All electric range
#CITY_FE = 53.62       # (mi/kg) UDDS Fuel Economy
#HWY_FE = 56.82        # (mi/kg) HWFET Fuel Economy
# 30mi all electric range
#EV_RANGE = 30        # (mi) All electric range
#CITY_FE = 52.91       # (mi/kg) UDDS Fuel Economy
#HWY_FE = 55.55        # (mi/kg) HWFET Fuel Economy
# 40mi all electric range
#EV_RANGE = 40        # (mi) All electric range
#CITY_FE = 52.36       # (mi/kg) UDDS Fuel Economy
#HWY_FE = 54.88        # (mi/kg) HWFET Fuel Economy
TANK_CAP = 1.65*3 # (kg) capacity of CSU's H2eV hydrogen storage tanks at full 5000psi
```

```
    for i in range(0,NUM_VEHICLES):
        for j in range(0,len(UNIQ_DAYS)):
            for k in range(1,length+1):
                if TRIP_MILES[k][1] == VEH_ID[i][0]: #Filtering for each vehicle of the household
                    VEH_TRIP_CITY_MILES[k][i] = TRIP_MILES[k][3] #City miles on trip
                    VEH_TRIP_HWY_MILES[k][i]  = TRIP_MILES[k][4] #Highway miles of trip
                    VEH_TRIP_TOT_MILES[k][i]  = TRIP_MILES[k][3] + TRIP_MILES[k][4] #Total miles on trip
                else:
                    VEH_TRIP_CITY_MILES[k][i] = 0
                    VEH_TRIP_HWY_MILES[k][i]  = 0
                    VEH_TRIP_TOT_MILES[k][i]  = 0
                if TRIP_DATE[k] == TRIP_DATE[k-1]: #Determining if the current trip is on the same day as the previous trip
                    TOTAL_MILES[k][i] = TOTAL_MILES[k-1][i] + VEH_TRIP_TOT_MILES[k][i] #Summing the total amount of miles driven on each unique travel day
                    EV_MILES[k][i]    = EV_MILES[k-1][i] + VEH_TRIP_CITY_MILES[k][i] #Summing the total amount of EV miles driven on each unique travel day
                    if EV_MILES[k][i] < EV_RANGE:
                        H2_MILES[k][i] = VEH_TRIP_HWY_MILES[k][i] #Amount of miles driven with fuel cells
                        H2_FUEL[k][i]  = VEH_TRIP_HWY_MILES[k][i]/HWY_FE + H2_FUEL[k-1][i]#Amount of hydrogen consumed while driving on highway
                    else:
                        if VEH_TRIP_TOT_MILES[k][i] > 0:
                            H2_MILES[k][i] = VEH_TRIP_CITY_MILES[k][i] - (EV_RANGE - EV_MILES[k-1][i]) + VEH_TRIP_HWY_MILES[k][i] #Amount of miles driven with fuel cells after battery depleted
                            H2_FUEL[k][i] = (VEH_TRIP_CITY_MILES[k][i] - (EV_RANGE - EV_MILES[k-1][i]))/CITY_FE + VEH_TRIP_HWY_MILES[k][i]/HWY_FE + H2_FUEL[k-1][i] #Amount of hydrogen consumed on city streets and highway
                        else:
                            H2_MILES[k][i] = 0
                            H2_FUEL[k][i]  = 0 + H2_FUEL[k-1][i]
                else:
                    TOTAL_MILES[k][i] = VEH_TRIP_TOT_MILES[k][i] #Summing the first travel of the new unique travel day
                    EV_MILES[k][i]    = VEH_TRIP_CITY_MILES[k][i] #Summing the first city travel of the new travel day
                    if EV_MILES[k][i] < EV_RANGE:
                        H2_MILES[k][i] = VEH_TRIP_HWY_MILES[k][i] #Amount of miles driven with fuel cells
                        H2_FUEL[k][i]  = VEH_TRIP_HWY_MILES[k][i]/HWY_FE + H2_FUEL[k-1][i] #Amount of hydrogen consumed while driving on the highway
                    else:
```

