1-1-2007

Analysis of a fuel cell-internal combustion engine series hybrid vehicle

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ANALYSIS OF A FUEL CELL – INTERNAL COMBUSTION ENGINE SERIES HYBRID VEHICLE

by

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Bachelor of Engineering
Bharathiyar University, India
2002

Master of Science
University of Nevada, Las Vegas
2007

A thesis submitted in partial fulfillment
of the requirements for the

Master of Science Degree in Mechanical Engineering
Department of Mechanical Engineering
Howard R. Hughes College of Engineering

Graduate College
University of Nevada, Las Vegas
August 2007

UNIVERSITY OF NEVADA LAS VEGAS

Thesis Approval

The Graduate College
University of Nevada, Las Vegas

07/03, 2007

The Thesis prepared by

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Entitled

Analysis Of Fuel Cell - Internal Combustion Engine Series Hybrid Vehicle

is approved in partial fulfillment of the requirements for the degree of

Master Of Science In Mechanical Engineering

Examination Committee Chair

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Examination Committee Member

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Graduate College Faculty Representative

1017-53

ABSTRACT

Analysis of a Fuel Cell – Internal Combustion Engine Series Hybrid Vehicle

by

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A theoretical analysis of a Fuel Cell- Internal Combustion Engine Series Hybrid Vehicle was conducted using ADVISOR software. ADVISOR is an open source vehicle simulation software developed by NREL. The main purpose of this work was to visualize a fuel cell (FC) – internal combustion engine (ICE) powered series hybrid vehicle with no energy storage system like a battery or an ultracapacitor. The study included plotting the fuel economy of the vehicle and dynamic response of the FC and the ICE to the load requirements under two different test conditions. 1985 Toyota pick-up truck parameters were used to model the vehicle. The conventional vehicle has a 72 kW (@ 4500 rpm), 172 Nm (@2600 rpm) Toyota 2.4 L SI gasoline engine. The empirical data in the ADVISOR software were extensively used to model the various components of the series vehicle like fuel cell, power bus, electric motor, generator and gear box. Modifications were made to the default series control logic and Matlab sub-routines were written to plot the fuel use data from the simulation. Various degrees of hybridization (in increments of 10% power from fuel cell) from conventional up to a complete fuel cell vehicle was

simulated. Two driving cycles, Urban Dynamometer Driving Schedule and US 06 cycle, that collectively represent the overall vehicle usage, were used to find the fuel economy of the vehicle. Also, a cost analysis of fuel converters for the conversion was carried out. The results of the simulation show that an FC-ICE series hybrid with a base power from a 15 kW FC and a down sized 57 kW ICE will be the best design for converting the conventional 72 kW gasoline vehicle. This 20% hybridized truck, at an additional investment of 5.7 % of fuel converter cost, will improve the fuel economy of the vehicle by 73% within the city and 49.2% on highways.

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ACKNOWLEDGEMENTS

I would like to profusely thank Dr. Robert F. Boehm who patiently guided me throughout the thesis process as Committee Chair. He procured me the ADVISOR software without which this research would not have been possible. Dr. Boehm not only served as my committee chair but also encouraged and motivated me throughout the academic program as my advisor. I thoroughly enjoyed working under him.

I would like to thank the following people for serving as my committee members: Dr. Yitung Chen, Dr. Woosoon Yim and Dr. Rama Venkat.

Last but not the least I would like to thank my family and friends, especially Ajay Mandava, who lent their time, love and support to make this research possible.

CHAPTER 1

INTRODUCTION

Automobile industry has seen a tremendous growth with the increase in mobility of people. Transportation is being regarded as a fundamental necessity and comfort. However, the use of automobiles with conventional fuels like gasoline has had detrimental effects on the environment in the form of air pollution. In addition, fossil fuels are being exhausted at an alarming rate which apparently leads to an increase in the cost of these fuels. United States uses approximately two thirds of imported petroleum for transportation purposes.

The growing environmental awareness and concerns have led to energy reforms and research on reducing the vehicular fuel usage. New automobile technologies to make vehicles run on renewable and alternate energy resources are being contemplated, designed and prototyped. The primary focus of these is to increase well to wheel efficiencies, reduce emissions and if possible, eliminate them without compromising on the existing mileage and comfort.

To give a boost to the ongoing efforts, the Unites States Department of Energy together with the three major U.S auto manufacturers – Ford, Chrysler and General Motors, formed an alliance called Partnership for New Generation of Vehicles (PNGV). One of the goals of this alliance is to produce a mid-size passenger car that has three times the fuel economy and ultra low emissions compared to current cars. Toyota, Honda, BMW and other car manufacturers are also working independently and forging alliances to advance alternate vehicle technologies and mass produce these vehicles by 2010.

Hybrid vehicles seem to provide the best solution to address the emission problems and improved fuel economy. Hybrids (as they are called) are those that have more than one source of power. These vehicles have capabilities to use alternate energy resources like hydrogen, bio-fuels, electricity, etc.

The major two classifications of hybrids are Series and Parallel hybrids.

Parallel Hybrid

Parallel hybrids have both electric motor and ICE each mechanically coupled to the drive wheels of the vehicle. One of the advantages of this setup is that if either of the drive systems should fail, the other system would still be able to drive the vehicle. They have less mass compared to series hybrids and also provide better highway economy and grading ability. But, they offer little flexibility for placing the components and need complex design of the mechanical coupling.

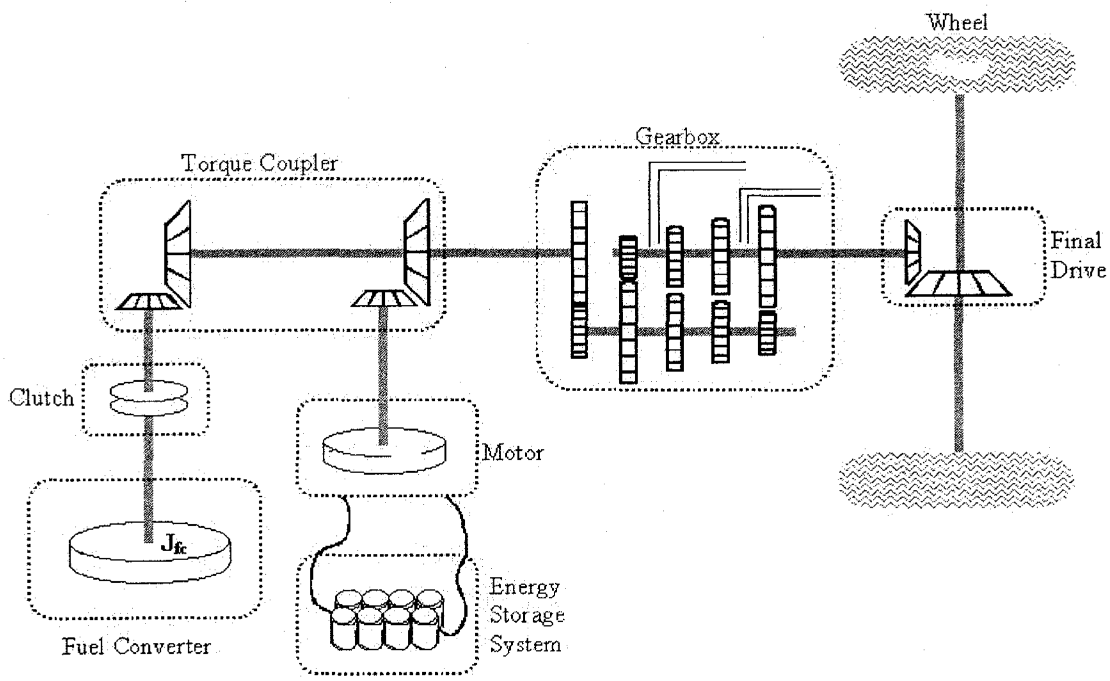

Figure 1 Parallel Hybrid System

Series Hybrid

Series hybrids have only an electric motor mechanically coupled to the drive wheels. The ICE is connected in series to the motor through an alternator that generates electrical energy to power the electric motor. This provides accommodative placing of the various components. The mechanical connection to the wheels is simpler and the electric motor can be easily sized such that only a single speed transmission is required. These hybrids provide excellent fuel economy under city driving conditions. They are slightly heavier compared to parallel hybrids.

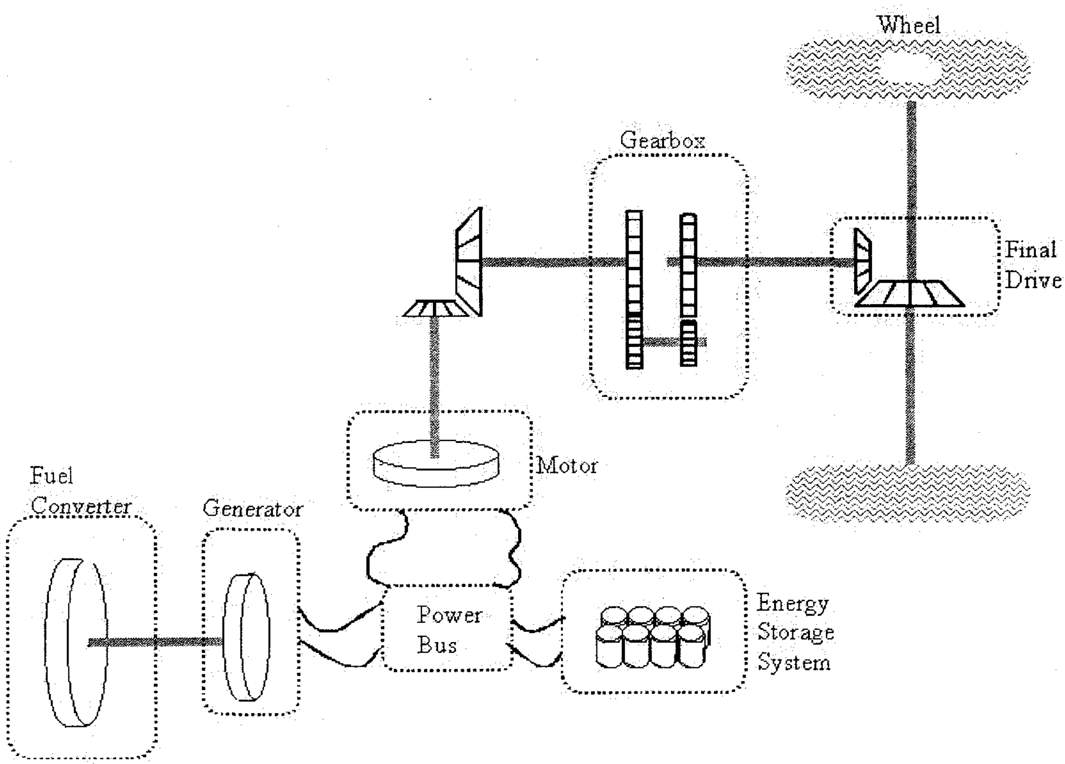

Figure 2 Series Hybrid System

In this thesis, a theoretical study has been conducted to find the most optimal degree of hybridization in the conversion of 1985 Toyota pick-up truck into a series Fuel Cell-Internal Combustion (FC-ICE) hybrid. The simulation was carried out in Matlab Simulink using ADVISOR (Advanced Vehicle Simulator). Modifications to the existing ADVISOR codes were done to accommodate two fuel converters and get the desired results. The research includes varying the configuration from a conventional ICE type to a complete Fuel Cell vehicle in increments of 10% total vehicle power from fuel cell. The fuel economy along with the approximate cost of each configuration has been calculated and plotted.

CHAPTER 2

LITERATURE SURVEY

A number of reports that discuss the hybrid conversion simulation using ADVISOR are available. ADVISOR is widely used by research organizations and academic institutions. Most of the conversions are with either battery -fuel cell or battery- ICE configurations. NREL published a paper [Markel, 2002] that gives an overview of what ADVISOR is and how modeling is done on ADVISOR. The advantages and limitations of this tool are clearly listed and a brief summary of the overall structure with in-built GUI's, component options available and their background Matlab codes are discussed. It throws light on the combined hybrid backward-forward approach in simulating the vehicle. A short energy usage analysis of a conventional and hybrid vehicle using ADVISOR is included to substantiate the versatility of the software.

In Wipke [1999] an underpowered series hybrid vehicle with ICE and battery power sources has been simulated using ADVISOR. The motor controller characteristics and the different modeling approaches are explained lucidly. A demanding US06 driving cycle with different acceleration schemes is used to find the performance of this hybrid. The study shows that ADVISOR is able to predict the acceleration time to within 0.7% and energy use to within 0.6% of the actual values for this driving cycle.

A validation study of ADVISOR was conducted at Virginia Tech [Senger, 1998]. The study modified the default ADVISOR codes to accommodate their FutureCar Challenge entry. The results show ADVISOR as a valid simulation tool particularly for HEV's. The research also predicted that vehicle energy use to be within 5 to 10% of the measured data and vehicle fuel economy over the stated driving vehicles using standard test procedures to be within 12 to 19% of actual data. It recommended that ADVISOR could be used with a great degree of confidence in predicting future behavior and making informed design decisions with minimal amount of additional testing.

Another study [Cuddy, 1996] was initiated by NREL to demonstrate the capabilities of ADVISOR in consistent with the goals of the Partnership for New Generations of Vehicles. Since the software is based on open programming environment of MATLAB/ Simulink, it is ideally suited for doing parametric studies of potential high fuel economy vehicles. NREL modeled five separate vehicle configurations including three light vehicles. The sensitivity of each vehicle economy to critical vehicle parameters was then examined. The results indicated, the fuel economy improvement due to hybridization was found to be 17 to 24 %.

Virginia Polytechnic Institute and State University [Doughlas, 2001] developed an ADVISOR model of a large sport utility vehicle with a fuel cell / battery hybrid electric drive train. The fuel cell and battery models were validated and the consolidated vehicle ADVISOR model of FCHEV was tested on highway cycle. The study plotted the fuel economy results and demonstrated that some degree of hybridization can improve energy efficiency. It also concluded that there is complex interaction between the drive cycle dynamics, component efficiencies and the control strategy.

Both series-parallel hybrid vehicles with ICE and FC have a high potential for the future. Iwai [1999] discusses the efficiency improvement techniques through conversion of conventional ICE vehicle into Series-Parallel Hybrids. It was estimated that fuel economy of vehicles can be doubled by eliminating engine idling during vehicle stops, energy saving in acceleration during brake energy recovery and high efficiency operation on low load condition.

Argonne National Laboratory conducted a study [An, 1999] to analyze why, how and by how much vehicle hybridization can reduce energy consumption. Specifically, they evaluated the energy efficiencies and fuel economies of a baseline Corolla-like conventional vehicle (CV), a hypothetical Corolla-based minimal hybrid vehicle (MHV) with 10-20 kW electric power capability and Prius-like full hybrid vehicle (FCV). The study concluded that the energy benefits of hybridization varied not only with the test cycles, but also with performance requirements. The MHV can significantly improve fuel economy (up by 21%) under relatively slow-speed urban driving cycles.

CHAPTER 3

METHODOLOGY

ADVISOR

ADVANCED VEHICLE SIMULATOR was developed at the National Renewable Energy Laboratory in Golden, Colorado. It was designed to help US Department of Energy in testing hybrid electric vehicles. ADVISOR is widely used in industry, academic institutions and government research organizations. It is created in the MATLAB/Simulink environment. All the systems and subsystems are graphically represented using block diagrams. The three primary GUI screens (see Figures 3, 4 and 5) help the user to navigate through the simulation process. Various parameters like vehicle performance, fuel economy and emissions can be studied. Most of the components built in are based on empirical data and feedback from users. The general process followed while using ADVISOR is

1. The user chooses the configuration of the vehicle to be studied from the library. ADVISOR has options to create conventional, series, parallel or a customized combination of these models.
2. The individual components like fuel converters (FC, ICE) energy storage devices, electric motors, drive train, final wheel drive, etc. that go into the overall vehicle are then selected. The user can modify the component data based on measured values or let ADVISOR size the component parametrically.

3. ADVISOR then plots the various component characteristics like torque vs. speed and efficiency vs. speed. At any point the user can override the default with the desired values. Whenever such modifications are made, the software automatically updates the corresponding Matlab source files.

