Volume 25 | Issue 1 Article 4

1-1-2014

Alternative Energy Technologies for Transportation

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ALTERNATIVE ENERGY TECHNOLOGIES FOR TRANSPORTATION

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I. INTRODUCTION

Fuel cells are considered a clean, highly efficient alternative to internal combustion engines that are universally employed today for automotive transportation. We have been very active on our campus at the University of Delaware in using fuel cell hybrid vehicles for transit applications. During this talk, I will present information about the UD Fuel Cell Bus Program that we have been successfully operating on our campus for the past six years.

The outline of my talk is as follows. First, I will discuss the current need for alternative transportation technologies and fuels. The two obvious reasons are the depletion of conventional fossil fuels, and environmental concerns arising from their unbridled use. These are the precise reasons why we are gathered here today, at a symposium focusing on de-carbonization. Since automobiles consume substantial amounts of fossil fuels and contribute so significantly to global greenhouse gas emissions, I will next highlight three alternatives for transportation that could reduce our dependence on fossil fuels and mitigate emissions: biofuels, battery electric vehicles, and fuel cell hybrid vehicles. My particular area of interest is fuel cells for urban transit applications. Although I am not an expert in either biofuels or battery electric vehicles, I believe that discussing these two topics first will help to lead logically into the fuel cell topic. Finally, I will discuss some key features of our fuel cell bus program.

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II. THE NEED FOR ALTERNATIVES

The need for alternatives to the current fossil-fuel based economy is clearly revealed in two graphs produced by Steven Koonin, the former Under Secretary for Science at the U.S. Department of Energy. The first graph (slide #2 in Dr. Koonin's presentation[1]) depicts primary energy demand per capita plotted against GDP per capita. Here, Gross Domestic Product (GDP) is calculated on a Purchasing Power Parity (PPP) basis using 2000 U.S. dollars, and the data presented in this graph is a summary from 1980 to 2004. The most striking feature of this graph is the strong, almost linear, correlation between per capita energy demand and per capita GDP; all of the data indicate that higher GDP correlates with higher energy demand. The United States occupies the top-right corner of the graph, implying that not only are we highest in the world in terms of per capita GDP ($37,000), but also in terms of per capita energy consumption (360 gigajoules, or GJ). It is sobering to compare ourselves with the rest of the world, not only with the developed countries in Europe and elsewhere, but also with the most highly populated nations such as China and India. For example, while the UK, France, and Japan have a per capita GDP of around $27,000 (about twenty-five percent lower than the U.S.), their per capita energy demand is about around 180 GJ (about one-half of that of the U.S.). Towards the lower-left of the graph are China and India, with per capita energy demands of fifty GJ (one-seventh that of the U.S) and 15 GJ (one-twenty-fourth that of the U.S), respectively. China and India together comprise one-third of the world's population. As these countries industrialize rapidly and their standard of living improves, their per capita GDP will rise. This graph suggests that as they travel to the right in terms of GDP, they will undoubtedly travel upwards in terms of energy consumption.

Higher energy use is, of course, linked to higher emission rates of greenhouse gases because most of our energy today comes from burning fossil fuels. The second graph (slide #12 in Dr. Koonin's presentation[2]) presents per capita CO_2 emissions plotted against GDP. As one would expect, the data indicate an almost linear dependence of emissions on GDP. The one interesting outlier to this

1. Steven E. Koonin, Chief Scientist, BP plc, Toward Sustainable Energy Strategies, Presentation before Aurelio Peccei Centenary Conference, slide 2 (June 16, 2008), *available at* http://regionali.wwf.it/UserFiles/File/News%20Dossier%20Appti/DOSSIER/Sostenibilit/Koonin_16_06_08.pdf.

2. *Id.* at slide 12.

general trend is France, primarily because France has deployed nuclear energy more aggressively than any other nation. Although nuclear power has its own problems, as shown by the Fukushima disaster, its saving grace is that nuclear power generation does not produce CO_2 emissions. This graph indicates that the per capita carbon footprints of China and India are about one-seventh and one-twentieth of the United States, respectively. As these countries increasingly prosper, their energy consumption and emission rates will increase, so mitigation strategies are critically important.

