# Validation of ADVISOR as a Simulation Tool for a Series Hybrid Electric Vehicle Using the Virginia Tech FutureCar Lumina

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## Abstract

Growing environmental and economic concerns have driven recent efforts to produce more fuel efficient and lower emissions vehicles. These goals are reflected by the Partnership for a New Generation of Vehicles (PNGV), a government, industry, and educational partnership in the United States. The major goal of this partnership is to have production vehicles by 2010 to address these concerns. Ideally, these vehicles will achieve three times the current fuel economy while drastically lowering emissions levels, without sacrificing the features, comfort, and performance of current conventional automobiles.

Hybrid Electric Vehicles (HEVs) are automobiles which have both electric drivetrains and fuel-consuming powerplants. HEVs provide some of the most promising designs with the capability of meeting the PNGV goals. However, the development of these vehicles within the next ten years will require accurate, flexible simulation tools. Such a simulation program is necessary in order to quickly narrow the technology focus of the PNGV to those HEV configurations and components which are best suited for these goals. Therefore, the simulation must be flexible enough to encompass the wide variety of components which could possibly be utilized. Finally, it must be able to assist vehicle designers in making specific decisions in building and testing prototype automobiles.

One of the most widely used computer simulation tools for HEVs is the ADvanced VehIcle SimulatOR (ADVISOR) developed by the National Renewable Energy Laboratory. This program is flexible enough to operate on most platforms in the popular MATLAB/SIMULINK programming environment. The structure of ADVISOR makes it ideal for interchanging a variety of components, vehicle configurations, and control strategies. Its modern graphical user interface allows for easy manipulation of various inputs and outputs. Also, the capability to quickly perform parametric and sensitivity studies for specific vehicles is a unique and invaluable feature of ADVISOR.

However, no simulation tool is complete without being validated against measured vehicle data so as to ensure the reliability of its predictions. ADVISOR has been tested using data from a number of student-built HEVs from the top engineering colleges and universities around the country. As ADVISOR evolves to meet the changing needs of the vehicle design teams, this testing continues to ensure that ADVISOR maintains its usefulness as a simulation tool. One current validation study was recently completed at Virginia Tech using the FutureCar Challenge entry.

This paper details the validation of ADVISOR using the Virginia Tech Lumina, a series HEV. The basic structure of the ADVISOR code is covered to ensure the validity of the vehicle modeling techniques used. The modeling process is discussed in detail for each of the major components of the hybrid system: transmission, electric motor and inverter, auxiliary power unit (fuel and emissions), batteries, and miscellaneous vehicle parameters. The integration of these components into the overall ADVISOR model is also described.

The results of the ADVISOR simulations are then explained and compared to measured vehicle data on energy consumption, fuel efficiency, emissions output, and control strategy function for a variety of driving cycles and test procedures. Uncertainties in the measured data are discussed. Finally, the discrepancies between predicted and actual behavior are analyzed. This validation process shows that ADVISOR has extensive value as a simulation tool for HEVs. The existing limitations of the program are also detailed, with recommendations for improvement.

## Acknowledgements

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## Chapter 1. Introduction

Freedom of personal transportation is one of the most highly valued liberties enjoyed by Americans. The dominant means for this transportation has been in the form of the automobile. However, the extensive use of automobiles has begun to show some detrimental environmental effects, such as poor air quality and a drain on natural energy resources, particularly in the United States. Limited domestic fuel reserves also leads to economic concerns about American dependence on foreign energy markets. The United States currently imports approximately half of its petroleum products and that percentage is predicted to increase. Two-thirds of imported petroleum is used to fuel the transportation sector (Riley, 1994).

In order to improve the air quality, the amount of harmful emissions produced by automobiles must be reduced. The dependence on foreign oil can be minimized by improving the efficiency of automobiles or by utilizing an alternative fuel where possible. These solutions to the environmental and foreign oil dependence will not encroach on the freedom of transportation.

Concerns such as these have started new ways of thinking about personal transportation. The United States government realized the need for a concerted effort to develop solutions to these problems. Together with the three major U.S. auto manufacturers—Ford, Chrysler, and General Motors—the Department of Energy formed the Partnership for a New Generation of Vehicles (PNGV). The PNGV goals are to increase the competitiveness of the United States in the world automobile market and reduce the detrimental environmental effects caused by automobiles. Some of the tangible goals of this process will be the development of mid-size passenger vehicles with similar consumer acceptability and performance to current cars, but with three times (3X) the fuel economy—approximately 34 km/l (80 mpg)—and ultra-low emissions. The vehicles should include near-term technologies such that the vehicles can be mass-produced by 2010.

These are daunting challenges, but one promising solution to these problems is hybrid vehicles, which have the potential for utilizing alternative energy sources, improving fuel economy, and reducing harmful emissions. A hybrid vehicle is a vehicle with two distinct sources of potential energy that can be separately converted into useful motive (kinetic) energy. This potential energy may be stored in a number of forms including capacitors (electrical), batteries (electrical), pressurized fluids (mechanical), rotating flywheel (mechanical), and fuel (chemical).

The devices for converting this potential energy vary widely. Generally, electric motors are used to convert all types of electrical energy directly into work at the wheels of the vehicle. Compressed fluid energy can be used to drive a turbine to produce mechanical energy. Rotating mass energy found in a flywheel is usually converted to electrical energy by attaching a generator mechanism. Fuel energy can be converted into mechanical energy using a number of heat engines, such as an internal combustion engine, an external combustion engine, or a gas turbine. This resulting mechanical energy is often further transformed into electrical energy, when needed, by coupling a generator to the output shaft of the heat engine. Fuel energy can also be converted directly to electrical energy with a fuel cell.

With the existing technology, the most common form of a hybrid passenger vehicle is that of a hybrid electric vehicle (HEV). Most existing HEVs utilize batteries for electrical energy storage, which is converted to mechanical work at the wheels of the vehicle. Fuel is also stored on-board and is usually converted through an internal combustion engine (ICE) to produce mechanical work, which can be used to drive the wheels of the vehicle or can be further converted to electrical energy.

HEVs provide the benefits of both electric vehicles (EVs) and traditional internal combustion vehicles, while minimizing the limitations of each. HEVs utilize the high efficiencies and low emissions of pure electric vehicles and the range and quick refueling capabilities of ICE vehicles. The basic design of a HEV generally falls into one of two categories: parallel or series.

Parallel HEVs are configured such that both the electric motor and the ICE are mechanically coupled to the drive wheels of the vehicle as shown in Figure 1.1. This design offers the advantage of drive system redundancy. If either of the drive systems should fail, the other system would still be available to move the vehicle for service. A parallel hybrid usually provides better highway fuel economy, due to its efficient engine loading at steady highway speeds, and less mass than its series counterpart. It also provides the ability to withstand long uphill grades. The design often allows for a pure electric vehicle, or zero emissions vehicle (ZEV), mode. However, the parallel design does not allow for full vehicle power when operating in ZEV mode. The mechanical coupling of the motor, engine, and wheels can also be complex, often requiring a multi-speed transmission. The direct mechanical connection between the engine and the wheels also makes engine tuning more difficult, since the engine must operate over a range of speeds and loads.

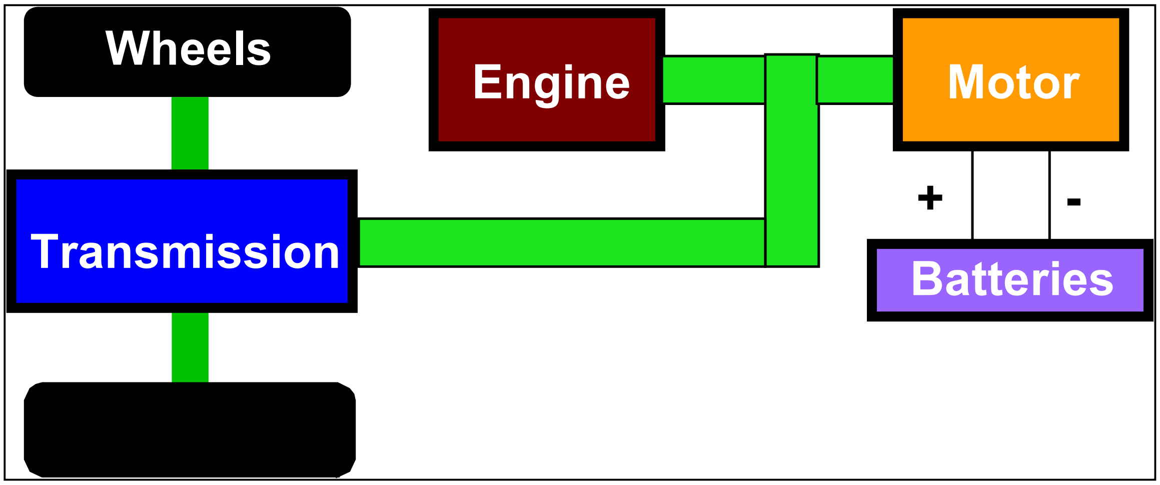

Figure 1.1. Parallel HEV Schematic

Series HEVs are similar to pure EVs in that only the electric motor is mechanically coupled to the drive wheels of the vehicle as shown in Figure 1.2. The ICE is used only to drive an alternator to generate electrical energy, which can be used to power the electric motor or to recharge the batteries. The entire assembly, from the fuel input to the electrical output, is known as the auxiliary power unit (APU). This design results in a simpler mechanical connection to the wheels than parallel hybrids, which, in turn, allows more freedom in component placement. The electric motor can easily be sized such that only a single-speed transmission is required. Full power is available at all times, even when operating in ZEV mode. Since the ICE is not mechanically coupled to the wheels, isolation of the engine load from that of the vehicle is simplified. This provides excellent fuel economy, even under the varying loads required by city driving. The design also lends itself well to future improvements in battery technology. As the energy storage capability of batteries improves, a series vehicle can simply use the ICE less and less, moving toward a pure EV design. However, there is no redundancy in the drive system, so a failure in the electric drive system renders the vehicle incapable of driving (similar to an ICE failure in a conventional vehicle). The ability of a series HEV to sustain a long uphill grade at a given speed is determined by the sizing of the battery pack and APU, and may not be acceptable under extreme conditions. Finally, series hybrids are usually slightly heavier than a comparable parallel HEV.

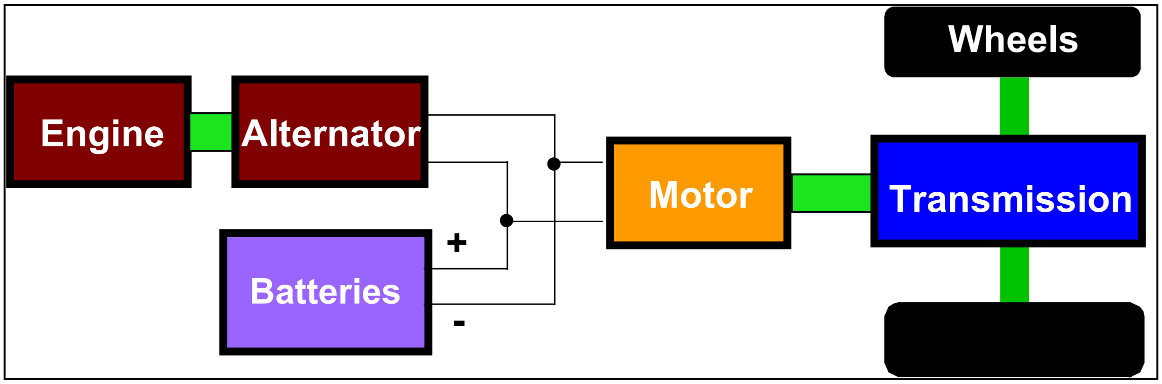

Figure 1.2. Series HEV Schematic

In order to realize the benefits of HEVs, the designs must be extensively modeled and refined before improved emissions and fuel economy can occur on a large scale. This will require accurate, flexible simulation tools, which will expedite the design processes for HEVs. This will enable engineers to compare the relative performance of one design to another and concentrate on the best designs.

This thesis begins with a discussion of the available tools for performing HEV simulations, and compares their features and abilities. One of these, ADVISOR, is the simulation tool used in this thesis. The basics of ADVISOR are explained, including the information required for simulating a series HEV. The necessary data include general vehicle parameters and models for each major component of the vehicle: APU, motor/inverter, transmission, and batteries.

Each component of the Virginia Tech FutureCar is described in detail. The testing procedures for each component and the integration of the test data into the ADVISOR model are described. These test data are displayed and explained for each component. Much of the battery component data included in this thesis were obtained from research performed by Matthew Merkle in his work on this project (Merkle, 1997).

Mr. Merkle was also responsible for a number of modifications to the ADVISOR code itself which were necessary to accurately reflect the operation of the Virginia Tech vehicle (Merkle, 1997). A summary of these changes is included and the effects of these changes are discussed. A number of simulations are subsequently performed to test the validity of ADVISOR under a broad spectrum of operating conditions. The accuracy of the ADVISOR predictions are described and contrasted with measured test data at various intermediate points, including vehicle road load, electric drivetrain energy use on standard driving cycles, and APU/battery energy use on standard driving cycles. The final measure of the simulation is the comparison of the vehicle's city fuel economy, highway fuel economy, and emissions, which are presented and explained.

Conclusions are then drawn from the results of these simulations. The details of the discrepancies and uncertainties in the ADVISOR code, the component models, and the measured data are discussed. The validity of ADVISOR as a simulation tool for this vehicle and similar vehicles is evaluated and recommendations for reliable use are listed.

## Chapter 2. Review of Literature

A search of the recent literature reveals a number of computer software simulations are available specifically for HEVs. These simulation tools have varying abilities to predict vehicle performance in one or more areas, such as fuel economy, emissions, acceleration, and grade sustainability. Some of the more prominent tools are reviewed here with their capabilities and features.

### SIMPLEV

SIMPLEV, A Simple Electric Vehicle Simulation Program, Version 2.0 (Cole, 1993) is a computer software program developed at Idaho National Engineering Laboratory for modeling EVs and series HEVs. Its interactive, menu-driven interface allows the selection of a particular vehicle, individual components (batteries, motor, inverter, transmission, engine, generator, and catalysts), and a specific standard driving cycle. It is limited by the fact that it does not have the ability to simulate either parallel HEVs or conventional ICE vehicles. Also, the operation of the series HEV provides an initial estimate of the APU contributions, but does not model the exact behavior of the Virginia Tech vehicle. Due to the nature of the source code for SIMPLEV, implementing changes to model other series and parallel control strategies would be very difficult.

The general simulation theory is similar to all of the simulation programs described here. The vehicle power at the wheels required to meet the driving cycle is calculated, and the power required from the bus is determined using the individual component efficiencies. It has the capability for plotting output data or saving the data at each time step of the simulation. SIMPLEV can report vehicle fuel economy, energy usage, emissions (HC, CO, $NO_x$) and a number of other vehicle variables.

The energy use predictions of SIMPLEV (using version 3.0) were compared against measured data by the National Renewable Energy Laboratory (NREL) (Cuddy, 1995). The measured data were obtained from the 1994 Hybrid Electric Vehicle Challenge entries of Pennsylvania State University and California State Polytechnic University-Pomona. However, the measurements contained significant uncertainties (∀50%). This analysis showed the SIMPLEV model accurately predicted the actual vehicle energy use within the uncertainties for a 200 m (1/8 mi) acceleration test and a 58 km (36 mi) range test.

### CarSim

CarSim 2.5.4 is a simulation tool developed by AeroVironment, Inc. with essentially the same capabilities and limitations as SIMPLEV. This code was also included in the NREL study (Cuddy, 1995) discussed above. The results of the CarSim simulation were compared to measured data from both vehicles and to the SIMPLEV results. CarSim agreed with SIMPLEV to within 5% for the acceleration test and the range test. It also correctly predicted the actual energy use to within the uncertainty of the test measurements.

### HVEC

A Hybrid Vehicle Evaluation Code (HVEC) was developed by Lawrence Livermore National Laboratory (Aceves, 1995) to simulate only pure EVs and series HEVs. This menu-driven code does have existing models for a number of unique components not available to the previously mentioned simulations. Fuel cells may be used in place of ICEs as an APU, a flywheel may be chosen as the energy storage device instead of batteries, and a number of alternative fuels (such as hydrogen and compressed natural gas) can be used instead of gasoline. The code has the ability to model the overall vehicle fuel economy, emissions, and performance characteristics. Once again, the flexibility of HVEC as a simulation tool is limited due to its fixed structure.

### CSM HEV

CSM HEV is a simulation tool developed by the Colorado School of Mines to predict the behaviors of HEVs (Braun, 1996). This code operates in the user-friendly environment of MATLAB/SIMULINK, which allows for easier configuration changes than any of the tools discussed previously. The program also allows for parametric analysis of the sensitivity of various HEV designs to changes in input parameters. However, the literature admits that the code was still very much under development and not ready to be validated against actual measured data. This severely limits the availability of this simulation tool to a wide variety of users.

### V-Elph

V-Elph, or Versatile-Elph, is an extension of the Electrically-Peaking Hybrid (ELPH) simulation code developed at Texas A&M University (Butler, 1997). The original ELPH code was limited to one particular HEV control strategy, but V-Elph expands the capabilities to any general series and hybrid HEV. The code is based in MATLAB/SIMULINK and can be more easily modified to reflect the operation of real-world HEVs. This code is considerably simpler than the others mentioned because the dynamic interactions between vehicle components are easily visualized with intuitive subsets of blocks and connecting lines instead of many complicated, difficult-to-comprehend equations. This block diagram system model represents a major improvement in the usefulness of a single simulation tool to a wide range of users.

The code utilizes a standard data flow for all component models which allows easy transitions to unique components, fuels, and control strategies. It is unclear from the literature whether the current version of V-Elph has the ability to predict emissions output, but the flexibility of the code would allow this feature to be added. Custom fuel economy and performance data can also be easily plotted using V-Elph.

