Variable Bus Voltage Modeling for Series Hybrid Electric Vehicle Simulation

By

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Abstract

A growing dependence on foreign oil, along with a heightened concern over the environmental impact of personal transportation, had led the U. S. government to investigate and sponsor research into advanced transportation concepts. One of these future technologies is the hybrid electric vehicle (HEV), typically featuring both an internal combustion engine and an electric motor, with the goal of producing fewer emissions while obtaining superior fuel economy.

While vehicles such as the Virginia Tech designed and built HEV Lumina have provided a substantial proof of concept for hybrids, there still remains a great deal of research to be done regarding optimization of hybrid vehicle design. This optimization process has been made easier through the use of ADVISOR, a MATLAB simulation program developed by the U. S. Department of Energy's National Renewable Energy Lab. ADVISOR allows one to evaluate different drivetrain and subsystem configurations for both fuel economy and emissions levels.

However, the present version of ADVISOR uses a constant power model for the auxiliary power unit (APU) that, while effective for cursory simulation efforts, does not provide for a truly accurate simulation. This thesis describes modifications made to the ADVISOR code to allow for the use of a load sharing APU scheme based on models developed from vehicle testing. Results for typical driving cycles are presented, demonstrating that the performance predicted by the load sharing simulation more closely follows the results obtained from actual vehicle testing. This new APU model also allows for easy adaptation for future APU technologies, such as fuel cells. Finally, an example is given to illustrate how the ADVISOR code can be used for optimizing vehicle design.

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Chapter 1. Introduction

For quite some time, the U. S. government and public awareness groups have noted the increasing dependence on foreign oil. As Americans continue to travel further each year, and with relatively low fuel costs, the public has shifted its choice of transportation towards notably inefficient trucks, vans, and sport utility vehicles. To address this concern, along with attempting to reduce the environmental impact of passenger vehicles and to improve the global competitiveness of American industries, the Partnership for a New Generation of Vehicles (PNGV) was formed in September 1993. PNGV is composed of representatives from Chrysler Corporation, Ford Motor Company, and General Motors, along with several government agencies, including the national labs.

One of the three main goals of PNGV is the development of a mid-size five passenger sedan with the same safety, performance and conveniences of a conventional vehicle, but with three times the current fuel economy – a goal of nearly 80 miles per gallon. This challenge is being addressed through the development of lightweight materials, more efficient accessories, and alternative powertrain configurations. The most promising future powertrain is that of a hybrid electric vehicle.

A hybrid electric vehicle (HEV) has two on-board energy sources, typically a liquid or gaseous fuel that powers an internal combustion engine, and a battery pack that powers an electric drive system. Hybrid can further be classified as either a parallel or series HEV. A parallel hybrid, as shown in Figure 1.1, features an internal combustion engine and electric motor which are both used to propel the vehicle. Although a parallel HEV has a mechanically complex system for coupling the drivetrain components, the redundant nature of two propulsion systems provides for a 'limp home' mode if either the engine or motor fail.

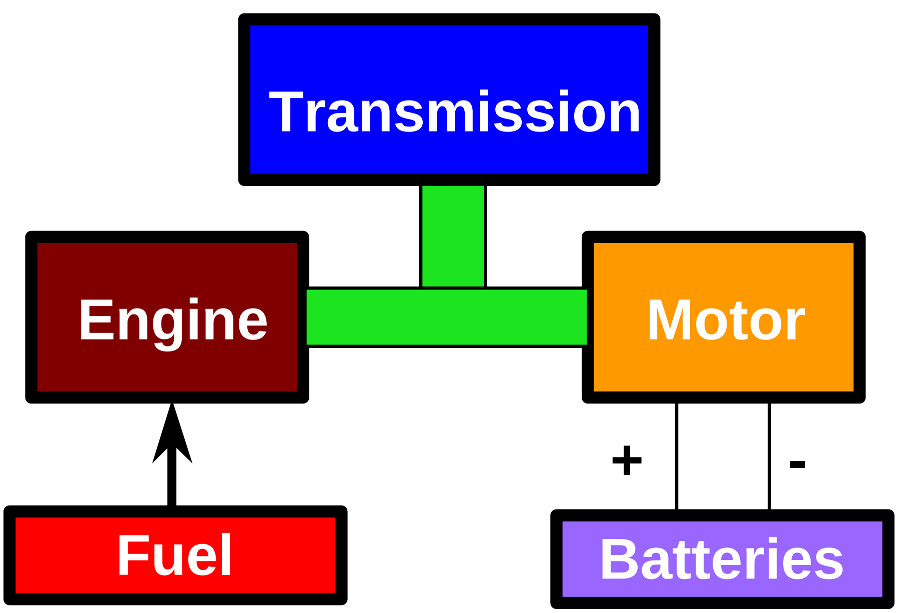

Figure 1.1 Parallel HEV configuration

A series hybrid schematic is shown in Figure 1.2. This type of HEV features an engine and alternator that are used strictly to generate electrical power as an auxiliary power unit (APU), while an electric drivetrain propels the vehicle. Future HEVs will likely feature a hydrogen fuel cell as the APU system.

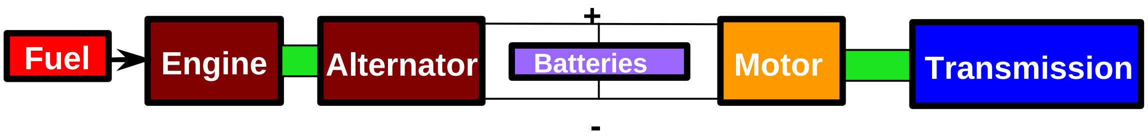

Figure 1.2 Series HEV configuration

Technology for hybrids is developing at a fairly rapid pace, as new battery technologies evolve, higher efficiency drivetrains are developed, and alternative energy sources, such as fuel cells, approach practicality. In order to evaluate these new components, the use of computer simulation tools to analyze driving cycles for a theoretical vehicle composed of these test components can save substantial time and resources. To date, the best simulation program has been the Advanced Vehicle Simulator (ADVISOR), a SIMULINK routine written for MATLAB by researchers at the U. S. Department of Energy's National Renewable Energy Lab. ADVISOR is based on individual component models, and analyzes vehicle performance on a second by second time basis for a specified driving cycle, including the standard Federal Test Procedure (FTP). The flexibility of ADVISOR allows the user to investigate the impact of modifying or changing a system component without actually modifying a real vehicle under test. Optimization code allows one to experimentally determine optimum sizing for various components. The code features the ability to run multiple test cycles, and presents state-of-charge (SOC) corrected results for emissions and fuel economy, based on draft SAE HEV test procedures (SAE J1711).

However, in the case of modeling series hybrid electric vehicles, the simple APU model used by the current version of ADVISOR does not allow for modeling of a load sharing APU. This particular type of modeling is of interest for most series hybrids, and in particular the HEV Lumina, a vehicle designed and built by students at Virginia Tech, and used to verify simulation results from ADVISOR. In a series HEV, the output of the APU is connected to the same high voltage bus shared by the battery pack and electric drivetrain. Based on lower and upper battery SOC limits, the APU is cycled on and off to keep the battery pack within the desired SOC window. However, neither the APU nor the battery pack is an ideal voltage source, and the amount of power delivered by each will vary under different loading conditions. The original version of ADVISOR underestimates this fact, and uses a simple model that views the APU as a constant power source when active. To accurately model the load presented to the APU, and subsequently the variation in the bus voltage, a model had to be developed to reflect the true load sharing between the APU and battery pack.

The battery pack model used by ADVISOR is based on a simple Thevenin equivalent, with an open circuit voltage and internal resistance, both functions of state of charge. However, cursory simulations showed that initial model was incorrect in assuming the same internal resistance for both charge and discharge situations. A battery test procedure was developed, and tested with an Aerovironment ABC-150, yielding an improved ADVISOR battery model.

Similarly, a Thevenin model for the APU was developed, modeled by an open circuit voltage proportional to speed, and an internal resistance proportion to speed and load, to account for diode losses and magnetic saturation of the alternator. The result is two independent Thevenin circuits, which are paralleled to model a series HEV. By modeling in this way, one can then determine the flow of power between the batteries and APU, as shown in chapter 2. The result is a series HEV simulation that more accurately reflects the true operation of the Virginia Tech test vehicle, and demonstrates the practical application of this revised ADVISOR code to all series HEVs with SOC thermostatically controlled constant speed APU operation.

This thesis will outline the steps in modifying ADVISOR to reflect this new load sharing capability. Results comparing test data to both versions of the ADVISOR code will show that the load sharing version is a more accurate method of simulation. Details will be presented to show how models were determined for each subsystem. Finally, an example of battery sizing considerations, using this new version of ADVISOR, will demonstrate the usefulness of this simulation tool.

Chapter 2. ADVISOR

ADVISOR is a MATLAB/SIMULINK program, featuring basic series and parallel HEV models, and a selection of various system component 'building blocks', including several different battery types, internal combustion engines, and electric drivetrain systems. A graphic interface, as shown in Figure 2.1, allows the user to pick which component models are used to create the theoretical HEV, which driving cycle tests will be performed, and what variables will be presented as outputs.

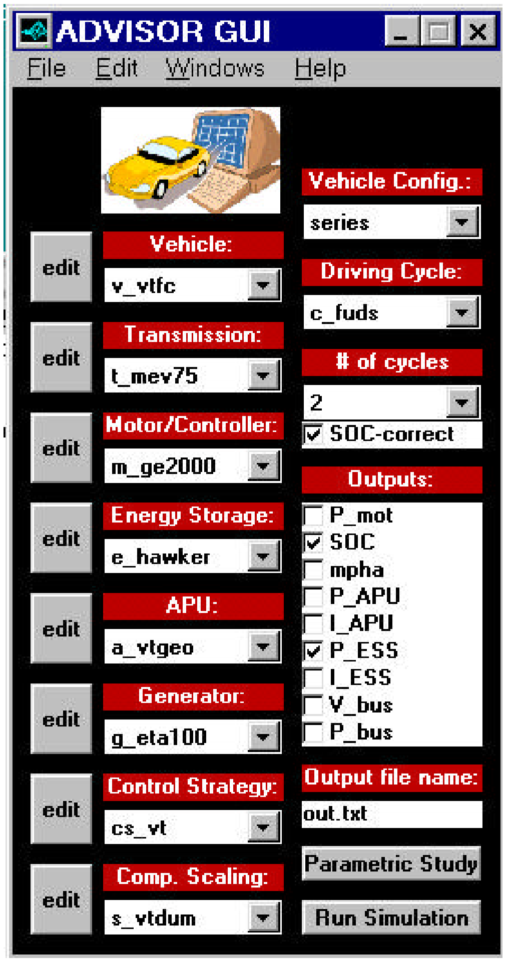

Figure 2.1 Graphic user interface for ADVISOR

By nature of being a SIMULINK routine, the user has the option of changing visual block diagrams to reflect changes in the simulation structure of ADVISOR. Each component, such as the APU or battery pack, has its own block to represent efficiencies and other key model parameters. An upper level schematic of the basic series HEV routine is shown in Figure 2.2.

