2000-01-1566

Modeling and Validation of a Fuel Cell Hybrid Vehicle

Michael J. Ogburn and Douglas J. Nelson
Mechanical Engineering, Virginia Tech

Keith Wipke and Tony Markel
National Renewable Energy Laboratory

ABSTRACT

This paper describes the design and construction of a fuel cell hybrid electric vehicle based on the conversion of a five passenger production sedan. The vehicle uses a relatively small fuel cell stack to provide average power demands, and a battery pack to provide peak power demands for varied driving conditions. A model of this vehicle was developed using ADVISOR, an Advanced Vehicle Simulator that tracks energy flow and fuel usage within the vehicle drivetrain and energy conversion components.

The Virginia Tech Fuel Cell Hybrid Electric Vehicle was tested on the EPA City and Highway driving cycles to provide data for validation of the model. Vehicle data and model results show good correlation at all levels and show that ADVISOR has the capability to model fuel cell hybrid electric vehicles.

BACKGROUND

Hybrid electric vehicles (HEV's) combine the benefits of several propulsion components in an attempt to produce a more efficient vehicle. A common approach to hybrid vehicle design takes a conventional vehicle drivetrain and combines it with components commonly found in an electric vehicle. In this type of vehicle, a gasoline engine might be augmented by an electric motor. In a fuel cell hybrid a different approach must be taken to harness the electrochemical energy produced by the fuel cell. In this case, hydrogen is converted into electrical energy that drives the wheels of an electric vehicle. In a fuel cell hybrid vehicle the power generation system does not completely replace the battery pack but rather serves to supply the average power demands of the vehicle. This allows for a smaller fuel cell than in a non-hybrid 'pure' fuel cell vehicle. As a flurry of recent developments has shown, such as 68 mpg by the hydrogen-fueled Ford P2000, fuel cells have the potential to provide high efficiency, high vehicle fuel economy, and very low emissions for hybrid electric vehicles.

The purpose of the research outlined in this paper is to provide vehicle-level validation of modeling performed using ADVISOR, a Matlab/Simulink based vehicle simulation package, on Virginia Tech's 1999 entry into the FutureCar Challenge, a 5-passenger fuel cell hybrid vehicle. Developed by engineering students for a Department of Energy student competition, it consists of 100kW (134hp) electric vehicle drivetrain, 324V sealed lead acid battery pack, and on board power generation provided by am Energy Partners 20kW PEM hydrogen fuel cell. (Figure 1)

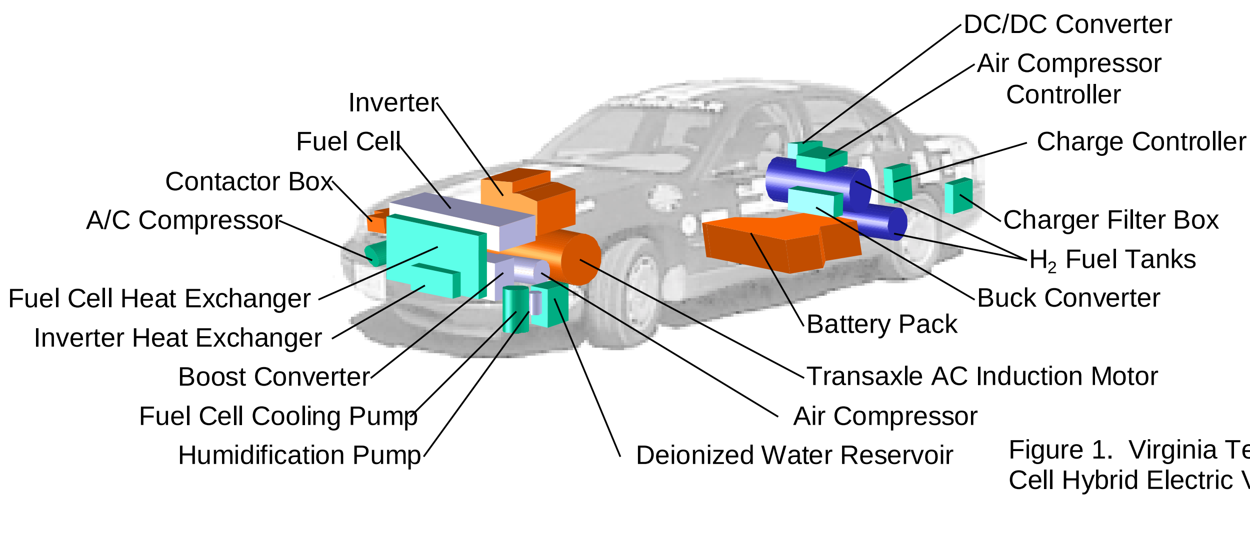


Figure 1. Virginia Tech Fuel Cell Hybrid Electric Vehicle

INTRODUCTION

The National Renewable Energy Laboratory has developed ADVISOR, an Advanced Vehicle Simulator that is a very useful computer simulation tool for analysis of energy use and emissions in both conventional and advanced vehicles. By incorporating various vehicle performance and control information into a modular environment within Matlab and Simulink ADVISOR allows the user to interchange a variety of components, vehicle configurations, and control strategies. Modification of data files to represent new or unique vehicle components is straightforward and a user friendly graphical user interface (GUI) allows for easy manipulation of input files, test routines, and output plots. Other unique and invaluable features of ADVISOR include the ability to quickly perform parametric and sensitivity studies of vehicle parameters on overall performance and economy.

However, no simulation tool is complete without being validated against measured vehicle data to ensure the reliability of its predictions. This paper outlines a validation study recently completed using the Virginia Tech Fuel Cell Hybrid Chevrolet Lumina that placed first and second, respectively, at the 1998 and 1999 FutureCar Challenges. A 3-D packaging layout is shown in Figure 1.

The work was focused on two areas: testing of the fuel cell stack and related subsystems, and modeling of the systems and their controls in Simulink. After construction, the vehicle was subjected to EPA city and highway driving cycles in controlled conditions at an emissions dynamometer facility. The data acquired from the vehicle test and the output of the ADVISOR model of the vehicle were compared to judge the accuracy and validity of the model.

TESTING AND MODELING

ADVISOR is a simulation package based on Simulink block diagrams and supported by Matlab data files that contain vehicle configuration, control, and performance data. Unlike other simulation packages which are set up only as executable code, these files are by their nature the source code for the simulation. Because of their graphical nature and straightforward construction the block diagrams are almost self-documenting, making modification relatively easy. This also makes ADVISOR well suited to collaboration between researchers and for distribution to the public. The graphical user interface (GUI) is shown in Figure 2.

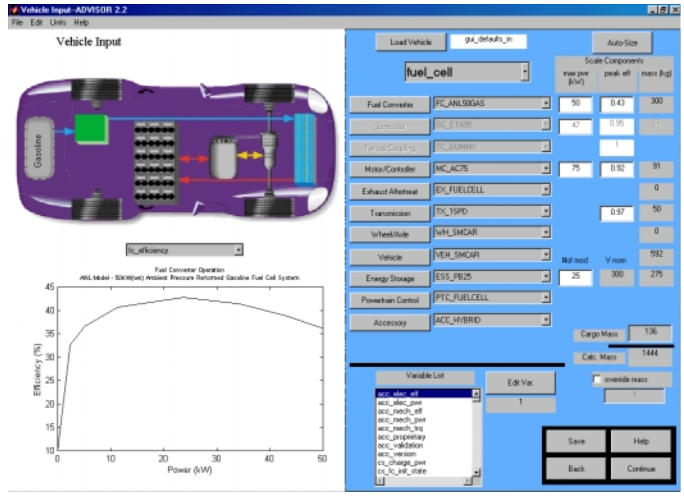


Figure 2. ADVISOR GUI, Vehicle Setup Screen

ADVISOR 2.2 incorporates many drivetrain types including conventional Internal Combustion Engine (ICE), electric, series and parallel hybrid, and fuel cell hybrid models. (Cuddy, Wipke, Burch, 1998) The fuel cell model that is integrated into ADVISOR 2.1 provides a temporary way of including a fuel cell hybrid simulation capability in a modeling package originally designed for ICE hybrids. However, this is not an ideal method to accurately represent the behavior of a fuel cell system. A major goal of this modeling effort is to improve the ability of ADVISOR to predict the energy flow and fuel usage of a fuel cell hybrid electric vehicle

DATA ACQUISITION

To acquire data about a vehicle for the purposes of characterizing its operation often requires an off-board computer and many additional sensors. Since it was known prior to the test that these facilities would not be available, other methods had to be developed. The vehicle control system, developed by undergraduate engineering students at Virginia Tech, serves to monitor operating parameters of the fuel cell system and of the vehicle level components and then to make decisions that allow the vehicle to function properly. This system consists of sensors and student-built signal conditioners that are fed into the input channels of a microprocessor control board. The secondary purpose of the control system is to support the research and analysis discussed here by also operating as a data logging system. After this information is used to make control decisions, it is sent out over a serial data line to an onboard computer that logs the 60 channels of sensor information whenever the vehicle is on.