## ADVISOR

The Advanced Vehicle Simulator (ADVISOR) developed by the National Renewable Energy Laboratory is the most recent of the HEV simulation tools, and was selected as the tool for this analysis of the Virginia Tech FutureCar. The code, like V-Elph, operates in the MATLAB/SIMULINK visual block diagram programming environment. It contains the wide range of features and broad flexibility necessary to model any type of HEV or ICE vehicle, with a minimum of change.

As with many of the simulations mentioned previously, ADVISOR can utilize a variety of custom and standard driving cycles. However, unlike any of the other tools, it also easily generates results from batches of cycles, including the most recent draft SAE test procedures for HEVs (SAE, 1997), with state-of-charge corrections and vehicle soak periods. It can predict the fuel economy, emissions, acceleration, and grade sustainability of a given vehicle and plot or data log any number of intermediate and final values. Another particularly convenient feature unique to ADVISOR is the well-refined graphical user interface (GUI) which allows the user to easily select from a list of custom or pre-defined base vehicles, interchangeable components, driving cycles, and outputs. Finally, the components and control strategy can be run through the standard MATLAB optimization routines to determine the ideal operating conditions for a particular configuration.

ADVISOR has been a primary tool used by the PNGV as it narrows the technology focus in attempt to meet its goals. A study conducted by NREL utilized ADVISOR to analyze various theoretical vehicle configurations (Wipke, 1996), which is one of the primary uses of this simulation tool. The vehicles studied were three ultra-lightweight chassis, one each with a parallel HEV, series HEV, and ICE drivetrains, and two vehicles with 1996-weight chassises, one a parallel HEV and the other an ICE drivetrain.

The sensitivity of the fuel economy of these vehicles to certain vehicle parameters was the first item studied. This type of analysis helps to show the strengths and weaknesses of different configurations in a short amount of time and with minimal expended effort—the value of such a simulation tool. It also highlights areas of concentration necessary to meet the desired fuel economy goal of 34 km/l (80 mpg). One result of this study was that both parallel and series HEV configurations showed approximately the same sensitivity to all parameters, with the exception of electric drivetrain and battery efficiencies. The fuel economy of the lightweight series vehicles tended to be 2-3 times more sensitive to these efficiencies as their parallel counterparts. This sensitivity can have a major effect on series HEV performance: relatively low efficiencies would discredit the plausibility of series vehicles, while high efficiencies would demonstrate excellent fuel economy.

The NREL study also examined the possible design spaces for these vehicle configurations. To reach the 34 km/l (80 mpg) goal with a parallel HEV, one of the most likely designs would require an average APU efficiency of 35% with a vehicle mass of

1000 kg (2200 lb). This represents a weight savings of 50% over current conventional vehicles and the very best of current ICE technology.

Finally, the study concluded that the 1996-weight hybrid vehicles would result in nearly a 20% fuel economy improvement over the current ICE vehicles, and a 25% improvement compared to the lightweight vehicles. Both series and parallel designs demonstrated similar potential in achieving these goals.

Another study, also conducted by NREL, examined the differences between the parallel and series configurations in more detail than before by allowing for different control strategies within each configuration (Wipke, 1997). This is an excellent example of using the simulation tool to determine the best vehicle configurations, saving valuable time, effort, and expense. It was concluded that parallel HEVs could expect a 24% improvement in fuel economy over ICE vehicles when both use the best available technology and low road load designs. The parallel design was also shown to have a 4% improvement over a similarly-designed series HEV.

In order to have confidence in the predictions produced by ADVISOR, it must first be shown to provide data which accurately reflect the as-built behavior of current HEVs. This thesis will confirm the validity of the ADVISOR simulation tool in modeling the Virginia Tech FutureCar, which is a fully operational series HEV developed for competition in the 1996-1997 FutureCar Challenges. This validation, in conjunction with other such studies, will provide a solid background for future ADVISOR theoretical simulations.

## Chapter 3. Vehicle Modeling

### Basic ADVISOR Operation

All vehicle modeling, whether for conventional ICE vehicles, EVs, or HEVs, is derived from the basic equation of solid-body motion (Newton's Second Law), as given in Equation 3.1 in its scalar form.

$$F = ma \qquad \text{Equation 3.1}$$

This equation can be modified with the specific forces which typically act on vehicles and can be rearranged into the form of Equation 3.2.

$$F = mgC_{rr} + \frac{1}{2}\rho C_D A v^2 + ma + mg\sin(\theta) \qquad \text{Equation 3.2}$$

| | |
|---|---|
| F | force required at the wheels of the vehicle |
| m | mass of the vehicle |
| $C_{rr}$ | coefficient of rolling resistance between the tires and the road surface |
| $\rho$ | density of the ambient air |
| $C_D$ | coefficient of drag of the vehicle in the direction of travel |
| A | cross-sectional area of the vehicle |
| v | magnitude of the velocity (i.e., speed) of the vehicle in the direction of travel |
| a | acceleration of the vehicle |
| g | local acceleration of gravity |
| $\theta$ | angle of inclination of the road surface upon which the vehicle is traveling |

This simple modeling equation provides an accurate method for describing the straight-line motions of an automobile. The first term indicates the force required to overcome the rolling resistance of the vehicle. Note that this force is constant regardless of the speed of the vehicle and tends to dominate at relatively low speeds. The second term represents the drag force which the vehicle must overcome at a certain speed. This term is proportional to the square of the speed of the vehicle and, therefore, tends to be small at low speeds, but increases rapidly with velocity. The mass inertia of the vehicle is shown in the third term of this equation. It is non-zero only when the vehicle is accelerated or decelerated and has no effect under constant-speed cruising conditions. Finally, the force required to propel the vehicle on a non-zero grade is accounted for in the last term of the equation.

Although this equation uses only the first-order approximations for each term, it is accurate enough for most analyses, and it is the basis for almost all vehicle simulation tools, including ADVISOR.

ADVISOR uses a quasi-steady approximation approach to vehicle modeling for parallel and series HEVs, pure EVs, or ICE vehicles. At each discrete time step, ADVISOR calculates the required energy at the wheels of the vehicle using a pre-determined vehicle velocity profile. It then determines the amount of input energy required by each component to meet the energy requirement at the wheels. The structure used for series HEV modeling is shown in block diagram form, Figure 3.1.

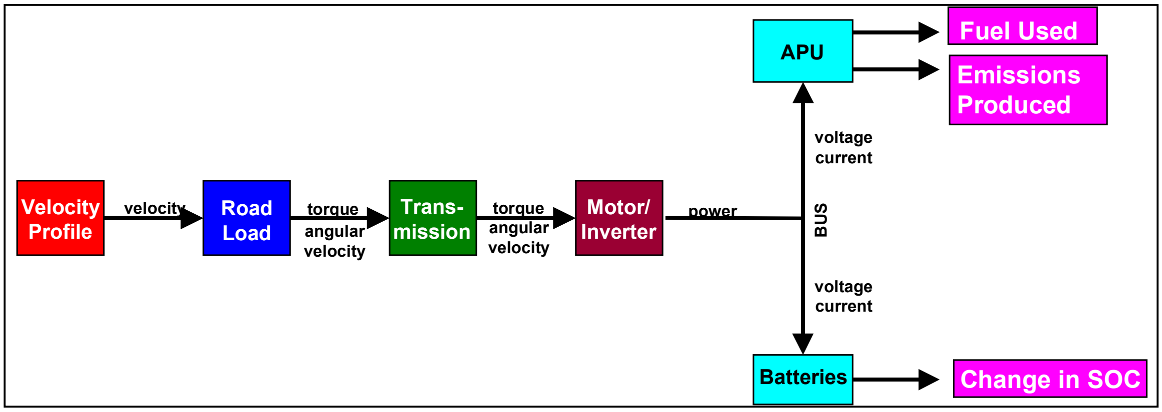

Figure 3.1. ADVISOR Series HEV Data Flow

At each discrete time step, ADVISOR first determines the desired vehicle speed from the desired trip profile, which is often a standard driving cycle. It then uses vehicle parameters such as vehicle mass, coefficient of drag, frontal area, and rolling resistance in Equation 3.2 to compute the vehicle road load (force required at wheels). This allows the calculation of the required torque at the wheels using Equation 3.3, and the required angular velocity of the wheels using Equation 3.4.

$$T = Fr_r \qquad \text{Equation 3.3}$$

$$\omega = \frac{v}{r_r} \qquad \text{Equation 3.4}$$

The input angular velocity of the transmission is calculated using the overall reduction ratio of the transmission in Equation 3.5. Compensating for the transmission efficiency as a function of input speed and torque, the input torque can be computed with Equation 3.6.

$$\omega_{in} = \omega_{out} R_{trans} \qquad \text{Equation 3.5}$$

$$T_{in} = T_{out} \frac{1}{R_{trans}} \eta_{trans}(T_{out}, \omega_{out}) \qquad \text{Equation 3.6}$$

Similarly, using the efficiency of the motor/inverter at that particular speed and torque, the input power required from the vehicle’s high-voltage bus is determined, as in Equation 3.7.

$$P_{bus} = \frac{T_{out}\omega_{out}}{\eta_{mot}(T_{out}, \omega_{out})\eta_{inv}(T_{out}, \omega_{out})} \qquad \text{Equation 3.7}$$

The power from the bus is supplied either by the batteries exclusively (APU off), or by a combination of the batteries and the APU (APU on). The relative amount of power contributed by each source is dependent upon the equivalent internal resistances of the APU alternator and the batteries. Once this power distribution has been calculated, ADVISOR updates the battery state of charge (SOC), fuel used, and emissions produced based on this information, and then proceeds to the next time step.

### Component Modeling

The accuracy of the simulation is largely dependent upon the accuracy of the various component models and parameters which ADVISOR requires: APU, motor/inverter, transmission, batteries, and general vehicle parameters. It is imperative, therefore, that these component models be carefully determined in order to best represent the actual performance of that component within the system as a whole. This is especially true of the APU model, since it directly determines the fuel usage and emissions produced. This is not always straightforward, because in order to test individual components, that device must often be removed from the system. When tested separately, component performance may be different than when incorporated in the rest of the system, thereby skewing the results of the entire simulation.

In order to accurately model a series HEV, it is first necessary to understand the operation of the individual components in that system, the interactions between components, and, finally, the behavior of the system as a whole. The actual vehicle used for validation of the ADVISOR simulation was a 1996 Chevrolet Lumina converted to series HEV operation as shown in Figure 3.2. This same car was the Virginia Tech entry in the 1996 FutureCar Challenge (FCC).

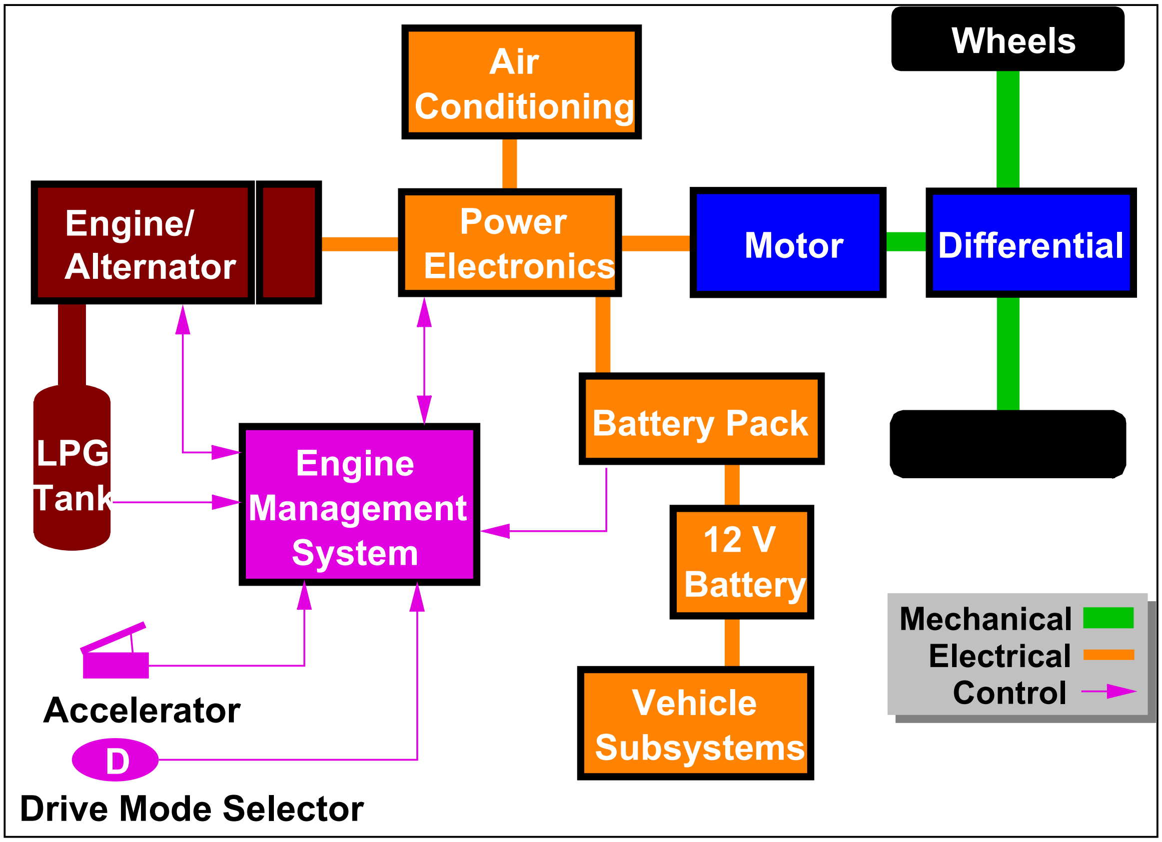

Figure 3.2. Virginia Tech FutureCar System Schematic

The Virginia Tech FutureCar is a classic range-extending series HEV. The vehicle typically operates as a pure EV with an on-board generator (the APU), which maintains the batteries at an acceptable SOC. Under normal operation, when the APU controller senses a low battery SOC, it executes a start-up procedure for the engine, then maintains the engine speed at the proper level to produce power until the batteries reach a high SOC. It then shuts down the engine and continues to monitor battery SOC.

The packaging of the various components can also have a significant effect on the operation of the system. Temperature, vibration, and orientation can drastically affect the operation of the individual HEV components. The location of the components in the 1996 FutureCar Challenge entry is shown in Figure 3.3.

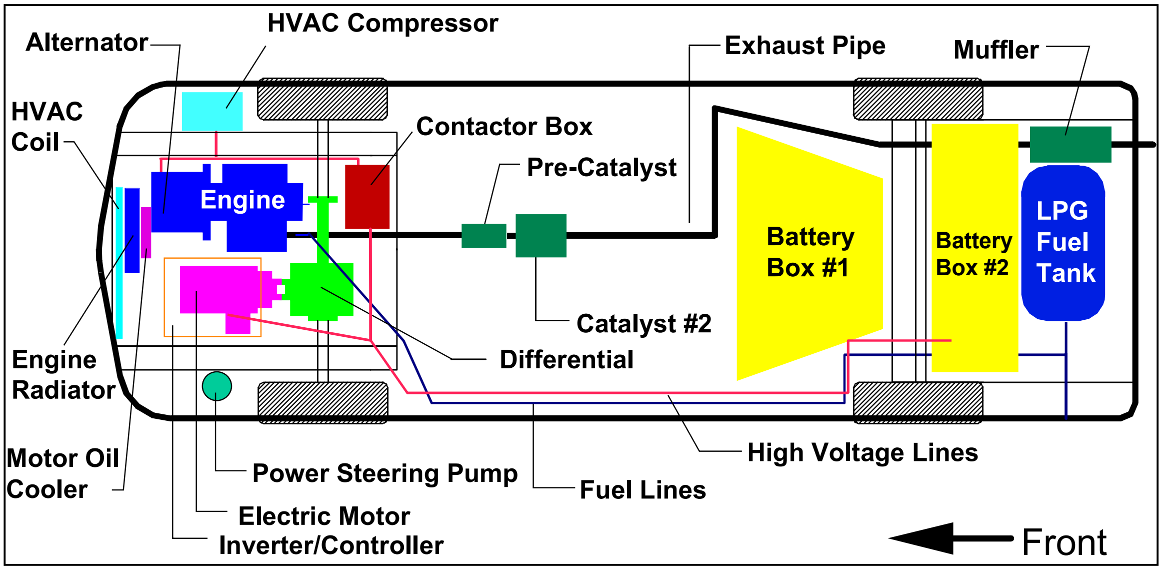

Figure 3.3. Virginia Tech FutureCar Component Packaging Diagram

Each major component is described in detail below. The required information for each component is unique, and, therefore, each has its own procedures for testing. During all testing, the care was taken to ensure that the measurements represented the actual operation of the component as it operates in the system and to ensure that each measurement was as accurate and certain as possible.

## Auxiliary Power Unit (APU)

The design parameters for the Virginia Tech FutureCar APU specified a small, quiet, lightweight ICE, preferably from a production automobile with existing emissions control devices, with the capability to produce the average highway power required (approximately 20 kW) for extended periods of time. The APU chosen to meet these requirements was a Suzuki three-cylinder, 1.0 liter (61 $in^3$), spark-ignited internal combustion engine, which is normally used in Geo Metro automobiles. It is rated with a peak power of 41 kW (55 hp) at 5700 rpm and peak torque of 79 Nm (58 ft-lbf) at 3300 rpm using the stock engine control unit (ECU) operating on gasoline at the stock compression ratio of 9.5:1.

The engine was modified to operate on liquefied petroleum gas (LPG, or propane). A programmable GFI Controls throttle-body injection system was used for fuel control, with a programmable Electromotive TEC-II unit used for spark advance control.

The APU includes a Fisher three-phase, permanent magnet alternator rated nominally at 18 kW (24 hp) at 2800 rpm. The alternator is permanently mounted to the engine and is driven directly by the engine crankshaft.

