5-2012

Sustainability Analysis of Personal Transportation for Near Urban Commuting

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<u>NCER Assistance Agreement Project Report Executive Summary</u>
Date of Project Report: 3/21/2011

EPA Agreement Number: SU834698

Project Title: Sustainability Analysis of Personal Transportation for Near Urban Commuting

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Project Period: 8/15/2010 – 8/14/2011

Description and Objective of Research: The goal of this P3 project was to test three hypotheses: 1) there exists a vehicle or class of vehicles that can be effectively used to replace a car for near-urban commuting and short range transportation in cities of similar population, topology and traffic volume as Knoxville, TN with significantly less environmental impact than a typical automobile, 2) this vehicle has the appropriate capacity, convenience, and comfort such that people who are not likely to use other forms of alternate transportation will adopt it, and 3) between a fuel cell hybrid and fully battery electric, one of the two designs will prove to be more effective at satisfying our criteria for low environmental impact with appropriate capacity, convenience, and comfort.

A three-wheeled plug-in battery electric vehicle (BEV) was constructed and comprehensively road tested. The fuel cell hybrid equivalent was designed and is currently awaiting installation of an appropriate fuel cell. The overall sustainability of these two vehicles (BugE® BEV and BugE® H_2) is compared to that of the best selling passenger car, the Toyota Camry, and a smart fortwo® (intentional non-capitalization). This study analyzes the environmental, social, and economic sustainability of the four vehicles, and was conducted to examine the sustainability of the typical commuting options used for individuals currently commuting in near-urban environments as single passengers in an average passenger car. A public survey of consumer vehicle preferences was created and distributed. We defined "near-urban" as a driving distance of less than 15 miles, one way. Also, these near-urban commuters must have available to them an appropriate route that does not require interstate travel (meaning: a route exists with posted speeds 45 mph or less) although the commuter may currently use the interstate to commute.

Summary of Findings (Outputs/Outcomes): *Construction:* There proved to be difficulties in purchasing the fuel cell. Once those details were ironed out, Heliocentris had problems with quality control in a vendor-supplied part and the team's order was delayed by months. Due to this, only the BugE® BEV was completed before the time of the competition. The first change made to the original plan was the motor. The diameter of the 7 hp motor that was initially chosen was too large and a 36V brushed motor was chosen. The ME team ran stress simulations on the motor mount, and found that a gusset was needed to limit flexing of the motor mount. A chain tensioning device for the rear wheel was also added. These were fabricated and welded to the frame. Some students found that the transition from modeling and planning to construction was difficult, and in fact felt so out of place they chose not to continue with hands-on work. Other students found that the hands-on work brought all the fundamentals together and gave them a sense of confidence in their engineering abilities.

Results: The construction phase ended as the car rolled out of the garage on February 8 for its first test run, which was highly successful. The students took turns driving the car every morning and every evening for two weeks. The goal was to drive it from 10 – 15 miles one-way, each morning and evening, as if it were being used in a daily commute and to record data containing various information on distance, current, and voltage. There were two courses used; one had little elevation change, where the other had a sizeable grade. A Grin Cyclery (Vancouver, B.C.) Cycle Analyst® and Analogger® were used to record real-time data on the energy system and car performance and a Watts Up meter was used to find the power pulled from the wall to recharge the battery. With this information the exact power needs of the car were determined.

In order to address the second goal of capacity, convenience, and comfort, the drivers were polled. All agreed that the capacity was sufficient for a quick trip past the grocery on an average commuting day. There is a small trunk in the front of the BugE® appropriate for two average size grocery bags. It was also suggested that there is room behind the driver to add motorcycle type saddlebags for more storage. The BugE® convenience was rated higher than that of both bicycles and motorcycles based on inclement weather gear required for the later. The windshield offers protection from the wind and rain. In the cold weather, it was noticed that only the hands need significant extra protection. The driver's felt they didn't need to wear any more layers on their bodies than they already did for winter. As for comfort, the same can be said; a BugE® is more comfortable, due to weather protection, than a bicycle or motorcycle. The average passenger car was considered more convenient, capable, and comfortable, but the goal aimed for appropriate levels of these, which all drivers agreed were met by the BugE®. The BugE was driven in temperatures from 22°F to 66°F, and all conditions including rain and dark.

Sustainability Analysis: After the actual driving data was gathered, the following comparisons could be made. Each of the following sections ranks the cars from most to least sustainable. The emissions reported are from the full life of the energy source. The yearly numbers are based on 7800 miles traveled per year (30 miles/day, 5 days/week, 52 weeks/year). The gas price used for the Camry is $3.23 per gallon (Knoxville average of regular at time of report). The smart car requires premium, which is $3.54 per gallon. The cost for electricity in Knoxville is $0.087 per kW and the mix is 62% coal, 28% nuclear, and 10% hydroelectric. The miles per gallon equivalent (MPGe) for BugE® BEV and BugE® H_2 are based on 33.7 kWh per gallon of gasoline, which is the number used by the US EPA. The average price for H_2 is based on $2.47 per MPGe from Holston Gases in Knoxville. The survey data mentioned in the write up comes from 310 respondents.

Environmental Sustainability: The four vehicles were compared based on air emissions (including the production of the fuel) and natural resource use. The BugE® H_2 has the advantage since fuel cells generate zero tailpipe emissions. Even though hydrogen is produced by steam reformation of methane, the BugE® H_2 requires little energy compared to the average car. For the same miles traveled the Camry, smart fortwo®, BugE® BEV, and BugE® H_2 attribute 7.2, 5.2, 0.309, and 0.287 tons of CO_2 emissions per year. In Knoxville, based on 113,520 commuters totals for each vehicle of 817 kton, 590 kton, 35 kton, 33 kton a year are emitted. By switching from a Camry to the BugE® H_2 784 kton of CO_2 reduction would occur. Switching to BugE® BEV, would save 782 kton of CO_2. Likewise a switch to the BugE® H_2 from the Camry would reduce NO_x by 1.4 kton per year. This is a very important number because it is directly related to smog, and currently Knoxville is in nonattainment for 8 hour ozone. Emissions for electric vehicles fall short for methane. In this study the BugE® BEV produces 2600 times more than the gasoline car, although the total emission of methane is relatively low in either case. For overall air emissions from best to worst, the cars rank BugE® $H_{2,}$ BugE® BEV, smart fortwo®, and Camry.

For a primary energy source, the Camry and smart fortwo® use gasoline, the BugE® BEV uses some coal, and the BugE® H_2 uses hydrogen, none of which are renewable resources (at this point). Both oil and coal are produced by millions of years of organic decay differing in result by pressure and temperature conditions. It will never be replaced faster than the rate at which it is being used. Hydrogen is currently manufactured industrially through steam reformation of hydrocarbons, primarily methane. There is, however, a lot of research taking place that could make renewable hydrogen cost effective. The impetus for this would increase with market demand for hydrogen. The standard used thus far in this reporting has been based on current prices and technologies. Due to that, the efficiency of the motors and MPG ratings put the BugE® BEV on top for the least amount of natural resources used. The cars rank, in order from least to most natural resource usage, BugE® BEV, BugE® H_2, smart fortwo®, and Camry.

It is not the intent of this report to imply that coal is a cleaner burning fuel than gasoline. The intent is to show that a reduction in vehicle weight saves energy, and the 64% efficiency of an electric car (grid to wheels) helps to better utilize energy, therefore using less than the 34% efficient (service station to wheels) ICE powered car. However, it should be noted that electricity is becoming greener and the EPA has time sensitive goals for power plants to meet. As sources for renewable energy become more cost effective, and standards for flue gas emissions become more stringent, electricity will become cleaner. Further, based on the Sanyo residential solar panel technology, the BugE® BEV could be charged completely grid free from six 1.2 m^2 panels. This would easily fit on less than 10% of the southern facing half of an average US home.