The atmospheric CO_2 levels plotted in Figure 1 show a very steep increase starting from about 320 parts per million by volume (PPMV) in the 1960s to about 400 PPMV today. The effect of anthropogenic emissions on global CO_2 levels cannot be denied. Figure 2 shows the results from a model[3] that depicts atmospheric CO_2 concentrations under various mitigation scenarios. The black curve predicts CO_2 levels in the absence of any mitigation strategy (business as usual). In this scenario, CO_2 levels would reach 500 PPMV by 2050 and 700 PPMV by about 2080. The model predicts that stringent mitigation strategies would be required going forward to stabilize CO_2 levels at about the 450-550 PPMV range by 2150. For example, to stabilize at 450 PPMV, we would need to cut CO_2 emissions almost linearly from the current value of seven gigatonnes (Gt) per year to about three Gt per year in the next 100 years.

3. S. Pacala & R. Socolow, *Stabilization Wedges: Solving the Climate Problem for the Next 50 Years with Current Technologies*, 305 SCIENCE 968, 968-72, Supporting Online Material (2004), *available at* http://www.sciencemag.org/content/305/5686/968.short.

FIGURE 1. Atmospheric CO_2 concentration in parts per million by volume (PPMV).

Credit: National Oceanic and Atmospheric Administration[4]

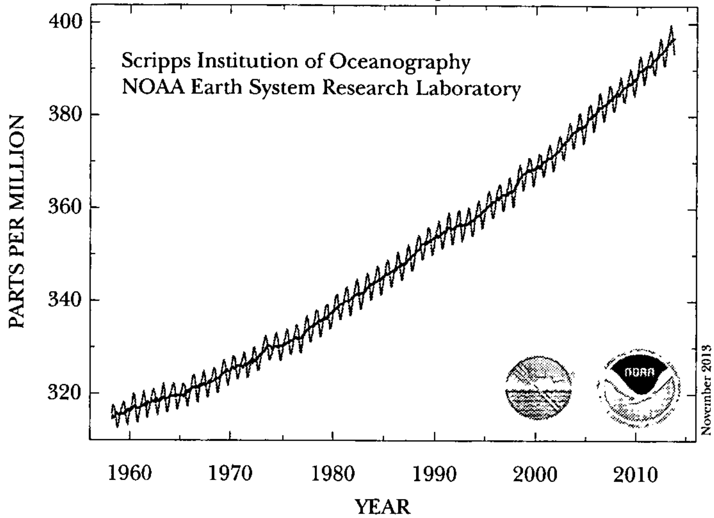
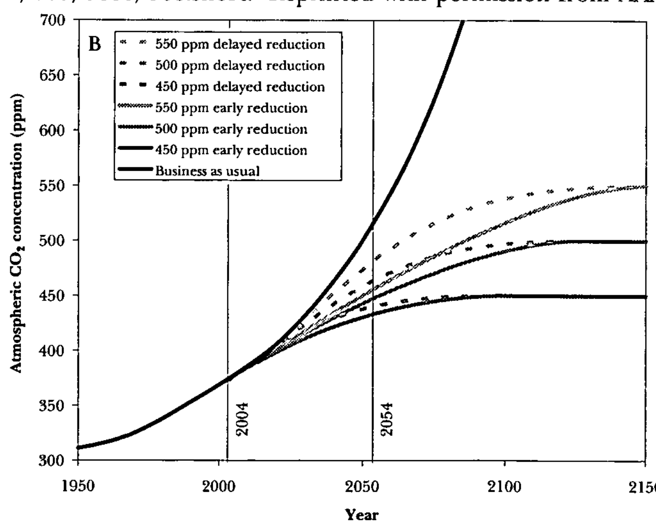


FIGURE 2. Predicted atmospheric CO2 concentrations under various mitigation scenarios.

From S. Pacala & R. Socolow, *Stabilization Wedges: Solving the Climate Problem for the Next 50 Years with Current Technologies*, 305 SCIENCE 968, Supporting Online Material, Figure S1 (B) (2004), *available at* http://www.sciencemag.org/-content/305/5686/968.short. Reprinted with permission from AAAS.[5]



4. Dr. Peter Tans & Dr. Ralph Keeling, *Trends in Atmospheric Carbon Dioxide*, NOAA (Nov. 2013), http://www.esrl.noaa.gov/gmd/ccgg/trends.

