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Progress on Improvements to a Hydrogen/Electric Hybrid Bus

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Abstract

The primary goal of the reported work is to extend the range of the bus in a cost-effective manner. Among the modifications underway are the development of a new engine, upgrading the power control system, rewiring critical elements, adapting a supercapacitor regenerative braking system, devising more effective changes to the hydrogen safety systems, and adding a high pressure gas storage system to supplement the existing hydride bed hydrogen storage. All of this work is being supplemented with the use of a dynamic simulation code to determine optimal operational strategies.

Introduction

The hydrogen-powered bus was constructed for the Atlanta Summer Olympics. This bus began as an all-electric vehicle that carried four battery packs in under-vehicle compartments. Two of the battery packs were removed and replaced by two metal-hydride beds for hydrogen storage. Then the rear portion of the bus was modified so that a large, industrial V-8 engine with large electrical generator could be installed in that location. This engine was modified from its standard gasoline form to one that was specially designed for hydrogen fuel.
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The system is designed so that all of the electrical energy went through the batteries. When the battery state-of-charge reaches sufficiently low levels, the driver starts the engine to accomplish a recharge. When the state-of-charge in the battery bank is restored to a predetermined level, the driver turns off the engine. More complete information on the initial vehicle design can be found in Jacobs et al. (1999a, b) at the end of the paper.

Several problems were encountered with the bus operation. One of these was that the range was deemed to be too small. Another was that oil consumption of the engine was reported to be particularly high. Premature battery system failure was observed. This may have been related to the operation of the regenerative braking system that came with the bus. The electrical power controller was found to overheat. In addition, the flammable gas sensors that were an integral part of the hydrogen safety system of the bus did not have the appropriate hydrogen selectivity necessary.

This project began after the bus was shipped to Nevada in 1999.

Electrical System

The current electrical system of the H2 Bus consists of three main components the auxiliary power unit, the battery bank, and the electric drive system. A fourth major component that is currently under development is the supercapacitor bank.

Auxiliary Power Unit

The auxiliary power unit consists of an engine (described in a later section of this paper) that drives a 4-pole, 277 V, 80 Hz, 70 kVA synchronous generator. The generator AC voltage is converted to DC through a diode rectifier. The generator performance characteristics were determined by conducting laboratory tests last summer. The generator-rectifier efficiency at full load was estimated near 83% with a voltage regulation of 8%. Plans are made to replace the generator unit with a larger and more efficient one.

Battery Bank

The battery bank consists of two parallel sets of deep-cycle VRLA batteries, each containing a series connection of 28 units. Each unit is rated at 12 V, 85 Ah @ C/3. The total battery system operates at 336 V with a capacity of 170 Ah @ C/3. The equivalent maximum energy storage is 57 kWh, but only 80% of this energy (i.e., 46 kWh) can actually be used since VRLA batteries are not allowed to be discharged below 20 state-of-charge (SOC).

The original bus batteries reached their life cycle prior to the bus transfer from Georgia. Consequently, new batteries have recently been installed. Monitoring of the battery cells is accomplished by a battery management system that provides several advantages including charging of individual units to help restore them to normal state. When the bus is not in operation, the battery bank state of charge is maintained with an external battery charger which requires 480V, 100 A, 3-phase power supply. The new batteries are equipped with internal thermistors to determine the temperature of each battery. One of the current tasks related to bus improvements is considering aspects of battery thermal management that would extend battery life.

Electric Drive System

The electric drive system is composed of an IGBT-based inverter that converts the DC voltage to three-phase pulse-width-modulated (PWM) AC voltages. These voltages are fed to an AC induction motor that is capable of producing 230 hp in addition to its 250 ft-lb of torque. The traction motor is wound with dual 3-phase windings and is capable of continuous operation at a maximum speed of 12,500 rpm. Both the motor and inverter electronic switches are oil cooled. Drive motor and traction battery current flow are monitored and controlled by an electronic subsystem known as the chassis vector controller (CVC). Due past thermal problems which limited the maximum power demand, the inverter has been upgraded to a more efficient and more heat-tolerant one.