The APU, as defined for these simulations, encompasses all components which convert the fuel energy of the LPG entering the system to mechanical work to AC electrical energy to DC electrical energy leaving the system. In addition to the components listed above, the APU also includes wiring, fuses, connectors, and a bridge rectifier.

In order to satisfy the ADVISOR requirements for APU component mapping, a number of different parameters were measured. Each of the APU maps was determined as a function of bus voltage and APU output current. All measurements were taken at steady-state conditions to satisfy the quasi-steady assumptions used by ADVISOR. The APU was mounted normally in the vehicle, with the complete fuel and exhaust systems operational during testing. However, the DC output was disconnected from the vehicle bus and attached to an external electrical resistance load bank, which allowed for easier mapping. DC output voltage was measured across the load with a standard multimeter and DC output current was measured with a standard multimeter using a precision shunt on the positive leg of the load. The uncertainty in the electrical measurements was determined to be less than 1%. Fuel mass flow was measured using the GFI monitoring software designed for use with the fuel system. The accuracy of this method was tested using a known mass of fuel and compared to the measurements given by the software. Under standard operating conditions for the APU, the variance between the two measurements was less than 5%. All emissions levels were measured using a calibrated OTC 5-gas exhaust analyzer.

Fuel efficiency was defined as the fuel energy flow into the system divided by the electrical energy flow out of the system. This was determined by measuring the mass flow of fuel into the engine and the DC voltage and current out of the APU over the entire operating range of the APU. The efficiency, shown in Figure 3.4, was then expressed in terms of grams of fuel in per kilowatt-hour (kWh) of DC energy out.

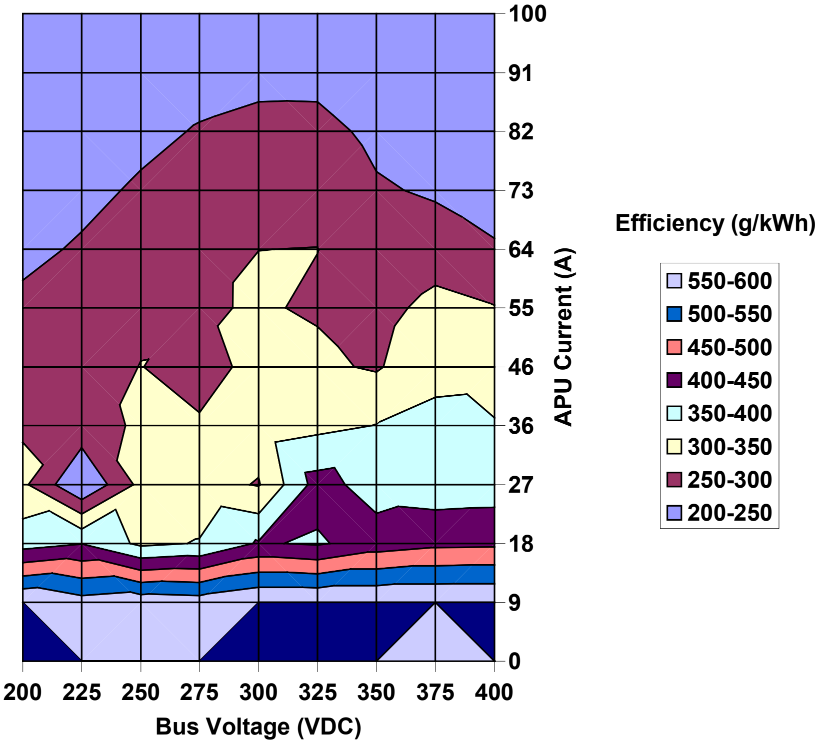

Figure 3.4. APU Fuel Efficiency

Three categories of vehicle emissions are of particular importance to study because they are regulated by the federal government: hydrocarbons (HC), carbon monoxide (CO), and oxides of nitrogen ($NO_x$). Engine-out emissions levels were reported in parts per million (ppm) of the total exhaust gas flow. For each emission (HC, CO, and $NO_x$), the values were then converted to grams of emission per kWh of DC energy out using Equation 3.8. The molecular weight of CO is 44 g/mole; for $NO_x$, all of the oxides were assumed to be in the form of NO, which has a molecular weight of 30 g/mole; and for HC, the majority of the species was assumed to be in the form of propane, $C_3H_8$, with a molecular weight of 44 g/mole.

$$M_{emiss} = \frac{(25.8)(PPM)(10^{-6})(MW_{emiss})}{44}(\dot{W}_{out})(\dot{m}_{fuel}) \qquad \text{Equation 3.8}$$

The engine-out emissions levels as functions of APU voltage and current are given in Figures 3.5, 3.6, and 3.7 for HC, CO, and $NO_x$, respectively.

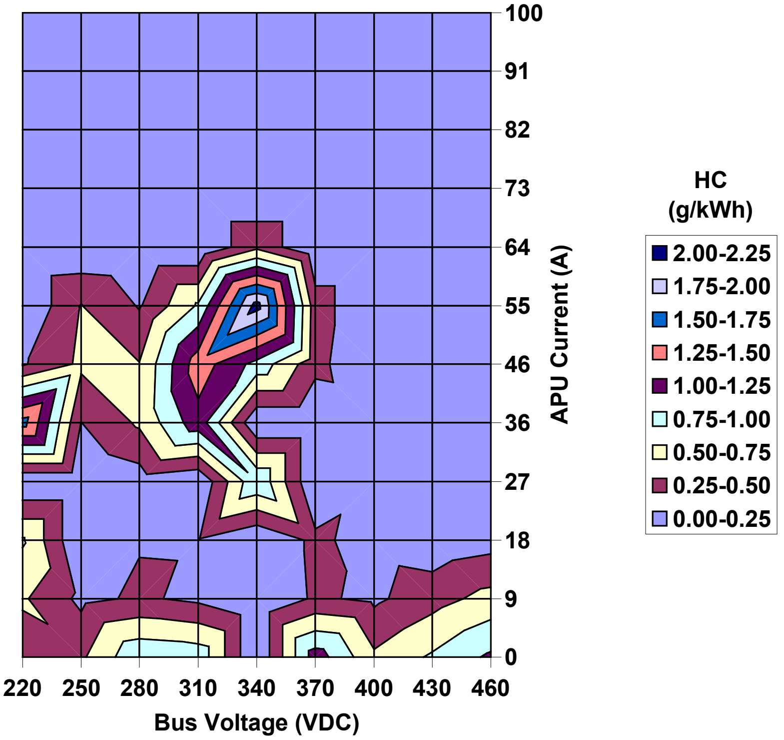

Figure 3.5. APU Engine-out HC Emissions

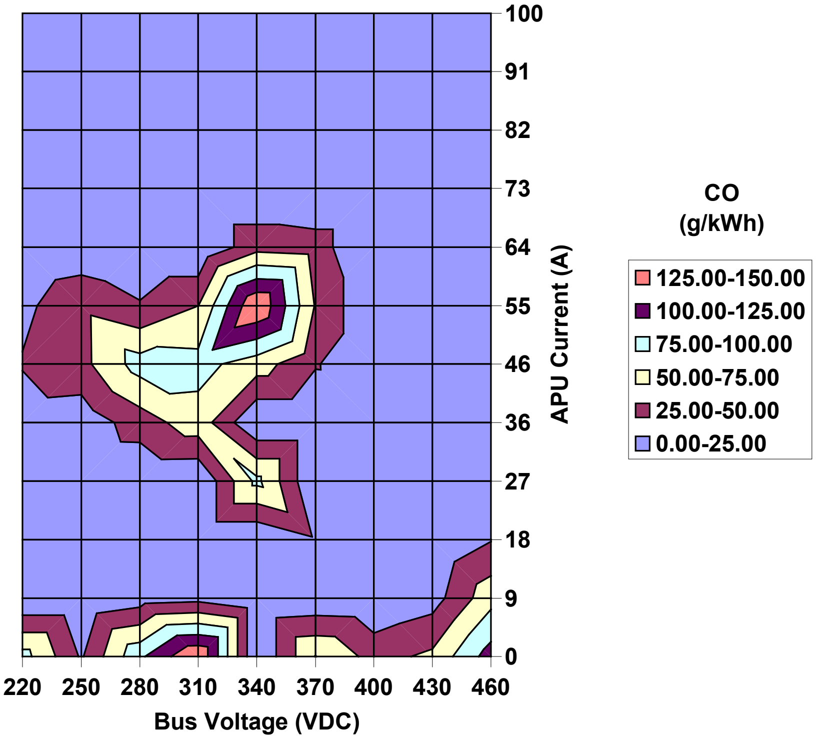

Figure 3.6. APU Engine-out CO Emissions

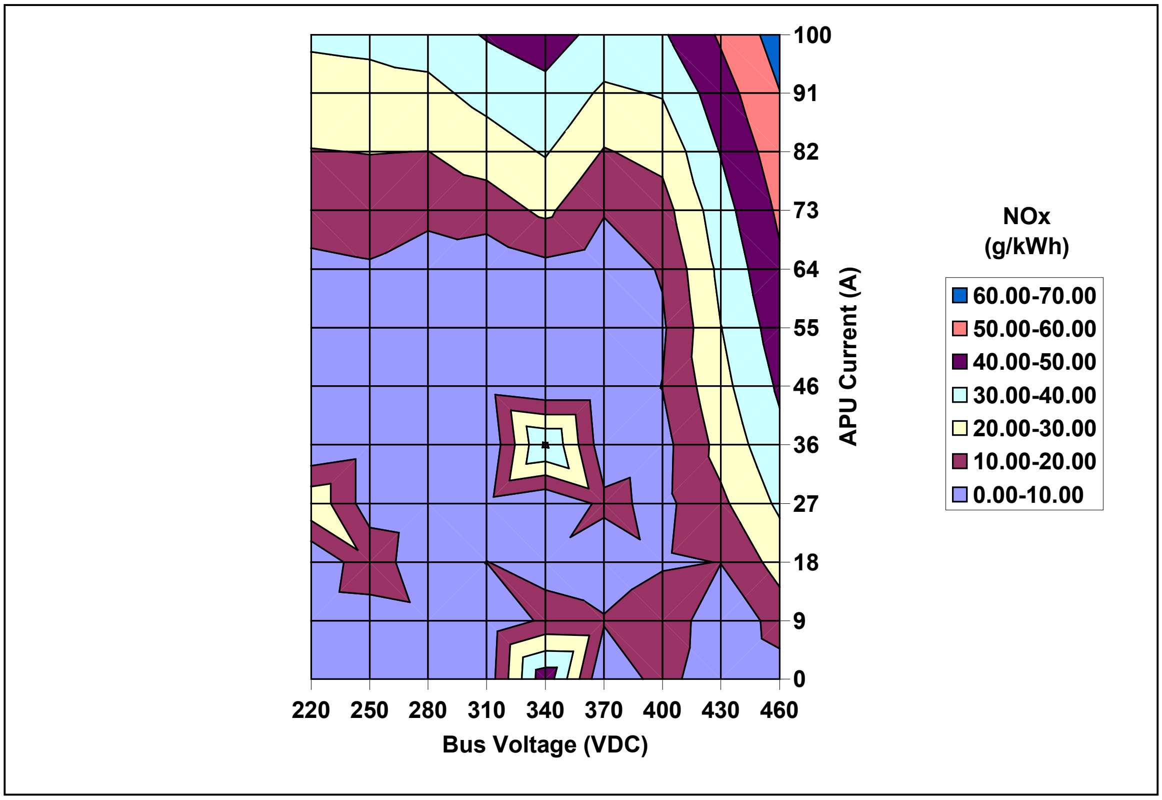

Figure 3.7. APU Engine-out $NO_x$ Emissions

Catalyst reduction efficiencies as functions of speed and load were determined by simultaneously measuring before and after catalyst emissions levels for HC, CO, and $NO_x$. The catalyst reduction efficiency for HC is then given by Equation 3.9, with similar equations for CO and $NO_x$.

$$\eta_{HC} = \frac{HC_{in} - HC_{out}}{HC_{in}} \qquad \text{Equation 3.9}$$

The resulting reduction fractions are given in Figures 3.8, 3.9, and 3.10 for HC, CO, and $NO_x$, respectively.