```
                        if VEH_TRIP_TOT_MILES[k][i] > 0:
                            H2_MILES[k][i] = VEH_TRIP_CITY_MILES[k][i] - (EV_RANGE - EV_MILES[k-1][i]) + VEH_TRIP_HWY_MILES[k][i] #Amount of miles driven with fuel cells after battery depleted
                            H2_FUEL[k][i] = (VEH_TRIP_CITY_MILES[k][i] - (EV_RANGE - EV_MILES[k-1][i]))/CITY_FE + VEH_TRIP_HWY_MILES[k][i]/HWY_FE + H2_FUEL[k-1][i] #Amount of hydrogen consumed on city streets and highway
                        else:
                            H2_MILES[k][i] = 0
                            H2_FUEL[k][i]  = 0 + H2_FUEL[k-1][i]
    ## DETERMINING THE TRIP ID ASSOCIATED WITH H2 REFUELING
    H2_REFIL_TRIP_ID = [[0 for col in range(NUM_VEHICLES)] for row in range(int(math.ceil(max(H2_FUEL[-1])/TANK_CAP))-1)] #Initializing list for recording the trip ids associated with H2 refills
    DEBUG = [[0 for col in range(NUM_VEHICLES)] for row in range(int(math.ceil(max(H2_FUEL[-1])/TANK_CAP))-1)]
    for i in range(0,NUM_VEHICLES):
        for m in range(1,int(math.ceil(max(H2_FUEL[-1])/TANK_CAP))):
            for k in range(1,length+1):
                if H2_FUEL[k][i] > m*TANK_CAP: #Determining if the accumulated H2 fuel consumption at the current trip is greater than the capacity of the tanks
                    H2_REFIL_TRIP_ID[m-1][i] = TRIP_MILES[k][0] #Storing trip id of refill
                    DEBUG[m-1][i] = k
                    m = m + 1
    ## DETERMINING THE DISTANCE ON THE TRIP AT WHICH THE FCPHEV WOULD NEED TO REFILL
    REFIL_TRIP_DIST = [[0 for col in range(NUM_VEHICLES)] for row in range(len(H2_REFIL_TRIP_ID))] #Initializing list for calculating total miles driven on trip up to H2 refill locaiton
    REFIL_TRIP_H2_FUEL = [[0 for col in range(NUM_VEHICLES)] for row in range(len(H2_REFIL_TRIP_ID))] #Initializing list for calculating the total amount of H2 fuel consumed during refill trip
    REFIL_TRIP_H2_MI_CONS = [[0 for col in range(NUM_VEHICLES)] for row in range(len(H2_REFIL_TRIP_ID))] #Initializing list for calculting the amount of H2 consumed per mi
    REFIL_TRIP_H2_FUEL_TO_EMPTY = [[0 for col in range(NUM_VEHICLES)] for row in range(len(H2_REFIL_TRIP_ID))] #Initializing list for calculating the amount of H2 before refill at beginning of trip
    REFIL_TRIP_MILES_TO_REFIL = [[0 for col in range(NUM_VEHICLES)] for row in range(len(H2_REFIL_TRIP_ID))] #Initializing list for calculating miles from beginning of trip to point of refill
    for i in range(0,NUM_VEHICLES):
        for m in range(1,int(math.ceil(max(H2_FUEL[-1])/TANK_CAP))):
            for k in range(1,length+1):
                if H2_REFIL_TRIP_ID[m-1][i] == TRIP_MILES[k][0]: #Finding the data for the trip id associated with a H2 refill
                    if TRIP_DATE[k] == TRIP_DATE[k-1]:
                        REFIL_TRIP_DIST[m-1][i] = TOTAL_MILES[k][i] - TOTAL_MILES[k-1][i] #mi, total miles of trip
                        REFIL_TRIP_H2_FUEL[m-1][i] = H2_FUEL[k][i] - H2_FUEL[k-1][i] #kg, total H2 fuel used on trip
```

```
            REFIL_TRIP_H2_MI_CONS[m-1][i] = REFIL_TRIP_H2_FUEL[m-1][i]/REFIL_TRIP_DIST[m-1][i] #kg/mi, calculating H2 consumption on trip per miles

            REFIL_TRIP_H2_FUEL_TO_EMPTY[m-1][i] = m*TANK_CAP - H2_FUEL[k-1][i] #kg, calculating amoutn of H2 fuel left in tank at beginning of trip

            REFIL_TRIP_MILES_TO_REFIL[m-1][i] = REFIL_TRIP_H2_FUEL_TO_EMPTY[m-1][i]/REFIL_TRIP_H2_MI_CONS[m-1][i] #mi, distance into trip at which refilling required

          else:

            REFIL_TRIP_DIST[m-1][i] = TOTAL_MILES[k][i] #mi, total miles of trip

            REFIL_TRIP_H2_FUEL[m-1][i] = H2_FUEL[k][i] - H2_FUEL[k-1][i] #kg, total H2 fuel used on trip

            REFIL_TRIP_H2_MI_CONS[m-1][i] = REFIL_TRIP_H2_FUEL[m-1][i]/REFIL_TRIP_DIST[m-1][i] #kg/mi, calculating H2 consumption on trip per miles

            REFIL_TRIP_H2_FUEL_TO_EMPTY[m-1][i] = m*TANK_CAP - H2_FUEL[k-1][i] #kg, calculating amoutn of H2 fuel left in tank at beginning of trip

            REFIL_TRIP_MILES_TO_REFIL[m-1][i] = REFIL_TRIP_H2_FUEL_TO_EMPTY[m-1][i]/REFIL_TRIP_H2_MI_CONS[m-1][i] #mi, distance into trip at which refilling required