Data on vehicle power flows are collected using a data acquisition system that tracks energy generation by the fuel cell system and energy flow to and from the batteries. After collection this information is streamed to the main onboard computer. When operating, the system makes measurements and decisions at varying sample rates and output the information to a data file on a second by second basis.

Uncertainties in this data acquisition system are believed to be <5%, because nearly all measurements are direct readings of reliable sensors. Measurements taken on power usage are particularly accurate, because these portions of the system are commercially designed and manufactured. The remainder of the system channels were calibrated by VT engineers over the ranges seen during normal operation of the fuel cell system. Overall, this system has proven to be accurate for all practical purposes, but it should be noted that the system does not respond quickly to transient events. For this reason, there is noticeable transient data scatter in several of the plots throughout this paper. The major data channels are summarized in Table 1.

Table 1. Main Sensor Channels

Battery Pack	Units	Measurable Range
Voltage	V	0-500V
Current	A	+/- 400A
Cumulative Charge	A-h	n/a
Energy Use	kW-h	n/a
Fuel Cell System Ouput:		
Current	A	+400A
Cumulative Charge	A-h	n/a
Energy Use	kW-h	n/a
Fuel Cell System Parameters:		
27 cell group voltages, total: 110	q	0-5V each
Total Stack Current	A	0-350A
Fuel Cell Power	W	n/a
Air Inlet Temperature	C	5-70C
Air Inlet Humidity	RH%	0-100%
Air Inlet Pressure	Kpa (psi)	101-234kPa (0-20psig)
Air Compressor Current Used	A	0-20A
Hydrogen Inlet Temperature	C	5-70C
Hydrogen Inlet Humidity	RH%	0-100%
Hydrogen Inlet Pressure	Kpa (psi)	101-235kPa (0-20psig)
Hydrogen Intermediate Pressure	Kpa (psi)	101-2164kPa (0-300psig)
Hydrogen Tank Pressure	Kpa (psi)	0-27.6mPa (0-4000psig)
Hydrogen Flow Rate	slpm	0-500slpm
Coolant Temp In	C	5-70C
Coolant Temp Out	C	5-70C
Coolant Inlet Pressure	psi	101-235kPa (0-20psig)

FUEL CELL SUBSYSTEMS

The goal of an ADVISOR model is to produce a computer simulation of the energy storage, energy generation, and energy flow within the vehicle that is used to propel it along a particular speed vs. time trace. Figure 3 shows the systems that store and generate energy aboard the VT FC-HEV and that are incorporated into the modified ADVISOR model (figure 12).

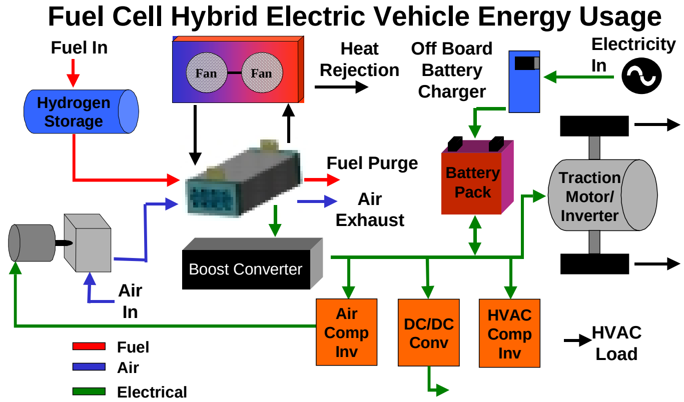


Figure 3. Energy Flow on the VT FC-HEV

<u>Fuel Cell Stack</u>

Fuel cell stack performance testing was completed by Energy Partners (EP) before shipping and was verified by system tests and on-vehicle testing (IN HEV). (See Figure 4)

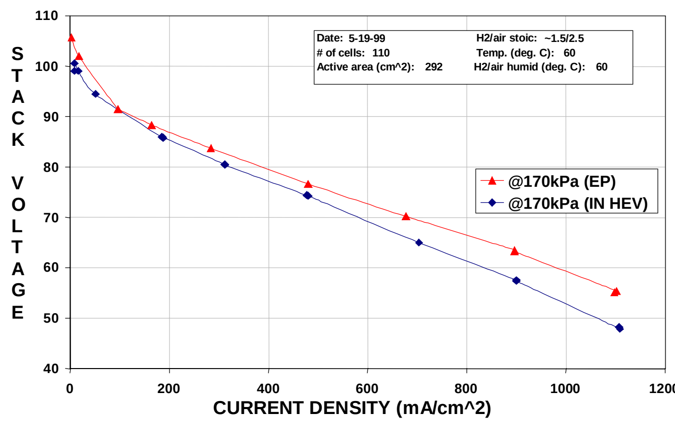


Figure 4. Polarization Curve, manufacturer vs. FC-HEV

Although the stack did not perform as well in the vehicle as it did in the laboratory, the differences can be explained by quality of reactant streams as well as minor damage to the stack that occurred prior to testing in the vehicle.

<u>Reactant Supply System</u>

To function at peak performance, a proton exchange membrane fuel cell such as the 20 kW Energy Partner's stack in Virginia Tech's fuel cell hybrid requires reactant streams that are under pressure and are humidified. On the fuel side of the fuel cell stack, pressurized hydrogen from tanks requires no additional energy as it flows through pressure regulators into the 170 kPa (10 psig) fuel lines and recirculation loop. The oxidant for this fuel cell is air, supplied at 1415 slpm (50 cfm) by a 7000 rpm screw compressor. Initial testing demonstrated that 4 to 5 kilowatts of electrical power would be needed at the input to the Air Compressor Motor Controller to create a 239 kPa (20 psig) air stream. This is nearly 25% of the fuel cell's total output. While this high pressure allowed improved fuel cell performance over 10 psig operation, the overall system efficiency was lowered due to the high parasitic energy demand. Because of this, the operating pressure of the stack was chosen to be 70 kPa (10 psig), allowing for more efficient operation overall.

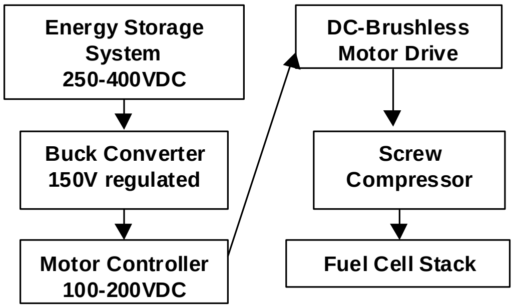


Figure 5. Air Compression System Power Flow

As seen in figure 5. the air compressor used on the VT FC-HEV vehicle must incorporate a regulating power supply called a buck converter to step vehicle battery voltage down to a level acceptable to the motor controller. This means that power must flow first through the buck converter, then the motor controller, and finally into the electric motor before entering the air compressor as mechanical power. This string of components does not contribute favorably to the overall efficiency of the system but it is required due to the limited availability of suitable components to operate a fuel cell system. Testing of the Air Compression System treats this entire system as one unit, measuring the input power used at the input to the buck converter to produce the required air flows at the output of the air compressor. This testing, verified by data recorded on board the vehicle, showed that the system needed 3.65 kW to supply the airflow needed at full fuel cell power.