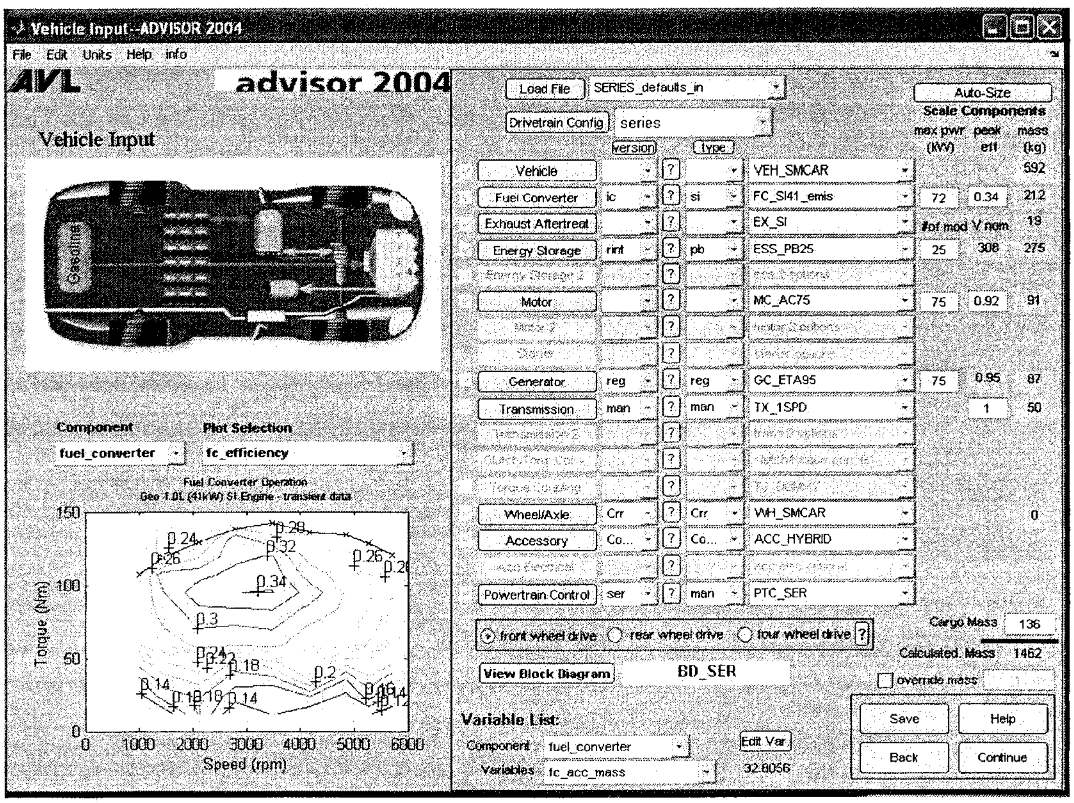

Figure 3 – Vehicle Input Screen in ADVISOR

4. The user specifies the driving cycle to be followed by the vehicle. ADVISOR has more than 40 different driving cycles to choose from. The user can also combine different driving cycles to create his or her own test procedure.

5. Acceleration and gradeability test can also be included with the standard test.

6. Finally, ADVISOR runs the simulation and plots the desired output variables against time. Some sample screen shots are shown below.

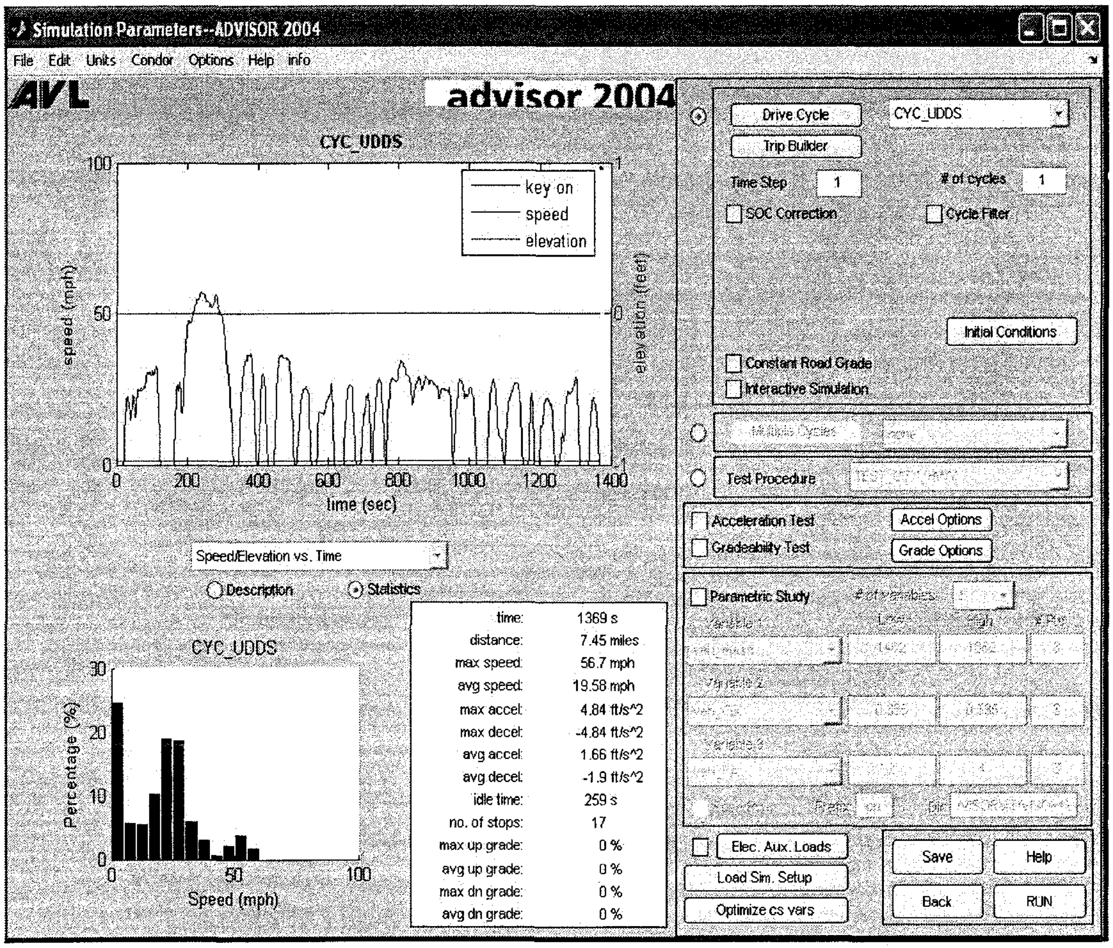

Figure 4 – Drive Cycle Input Screen in ADVISOR

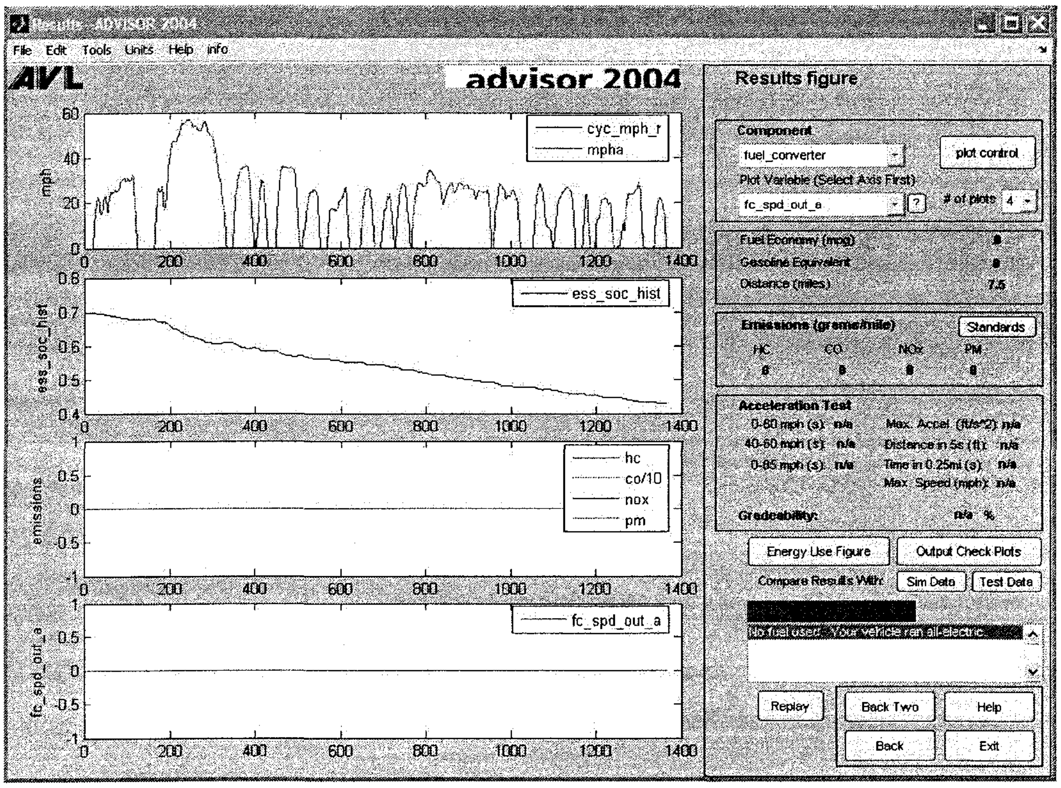

Figure 5 – Results Screen in ADVISOR

Vehicle Simulation Approaches

Backward-Facing Approach

Backward -facing approach typically answers the question “assuming the vehicle met the required driving cycle, how must each component perform?” In this approach the driver behavior model is not required. The force required to accelerate the vehicle through the time step is calculated directly from the required speed. The force is then translated to a torque that must be provided by the component upstream. Similarly, the vehicle’s linear speed is converted to a required rotational speed. This calculation is carried backward from the wheel to the drive train and finally to the power source where the fuel use is calculated. One of the main disadvantages of this approach is that it is not well suited to compute best performance when the accelerations of the speed trace exceed the capabilities of the drive train.

Forward-Facing Approach

In this approach, a driver model is created to consider the required speed and the present speed. This is then used to develop appropriate throttle and break commands. The torque provided by the power source, based on throttle position, is passed to the downstream components. The main disadvantage of the forward facing approach is its large time consumption. It is desirable only for hardware development and detailed controlled simulation.

The main difference between the backward and forward approaches is that while in the former the engine torque flow is against the tractive power flow direction, in the latter they are both in the same direction.

ADVISOR is hybrid of backward facing vehicle simulation and a forward facing simulation.

Basic Equations

All vehicle modeling is derived from Newton's second law as given by

$$F = ma \qquad (1)$$

There are typically four kinds of forces that act on vehicles namely acceleration, surface grade, air resistance and rolling fiction as given in the Equation (2).

$$F = ma + mgC_r + 0.5\rho C_D A v^2 + mg\sin\theta \qquad (2)$$

Where

F – total force required in Newtons

m – mass of the vehicle in kg

a – acceleration of the vehicle in m/s^2

g – acceleration due to gravity (9.81) m/s^2

C_r – coefficient of rolling resistance

ρ – density of air in kg/m^3

C_D – Coefficient of drag

A – Frontal area of vehicle in m^2

v – velocity of vehicle in m/s

θ - road grade in degrees

Here the first term indicates the force required to overcome mass inertia of the vehicle. The second term represents the force required to overcome the rolling resistance of the vehicle. This force is constant regardless of the speed of the vehicle. The third term represents the aerodynamic drag force which the vehicle must overcome at a certain speed. This force is proportional to the square of the speed of the vehicle and therefore increases rapidly with velocity. The last term is the force required to propel the vehicle on a graded surface.

This equation is the basis for all vehicle simulation tools including ADVISOR.

1985 Toyota Pick-up Truck Parameters

A light-duty 2 wheel (rear) drive pick-up truck with a wheel radius of 0.343m has been considered. Other parameters used are given in Table 1.

Table 1 – Pick-up truck Parameters

Coefficient of aerodynamic drag	0.45
Frontal area, m^2	2.97
Rolling resistance coefficient	0.008
Vehicle glider mass, kg	1250

Some of the important assumptions made are

(i) Only two sources of power namely ICE and FC have been considered.

(ii) The cold start effects of FC have been ignored to reduce the logical complexity.

(iii) Batteries are not used to drive the vehicle but just to start the ICE.

(iv) There is no regenerative braking.

(v) With no measured data for individual components in hand, care has been taken to model them closely to the empirical values within the tolerance level of ADVISOR.

(vi) Analysis of exhaust gas emissions is not done as measured values are important for plotting the emissions map for ICE and FC.

(vii) Empirical data from ADVISOR has been used for motor and generator torque look up tables.

Component Modeling

The results of simulation are largely dependent on the choice of various component models and parameters chosen like fuel convertor, motor, transmission and general vehicle parameters. The overall block diagram of the vehicle created using ADVISOR is shown in Figure 6.

A series HEV has been modeled to visualize the converted vehicle. This has two sources of power, internal combustion engine (ICE) and fuel cell (FC). Under normal operation, the fuel cell drives the vehicle (i.e. the base power of the vehicle is derived from FC) and whenever the required power exceeds the FC limit, the ICE turns on to give balance power boost. The parameterized models from ADVISOR library was widely used to size the FC and the ICE. The location of the components and exhaust gas emissions has not been considered at present.

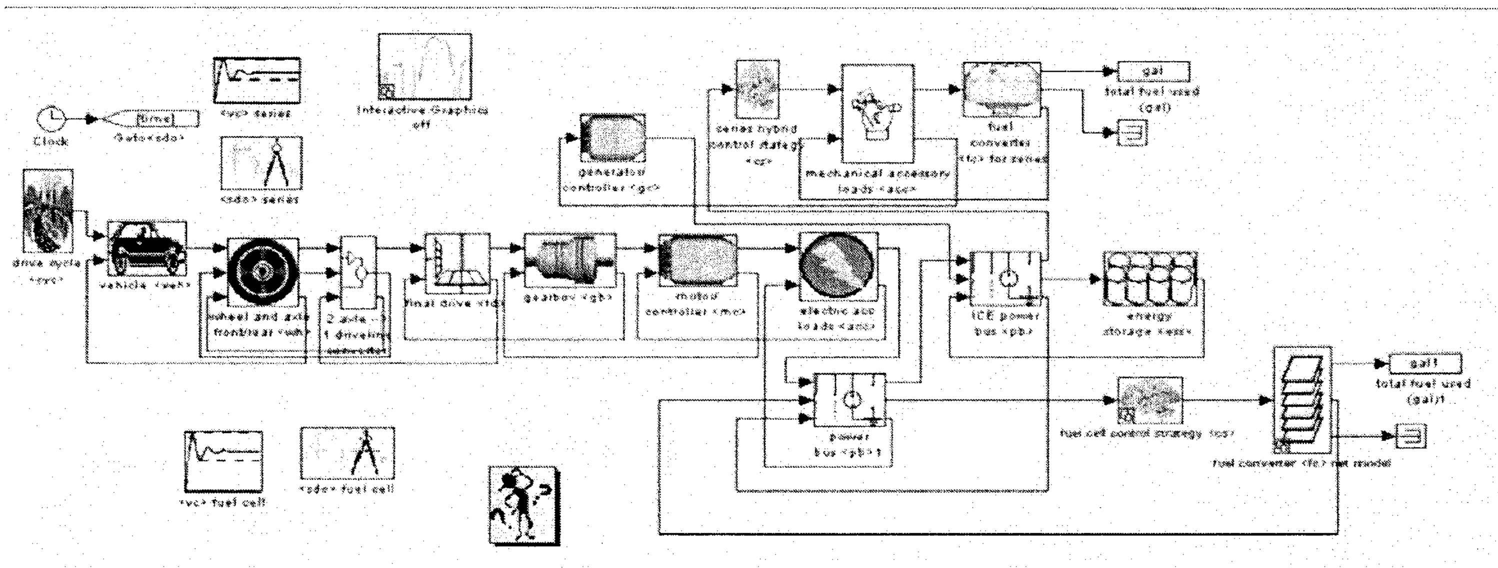

Figure 6 – Overall FC-ICE Series Hybrid Pick-up Truck Model

Fuel Cell

There are two empirically based fuel system models available in the ADVISOR efficiency vs. power model and polarization curve model. The first model combines the entire fuel system into a single element with characteristic system efficiency as a function of net power out of the system. The complexity of the system is ignored while calculating the amount of the fuel consumed. The polarization curve model is similar to the first, except that the auxiliary systems' (air compressors, fans, fuel pump) performance can be specified separately from the fuel cell stack. The number of individual cells within the stack is important to characterize the stack performance and is specified separately.