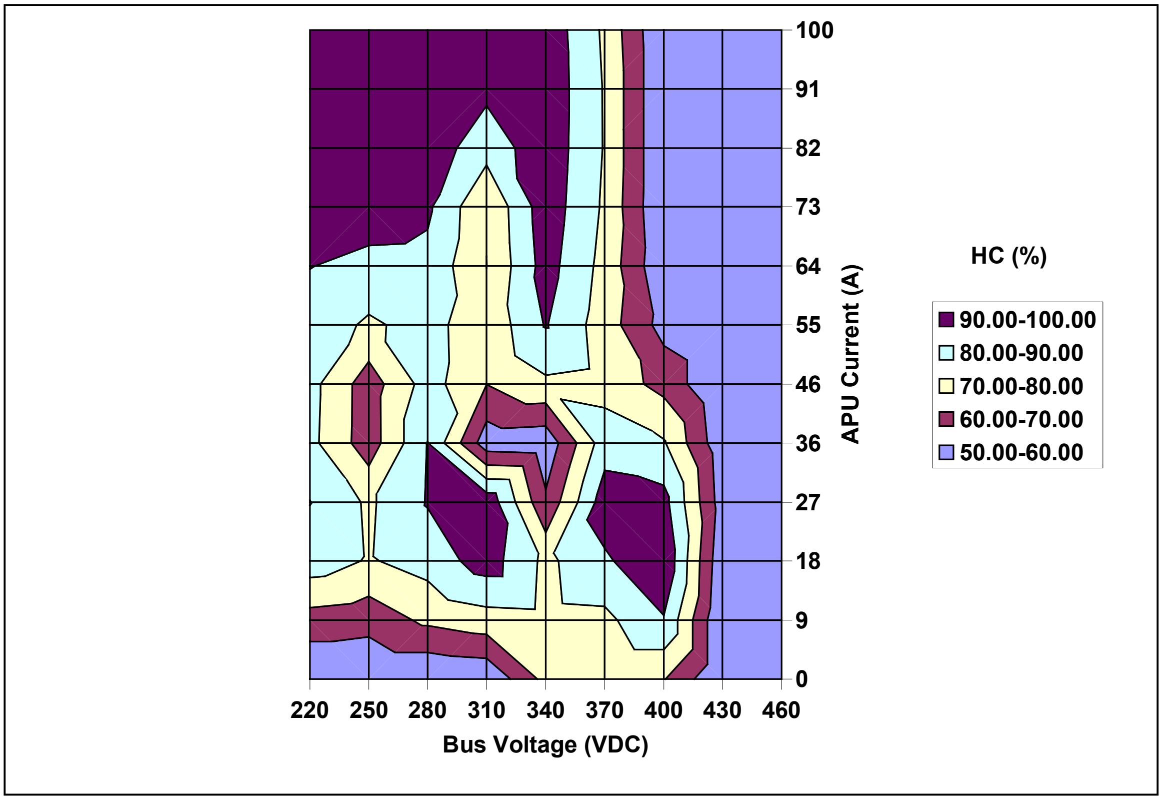

Figure 3.8. APU HC Catalyst Efficiency

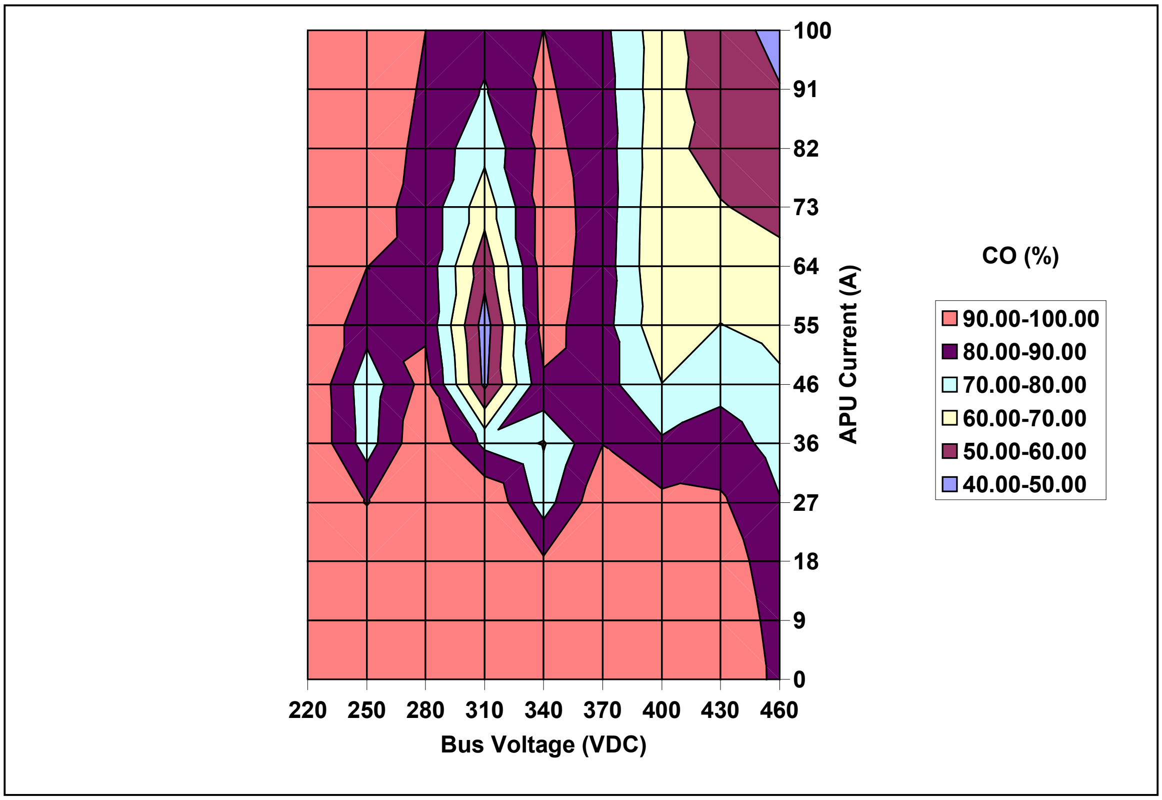

Figure 3.9. APU CO Catalyst Efficiency

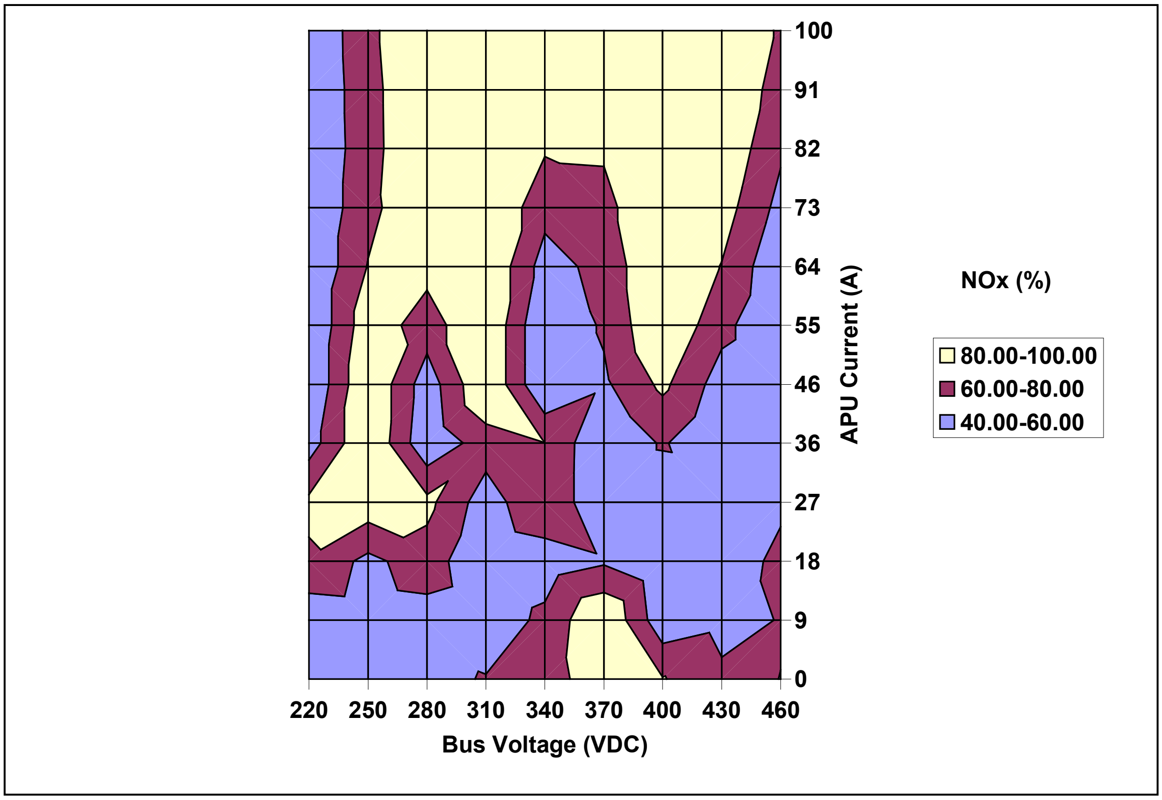

Figure 3.10. APU $NO_x$ Catalyst Efficiency

Finally, the warm-up efficiency of the catalysts from a "cold" (APU at ambient temperature) start for each species of emission was determined as a function of temperature. These are reported as the percentage of the full efficiency of the catalyst at steady state conditions in Figure 3.11.

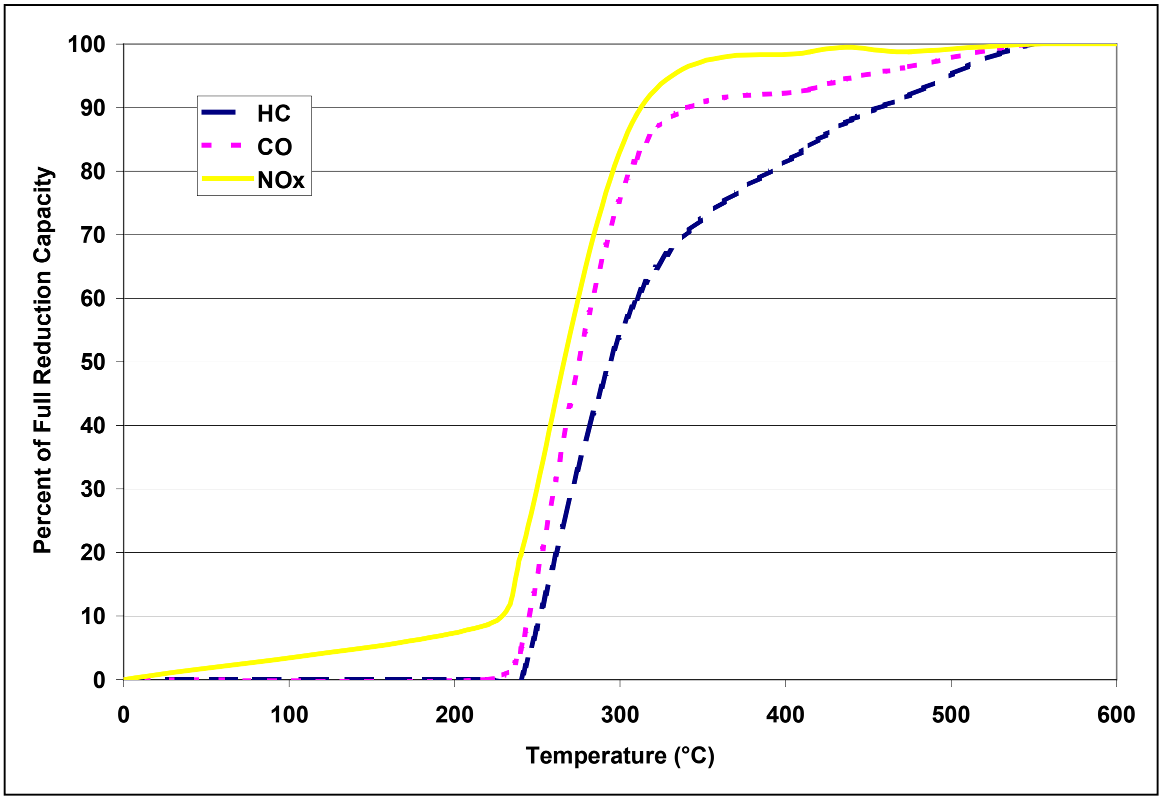

Figure 3.11. APU Catalyst Warm-Up Efficiency

These measurements provide the necessary data for the APU component model in ADVISOR. Once the above values were entered into the proper ADVISOR format, the APU model was complete.

Motor/Inverter

The design of the Virginia Tech FutureCar utilizes a General Electric EV2000 prototype electric vehicle drive system. This system is ideal for a series HEV because it was originally designed as a pure EV drivetrain. The electric motor is a three-phase, AC induction motor rated at 80 kW (107 hp) continuous and 100 kW (135 hp) peak. The graph (Boothe, 1997) of the maximum continuous motor power and torque at the rotor is given in Figure 3.12, with a peak torque of 190 Nm (140 ft-lbf) occurring at 0 rpm. The rotor speed is reduced from a maximum 13,500 rpm by an integral 4.29:1 planetary gear set such that the maximum output shaft speed is 3150 rpm. The motor is cooled and its gearset lubricated by lightweight synthetic oil, which is pumped through the motor and external oil cooler.

The DC-to-AC inverter is based on insulated gate bipolar transistor (IGBT) power switching devices. The inverter can operate with input voltages from 200 VDC to 400 VDC and input currents of up to 400 A. The variable frequency AC output is used to control motor speed. It is mounted on an air-cooled heatsink. The inverter (and motor) support regenerative braking, during which the motor performs as a generator and recharges the batteries. This provides improved braking performance and recaptures some of the vehicle's kinetic energy which would typically be dissipated as heat. A large number of driveability factors can be customized through a PC-based software interface. The inverter control contains various self-protection routines, which help avoid damage resulting from high voltages, excessive currents, motor overspeed, etc.

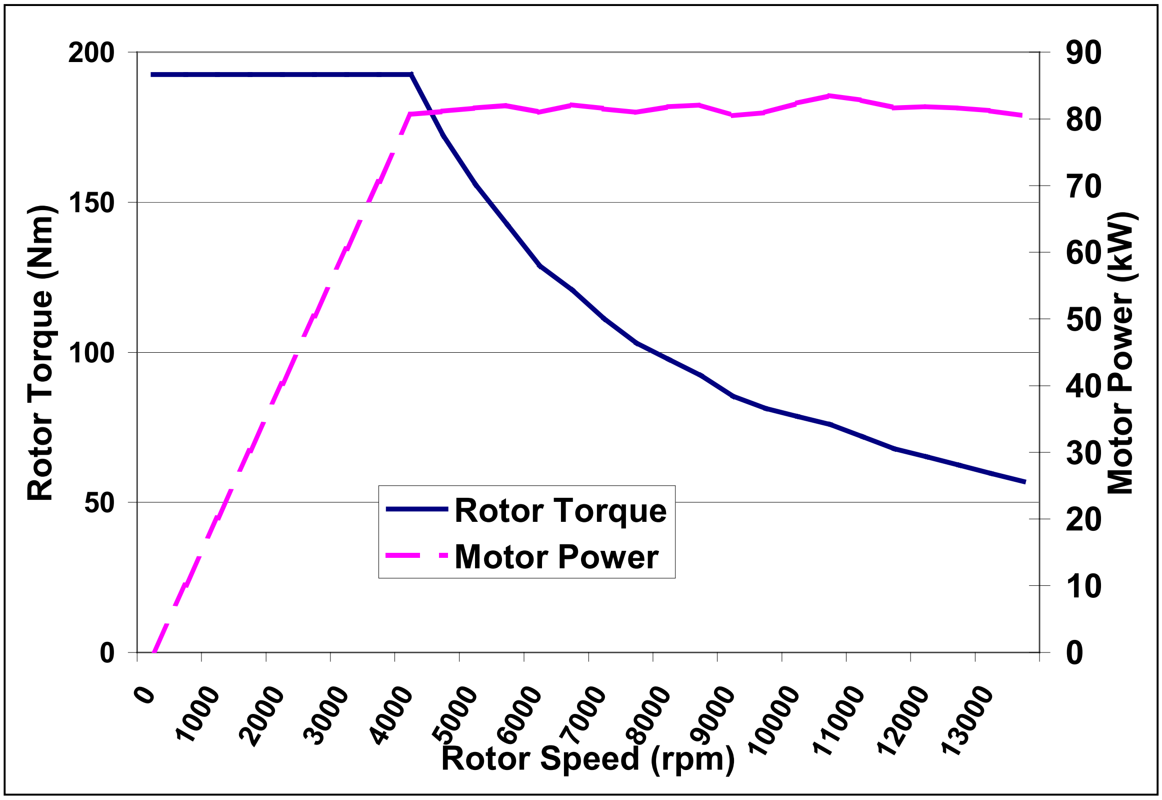

Figure 3.12. Maximum Continuous Motor Torque and Power

The motor and inverter efficiency maps were obtained from personal communications with General Electric and with the consent of Virginia Power Technologies (Boothe, 1997). The maps are separated into a motor efficiency map and an inverter efficiency map. The motor efficiency map, shown in Figure 3.13, gives the ratio of mechanical energy output to electrical energy input as a function of output speed and output torque. Regenerative braking consists of merely operating the motor at a negative torque value; therefore, the regenerative braking map is simply the mirror image of the motive map. The inverter efficiency, the ratio of AC electrical energy output to DC electrical energy input, is given in Figure 3.14 as a function of motor output speed and torque. Again, the regenerative braking map is merely the mirror image of the motive map.

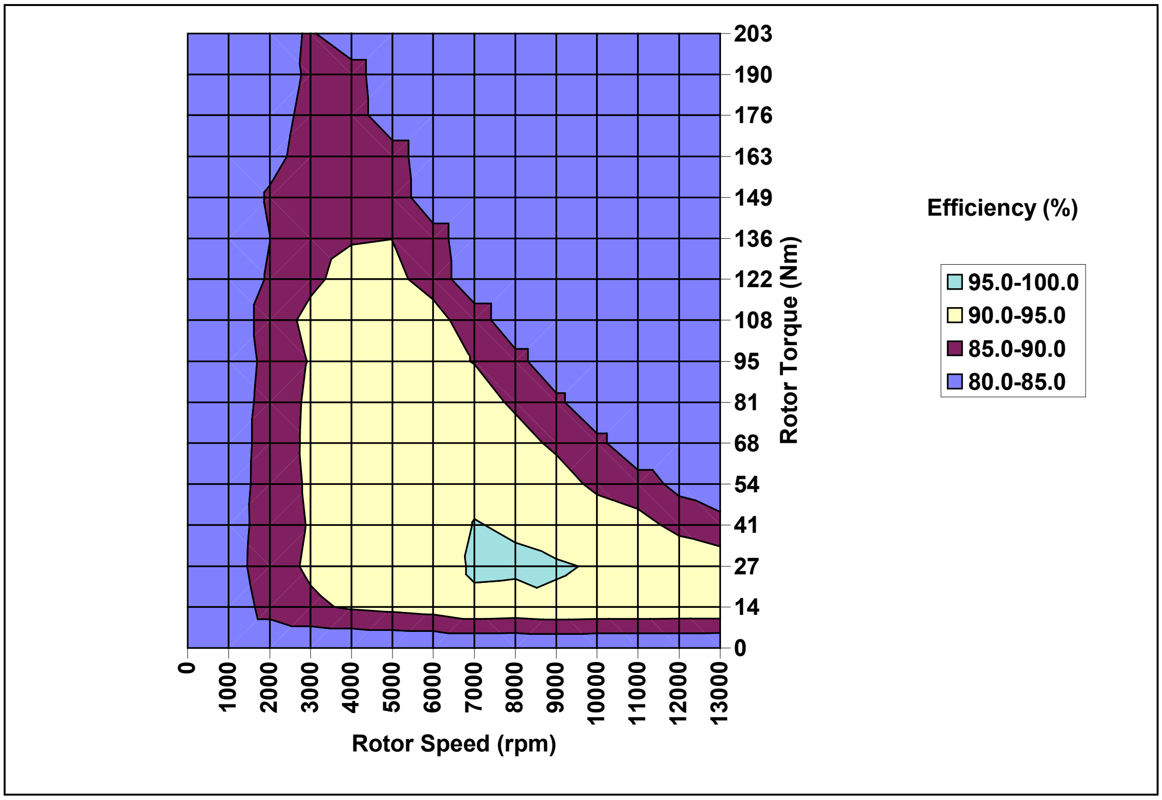

Figure 3.13. Motor Efficiency Map

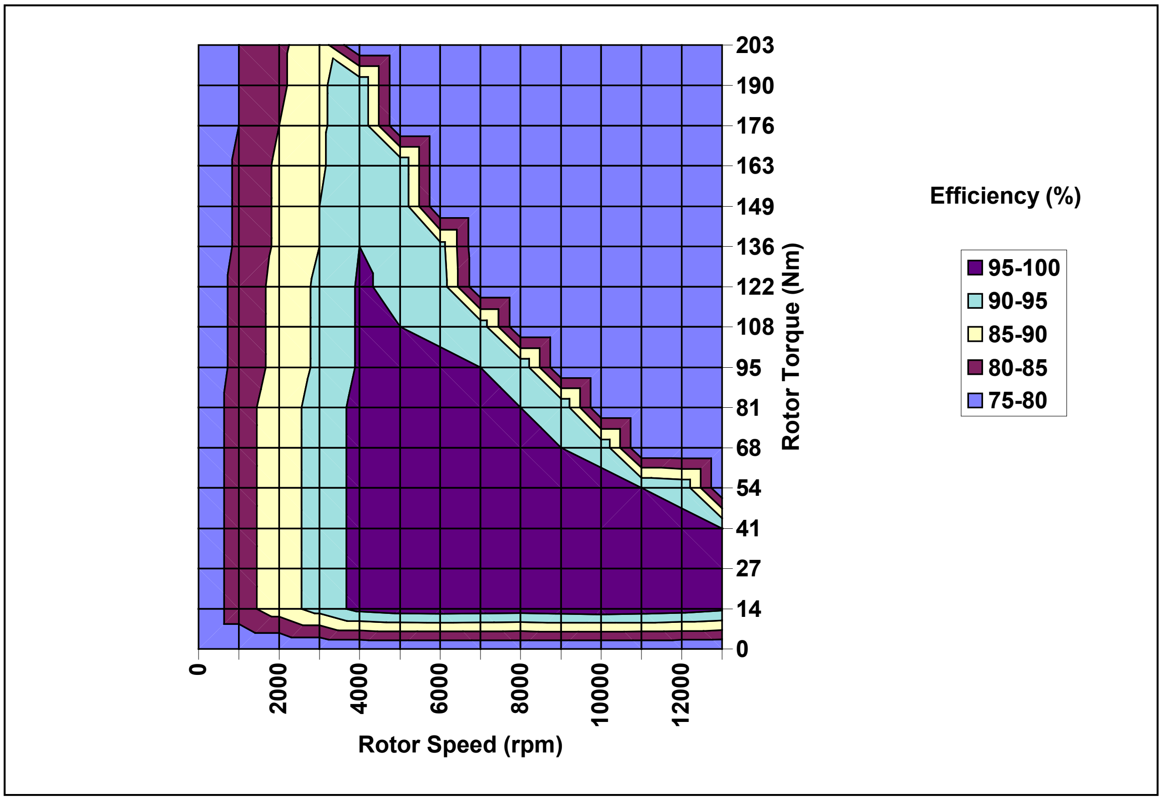

Figure 3.14. Inverter Efficiency Map

## Transmission

The transmission in the Virginia Tech FutureCar was directly coupled to the output shaft of the electric motor and to the front axles of the vehicle. Because the electric motor provided enough torque to adequately power the vehicle over its entire operating range, a single-speed transmission was desired for its small size and weight. However, to improve component packaging, it was determined that a right-angle drive was preferred. The lightest, smallest, unit found was the front differential used in a four-wheel-drive Chevrolet S-10. This oil-lubricated transmission provides an acceptable 3.41:1 gear reduction, with a torque rating to handle the output of the motor.