Economic Sustainability: The vehicles were compared based on purchase price, annual maintenance, and fuel cost. The BugE® BEV saves $1080 per year in fuel costs over the Camry, but this will likely increase. Gasoline prices have steadily increased from $1.19/gal to $3.57/gal from 1990 to 2011. The savings in fuel and annual maintenance is $1175 per year. The team sees this vehicle as a secondary vehicle. In this capacity, the BugE® BEV would pay for itself in 6 years. It could also take the place of one car in a two-car household, saving additional costs of around $13,000. In the survey conducted by the sustainability team, 45% of respondents ranked initial purchase price as the #1 most important factor when buying a commuting car, and 68% ranked daily cost to operate in the top three. The smart fortwo® claims to be the most affordable car on the market right now, and that appears to be the case. When ranking the cars from lowest to highest direct cost, they rank BugE® BEV, smart fortwo®, BugE® H_2, and Camry.

Social Sustainability: A study conducted in San José, CA concluded that low-income families have to actively and strategically manage their transportation costs concerning small changes in their income. Often better transportation options open up more job opportunities, which could help to stabilize such incomes. Some interviewees said they were willing to pay higher transport cost with the hope of improved income. The BugE® BEV offers this. The upfront cost is less than buying a car, and the annual maintenance and fuel costs are 5 times less. This type of low weight, low energy vehicle would promote social equity.

One concern of many in purchasing a lightweight vehicle is safety. The 2011 Camry comes equipped with 7 air bags, vehicle stability control, traction control, and electronic brake force distribution. None of which is offered in BugE® BEV or H_2. Important to note, though, the Insurance Institute for Highway Safety (IIHS) has given the Camry the best rating, "Good," in the ability to keep the passenger cabin intact in the event of a roll over. The smart fortwo® has a tridion safety cell, which is the silver C-shape that can be seen on the exterior design. It is designed to distribute the impact of a crash around the whole car's body, and therefore protects the passengers. The rear-mounted engine breaks away and slides underneath the passenger compartment in the event of a rear impact. This dissipates the collision energy and reduces rebound shock. The IIHS also rated smart fortwo® a "Good" for impact safety. It has four airbags and traction stability measures. These impact ratings cannot be directly compared, since neither the BugE® BEV nor H_2 has been tested in that way. What can be said is the cabin does not offer protection from side impact or roll over. However, the low speeds of city driving do not offer much opportunity for roll-over accidents. We note that for the BugE® H2, there is also the added negative public perception of driving with compressed H_2 cylinders.

As for the perception of safety, there is not a metric that can be directly derived from personal opinion. In our own survey, only 20% ranked safety #1 for importance on purchase, but 62% ranked it in the top three. The Camry received an average 2.3 (1 was very safe; 7 was very unsafe), and 29% scored it as a 1. The smart fortwo® received an average of 4.4, and 2% scored it as a 1. The BugE® received an average of 4.6, and 5% scored it as a 1. The ranking for safety measures and perception, from most safe to least, is Camry, smart fortwo®, BugE® BEV, BugE® H_2.

The two previously mentioned high rankings of the BugE® BEV and H_2 in economic and environmental impacts also apply to the social dimension. There is more coal domestically than oil; in fact the US reserves have more total energy content than all of the world's recoverable oil. The governmental push to electrify the US fleet can arguably be directly related to this fact. Reducing oil consumption directly reduces the US dependence on resources from politically unstable foreign countries. This is a significant improvement in the socio-political impact of these vehicles with 17% of oil imports coming from the Persian Gulf and 10.7% coming from Venezuela. Likewise, reducing emissions by such a large margin improves the health of the nation. In a London, UK study, it was predicted that reducing CO_2 emissions from urban transport by 35% would save 160 disability-adjusted life years (DALYs) and 17 premature deaths per million population per year. In Knoxville, that would equate to saving 32 DALYs and 3.4 premature deaths per year.

Conclusions: Of the four cars compared, the BugE® BEV appears to have the best balance of reducing emissions and saving money while still getting people to work. The team realizes that there are a number of weighted variable models that can be employed to determine a best option from the sustainability analysis. Since sustainability metrics are still an active area of development and study, a significant amount of speculation and justification must go into these models. At this time the team has chosen to assess the findings with their best objectivity in order to declare the best choice. The important thing to note is that all goals of the project were met, and the team successfully completed undertaking this challenging task in such a short amount of time.

Proposed Phase II Objectives and Strategies: As part of Phase I, we developed a vehicle that greatly reduces the negative environmental footprint of near-urban commuting. A plug-in battery electric vehicle (BEV) was constructed for testing purposes so that it would be possible to answer questions with facts supported by real data obtained from testing. Because of the data, the team found that it was easier to answer questions related to the cost of daily operation, what it was like to drive the vehicle, and the overall positives and negatives of what owning an electric vehicle might be. The team found that it was more helpful to state facts from personal experiences when the vehicle was set up for display. Because there was explicit data from testing and personal experience, the team was able to more quickly and more precisely determine what place the electric vehicle holds in the minds of the public.

The Phase I work will be continued by studying what advances could be made to the electric vehicle to raise potential public acceptance of the electric vehicle. Also the aim is to analyze the connection between electric vehicles and the power grid to determine the exact effects that these vehicles will have on the grid. In addition, what modifications must be made to both the grid and to the design requirements of future electric vehicles will be studied in order to provide a mutually beneficial relationship between the two.

During Phase I, the BugE® BEV was constructed and comprehensively road tested. With this data it was determined that the initially selected 1.2 kW fuel cell would not be powerful enough to meet the desired requirements. As such, the hydrogen fuel cell vehicle, BugE® H_2 will need to be constructed with a power source more capable of providing higher instantaneous power. It will also take more effort to construct a vehicle with higher power capabilities since a custom-made battery hybridization system will have to be designed and built to meet the ratings of the new fuel cell, and provide a safe level of power from the fuel cell to the battery system while battery recharging capabilities are enabled. The BugE® H_2 from Phase I will still be constructed and tested in Phase II.

Publications/Presentations: University of Tennessee, Exhibition of Undergraduate Research and Creative Achievement (EUReCA), March 31st, Poster Competition

Supplemental Keywords: hydrogen, battery electric vehicles, fuel cell hybrid, emissions

Relevant Websites: None

A. Summary of Phase I Results

1. Background and Problem Definition

As developing countries continue to cultivate economic growth and population levels increase exponentially, there is an ever-increasing demand for energy. The US Energy Information Association (EIA) stated that energy consumption will increase worldwide from 495 quadrillion Btu to 739 quadrillion Btu between 2007 and 2035; that is a 49% increase in just 28 years [1]. Transportation currently represents 40% of the total energy use in the US, and is fueled almost entirely by petroleum [2]. Unfortunately, if petroleum is not replaced, there will be serious consequences.

Oil is a finite resource [3]. Although it is difficult to put an exact number on remaining oil reserves, it is certain that we are using it at a rate much faster than it is being replenished. Hubbert predicted peak oil production for the US in the early 70's, and was right. His model also shows that the oil production of known worldwide reserves peaked in 2005 [4]. Other scenarios predict anywhere from 2026 to 2047 [5]. This is an important fact for areas other than transportation as well. Petroleum is a key component to the polymers' industry, which produces medical supplies that have become an integral part of saving lives. The polymers industry uses 7% of oil production for feedstock and processing [6]. This could be sustained a long time without the drain caused by transportation needs. Continued use of petroleum keeps the U.S. involved in war torn countries, and the burning of it is a major contributor to air pollution.