For the current simulation, power vs. efficiency model of fuel cell is used as specific operating characteristics of the fuel cell are not of main interest. Direct hydrogen and air are fed to the fuel cell. The fuel convertor operation of the chosen ambient pressure hydrogen fuel cell system is shown in Figure 7.

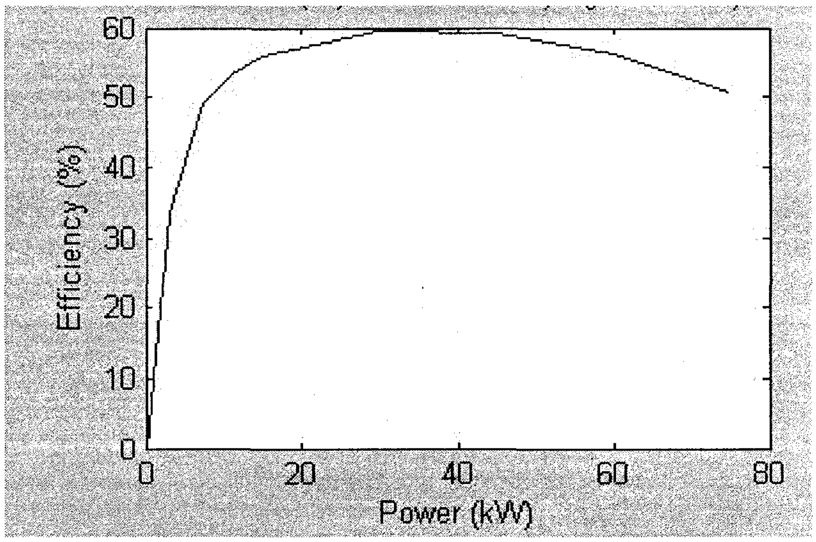

Figure 7 – FC Efficiency vs. Net Power Output Curve

This characteristic curve remains constant for all capacities of fuel cell used throughout the simulation. The maximum efficiency of the fuel cell is 60% at approximately 38 kW. The base mass of the fuel cell stack is assumed as 2.5 times its maximum power, based on the 2004 Department of Energy target. The Simulink block diagram of FC is shown in Figure 8.

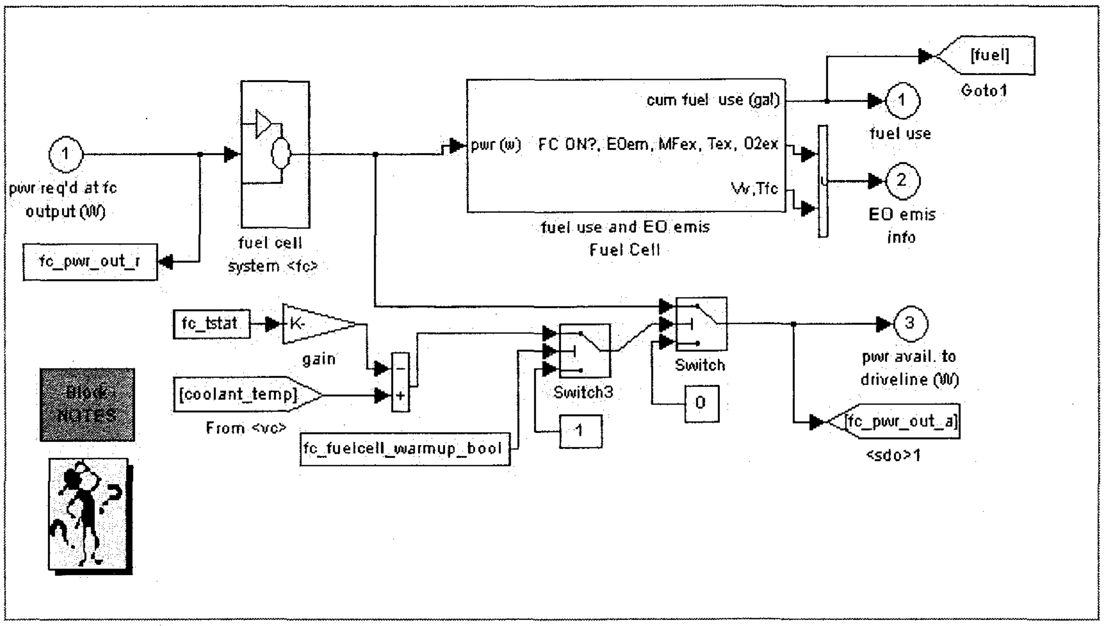

Figure 8 – Simulink Model of FC

The fuel economy results of the FC are plotted in miles per gallon gasoline equivalent (mpge). The following hydrogen fuel data are considered: density = 18 g/l and lhv = 120,000 J/g .

Refer to Appendix A for equations used in this subsystem.

ICE

The ICE model accepts torque and speed requested by the vehicle power burst controller as the input through interpolation of the input fuel consumption data at the specified speed and load. The resulting fuel consumption is calculated for the time step. The ICE considered is a 72 kW(@4500 rpm), 172 N.m(@ 2600 rpm) Toyota 2.4L SI gasoline engine with a peak efficiency of 42%. The torque vs. speed map of the ICE is shown in Figure 9.

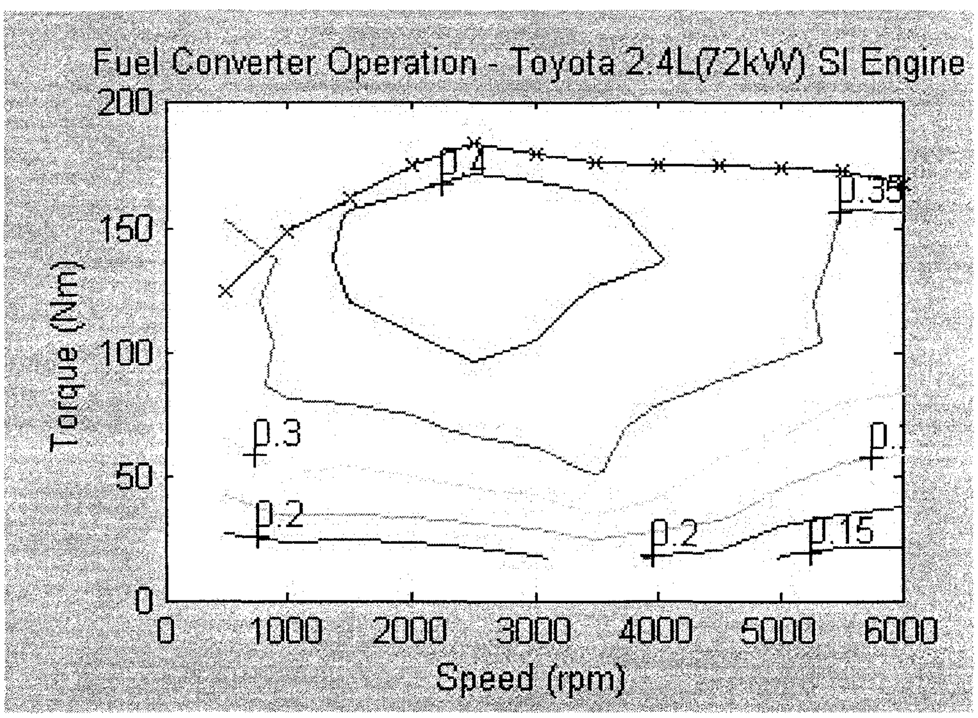

Figure 9 – Gasoline ICE Torque vs Speed Characteristic Curve

It is safely assumed that maximum torque varies linearly with the speed (rpm) as the power of the ICE increases. ADVISOR is capable of automatically generating torque characteristics based on the maximum power (specified by the user) of the ICE. The following are the fuel data assumed, gasoline density= 749 g/l and lhv of gasoline= 42600 J/g.

Since the ICE runs on gasoline, the results for fuel economy are obtained directly in miles per gallon (mpg). The fuel use map of the ICE is based on empirical Saber 75kW engine with similar torque characteristics. The block diagram of ICE is show in Figure 10. Based on the requested speed and torque calculated by the power bus, this block determines the engine operating point required to meet these requirements taking in to account the inertial losses and accessory loads. The engine controller in the block does not allow the engine to operate outside of its normal operating speed and torque ranges. The controller switches of the engine when the cultch is disengaged. Once the achievable speed and torque have been determined, these values are passed back to the downstream block. The fuel use values are stored in tables indexed by ICE speed and torque.

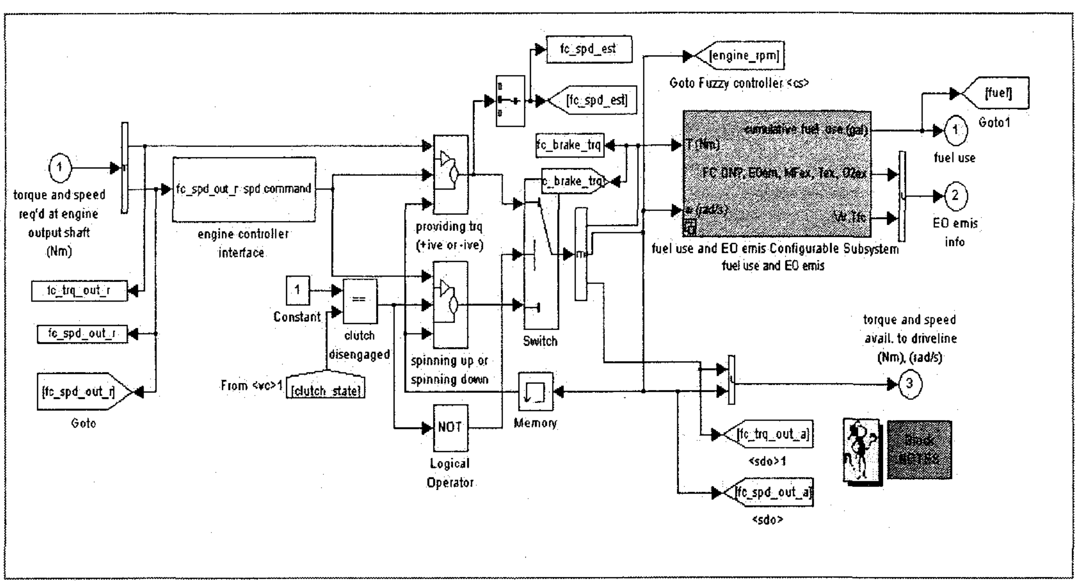

Figure 10 - Simulink Model of ICE

Refer to Appendix A for equations used in this subsystem.

Generator

The purpose of generator is to convert the rotary power of the ICE into electrical energy to the power bus. It is assumed to be coupled to the flywheel of the ICE. The block model of generator includes the generator inertia and a built in 2-D lookup table indexed by rotor speed and input torque. The generator is assumed to be 95% efficient with the maximum current of 480A and a minimum voltage of 120V. The maximum speed of the rotor is 7000 rpm and has a maximum torque of 200 N.m. The block diagram of the generator modeled is shown in Figure 11.

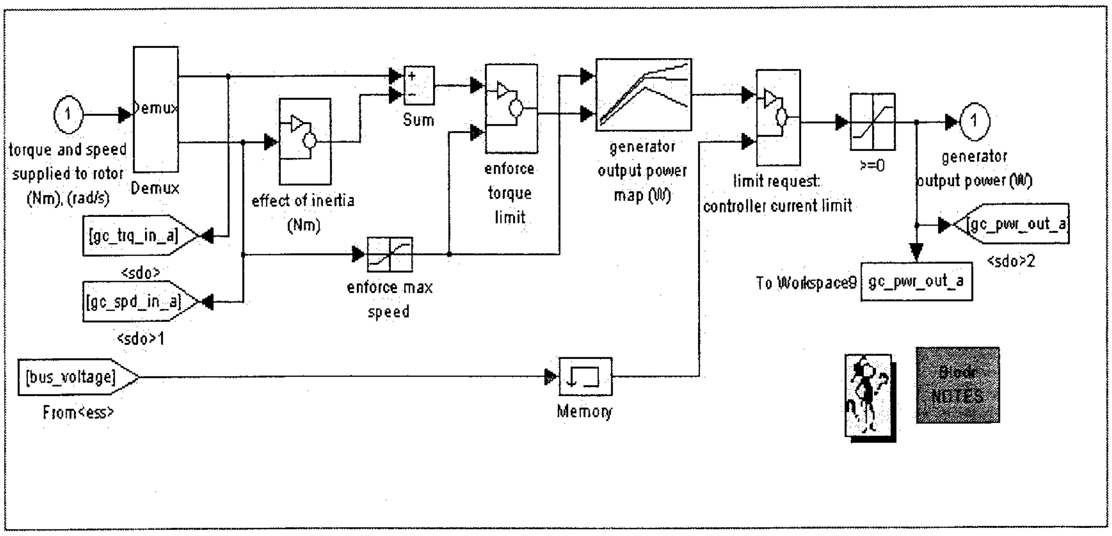

Figure 11 - Simulink Model of Generator

Main Power Bus

Power bus forms an interface between the electric motor and the power sources of the vehicle. It acts like the brain of the vehicle and decides the power flow from the fuel convertors. The block diagram of the power bus is shown in Figure 12.

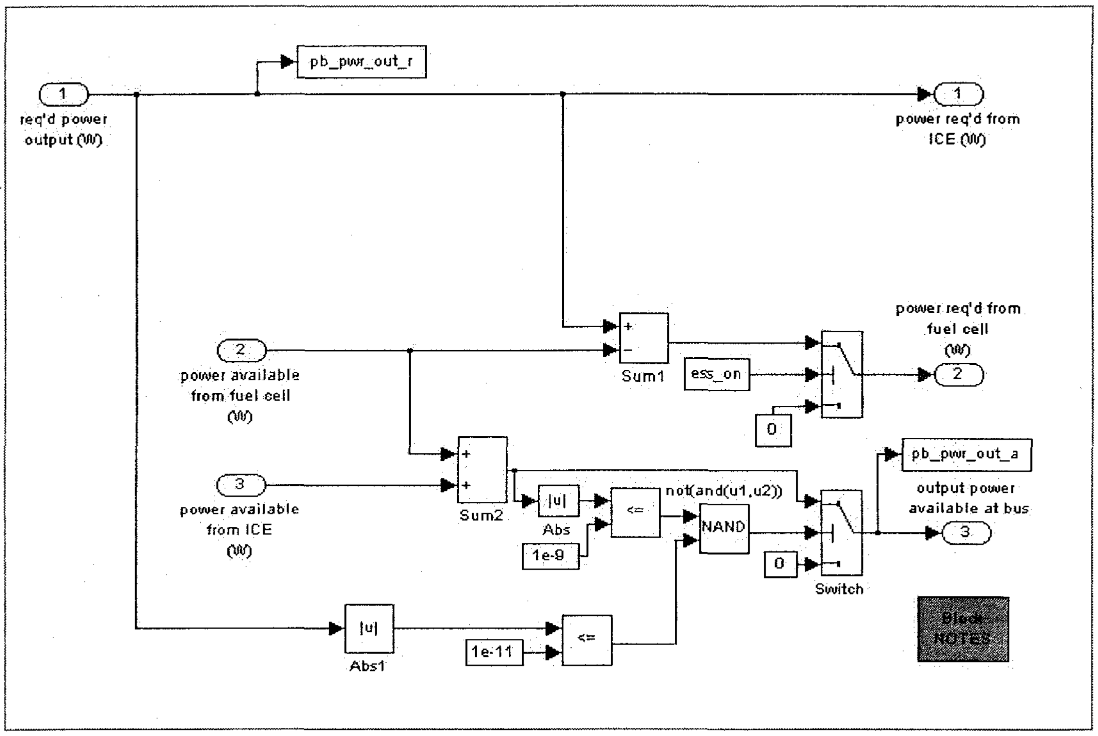

Figure 12 - Simulink Model of Main Power Bus

Electric Motor

A Westinghouse 75 kW(continuous) AC induction motor with a peak efficiency of 92% has been chosen. The maximum shaft speed is 10000 rpm and a maximum torque of 200 N.m. The maximum current cut off is 480 A and the minimum voltage is 120V. The block model of motor also includes the efficiency lookup table based on motor speed and torque.