  ## DETERMINING QGIS GEOMETRICAL COORDINATE OF THE REFUELING LOCATIONS

  TEMP_TRANS = [[0 for col in range(4)] for row in range(500)] #Declaring temporary list to store SQL query results

  LAT_LONG = [[0 for col in range(NUM_VEHICLES*2)] for row in range(len(H2_REFIL_TRIP_ID))] #Declaring list to store the latitude and longitutde points of the vehicle refills

    REFIL_QUERY = """

  TRUNCATE TABLE REFILGEOM;

  DROP TABLE REFILGEOM;

    CREATE TABLE REFILGEOM

  (Point_GEOM varchar(50),

  Point_MILE float,

  Point_LAT float,

  Point_LONG float

  );

  INSERT INTO REFILGEOM

  (Point_GEOM,

  Point_MILE,

  Point_LAT,

  Point_LONG

  )

    SELECT

  points.geom,

  points.calc_miles_duration,
```

```
points.latitude,
points.longitude
    FROM
normal.points
    WHERE
points.trip_id = %s
    ORDER BY
points.local_ts;
    SELECT *
FROM REFILGEOM
""""
for i in range(0,NUM_VEHICLES):
    for j in range(0,len(H2_REFIL_TRIP_ID)):
        REFIL_TRIP_ID = H2_REFIL_TRIP_ID[j][i] #Selecting trip ID from generatled list of refill trips
        if REFIL_TRIP_ID == 0:
            j = j+1
        else:
            cur.execute(REFIL_QUERY,(REFIL_TRIP_ID,)) #Passing SQL query to database
            (temp) = cur.fetchall() #Collecting SQL query results
            TEMP_TRANS = temp
                MI_CNT = [[0 for col in range(1)] for row in range(len(TEMP_TRANS))] #Declaring list to count the total miles of trip up to time of refil
                for k in range(0,len(TEMP_TRANS)):
                MI_CNT[k][0] = MI_CNT[k-1][0] + TEMP_TRANS[k][1]
                if MI_CNT[k][0] < REFIL_TRIP_MILES_TO_REFIL[j][i] + 0.15 and MI_CNT[k][0] > REFIL_TRIP_MILES_TO_REFIL[j][i] - 0.15:
                    LAT_LONG[j][i*2] = TEMP_TRANS[k][2]
                    LAT_LONG[j][(i*2)+1] = TEMP_TRANS[k][3]
                    k = len(TEMP_TRANS)
                else:
                    k = k+1
for i in range(0,len(LAT_LONG)):
    FINAL_RESULTS.append(LAT_LONG[i])
    ## OUTPUT CHOSEN RESULTS TO .csv FILE
with open('Output.csv', 'wb') as csvfile:
```

```
        a = csv.writer(csvfile, delimiter = ',')
        a.writerows(FINAL_RESULTS)
## CLOSING CONNECTION TO DATABASE
cur.close()     #Closing cursor
conn.close()    #Closing connection
TIME_END = time.time()
print "Script Execution Time:"
print TIME_END-TIME_START
```

LIST OF ABBREVIATIONS

CAFE – Corporate Average Fuel Economy
ZEV – Zero Emission Vehicle
DOT – Department of Transportation
MY – Model Year
OEM – Original Equipment Manufacturer
HEV – Hybrid Electric Vehicle
PHEV – Plug-in Hybrid Electric Vehicle
FCV – Fuel Cell Vehicle
DC – Direct Current
FCTO – Fuel Cell Technologies Office
CV – Conventional Vehicle
BEV – Battery Electric Vehicle
MILP – Mixed Integer Linear Programming
GIS – Geographical Information System
AVTC – Advanced Vehicle Technology Competition
PEV - Plug-in Electric Vehicle
CSU VIT – Colorado State University Vehicle Innovation Team
SAE – Society of Automotive Engineers
SQL - Structural Query Language
PSRC - Puget Sound Regional Council
DAQ – Data Acquisition
CARB – California Air Resource Board
EPA – Environmental Protection Agency
NHTSA – National Household Transportation Survey Administration
FE – Fuel Economy
MPG – Miles Per Gallon
ICE – Internal Combustion Engine
CD – Charge Depleting
FCPHEV – Fuel Cell Plug-in Hybrid Electric Vehicle
DOE – Department of Energy
NREL – National Renewable Energy Laboratory
EPRI – Electric Power Research Institute
DP – Dynamic Programming
HSC – Hydrogen Supply Chain
ITS – Institute of Transportation Studies
GM – General Motors
GHG – Greenhouse Gas
HV – High Voltage
QGIS - Quantum Geographic Information Systems
ANL – Argonne National Laboratory
GPS - Global Positioning Systems
UF - Utility Factor

NHTS - National Household Transportation Survey

PEM - Proton Exchange Membrane

HWFET - Highway Fuel Economy Driving Schedule

TSDC - Transportation Secure Data Center

UDDS - Urban Dynamometer Drive Schedule