The gas stream from an internal combustion engine (ICE) contains hydrocarbons, nitrogen oxides (NO_x), carbon monoxide (CO), carbon dioxide (CO_2), and water. When exposed to sunlight in the presence of NO_x, hydrocarbons create ground level ozone. Ozone contributes to asthma, lung cancer, and other respiratory illnesses. 10% to 20% of all summer respiratory hospital visits are caused by ozone contamination [7]. Ozone is also responsible for $500 million of lost crop production per year [8]. CO is extremely toxic. It reduces the body's ability to supply the organs with oxygen and on the higher end of concentration causes death. CO_2 is a special case. It is not toxic, but it is a greenhouse gas (GHG) meaning that it does not allow heat radiated from the earth to pass through into space. The accumulation of CO_2 over the years will increase the temperature of the earth's atmosphere. CO_2 concentrations have increased by 36% since the late 1700's; N_2O has increased by 18%. This corresponds directly to industrialization (the steam engine was invented in 1769). In the last 100 years the overall average climate temperature has increased by 1.3º F [9]. Ice caps and sheets have shrunk causing sea level to rise at a rate of 1.8 mm per year from 1961 to 2003 [10]. The increased temperature has developed a higher saturation of water vapor in the air, meaning the water supply is being lost to the atmosphere.

The EIA reported in 2010 that the transportation sector used the most energy of the four end-use energy sectors weighing in at 40% of all the energy consumed in the U.S in 2009 [2]. Transportation also came in first for CO_2 emissions out of the four sectors with 31%. More than 5.8 billion metric tons of CO_2 equivalent (eq) were produced in 2009, creating 113 million metric tons more CO_2 than the next leading end-use sector, industry [11]. Automobiles and light trucks make up 63% of emissions for the transportation sector [12].

An inherent influence on fuel use is vehicle weight. The fuel efficiency of even the most fuel-efficient power system is impeded by the curb weight of the vehicle. Gas mileage ranges from 36 mpg at 3100 lbs for a passenger car, to 19 mpg at 5200 lbs for a light truck [13]. This is not a linear trend. The gas mileage decreases faster than the vehicle weight increases. An average vehicle weighs 4000 lbs and requires 30kW of power to travel at a speed of 30 mph up a hill of 10% grade. Even the lightest weight battery technology would require batteries weighing over 300 lbs just to meet the instantaneous power requirement for this moderate hill. For a gross vehicle and passenger weight of 600 lbs, it takes only 4 kW of power to travel at a speed of 30 mph up the same hill.

The Knoxville Regional Office of Transportation reported in 2000 that approximately 132,000 residents in the metropolitan Knoxville area, which is 63% of commuters, travel less than 15 miles one-way on the average day. This is inline with the national average of 68%. Further, 86% of those travelers are single passengers [14]. If Knoxville commuters are also inline with this national average, 113,520 people in Knoxville are commuting by themselves less than 15 miles one-way to get to and from work in a personal automobile. Using the numbers for a 4-cylinder, automatic, Toyota Camry 1.14 lbs. of CO_2 is generated per mile traveled [15]. Using a 49-week work-year and a 5-day workweek, these near-urban Knoxville commuters as sole occupants in a conventional vehicle could produce as much as 1 billion pounds of CO_2 per year. If all this driving were done in a carbon-neutral alternative fuel vehicle, the CO_2 and previously mentioned pollutants generated by these residents could be greatly reduced.

The goal of this P3 project was to test three hypotheses: 1) there exists a vehicle or class of vehicles that can be effectively used to replace a car for near-urban commuting and short range transportation in cities of similar population, topology and traffic volume as Knoxville, TN with significantly less environmental impact than a typical automobile, 2) this vehicle has the appropriate capacity, convenience, and comfort such that people who are not likely to use other forms of alternate transportation will adopt it, and 3) between a fuel cell hybrid and fully battery electric, one of the two designs will prove to be more effective at satisfying our criteria for low environmental impact with appropriate capacity, convenience, and comfort.

A three wheeled plug-in battery electric vehicle (BEV) was constructed and comprehensively road tested, Fig. 1. The fuel cell hybrid equivalent was designed and is currently under construction. The overall sustainability of these two vehicles (BugE® BEV and BugE® H_2) is compared to that of the best selling passenger car, the Toyota Camry, and a smart fortwo® (intentional non-capitalization). This study analyzes the environmental, social, and economic impacts of the four vehicles, and was conducted to examine the sustainability of the typical commuting options used for individuals currently commuting in near-urban environments as single passengers in an average passenger car. For the purpose of this study, "near-urban" is defined as a driving distance of less than 15 miles, one way. Also, these near-urban commuters that are considered must have available to them an appropriate route that does not require interstate travel (i.e.; a route exists with posted speeds 45 mph or less) although the commuter may currently use the interstate to commute.

Figure 1. The commercially available BugE® frame and chassis kit.

2. Purpose, Objective, Scope

Purpose: The purpose of this project was to drastically reduce the environmental footprint of near-urban commuting while still offering an appropriate level of comfort and convenience that would allow it to be adopted by short-range commuters.

Objective: The objective of this project was to construct two vehicles (BugE® BEV and BugE® H_2) for near-urban commuting, and to gather data by test-driving them, that could be used for comparison to vehicles currently used for commuting. One car would be a plug-in battery electric and the other a fuel cell-battery hybrid. They would provide a level of comfort, convenience, and capacity intermediate between bicycles and automobiles.

Scope: The scope of this project was to evaluate the pollution contribution of a passenger vehicle, and design a car that would significantly reduce this, where it would have the most impact, in order to help reduce GHGs, and to decrease the long term effects of pollution on the overall health of people. The car design would then be used to build two cars fueled by two different energy sources. The current design of the average passenger vehicle uses the bulk of its energy to move around the car itself. In order for alternative fuels to be successful, this trend must be re-evaluated. The biggest factor in the energy needs of a vehicle is its weight. The efficiency of the ICE also plays a major role in the energy needs of the typical car. All of these factors were used to design two vehicles in hopes to reduce negative impacts to health and the environment.

Mechanical and electrical engineering students (ME and EE) were given the task of determining the power and structural needs in order for a car to meet the criteria (15 miles one-way, less than 45 mph, single passenger, lower emissions). Chemical engineering students along with a civil and environmental engineering student were given the task of performing the sustainability analysis and developing and conducting a public survey of commuting preferences. Some students used the car design and construction as their senior design projects. Others used the project to obtain anywhere from 1 to 3 hours of technical elective credit. Time or practicality did not warrant body/frame design or fabrication, so the commercially available BugE® frame and chassis were purchased. The ME and EE teams started by simulating a route on campus with hills representative of an average commute in Knoxville. From here they estimated the power needed and the motor specifics were determined. The project then moved from desktop to workshop. Physics and mechanics concepts and models were put to use in order to predict what would be needed. Practical hands-on knowledge was obtained by applying engineering concepts during construction. During the test-driving stage, the students learned the value of a well-planned design through the results obtained. Possibly the most crucial lesson learned was the importance of teamwork. Both the ME and EE teams learned that their own work could not be completed independently from each other, but rather in tandem as the construction progressed. The Sustainability team learned the importance of communicating with the public. The BugE® BEV was taken to a high traffic downtown location and the team solicited surveys from interested parties. The public interest was high as the team didn't have to approach anyone, but were themselves solicited for more information.