The required output torque and speed are input at the top left hand corner of the block diagram (see Figure 13) and the required input power is output at the top right hand corner. The required speed is limited to the motor's maximum speed. The required torque is limited to the difference between the motor's maximum torque at the limited speed and the torque required to overcome the rotor inertia. The limited torque and speed are then used to interpolate in the motor's input power map. Finally, the interpolated the input power is limited by the motor controller's current limit.

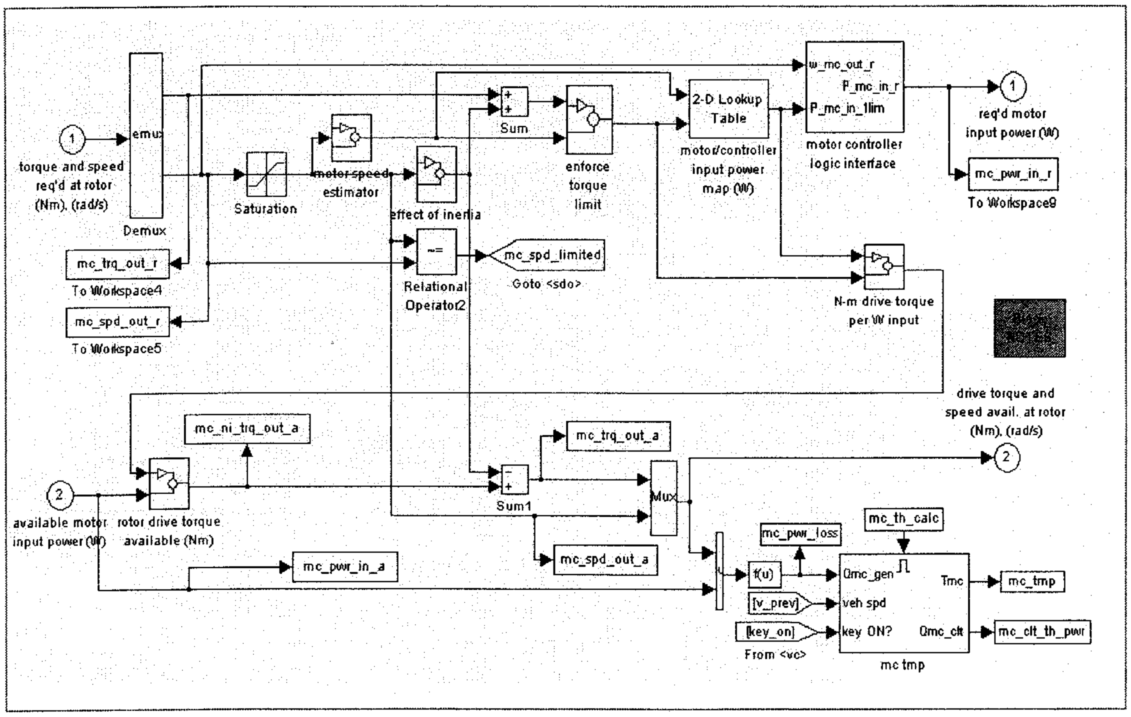

Figure 13 - Simulink Model of Motor

Energy Storage System

This system is not very significant in this analysis as only a regular 12V battery is used to start the engine. It does not provide any power for driving the vehicle nor accept any energy during braking. The ICE power bus uses SOC of the battery to kickstart the engine. In this simulation, a Rint battery model, which represents flooded lead–acid battery, has been used.

Gearbox

Two types of gearboxes are used depending on the vehicle type. In case of the series configuration when both ICE and FC are present, a single speed gearbox has been used. The gear ratio of this is chosen so as to allow 90 mph at given maximum motor speed and 10% wheel slip.

In case of an only - ICE (conventional) vehicle, the default manual 4 speed gearbox with gear ratios 3.928, 2.33, 1.45 and 1.00 is chosen. The block diagram of the Gearbox is shown in Figure 14.

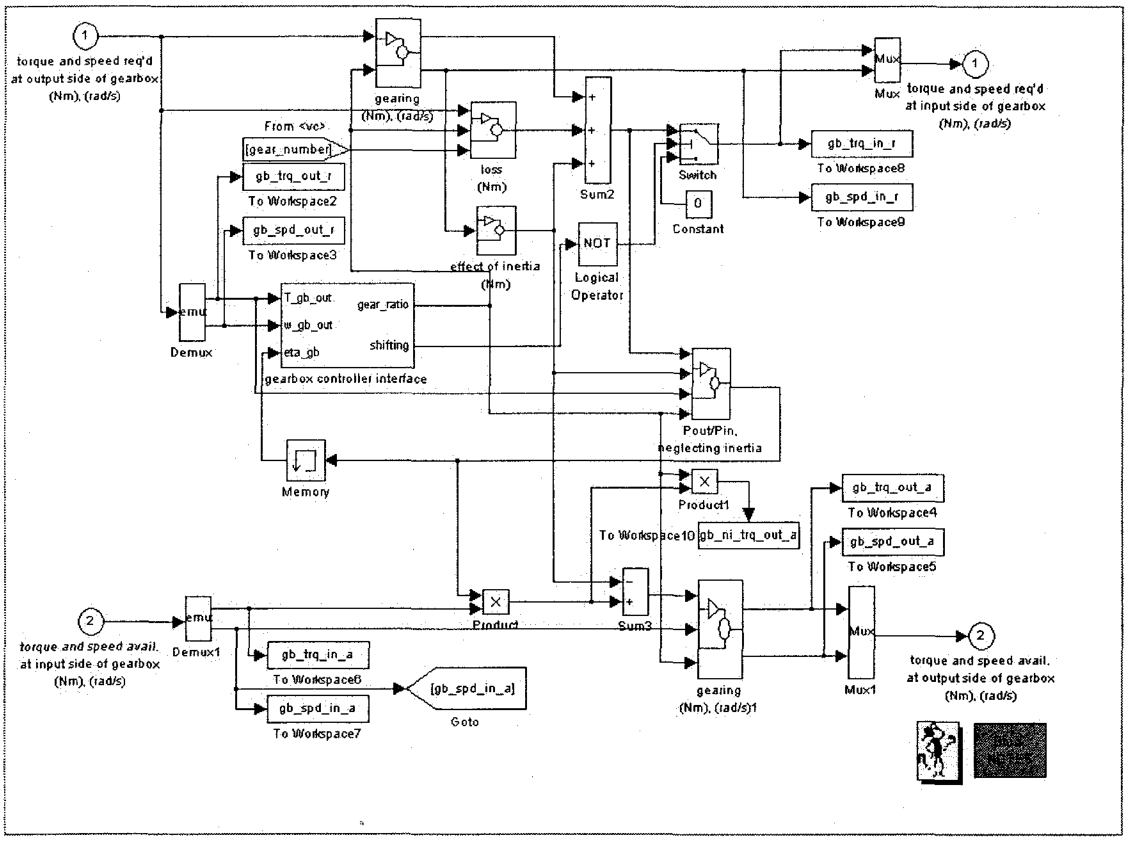

Figure 14 - Simulink Model of Gearbox

Vehicle

The vehicle block diagram (Figure 15) accepts the vehicle parameters such as frontal area, rolling resistance and mass of the vehicle. The equation of vehicle dynamics Equation (2) discussed earlier is implemented in this block. It also computes the tractive force based on the speed required at the end of each time step.

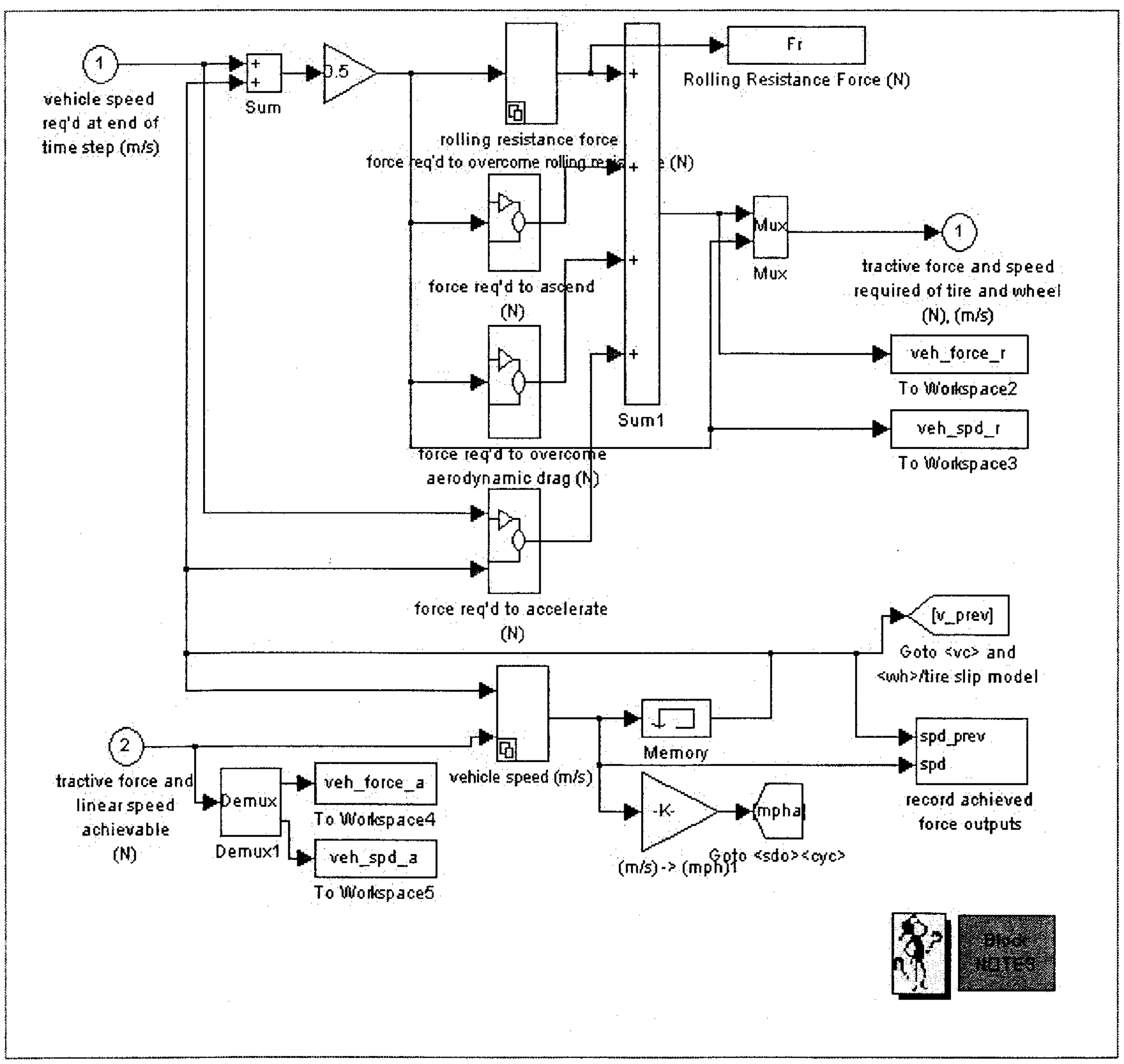

Figure 15 - Simulink Model of Overall Vehicle Dynamics

Modifications to the ADVISOR model

1. The GUI's in ADVISOR are capable of choosing only one fuel converter with a battery. Hence, to accommodate both an ICE and a fuel cell, two power bus controls were used – ICE power bus and main power bus. In a default ADVISOR model, the power bus senses the SOC of the battery and starts the fuel converter. In the present research, the ICE power bus is allowed to serve as a default case. Since, the battery does not drive the vehicle, the SOC is calculated only to switch on the ICE. This power bus also restricts any flow of current to the battery from the driveline for charging. The main power bus input and output ports were modified to accept signals from FC and ICE power bus only.
2. Fuel Converters in the inherent ADVISOR model share the same parameter names like power output, fuel converter efficiency, temperature, fuel use etc., Hence to avoid redundancy and error during simulation run, when both the FC and ICE are used, all the parameter names of the FC model were renamed uniquely.
3. The emissions output ports of the FC and ICE models were terminated.
4. The control strategies of the ICE and the FC were extensively modified. In the case of the ICE, the engine controller switches off the engine when the clutch is disengaged. This eliminates the engine idling and thus uses the engine only when required. The FC controller switches on the FC when the vehicle ignition is on and does not use the SOC of battery for its operation. The FC also powers all the mechanical and electrical accessories.

5. A Matlab code was written to get the fuel use data from the FC and the ICE separately and combine them to calculate the consolidated fuel economy in miles per gallon equivalent (mpge). This file also plots the overall fuel economy by storing the individual fuel use values during every run of the simulation.

Driving Cycles

Two common driving cycles, Urban Dynamometer Driving Schedule (UDDS) and US06, that collectively represent the overall usage of the vehicle has been utilized.

UDDS

The driving schedule and characteristics of this cycle are shown in Figure 16. It represents the regular city driving with a number of stops and relatively lesser acceleration compared to highway driving. The average speed of this cycle is 19.6 mph to cover a total distance of 7.45 miles in 1369 seconds.

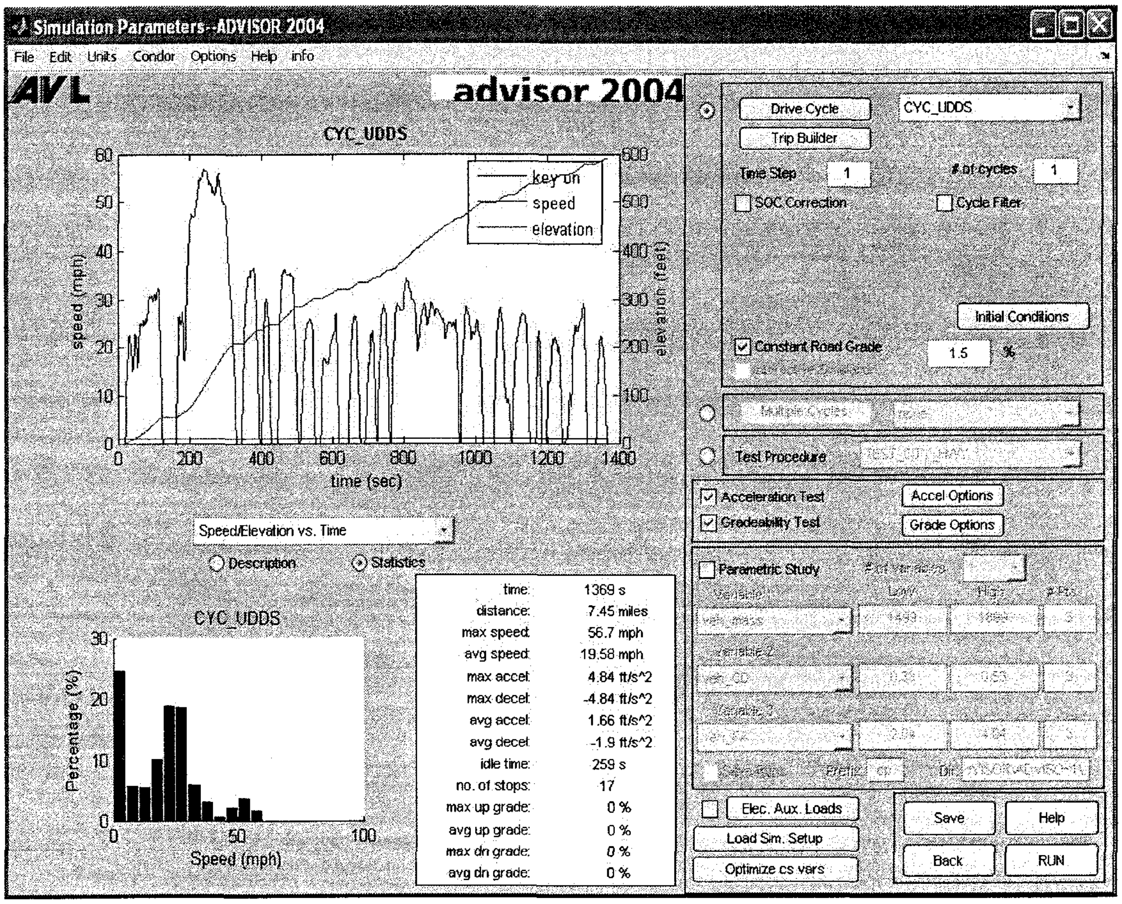

Figure 16 – UDDS Drive Cycle Characteristics

US06 Cycle

This cycle demands large accelerations and high speed operation. The average speed of the cycle is 48 mph to cover a distance of 8.01 miles in 600 seconds with just 5 stops in between (see Figure 17)