No facilities were available on-site which would allow for accurately determining a transmission efficiency map as a function of speed and torque over the operating range. It was decided that an engineering estimate using established data was more desirable than inaccurate test data. The MEV-75 single-speed transmission map used with the SIMPLEV simulation (Cole, 1993) was adapted for use with ADVISOR. This transmission was integrated with a similar motor/inverter combination used in the Ford Ecostar electric minivan, and provides a reasonably accurate approximation for the Virginia Tech FutureCar transmission. This efficiency map is shown in Figure 3.15.

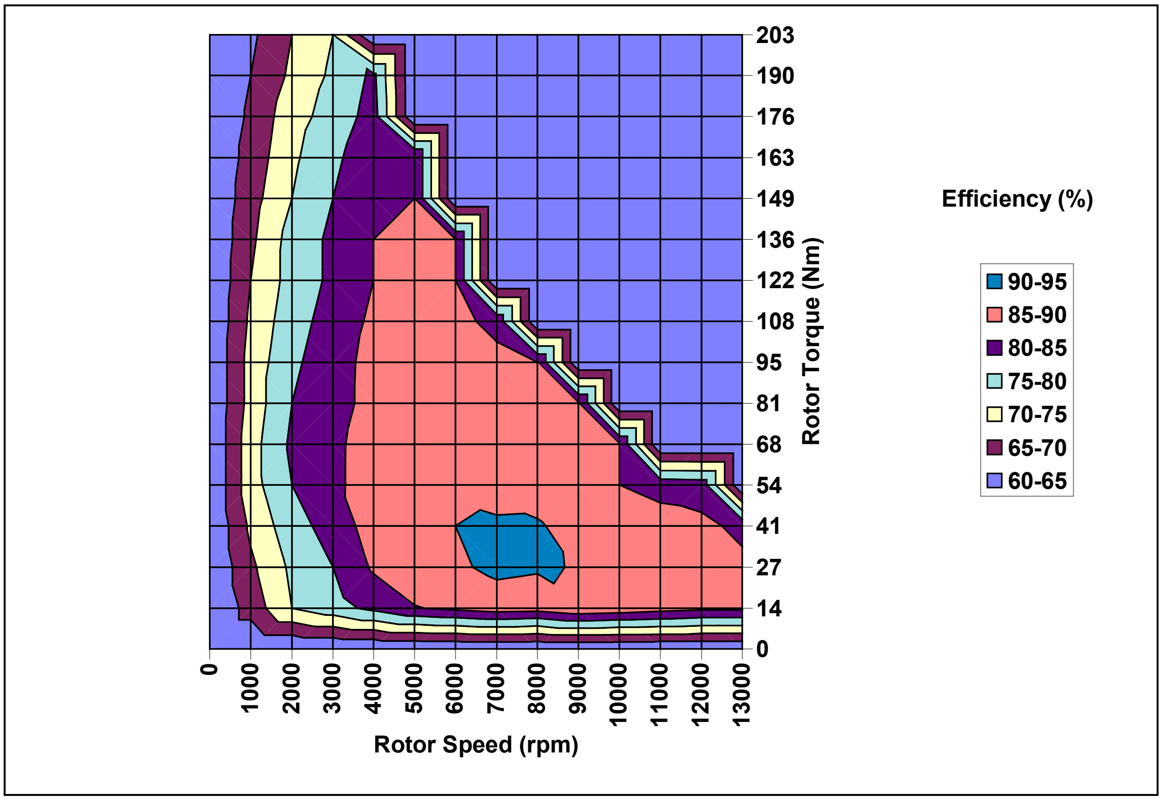

Figure 3.15. Transmission Efficiency Map

Batteries

The batteries used in the Virginia Tech FutureCar were valve-regulated, non-spillable, sealed lead-acid modules manufactured by Hawker Energy Products under the model name of Genesis. The nominal 12 VDC modules were rated at 26 Ah at the c/10 rate, with a mass of 11 kg (24 lb) per module. Twenty-seven modules were connected in series to form a nominal 324 VDC battery pack with 7.1 kWh of energy storage at the c/3 rate and 6.1 kWh at the c/1 rate (Hawker, 1996).

The testing procedures and considerations for battery testing are not covered in this thesis, but the results of that testing are presented for completeness. The battery model requires the determination of a number of parameters as functions of SOC. First, the internal resistance of each module (including interconnects) was computed as a function of SOC. Open-circuit voltage of a module was also given as a function of SOC (Hawker, 1996). Both the internal resistance and open-circuit voltage functions (Merkle, 1997) are shown in Figure 3.16.

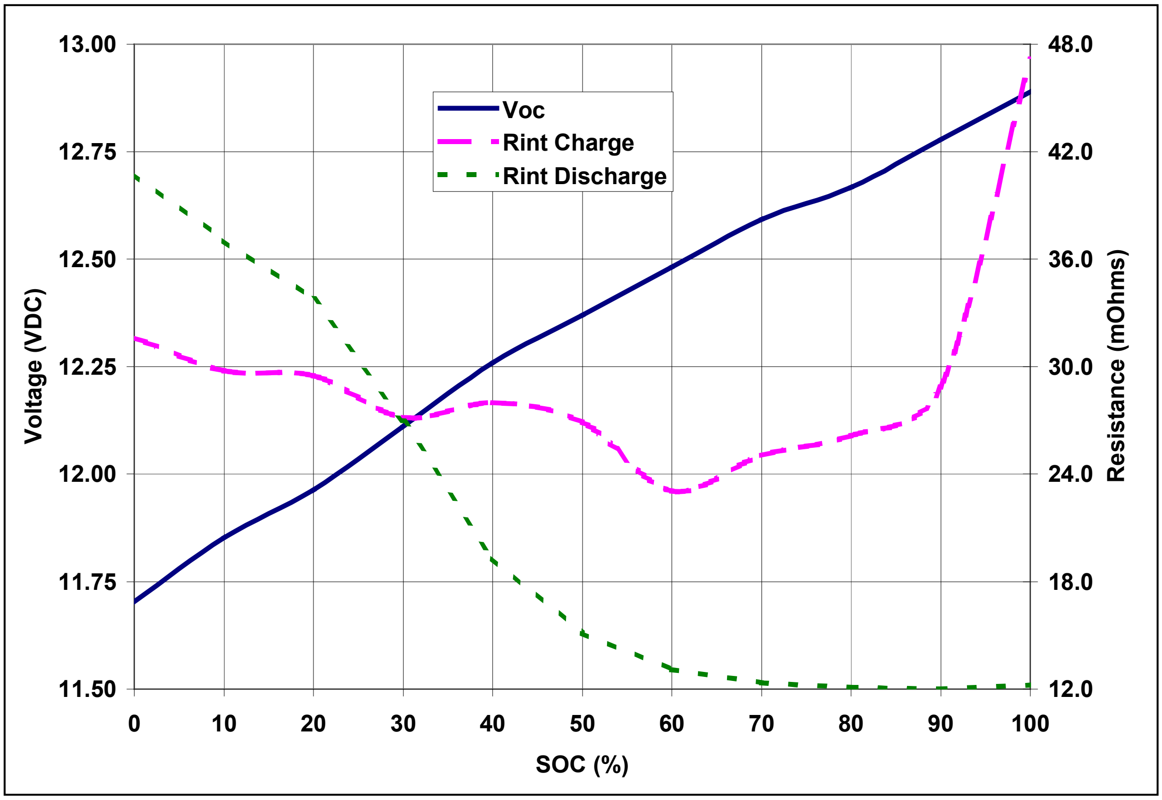

Figure 3.16. Battery Module Internal Resistance and Open-Circuit Voltage

The “round-trip” charging efficiency, defined as the ratio of the output capacity of the battery to the input capacity of the battery, was 90%. Finally, the useable capacity of the batteries was determined to be 20 Ah at the c/1 rate.

Miscellaneous Vehicle Parameters

ADVISOR utilizes a number of miscellaneous parameters to describe the vehicle as a whole. These parameters are important to an accurate simulation of the vehicle, since an error in these will propagate throughout the rest of the model. The determination of the major values is summarized below.

The first parameters are used to determine the road load of the vehicle at a given speed. This same road load information was required to properly set the dynamometer at the 1996 FutureCar Challenge, so that set of data was already available. The road load of the Virginia Tech FutureCar was measured on Ford's Dearborn Proving Grounds in Dearborn, MI. The rolling resistance of the vehicle and the drag product (product of the coefficient of drag and frontal area) can be determined by fitting the measured road load curve with Equation 3.2. Using the frontal area provided by General Motors for a 1996 Chevrolet Lumina (the aerodynamics of the Virginia Tech Lumina were essentially unmodified), the coefficient of drag was computed.

The weight of the vehicle was also measured at the 1996 FCC. The regenerative braking fraction (fraction of total energy expended which is recaptured by regenerative braking) was calculated using data acquired during dynamometer testing at the 1996 FCC, which was performed at the Environmental Protection Agency in Ann Arbor, MI. Representative fuel energy and fuel density properties were determined by a laboratory analysis of the LPG. Accessory loads are the estimated average of all vehicle subsystems required to operate the vehicle in its different modes, such as ZEV mode versus APU-On mode. Standard temperature and pressure ambient conditions were assumed for all testing and simulation. A summary of the miscellaneous vehicle parameters used in the simulations is given in Table 3.1.

Table 3.1. Miscellaneous Vehicle Parameter Summary

| Parameter | Value | Units |
|---|---|---|
| Coefficient of drag | 0.325 | |
| Frontal area | 2.04 | $m^2$ |
| Rolling resistance | 0.005 | |
| Rolling radius | 0.323 | m |
| Mass | 2000 | kg |
| Front weight fraction | 0.53 | |
| Regenerative fraction | 0.5 | |
| Accessory load | 500 | W |
| Fuel specific energy (LHV) | 47.3 | MJ/kg |
| Fuel density (STP) | 1.92 | $kg/m^3$ |
| Fuel density (liq.) | 498 | $kg/m^3$ |
| Ambient air density | 1.2 | $kg/m^3$ |
| Local acceleration of gravity | 9.81 | $m/s^2$ |

# Chapter 4. Simulation Results

## Modifications to Original ADVISOR Code

Accurate system simulation requires that models of individual components be representative of component performance when assembled into the system. In order to accurately simulate the Virginia Tech FutureCar using ADVISOR, a number of changes were implemented into the code.

A significant change was made to the APU loading calculation. ADVISOR originally determined the load on the APU using a single, pre-defined operating speed and torque. This operating point did not vary under any circumstances, producing a constant power when on. This type of operation is the ideal "single operating point" type of series HEV. However, the Virginia Tech APU functions more as a "load following" type of series HEV, where the APU speed is regulated to a specific speed. The APU controller actuates the throttle position to maintain constant speed under the different torques required by the vehicle bus.

In order to calculate the APU load for a given battery SOC and vehicle load, the engine speed must be given as well. A quadratic equation is used to compute the bus voltage of the vehicle. The required battery current is determined using a standard battery model of a perfect voltage source with an internal resistance. The required APU current is found using a similar model for the APU alternator (Merkle, 1997).

Since ADVISOR determines the APU loading in its "Energy Storage" subsystem, the majority of changes occurred within that block, with only a few cosmetic changes to the "APU" subsystem. An iteration was introduced into the Energy Storage block diagram which used battery SOC and the required power from the bus to determine the proper bus voltage and the correct current flows from the batteries and APU respectively. The APU block diagram was then changed, such that its look-up tables (for fuel economy, emissions, etc.) were functions of its voltage and current instead of its speed and torque.

With these modifications in place, the results from the simulation were taken step-by-step and compared to the actual measured data and checked for accuracy before moving on to the next step. The comparisons for each step are detailed below.

## Road Load Comparison

The first major calculation performed by ADVISOR during a simulation is that of the vehicle road load. Measured road load points for the Virginia Tech FutureCar were available for constant speeds on a zero grade; therefore, this was used as the standard for determining the accuracy of the ADVISOR road load predictions. This data set was collected at the 1996 FutureCar Challenge during coastdown testing, which was used to set the road load for the subsequent dynamometer testing. The measured and predicted curves are given in Figure 4.1.

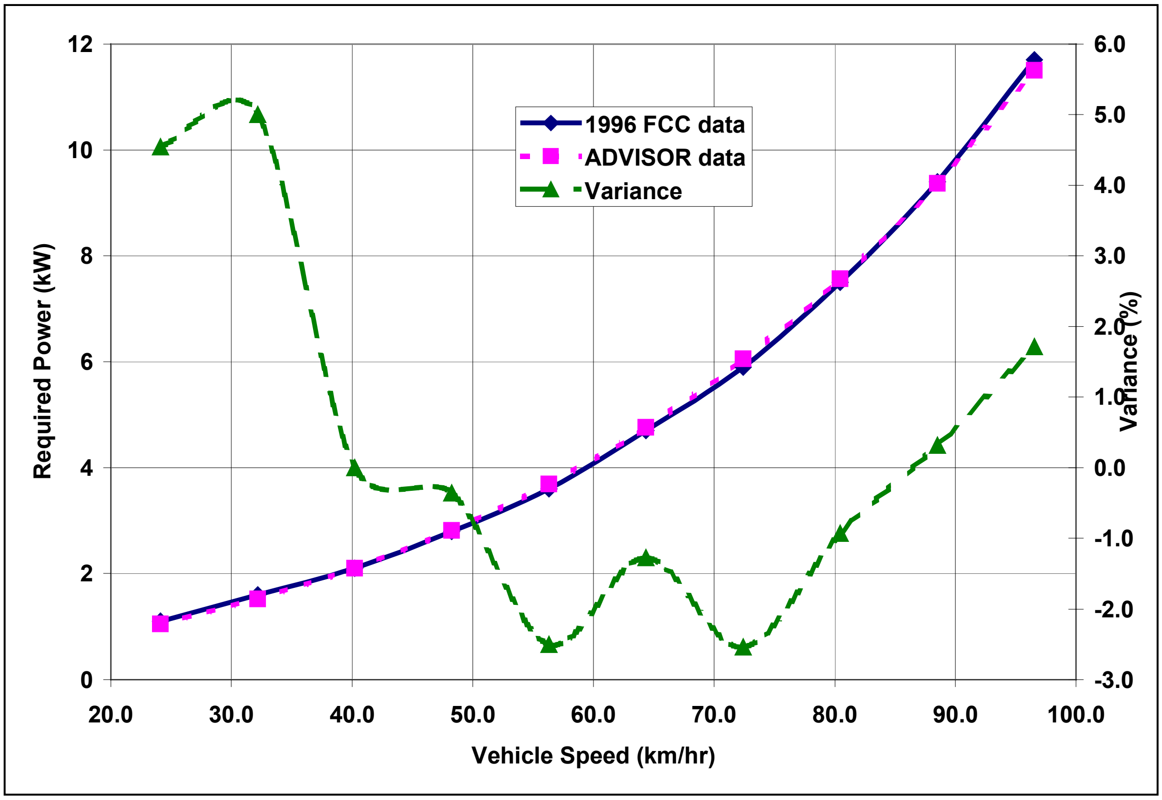

Figure 4.1. Road Load Curve Comparison

The variance between the actual and predicted values is less than 3% at speeds above 35 km/hr (22 mph). Only at low speeds, where power requirements are a small component of the overall energy usage, does the discrepancy approach 5%. This excellent agreement between the values is necessary for an accurate simulation since these power requirements will be used to determine the other vehicle energy usages.

## Standard Driving Cycles

Standard industry methods of comparison were used to evaluate the effectiveness of ADVISOR as a simulation tool for series HEVs. Most of the comparisons were performed using the standard driving cycles. The Federal Urban Driving Schedule (FUDS) is the current federal government cycle which is used to represent typical city driving. The Federal Highway Driving Schedule (FHDS) is used to imitate typical highway driving. However, these tests generally reflect more conservative driving behaviors than those typical of most Americans. Both the FUDS and FHDS are defined by speed versus time traces on a zero grade which are shown in Figures 4.2 and 4.3, respectively.