As the design required consideration concerning the three Ps (people, prosperity, and the planet), each was considered. The planet is an obvious focus as reducing emissions is the main objective, and a secondary benefit is reducing the drain on the dwindling supply of oil. Reducing the use of oil affects people and prosperity just as heavily. Since oil production has peaked in the US and 60% of the oil used is imported, the U.S. has taken a larger role in the unrest associated with the oil producing countries of the Middle East. Keeping mortalities due to global conflict at a minimum is a clear benefit to an oil alternative vehicle. People also benefit from improved health. A reduction in ozone allows for healthier outdoor activities, and promotes a decline in respiratory related medical visits. As for prosperity, the big benefit is to the consumer's wallet. As China and India develop their economies and thus their need for personal transport, the price of oil rises. As societies in the Middle East struggle for democracy, the price of oil rises. In February of 2011 the price of gasoline rose $0.19 in one week. This substantial change in price came from a disruption in Libyan oil production, which is only responsible for 2% of global production [16]. For these reasons, in this project, we are exploring transportation options that are petroleum-free and benefit people, their prosperity, and the planet on which they live.

3. Data, Findings, Outputs/Outcomes

Experimental: To evaluate the power requirements of the energy systems, a course around the University of Tennessee Knoxville campus was plotted that would simulate likely driving conditions for an average commute in town. This course was driven in a typical passenger vehicle. A Race Technologies® DL1 GPS/Accelerometer unit was used to map the terrain. Power and energy requirements were then calculated from this data. When mapping the course, the car was driven speeds below 45 mph with conservative accelerations used throughout the course. The power requirements were calculated using assumptions found in Table 1, some of which were obtained from the BugE® manufacturer website. Average values for the weight of the power systems used in similar configurations were assumed. From this information, a max value for the power, 4 kW, and the total amount of energy needed for the trip, 0.215 kWh, were determined. A summary of the salient values can be found in Table 2. 20% more was added to each estimate in order not to damage the fuel cell or deep cycle the batteries, which helps to avoid fast degradation of the fuel sources. Power vs. Motor Speed and Torque vs. Motor Speed curves were plotted in order to find the operating parameters of the needed motor. Based on the information gathered, the Heliocentris 52 A, 36 V, 1200 W Fuel Cell with a high C-rating/low capacity A123 battery for high instantaneous power demai, and the Thundersky 36V, 60Ah lithium iron phosphate ($LiFePO_4$) battery were chosen as energy sources. The two energy sources can be easily compared due to the use of identical vehicles differing only in weight due to these different systems. In the planning stage the Golden Motors 7 hp brushless motor was chosen for both vehicles.

Table 1. Assumptions for Values for Power, Energy, and Torque Calculations.

Variable	Value	Assumptions
Weight	600 lbs	BugE® vehicle weight w/o passenger is 350 lbs, assuming 200 lb combined passenger/cargo weight plus 50 lbs of modifications.
Coefficient of Drag C_D	0.4	BugE® estimated C_D = 0.35, conservative estimate of C_D
Rolling Resistance	0.017	Conservative estimate for rubber-asphalt friction
Max Speed	45 mph	Speed limit is 45 mph or below for all areas of course and for local commutes into downtown Knoxville.
Voltage	36 Volts	Operating voltage of possible motor

Table 2. Salient Values for Determining Motor and Energy Source Characteristics

Variable	Value	Importance
Max Power	4.01 kW	Batteries must provide enough power to reach top speed to match course requirements
Max Torque	35 ft-lb	Motor must output this torque to match course requirements and to overcome starting torque at highest grade on course (20 ft-lbs, 4% grade)
Total Energy/mile	0.044 kWh/mi	Energy source must be able to provide this much energy
Max Instantaneous Current	123 A	Maximum current draw must be matched by energy source so that the best performance on the course is attained.
Average Current	19 A	Average and Max current must be identified for analysis of tradeoffs of higher instantaneous draw vs. weight

Construction: There proved to be difficulties in purchasing the fuel cell. Once those details were ironed out, Heliocentris had problems with quality control in a vendor-supplied part; the team's order was delayed by months. Due to this only the BugE® BEV was completed before the time of the final report. The first change made to the original plan was the motor. The diameter of the 7 hp motor that was initially chosen was too large, so a 36V brushed motor was chosen. The ME team ran stress simulations on the motor mount, and found that a gusset was needed to limit flexing of the motor mount. A chain tensioning device was also added. These were fabricated and welded to the frame. Some students found that the transition from modeling and planning to construction was difficult, and in fact felt so out of place they chose not to continue with hands-on work. Other students found that the hands-on work brought all the fundamentals together and gave them a sense of confidence in their engineering abilities.

Results: The construction phase ended as the car rolled out of the garage on February 8 for its first test run, which was highly successful. The students took turns driving the car every morning and every evening for two weeks. The goal was to drive it from 10 – 15 miles each time as if it were being used in a daily commute and to record data containing various information on distance, amps, and voltage. There were two courses used; one had little elevation change, where the other had a sizeable grade. A Grin Cyclery (Vancouver, B.C.) Cycle Analyst^R and Analogger^R were used to record real-time data on the energy system and car performance, and a Watts Up meter was used to find the power pulled from the wall to recharge the battery. With this information the exact power needs of the car were determined. The average results from all the trials can be seen in Table 3. The Instantaneous Power vs. Motor Speed plots from the actual were created and compared to the predicted, Figure 2. It is a good example of how grade affects power needs.

Table 3. BugE® BEV results from 14 days of test driving

Total Miles Driven	263.1	Avg. kWh/mile	0.050	Avg. discharge per 30 miles (kWh)	1.5
Total Hours Driven	13:09	Max Amps Logged	260.1	Avg. discharge per 30 miles (Ahr)	40.5
Max Range Driven (miles)	30	Total kWh Used	13.48	Avg. time to charge per 30 miles (hrs)	6
Max Speed	44	Cost/30 miles	$0.25	Avg. energy to charge per 30 miles (kWh)	2.9
Average Speed (mph)	18.6			Avg. Charging Efficiency	52%

The delayed fuel cell delivery turned out to be a benefit. The instantaneous power predicted showed that the power could be supplied 80% of the time with a 1.2 kW fuel cell. However, the actual driving habits of the BugE® show that a 1.2kW fuel cell only supplies enough power 55% of the time, leaving 45% of the overage power to be supplied by the battery. This amount was too much for the predicted battery and the space of the car. A spreadsheet was used to analyze the effect of different size fuel cells on the state-of-charge in a 10 amp-hr battery, to which the fuel cell would be hybridized. Figure 3 shows how changing to a 2 kW fuel cell can drastically change the battery capacity needed when the actual power data from the hilly route was used. A bigger fuel cell and smaller battery will weigh less than the fuel cell originally specified with a large enough battery to cover the overage. The tank size of the BugE® H_2 was chosen based on convenience; we started with the assumption that fueling would occur weekly, where the BEV would be charged daily. The volumetric density of H_2 at 5000 psi is 2.75 MJ/l. Based on 50% efficiency for the fuel cell, 17 liters per week would be needed. Due to commercially available tank sizes the car would need three 7-liter tanks.

In order to address the second goal of capacity, convenience, and comfort, the drivers were polled. All agreed that the capacity was sufficient for a quick trip past the grocery on an typical commuting day. There is a small trunk in the front of the BugE® appropriate for two average size bags. It was also suggested that there is room behind the driver to add motorcycle type saddlebags for even more storage. The BugE® convenience was rated higher than that of both bicycles and motorcycles based on the additional inclement weather gear required for the later. The windshield offers protection from the wind and rain. In the cold weather, it was noticed that only the hands needed extra protection due to back draft. The driver's felt they didn't need to wear any more layers on their bodies than they already did for winter. As for comfort, the same can be said; a BugE® is more comfortable, due to weather, than a bicycle or motorcycle. The average passenger car is the most convenient, capable, and comfortable, but the goal aimed for appropriate levels of these, which all drivers agreed were met by the BugE®. The BugE® was driven in temperatures from 22°F to 66°F, and all conditions including rain and dark.