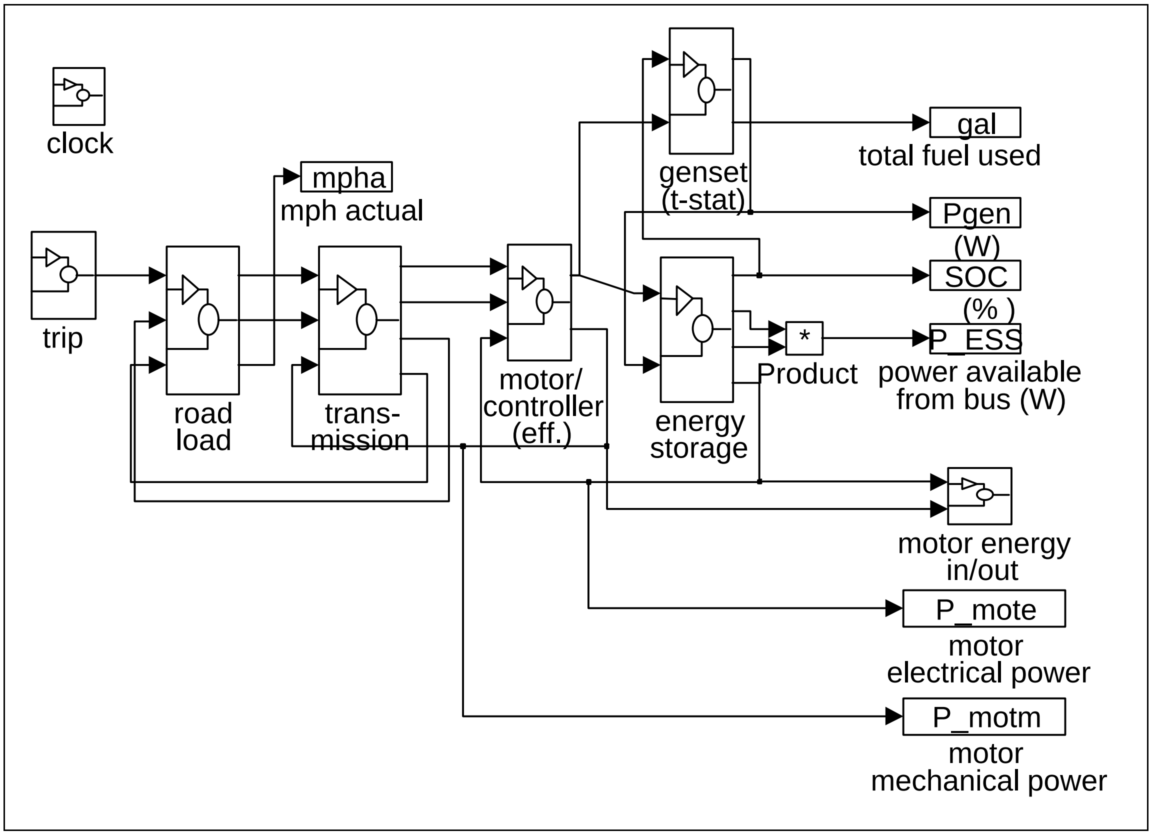

Figure 2.2 SIMULINK representation of a series HEV in ADVISOR

A trip profile, consisting of time and speed data points from a requested driving cycle, provides the basis for the test sequence. This data is used by the road load routine, where vehicle parameters such as mass, coefficient of rolling resistance, frontal area and drag coefficient are used to calculate the power requirement at the wheels. The efficiency of the differential and transmission, as well as the motor and controller efficiencies, then augment this power requirement. The genset block represents the APU, and based on battery SOC, provides electrical power to the energy storage block. The energy storage program uses the power requested by the electric drivetrain and the power produced by the APU to determine the net flow of energy from the battery pack. Feedback in the simulation loop allows for the possibility that the vehicle may not be able to achieve the speed requested by the trip profile. This could be due to limitations of the ability of the drivetrain or the amount of power that is available from the APU and battery pack; the actual vehicle speed is sent to a worksheet, where it may be compared to the desired vehicle speed. Other measurements, such as battery power, APU power, emissions produced and fuel consumption, are also provided as output variables, for post-processing operations.

The area of investigation for this method of simulation centers on the energy storage block, shown in Figure 2.3. Within this block, the power supplied by the APU is added to the amount of power available from the battery pack. Power losses from accessory systems are then subtracted, resulting in some amount of power being available to the electric drivetrain. Within the genset block, the output power level of the APU is held fixed, based on a desired speed and torque operating point for the engine.

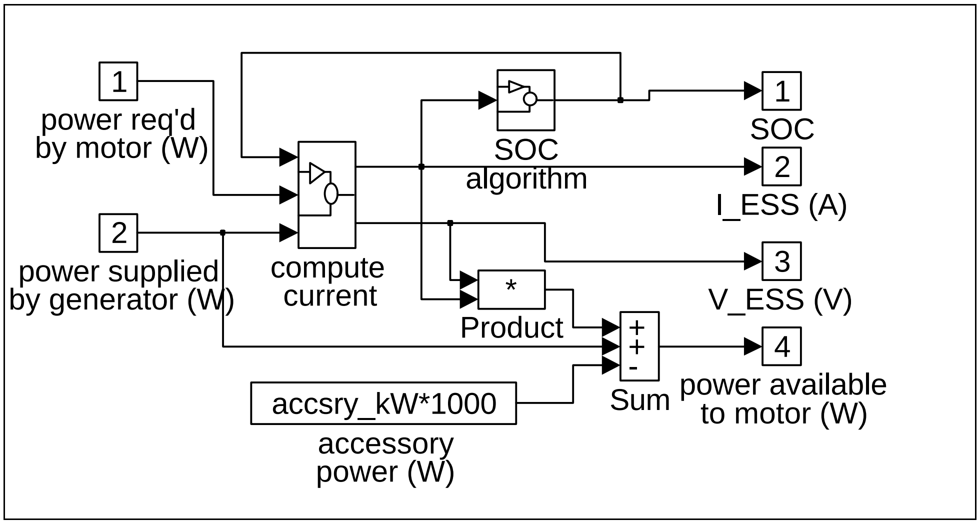

Figure 2.3 Energy storage block

This results in the battery pack being treated as a power source, rather than a voltage source. When the APU is operating, the amount of power draw from the battery pack is simply offset by the constant level of power being produced by the APU. Even though the APU and battery pack are connected in parallel to the same high voltage bus in an actual HEV, no attempt is made in ADVISOR to synchronize the voltages and currents of these two power sources.

While this method of determining the power split between the APU and battery pack is a very simple model, it does not realistically address the load sharing that occurs between the battery pack and APU, particularly for constant speed APU operation, as featured in the Virginia Tech HEV. Reasonable intuition, backed by actual data, suggests that the split of power varies, depending on the total amount of power required by the motor. For instance, under heavy acceleration (i.e. high power requirement by the motor controller), the battery pack and APU will each contribute large amounts of power. Under deceleration, however, the APU will be lightly loaded, perhaps even not producing any power, depending on battery SOC and the amount of regenerative braking that may occur. Even through the use of power electronics, such as a boost or buck converter, to minimize the bus voltage swing under load, it is not possible to fully separate the road load power requirement from the APU. Although the constant power APU model does make for easy simulation and provides reasonable feedback for monitoring hybrid operation, the fact that it is applicable only to a limited range of driving conditions and does not correctly estimate power contributions from the APU and battery pack makes the need for a load sharing APU model obvious.

The solution is to model the APU electrically. This involves determining an open circuit voltage and equivalent series resistance, further discussed in chapter 3. An electrical schematic for the load sharing between the battery pack and APU is shown in Figure 2.4.

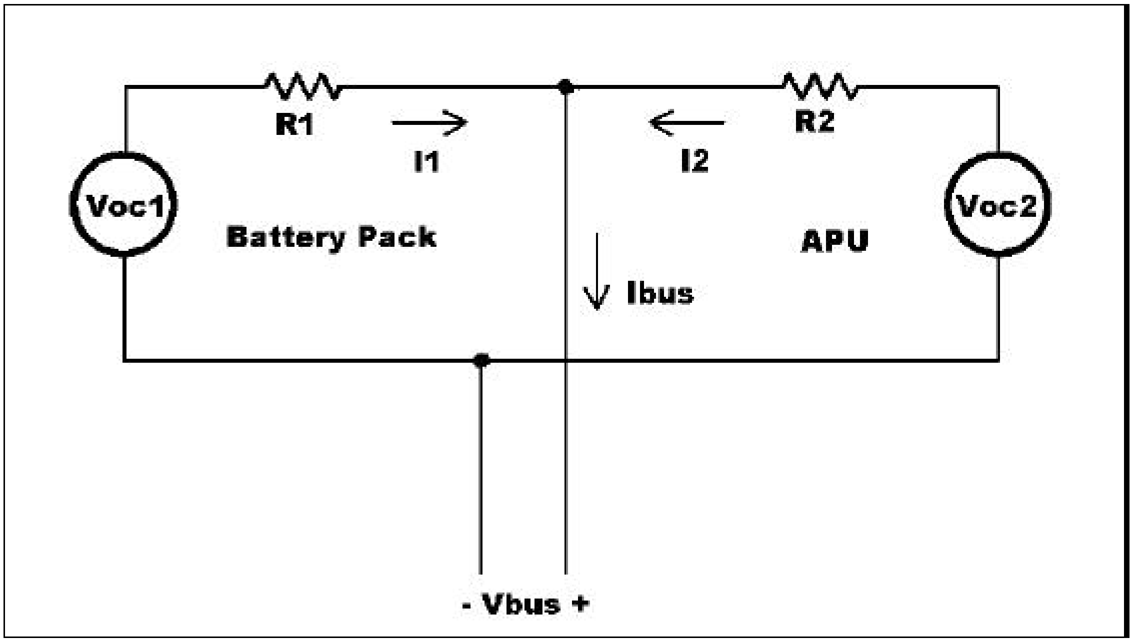

Figure 2.4 Electrical representation of battery pack and APU

The battery pack is modeled as an open circuit voltage V_{oc1} and an internal resistance R_1 (which are dependent on state of charge, age, and temperature, as discussed in chapter 3), while the APU is modeled by V_{oc2} and R_2 (dependent on speed and load). Since ADVISOR calculates a power required at the wheels, and consequently an electrical power drawn from the bus, it is necessary to devise an equation to solve for the power required separately from the batteries and APU. Using simple circuit analysis, one has the equations:

$$V_{oc1}+I_1R_1=V_{bus}=V_{oc2}+I_2R_2$$

$$I_{bus}=I_1+I_2$$

$$P_{bus}=V_{bus}I_{bus}=V_{bus}[(V_{bus}-V_{oc1})/R_1+(V_{bus}-V_{oc2})/R_2]$$

Which can be arranged into a quadratic equation:

$$V_{bus}^2(R_1+R_2)-V_{bus}(V_{oc1}R_2+V_{oc2}R_1)-P_{bus}R_1R_2=0$$

Thus, the bus voltage V_{bus} can be determined by solving the quadratic, given the known values for V_{oc1}, R_1, V_{oc2}, R_2, and the required power level P_{bus}. It is then a trivial matter to solve for the currents from the battery pack and APU. Limits on the current that can be drawn from the APU are also part of this revised ADVISOR code, to prevent backward flow of current, and ensure that the engine is not loaded beyond its power capacity. The result of implementing these calculations is a new energy storage block, shown in Figure 2.5.