5. S. Pacala & R. Socolow, *supra* note 3, Supporting Online Material, Figure S1 (B).

Today, the bulk of our energy needs are met by fossil fuels: petroleum, coal, and natural gas. In the United States, thirty-six percent of our total energy needs is supplied by petroleum. Furthermore, seventy percent of all the petroleum consumed in the United States is used for transportation (diesel, gasoline, and jet fuel). Consequently, about a quarter of our nation's entire energy consumption is devoted to transportation. There are over 200 million vehicles in the United States today, and the number of vehicles worldwide has crossed one billion. As less developed nations prosper and their populations aspire to car ownership, the number of cars worldwide may even touch two billion in the not-too-distant future.

Therefore, it is imperative for us to consider alternatives to the current fossil fuel-based modes of transportation. I am going to examine three: (A) biofuels, (B) battery electric vehicles, and (C) fuel cell hybrid vehicles.

III. ALTERNATIVE FUELS AND TECHNOLOGIES

A. Biofuels

In the United States, the principal source of biofuels is corn. Approximately fifteen percent of U.S. corn production is diverted towards ethanol production. In Brazil, biofuels come primarily from sugar cane. Ethanol yields are substantially higher with sugar cane than they are with corn. Biofuels may be considered as a renewable resource because plant growth results in CO_2 capture from the atmosphere. When that ethanol is combusted in the engine of a car, that same CO_2 is released back into the atmosphere. As a result, biofuels could be labeled carbon neutral. However, the analysis is not quite so straightforward, and besides, there are significant societal issues that must also be considered with biofuels.

For example, the fuel required to supply one car for one year requires the cultivation of about one acre of corn. As stated earlier, the United States has over 200 million vehicles today. So, operating even half of them purely on biofuels would imply that 100 million acres would have to be dedicated to the production of corn purely for fuel. This leads to important issues such as land and water use, deforestation, soil erosion, lack of biodiversity, and so on. Serious societal problems can also arise from the concern about food versus fuel.

Apart from the socioeconomic questions surrounding biofuels, it is also pertinent to question biofuels' claim of carbon neutrality.

It turns out that the production of biofuels requires substantial inputs of conventional energy. Corn, in particular, provides a rather small overall benefit; some studies indicate that it takes one unit of conventional energy to produce 1.3 units of corn ethanol. Other studies suggest that corn is actually energy negative, i.e., it actually takes more than one unit of conventional energy to produce one unit of corn ethanol. On the other hand, sugar cane ethanol has a far better claim to carbon neutrality as the experience of Brazil has shown; about eight units of ethanol can be produced for each unit of conventional energy. The real promise, of course, is from cellulosic ethanol. Here, instead of just using the kernels on the corn plant, the entire corn plant could be converted to ethanol. Switchgrass, woodchips, and any kind of forest or agricultural waste could potentially be converted to ethanol. The payoff is ten to twenty units of biofuels from one unit of conventional energy. While companies have successfully demonstrated the process for converting cellulosic biomass into ethanol, the challenge is in reducing the cost and making it cost competitive with conventional sources of energy.

B. Battery Electric Vehicles

Let's look at a second alternative: battery electric vehicles. Currently, over twenty companies worldwide are producing all-electric vehicles which include the Nissan Leaf, Tesla Model S, Ford Focus Electric, Chevrolet Spark EV, BMW ActiveE, Smart ED, Renault Fluence Z.E., Renault Zoe, Honda Fit EV, Toyota RAV4 EV, Mitsubishi i MiEV, Mahindra e2o, and others. The Nissan Leaf, a five-passenger family car, can travel about 100 miles per charge and is designed for urban use. It employs a twenty-four kilowatt-hour (kW-hr) lithium ion battery with a 3.3 kW onboard charger, which means that it would take about eight hours to "refuel" this car. A fifty kW home charging station that can greatly reduce charging time is available, but obviously, this is not an option during a road trip. On the other hand, the Tesla Roadster is aimed at the sports-car segment. It employs a fifty-three kW-hr lithium ion battery pack weighing about 1000 lbs. that gives it a 245-mile range. Its 185 kW motor provides rapid acceleration from zero to sixty miles per hour (mph) in 3.7 sec. The slow-charge option (120V, 15A) permits a rather slow recharging rate of five miles an hour, while even the fast-charge option (240V, 90A) allows a gain of only fifty-six miles an hour. Even with the fast-charge option, the Tesla Roadster would require four to five hours for a full charge.