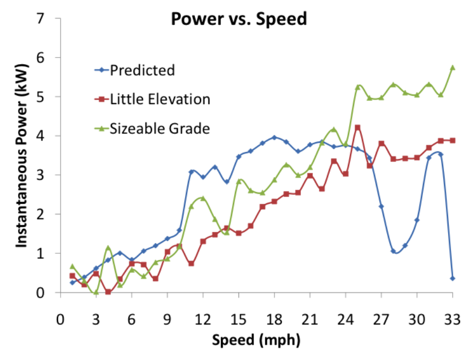

Figure 2. Comparing the instantaneous power vs. speed of the predicted needs, the little elevation route and the sizeable grade route.

Sustainability Analysis: After the actual driving data was gathered, the following comparisons could be made. Each of the following sections ranks the cars from most to least sustainable. Table 4 shows the numbers used for the sustainability analysis. The emissions reported are from the full life of the energy source. The yearly numbers are based on 7800 miles (30 miles/day, 5 days/week, 52 weeks/year). The gas price used for the Camry is \$3.23 per gallon (Knoxville average of regular at time of report). The smart car requires premium, which is \$3.54 per gallon. The cost for electricity is \$0.087 per kW in Knoxville and the mix is 62% coal, 28% nuclear, 10% hydroelectric. The miles per gallon equivalent (MPGe) for BugE® BEV and BugE® H_2 is based on 33.7 kWh per gallon of gasoline [15]. The average price for H_2 is based on \$2.47 per MPGe from Holston Gases in Knoxville. The survey data mentioned in the write up comes from 310 respondents.

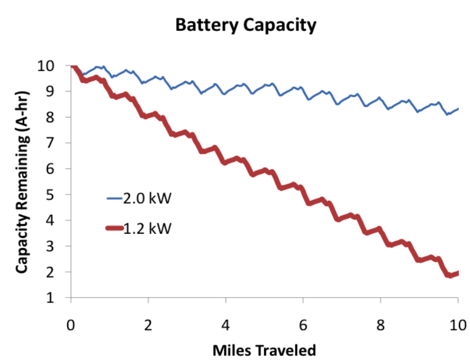

Figure 3. Battery capacity remaining based on output (kW) of fuel cell

Environmental Sustainability: The four vehicles were compared based on air emissions (including the production of the fuel) and natural resource use. The BugE® H_2 has the advantage since fuel cells generate zero tailpipe emissions. Even though hydrogen is produced by steam reformation of methane, the BugE® H_2 requires little energy compared to the average car. For the same miles traveled the Camry, smart fortwo®, BugE® BEV, and BugE® H_2 attribute

Table 4. Comparison of four vehicles

	Camry	smart fortwo®	BugE® BEV	BugE® H_2
City MPG/MPGe	22	33	778	778
Miles per kWh	0.65	0.98	23	23
Cost to Drive 30 miles	$4.40	$2.94	$0.25	$2.74
Cost of Fill Up	$58.61	$29.44	$0.11	$13.69
Range in Miles	433	282	30	150
Weight	3307	1609	350	386
Cost of vehicle	$20,870	$11,590	$7,500	$14,500
Est. Annual Maintenance	$360	$696	$265	$275
Annual Fuel Cost	$1,145	$837	$58	$283
Barrels of Oil/yr	13.2	9.5	0	0
EPA Score	5	5	NA	NA
Annual Emissions				
CO_2 eq. (ton)	7.20	5.20	0.309	0.287
NO_x (lbs)	25.8	25.8	3.02	0.681
CH_4 (lbs)	0.298	0.298	792	7.88
SO_x (lbs)	0	0	4.52	0.522

All the Camry and smart fortwo® gas and CO_2 numbers are from www.fueleconomy.gov
The NO_x, CH_4 and SO_x, are an avg/mi from http://www.epa.gov/oms/consumer/f00013.htm
The est. annual maintenance costs are from www.motortrend.com
Fuel cell replacement costs obtained from the Center for Hydrogen Research, SRNL
Coal emissions: IWRC, Emissions for Coal-Fired Power Plants. Center, S. B. P. P., Ed. 2008.
SMR H2 emissions: C. Koroneos et al. Int J Hydrogen Energy 29 (2004) 1443–1450

7.2, 5.2, 0.309, and 0.287 tons of CO_2 emissions per year. In Knoxville, based on 113,520 commuters (number from above) approximately 817 kton, 590 kton, 35 kton, 33 kton a year are emitted. By switching from a Camry to the BugE® H_2 784 kton of CO_2 reduction would occur. Switching to BugE® BEV, would save 782 kton of CO_2. Likewise a switch to the BugE® H_2 from the Camry would reduce NO_x by 1.4 kton per year. This is a very important number because it is directly related to smog, and currently Knoxville is in nonattainment for 8 hour ozone [17]. Emissions for electric vehicles fall short for methane. In this study the BugE® BEV produces 2600 times more than the gasoline car; however, the total is low for each fuel source. For overall air emissions from best to worst, the cars rank BugE® H_2, BugE® BEV, smart fortwo®, and Camry.

For a primary energy source, the Camry and smart fortwo® use gasoline, the BugE® BEV uses coal, and the BugE® H_2 uses hydrogen, none of which are renewable resources (at this point). Both oil and coal are produced by millions of years of organic decay differing in result by pressure and temperature conditions. It will never be replaced faster than the speed at which it is being used. Hydrogen is currently manufactured industrially through steam reformation of hydrocarbons (fossil fuels). There is, however, a lot of research taking place that could make renewable hydrogen cost effective [18-22]. The impetus for this would increase with market demand for hydrogen. The standard used thus far in this reporting has been based on current prices and technologies. Due to that, the efficiency of the motors and MPG ratings put the BugE® BEV on top for the least amount of natural resources used. The cars rank, in order from least to most natural resource usage, BugE® BEV, BugE® H_2, smart fortwo®, and Camry.

It is not the intent of this report to imply that coal is a cleaner burning fuel than gasoline;

it is not [21]. The intent is to show that a reduction in vehicle weight saves energy, and the 64% efficiency of an electric car (grid to wheels [21]) helps to better utilize energy, therefore using less than the 34% efficient ICE powered car [23]. However, it should be noted that electricity is becoming greener and the EPA has time sensitive goals for power plants to meet. As sources for renewable energy become more cost effective, and standards for flue gas emissions become more stringent, electricity will become cleaner. Further, based on the Sanyo residential solar panel technology the BugE® BEV could be charged completely grid free from six 1.2 m^2 panels. This would easily fit on less than 10% of the southern facing half of an average US home.

Economic Sustainability: The vehicles were compared based on purchase price, annual maintenance, and fuel cost. The BugE® BEV saves $1080 per year in fuel costs over the Camry, but this will likely increase. Gasoline prices have steadily increased from $1.19/gal to $3.57/gal from 1990 to 2011 [24]. The savings in fuel and annual maintenance is $1175 per year. The team sees this vehicle as a secondary vehicle. In this case the BugE® BEV would pay for itself in 6 years. It could also take the place of one family car, saving additional costs of around $13,000. In the survey conducted by the sustainability team, 45% of respondents ranked initial purchase price as the #1 most important factor when buying a commuting car, and 68% ranked daily cost to operate in the top three. The smart fortwo® claims to be the most affordable car on the market right now, and that appears to be the case. When ranking the cars from lowest to highest direct cost, they rank BugE® BEV, smart fortwo®, BugE® H_2, and Camry.

Social Sustainability: A study conducted in San José, CA concluded that low-income families have to “actively and strategically” manage their transportation costs concerning small changes in their income [25]. Often better transportation options open up more job opportunities, which could help to stabilize such incomes. Some interviewees said they were willing to pay higher transport cost with the hope of improved income. The BugE® BEV offers this. The upfront cost is less than buying a car, and the annual maintenance and fuel costs are 5 times less. This type of low weight, low energy vehicle would promote social equity.