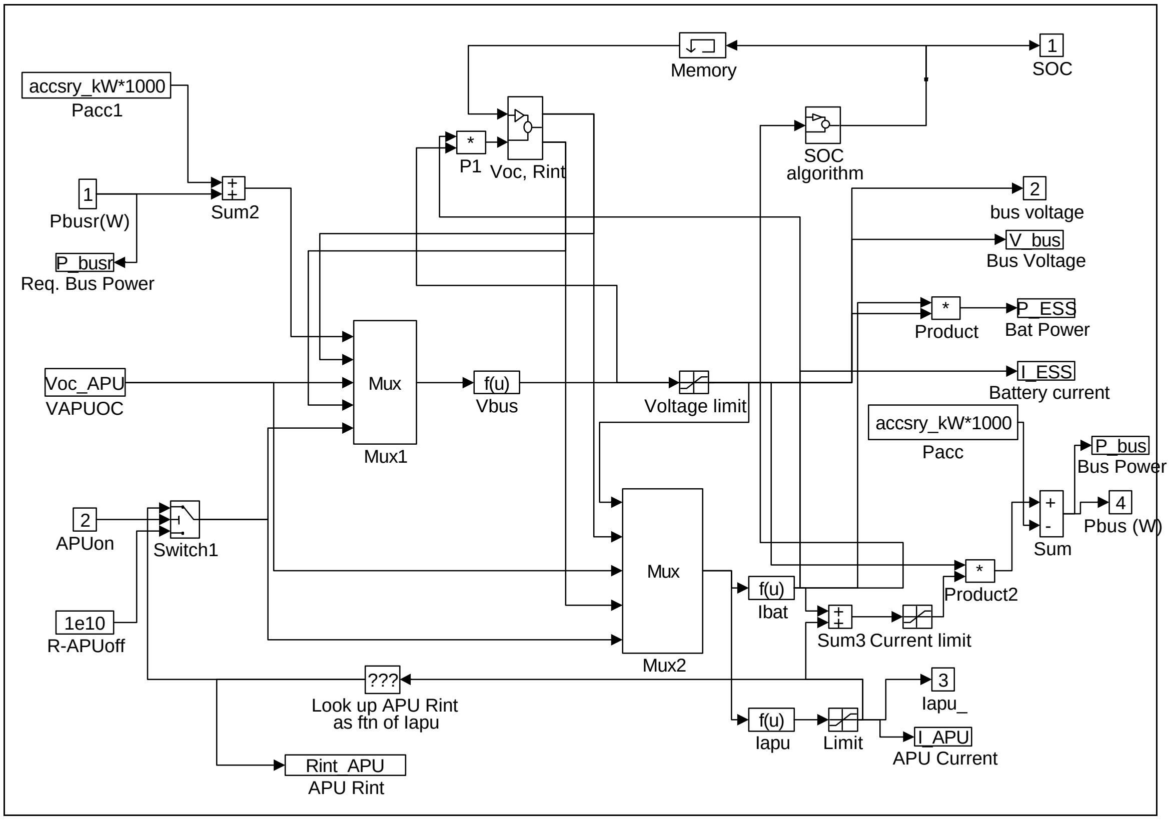

Figure 2.5 Revised energy storage block diagram

This new model now includes voltage and current output variables for the APU model. The original model for the APU based emissions and fuel consumption on the fixed speed and torque operating point. To be used within the new load sharing model, the APU code was revised to base emissions and fuel use on the voltage and current requirements.

The result of these changes is a revised version of ADVISOR that can accurately determine the power split between the battery pack and APU. Specific results are discussed in chapter 4.

Chapter 3. Component Modeling

ADVISOR requires each vehicle component to have an associated model, whether it is an efficiency look-up table for a transmission, or a listing of open circuit voltages and equivalent series resistances for a battery pack. As this revised version of ADVISOR deals with the electrical modeling of the battery pack and APU, results from those tests are presented here. Additional vehicle component models, such as the drivetrain system, and APU fuel and emissions measurements, are available from other sources (Senger, 1997).

Battery Modeling

The initial battery model used in ADVISOR consists of two one-dimensional look-up tables: a table for open circuit voltage based solely on SOC, and a table of internal resistance versus SOC. The model also assumes that the value for internal resistance is the same for both charge and discharge currents. Practical experience suggests that this is a flawed assumption, as batteries exhibit their best performance at a high SOC (i.e. low discharge resistance), while best charge acceptance occurs at a low SOC (i.e. low charge resistance).

To develop a better model for the high voltage battery pack, the resources of Virginia Power's Electric Transportation Division were employed, through the use of an Aerovironment ABC-150 programmable battery load system. The microprocessor-controlled ABC-150 accepts an ASCII text file with requested data points of time and either power, voltage or current, and adjusts its power electronics to present the requested load (or source) to the battery pack under test. Data is logged for the entire test, recording actual test time, voltage, current, and accumulated amp-hours and kilowatt-hours. The ABC-150 provides measurement of voltage accurate to 250 mV and current values accurate to 250 mA for the test ranges used.

Although battery data from Hawker Energy Products demonstrated that battery open circuit voltage could easily be modeled as a function of SOC (Figure 3.1), it was not

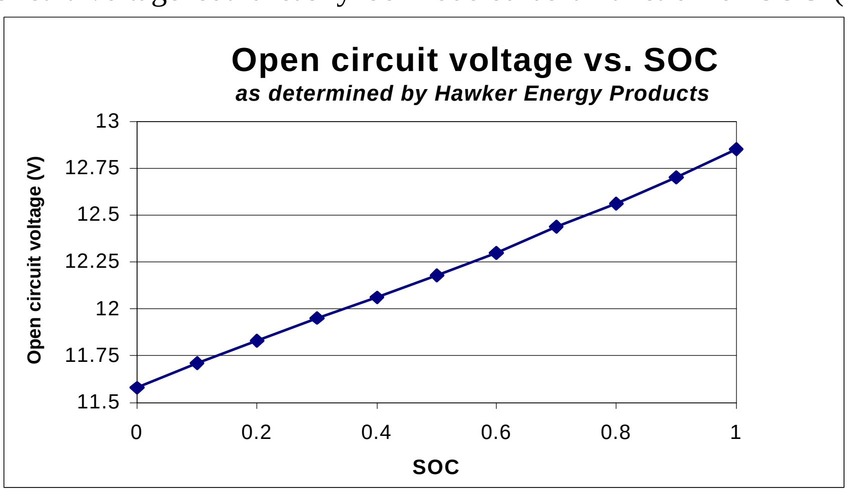

Figure 3.1 Open circuit versus SOC

known if the one-dimensional resistance table described an accurate model. To allow for the case of a nonlinear resistance model (i.e. resistance as a function of both SOC and charge/discharge current), the following test pattern was developed:

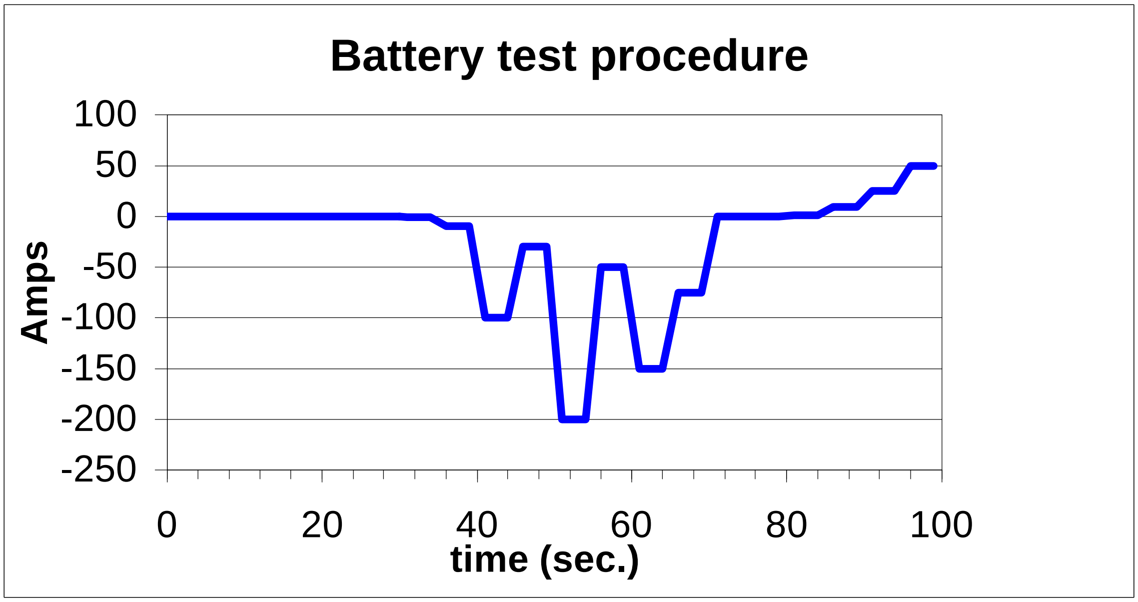

Figure 3.2 Battery test procedure

A three-second settling time was allocated at each current level. The step change in current was to allow for the model to incorporate current as well as SOC for estimating internal resistance. Discharge currents of up to 200 amps and charge currents of up to 50 amps were used to represent values that would be encountered during actual driving cycle tests. The cycle was repeated until the battery pack had reached zero SOC, as determined by recording the total amp-hours of capacity removed from the pack versus the nominal amp-hour capacity of the battery pack at the one hour discharge rate. The procedure was designed to produce a change in SOC of roughly 2% for each cycle, to allow for accurate measurements to be taken without the need to correct for a changing SOC during a cycle. A 30-second rest period at the start of each cycle allows for any surface charge voltage present from the previous cycle to abate before the cycle resumes.

After the data were collected, the resultant voltage-current tests points were plotted over a 5% range of SOC (i.e. 88-92% SOC), and linear equations were fitted to charge and discharge pairs, as shown in Figure 3.3.