Any time the fuel cell system is operating the air compressor operates at its full 3.65 kW load to ensure that adequate oxidant is supplied to the fuel cell stack. If the Fuel Cell is operating at full power, this amount of air flow meets the manufacturers recommended stoichiometric ratio of 2.5 times the required oxygen. As fuel cell power decreases, the air flow may also decrease to lighten parasitic loading as long as the stoichiometric ratio is greater than or equal 2.5. Due to system complexity constraints, the VT FC-HEV did not employ this "load following" technique to the fuel cell reactant supply systems and therefore suffers a system efficiency penalty when the system is producing less than peak power.

Other Accessory Loads

In addition to fuel and air supply, the Virginia Tech system required several other support systems, including thermal control through a water cooling loop with pump and fans, humidification control and water recovery using 2 small pumps, as well as fans to provide for electronic cooling. These constant loads were lumped into an accessory power block (Figure 6) in addition to existing vehicle accessories

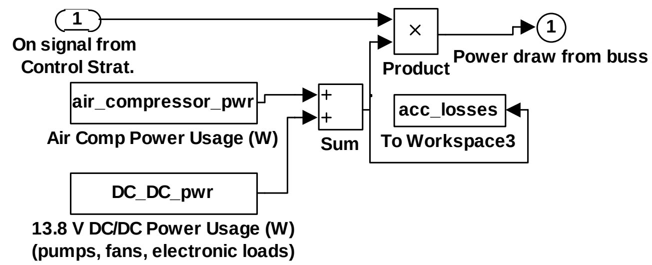


Figure 6. Accessory Load Block

The accessory block shows how the air compressor power is incorporated as a simple constant load accessory of the fuel cell system. This block also incorporates the additional 12V loads incurred by pumps and fans that are mentioned above.

Power Processing – Design Philosophy

A component unique to the design of the Virginia Tech Fuel Cell Hybrid Electric Vehicle is a power electronic device know as a boost converter. The boost converter used in this design serves two important purposes in the Virginia Tech Fuel Cell Hybrid Electric Vehicle (VT FC-HEV). First, it boosts the low voltage output of the fuel cell to match the voltage of the vehicle's battery pack, which varies widely with state of charge (SOC) and vehicle load. Secondly, it incorporates a load following portion of the vehicle control strategy to the fuel cell system, supplying a higher power level to the vehicle when it is under higher load. By sensing battery pack voltage, the boost converter allows the fuel cell to operate efficiently at low power when the vehicle sees light loads, while still supplying it with adequate power to maintain adequate SOC when vehicle power demand is high or to return power to the battery pack when it is discharged. Figure 7 shows a plot of this load following function.

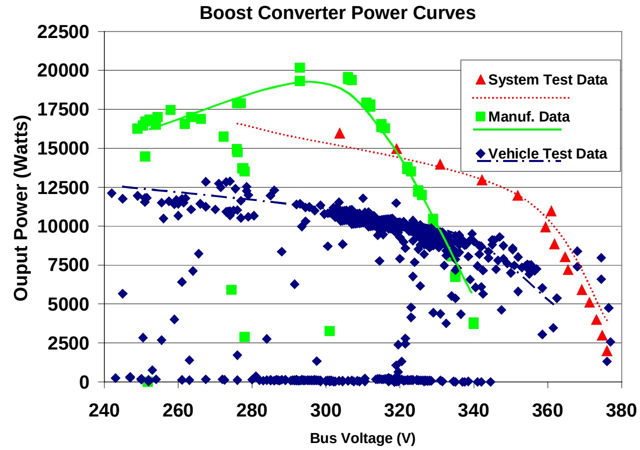


Figure 7. Boost Converter Power Transfer Curve

Safety comes first in any design. Human safety is incorporated into the boost converter by isolating the high voltage electronics of the system from the vehicle chassis and from the environment. However, In the design of this component's function and performance, it was safety of the fuel cell stack itself that was most important. The fuel cell provided by Energy Partners was made possible through a one-time grant from the Department of Energy that did not include any warrantee coverage or extra monies for repair. Failure to carefully plan measures that would protect the stack could doom the success of a 2 year project. There are two types of limits in place to protect the stack, a maximum current limit set to 300 amps, and a minimum voltage limit of 60V, both recommended by the manufacturer. With a proper reactant supply system installed and these limits in place, the fuel cell is properly protected from being overloaded. Regardless of fuel cell voltage, the boost converter will not allow higher currents under any condition. Should fuel cell voltage drop below 60V it can be inferred that inadequate reactants are available for the power requested. In this case, the power drawn from the stack is scaled back until voltage rises again. If fuel cell voltage should fall to 55V or less, the boost converter completely shuts down.

When specifying the operating controls of the boost converter in the preliminary design phases, the best available example of a successful hybrid control strategy was that of ANIMUL, the vehicle built by students at Virginia Tech that placed first in the nation in 1996. This series propane hybrid had a constant speed alternator with an open circuit voltage of about 400V under no load. When connected to the battery pack used in ANIMUL, the generator produced about 10kW at 350V. When the vehicle was under high load and the battery pack was at 250V, the generator produced about 20kW. This configuration proved effective in maintaining battery pack state of charge in ANIMUL during city and highway driving.

Since the fuel cell's open circuit voltage is 110V, operation by direct connection to the battery pack was not an option. The boost converter provided a way to boost the power of the fuel cell up to the voltage of the battery pack. Since a system that provided full power at around 250V and no power at 400V was so successful in the past, it was decided that an attempt to make a fuel cell system operate in a similar manner would give the best chance for success. Based on this assumption and additional information about the fuel cell system, the boost converter was designed to give full power at any voltage below 300V, and give zero power transfer at 380V. This range is slightly tighter than before, but assures that energy transfers at a rate fast enough to maintain battery state of charge while allowing the fuel cell to operate at medium to light loads a majority of the time. Because fuel cells are more efficient at light loads than engines, operation in this region allows for higher fuel economy.

To define this operation, we developed a "power transfer curve" for the boost converter. By watching the voltage on the battery pack, the boost converter demands a certain load from the fuel cell stack and processes this power from the low voltage of the fuel cell up to the battery pack voltage at that moment. See Figure 7.

The boost converter needed to be a simple device from an external control standpoint. Because of the complexity of the other systems on the vehicle and the team's limited experience with fuel cells, control was embedded within as many subsystems as possible. This included the boost converter, as it was the single most control-intensive fuel cell system in the vehicle. Another reason for this was that the fuel cell controller was not a particularly powerful package and its microprocessor was heavily taxed with other operations even without consideration of load control. Simplicity in integration also mattered and led to a design that was constructed to meet the space constraints within the vehicle. The end result was a boost converter that fit into the vehicle, operated on a pre-programmed 'power transfer curve,' and was turned on and off by a single 12V on/off signal.

Power Processing – Design Realization

Power Curves for the Boost Converter were produced from 2 test runs and are displayed with in vehicle test data in Figure 7. The first test was relatively noisy data