One concern of many in purchasing a lightweight vehicle is safety. The 2011 Camry comes equipped with 7 air bags, vehicle stability control, traction control, and electronic brake force distribution. None of which is offered in BugE® BEV or H_2. Important to note, the Insurance Institute for Highway Safety (IIHS) has given the Camry the best rating, “Good,” in the ability to keep the passenger cabin intact in the event of a roll over [26]. The smart fortwo® has a tridion safety cell, which is the silver C-shape that can be seen on the exterior design. It is designed to distribute the impact of a crash around the whole car's body, and therefore protects its passengers. The rear-mounted engine breaks away and slides underneath the passenger compartment in the event of a rear impact. This dissipates the collision energy and reduces rebound shock. The IIHS also rated smart fortwo® a “Good” for impact safety. It has four airbags and traction stability measures [27]. These impact ratings cannot be directly compared, since neither the BugE® BEV nor H_2 has been tested in that way. What can be said is the cabin does not offer protection from side impact or roll over. However, the low speeds of city driving do not offer much opportunity for roll over accidents. There is also the added negative public perception of driving with compressed H_2 cylinders.

As for the perception of safety, there is not a metric that can be directly applied to personal opinion. In the survey only 20% ranked safety #1 for importance on purchase, but 62% ranked it in the top three. The Camry received an average 2.3 (1 was very safe; 7 was very unsafe), and 29% scored it as a 1. The smart fortwo® received an average of 4.4, and 2% scored it as a 1. The BugE® receive and average of 4.6, and 5% scored it as a 1. The ranking for safety measures and perception, from most safe to least, is Camry, smart fortwo®, BugE® BEV, BugE® H_2.

The two previously mentioned high rankings of the BugE® BEV and H_2 in economic and environmental sustainability also apply to social. There is more coal domestically than oil, in fact the US reserves have more total energy content than all of the world's recoverable oil [28]. The governmental push to electrify the US fleet can arguably be directly related to this fact. Reducing oil consumption directly reduces the US dependence on resources from politically unstable foreign countries. This is a definite win in the social category with 17% of oil imports coming from the Persian Gulf and 10.7% coming from Venezuela [29]. Likewise, reducing emissions by such a large margin improves the health of the nation. In a London, UK study it was predicted that reducing CO_2 emissions from urban transport by 35% would save 160 disability adjusted life years (DALYs) and 17 premature deaths per million population per year [30]. In Knoxville, that would equate to saving 32 DALYs and 3.4 premature deaths per year.

4. Discussion, Conclusions, Recommendations

Questions to Consider:

i. The project balanced people, prosperity and the planet. The project design focused on reducing emissions and natural resource consumption, which has the largest impact on people and the planet. The reduced ownership costs effect prosperity. As does the increased availability of transportation for low-income families, that could offer them more employment options.

ii. The team sought to design a vehicle that would reduce emissions, and that people would find convenient enough to replace their commuting vehicle. The team was successful in achieving both these goals. The team was also successful in the third goal to determine a winner for improving emissions as the BugE® H_2 has zero emissions. The success was achieved due to the vision and passion of the lead advisor, and the willingness of the students to work hard. The advisor set up the project in such a way that it would have a large impact in emissions reduction, and the students were encouraged by the prospect of attaining that goal. The one change to be made if it were to all be done again would be time management and total team involvement. As with any project some members put in a lot more hours than others, and the reduced team involvement lead to conflicts associated with finishing the project on time.

iii. The EE team primarily interacted with the ME team, since their chief responsibility was to build the car. The ME team was very skilled in design and troubleshooting problems. One specific instance of this was that the seat would not move back because there was a knob that connected the bottom fairing to the frame. To fix this, a latch was fashioned that was a slimmer profile, allowing it to fit under the seat. The mechanical side was almost finished when the electrical work began. This was a proactive move by the ME team to get the ball rolling, but it caused great difficulty for the EE's to route wires and install parts around fairings that normally wouldn't have been there had there been better communication on the front end. The EE team, however, rolled up their sleeves and got the work done. Both the ME and EE teams put a lot of faith in the sustainability team as their work did not have a physical culmination like the EE's and ME's. The sustainability team came together and got their part completed. However, a larger boundary for the analysis could have been implemented had the team used their time more wisely.

iv. This vehicle targets a majority of the commuting population, which is producing the majority of air emissions. It could easily be a viable option toward a more sustainable mode of transportation. Even if a small percentage of people adopted this style of vehicle right away, it would be a visual example that others would see on the road to make them think about their own transportation choices.

v. This project has a very specific niche. The BugE® BEV and H_2 give up some comfort and convenience, both of which could be agreeably sacrificed within the criteria established and not create a huge penalty to the driver. A short ride to work, although taken everyday, is within the ability of these vehicles. When considering longer trips with passengers, this vehicle obviously would not be suitable. It does help out the individual who feels compelled to ride a bike for the environmental benefit, but struggles with arriving at work sweaty or rain soaked. However, the lesson learned about weight vs. footprint is easily applicable to all transportation. The greatly reduced weight of the BugE® BEV and H_2 show what a difference weight makes both in consumption of natural resources and air emissions. Transportation vehicles could certainly benefit from designs that reduce excess weight.

vi. There were six sponsors who donated to the project. The front hydraulic brake, handlebars, tail light, front and rear turn signals, mirrors, racing seat and advice were supplied by Killboy, Somethin Extra Cycles, Willis Cycle Works, Performance Products, and Meineke Car Care Center of Knoxville. The best part of the search for sponsors was that the ones found were all small, locally owned companies that had an interest in helping the local school with an idea that could help the entire world. Special note is given to Schrader's Cycle Center who donated a custom paint job. In addition to the $10,000 EPA grant, $12,673 was given as cost sharing funds from the Associate Vice Chancellor of Research at the University of Tennessee.

vii. The prospect of using a fuel cell hybrid technology with fossil fuel free hydrogen eliminates all tailpipe emissions. This would essentially reduce US CO_2 emissions by 60% if the whole fleet were changed. In the meantime, if fuel cell technology is not quite there yet, a switch to lower weight, electric vehicles would reduce CO_2 emissions in Knoxville by 782 kton. It would reduce NO_x by 1.3 kton, which would allow Knoxville to be in ozone attainment.

viii. There were some qualitative benefits associated with this project. The drivers felt this was a legitimate car replacement, since the comfort and convenience would meet their needs. They also commented on the fact that driving a BugE® would give them a true sense of environmental responsibility. There is some value of increased social equity associated as well.

ix. The benefits of the two small vehicle designs to a city like Knoxville would be immediate. The geography of Knoxville is such that the mountains on either side of the area trap the air. Knoxville is currently in nonattainment for ozone. It is obvious. The haze can be seen daily in the summer. Most people who move into the area immediately complain of allergies and other respiratory problems of which they did not have prior. Most days in the summer are poor air quality days. Knoxville ranked 2nd in the country for highest cases of asthma in 2011. In fact 3rd and 4th go to Memphis, TN and Chattanooga, TN respectively, while Nashville, TN is 10th. Big cities like LA and New York aren't even on the list [31]. A change in transportation habits would certainly help to get Knoxville off this list.

x. The BugE® frame and chassis was not an original design, but rather purchased. The success of it in cutting down on operational costs and air emissions, were contributions made by the team. For instance, the kit suggested a battery that weighed 115 lbs. more than the chosen battery. The purpose of the vehicle was restricted to a section of transportation where it would have the most impact. The project was designed to fit the specific needs of an environmentally conscientious short-range urban commuter.