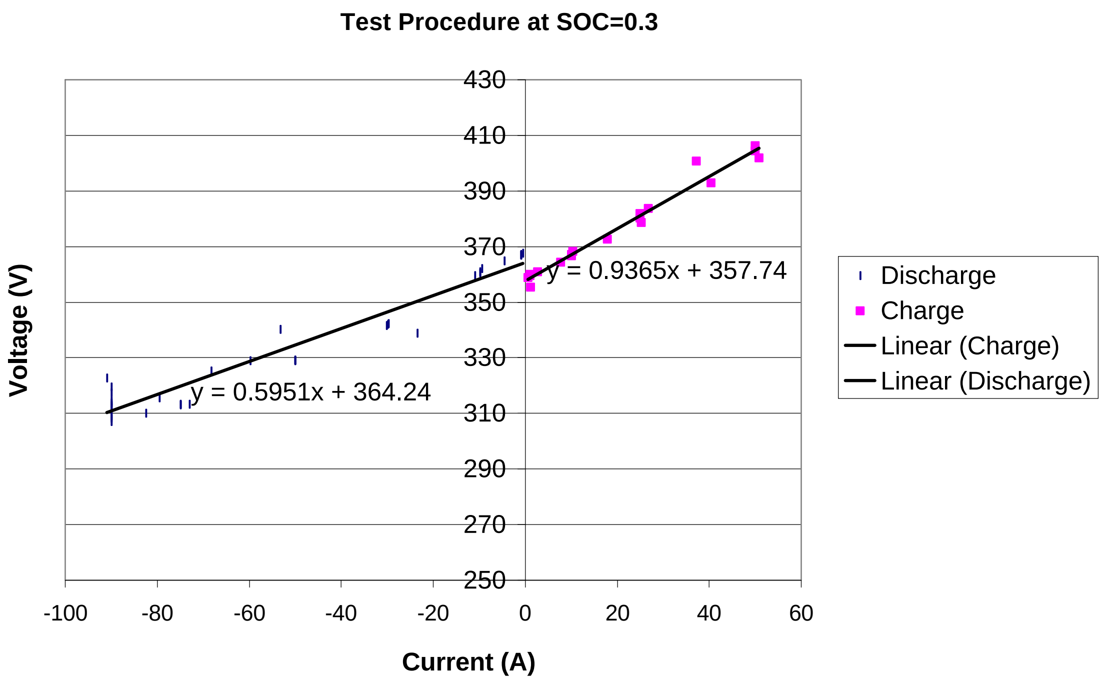

Figure 3.3 Test results at 30% SOC for a 16 Ah battery pack (30 modules)

The slopes of the fitted lines provide estimations of the equivalent internal resistances, while the average of the intersection of the charge and discharge lines at zero current represents the open circuit voltage for each particular SOC. This method of fitting the collected data points was repeated for 10% SOC change. The culmination of this effort is a graph (Figure 3.4) of internal resistance and open circuit voltage as a function of SOC.

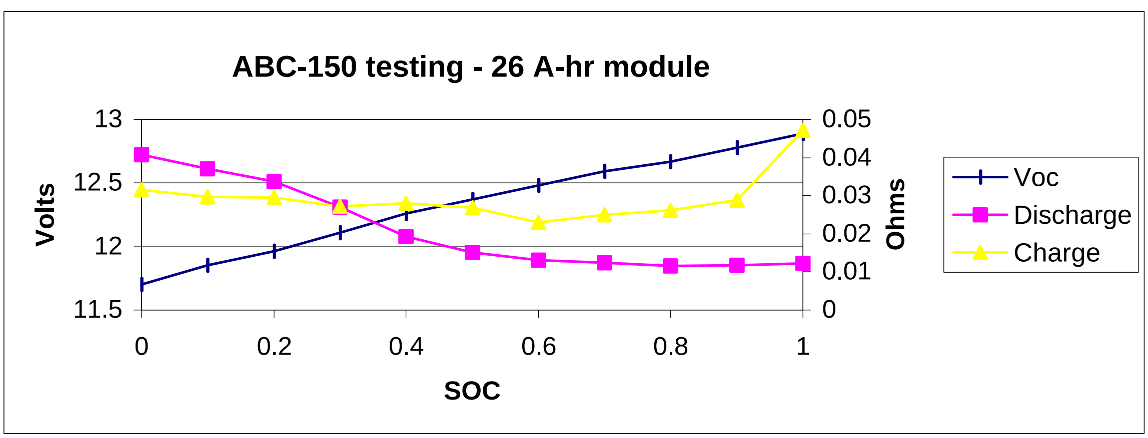

Figure 3.4 Open circuit voltage and internal resistance model of 26 Ah battery module

This battery test procedure was performed for both the Hawker G12V26AhEP (26 amp-hour) and G12V16AhEP (16 amp-hour) battery modules. Results at each SOC increment showed trends similar to Figure 3.3. From these trend lines, two important conclusions can be drawn. First, as demonstrated by the excellent linearity between the current and voltage data points for a given state of charge, the one-dimensional model of resistance as only a function of SOC is validated. Second, the obvious difference in slopes (i.e. resistance) demonstrates a flaw in the original ADVISOR code: the assumption that internal resistance is not influenced by whether the battery is being charged or discharged. As expected, the equivalent resistance during battery discharge starts off relatively low at a high SOC, and increases as SOC drops, while the resistance during charging shows the opposite effect.

The data also provide some insight into selecting the window of operation for the APU in a series HEV. The notable increase in resistance during charging, along with the increasing discharge resistance suggests a lower operating point for the APU of no less than 20%, while the marked increase in resistance during charging suggests an upper SOC point of 80%. This closely matches the operating point chosen for the Virginia Tech HEV of 30% and 70%, derived from on the road testing and evaluation of battery and APU performance.

Testing also revealed the importance of battery temperature on performance. Figure 3.5 shows the equivalent resistance and open circuit voltage model for a 16 A-hr battery at 50° C, while Figure 3.6 shows the resistance and open circuit voltage of the same module

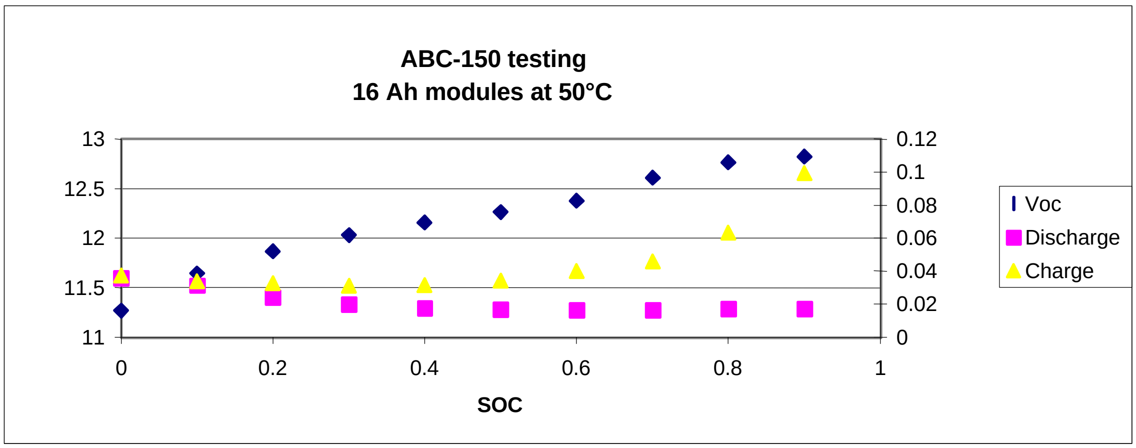

Figure 3.5 Test results for 16 Ah battery module at 50°C

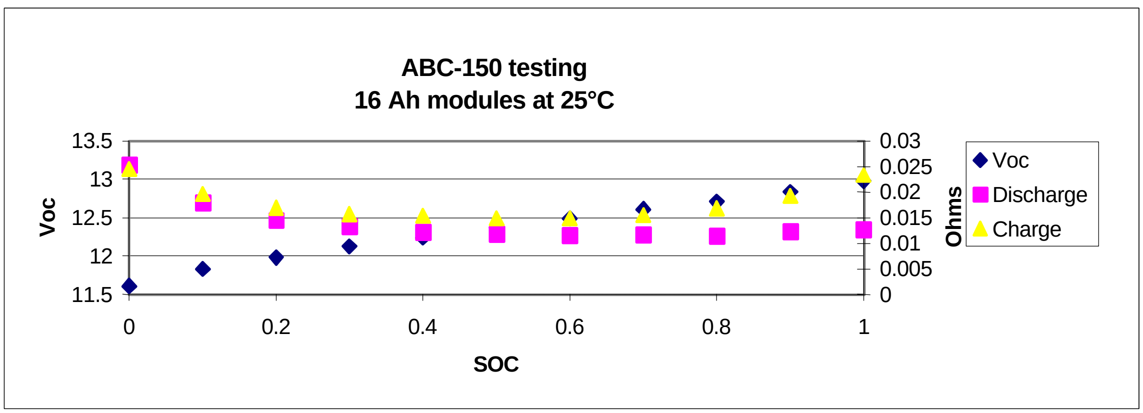

Figure 3.6 Test results for 16 Ah battery module at 25°C

at 25° C. The much hotter battery pack demonstrates a reduced discharge performance as a result of the higher internal resistance under current draw, while the lower charge resistance is indicative of the lower voltage required to recharge a cell using proper temperature compensation.

Age is also an important factor. Figure 3.7 shows the modeling data for a battery pack tested in June, 1996, from on the road driving, while Figure 3.8 shows the same battery pack tested on the ABC-150 in April, 1997, after the pack had been subject to an estimated 250 charge/discharge cycles. Both tests were conducted with the pack at 25° C. As expected, battery pack performance degrades with age.

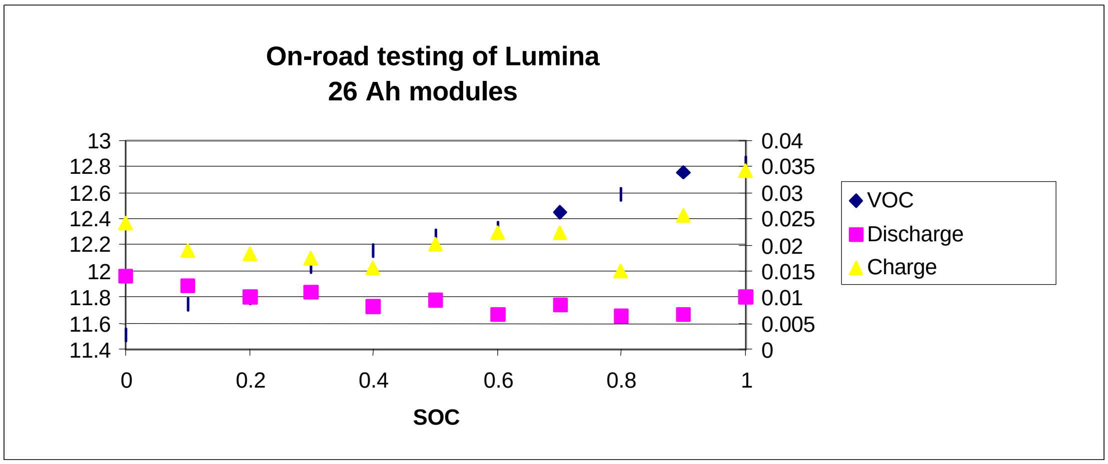

Figure 3.7 Battery pack consisting of new 26 Ah modules

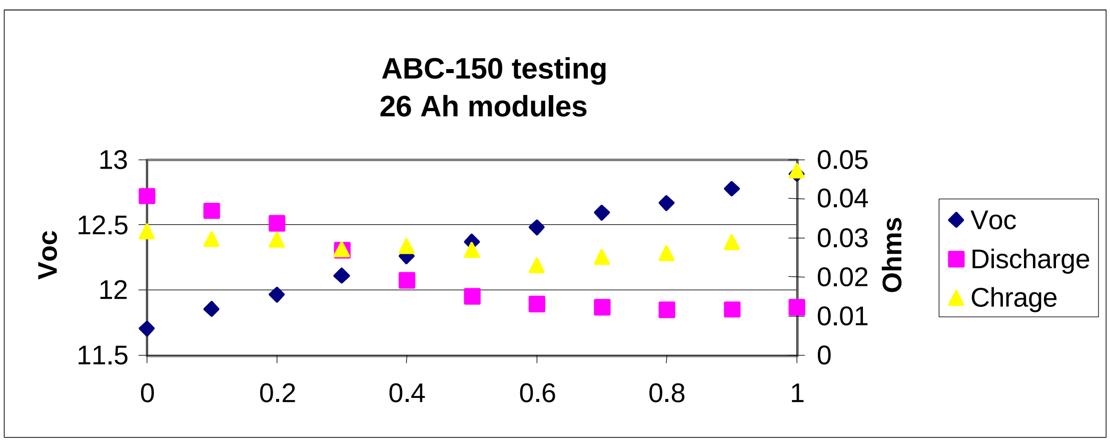

Figure 3.8 Battery pack model after approximately 250 cycles

APU Modeling

The APU for the Virginia Tech HEV consists of a Geo Metro 1.0 liter, three cylinder engine, directly coupled at the flywheel to a Fisher Electric Technologies 24 pole, permanent magnet, three phase alternator. This output is sent to a Crydom Co. high thermal efficiency 3-phase rectifier block (model EFE15F), and the resultant DC is connected to the vehicle high voltage bus. During normal operation of the APU, a closed-loop throttle controller attempts to maintain a steady speed of approximately 3800 RPM. At this speed, the output of the APU is 415 VDC at no load, and falls to 330 VDC at 82 A full load.