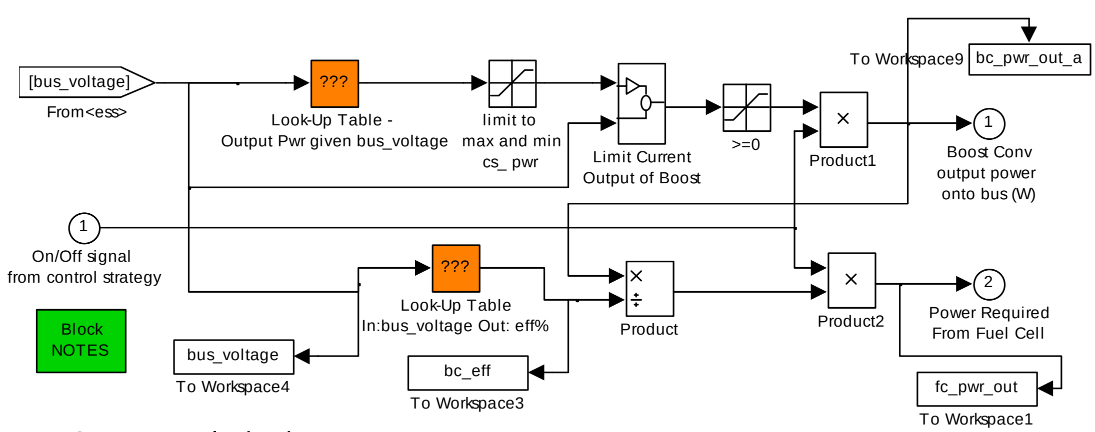


Figure 8. Boost Converter Block Diagram

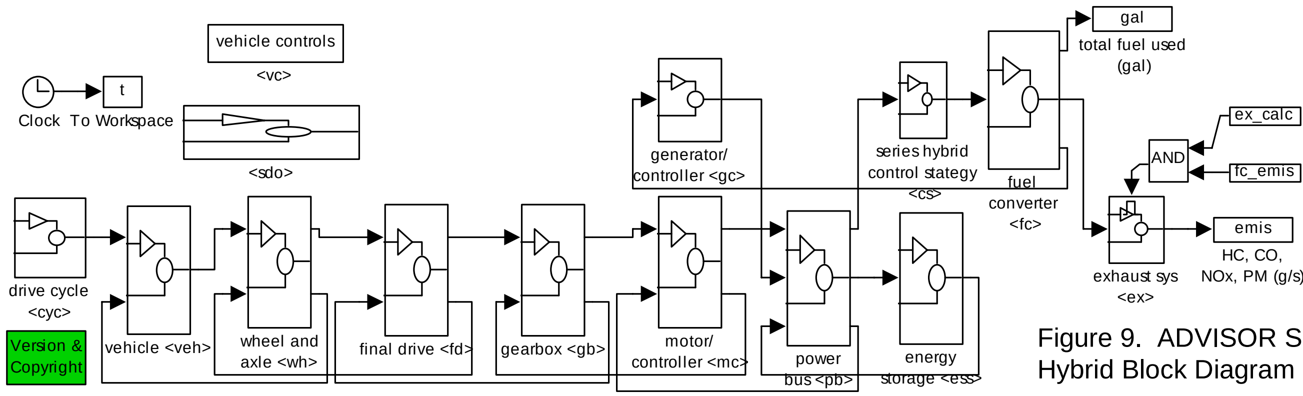


Figure 9. ADVISOR Series Hybrid Block Diagram

provided by the manufacturer of the unit. In an effort to verify the accuracy of this data and to gain a better understanding of how the device would function in the a hybrid vehicle a test session was arranged on an ABC-150 controlled DC power source that would simulate the operation of the fuel cell, the boost converter was tested to approximately 80% of full power, limited by maximum current available from the ABC-150. An attempt to model the fuel cell polarization curve was implemented on the ABC-150 by using a straight-line approximation. This approximation was coded into a script file that varied the ABC-150's voltage levels to match 138kPa (20psi) fuel cell performance data collected by Energy Partners. However, the ABC-150 was slow to respond to this script file and it could not properly simulate the fuel cell's power curve at light load. Despite limitations, the results of this test were good, both in verifying the manufacturers data and in learning more about the operating characteristics of the Boost Converter.

Lastly the boost converter was tested in the vehicle after all systems were operational. However, it is important to note that the fuel cell itself was slightly damaged prior to dynamometer testing of the vehicle. It's output voltage was not as high as desired, causing the boost converter to protect the fuel cell from delivering maximum power. This affects the power transfer curve of the fuel cell system and prevents the vehicle from receiving as much power as it needs to maintain battery state of charge.

The model shown in Figure 8 recreates the action of the Boost Converter, the device that boosts power from the ~60V fuel cell to the ~330V battery pack. When the system is operating, this block transfers power to the Power Buss at a rate controlled by a 1-D lookup table based on in-vehicle testing. The input to this table is the calculated battery pack voltage of the Energy Storage System (ESS) block to emulate the behavior of the battery pack in the actual vehicle.

Further testing showed that the load following strategy built into the boost converter was not aggressive enough to maintain adequate SOC during vehicle operation. To combat this the vehicle buss voltage was lowered by changing the number of batteries in the string to 27. Seeing this lower average voltage, the boost converter would go to a higher average load and help to maintain a higher battery SOC.

NEW SIMULINK BLOCK DIAGRAM

Figure 9 shows the structure the block diagram that models a series hybrid electric vehicle. Figure 10 shows how the vehicle layout, originally described in Figure 3, is incorporated into the new fuel cell block diagram. The basic flow of energy in an ICE series hybrid is the same as that in a fuel cell hybrid however a fuel cell produces electrical power, not speed and torque as the series model in Figure 9 requires.

To better model the Virginia Tech fuel cell hybrid the series hybrid block diagram is altered to contain the proper components blocks and data files are loaded with information from the test phase of the project. This

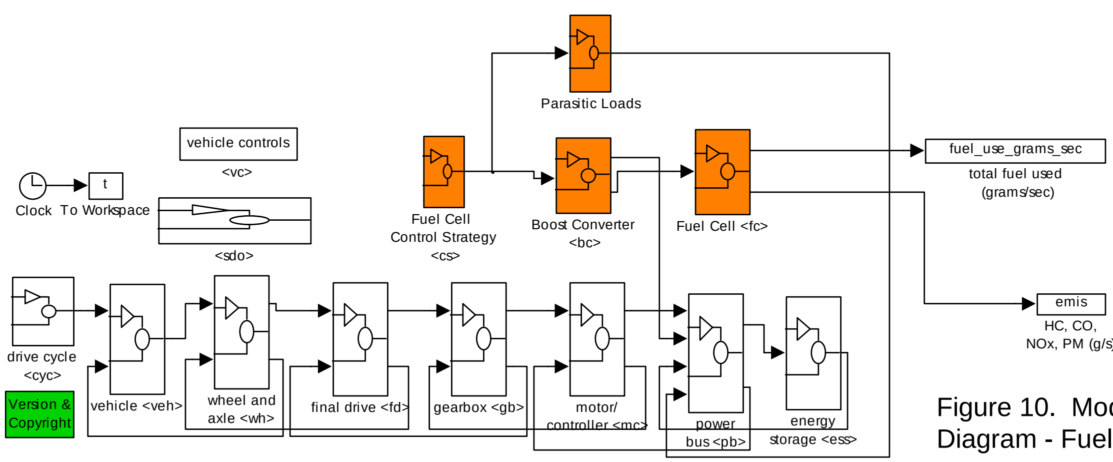


Figure 10. Modified Block Diagram - Fuel Cell System

model begins with the well validated electric drivetrain model that exists within ADVISOR (Senger, Merkle, and Nelson, 1998) and adds the components that make up the fuel cell system in the current Virginia Tech fuel cell hybrid electric vehicle.

RESULTS

Vehicle testing was performed at an emissions test facility equipped with roller dynamometers capable of performing a range of tests including the Federal Urban Driving Schedule (FUDS) and the Highway Fuel Economy Test (HWFET). See Figure 11. The VT FC-HEV completed each of these tests running on hydrogen as a fuel cell hybrid vehicle.

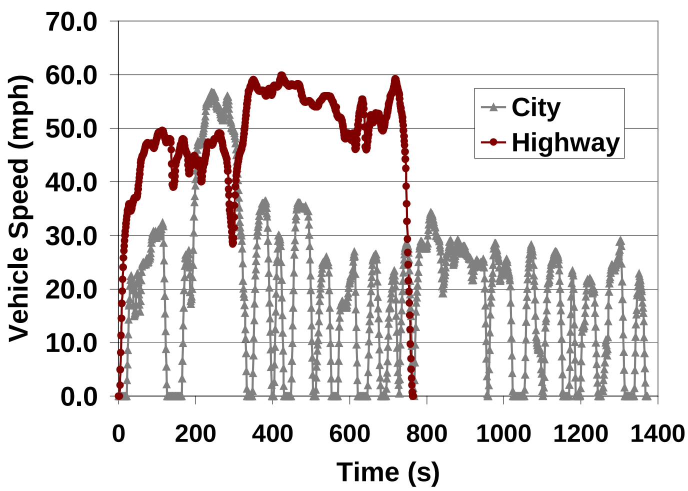


Figure 11. EPA City and Highway Driving Cycle Speed Traces – mph vs. time

COMPARISON OF VEHICLE DATA TO MODEL DATA

The dynamometer tests were successful, however the problems that developed prior to the testing meant that the vehicle did not operate as a charge sustaining hybrid vehicle as it was designed. Damage to the hydrogen fuel cell prevented it from reaching higher power levels that would have provided enough power to maintain the charge in the vehicle battery pack. Because of the reduced power, a net amount of energy was withdrawn from the battery during the cycle which would have prevented operation after the batteries were discharged completely. Had this damage not occurred, it is believed that the system would have been able to sustain charge during successive cycles until the onboard hydrogen storage was depleted.