Supercapacitor Bank

The bus came equipped with a regenerative braking system that converts the vehicle kinetic energy back to electrical energy during braking. This feature is known to increase the driving range by up to 20%. Currently, the regenerative braking uses the battery bank to store the energy gained. Since VRLA batteries are not designed to accept large, short bursts of power, especially when near full charge, conventional regenerative braking may cause them to overcharge and result in battery damage. For this reason, the existing regenerative braking system is temporarily disabled.

A supercapacitor bank in series with a DC/DC chopper (currently at the design stage) is being developed to act as an energy buffer: It has the ability to store energy as quickly as needed, and then supply back this energy when required during acceleration.

Miscellaneous

Much of the originally modified bus wiring was found to be very poorly documented as well as poorly installed. In many cases violations with the NEC code were found. Much of the electrical wiring has been corrected, re-wired, and documented.

A data acquisition system (DAS) was included in the original bus system. This apparently is not designed for the expected rugged condition in normal service, its ports and connectors are not standard, and its programs run on a special computer. The entire DAS is being analyzed for further improvements.

Engine

The Original Engine

An area that is being closely examined for increasing bus performance is the hydrogen-fueled engine. The necessary power output for the engine was established as 70 kilowatts at a speed of 2500 revolutions per minute. This was determined as a function of the operating range of the generator. Changes that had been made to the engine for the conversion to hydrogen gas included the addition of an HCI Constant Volume Injection system (see Jacobs et al. 1999a, b), the addition of exhaust gas recirculation, and modifications to the heads and pistons.

The Constant Volume Injection system is a unique sequential multi-port fuel injection method to meter the flow of hydrogen into each cylinder. The system is based upon the ideal gas relationship between pressure, volume and temperature. Not only do the pressure and volume effect the flow of gas into the engine, but changes in temperature can have adverse effects. To combat this, an electronic control system was incorporated into the injection arrangement.

An exhaust gas recirculation system was employed to reduce emissions. The system drew the exhaust from one bank (four of the eight cylinders) of the engine through four parallel coolers, into a condenser and then into a mixer at the intake manifold. This did increase the load on the engine but it was assumed that it would not drop the power output below the desired level.

The engine heads were replaced to increase the compression ratio to then improve the brake thermal efficiency. In an attempt to increase further the compression ratio and to reduce the excessive amounts of oil lost during operation, new pistons and rings were installed.

Test Results, Modifications and Improvements

Shortly after acquisition of the bus from Georgia, extensive research was performed to determine what needed to be improved. It was decided that substantial changes needed to be made to achieve the desired performance, efficiency and emissions results. Of primary concern was increasing the operational range of the bus, which could be accomplished by improving the performance of the engine, among other aspects described in this paper.

To study what improvements could be made to the engine, it was first removed from the bus and mounted on an engine dynamometer. Extensive diagnostic tests were then performed in a controlled environment.

The use of hydrogen as a fuel for internal combustion engines has been researched greatly in recent years primarily because of its ‘clean’ burning properties. The greatest concern involved with emissions control is the production of NOx.

Nitrous oxide production is commonly triggered by high temperature ‘hot spots’ located within each combustion chamber. Coupled with high pressures within the cylinders and a relatively rich air-to-fuel ratio, levels of this harmful pollutant can easily become a problem. It was found that the rate of NOx produced by the engine was unstable and varied between 6 and 55 parts per million as measured at the tailpipe. Reviewing the emissions data gathered via a synchronized dynamometer/exhaust analyzer in conjunction with thermistors located within each cylinder, the largest production of NOx occurred while the greatest difference between cylinder temperatures existed.

The conclusion inferred from the correlation between increased NOx production and temperature variance between cylinders was the assumption that non-uniform burns were occurring within cylinders. Mixtures of fuel and air abnormally rich were believed to be increasing the temperatures of some of the cylinders. While the NOx readings generally registered below 6 PPM, they subsequently increased to figures as high as 45 PPM at points where cylinder temperature differences reached 106°F.

In an attempt to locate the cause of this non-uniformity, a pressure transducer was installed to measure the line pressure of the hydrogen upstream of the constant-volume injector pump.

Readings from this sensor revealed violent oscillations in the pressure of the fuel supply. The design of the injection system did not allow for the compensation of this anomaly; in actuality it caused large variations in the amount of fuel delivered to each cylinder. This was most likely due to the compressibility of the gaseous fuel as it passed through the volumetric metering chambers of the injector pump. The excess hydrogen introduced to the cylinders may have been the catalyst for the production of the ‘hot spots’ and thus the high levels of nitrous oxide.