To model the electrical characteristics of the APU, a load bank consisting of 12 hot water heater elements (nominally 240 V, 2400 W each) was constructed, as shown in Figure 3.9. By keeping the elements immersed in a hot water bath, a near-constant resistance could be maintained throughout testing. Jumpers allowed the elements to be connected in various parallel-series arrangements for reflecting different loads back to the APU. Voltage was measured directly with a Metek digital multimeter, while current was measured with a 200A/50mV calibrated shunt. The engine throttle was varied for fixed resistance loads, and the resultant output voltage and current were recorded, along with the fuel consumption rate and emissions levels.

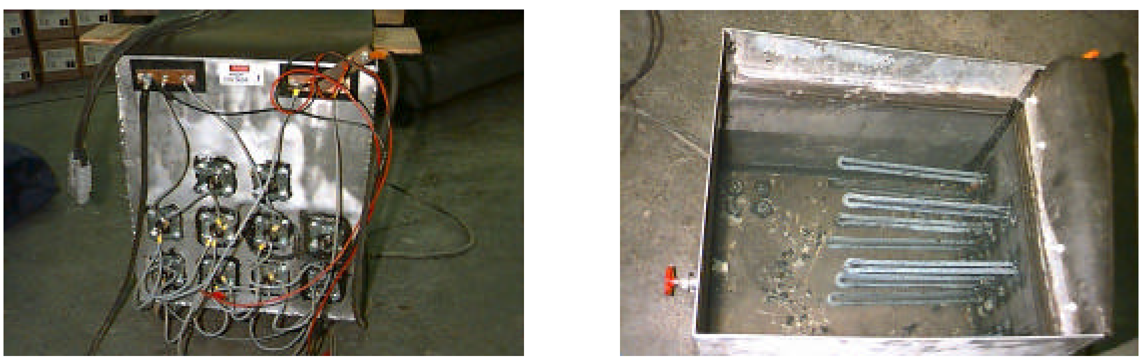

Figure 3.9 Two views of the APU load bank, comprised of multiple water heater elements.

The stability of the load bank is demonstrated in Figure 3.10. The excellent linearity of the measured data points shows that a constant load resistance was maintained during testing.

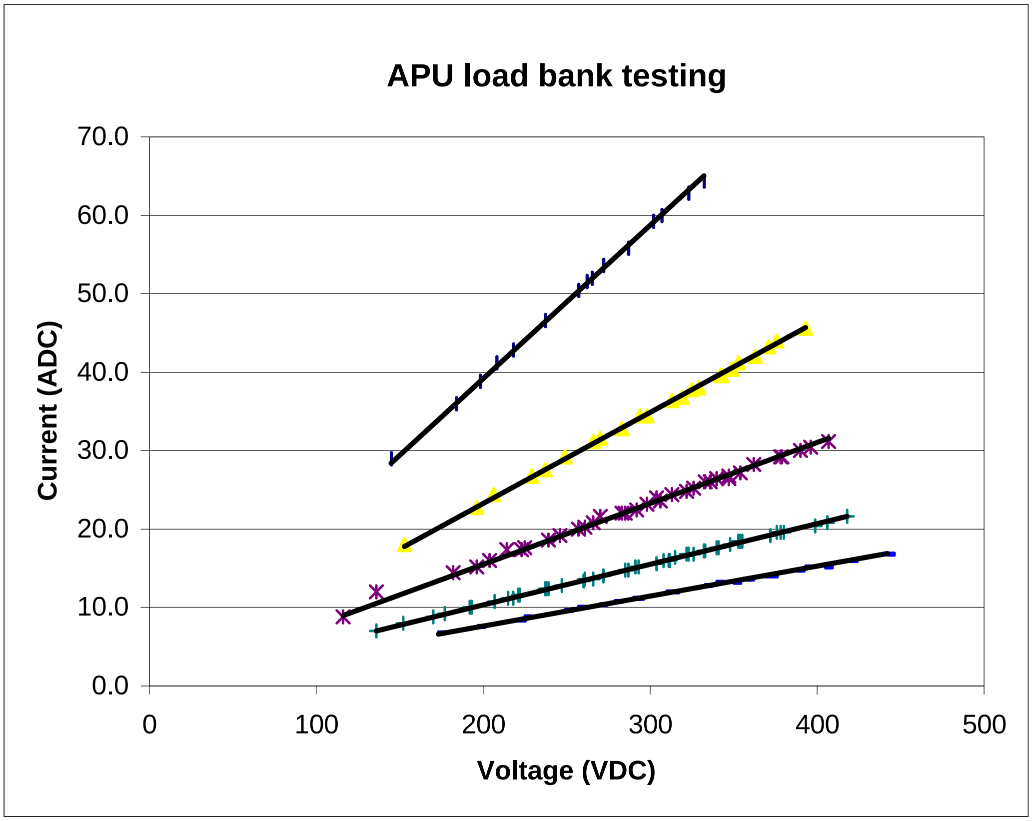

Figure 3.10 Voltage and current measurement of load bank.

In addition to recording data at various loaded conditions, the open circuit characteristics of the APU had to be determined. This was accomplished by recording engine speed and open circuit voltage at several points, as shown in Figure 3.11. By fitting a first order equation to the data, with an intercept at 0, it was determined that the open circuit voltage of the APU was equivalent to 0.1138 volts/rpm.

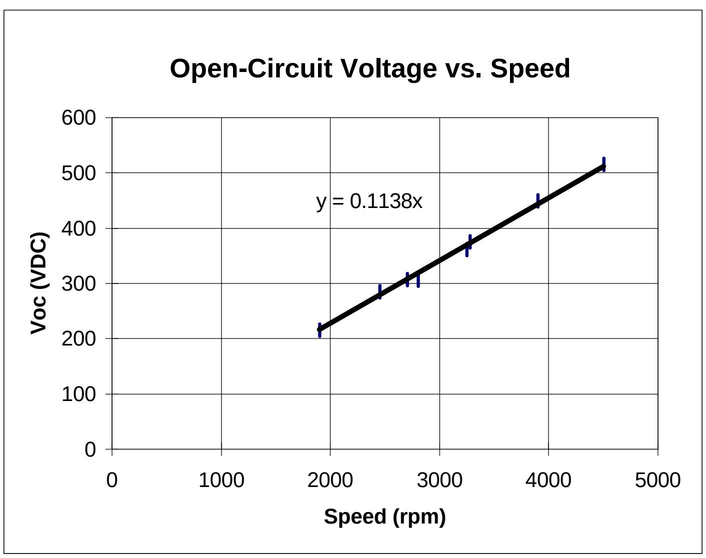

Figure 3.11 Open circuit APU characteristics

All that remains for completing the electrical model of the APU is the equivalent series resistance. This can be determined by looking at sets of data over a small range of speed (approximately 500 rpm). Knowing the open circuit voltage predicted for the given speed, and noting the output voltage under loaded conditions, one can use this ratio of voltage drop to output current to determine the equivalent series resistance. In this manner, the series resistance will include the effects of switching and conduction losses in the diode bridge rectifier, as well as the magnetic saturation of alternator at high speeds and loads.

The result of analyzing the data is an equivalent series resistance that is a function of current and speed, as shown in Figure 3.12. The equivalent series resistance was determined over two speed ranges: 3200-3500 rpm, and 4000-4500 rpm. Ideally, more data points over a slightly smaller rpm range would yield a somewhat better model. As the ideal operation of the APU occurs over a small range of speeds, one need simply choose the correct resistance model for the average speed desired.

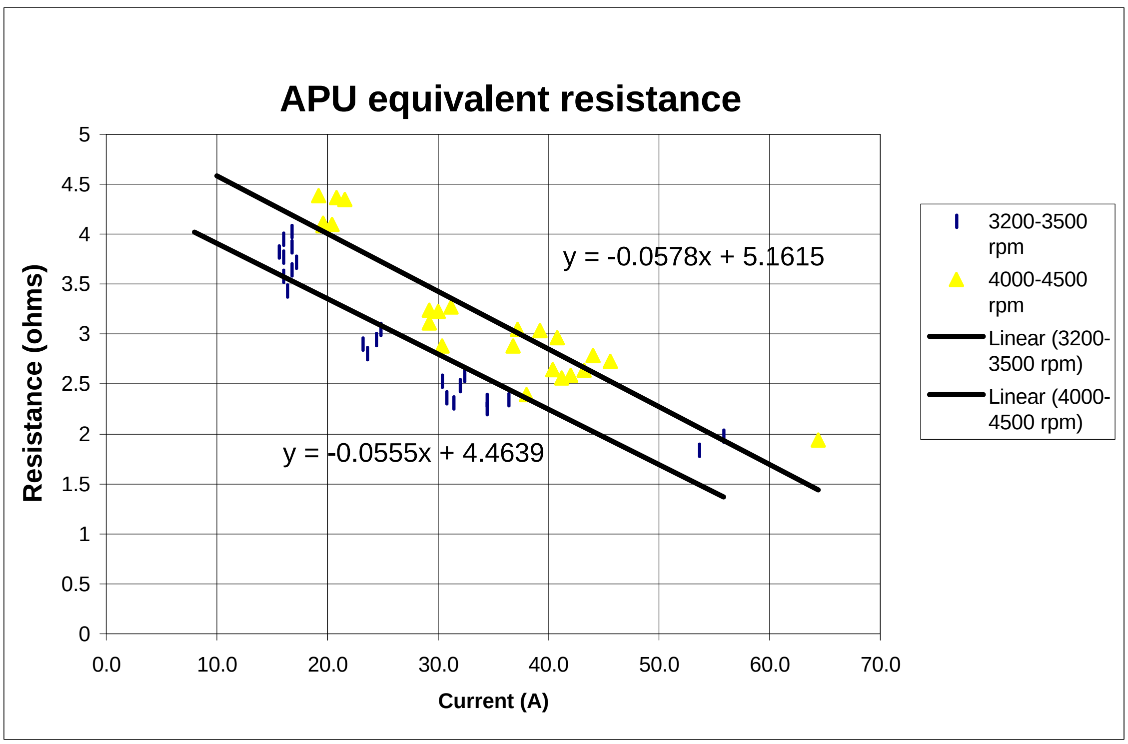

Figure 3.12 Calculated APU series resistance

Chapter 4. Results

Several tests were run to validate the simulation accuracy of ADVISOR, as well as evaluate the changes made to reflect the load sharing model, including an urban driving cycle pair (FUDS) at both high and low SOC, and a highway driving cycle (FHDS) at a high SOC. The following vehicle data required by ADVISOR was previously determined (Senger, 1997) to match the characteristics of the HEV Lumina:

Table 4.1 Vehicle parameters

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	0.3	
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

Using these parameters, a zero emissions mode (ZEV) run for a high SOC FUDS test was simulated. Results of the simulation correlated extremely well with the actual recorded data, as shown in Figure 4.1. This validates the models used for the vehicle, drivetrain, and battery pack.