Component Data

Because of the difference in the designed operating parameters for the vehicle and the way the vehicle actually functioned, the original model that was based on component data prior to vehicle construction had to be altered slightly. The main change from the ideal model of the vehicle was the power transfer model in the boost converter. Because the fuel cell was not able to provide the expected power, that the boost converter accordingly limited in the amount of power it could supply to the vehicle. This power transfer characteristic was altered in the model to produce a behavior that matched the reduction in available power so the model could emulate the way the vehicle performed.

It is immediately apparent that the plots of data from the boost converter manufacturer, from the out-of-vehicle testing, and from on vehicle testing do not totally agree. (See Figure 7) While this seems unusual, it is important to notice that the vehicle test data and the system test data do follow very similar trends. The reason for this lies within the fundamental design of the boost converter, as much of the internal controls that relate its output power to output voltage are preprogrammed to account for changes of both input and output voltages. Changes in these voltages greatly affect the power transfer of the system. A design criterion even more important than the power transfer curves above was the boost converter had to protect the fuel cell from being overloaded at any point in time. An abnormally low fuel cell voltage, such as that caused by fuel cell damage, would cause the boost converter to limit power output.

During normal operation a decrease in battery voltage at the output terminals would cause an increase in power transfer. In times when the fuel cell was unable to provide the requested power and its voltage fell due to overloading, the boost converter would relax its request. This meant that the boost converter's behavior could only be characterized through testing methods that *exactly* matched the behavior of the fuel cell polarization curve. The factors influencing this curve are so numerous and system dependent (operating pressure, temperature, rate of reactant flow, etc) that accurate information could only be gathered from a full system test with the fuel cell as the power source.

In summary, system testing data shown in figure 14 is believed to represent the true operation of the of an undamaged fuel cell in the VT FC-HEV fuel cell system, while the "vehicle test data" plot represents how the system operated during the EPA test procedure with the damaged fuel cell.

Time Based Data Tracking

Figures 12 and 13 show the time history of data recorded onboard the vehicle during dynamometer testing at Ford's labs vs. the output of the ADVISOR model of the VT FC-HEV.

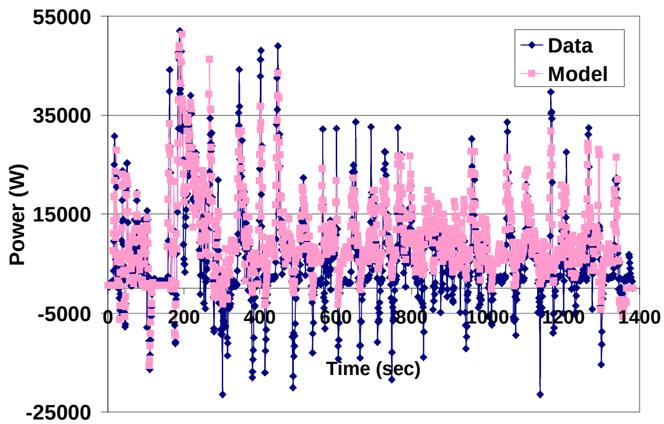


Figure 12. City Cycle - Motor Power

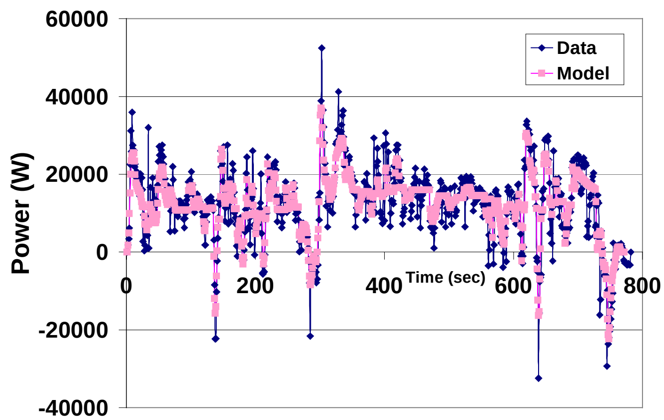


Figure 13. Highway Cycle – Drive Motor Power

As you can see, the model does a good job of tracking the overall electrical power required to operate the electric motor and the accessories on the vehicle data throughout driving cycle. This is a critical first step to creating an accurate model of a hybrid vehicle. Once the loads of the electric vehicle are quantified, the model must correctly determine how that power demand is split between the battery pack and the fuel cell system. Because this split changes as battery state of charge increases or decreases, accurate modeling of the battery pack and of the boost converter that transfers power from the fuel cell system is very important, as discussed above.

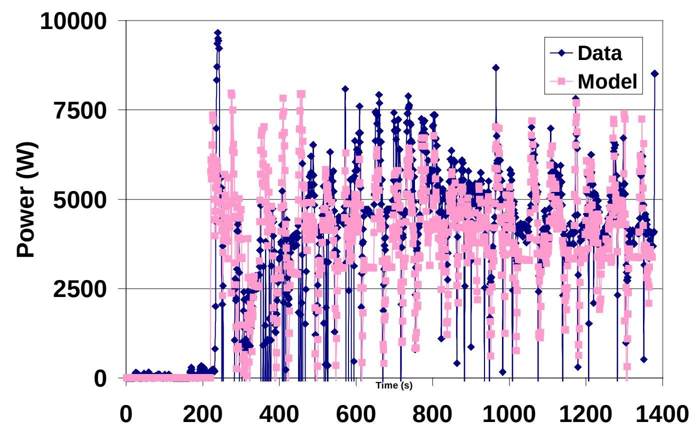


Figure 14. City Cycle – Fuel Cell System Net Power

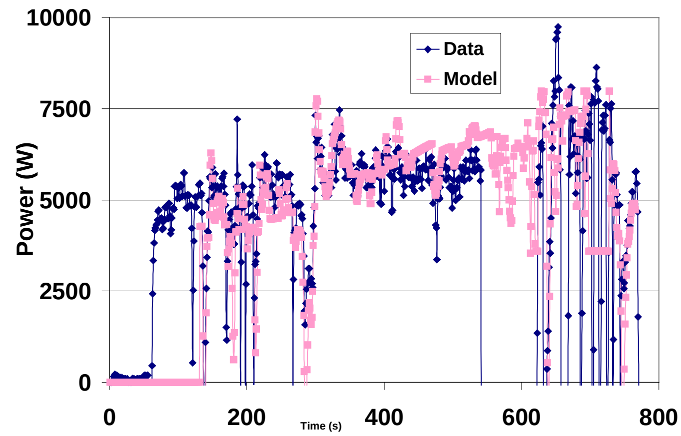


Figure 15. Highway Cycle - Fuel Cell System Net Power

The graphs of power output of the fuel cell, seen in Figures 14 and 15, vary for two different reasons. The fuel cell was operating in a diminished state due to damage incurred before the testing began. Because of this, combined with the fact that the fuel cell was cold at the beginning of the FUDS test the system controller commanded temporary shutdowns to protect the fuel cell from further damage. No compensation was made for this in the model. On the highway cycle, an unexpected problem occurred with the vehicle controller that caused the fuel cell to go into temporary shutdown near the end of the cycle. In this case, the model's fuel cell started later than the fuel cell started during the actual test, but this is accounted for by the fact that the fuel cell was off for a matching amount of time. Any time the fuel cell is off requires more power to be drawn from the battery pack to supply the loads onboard the vehicle. During times when this occurred, more power was required from the batteries, making the Amp Hour data plots diverge as seen in Figures 16 and 17.