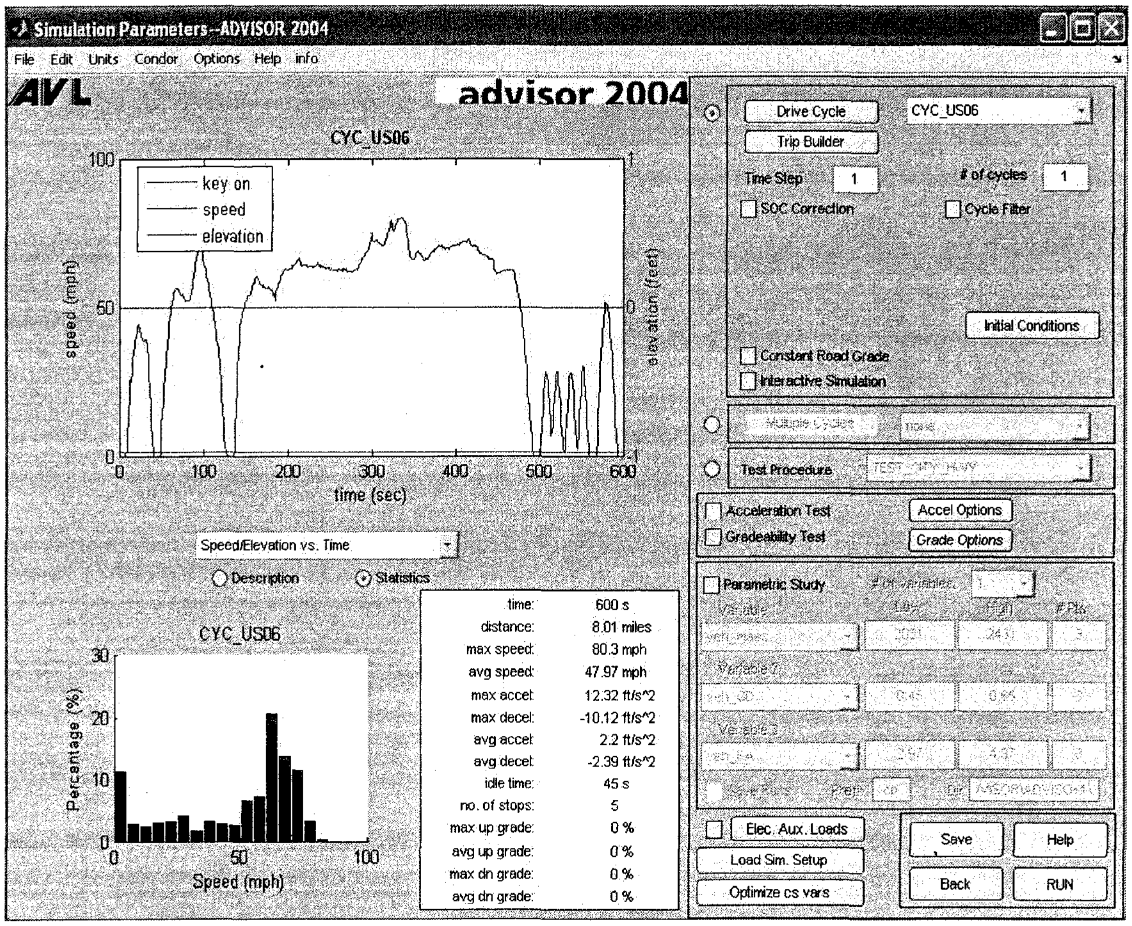

Figure 17 – US06 Drive Cycle Characteristics

CHAPTER 4

RESULTS AND DISCUSSION

Results for UDDS Cycle

The fuel economy results for the UDDS cycle are shown in Figure 18.

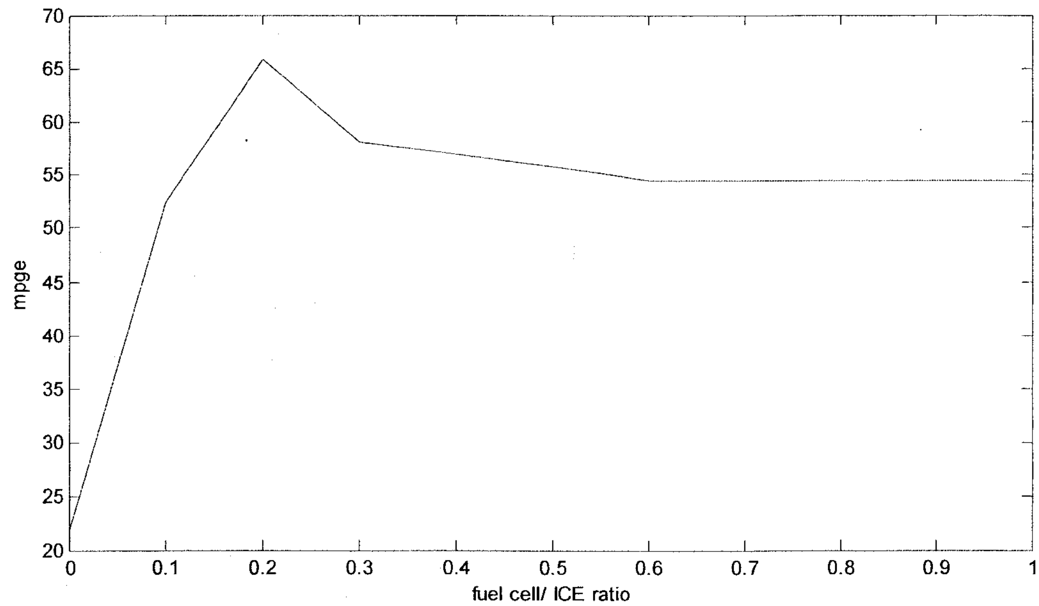

Figure 18 – Fuel Economy in UDDS

The maximum power required for UDDS cycle is around 42 kW in both ICE only and FC only modes (refer Figure 19 and 20). While the fuel economy for conventional (ICE only) vehicle is 22 mpge for the full FC model it is 54.4 mpge (refer Figures 21 and 22). The least fuel economy is for a conventional vehicle as the efficiency of an ICE is less during continuous stop and go operations as demanded. It is clear that the fuel economy closely follows the efficiency curve of the FC as the base power is from the FC.