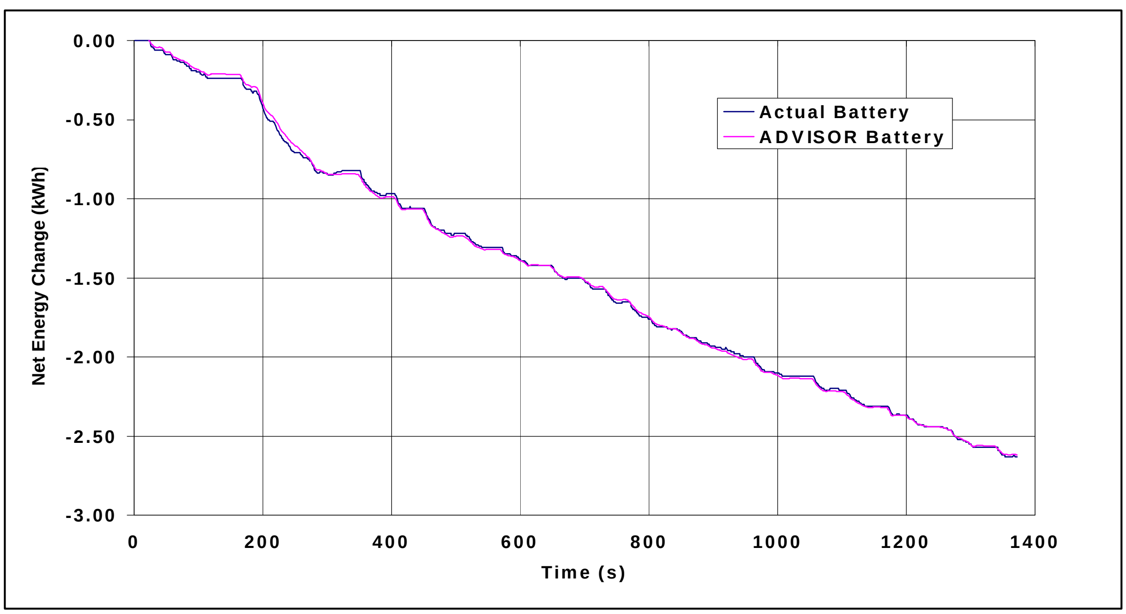

Figure 4.1 Comparison of ADVISOR to actual high SOC FUDS test

Using the battery and APU electrical models for the HEV Lumina, several iterations of the load sharing simulation were run for each driving cycle. The operating point of the APU (open circuit voltage and SOC trigger points) was adjusted to most accurately correspond to data obtained from dynamometer testing performed June 1996, at the U.S. Environmental Protection Agency test center in Ann Arbor, Michigan. The best data fit was obtained under the following APU operating conditions:

Table 4.2 Operating points for ADVISOR simulation

Test	SOC high limit	SOC low limit	Open circuit voltage
FUDS low SOC	0.70	0.40	395 VDC
FUDS high SOC	0.70	0.27	410 VDC
FHDS high SOC	0.70	0.64	425 VDC

The notably high value for the SOC low limit on the FHDS test was necessary to reflect that during the actual dynamometer test, at the request of representatives of Argonne National Labs who were responsible for data collection, the APU was manually forced to turn on early in the test. Normal driving operation would still occur around 30% SOC.

For the constant APU power model of ADVISOR, the APU output power level was adjusted to match the actual state of charge obtained at the end of each cycle. This resulted in the following constant power APU values:

Table 4.3 APU power levels for constant power simulation

Test	Power level (kW)
FUDS low SOC	8.92
FUDS high SOC	13.77
FHDS high SOC	10.75

The battery SOC from the dynamometer test data was evaluated by linearly interpolating between the initial SOC and comparing the number of amp-hours drawn from the battery pack to an average pack capacity of 19.6 Ah. The SOC values given by the ADVISOR routines are also directly based on amp-hours removed, but include a round trip efficiency of 90% (i.e. only 90% of the current being returned to the battery pack is used to increase the SOC), whereas the dynamometer data assumes 100% amp-hour efficiency. This difference was determined to be negligible, as repeating the simulations using 100% amp-hour efficiency changed final SOC results by less than 1%. Figures 4.2, 4.3 and 4.4 show the relationship of measured and simulated SOC for three test conditions. With the exception of the low SOC FUDS test, in which a defective engine speed controller produced erratic results, the agreement between simulation and test data is generally quite good.

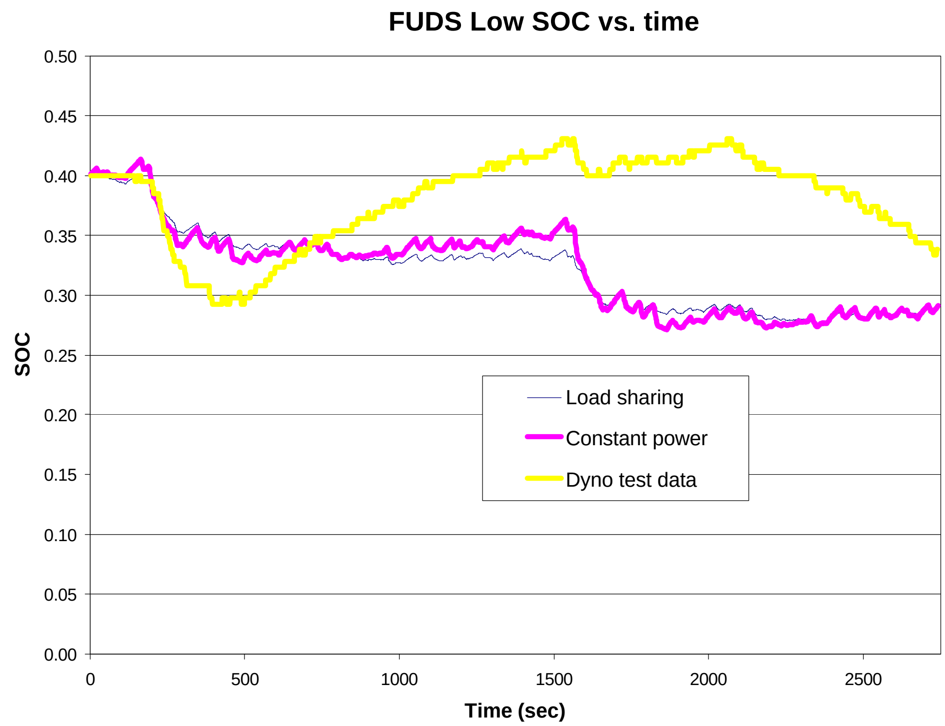

Figure 4.2 FUDS low SOC testing

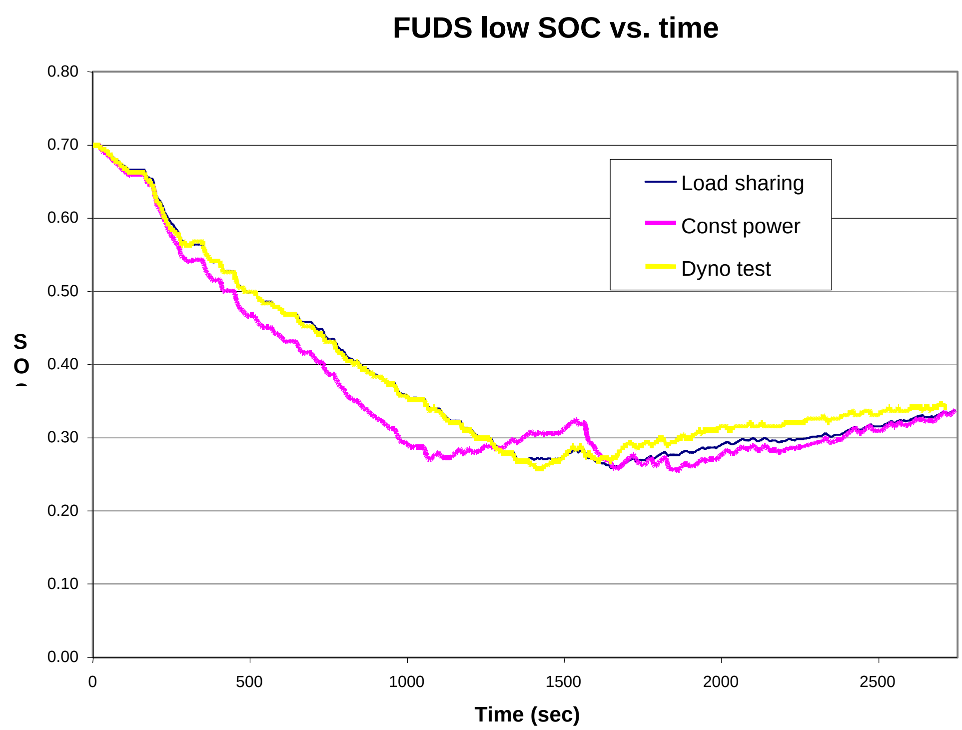

Figure 4.3 FUDS high SOC testing

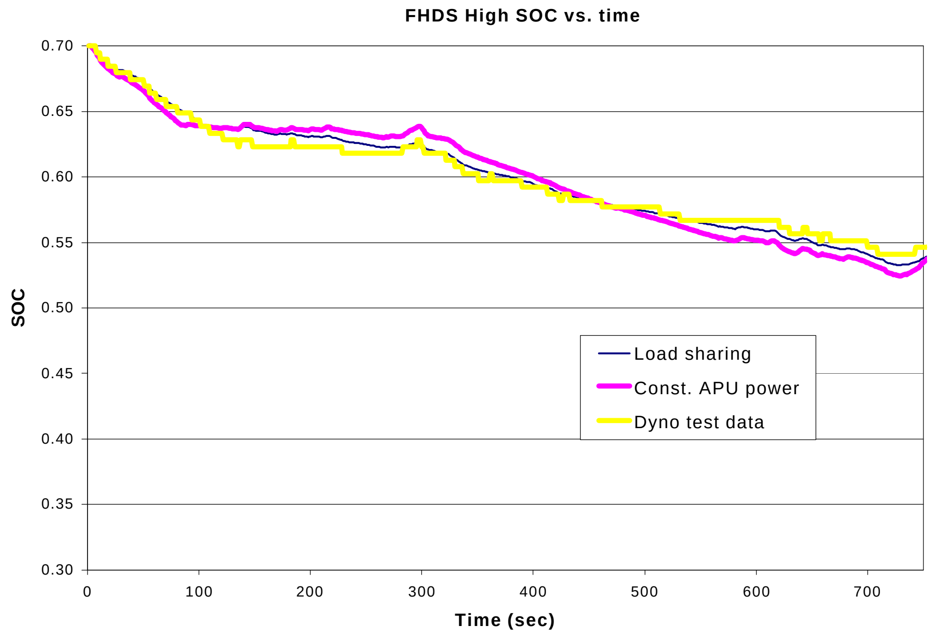

Figure 4.4 FHDS high SOC testing

From the above graphs, one can note that the load sharing model tends to follow the actual test SOC better than the SOC predicted by the constant APU power model. The superiority of the load sharing model becomes even more apparent when one looks at the energy contribution of the battery pack and APU over the test driving cycles, as shown below. Again, erratic APU speed control has resulted in less than ideal test data for the low SOC FUDS test.