It was then determined that further analysis of the exhaust elements would be more useful once the engine’s air/fuel supply could be more accurately controlled. It was assumed that the engine would exhibit less variable emissions readings once the combustion inside each of its cylinders could be more accurately predicted and controlled.

Fuel Delivery

In order to determine the possible power output of the existing engine and to evaluate its integrity, dynamometer tests were preformed while the engine was run with several fuels. A performance test was conducted on the engine in its original condition using hydrogen fuel. In order to compare the output of the engine with its gasoline fueled counterpart, a carburetor (Holley 833 CFM) was mounted to the intake manifold and the engine was run on VP-C12 (108 octane) gasoline. To study the performance of the engine as run on gaseous fuels in general, Compressed Natural Gas (CNG) was introduced through the carburetor for the next test. These two initial tests were to evaluate the performance of the engine to comparable engines for which data was already available. The engine was then returned to its original setup for hydrogen with the addition of an electronic control unit capable of adjusting the overall air/ fuel mixture. The engine was then run with a leaner mixture.

Results of these tests indicated performance derating typical of the use of gaseous fuels. Comparative (at least generally so, since different types of fuel input systems were used) maximum outputs (in kW) were found at 3000 rpm as follows: gasoline-170; natural gas-130; hydrogen (A/F ratio of 30)-75; and hydrogen (stoichiometric)-45. It was desired to have higher outputs with higher efficiency than what was demonstrated with this engine.

Several characteristics of the existing Constant Volume Injection (CVI) system gave cause for concerns related to good performance. First and foremost, the mass of hydrogen metered by the CVI was directly dependant on the line pressures upstream and downstream from the pump. Secondly, the presence of petroleum-based lubricants in the piston/ cylinder design of the CVI allowed for the contamination of the hydrogen gas before it reached the combustion chamber.

These factors made the possibility of utilizing an Electronic Fuel Injection (EFI) system an appealing one. If electronic fuel injectors could be used, little or no contaminants would be introduced to the fuel supply and the amount of fuel delivered to each cylinder could be far more accurately controlled. Furthermore, the air/fuel ratio and the injection timing could be easily optimized. The concentration of fuel within each intake of air could be controlled so that the occurrence of the aforementioned ‘hot spots’ might be eliminated.

Research showed that fuel injectors designed for metering hydrogen gas were not generally available. The use of injectors designed for the delivery of petroleum-based fuel raised two concerns. Because the energy density of hydrogen is much less than that of gasoline, significantly larger volumes of hydrogen must be delivered at each injection interval. And, as opposed to a petroleum-based fuel, pure hydrogen gas exhibits 'dry' properties that do not provide the lubrication needed to keep the internal mechanisms of a standard fuel injector working properly.

A testing apparatus was constructed to determine if the necessary volumes of hydrogen could be passed through a large bore fuel injector commonly used in the racing industry. Given proper upstream pressures, it was found that the fuel injectors were capable of providing the necessary mass flow rates.

Similar studies performed using electronic fuel injectors to control hydrogen flow revealed that the mechanism failed after a remarkably short duration of operation. The 'dry' hydrogen had caused the contacting metal surfaces within the injector to seize in the open position and hydrogen was allowed to flow continuously through the injector. This situation was not acceptable for many reasons, including the safety risks involved with hydrogen gas.

In an attempt to find commercially available injectors capable of operating in a hydrogen environment, injectors intended for use with Compressed Natural Gas (CNG) were then obtained. The major point of interest concerned with this type of injector was the method by which they delivered larger volumes of fuel. While the same seizure problem was likely to occur in these injectors as well, the design methodology used to obtain higher flow rates was noted and the engineering of a new injector specifically designed for hydrogen was begun. This development included considerations for the larger flow rates as developed by the CNG injectors as well as novel methods to resist the premature failure of the mechanism.

Concurrent with the aforementioned development of a new injector, the investigation for a commercially available injector continued. Custom fuel injectors further along in development were discovered that allowed us to focus our efforts on the implementation of the injection and intake systems.