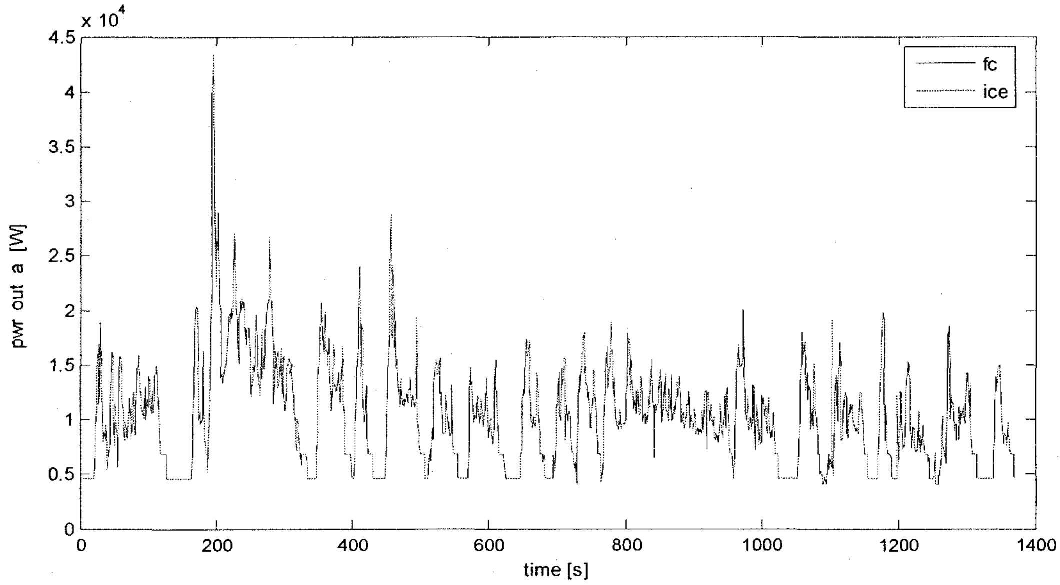

Figure 19 - 100% ICE_UDDS

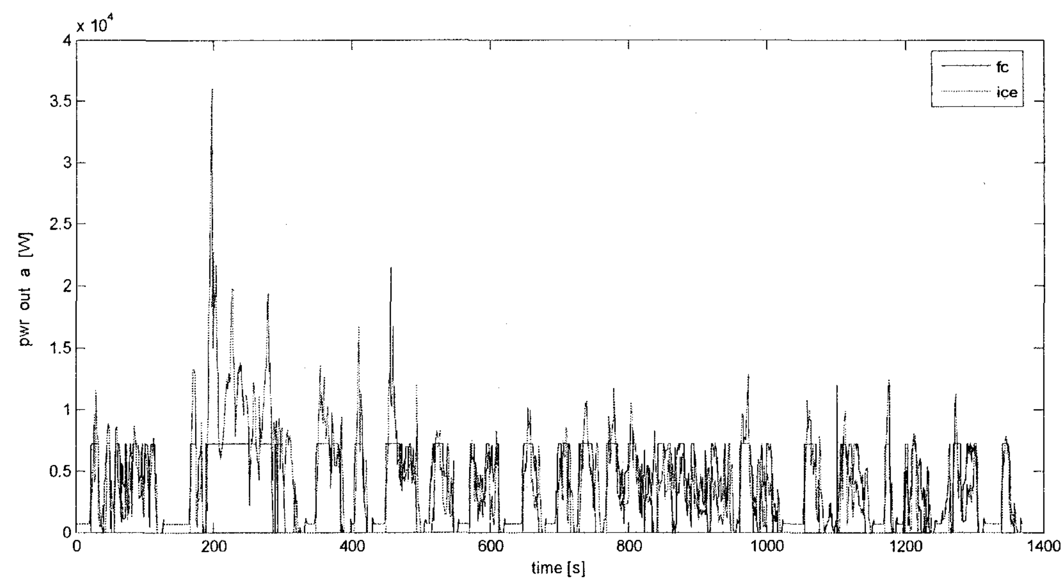

Figure 20 - 10% FC_UDDS

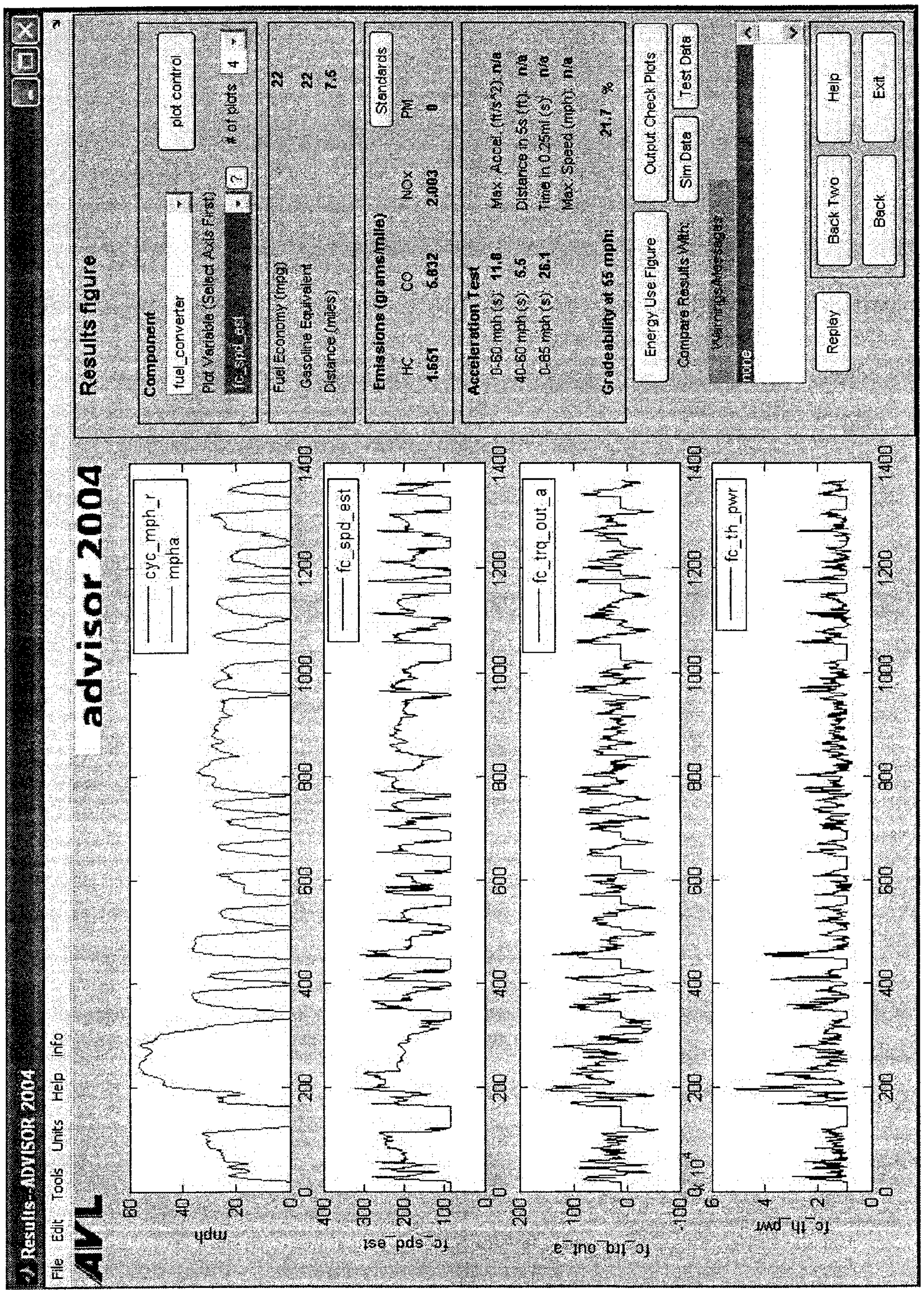

Figure 21 – Conventional Vehicle Simulation Results

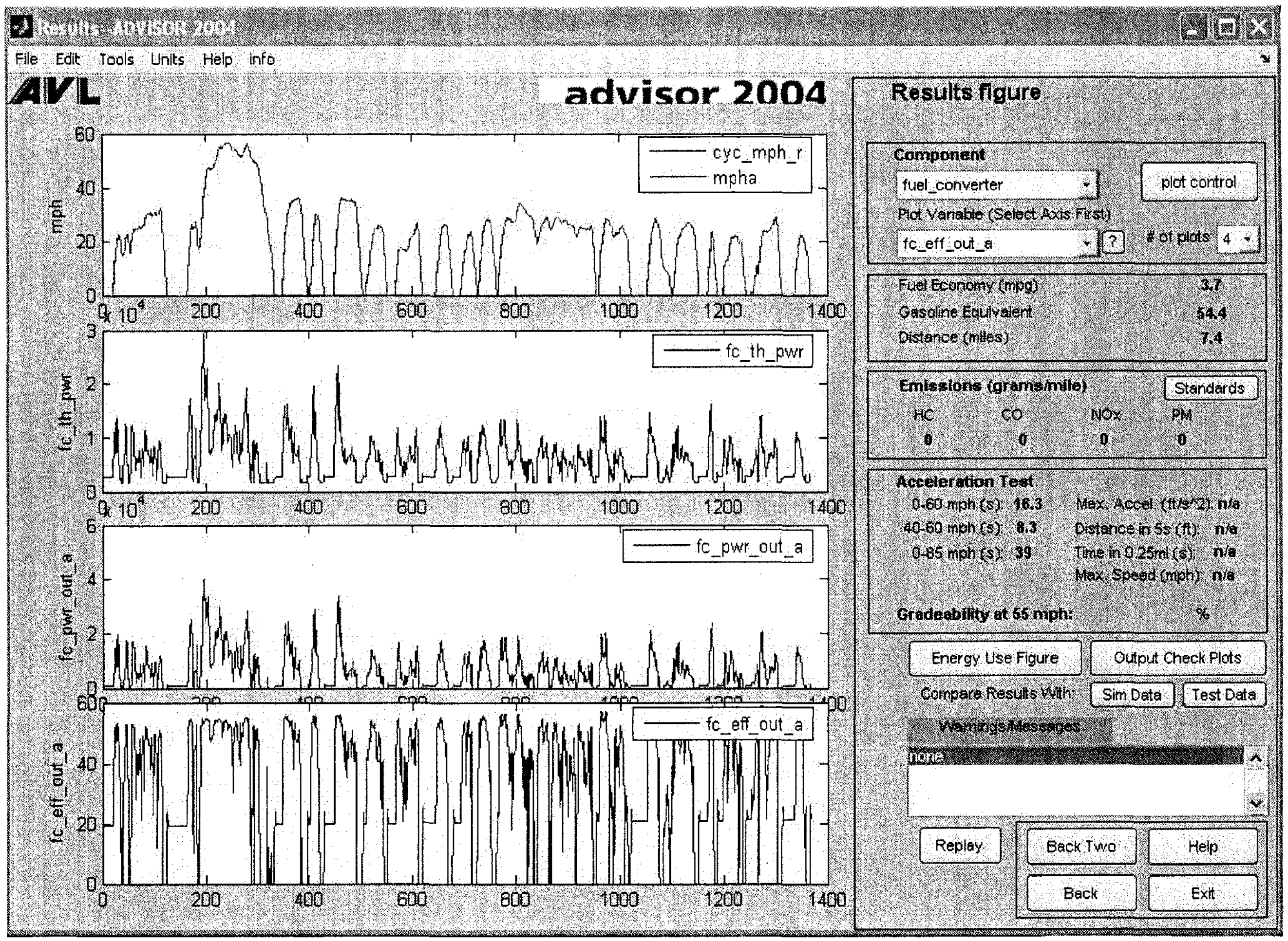

Figure 22 – Fuel Cell Vehicle Simulation Results

A maximum fuel economy of 65.8 mpge is achieved at 20% hybridization when the size of the FC is 14.4 kW (refer Figure 23). This is when the FC is at near maximum efficiency and fully utilized throughout the driving cycle. Also, the ICE is on for most of the cycle and furnishes the excess power. Frequent switching on and off of the ICE is reduced. The idling of the ICE is also eliminated thus enabling it to operate in a high efficiency range.

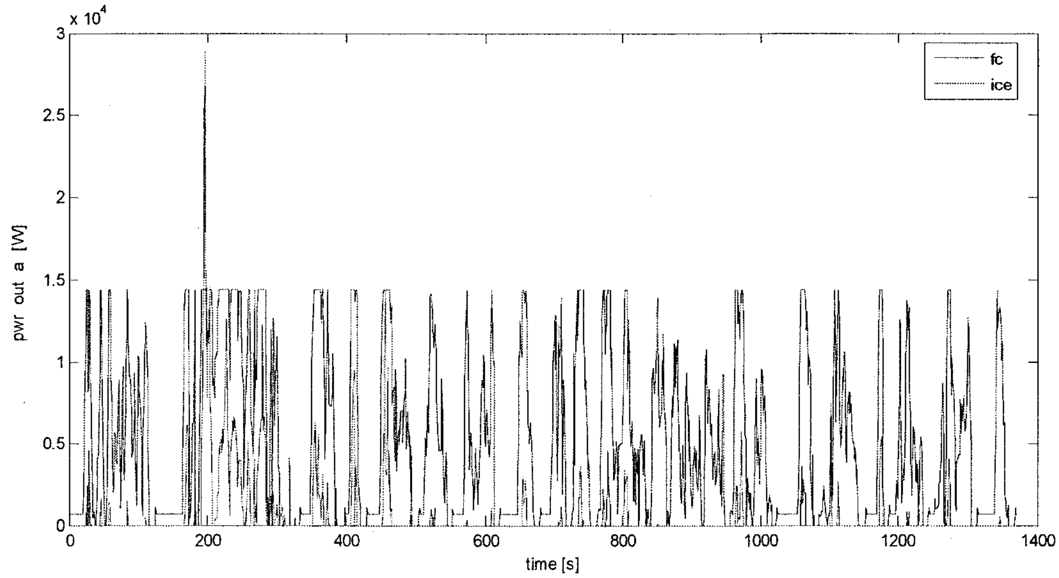

Figure 23 - 20% FC_UDDS

The usage of the ICE decreases as the power capacity of the FC increases (refer Figures 24 to 26). The fuel economy curve then flattens at 60% and remains constant for the rest of hybridization. This is because, at this point, the FC of capacity 43 kW (refer Figure 27) is able to cater completely to the power demands of the entire cycle while the ICE is not required anymore.

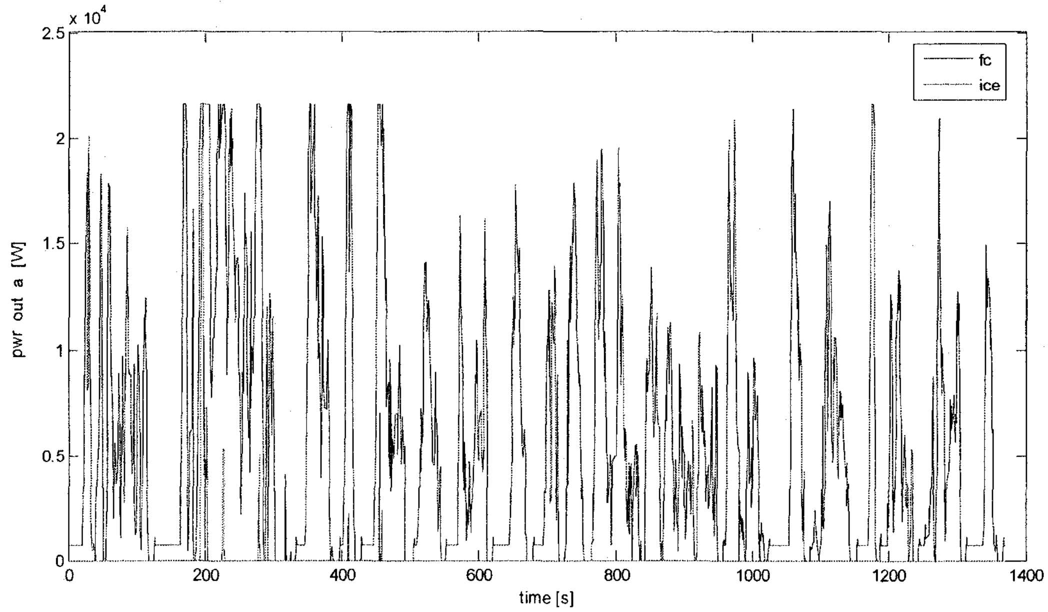

Figure 24 - 30% FC_UDDS

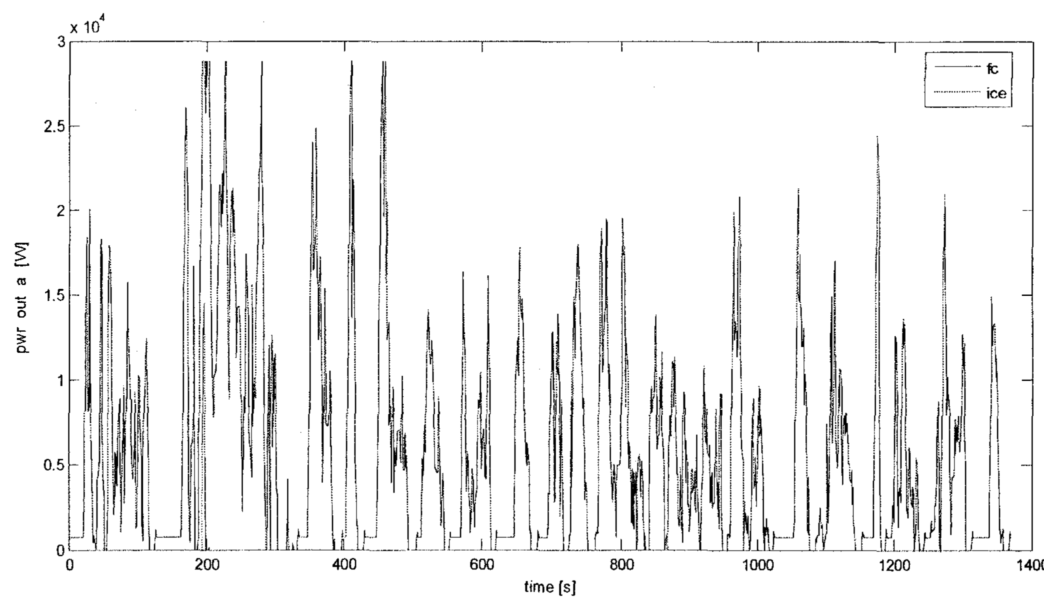

Figure 25 - 40% FC_UDDS

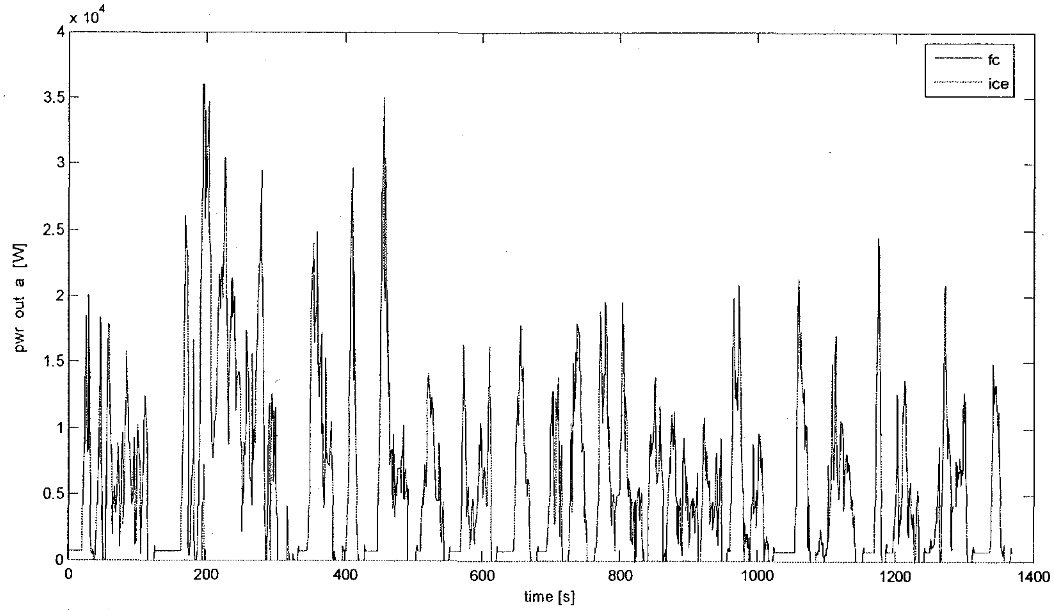

Figure 26 - 50% FC_UDDS

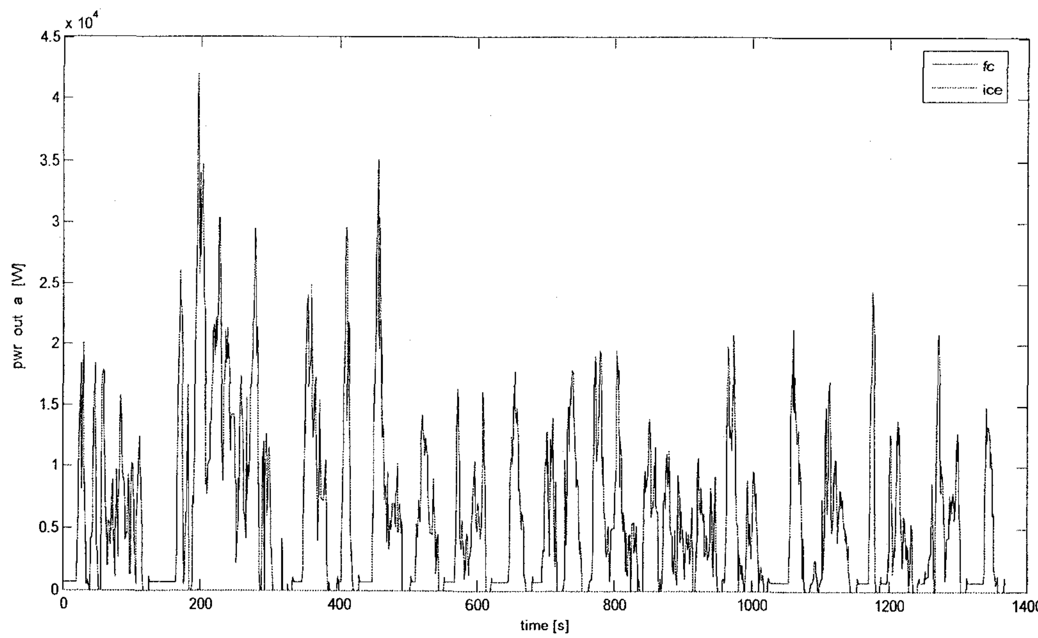

Figure 27 - 60% FC_UDDS

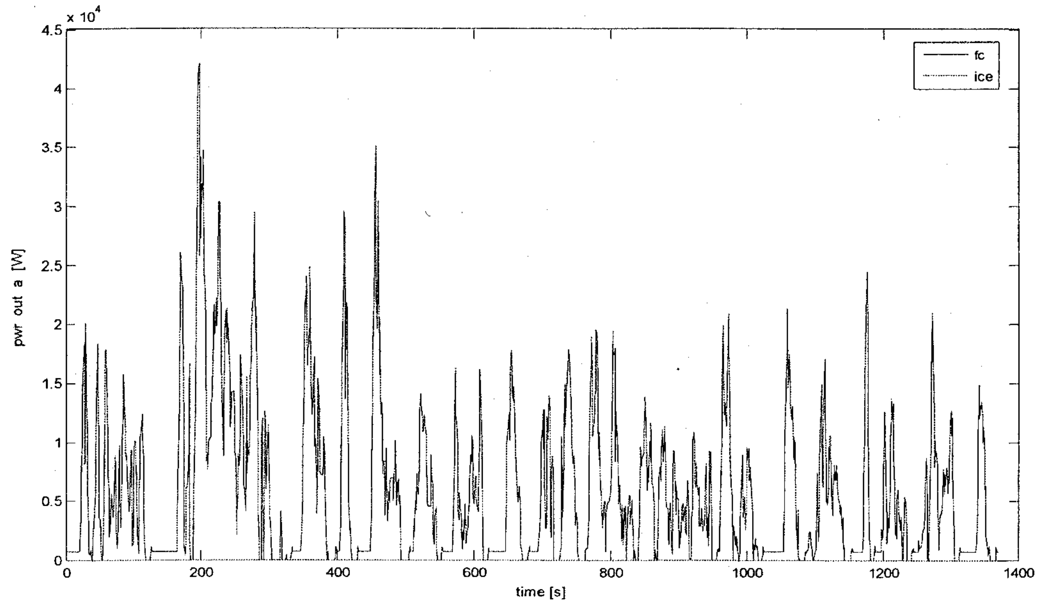

Figure 28 - 100% FC_UDDS

Results for the US06 Cycle

The fuel economy plot for the US06 cycle is shown in Figure 29.