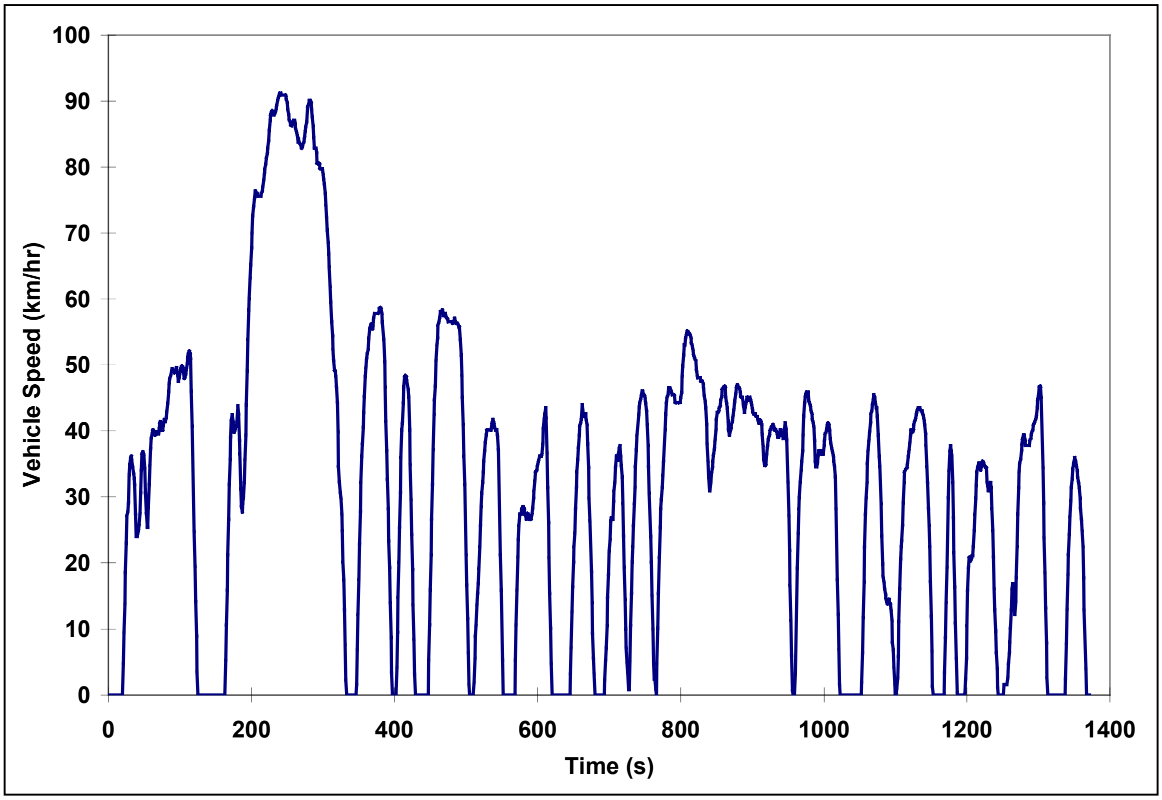

Figure 4.2. FUDS Driving Trace

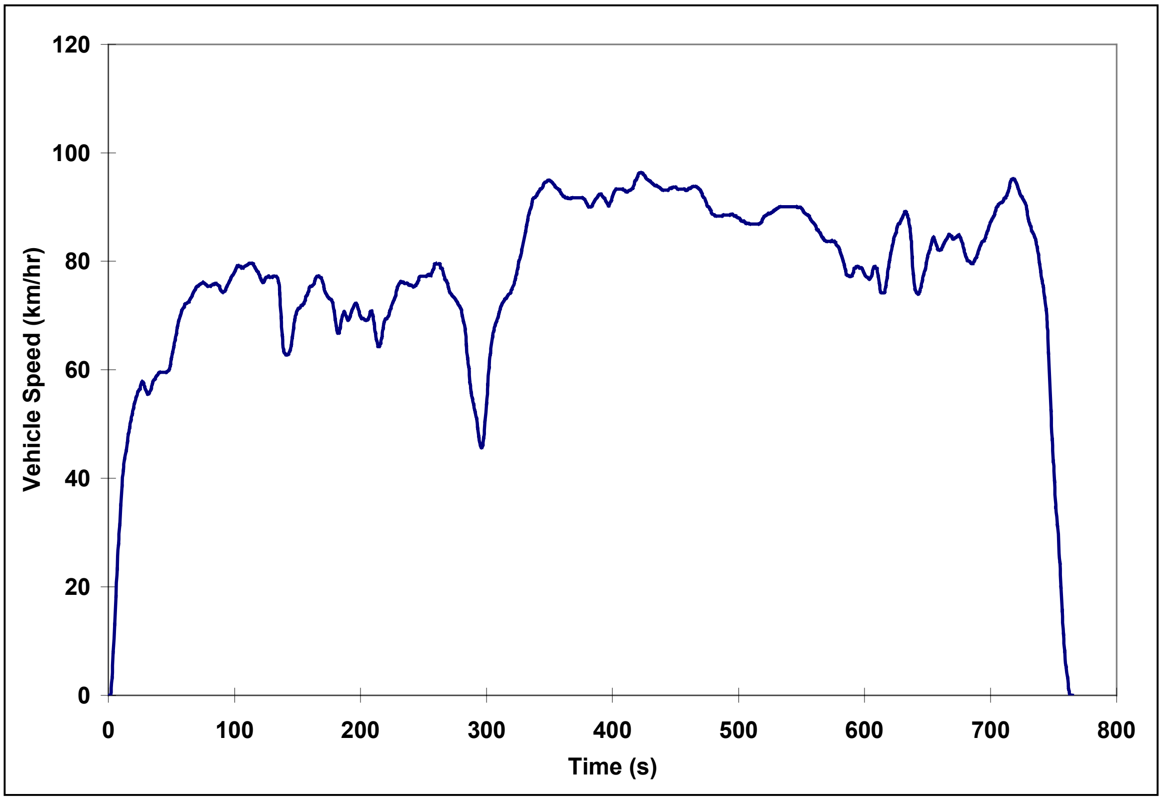

Figure 4.3. FHDS Driving Trace

The FUDS is 1371 seconds in length and covers a distance of 12.0 km (7.5 mi). The average vehicle speed for the test is 31.5 km/hr (19.6 mph) with a maximum speed of 91.2 km/hr (56.7 mph). As indicated in Figure 4.2, the cycle includes nearly 20 complete stops and restarts.

The FHDS is 765 seconds long and covers a distance of 16.5 km (10.3 mi). The average speed during the test is 77.7 km/hr (48.3 mph) with a maximum of 96.4 km/hr (59.9 mph). No stops are required until the end of the test.

<u>Electric Drivetrain Energy Usage Comparisons</u>

The electric drivetrain of the vehicle, defined as the components which take electrical energy from the bus and transform it into the mechanical energy necessary to meet the road load, consists of the transmission, electric motor, and inverter. A simulation tool must accurately describe the energy use of these components as a system in order for the simulation to accurately predict vehicle fuel economy and emissions. This electric drivetrain system can be isolated and studied by operating the vehicle in ZEV mode, which does not allow the APU to operate. By isolating the electric drivetrain from the APU, the APU-related effects and battery efficiencies are eliminated, leaving only a true picture of the electric drivetrain energy efficiency. For the 1996 Virginia Tech FutureCar, the only available ZEV test data was for a single FUDS cycle, starting at a high SOC (HSOC), defined by the upper limit of the vehicle's control strategy. Table 4.1 and Figure 4.4 give comparisons of the ADVISOR predictions and the actual measured data from this test.

Table 4.1. ZEV-mode FUDS (HSOC) Energy and Capacity Use Comparison

| **Cycle** | **Actual** | | **ADVISOR** | | **Difference** | |
|---|---|---|---|---|---|---|
| | **Energy (kWh)** | **Capacity (Ah)** | **Energy (kWh)** | **Capacity (Ah)** | **Energy (%)** | **Capacity (%)** |
| **FUDS (HSOC)** | 2.63 | 8.2 | 2.63 | 8.1 | 0.0 | -1.2 |

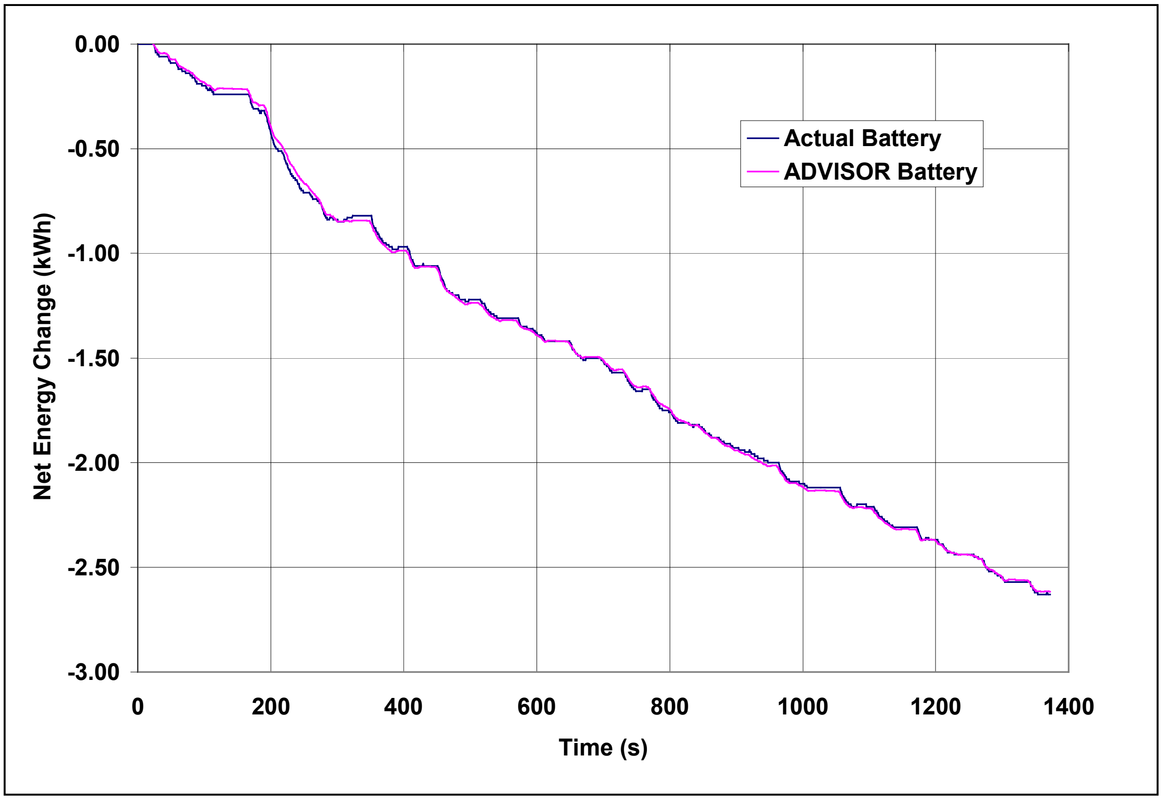

Figure 4.4. ZEV FUDS (HSOC) Comparison

Analyses of Table 4.1 and Figure 4.4 indicate that the ADVISOR battery capacity and energy use predictions deviated less than 2% from actual vehicle performance. This high level of accuracy is necessary if the simulation tool is to be used for obtaining absolute numbers instead of relative comparisons.

## APU/Battery Energy Usage Comparisons

Once APU operation is included during a driving cycle, the complexity of the system increases, and an accurate simulation is more difficult to achieve. However, data comparisons can then be made using not only electric drivetrain energy use, but also the relative battery and APU energy use required over a given driving cycle. Comparisons of this energy split are given in Table 4.2 for the totals and as a function of time in Figure 4.5 for an urban driving cycle pair (two consecutive cycles) with a low initial SOC (LSOC).

Table 4.2. FUDS Pair (LSOC) Energy and Capacity Use Comparison

| Cycle | Actual | | ADVISOR | | Difference | |
|---|---|---|---|---|---|---|
| | Energy (kWh) | Capacity (Ah) | Energy (kWh) | Capacity (Ah) | Energy (%) | Capacity (%) |
| Batteries | -0.15 | -1.3 | -0.30 | -1.7 | -100.0 | -30.8 |
| APU | 5.28 | 15.8 | 4.95 | 15.4 | 6.3 | 2.5 |
| Total | 5.43 | 17.1 | 5.25 | 17.1 | 3.3 | 0.0 |

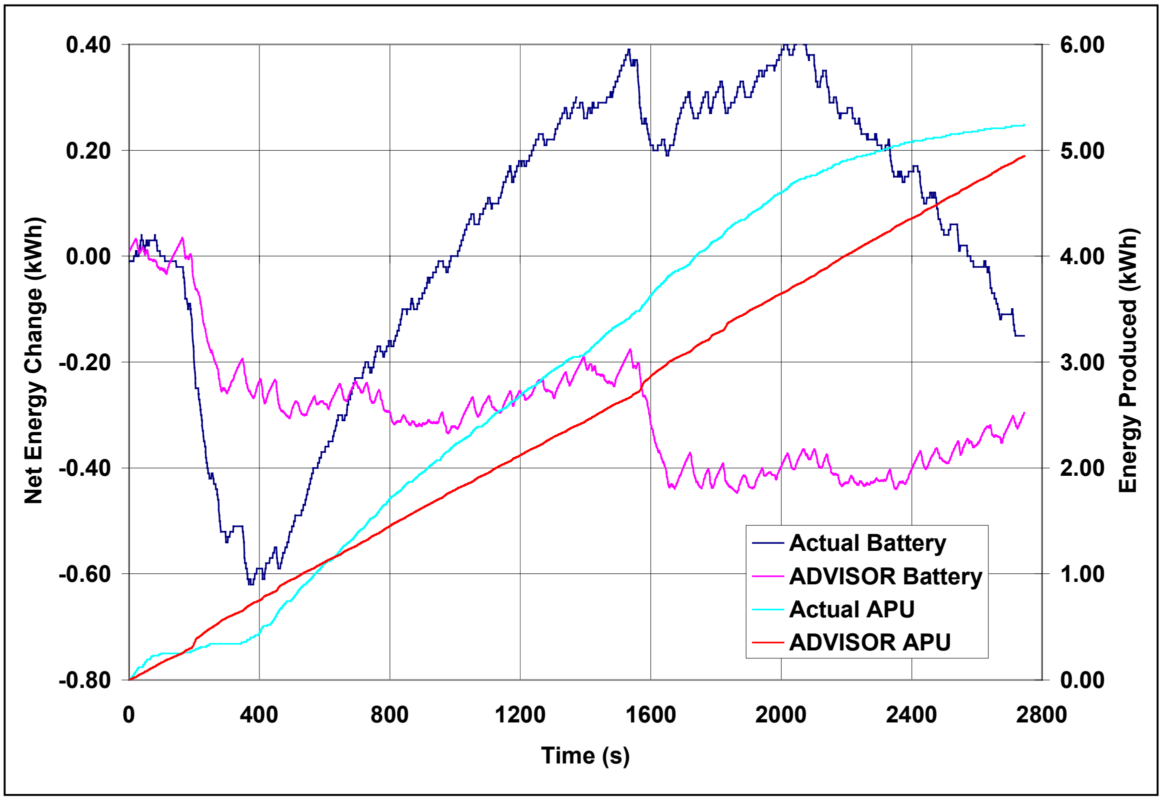

Figure 4.5. FUDS Pair (LSOC) Energy Comparison

In this case the simulation does not appear to be accurate at modeling the relative contributions of the batteries to the overall vehicle energy requirements. Table 4.2 indicates a difference of 100% in overall energy use, and Figure 4.5 shows an energy use curve with a drastically different shape. However, notes from the 1996 FutureCar Challenge indicate that the measured data may have been skewed. During this test, the APU speed control operated erratically, with frequent swings from low speed to high speed. When running too slowly, the APU output voltage is lower than the bus voltage of the vehicle, and no current is produced; when running too quickly, the APU output current becomes much higher than anticipated. These conditions can be seen in the data: from 0-400 seconds, the APU seemed to produce less power than expected; from 400-1600 seconds, more power than expected; from 1600-2000 seconds, about the correct amount of power; and again, less power than expected from 2000 seconds until the end of the test.

In order to accurately model the overall energy use over the entire FUDS pair, a nominal value of 3450 rpm was used for average engine speed. This was lower than the setpoint of the engine speed controller, but was more indicative of the actual average speed of the engine during the test.

Table 4.3 and Figure 4.6 show the same types of comparisons for the urban driving cycle pair with a high initial SOC.

Table 4.3. FUDS Pair (HSOC) Energy and Capacity Use Comparison

| Cycle | Actual | | ADVISOR | | Difference | |
|---|---|---|---|---|---|---|
| | Energy (kWh) | Capacity (Ah) | Energy (kWh) | Capacity (Ah) | Energy (%) | Capacity (%) |
| Batteries | -2.02 | -6.7 | -1.93 | -6.8 | 4.5 | -1.5 |
| APU | 3.42 | 10.0 | 3.31 | 10.2 | 3.2 | -2.0 |
| Total | 5.44 | 16.7 | 5.24 | 17.0 | 3.7 | -1.8 |

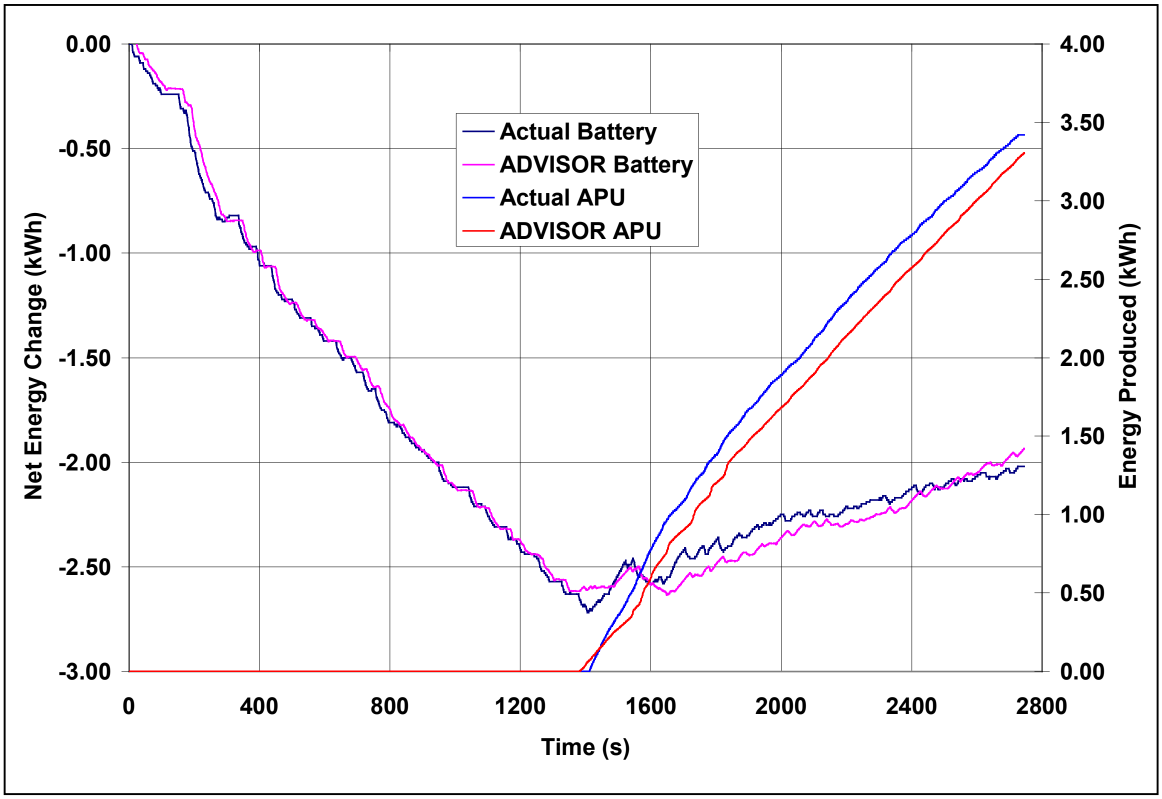

Figure 4.6. FUDS Pair (HSOC) Energy Comparison

During this test at the 1996 FCC, the problems with the APU speed control had been corrected as witnessed by the much smoother APU operation. The LSOC limit (APU turn on point) of the control strategy was lowered from its normal value of 40% to 27% in order to better match the test data. This lower APU-on point could have been due to inconsistencies in the vehicle's SOC-determination or by a driver-selected APU-off selection until the beginning of the second cycle of the FUDS pair (at approximately 1400 seconds). Also for this simulation, the average engine speed set in ADVISOR was a more realistic 3600 rpm. As a result, this study shows a much more reasonable agreement between the actual test data and the ADVISOR predictions, with less than 5% error at any time during the test and an almost exact match between the shapes of the energy curves.