Intake and Exhaust Systems

The new hydrogen-fueled engine was a converted internal combustion engine with high flow cylinder heads. The intake manifold, cylinder heads, and exhaust manifold were originally designed for use at variable engine speeds. Since we intend to run the engine at a constant speed (in the general range of 2500-3000 RPM), it was decided to develop manifolds and head porting with a geometry that would provide the maximum efficiency and power at the desired operational speed.

Intake and exhaust geometries are generally designed to provide the maximum efficiency of airflow over a wide bandwidth that will include all engine-operating speeds. Since the APU must only run at a single speed, the method by which air is delivered to and removed from the engine could be optimized.

Using fluid flow principles, intake runners were designed that use the inertia of the air flowing to the individual intake ports on the cylinder heads to pressurize the inlet air. When the intake valve is closed, the mass of air flowing through the tube above it compresses until the next opening of the valve. By carefully timing the valve opening, the air/fuel mixture can be introduced to the cylinder at the point of maximum upstream pressure. As will be discussed below when addressing the camshaft aspects, this has multiple benefits for our application.

We treated the exhaust headers in a similar fashion. Each exhaust runner was designed such that the mass of the air flowing through it creates a pressure drop behind each exhaust valve while the valve is closed. When the valve is opened, the exhaust gasses in each cylinder escape to pressures less than that of ambient. Engines employing similar intake and exhaust methods have yielded volumetric efficiencies greater than 120%.

Cylinder heads were then designed to accommodate the intake and exhaust runners, and to provide a higher compression ratio so that a greater thermal efficiency could be achieved.

To mate the custom fuel injectors to the new intake manifold, special mounting hardware was developed. The design consisted of four individual mounts, each of which holds two injectors. These mounts are interconnected using reservoirs of ample internal volume so that the cyclic firing of injectors will not induce any substantial pressure variations.

In addition, higher precision cylinder surfaces and corresponding piston interfacing has been accomplished. This was done to minimize oil consumption and the resulting negative impacts upon exhaust emissions.

Cam

A new camshaft was designed to meet the custom needs of the hydrogen application. The variables with the most significant impact on the design of the cam profile are the range of speeds of operation and the combustion characteristics of the fuel being used. Since the engine was intended for operation at a constant speed, the valve actuation could be designed in such a way that the most efficient cycle could be obtained.

The burn properties of hydrogen differ significantly from those of gasoline, and thus several special considerations were made in the camshaft design. The original engine exhibited frequent ‘flash backs’ that were presumably caused by the high flame speed and low ignition temperature of hydrogen. Unstable fuel delivery and the existence of ‘hot spots’ within the cylinders undoubtedly contributed to their prevalence as well. To eliminate ‘flash backs’ and to better control the combustion of the fuel, the valve timing was altered to fit the characteristics of hydrogen.

The amount of time that the exhaust valve remains partially open while the intake valve is being opened, otherwise known as overlap, also needed to be addressed. While overlap is commonly used on variable speed engines to control the amount of exhaust remaining in the cylinder after combustion, our methods of introducing fuel and air and extracting it once burned allowed us to more closely time the valve actuation and to use the fuel more efficiently. To prevent the escape of unburned fuel and air and to reduce the possibility of premature ignition, the degree of overlap was significantly reduced.

Predicted Results

Utilizing custom driver software for the electronic fuel injection system, very precise metering of hydrogen delivery can be achieved. Herein may lie the largest improvements that will be realized over the existing engine design. With the ability to control accurately the amount of fuel entering each cylinder during the cycle, the optimum control system can be developed to provide the greatest overall efficiency.

An emissions-testing apparatus has been designed with special attention to two key elements in the exhaust, namely NOx and unburned hydrogen. With predicted nitrous oxide levels falling below the detectable range of most automotive analyzers, a special, high sensitivity analyzer was required. Along with this, a flow-through hydrogen sensor was acquired for the detection of any unburned hydrogen in the exhaust stream. This will insure that any parametric changes made to the engine during development have not led to the presence of unburned hydrocarbons in the exhaust stream and will aid in the optimization of the control systems.

The concept of the hydrogen powered engine shows that there should not be any significant amount of carbon compounds in the exhaust (the only possible source being the combustion of engine oil). Nevertheless, a standard automotive analyzer will be employed to ensure that any possible exhaust emissions are within accepted levels.