Battery electric vehicles enjoy many advantages. Foremost, they offer a high battery-to-wheel energy efficiency of about eighty percent, which translates to over 100 miles per gallon gasoline equivalent (mpgge). Due to fewer moving parts, they are easier to maintain, and are potentially more reliable. They provide smooth, quiet operation, with high torque and acceleration. Certainly, they create zero emissions at the point of use. However, since the electricity they run on is largely produced from fossil fuels, they do incur greenhouse gas emissions when analyzed on a well-to-wheel basis. Even so, their overall emissions rates per mile traveled are potentially lower when compared with conventional vehicles. And because electricity can be produced from a variety of domestic sources, electric vehicles can reduce our dependence on foreign oil. When those electricity sources are non-fossil based such as nuclear, hydro, or renewables, greenhouse gas emissions can be mitigated. Furthermore, electric vehicles can be charged overnight when the cost of electricity is lower, and their ability to serve a load-leveling role for the electric grid can become important when the fraction of renewable energy such as wind and solar (which are inherently intermittent) entering the grid increases. Finally, electric vehicles can generate cash for the car owner by performing vehicle-to-grid (V2G) services.[6]

Despite these benefits, electric vehicles suffer from some drawbacks. One of these is limited range when compared with conventional vehicles – a condition commonly referred to as range anxiety. Their battery packs are large, heavy, and expensive. Moreover, batteries can undergo only a limited number of charge/discharge cycles and will eventually need to be replaced. Thermal management of batteries is also a key issue. Batteries must be cooled for optimal performance in warmer climates, and cold temperature operation severely curtails battery performance.

Most importantly, the recharging rate of electric vehicles is slow. As a point of comparison, it is interesting to determine the equivalent electric charging rate of a gasoline-powered car. A typical fueling rate at the gasoline pump is about five gallons per minute. The lower heating value of gasoline is about 120 megajoules (MJ) per gallon. Multiplying those two numbers, we get an equivalent charging rate of 600 MJ per minute or 10 MW. Even after adjusting for the lower efficiency of the internal combustion engine, a typical equivalent electric charging rate of a gasoline-pow-

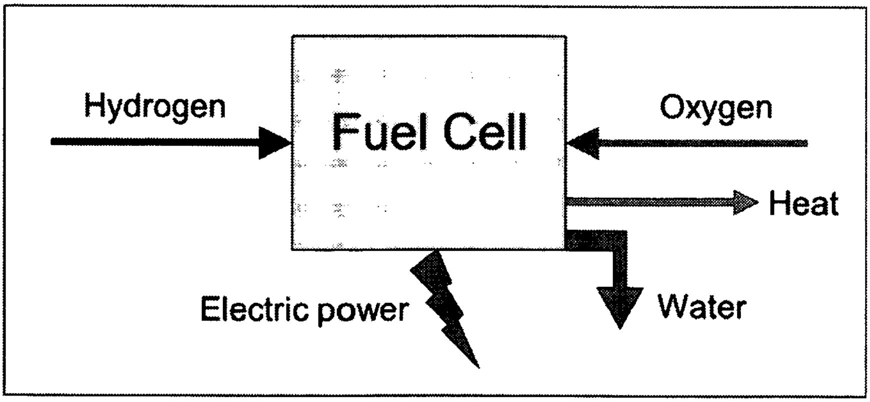
6. *See* Jasna Tomic & Willett Kempton, *Using Fleets of Electric-Drive Vehicles for Grid Support*, 168 J. OF POWER SOURCES 459, 459-68 (2007).

ered car is about five MW. This number is very impressive, especially when compared with the Nissan Leaf's home-charging station, which is rated at just fifty kW. Continuing this analysis a little further, let us consider, for example, the New Jersey Turnpike, where perhaps 200 cars are refueling at any instant in the multiple gas stations along the length of the turnpike. The electric supply required to support just this refueling operation would be one gigawatt (GW)! This equates to a full-fledged power plant required to recharge cars on just one 100-mile section of one highway. The point of this exercise is that serious infrastructural issues would have to be solved as electric cars become more widespread.