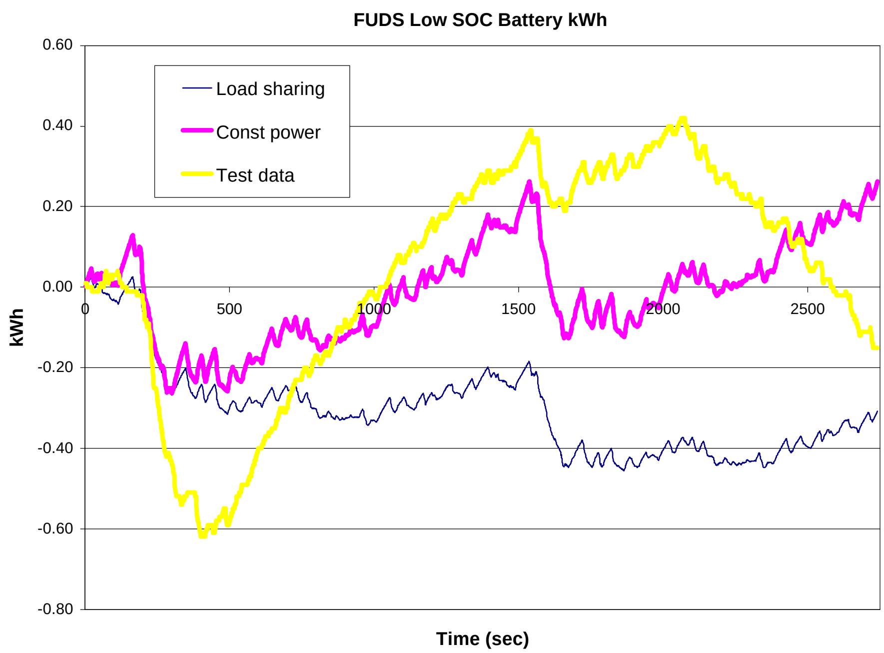

Figure 4.5 FUDS low SOC battery testing

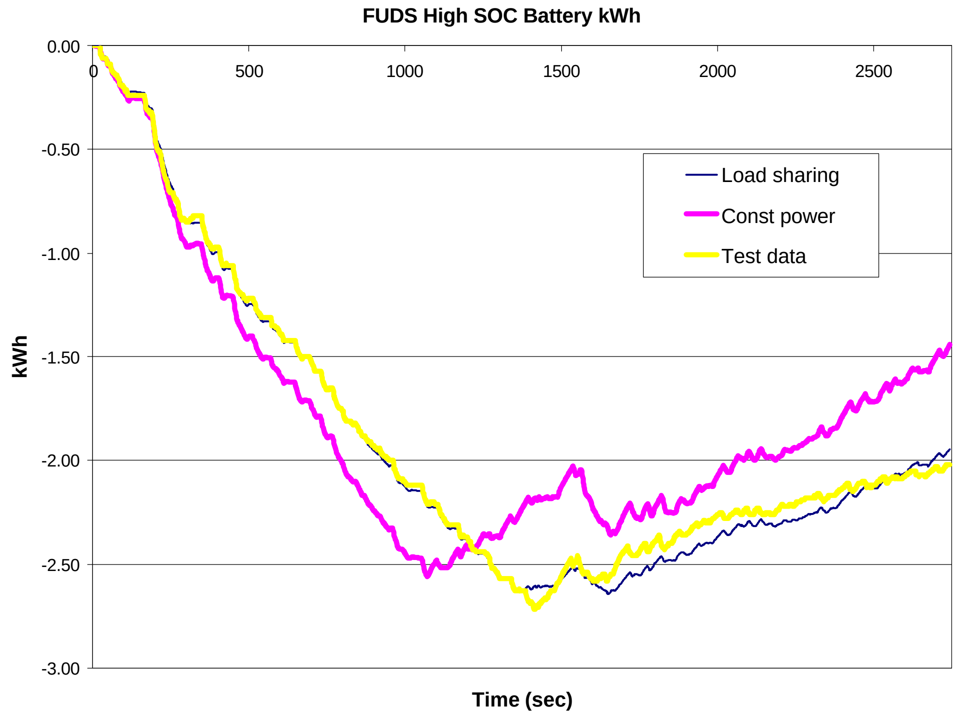

Figure 4.6 FUDS high SOC battery testing

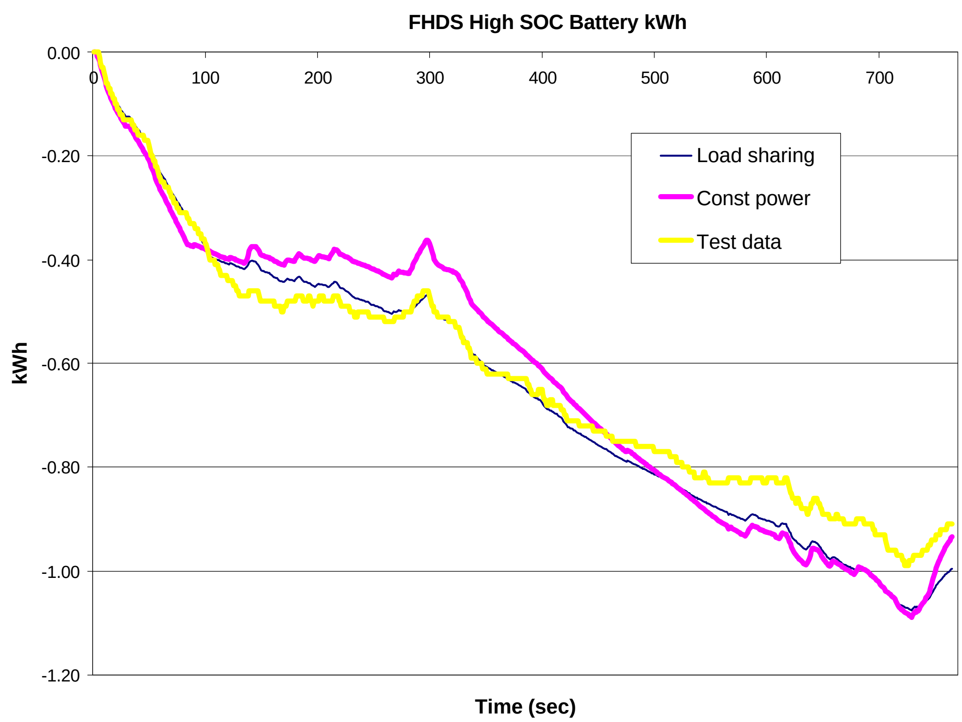

Figure 4.7 FHDS high SOC battery testing

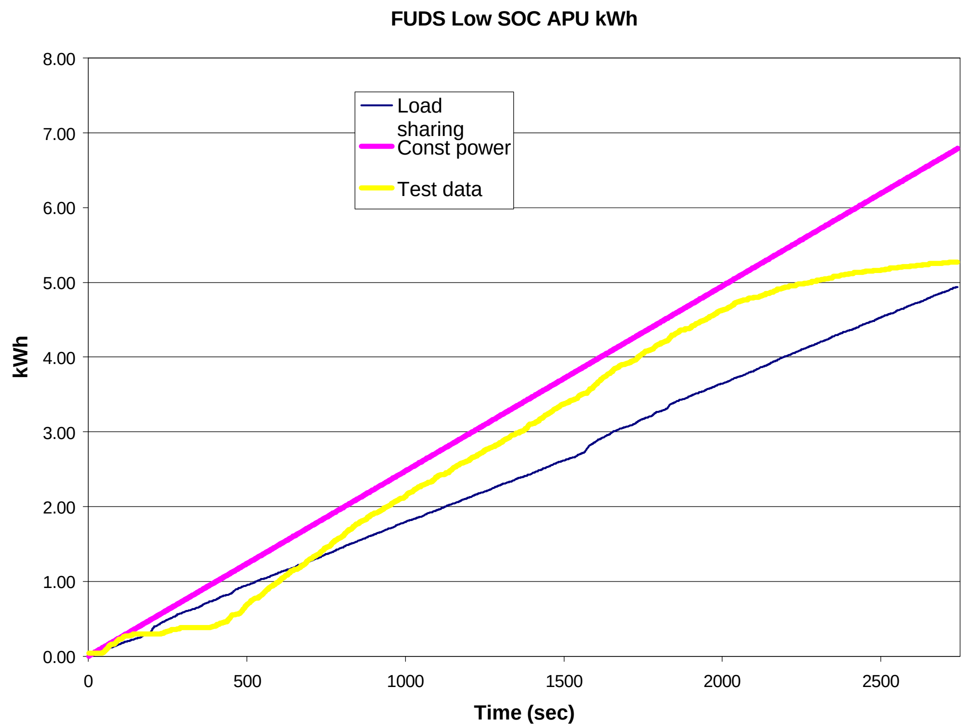

Figure 4.8 FUDS low SOC APU testing

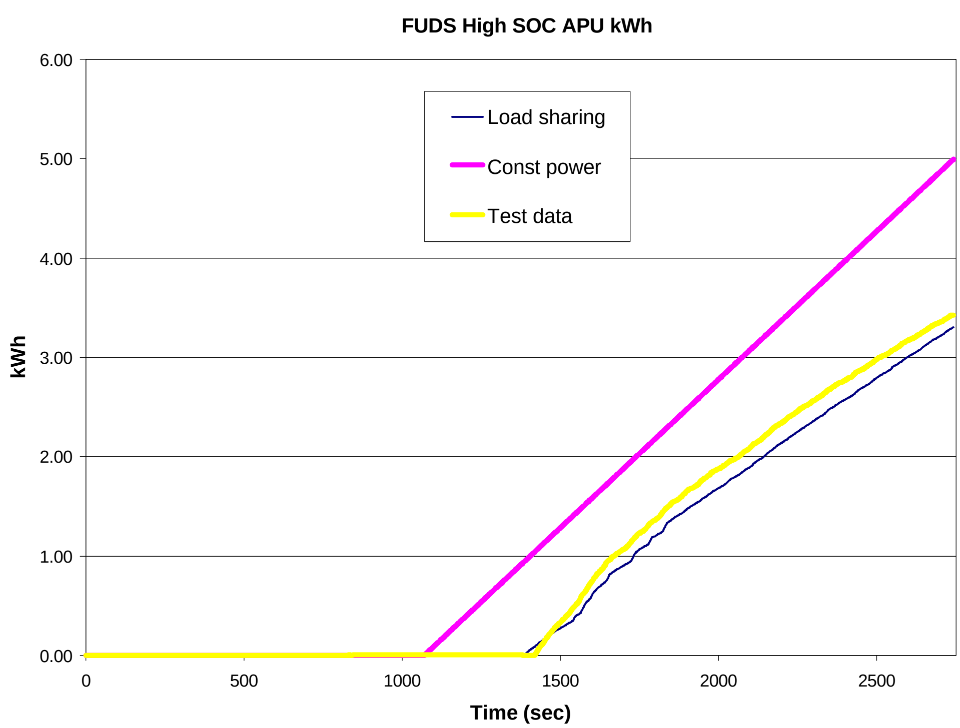

Figure 4.9 FUDS high SOC APU testing

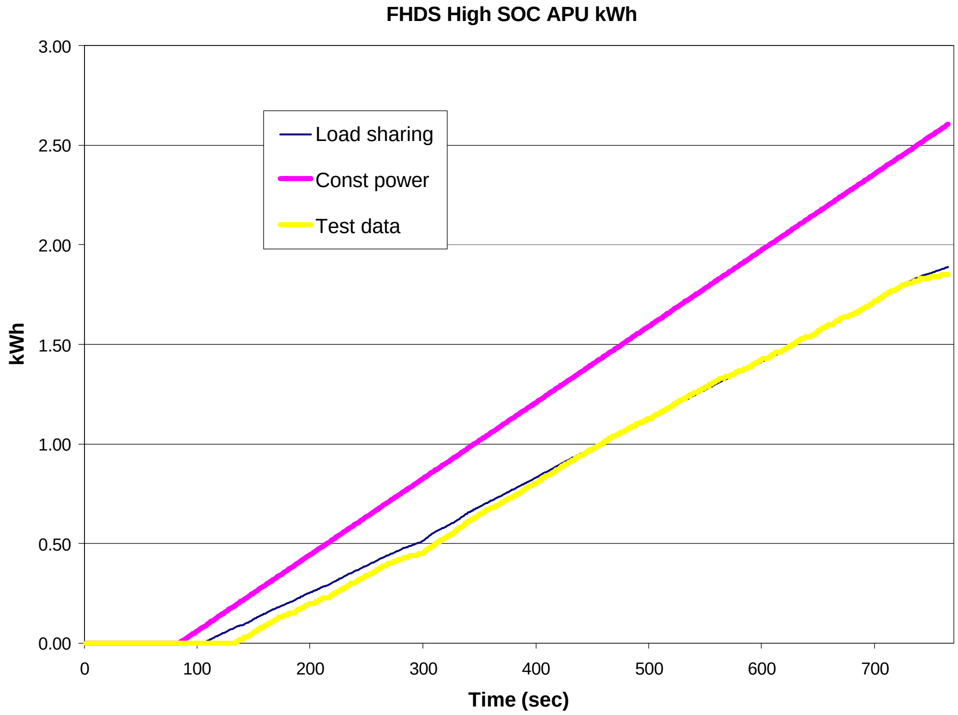

Figure 4.10 FHDS high SOC APU testing

These results can best be summarized in table form:

Table 4.4 Summary of simulation comparison

Test	Data source	APU		Battery		Change in SOC
		kWh	Ah	kWh	Ah	
FUDS low SOC	ADVISOR - original code	6.79	n/a	0.26	-1.25	0.11
	ADVISOR – load sharing	4.94	15.35	-0.31	-1.69	0.11
	Dynamometer	5.27	15.8	-0.15	-1.2	0.08
FUDS high SOC	ADVISOR - original code	5	n/a	-1.44	-6.47	0.36
	ADVISOR – load sharing	3.3	10.14	-1.95	-6.85	0.36
	Dynamometer	3.42	10	-2.02	-6.7	0.35
FHDS high SOC	ADVISOR - original code	2.6	n/a	-0.93	-3.01	0.16
	ADVISOR – load sharing	1.89	5.68	-1	-3.1	0.16
	Dynamometer	1.85	5.7	-0.91	-3.08	0.15

In general, the load sharing model more closely follows the actual dynamometer data than the original constant APU power ADVISOR model. The original model tends to overestimate the APU energy contribution and underestimate the battery energy; this is particularly obvious in the low SOC FUD test, where the APU energy prediction is off by more than 29%, and the battery pack shows a net gain of energy despite a net loss of amp-hours. The slight differences between the actual test data and the load sharing simulation are mostly due to selection, by manual trial and error, of several operating conditions, such as APU operating speed and initial SOC, as well as the fact that the APU does not operate at exactly constant speed in actual operation.

A noteworthy benefit of modeling the APU electrically is that this load sharing model is now quite easily adapted to simulate a series hybrid with a fuel cell APU. By performing the same modeling tests on the fuel cell, such as open circuit voltage, and current, voltage, fuel use and emissions (from a reformer, if applicable) under various loads, this revised version of ADVISOR should now accurately predict how a fuel cell hybrid will behave under various driving scenarios.

A practical example

The accuracy and ease of use of the load sharing ADVISOR model invites one to investigate changes that could be made to the vehicle, in the hopes of improving efficiency and fuel economy. For instance, the hybrid Lumina that is the modeled vehicle for this simulation recently was changed to a smaller capacity battery pack. Although a little over 100 kg was saved in weight, the smaller batteries have the drawback of a higher internal resistance. Using the internal resistance of the original 26 Ah batteries as the reference value, a series of simulations were run for the two different battery packs, varying the resistance of the 26 Ah pack +-50%, and simulating with a 16 Ah pack at 100% and 150% of the 26 Ah resistance (the 16 Ah pack at 150% of the 26 Ah resistance is close to the actual performance of a true 16 Ah system).

Results of these simulations are summarized in Table 4.4. As one can see, varying the internal resistance of the battery pack does affect the split of energy between the APU and batteries, but the overall vehicle energy usage did not change noticeably. The decrease in vehicle mass by 6.3% resulted in an overall vehicle efficiency gain of 3.3% for the urban driving cycle, but only a 1.4% improvement for highway driving. This is reasonable, as the city cycle features constant accelerations and braking, which require more energy that the reasonably constant speed highway simulation. APU efficiency, which includes engine, alternator and diode bridge efficiencies, remained fairly constant at approximately 22%. This suggests that while weight can be an important factor in vehicle efficiency, improvements to fuel economy would best be realized by improving the efficiency of the APU, as one might do by using a fuel cell or diesel-based APU. It also demonstrates that while a higher internal resistance of a battery pack can limit performance as a result of a larger bus voltage drop, it does not notably effect vehicle efficiency.

Table 4.5 Simulation for different battery configurations.