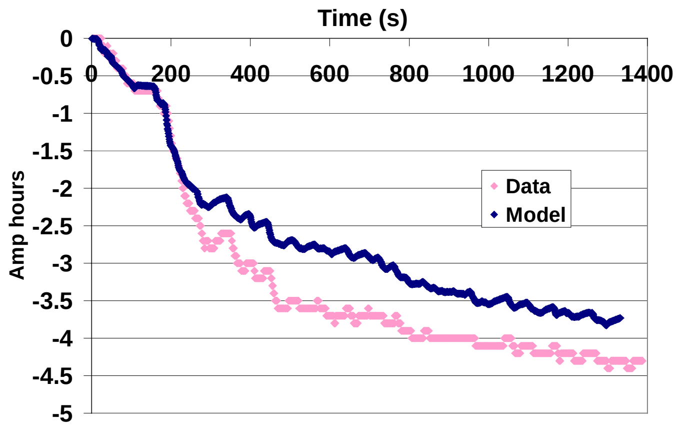


Figure 16. City Cycle – Battery Amp Hours Used

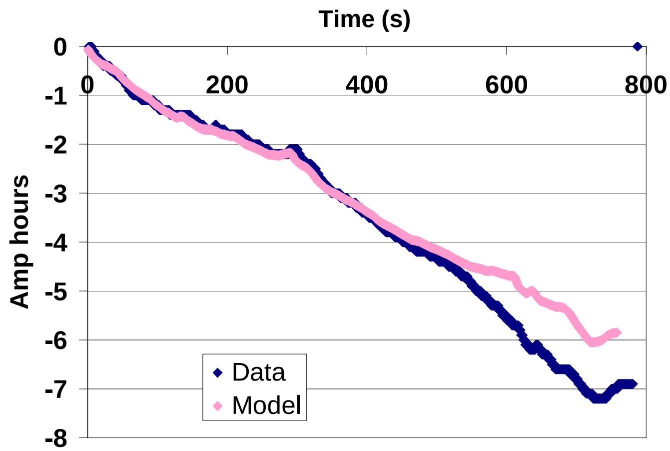


Figure 17. Highway Cycle – Battery Amp Hours Used

Tracking vehicle buss voltage is most critical to the operation of the VT FC-HEV. In both the vehicle and the model, buss voltage is used as a signal to the fuel cell system to provide varied power to the buss under varied loads. In the model the Energy Storage System computes a buss voltage variable based on instantaneous power demand and state of charge and outputs this to the Boost Converter Block for processing into a fuel cell system power request. See Figures 18 and 19. To produce this output, the Energy Storage Block was loaded with a battery model to match the capacity an performance of the one in the VT FC-HEV

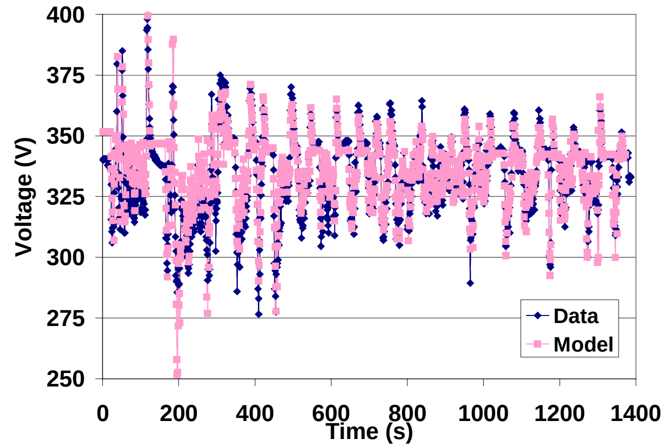


Figure 18. City Cycle - Battery Buss Voltage Tracking

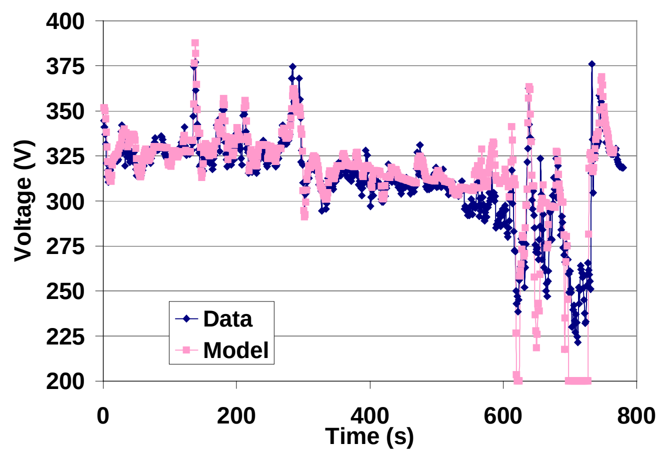


Figure 19. Highway Cycle - Buss Voltage Tracking

Further proof that buss voltage tracking and the upstream calculation of net power generated by the fuel cell system is accurate is shown in Figure 20. On a reduced time scale of 100 seconds and a reduced power scale of 4500W, the vehicle data and model results match very well.

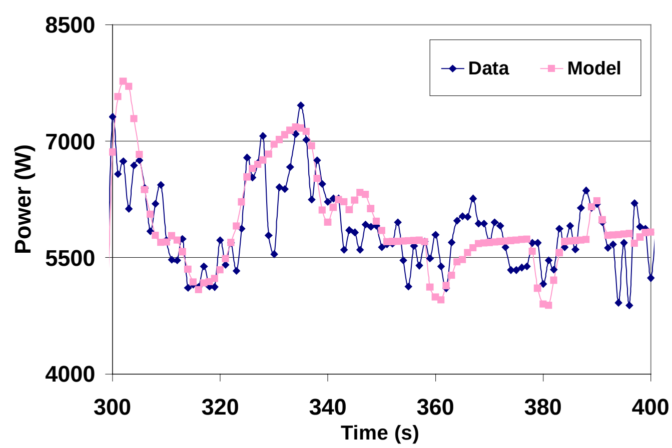


Figure 20. Detailed Data Tracking

SYSTEM EFFICIENCY

As seen in Figures 21 and 22, peak fuel cell system efficiency of the Virginia Tech fuel cell system is comparable with that of conventional energy generation systems and is somewhat less than what has recently been made possible in lightweight diesel and DI-gasoline engines. Although fuel cells, at first glance, have amazing efficiency potential, the engineering challenge is not trivial when all aspects of operating a fuel cell system are considered. Poor attention to detail can quickly yield a system that barely produces any net power at all. However, one must consider that this particular fuel cell system was built completely by undergraduate students with no prior experience with fuel cells and little more than a list of guidelines to start with. Their achievement is an impressive showing of ingenuity and persistence. Given only 8 months to complete their task, there is much room for improvement in the control and operation of the system itself and in the integration of the system into the Chevrolet Lumina chassis. Items for improvement include weight reduction, air compressor load following as discussed above, and control strategy optimization.

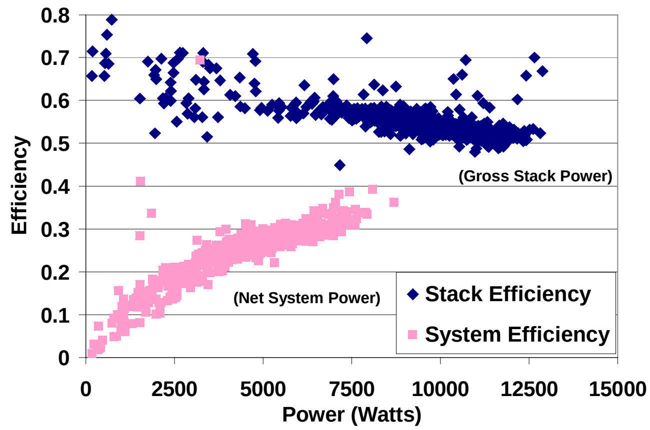


Figure 21. City Test Data- Electric Generation Eff.