Conclusion: Of the four cars compared the BugE® BEV appears to have the best balance of reducing emissions and economy while still getting people to work. The team realizes that the weights assigned to each dimension of sustainability will affect the choice of the most desirable option. However, using the data available at the time of this study, the BugE® BEV appears to be the most appropriate vehicle for the purpose of single passenger, near-urban commuting based on current technologies for generating the necessary energy for transportation

B. Proposal for Phase II Project

1. P3 Phase II Project Description

Overall Actual and Potential Sustainability Benefits of the Proposed Project:

There are two goals for Phase II: 1) build a BugE® battery hydrogen hybrid vehicle, and comprehensively road test it in order to gather data that would serve to refine the sustainability analysis of near urban transport, and 2) conduct simulations and experiments to determine the effects of small BEV and hybrid vehicles on the electrical infrastructure when integrated with the electrical grid.

Driving a personal vehicle is becoming more expensive by the year. The average gasoline price for 2010 was $2.78/gal, while diesel prices were even higher, at $2.99/gal. Prices are anticipated to rise $0.78/gal and $0.81/gal, respectively [32]. Any way that gasoline can be replaced with an inexpensive alternative transportation energy source would be an improvement to the economic standpoint of the American family. If the average commuter drove 30 miles each weekday with a vehicle that achieved 25 miles per gallon and did not drive on the weekends, the transportation cost would be approximately $870 in gasoline alone. Using the data obtained from testing the BugE® BEV, the 30 mile trip could be made 5 days a week for 52 weeks for under $60 at $0.087/kW [33]. Electric vehicles clearly have the capability to improve the cost of transportation for the average American commuter. As the preliminary findings predicted for the BugE® H_2 show promise for a sustainable transport option, it is of interest to build that car and further study the greening of near urban commuting.

In addition to the positive impact that electric vehicles may have upon the consumer, electric vehicles also provide benefits to the power grid. Many have proposed using the battery systems to supply power during peak hours. A123 Systems, a leading battery producer, designs and produces large scale battery packs to supplement power generated by utility services with great success [34]. A study was undertaken to determine the severity of the impact of power regulation provided by electric vehicle battery packs. The result of this study showed that the benefits of regulatory effects on the grid and the payment that would be associated with providing said benefit outweighed the cost of battery degradation [35]. It has also been proposed to use the battery charger to supply reactive power to increase overall grid efficiency [36]. The proposed study will investigate the impact of small electric vehicles on Vehicle-To-Grid (V2G) integration. It is the intent of Phase II to study the short and long term effects of peak shaving, power regulation, and reactive power (var) generation on both the vehicle and the grid.

General Relationship of Challenge to Sustainability:

According to Merriam-Webster, the definition of sustainability is "of, relating to, or being a method of harvesting or using a resource so that the resource is not depleted or permanently damaged". Current transportation methods are in direct opposition of this definition. It is well known that tailpipe emissions harm the environment. Electric vehicles that obtain their electricity from renewable energy sources provide a way to prevent tailpipe emissions, and therefore reduce their harmful effects. Not to be ignorant of the emissions related to the source of electrical power from which the battery electric BugE® receives its power, which also contributes to the overall environmental impact directly related to electric vehicles, advances in grid sustainability to decrease emissions would, therefore, also decrease the emissions of the transportation sector.

Electric vehicles may prove to help the grid rather than harm it. Electric vehicles are poised to increase the efficiency of the power grid by providing reactive power, by consuming power overnight when overall power consumption is low, and by assisting in regulating the power grid when the vehicle is plugged in. Typical power grid loads are highly inductive due to the effects of transmission lines, which means that a significant portion of the power generated is lost through them. In recent studies, it has been shown that electric vehicle chargers can be used to offset these losses [36]. Depending on when the vehicles are charged, it may be possible to charge the vehicles with a higher percentage of alternative sources, further reducing the environmental impact. Another study shows that with the integration of wind power, electric vehicles may play an important role in system regulation by storing energy provided by wind generation plants while the generation of the turbines vary with wind speed [37].

Challenge Definition and Relationship to Phase I:

Part of Phase I of this project was to develop a vehicle suitable for single passenger commuting within 15 miles of the commuter's home, then to compare this vehicle with other commuting alternatives for their impacts on the sustainability of personal transportation. A plug-in battery electric vehicle (BugE® BEV) was constructed for testing purposes so that it would be possible to answer questions with facts supported by data obtained from testing. Because of the data, the team found that it was easier to answer questions related to the cost of daily operation, what it was like to drive the vehicle, and the overall positives and negatives of what owning an electric vehicle might be. When the time came, the team found that it was more helpful to state facts from personal experiences when the vehicle was set up for display. Because there was explicit data from testing and personal experience, the team was able to more quickly and more precisely determine what place the electric vehicle holds in the minds of the public.

Phase I work in this area will be continued by studying what advances could be made to the electric vehicle to raise potential public acceptance of the electric vehicle. Also the aim is to analyze the connection between electric vehicles and the power grid to determine the exact effects that these vehicles will have on the grid. In addition, what modifications must be made to both the grid and to the design requirements of future electric vehicles will be studied in order to provide a mutually beneficial relationship between the two.

During Phase I, the BugE® BEV was constructed and comprehensively road tested. With this data it was determined that the initially selected fuel cell would not be powerful enough to meet the desired requirements. As such, the hydrogen fuel cell vehicle will need to be constructed with a power source more capable of providing higher instantaneous power. It will also take more effort to construct a vehicle with higher power capabilities since a custom made battery hybridization system will have to be designed and built to meet the ratings of the new fuel cell, and provide a safe level of power from the fuel cell to the battery system while battery recharging capabilities are enabled. The BugE® H_2 designed in Phase I will still be constructed and tested in Phase II.

Innovation and Technical Merit:

The main purpose of Phase II will be to evaluate the potential effects that electric vehicles, both small and large, will have on the power grid. There have been a number of studies that list potential effects of electric vehicles on the power grid. The concept of using electric vehicles as peak shaving and regulation providers to utilities date as far back as 1997 [38]. However, these studies have been exclusively on full sized electric vehicles, such as a

Beetle EV, Th!nk City, and Toyota RAV4 [35, 39]. Thus, the effect of smaller electric vehicles and electric motorcycles on the power grid has been absent from evaluation.

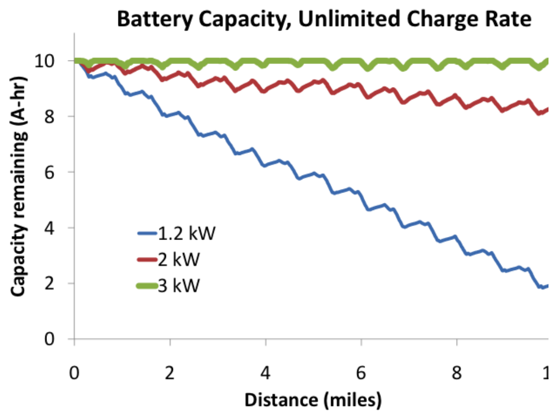

Figure 4. Battery capacity remaining based on output (kW) of fuel cell. The charging rate was unlimted. The following values were used to model recharging: charging efficiency= 50%, system voltage= 36V, no regen. braking

Results, Evaluation, and Demonstration:

As the Phase I construction had a very successful demonstration of an all-electric, battery-powered vehicle, Phase II will design, build, and demonstrate a fuel cell vehicle. Many of the same tests that were conducted during Phase I for the battery vehicle will be used for the Phase II fuel cell vehicle, though it is expected that the increased complexity of the fuel cell system will require more testing prior to its placement in the vehicle. Lessons learned from the design, assembly, and testing of the battery vehicle to the fuel cell vehicle will be incorporated in the BugE® H_2.