The intended nominal running speed of the existing engine was determined by the efficiency and the maximum output of the generator to which it was coupled. A more efficient generator that can operate at higher speeds will be incorporated into the modifications on the bus. Since the efficiency of the engine increases proportionately with its operating speed over a specified range, the new generator will allow us to operate the engine at a more efficient speed. The APU, consisting of the engine and the generator, can now be run at its combined peak efficiency.

Fuel Storage System

Existing System

The existing storage system on the bus is by means of a metal hydride system that is mounted under the bus. In this case a Lanthanum-Nickel-Aluminum (LANA) type alloy is used. The system consists of two separate beds that are cooled (usually by an external source of cool water) when hydrogen is to be added, and heated (with engine coolant in this case) when hydrogen is to be used. In its present configuration, the bed is estimated to be able to hold 15.2 kg of hydrogen. A great deal of additional information about the existing system can be found in Heung (1997) and Jacobs et al. (1999a, b).

Planned System

Plans are currently underway to install additional storage on the bus. This will take advantage of some new technology being developed by DOE: high-pressure composite material tanks. Current plans are to mount six 48” long x 18” diameter tanks on the top of the bus in the 2001 time frame. These tanks will allow a substantially increased amount of hydrogen fuel to be carried with the bus.

One of the design criteria for the modified fuel storage system is to have access to both a high-pressure-tank system and the low-pressure-hydride system by simple adjustments between the two. As new and more promising hydride bed systems are developed, it is hoped that the bus can serve as a test bed for evaluations.

System Modeling

Introduction

To enhance the system performance, a study of the system dynamics is being carried out. In this study, the special code is being used. This software, developed by the National Renewable Energy Laboratory (NREL) and called ADVISOR (ADvanced VehIcle SimulatOR), is available from the www (see the References section at the end of the paper). This is used to simulate and analyze the performance and fuel economy of this hybrid vehicle. In ADVISOR, this vehicle is handled in a series mode, which includes a fuel converter, a generator, batteries, and a motor. The fuel converter (an engine in this case) does not drive the vehicle shaft directly. Instead, it converts mechanical energy directly into electrical energy via the generator. All torque used to move the vehicle comes from the electric motor. The control strategy is a series power follower. The hybrid accessories are assumed to be a constant electrical power load.

Overall Performance Estimates and ADVISOR Simulation

For the H2-fuel bus system, we know the energy capacity of hydrogen and the battery, the efficiencies of engine, generator and motor, and the electrical power load at certain speed, we can use the energy equation (1) to calculate the total load and ranges vs. speed

$$(R_b + R_p)\,\eta_m = TL \tag{1}$$

where R_b is the rate of battery draw down, R_p is the rate of power produced from engine, η_m is the motor efficiency, TL is the total load.

In the bus system: the total hydrogen available = 15.2 kg; engine efficiency = 30%; generation efficiency = 95%; the battery starts at 100% state of charge (SOC) and ends at 20% SOC; motor efficiency = 88%. The load vs. speed is found in ADVISOR 2.2.1 as shown in Figure 1. The range vs. speed is shown in Figure 2 based on the energy balance, equation (1). The results are bus operation at constant speed.

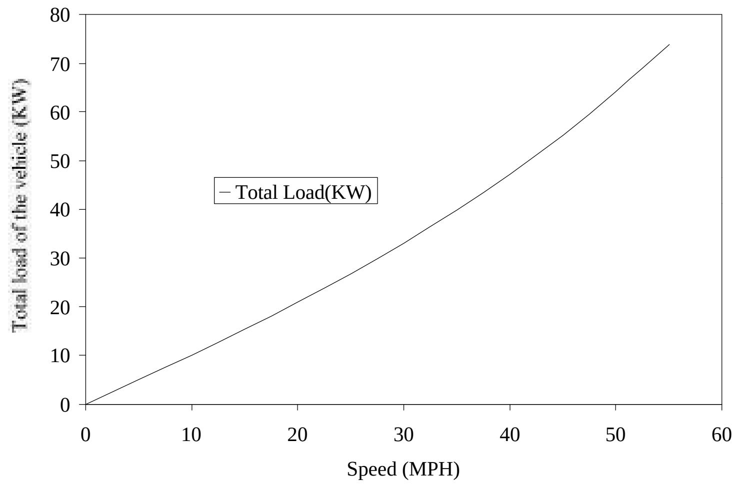

Figure 1. Electrical power load vs. speed for constant speed operation.