C. Fuel Cell Hybrid Vehicles

Finally, let us consider fuel cell powered vehicles. Fuel cells give you the advantages of battery vehicles in terms of zero emissions and high efficiency. At the same time, they provide the ability to refuel rapidly in a manner that is identical to gasoline or diesel-powered vehicles. It is possible to drive up to a hydrogen refueling station today and pump enough hydrogen for a 300-mile range in three to five minutes.

FIGURE 3. The operating principle of a hydrogen-powered fuel cell.[7]



A fuel cell is an electrochemical energy-conversion device that works on hydrogen stored in an external tank, and oxygen drawn from the air (Figure 3). Inside the fuel cell, the hydrogen is not combusted; there are no pistons or cylinders, or other moving parts. The fuel cell is not a heat engine. Instead, it directly con-

7. Ajay K. Prasad (created for use herein).

verts the chemical energy stored in the hydrogen fuel into electrical power by means of electrochemical reactions. Therefore, the fuel cell is very much like the AA battery in a flashlight. Like the AA battery, the fuel cell has electrodes and an electrolyte, and a positive and negative terminal from which power can be drawn to drive the traction motor in a car. However, there is one difference. In a AA battery, the chemicals undergoing the reactions are stored within the shell of the battery, and once the chemicals are expended, the battery must be discarded. On the other hand, in a fuel cell, the chemicals (hydrogen and oxygen) are supplied externally, and power is generated as long as the flow of reactants is maintained. Because they are not heat engines, fuel cells operate at an efficiency that is two to three times higher than that of internal combustion engines. Of course, when hydrogen reacts with oxygen, the only by-product is water, which emerges from the tailpipe mostly in the form of vapor. Hence fuel cells are truly zero-emission devices at least on a tank-to-wheel basis. It is because of these perceived benefits that automotive companies including GM, Honda, Toyota, Nissan, Hyundai, VW, and others are producing fuel cell cars for the future market; most are targeting 2015 or 2017 as the time to introduce fuel cell-powered cars in the showroom.[8]

Although fuel cells are zero-emission power sources at the point-of-use, they are not necessarily zero-emission on a well-to-wheels basis. Today, the cheapest way to make hydrogen is by steam reforming natural gas, which produces CO_2 as a by-product. In this case, hydrogen production is still reliant on fossil fuels, and the process does emit greenhouse gases. All the same, since the fuel economy of a fuel cell-powered vehicle is two to three times higher than that of an internal combustion engine, the emissions per mile of travel are proportionally smaller. Furthermore, it is possible to produce hydrogen from non-fossil sources, such as electrolysis of water using electricity from nuclear or renewable sources, or solar-based thermochemical processes.[9] Hence, hydrogen offers the potential to be truly zero-emission even on a well-to-wheels basis.

In particular, fuel cells are excellent for urban transit applications. Urban transit vehicles have low average speeds, and undergo

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8. *See, e.g.*, *Toyota Eyes Mass Production of Fuel Cell Car by 2015*, BBC NEWS (Nov. 20, 2013), http://www.bbc.co.uk/news/business-25023673.

9. Erik Koepf, Suresh G. Advani, Aldo Steinfeld, & Ajay K. Prasad, *A Novel Beam-Down, Gravity-Fed, Solar Thermochemical Receiver/Reactor for Direct Solid Particle Decomposition: Design, Modeling, and Experimentation*, 37 INT'L J. OF HYDROGEN ENERGY 16871, 16871-87 (2012).

start-stop operation. This makes them ideal for a battery-dominant series-hybrid platform. Series-hybrid implies that the fuel cell stack can be downsized, reducing capital cost. Furthermore, transit buses return to the depot for refueling and maintenance, which implies that infrastructure issues are easier to solve. Finally, they are an excellent way to introduce the public to a new technology, and to prove that it is clean, safe, and reliable.