A final example is given in Table 4.4 and Figure 4.7 for a single highway driving cycle beginning at a high SOC.

Table 4.4. FHDS (HSOC) Energy and Capacity Use Comparison

| Cycle | Actual | | ADVISOR | | Difference | |
|---|---|---|---|---|---|---|
| | Energy (kWh) | Capacity (Ah) | Energy (kWh) | Capacity (Ah) | Energy (%) | Capacity (%) |
| Batteries | -0.92 | -2.9 | -0.98 | -3.1 | -6.5 | -6.9 |
| APU | 1.86 | 5.7 | 1.89 | 5.7 | -1.6 | 0.0 |
| Total | 2.78 | 8.6 | 2.87 | 8.8 | -3.2 | -2.3 |

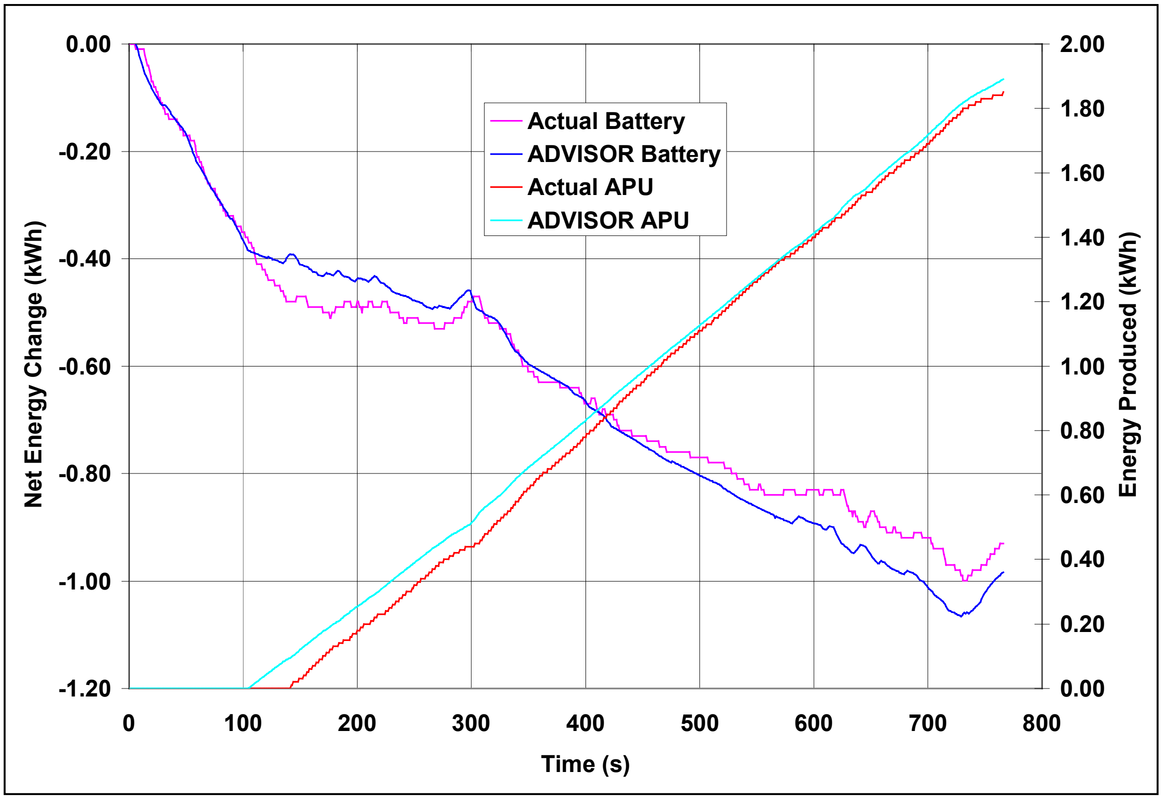

Figure 4.7. FHDS (HSOC) Energy Comparison

For this cycle, the average APU speed was raised slightly from 3600 rpm on the FUDS cycle to about 3700 rpm, since the engine tends to run somewhat faster on the more steady FHDS cycle. At the 1996 FCC, the APU was manually shifted on to ensure that the test produce data such that a highway fuel economy value could be accurately determined. According to the test data, this APU-on occurred at a SOC of 64%, so the ADVISOR value LSOC limit was set accordingly. Once again, the ADVISOR predictions accurately track the actual data, with the energy comparison graphs having nearly identical shapes, and with less than 10% discrepancy at any point during the test.

## HEV Test Procedures

Although energy use comparisons can be convenient for analyzing specific cases of HEV operation, a measure of the vehicle's overall efficiency for a broad spectrum of operating conditions is needed. This categorization also allows for easy comparison to other HEVs, EVs, and ICE vehicles. For conventional ICE vehicles, the standard test procedure consists of a cold (i. e., ambient temperature) start FUDS, followed by a 10-minute ambient temperature soak, followed by the first 505 seconds of another FUDS. This procedure determines the vehicle's city fuel economy and emissions level. An FHDS is then performed for which no data are taken, followed immediately by another FHDS for which vehicle fuel economy is obtained.

For series and parallel HEVs, however, the procedure is much more complex. This is due to the fact that HEVs not only have the ability to store energy in the form of an expendable fuel (always decreasing), but also in the form of a battery pack which can be charged and depleted. This results in the fuel economy and emissions of the vehicle being a function of the amount of energy stored in the batteries at the onset and conclusion of the testing.

In order to develop a reasonable test for which HEVs could be accurately compared to each other and to conventional vehicles, the Society of Automotive Engineers (SAE) established the Hybrid-Electric Vehicle Test Procedure Task Force. The HEV testing procedures have yet to be finalized, but the current draft of the procedure (known as SAE Recommended Practice J1711) from this committee (SAE, 1997) was used as the basis for the actual vehicle dynamometer testing and for the simulation modeling.

The procedure called for in SAE J1711 depends heavily upon the configuration and design strategy of the particular vehicle in question. The Virginia Tech FutureCar was designed to be a charge-sustaining, series HEV for both the city and highway cycles, which is defined as the ability to maintain a given battery SOC over the cycles. SAE J1711 calls for pairs of FUDS cycles to be run; each pair consists of one FUDS cycle followed by a 10-minute ambient soak, followed by another FUDS cycle. The vehicle tests also require that the high and low battery SOC points (HSOC and LSOC, respectively) be known for the vehicle under normal operating conditions. For this type of vehicle, the SAE test procedure is summarize below: (note, this procedure has since changed)

**Test 1:** One cold (ambient) start FUDS pair starting at the LSOC; change (increase) in SOC, fuel use, and emissions are recorded.
**Test 2:** Two consecutive FHDSs (no soak) starting at the LSOC point; change (increase) in SOC and fuel use are recorded.

**Conditioning:** Vehicle is soaked at ambient conditions for 12 hours.

**Test 3:** One cold (ambient) start FUDS pair starting at the HSOC; change (decrease) in SOC, fuel use, and emissions are recorded.
**Test 4:** Two consecutive FHDSs (no soak) starting at the HSOC point; change (decrease) in SOC and fuel use are recorded.

If this testing does indeed result in one test where SOC increases and one test where SOC decreases, then a SOC interpolation is possible. The recorded fuel use and emissions values for the city tests are linearly interpolated between the amount of charge gained during the LSOC test and the amount of charge used during the HSOC test to obtain a value for zero net change in SOC. An example of this procedure, called SOC correction, is shown in Figure 4.8.

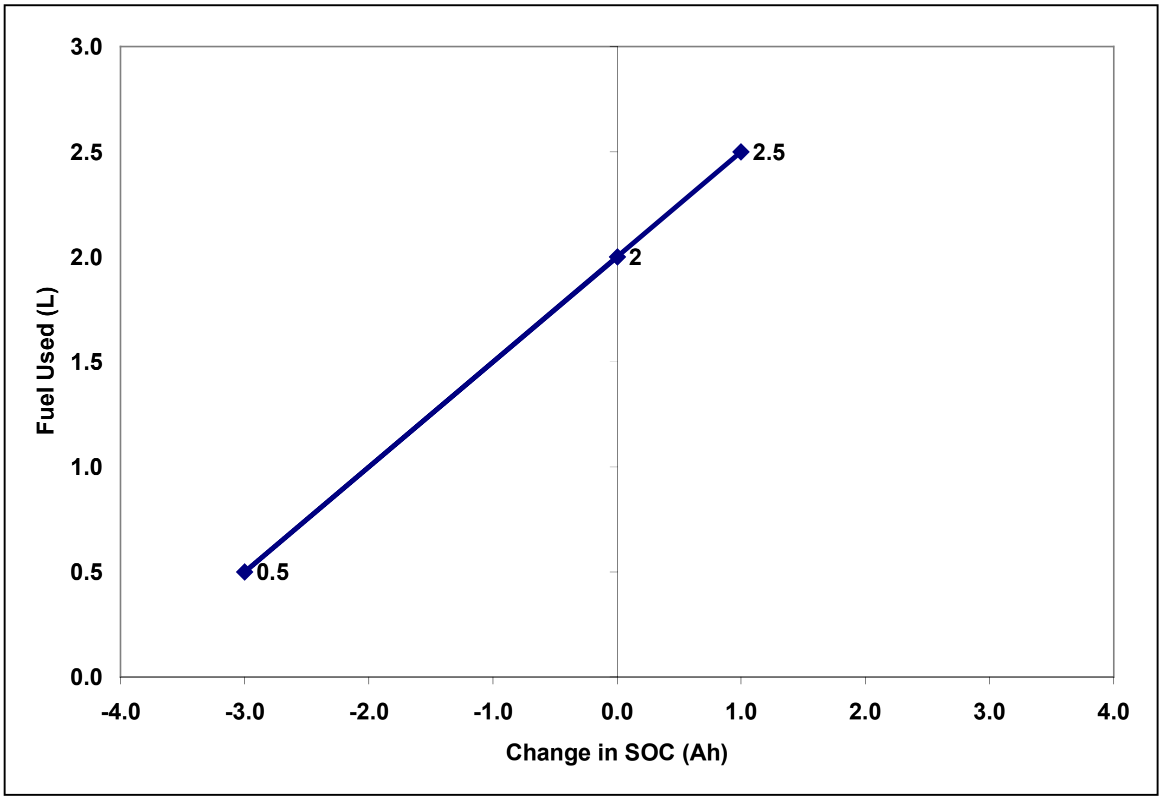

Figure 4.8. SOC Correction Example

For example, that the measured fuel usage during the LSOC and HSOC FUDS pairs is interpolated to obtain a value of 2.0 liters (0.53 gal) of fuel used for no net change in SOC. Over the 24.0 km (14.9 mi) distance of the FUDS pair, this translates to a fuel economy of 12.0 km/l (28.2 mpg). A similar procedure is used for the emissions on the city cycle. The highway fuel usage is also computed similarly.

However, if for some reason (such as charge-depletion on both HSOC and LSOC tests), a SOC interpolation is not possible, another method is used to obtain fuel economy and emissions numbers which reflect the vehicle's behavior under the condition of zero net change in SOC. This is done using a value for the electrical energy which can be obtained from gasoline through the efficiency of an average power plant in the United States. The 1996 FCC value used to compensate for electrical energy usage was 0.321x9.69 kWh/l (0.321x36.66 kWh/gal) (Duoba, 1996).

Another important concept used in testing alternative fuel vehicles to ensure relevant comparisons is fuel energy equivalency. For non-gasoline fuels, the reported fuel economy values are often translated into "gasoline-equivalent" numbers for easier comparison of different vehicles. This is done as shown in Equation 4.1 using the lower heating values (LHV) of the fuel with respect to that of gasoline. Table 4.5 gives the LHV of some common fuels (Aldrich, 1996).

$$FE_{eqiv} = FE_{fuel}\left(\frac{E_{gasoline}}{E_{fuel}}\right) \qquad \text{Equation 4.1.}$$

Table 4.5. Fuel Energy Comparison

| Fuel | Comments | Lower Heating Value | |
|---|---|---|---|
| **Gasoline** | | **32.2 MJ/liter** | **115,400 Btu/gal** |
| Diesel | | 36.0 MJ/liter | 129,000 Btu/gal |
| **Propane** | | **23.4 MJ/liter** | **84,000 Btu/gal** |
| E85 | (85% ethanol, 15% gasoline) | 22.6 MJ/liter | 81,000 Btu/gal |
| Ethanol | (100% ethanol) | 20.9 MJ/liter | 75,000 Btu/gal |
| LNG | (liquefied natural gas) | 20.5 MJ/liter | 73,500 Btu/gal |
| M85 | (85% methanol, 15% gasoline) | 18.2 MJ/liter | 65,350 Btu/gal |
| Methanol | (100% methanol) | 15.7 MJ/liter | 56,500 Btu/gal |
| Liquid Hydrogen | | 9.50 MJ/liter | 34,000 Btu/gal |
| Natural Gas (CNG) | @ 20.7 MPa (3000 psi) | 8.08 MJ/liter | 29,000 Btu/gal |
| Hydrogen | @ 20.7 MPa (3000 psi) | 2.70 MJ/liter | 9,667 Btu/gal |

Since the Virginia Tech FutureCar used propane fuel, Equation 4.1 translates 10.0 km/l (or 10.0 mpg) of propane to 13.7 km/l (13.7 mpg) of gasoline equivalent, denoted as km/$l_e$ (mpg$_e$).

SOC-Corrected Fuel Economy Comparisons

The fuel economy results from the 1996 FutureCar Challenge were obtained primarily by using the electrical energy equivalency method outlined above. Since the Virginia Tech vehicle showed slight charge-depleting properties, a true SOC interpolation was not possible. Therefore, the fuel use from the LSOC test (on a gasoline equivalent basis) was added to the amount of gasoline necessary to replenish the electrical energy used during the test. This total fuel use was then divided into the distance traveled during the test to arrive at the city fuel economy value. Originally, the city fuel economy was reported to be 20.9 km/$l_e$ (49.2 mpg$_e$), but subsequent analysis indicates that this value to be incorrect. A more reasonable value would be one half of that, or 10.5 km/$l_e$ (24.6 mpg$_e$). This value will be taken as the actual value for purposes of comparison in this study. (This value is also consistent with results from the 1997 FutureCar Challenge.)

The method used to obtain the highway fuel economy was similar to the city cycle. In this case, only a single FHDS cycle was run (from a HSOC), and the standard electrical energy conversion was used to determine the highway value. The actual value from the 1996 FCC is 17.1 km/$l_e$ (40.2 mpg$_e$), which seems much more likely to be correct. Only the final fuel economy numbers are available from the 1996 FutureCar Challenge, preventing the comparison of the measured fuel use on the individual cycles with the predicted fuel use from ADVISOR. A comparison of the final fuel economy values is given in Figure 4.9.