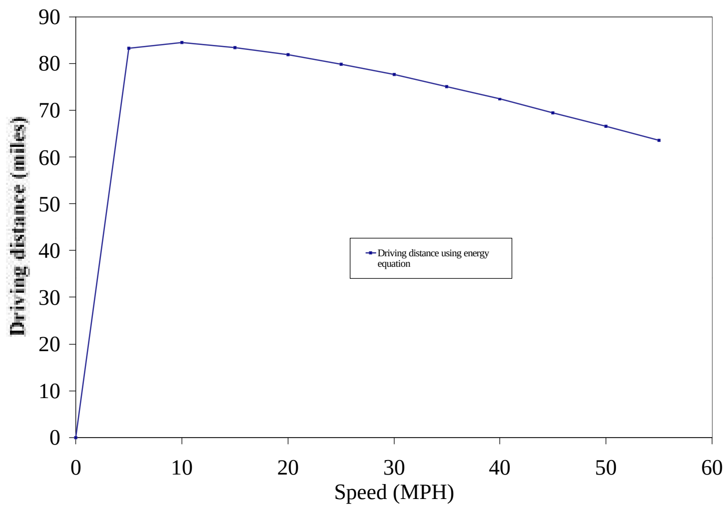

Figure 2. Maximum bus range at constant speed.

Implications of Different Driving Cycles

On a given trip, the bus may travel at a constant speed, or it may drive with many stops and starts. In the simulation using ADVISOR, the former case can be implemented using **CYC_constant**, and the latter is implemented using **CYC_FUDS** where FUDS stands for Federal Urban Driving Schedule. In Figure 3, the simulation results determining the battery-state-of-charge is given for a constant speed constant speed of 55 mph. The bus runs solely with the electrical battery for the first 27 minutes. The engine is on when the SOC of battery is at 40%. The power from the engine and the battery is used to drive the bus at 55 mph until all the hydrogen is used up. Then the bus runs only using the battery until the SOC reaches 20% which is assumed to be the lowest SOC the battery can tolerate before requiring recharging.

Now compare Figure 3, for constant speed, with Figure 4, which are related results but for the FUDS driving cycle schedule. The corresponding temporal use of fuel for the FUDS driving cycle is shown in Figure 5.

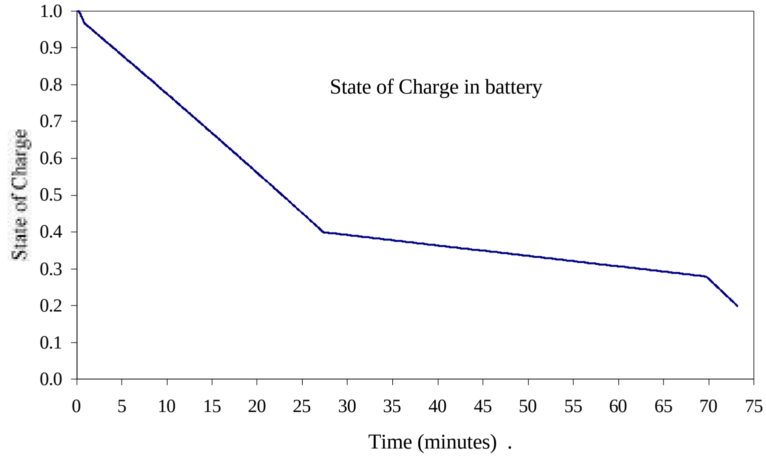

Figure 3. State of charge of battery at constant speed (55 mph).