Figure 4 illustrates the effect of different assumed fuel cell ratings on the capacity of a 10 A-hr, 36V battery used to hybridize the fuel cell. During the testing of the battery electric vehicle, it was learned that the current drain was significantly higher than had been predicted, and that the load tended to spike frequently. Both of these situations would negatively impact both the fuel cell and the battery used to hybridize a system based on a commercially available 1.2 kW fuel cell. As Figure 4 illustrates, a 1.2 kW fuel cell battery would be essentially depleted after 10 miles, based on a residual DOC of 20%. A 2 kW fuel cell would appear to be adequate, although the battery capacity still decreases and two issues should be noted: 1) the on-board recharging rate was allowed to be as high as the fuel cell could generate, and 2) a commercially-available 2 kW fuel cell could not be located. Also, it was assumed that the controller did not allow for regenerative braking, although this will be explored in Phase II. A 3 kW fuel cell was more than adequate, and a fuel cell of this size is commercially available (www.fuelcellstore.com).

Figure 5 shows the current to the battery assuming the on-board charging rate is not limited. In the case of the 3 kW fuel cell, the current reaches 8C, or 80 amps. This figure reinforces the importance of battery design; 8C is a high charging rate and is over 8 times the highest rate logged using the plug-in charger with the BEV car. Figure 6 shows

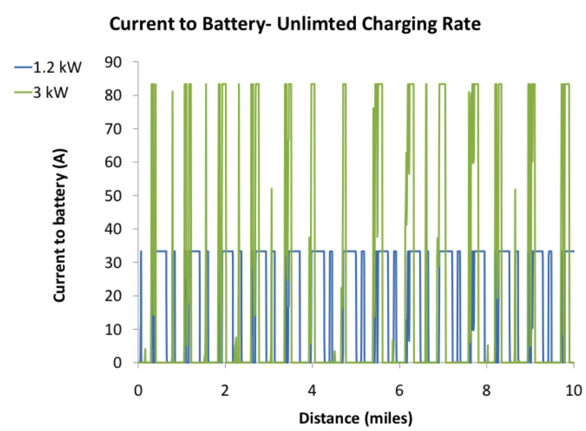

Figure 5. Predicted available charging current to the battery based on the hilly trial route, assuming two different fuel cell sizes. The assumed voltage was 36V. Using the 3 kW fuel cell, the charging rate can reach values over 80 amps, which is 8C, based on a 10 A-hr battery.

the battery state-of-charge assuming a 3C maximum charging rate; the batteries used on our current BEV design have a maximum charging rate of approximately 3C. At 10 miles, a 10 A-hr battery used to hybridize a 2 kW fuel cell would have been depleted to around 6 A-hr; extrapolating to 15 miles, this would be around 4 A-hr. While this would be sufficient for a new battery, an aged battery would have reduced capacity and this would probably not be sufficient for a 15 mile one-way trip. With this fuel cell, either a larger battery or a more advanced battery design (such as the high area electrode A123 batteries) would be required. However, the 3 kW fuel cell is still able to provide nearly all the required power and so the battery remains essentially fully charged and is only used for bursts, which was the intent of the original design.

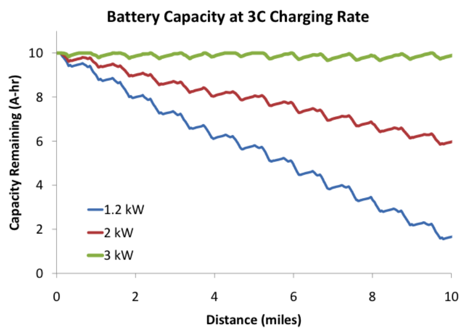

Figure 6. Battery capacity remaining based on output (kW) of fuel cell. In this case, charging was limited to 3C, or 30 A. The following values were used to model recharging: charging efficiency = 50%, system voltage = 36V, no regen. braking

As discussed above, the impact of small battery electric and battery hybrid vehicles on the electrical infrastructure is not known. Therefore, in addition to the work discussed above to build the fuel cell car, we will conduct simulations and then tests to show the vehicle to grid (V2G) capabilities of each of these vehicles, in order to provide an engineering and economic assessment of the possibilities that these vehicles may provide if penetration levels are substantial. The engineering possibilities to be tested will include, but not be limited to, the amount of power regulation that can be provided, reactive power that can be supplied, and the distance between refueling. All of the aforementioned attributes will be tested under a number of different conditions and compared. Economic possibilities that will be tested will be related to how often hydrogen tanks must be refilled, availability of hydrogen, and the times in which the services to the grid are most beneficial and most efficient.

Integration of P3 Concepts as an Educational Tool:

Each of the P3 Concepts (People, Prosperity, and Planet) are integral components to our project, and significant in terms of the education of the participants as well as others. The vehicles that were built for this project will be on display for high school students when they visit campus during "Engineers' Day" each fall. Also, the vehicle will be used in the freshman year Engineering Fundamentals class that all University of Tennessee students take. This allows future engineers to learn more about electric vehicles, and how they can make an impact in this important area of research. It will also be used to show how these vehicles would impact the electric grid and community, and ultimately our planet in terms of being a more sustainable form of transportation, and reducing our dependence on oil. The public has been surveyed in downtown Knoxville, as well as surveys having been circulated electronically, which was meant to raise the awareness of the public as a whole about electric vehicles and their potential impacts (both advantages and disadvantages). This work will continue into Phase II, as we gather data on the suitability of hydrogen as a potential transport fuel.

Interdisciplinary Teamwork

The same mixed, multidisciplinary team assembled in Phase I will be used in Phase II. The past team had and the next team expects to continue to have electrical engineering, computer engineering, chemical engineering, environmental engineering, and mechanical engineering students and faculty participate in this project. The computer engineering and electrical engineering students will be responsible for the electrical grid, vehicle interaction and vehicle analysis. Chemical engineering students will be tasked with the issues of hydrogen storage and dispensing in the fuel cell vehicle. The environmental engineering students will provide a study to show a comparison of the battery vehicle with the fuel cell vehicle in terms of power required by the two vehicles, the issues of hydrogen availability, and the environmental effects of obtaining energy from hydrogen stations and power generation plants. The mechanical engineering students will be responsible for assembly of the fuel cell vehicle. Because of the interdisciplinary nature of this project, all of the students and faculty involved thus far have learned to appreciate the issues of other disciplines and how individual choices made by each sub team have affected all involved.

2. Project Schedule

Task 1 (August 2011 – December 2011) – Complete assembly of the fuel cell vehicle.

Task 2 (January 2012 – June 2012) – Test fuel cell vehicle and tune control system to provide adequate balance of power between fuel cell and battery system such that vehicle runs smoothly and power flow is seamless between these two power sources.

Task 3 (January 2012 – December 2012) – Develop a computer simulation to model providing vehicle to grid (V2G) services from the vehicle and what impacts these would have on the vehicles' batteries, power electronics, and capacitors as well as impacts locally and nationally to the grid.

Task 4 (August 2012 – December 2012) – Complete a sustainability analysis that evaluates the two vehicles (battery only and fuel cell/battery hybrid).

Task 5 (January 2013 – July 2013) – Demonstrate V2G capabilities for each of the two vehicles in terms of providing reactive power to the grid while the vehicle is plugged in and fully charged as well as when the vehicle is plugged in a charging.

Deliverables: An annual report will be submitted to the EPA at the end of Year 1 and Year 2 for Phase II of this project. Team representatives will attend the 2012 National Sustainable Design Expo.

3. Partnerships

Currently, we have not identified specific partners for Phase II, due to the relatively preliminary nature of the proposed work. However, the Knoxville Utilities Board (KUB) has been contacted, and is interested in partnering when the project reaches a stage that warrants a partner.

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