IV. THE UD FUEL CELL BUS PROGRAM

FIGURE 4. The University of Delaware fuel cell buses;
Phase 1 bus (left), and Phase 2 bus (right).
Credit: Photos courtesy of the University of Delaware[10]

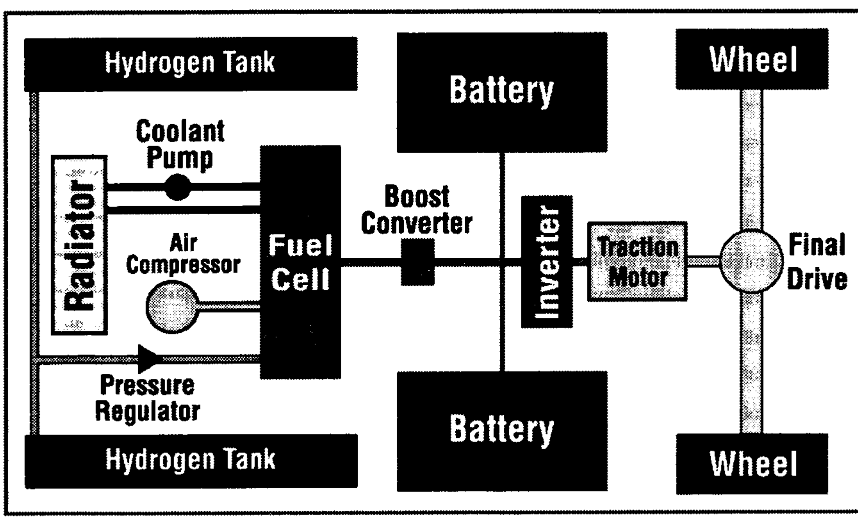
The University of Delaware's (UD) Fuel Cell Bus Program commenced in 2005 with funding from the Federal Transit Administration and the Delaware Department of Natural Resources and Environmental Control. Our mission is to research, build, and demonstrate fuel cell buses and a hydrogen refueling station in Delaware. Our buses are built by EBus located in Downey, California. The fuel cells on board the buses are manufactured by Ballard in Vancouver, Canada. Our hydrogen refueling station was built by Air Liquide and is located on their premises in Newark, Delaware.

Our first bus, shown in Figure 4, is a 22-foot long, 22-passenger bus with a gross weight of 20,500 lbs. and a maximum speed of forty-five mph. It is powered by a single Ballard Mark 9 SSL fuel cell stack providing twenty kW of power. Hybrid operation is supported by sixty kW-hr of NiCd batteries, and the bus is propelled by a 174 horsepower (hp) ac induction motor. Twin 5,000 pounds per square inch (psi) tanks in the roof store 12.8 kg of hydrogen, which is sufficient to provide a range of about 140 miles at a fuel economy of twelve mpgge. While the single stack can support an average driving speed of no more than twenty mph, this is perfectly ade-

10. Photos courtesy of the University of Delaware.

quate for an urban transit route. Bus 1 has been in operation since 2007 and transports about 100 students per day across campus.[11] Our second bus, also shown in Figure 4, was deployed in 2009. Bus 2 is identical to Bus 1 in every way, except that we doubled the size of the fuel cell power plant by adding a second Mark 9 SSL stack for a total of forty kW. Therefore, Bus 2 is capable of about thirty mph of sustained speed.

FIGURE 5. The battery-dominant fuel cell series hybrid configuration of the University of Delaware fuel cell buses.
Credit: Reprinted from Journal of Power Sources, Vol. 195 / Issue 12, Piyush Bubna, Doug Brunner, John J. Gangloff Jr., Suresh G. Advani, & Ajay K. Prasad, Analysis, Operation and Maintenance of a Fuel Cell/Battery Series-Hybrid Bus for Urban Transit Applications, 3939-3949, Copyright 2010, with permission from Elsevier.[12]



The hybrid configuration of Buses 1 and 2 is illustrated in Figure 5. Hydrogen from the twin rooftop tanks flows into the fuel cell via a regulator, while air is delivered to the fuel cell by an air compressor. The waste heat generated by the fuel cell is dissipated to the environment by a coolant pump and radiator. The voltage produced by the fuel cell stack (about seventy V) is stepped-up to the nominal battery voltage (300 V) by a boost converter. The dc power from the batteries is delivered to the traction motor via an inverter. During braking, the traction motor operates as a genera-