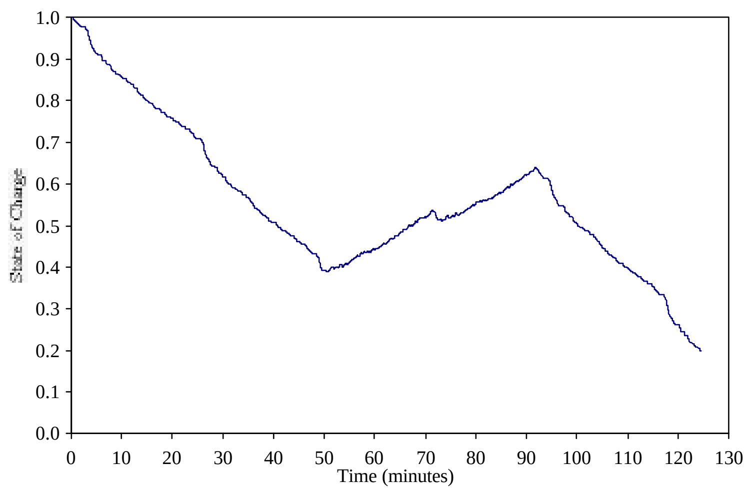

Figure 4. State of charge of battery using the FUDS driving cycle.

Regenerative braking is the process by which some of the kinetic energy stored in the vehicle's translating mass is stored in the vehicle during decelerations. In most electric and hybrid electric vehicles on the road today, this is accomplished by operating the traction motor as a generator, providing braking torque to the wheels and recharging the batteries.

In the system we are considering here, the regenerative braking will be by supercapacitors. Other than the dynamics of the two regenerative braking systems being different, the general energy considerations are similar. The energy provided by regenerative braking can then be used for propulsion or to power vehicle accessories. All scenarios were analyzed considering credit for regenerative braking or no credit.

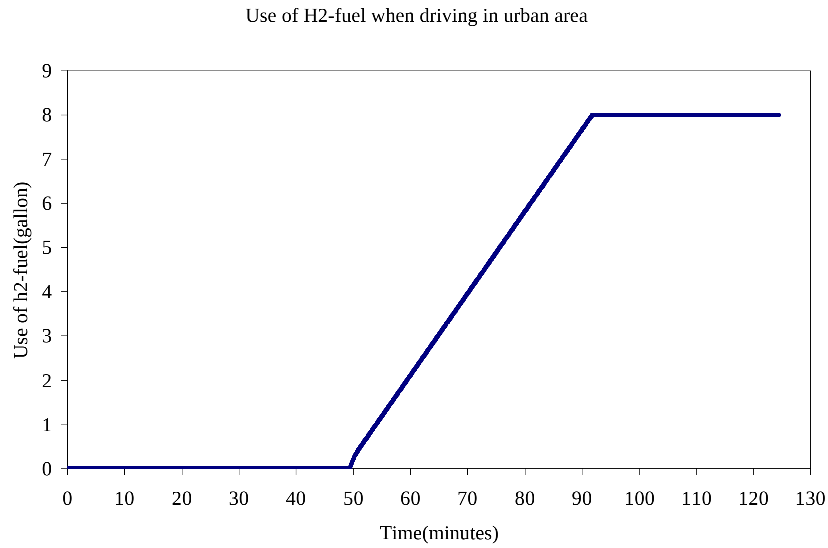

Figure 5. The temporal use of fuel during the FUDS driving cycle.

From Table 1, it can be seen that the bus with regenerative braking has a longer range. But note that the recharging time is not affected by regenerative braking. This is a result of the fact that the engine runs at full speed after it is turned on, and it is turned off when the total fuel is used up.

Table 1 Effects of Using Regenerative Braking

	With reg braking	Without reg braking
Trip elapsed time	155 min	124 min
Trip mileage	48.7 mi	39.3 mi
Recharging starts at	60 min	49 min
Recharging ends at	102 min	91 min
Recharging time	42 min	42 min

Concluding Comments

A project involving the development of a hybrid electric bus powered by a hydrogen fueled internal combustion engine has been described. This project is a continuation of some earlier work done by others. Extensive modifications are being made to the fuel system, engine, electrical system, and operation of the bus. All of these aspects are directed toward generally improving the performance of the bus.

Future Work

- Complete the modifications on the data acquisition system.
- Develop, install, and test the supercapacitor system

- Design, install, and checkout the hydrogen safety sensor system.
- Configure, design, and install the high pressure hydrogen storage system.
- Complete the design and fabrication of the new hydrogen engine.
- Test the engine and modify it to meet the performance goals, including total power, fuel efficiency, exhaust emissions.
- Install the engine into the bus.
- Operate the bus in a test mode.
- Perform additional system simulations and compare to actual operation.
- Detail a list of further modifications that would result in bus performance.

Acknowledgement

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