Test cycle	Rint scale	Vehicle mass (kg)	APU kW-hr	Battery KW-hr	Total kW-hr	Fuel used gms LPG	APU Effic.	Vehicle Whr/mi
FUD low SOC	1	1938.8	4.946	0.295	5.241	1723.6	0.218	351.7
	1.5	1938.8	5.075	0.166	5.242	1748.7	0.221	351.8
	0.5	1938.8	4.758	0.476	5.234	1679.1	0.216	351.3
	1	1817.3	4.843	0.225	5.068	1699.9	0.217	340.1
	1.5	1817.3	4.941	0.125	5.066	1716.7	0.219	340.0
FUD high SOC	1	1938.8	3.306	1.934	5.239	1074.5	0.234	351.6
	1.5	1938.8	3.501	1.739	5.239	1150.1	0.232	351.6
	0.5	1938.8	3.196	2.035	5.231	1018.4	0.239	351.1
	1	1817.3	3.117	1.949	5.066	1017.7	0.233	340.0
	1.5	1817.3	3.285	1.776	5.061	1083.4	0.231	339.7
FHDS high SOC	1	1938.8	1.891	0.984	2.875	598.9	0.240	280.2
	1.5	1938.8	2.057	0.820	2.877	648.8	0.241	280.5
	0.5	1938.8	1.801	1.064	2.865	564.3	0.243	279.3
	1	1817.3	1.999	0.838	2.838	632.5	0.241	276.6
	1.5	1817.3	1.865	0.970	2.834	590.4	0.240	276.3

Chapter 5. Conclusions and recommendations

ADVISOR has proven itself to be an extremely useful tool in simulating the performance of a hybrid electric vehicle. It is easy to use, flexible in design, and allows one to investigate control strategies and subsystem component effects quickly and with reasonable accuracy. The load sharing model presented in this thesis advances the ADVISOR program, producing more accurate results for a series HEV. The power split between the APU and battery pack can now be determined, which results in more accurate energy tracking for these sources.

Based on the information presented within this thesis, one could use the test methods presented to determine appropriate battery and APU models for other types and configurations of such systems. By modeling the APU electrically, the load sharing code features the ability to easily be adapted for modeling a fuel cell based HEV.

However, there is still room for improvement and refinement in the modeling process. The APU speed control is not an ideal system; ADVISOR has the flexibility that a system time response for the controller could be measured and integrated into the simulation more accurately reflect actual operating conditions. Additional dynamometer testing would prove beneficial, to determine the variance of the measured data, which could be implemented into ADVISOR to provide output with statistical bounds. Finally, it would be beneficial to record data of actual HEV real world driving, to validate that ADVISOR is capable of predicting all types of driving behavior, not just those defined in a FUDS or FHDS test.

While further testing is recommended to refine the models used, it is felt that this new method of load sharing simulation is currently the best way to simulate a series HEV.

References

Hawker Energy Products, Inc., 1997, “Genesis Application Manual,” second edition.

Senger, Randall D., 1997, “Validation of ADVISOR as a Simulation Tool for a Series Hybrid Electric Vehicle Using the Virginia Tech FutureCar Lumina,” Master’s Thesis, Virginia Tech.

Senger, Randall D., Merkle, Matthew A., Nelson, Douglas J., February 1997, “Design of the 1996 Virginia Tech FutureCar,” Society of Automotive Engineers publication SP-1234, The 1996 FutureCar Challenge, pp. 101-112.

Senger, Randall D., Merkle, Matthew A., Nelson, Douglas J., June 1997, “Design and Performance of the Virginia Tech Hybrid Electric FutureCar,” design paper presented for the 1997 FuutreCar Challenge.

Society of Automotive Engineers (SAE), February 26, 1997, “Draft SAE J1711: Recommended Practice for Measuring the Exhaust Emissions and Fuel Economy of Hybrid Electric Vehicles,” Society of Automotive Engineers Hybrid Electric Vehicle Task Force.

Vita

Matthew Alan Merkle graduated from Virginia Tech in May 1994 with a Bachelor of Science degree in Electrical Engineering. He then entered the graduate program in Electrical Engineering at Virginia Tech, graduating in December 1997 with a Master of Science. As part of his graduate responsibilities, Mr. Merkle held several Graduate Teaching Assistantships, as well as a Graduate Research Assistantship that focused on hybrid electric vehicles. He and Mr. Randall Senger served as team co-leaders for the Hybrid Electric Vehicle Team of Virginia Tech, leading the team to 1st place (1996) and 2nd place (1997) national finishes in the U. S. Department of Energy's FutureCar Challenge. As of this writing, Mr. Merkle is a Development Engineer for the Vehicle Dynamics/Handling group at the Goodyear Tire and Rubber Company – Technical Center, Akron.