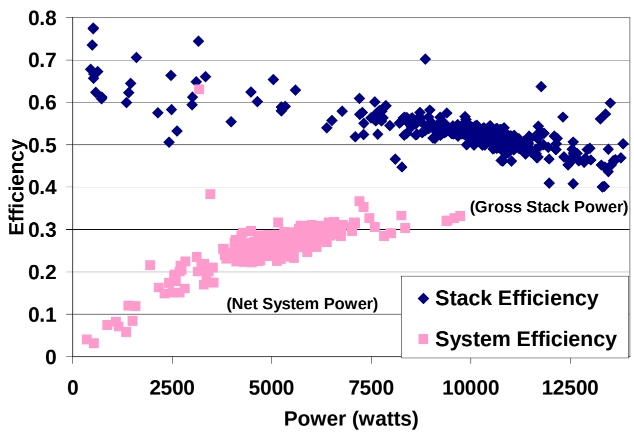


Figure 22. Highway Test Data - Electric Generation Eff.

Stack and system efficiency data are based on the ideal voltage potential for a hydrogen-fueled fuel cell and are computed at each instant as follows:

$$\text{Stack Eff} = \text{Average Cell Voltage} / 1.254\text{V}$$

$$\text{System Eff} = \text{Stack Eff} * \frac{(\text{stack power} - \text{parasitic power})}{\text{stack power}}$$

Overall Energy Consumption

As Shown in Figures 23 and 24, Total electric energy use and generation is very close between model and testing great proving the validity of the vehicle model and boost converter modeling technique. Overall fuel use is slightly off the highway driving cycle but was very accurate on the city cycle. This is due in part to the fact that the data used to predict fuel use was averaged over the both the city and highway cycles. Because the city cycle is nearly twice as long as the highway cycle, the fuel use during this period therefore has a greater impact on the averaged data than the highway cycle. Other factors that include thermal issues, since the fuel cell system was fully warmed up on the highway cycle and performed differently than when it was after a cold-start during the city cycle. The model did not incorporate thermal compensation and could not simulate this effect in final fuel economy numbers.

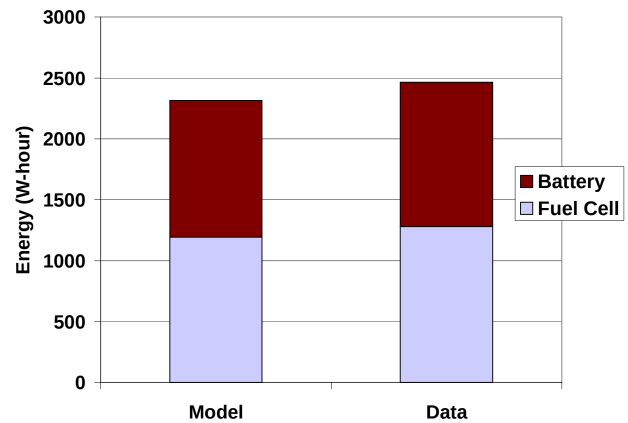


Figure 23. City Cycle - Total Energy Use

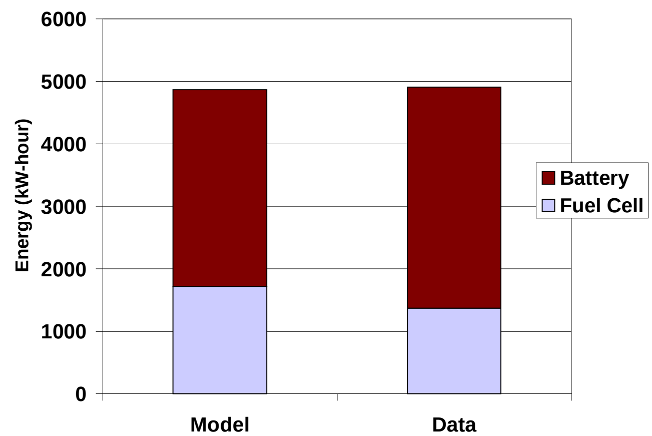


Figure 24. Highway Cycle - Total Energy Use

The fuel economy numbers shown in Table 2 combine the energy used from the energy storage system which was recharged with power generated at a power plant as well as the hydrogen fuel use to generate power in the fuel cell system. Had the fuel cell system been

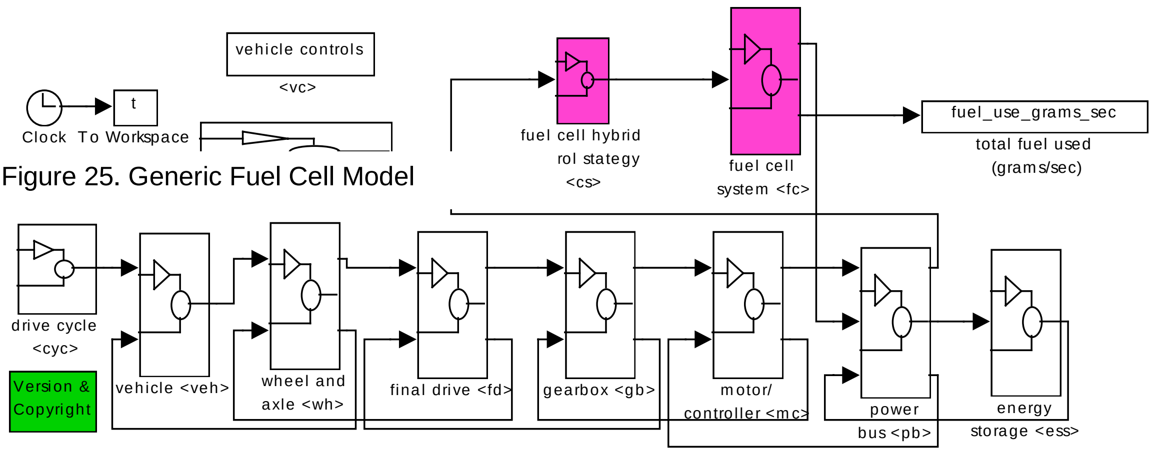


Figure 25. Generic Fuel Cell Model

functioning at full power, the energy storage system would have remained nearly charged and the majority of the power would have been generated directly from hydrogen.

Table 2.

MPGGE	Highway	City
VT_FuelCell Model Prediction	**28.3**	**29.1**
Data: from tank pressure	**26.8**	**29.1**

CONTINUED MODELING EFFORTS

The VT FC-HEV ADVISOR model provides a reasonably accurate model of the vehicle and the interconnection of vehicle and the fuel cell systems that are specific to the Virginia Tech design. Its disadvantages are that it requires a very accurate model of the vehicle's energy storage system and load-following power transfer system. This model is not versatile enough in its current form to be released into the ADVISOR environment for public usage. Therefore, a more generalized model was developed following the proven themes used in the initial model. This new "generic" model individually incorporates the behaviors of the fuel cell stack, reactant supply systems, and cooling systems to form a more integrated, thorough model.

This new model of a fuel cell system includes avenues to ease entry of new fuel cell data, and even incorporates a thermal model to help approximate the affect of cold starts on fuel consumption of a fuel cell stack. Work continues with NREL to complete the integration of this model into a release version of ADVISOR. Further work also includes modeling of the VT FC-HEV in its as-designed state with all systems functioning at full capability. This model is expected to show better fuel economy as well as be charge sustaining over the EPA driving cycles.

Validation of the "Generic Fuel Cell Model"

This model of a fuel cell system in ADVISOR is designed to integrate the new "Generic Fuel Cell Model" into the default series hybrid vehicle model for comparison to data from the 1999 FutureCar Challenge. Several major changes have been made from the original VT_FUELCELL model discussed up to this point, in an attempt to better represent actual vehicular fuel cell systems. The goal of these changes was to produce a model that is more straightforward and allows user access to system level and stack parameters.