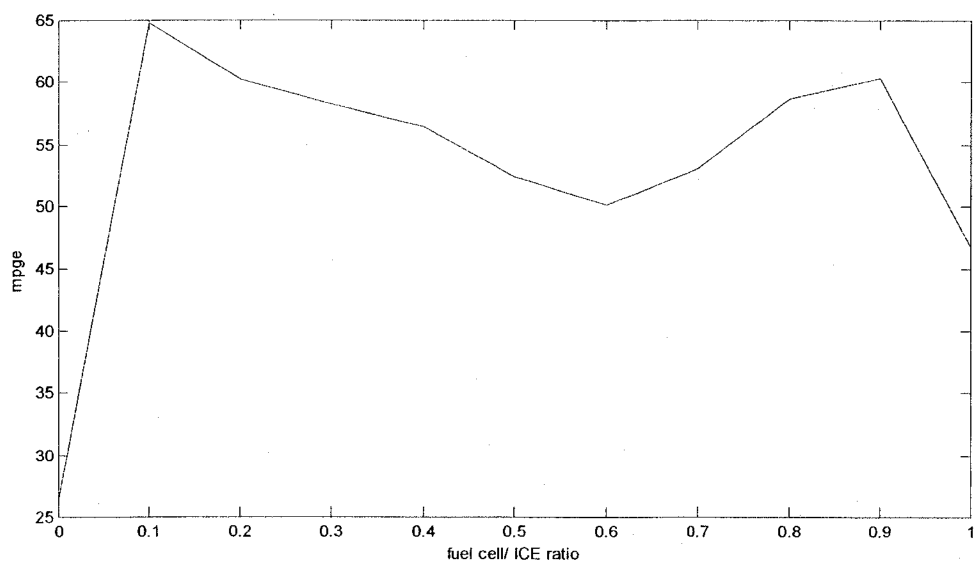

Figure 29 – Fuel Economy in US06

The maximum power required for US06 cycle is around 71.5 kW in ICE only and 68.5 kW in FC only modes (refer to Figure 30 and 40). The fuel economy for conventional ICE and full FC models is 26.4 mpge and 46.8 mpge respectively.

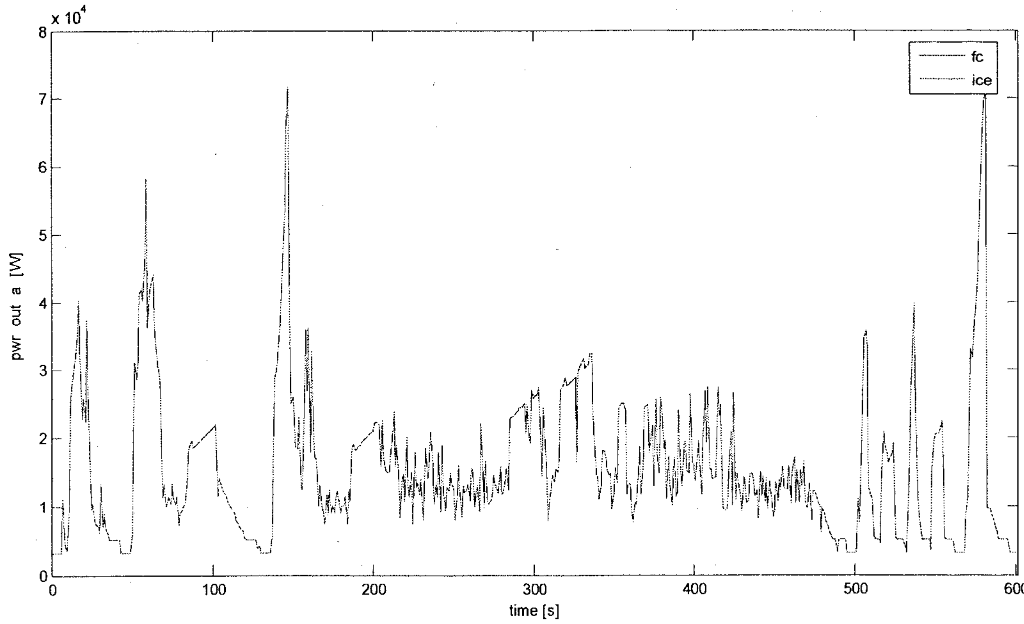

Figure 30 - 100% ICE_US06

It can be seen that a maximum fuel economy of 64.7 mpge is achieved at 10% hybridization. This is because, the FC takes care of the base power, eliminates engine idling and allows it to run on its high efficiency range (refer to Figure 31).

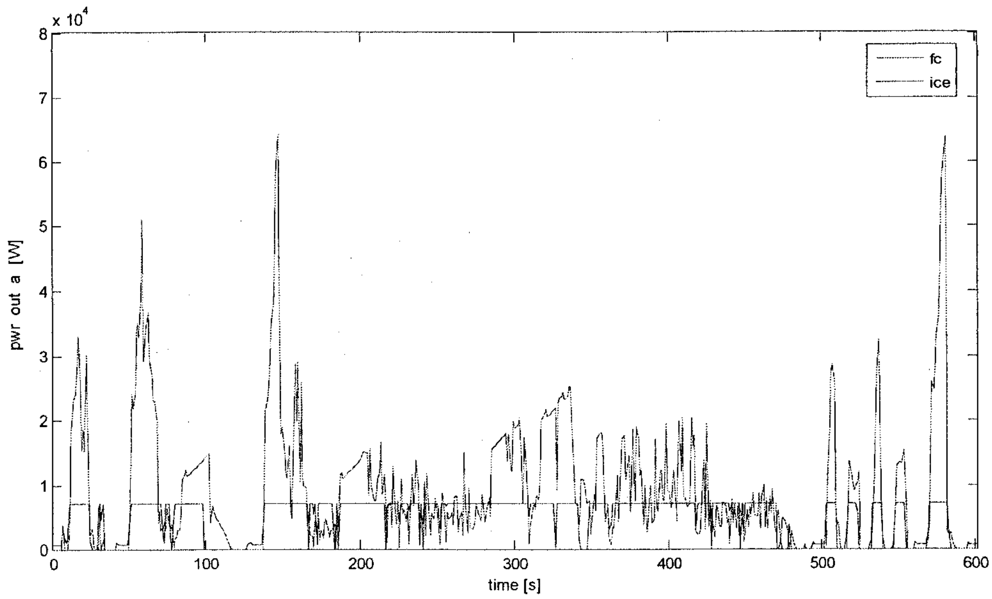

Figure 31 - 10% FC_US06

The fuel economy then decreases up to 60% hybridization as the ICE is frequently switched on and off. But the overall fuel economy values are greater than the FC only value because of increase in efficiency of FC (refer Figure 32 to 35).

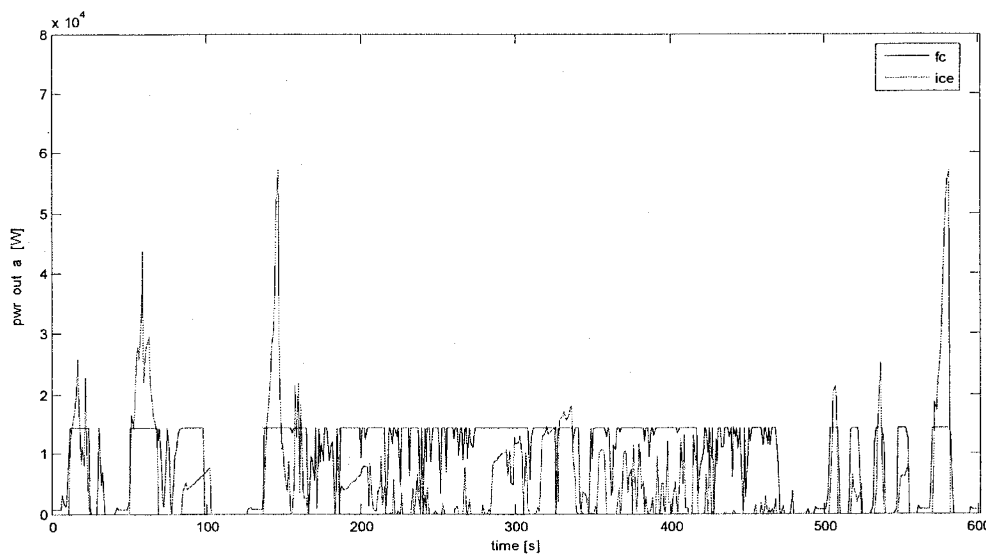

Figure 32 - 20% FC_US06

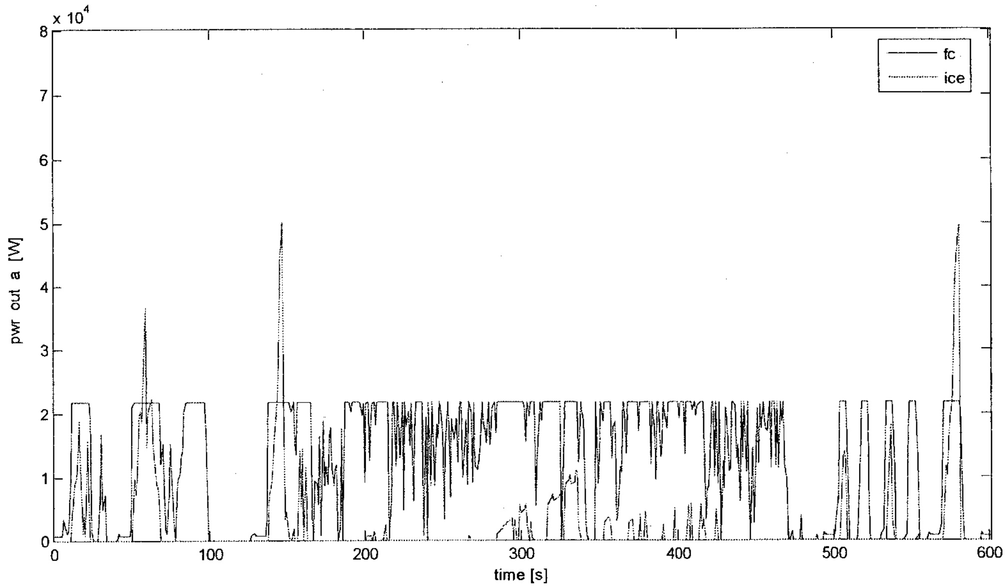

Figure 33 - 30% FC_US06

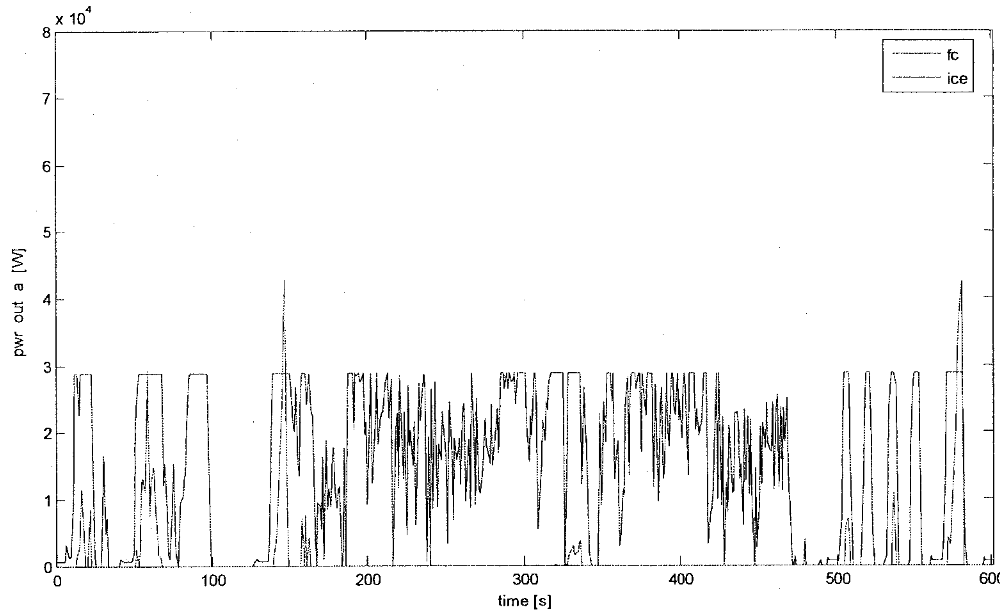

Figure 34 - 40% FC_US06

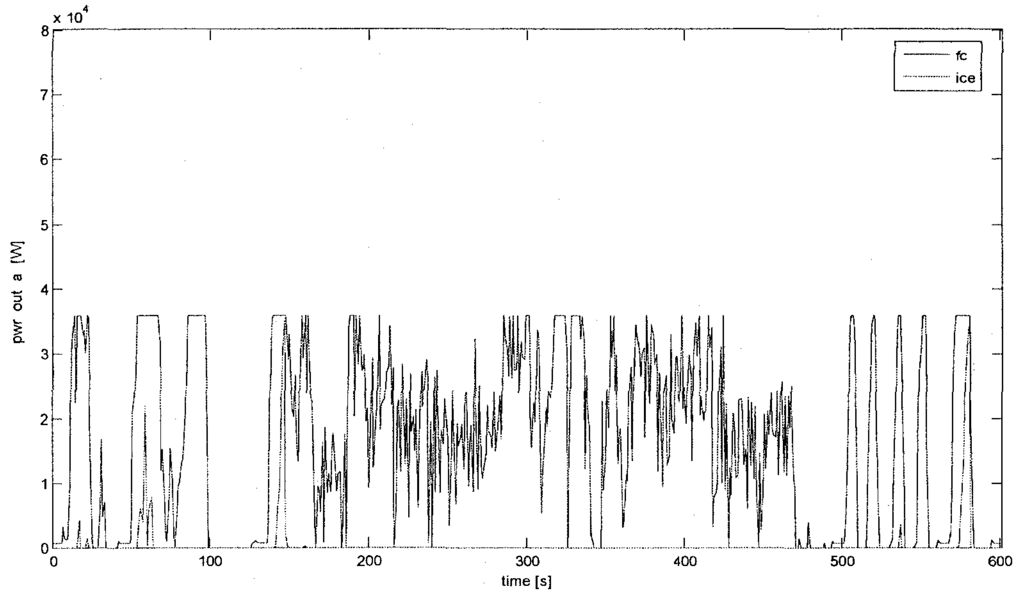

Figure 35 - 50% FC_US06

The fuel economy dips at 60% hybridization before tending an upward path again. This is when ICE is switched on to deliver large power within short span of time (rate of power demand is more) as shown in Figure 36.

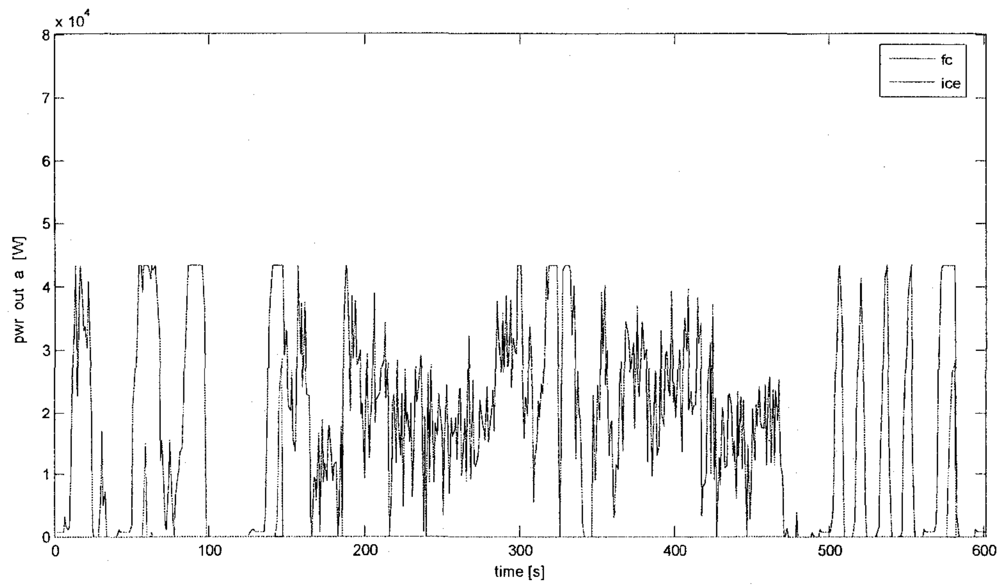

Figure 36 - 60% FC_US06

The trend is upward till 90% hybridization as the rate of power demanded from ICE decreases (refer Figures 37 to 39).