11. Piyush Bubna, Doug Brunner, John J. Gangloff Jr., Suresh G. Advani, & Ajay K. Prasad, *Analysis, Operation and Maintenance of a Fuel Cell/Battery Series-Hybrid Bus for Urban Transit Applications*, 195 J. OF POWER SOURCES 3939, 3939-49 (2010).
12. *Id.*

tor and converts the braking energy into electricity, which is stored in the battery, further improving fuel economy. The power management strategy employed on these buses is one in which the fuel cell operates continuously in the background at close to its peak efficiency point while charging the battery, and the battery provides the high power demands during acceleration and operation at higher speeds. These buses are fairly easy to drive, and have served the University of Delaware campus reliably and safely since their introduction.

When complete, the UD Fuel Cell Bus Program will have a fleet of four buses. Our third and fourth buses will arrive in 2014. Both of these are standard-size forty-foot buses. Bus 3 will include a triple stack for sixty kW of power and three hydrogen tanks for a total of nineteen kg of stored hydrogen. Importantly, the hybrid operation on Bus 3 will be supported by thirty-three kW-hr of lithium-titanate batteries which are lighter, more durable, and capable of higher power than the NiCd batteries employed on Buses 1 and 2. Our fourth and final bus will be identical to Bus 3, except that it will employ a quadruple-stack for a total of eighty kW, and four hydrogen tanks for a total of twenty-six kg of hydrogen. We have strived to ensure that each bus represents a major technological improvement over its predecessor, as our goal is to progress along the path to commercialization. Rather than repeating the technology from bus to bus, the lessons learned by building and operating each bus are used to improve successive buses. Our aim is to progress and evolve into a design that is commercially successful.

Refueling the buses with hydrogen is no different than filling up with diesel or gasoline. The driver pulls up to the station, inserts the nozzle and opens the valve. The refueling process takes no more than eight minutes. Our hydrogen refueling station is classified as "medium-fill" meaning that although it takes just a few minutes to fill a single bus, we have to wait several hours before the next refill owing to the time required by the compressor to bring the buffer storage tank up to full pressure. Nevertheless, this configuration serves our fleet operation quite adequately.

The topic of hydrogen safety often surfaces when discussing hydrogen-powered fuel cell vehicles. It should be noted that the composite tanks used to store hydrogen are extremely rugged in their design and construction. Therefore, the likelihood of a tank rupturing in a crash is very remote. Even in the event of a hydrogen leak, the gas being very lightweight will rise away rapidly and dissipate into the atmosphere rather than pooling up underneath the vehicle as in the case of a liquid fuel. Other metrics such as the lower flammability limit, lower detonation limit, and molecular diffusivity in air make hydrogen as safe, if not safer, than gasoline.

Over the past six years, we have learned a great deal about the operation and maintenance of fuel cell buses. Many innovations developed in our laboratory have been implemented within our fleet, and are now a regular feature in all buses built by EBus. We have developed and validated a vehicle simulator, called LFM, which allows us to evaluate novel fuel cell hybrid platform designs in software before committing to expensive hardware modifications.[13] The buses are equipped with numerous sensors that continuously relay data via a cellular link to a server in the lab, which allows us to examine key performance metrics in real time.

Our fleet of four buses is a model for the rest of the country. We are justifiably proud of our accomplishments and look forward to working with other cities and transit agencies that wish to replicate our program.

V. SUMMARY

In this talk, I have reviewed the current status of the transportation sector in the United States in terms of energy consumption and emissions, and reviewed three alternatives that are cleaner and make us less dependent on foreign petroleum: biofuels, battery electric vehicles, and fuel cell vehicles. All three options are promising; however, they require additional research to make them commercially viable. I also reviewed the UD Fuel Cell Bus Program and described the valuable experience we have gained in developing and operating a fuel cell bus fleet.

13. Darren Brown, Marcus Alexander, Doug Brunner, Suresh G. Advani & Ajay K. Prasad, *Drive-Train Simulator for a Fuel Cell Hybrid Vehicle*, 183 J. OF POWER SOURCES 275, 275-81 (2008).