Figure 27 compares the 1999 FutureCar Challenge data to the "Generic Model" results. However, rather than use the standard series power follower control strategy found in ADVISOR, a "boost converter style" of power request, based on buss voltage, was used to command the power level of the fuel cell system block. The following power history plot (Figure 27) shows that this

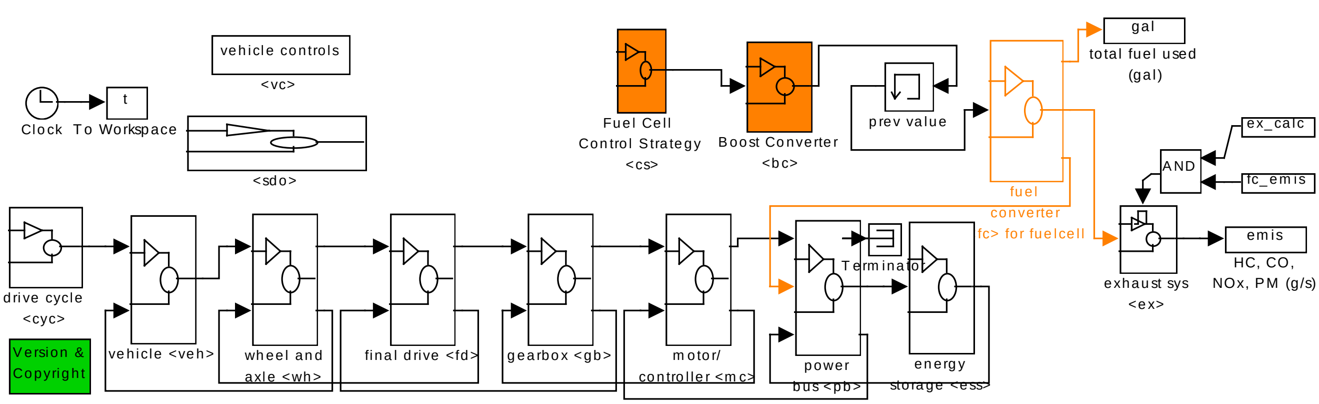


Figure 26. Generic Block Diagram with Boost Converter

new model, combined with the boost converter control methodology, functions accurately.

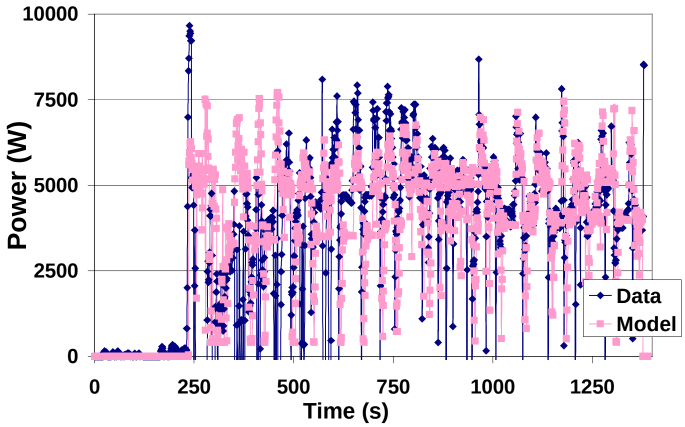
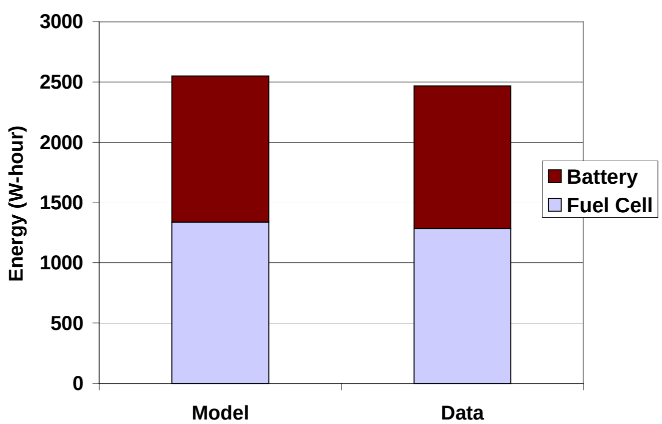


Figure 27. City Cycle - Fuel Cell System Power Tracking

Using this method, the power tracking and energy use for the generic fuel cell system much more closely resembled the test data.



Future 28. Energy Use - new ‘generic’ fuel cell model

Current status / Conclusions

The generic fuel cell model incorporated into ADVISOR 2.2 accounts for the major aspects of a fuel cell system. It allows for load following of fuel cell parasitic system loads, and has a fully separate power demand block (control strategy) instead of an integrated boost converter. Most importantly, the model provides the ability to perform parametric analysis on various fuel cell system parameters. Researchers at VT feel that this model provides a good representation of how a fuel cell system works (and how the VT system would have worked if not for system damage before testing). The original VT model showed that a fuel cell hybrid can be modeled in ADVISOR and matched to test data. Although no vehicle-level data exists to validate the new ADVISOR "generic" fuel cell model, VT recommends its future use for vehicle-level modeling of automotive fuel cell systems.

CONCLUSIONS

The Hybrid Electric Vehicle Team of Virginia Tech was successful in its attempt to convert a 5-passenger sedan to fuel cell power and the resulting data validated the new ADVISOR fuel cell system model. Testing of the fuel cell system and vehicle components yielded data that was used to determine overall fuel cell system efficiency, vehicle energy flow, and fuel usage. Using this data, a model of the VT FC-HEV was incorporated into ADVISOR. This model included a power sharing model to determine the load sharing between the fuel cell and the energy storage system for a given vehicle power demand. This model accurately represented the vehicle as it performed during real world testing. Comparison to vehicle test data shows that total fuel cell system energy production, total energy usage from the vehicle energy storage system, and total vehicle electrical energy use agree to within 10% in all cases. Overall vehicle fuel economy was accurate to within 1% on the city driving cycle and 6% on the highway driving cycle.

FUTURE WORK

To better model fuel cell vehicles, deeper investigation of the many complex issues involved is needed. Several critical areas of design that have a major impact on vehicle efficiency have been identified. The first area is an analysis into hybridization of fuel cell vehicles and the impact of drivetrain weight vs. drivetrain efficiency. Pure fuel cell vehicles generally weigh less than hybrid fuel cell vehicles, but do not have the capability of regenerative energy storage. Optimization of the degree of hybridization (size of battery vs. size of fuel cell) may yield a more efficient design overall.

Critical to the success of any vehicle is proper optimization of control systems to meet vehicle power needs over a range of driving conditions. In addition to vehicle level controls, system level controls and especially thermal control have a great impact on fuel cell efficiency. Better modeling of thermal characteristics is vital to an accurate understanding of fuel cell system.

ACKNOWLEDGEMENTS

This work was sponsored by The National Renewable Energy Laboratory under contract
XCL-8-18086-01.

NREL would like to thank the U.S. Department of Energy for continued support in the area of vehicle systems analysis and ADVISOR development.

The Hybrid Electric Vehicle Team of Virginia Tech extends its deepest thanks to Virginia Power for use if its ABC-150 for testing.

REFERENCES

Wipke, K., Cuddy, M., Burch, S., "ADVISOR 2.1: A User-Friendly Advanced Powertrain Simulation Using a Combined Backward/Forward Approach," IEEE Transactions on Vehicular Technology: Special Issue on Hybrid and Electric Vehicles, Nov. 1999.

Senger, R. D., M. A. Merkle, and D. J. Nelson (1998), "Validation of ADVISOR as a Simulation Tool for a Series Hybrid Electric Vehicle," Technology for Electric and Hybrid Vehicles, Proceedings of the 1998 SAE Intl. Congress, Detroit, MI, Feb. 23-26, SAE Paper 981133, SP-1331, pp 95-115.

William Luttrell, Brian King, Scott Postle, Robert Fahrenkrog, Michael Ogburn, Douglas J. Nelson, (2000), "Integration of Fuel Cell Technology into the Virginia Tech 1999 Hybrid Electric FutureCar," submitted to Proceedings of the 1999 FutureCar Challenge, June 2-9, 1999, Auburn Hills, MI, to be published by SAE, 15 pages.

Gromatzky, J., M. J. Ogburn, A. Pogany, C. A. Pare, J. Hutchinson, and D. J. Nelson (1999), "Integration of Fuel Cell Technology into the Virginia Tech 1998 Hybrid Electric FutureCar," Proceedings of the 1998 FutureCar Challenge, June 3-10, 1998, Auburn Hills, MI, published by SAE, SP-1452, Mar. 1999, 15 pages.

Senger, R. D., M. A. Merkle, and D. J. Nelson (1998), "Design and Performance of the 1997 Virginia Tech Hybrid Electric FutureCar," Proceedings of the 1997 FutureCar Challenge, SAE SP-1359, pp. 99-112.