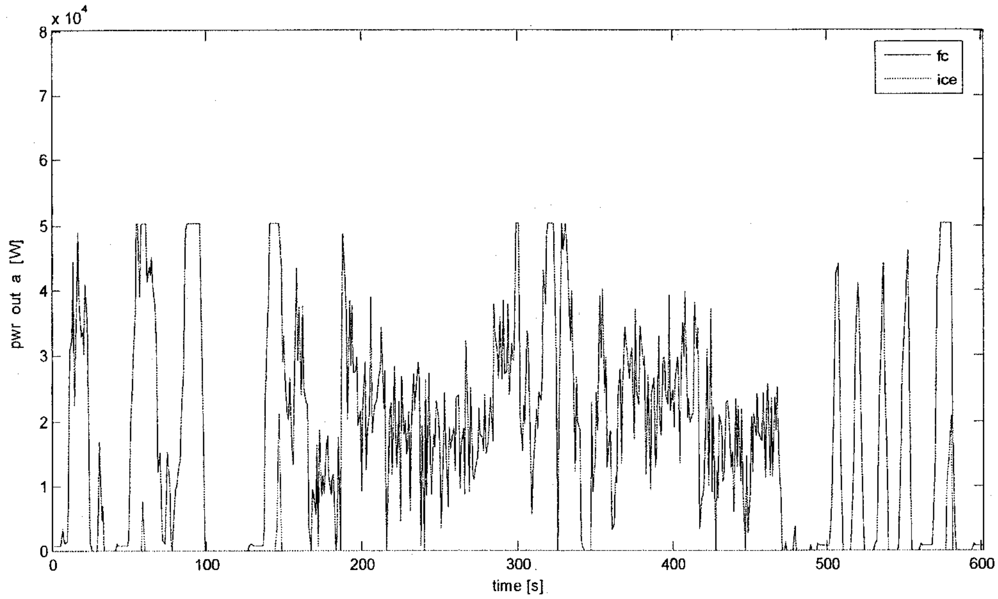

Figure 37 - 70% FC_US06

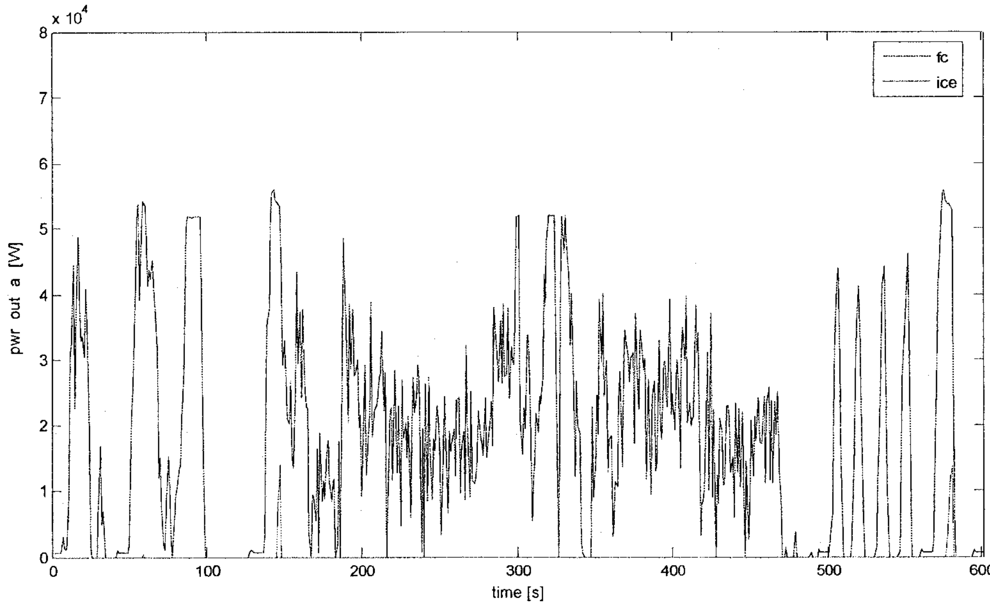

Figure 38 - 80% FC_US06

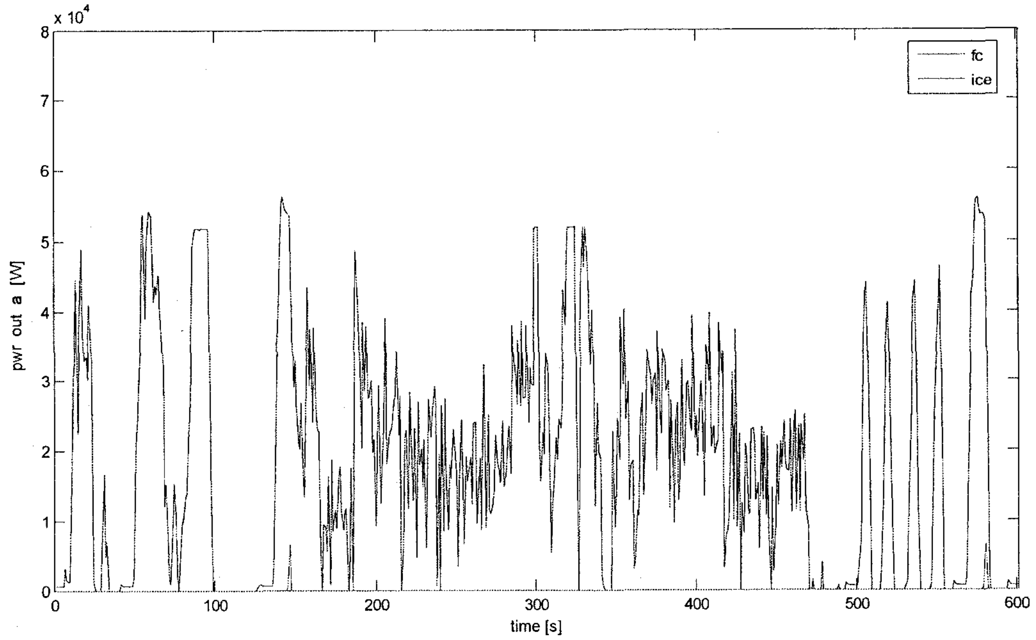

Figure 39 - 90% FC_US06

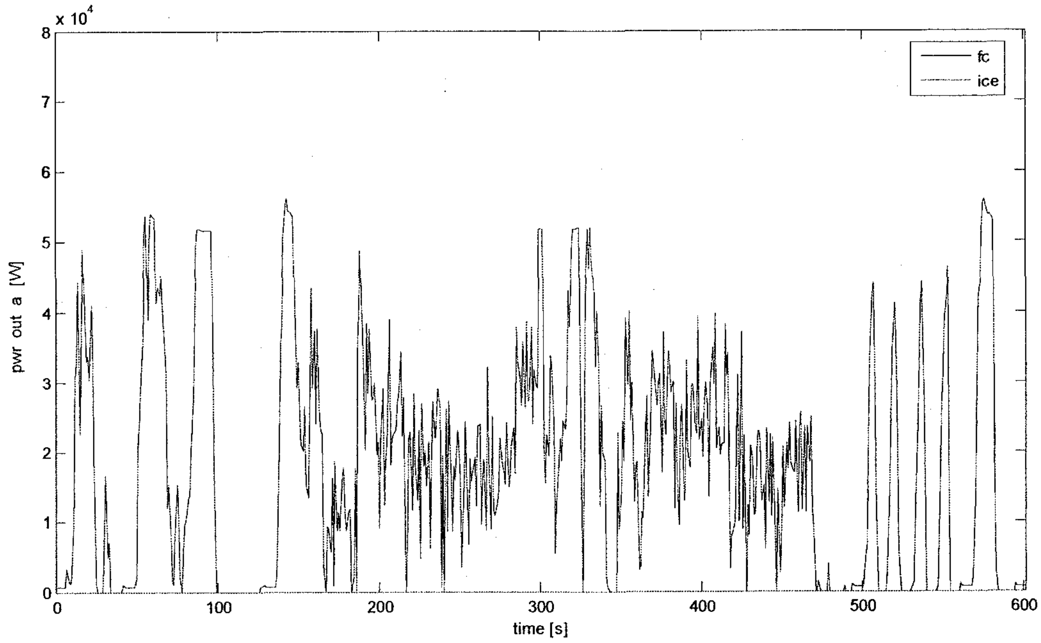

Figure 40 - 100% FC_US06

Comparison of results between UDDS and US06 Driving Cycles

Table 2 gives the consolidated fuel economy values for the two driving cycles chosen.

Table 2 – Comparison of Fuel Economy in UDDS and US06

Fuel Economy Results (mpge)		
Degree of Hybridization	UDDS Cycle	US06 Cycle
Conventional	22.0	26.4
0.1	52.4	64.7
0.2	65.8	60.2
0.3	58.1	58.2
0.4	56.9	56.4
0.5	55.7	52.5
0.6	54.4	50.1
0.7	54.4	53.1
0.8	54.4	58.7
0.9	54.4	60.3
Fuel Cell Vehicle	54.4	46.8

The maximum fuel economy is marginally less (1.67%) for US06 but its average is slightly more by 1.5% than UDDS. This might be due to increased power demand from the fuel converters and better usage of the ICE on highways.

The conventional vehicle fuel economy is 20% more while FC vehicle economy is 10.8% less for US06. This is because ICE is comparatively more efficient at higher speeds and longer cruising periods while the FC's are more efficient at lower vehicle speeds and frequent stop and go operations.

The fuel economy at 20% degree of hybridization for both the cycles is more than 60 mpge (65.8 for US06 and 60.2 for UDDS). This is approximately three times the fuel economy of conventional vehicle within the city driving.

Cost Analysis of Fuel Converter

The present cost of FC is between \$3000-\$4000/kW for private one time conversions and around \$1000/kW for automobile manufacturers. Big automobile companies like GM and Ford have forecast it to go down to \$300-\$500/kW in 2008 and the SAE's FreedomCAR 2010 goals are \$45/kW for a FC and \$35/kW for an ICE. Based on 2010 goals, Table 3 gives the cost of fuel converters at various degree of hybridization.

Table 3 – Cost of Fuel Converters on per kW basis

Fuel Cell / ICE ratio	Size of ICE, kW	Size of Fuel Cell, kW	Cost of ICE, \$	Cost of Fuel Cell, \$	Total Cost, \$
0	72.0	0.0	2520	0	2520
0.1	64.8	7.2	2268	324	2592
0.2	57.6	14.4	2016	648	2664
0.3	50.4	21.6	1764	972	2736
0.4	43.2	28.8	1512	1296	2808
0.5	36.0	36.0	1260	1620	2880
0.6	28.8	43.2	1008	1944	2952
0.7	21.6	50.4	756	2268	3024
0.8	14.4	57.6	504	2592	3096
0.9	7.2	64.8	252	2916	3168
1	0.0	72.0	0	3240	3240

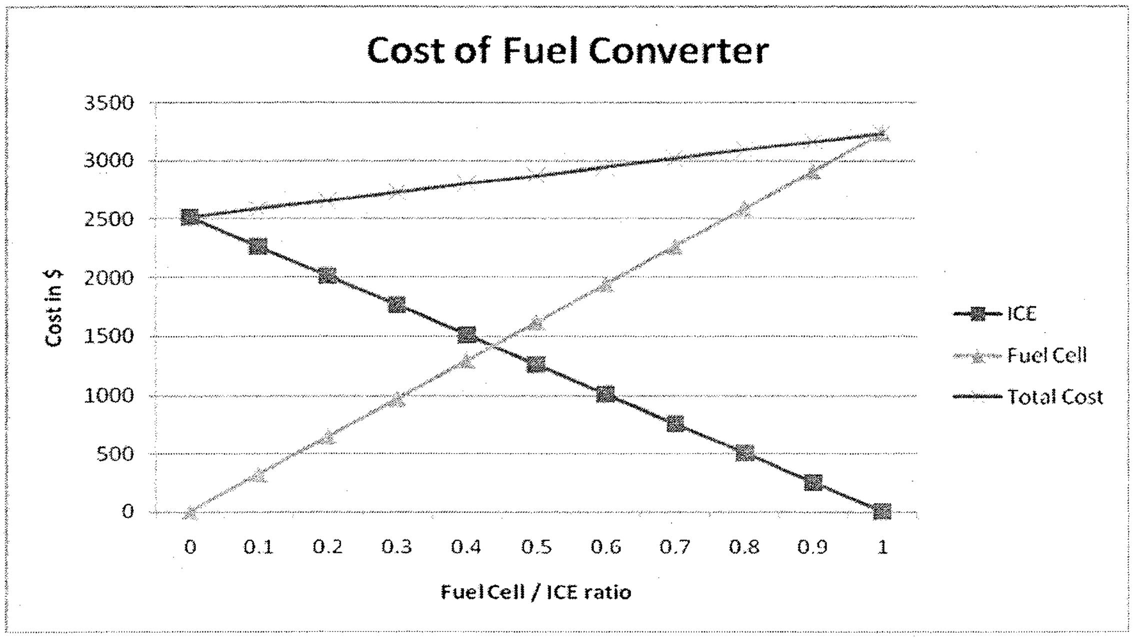

Figure 41 – Cost of Fuel Converters for Different Degrees of Hybridization

The Total Cost of fuel converters increases as the degree of hybridization increases (refer to Figure 41).

Hence, taking into account the fuel economy and the cost of fuel converters, the best trade off is at 20% hybridization. The default ICE can be downsized to 80% of its present rating while improving the fuel economy by 73% within city and 49.2% on highways at a moderate additional investment of 5.7% for fuel cells.

CHAPTER 5

CONCLUSION AND FUTURE SCOPE

Conclusions

The ever increasing environmental awareness and the need to improve fuel economy in vehicles present a daunting challenge for engineers and scientists. Everyday new designs and component improvements are being proposed. Under these circumstances, this research, though a theoretical one provides a good opportunity to learn and understand the concepts behind actual vehicle simulation. A systematic step by step approach was made to answer questions like what is the use of hybridizing the vehicle, how much hybridization is most beneficial, how to visualize the hybridized vehicle and how it responds under driving conditions.

Matlab/Simulink and ADVISOR softwares proved to be very versatile tools to carry out the simulations.

A 1985 Toyota pick-up truck was considered for hybrid conversion. A series hybrid configuration with both ICE and FC was modeled modifying the default ADVISOR codes. Then, various component data were carefully chosen and used in this model. Two common driving cycles were chosen to visualize the performance of the proposed series hybrid. The fuel economy values obtained from simulations were plotted and compared. The results were encouraging and provide strong reasons to go in for hybrid conversion.

will be the best design for converting the default conventional 72kW gasoline ICE vehicle. This 20% hybridized truck with an additional investment of 5.7% of the fuel converter cost will have 73% more fuel economy under city driving condition than the conventional truck considered.

Future Scope of the Project

This thesis points to new opportunities and avenues in the following areas

1. The current model can be modified to include energy storage modules like batteries or ultra capacitors that can capture energy through regenerative braking. This will improve the overall fuel economy of the vehicle.
2. The gasoline ICE used here can be replaced with hydrogen ICE. This will provide common fuel storage for both FC and ICE.
3. The analysis can be extended to include exhaust emissions.
4. Research can be extended to various other vehicle types like small, mid-size and large cars, SUV's, heavy duty trucks etc.
5. More driving cycles like HWFET (highway tests) can be utilized and the results from various cycles consolidated to predict the vehicle mileage closer to actual test procedures.
6. Measured data of components, if available, will make the simulation results more accurate.

APPENDIX - A

Equations used to model the ICE block

Equations used in subsystem

(torque available) = (engine torque available) – (accessories torque)

(accessories torque) = (accessories mechanical power) * (engine speed)
(engine torque available) = max((closed throttle torque), min((torque requested), (max torque)))

(torque requested) = (torque requested by clutch) + (inertial torque) + (accessories torque)

(inertial torque) = (shaft rate of acceleration) * (engine inertia)
(accessories torque) = (accessories power) / (shaft speed)

(speed available) = min((speed requested), (max engine speed)) * (clutch state = engaged) + (spin-down speed) * (clutch state ~= engaged)

(spin-down speed) = max((idle speed),(closed throttle speed))

(closed throttle speed) = ((closed throttle torque) - (accessories torque)) / (engine inertia) * (time step)

(speed requested) = (speed requested by clutch)

(gallons of fuel used) = sum(fuel used per time step)

(fuel used per time step) = (engine out fuel used) * (engine temperature fuel use correction factor)

Equations used to model the FC block

Power vs. Efficiency Model

(power available) = min(power requested, max power)

(gallons of fuel used) = sum(fuel used per time step)

(fuel used per time step) = (fuel used) * (temperature correction factor)

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ADVISOR Software Help Manual

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