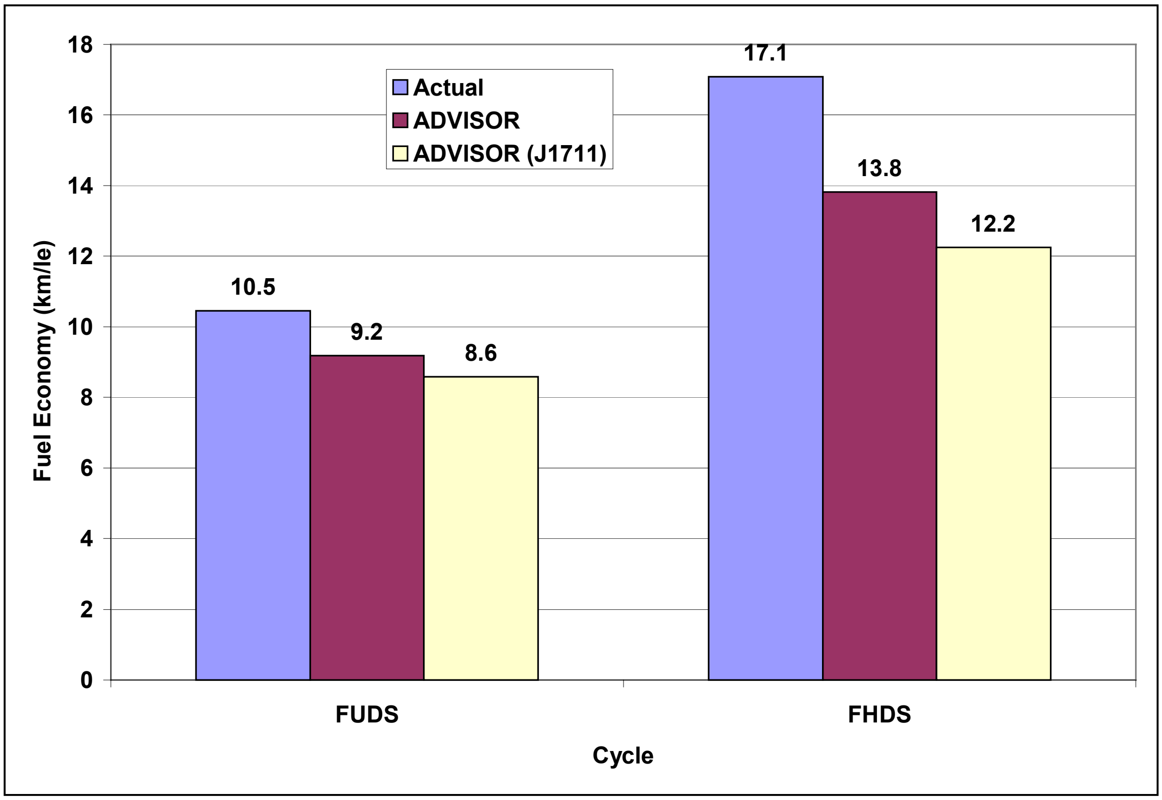

Figure 4.9. SOC-Corrected Fuel Economy Comparison

ADVISOR determined the fuel economy values in exactly the same manner as at the 1996 FutureCar Challenge. A FUDS LSOC pair was performed, with the results given in Table 4.6. A FHDS HSOC cycle was also executed, with its results also in Table 4.6.

Table 4.6. ADVISOR Fuel Economy Calculation

| Cycle | Quantity | Value | Gasoline Equivalent |
|---|---|---|---|
| **FUDS** | Actual fuel use | 3.44 liters LPG | 2.51 liters |
| | Net battery energy change | -0.30 kWh | 0.097 liters |
| | Total equivalent fuel use | | 2.61 liters |
| | Cycle distance | 24.0 km | |
| | **Fuel Economy** | | **9.2 km/l** |
| **FHDS** | Actual fuel use | 1.20 liters LPG | 0.88 liters |
| | Net battery energy change | -0.98 kWh | 0.32 liters |
| | Total equivalent fuel use | | 1.20 liters |
| | Cycle distance | 16.5 km | |
| | **Fuel Economy** | | **13.8 km/l** |

The ADVISOR predictions differ from the measured values by 12.2% and 19.2% for the city and highway, respectively. Considering the uncertainty surrounding the 1996 FCC fuel economy numbers, these numbers indicate that ADVISOR can provide reasonable predictions of SOC-corrected fuel economy.

SOC-Corrected Emissions Comparisons

In general practice, emissions numbers are only evaluated on the FUDS cycle. The 1996 FutureCar Challenge followed this standard, and as such, only the SOC-corrected FUDS cycles emissions numbers are available for the Virginia Tech vehicle. Also, only the major regulated emissions species (hydrocarbons, carbon monoxide, and oxides of nitrogen) were reported. A comparison of these data with the ADVISOR predictions is shown in Figure 4.10.

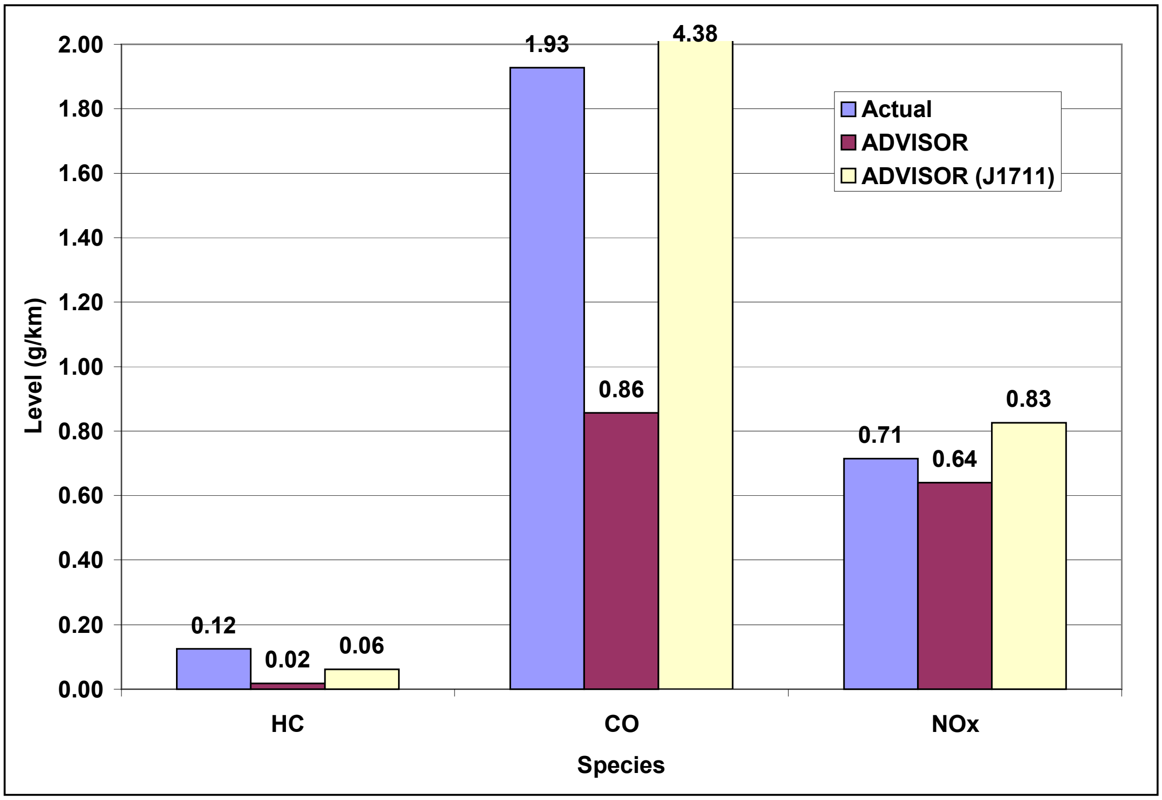

Figure 4.10. SOC-Corrected FUDS Emissions Comparison

Emissions values from ADVISOR were calculated similarly to the city fuel economy number using standard emissions equivalency factors for the amount of electrical energy used (HC: 0.016 g/kWh; CO: 0.117 g/kWh; $NO_x$: 1.25 g/kWh) (Duoba, 1996). The ADVISOR values are lower than the measured values by 86.0%, 55.5%, and 10.4% for HC, CO, and $NO_x$, respectively. These results indicate that ADVISOR does not predict the actual Virginia Tech FutureCar emissions to the same level of accuracy as its energy use and fuel economy predictions. However, its $NO_x$ prediction is quite close to the actual value, and its values are generally of the same order of magnitude of the actual values.

The ADVISOR code was also utilized to predict the operation of the Virginia Tech vehicle when tested following the exact SAE J1711 procedure, instead of attempting to match the procedures performed at the 1996 FutureCar Challenge. The fuel economy and emissions results of the SAE J1711 predictions are given in Figures 4.9 and 4.10, respectively. The fuel economy numbers under SAE J1711 are lower than the actual values and the predicted values using the FCC test procedures. The FUDS emissions values under SAE J1711 are generally higher than the actual values and the ADVISOR values using the FCC procedures. Both the fuel economy and emissions discrepancies are the result of using standard fuel use and emissions production values for an equivalent amount of electrical energy usage. These standard values do not necessarily reflect the actual operation of the Virginia Tech FutureCar, and, consequently, the use of these values would not result in accurate simulation results. The SAE J1711 procedure is evolving to reduce these types of problems.

All of the data for the APU component model were taken at steady state, while operation in the vehicle with varying load and the throttle control causes some variation in APU speed. The closed-loop feedback fuel control system also oscillates the air fuel ratio back and forth across the stoichiometric value, leading to variations in emissions. In addition, the results for the FUDS low state of charge pair (Fig. 4.5, where the APU speed control operated erratically) could not be separated out of the test results. The combination of the test uncertainty and our component model data uncertainty leads to the large differences between measurements and simulation results.

The various standards used here to test the validity of the ADVISOR simulations represent a thorough evaluation of the ADVISOR code and the Virginia Tech FutureCar model. This assessment is adequate for conclusions to be drawn about the accuracy specific to the Virginia Tech model, the general accuracy of ADVISOR, its strengths and weaknesses, and other potential uses as a simulation tool for HEVs.

## Chapter 5. Conclusions and Recommendations

Many aspects of the validation process are prone to misinterpretation, uncertainty, and mistakes. These can drastically alter the results of the simulation and therefore their effects must be carefully considered and accounted for in making conclusions about the usefulness of a particular simulation tool. With the proper understanding of the causes of discrepancies and the limitations of the program, a simulation can be quite useful even when the data may not exactly predict the actual values. The major influences on the ADVISOR predictions are discussed below with proposals for eliminating or reducing adverse effects on the results. Once these have been accounted for, the general validity of ADVISOR is evaluated, and its strengths and weaknesses are listed. Finally, some general conclusions about the possible uses of the program are given.

### Measured Data and Test Procedures

A number of problems with the procedures of collecting data and uncertainties in the accuracy of the data collected on the Virginia Tech FutureCar and its components contributed to difficulties in evaluating ADVISOR. The measured data were the single most significant source of uncertainty in the entire validation process.

The vehicle caused some measurement problems itself by not performing as designed. During the FUDS LSOC test, the engine speed control, designed to hold a constant speed, oscillated wildly during most of the test. This instability is difficult to model, and is consequently a source of uncertainty. Repeated attempts to start the engine during a test also occurred on at least one occasion, causing modeling problems. These problems could be corrected by more extensive vehicle testing and tuning to ensure reliable operation before recording data.

The actual electrical behavior of the vehicle as a function of time was recorded during all testing at the 1996 FutureCar Challenge. Careful study of these data allowed a number of possible discrepancies to be anticipated in the simulations. However, this type of data is not available for the actual vehicle speed, fuel use, or emissions production. The lack of intermediate data from the dynamometer testing prevents the reconciliation of other possible discrepancies in the simulation. Given the proper resources, these data would be used to verify the simulation results throughout the process, from road load calculation to SOC-corrections.

Differences in test procedure must be closely monitored and repeated if accurate simulations are to be performed. Even a slight difference in a test (vehicle preconditioning process, the catalyst temperature at the start of a test, the amount of soak time between tests, and the ambient temperature during engine testing are common examples) can cause large variations in the results. Every effort was made to replicate the testing as performed at the 1996 FutureCar Challenge in the ADVISOR simulations, but small errors were experienced, introducing a level of uncertainty. For this reason, detailed logs should be made during data collection which will allow the conditions of the actual test to be reproduced as closely as possible by the simulation.

In order to determine the APU model for ADVISOR, fuel efficiency, emissions, and catalyst efficiency maps were generated from extensive testing. However, the data for these results are extremely sensitive to the air/fuel ratio of the engine. On the Virginia Tech APU, this air/fuel ratio was controlled by a commercial closed-loop fuel controller, which oscillated about a stoichiometric ratio. Merely operating 1% on the lean side of a stoichiometric mixture results in drastically different emissions levels (high $NO_x$) than operating 1% on the rich side (high HC and CO). Significant changes in the emissions levels then cause significant changes in the catalyst efficiencies. As a result, large uncertainties are present in the measured APU and dynamometer data due to the inability to maintain a constant air/fuel ratio.

During all dynamometer testing, the speed of the vehicle was controlled manually. Therefore, there is inherent human error in the actual vehicle speed. This error, when taken to extremes by some of the less meticulous operators, can result in significant differences in vehicle performance. Improved speed control methods can be used to significantly reduce this source of error.

Finally, discrepancies in gathering or interpreting the measured data led to a large amount of uncertainty. For example, the originally quoted city fuel economy value for the Virginia Tech vehicle of 20.9 $km/l_e$ (49.2 $mpg_e$) was in error. This is verified by recognition that the quoted fuel economy would have required unrealistic thermal efficiency from the engine. This calls into question not only the city fuel economy, but also the correctness of the other data collected on the dynamometer at the 1996 FCC. With no way to retest the vehicle or reconstruct the data, the measured results must be re-evaluated, a new value must be ascertained from comparable data, and an appropriate uncertainty must be assigned to that value.

### ADVISOR

Some discrepancies in the simulation may result from the structure of the simulation itself. If the simulation code does not exactly reproduce the major features of actual vehicle operation (such as the vehicle control strategy), an accurate simulation is compromised. The constant engine speed with varying load based on bus voltage feature of the Virginia Tech control strategy was implemented in the ADVISOR code at the start of the validation process. This routine works very well at modeling the true behavior of the vehicle as shown by the accurate results of the APU/battery energy comparisons.

Another feature that should be incorporated in future simulation efforts is correction for variable engine speed. The extremely high loads caused by hard accelerations lower the engine speed due to the limited torque capacity of the engine. This reduced speed lowers the effective open-circuit voltage of the alternator (now set in ADVISOR as a constant). However, relatively few high loads occur during the standard driving cycles, and the effect of these speed changes is small. Therefore, it was decided that a routine to vary engine speed according to torque limitation was unnecessarily complex.

Another possible source of errors in the simulation occurs in the electric drivetrain efficiency maps. The maps used in the simulation were not determined from actual testing of the components in the Virginia Tech vehicle. The motor and inverter maps were obtained from the manufacturer (whose exact test conditions are not known) and the transmission map was obtained from an existing map of a similar device. Although using these maps introduces some uncertainty to the simulation, the accurate predictions demonstrated by ADVISOR show that these maps must have been reasonably accurate. A further check could be performed in the future by actual testing of these components to ensure the best possible models. (These maps have since been verified by testing for another project in the electrical engineering department.)

One feature of ADVISOR, which is inherent to its nature as a computer simulation, is its quasi-steady assumption. This type of model requires that all events occur in small steady-state steps. However, real systems do not behave as steady-state systems; rather, they consist of many transient phenomena often occurring simultaneously. Many of a vehicle's transients can be accurately modeled in a quasi-steady environment using a sufficiently small timestep, but not so small as to cause instability in the simulation. However, all transient events cannot be accurately predicted by a quasi-steady model, regardless of timestep size, thereby introducing some error.

One of the most important of these transients is the operation of the engine, which can be extremely nonlinear and is therefore not modeled well by the linear assumption and the quasi-steady approach. ADVISOR does contain a provision for including the inertia required for the angular acceleration required to go from one steady-state point to another, but this type of data is very difficult to measure, and was not used in the current APU component model. For example, the engine may need 1 g/s of fuel at 1000 rpm at a given load during one timestep, and 2 g/s of fuel at 1100 rpm at the same load during the next timestep, but it may actually require 3 g/s (and not 1.5 g/s) of fuel to accelerate from the first timestep to the next. If one adds in the effects of changing loads and the continuous variations in air/fuel ratios, it becomes difficult to model with any accuracy. Predicting emissions is even more difficult than fuel use. One possible solution to this problem would be to use a nonlinear modeling technique, such as a neural network, to represent the operation of the APU, with the remainder of the simulation operating in the traditional quasi-steady environment. This type of complexity may be excessive for ADVISOR, but it is necessary if more accurate modeling of transient phenomena, such as emissions, is desired.

### Validity of ADVISOR as a Simulation Tool

These results show ADVISOR to be a valid simulation tool, particularly for series HEVs and the Virginia Tech FutureCar. Its predictions of the vehicle behavior are consistently within the bounds of uncertainty for each step of the simulation process.

ADVISOR does have particular strengths and weaknesses which limit its use. The simulation itself is quite stable and is not overly sensitive to variations in components and conditions. It satisfactorily predicts the absolute values of particular vehicle attributes in addition to being a tool for the relative comparison of different vehicles. It predicts vehicle energy use to within 5-10% of measured data. It predicts vehicle fuel economy over the standard driving cycles using standard test procedures to within 12-19% of actual data. Emissions are predicted to within 85% uncertainty. All of these predictions are within the bounds of uncertainty for the data.

The quasi-steady simulations would likely be the most accurate for pure EVs, since the transient effects of an electric drivetrain are fairly small and would not introduce errors as discussed previously. Series HEVs, having the next most-steady operating characteristics, appear to be nearly as accurately modeled. Parallel HEVs may also be modeled with a fair degree of accuracy since their electric drivetrains behave primarily in a steady manner. The accuracy decreases as the transient effects of the ICE are increased—i.e., small variations in engine loading would be modeled with high accuracy, while the fuel use and emissions effects of large variations in engine operation would likely be less accurate.

ADVISOR is limited by the fact that it requires a large amount of accurate component testing (particularly of the APU) in order to arrive at accurate results, although this fact is inherent to all modeling. Its abilities to model emissions production are tied to the repeatability of the emissions testing. Its quasi-steady nature reduces its ability to accurately model certain items, such as the APU operation.

Keeping in mind its few limitations, ADVISOR is a valuable simulation tool for modeling the behaviors of HEVs in general, and the Virginia Tech FutureCar in particular. ADVISOR could be used with a great degree of confidence in predicting future behavior and making informed design decisions with a minimal amount of additional testing. However, as with any simulation, all results should be tempered by supporting data from representative testing, sound engineering judgement, and common sense.

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## Vita

Randall Donn Senger graduated from Virginia Tech in May 1995 with a Bachelor of Science degree in Mechanical Engineering. Following graduation, he entered the graduate program in Mechanical Engineering at Virginia Tech. During his graduate study he held Graduate Teaching Assistant and Graduate Research Assistant positions. Throughout his graduate work, he was also Team Co-Leader for the Hybrid Electric Vehicle Team of Virginia Tech, focusing his research in this area. He completed his Master of Science degree in the fall of 1997. He and his wife, Cynthia, reside in Mt. Sidney, Virginia.