Modeling and Simulation of A Hybrid Electric Vehicle Using MATLAB/Simulink and ADAMS

by

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Abstract

As the global economy strives towards clean energy in the face of climate change, the automotive industry is researching into improving the efficiency of automobiles. Hybrid vehicle systems were proposed and have demonstrated the capability of reducing fuel consumption while maintaining vehicle performance. Various hybrid vehicles in the form of parallel and series hybrid have been produced by difference vehicle manufacturers. The purpose of this thesis is to create a hybrid vehicle model in MATLAB and ADAMS to demonstrate its fuel economy improvement over a conventional vehicle system.

The hybrid vehicle model utilizes the Honda IMA (Integrated Motor Assist) architecture, where the electric motor acts as a supplement to the engine torque. The motor unit also acts as a generator during regenerative braking to recover the otherwise lost kinetic energy. The powertrain components' power output calculation and the control logic were modeled in MATLAB/Simulink, while the mechanical inertial components were modeled in ADAMS. The model utilizes a driver input simulation, where the driver control module compares the actual and desired speeds, and applies a throttle or a braking percent to the powertrain components, which in turns applies the driving or the braking torque to the wheels. Communication between MATLAB and ADAMS was established by ADAMS/Controls.

In order to evaluate the accuracy of the MATLAB/ADAMS hybrid vehicle model, simulation results were compared to the published data of ADVISOR. The West Virginia University 5 Peaks drive cycle was used to compare the two software models. The results obtained from MATLAB/ADAMS and ADVISOR for the engine and motor/generator correlated well. Minor discrepancies existed, but were deemed insignificant. This validates the MATLAB/ADAMS hybrid vehicle model against the published results of ADVISOR.

Fuel economy of hybrid and conventional vehicle models were compared using the EPA New York City Cycle (NYCC) and the Highway Fuel Economy Cycle (HWFET). The hybrid vehicle demonstrated 8.9% and 14.3% fuel economy improvement over the conventional vehicle model for the NYCC and HWFET drive cycles, respectively. In addition, the motor consumed 83.6kJ of electrical energy during the assist mode while regenerative braking recovered 105.5kJ of electrical

energy during city driving. For the highway drive cycle, the motor consumed 213.6kJ of electrical energy during the assist mode while the regenerative braking recovered 172.0kJ of energy.

The MATLAB/ADAMS vehicle model offers a simulation platform that is modular, flexible, and can be conveniently modified to create different types of vehicle models. In addition, the simulation results clearly demonstrated the fuel economy advantage of the hybrid vehicle over the conventional vehicle model. It is recommended that a more sophisticated power management algorithm be implemented in the model to optimize the efficiencies of the engine and the motor/generator. Furthermore, it is suggested that the ADAMS vehicle model be validated against an actual vehicle, in order to fully utilize the multi-body vehicle dynamics capability which ADAMS has to offer.

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Nomenclature

T_{out}	Motor torque output [Nm]
$P_{desired}$	Desire motor power [W]
ω_{engine}	Engine speed [rad/s]
ε	Consumed or generated by the motor/generator [J]
P_{mogen}	Power consumed or generated by the motor/generator [W]
P_{max}	Maximum power output available from the engine and the motor combined [W]
$\%_{throttle}$	Throttle input percent by the driver [W]
F_d	Vehicle drag force [N]
C_D	Drag coefficient of the Honda Insight
A	Frontal area of the Honda Insight [m^2]
ρ_{air}	Density of air [kg/m^3]
v_{act}	Actual vehicle velocity [m/s]
$steering_{output}$	Steering controller output signal [mm]
$steering_{desired}$	Desired vehicle steering path in Y-coordinate [mm]
$steering_{actual}$	Actual vehicle steering path in Y-coordinate [mm]
$steering_{gain}$	Proportional steering closed loop controller gain value
$Fuel_{equiv}$	Equivalent fuel amount of the motor/generator's electrical energy [L]
ε_{elec}	Electrical Energy of the motor/Generator [J]
ρ_{fuel}	Density of gasoline [g/L]
lhv_{fuel}	Lower heating value (does not contain water vapour energy) of gasoline [J/g]

Chapter 1

Introduction

As the global economy strives towards clean energy in the face of climate change, the industrial world is researching into alternative sources of energy. Since automobiles are currently a major source of air pollution, governments and major automotive companies are collaborating to provide a solution that will result in the reduction of vehicle emissions, while reducing the consumption of fossil fuel. Various forms of fossil fuel reduction methods and alternative power sources are currently researched by different manufacturers. The two notable categories in research are internal combustion (IC) engine vehicles and electric vehicles. Fuels presently utilized in internal combustion engine vehicle include turbo or supercharging gasoline, diesel, methanol, and natural gas. The energy path of the IC engine is to transform the energy content of various fuel sources into kinetic energy that propels the vehicle forward. This is accomplished by using the expansion of burning fuel in a chamber to provide a translational motion to propel the wheels. The advantage of IC engine is that fuels with high-energy content can be transported easily, while the disadvantage is that the burning of fuels creates emissions that are hazardous to the environment. Alternatively, the electric vehicle uses electric energy from a battery or fuel cell, and converts it into kinetic energy via electric motors. The advantage of an electric vehicle is that zero emissions are produced when the electric energy is converted into kinetic energy. Various methods of providing electric energy are currently being explored. Conventional battery is one method of storing electric energy, although current technologies prevent a working solution with reasonable vehicle mileage. Hydrogen fuel cell is an alternative method of storing electrical energy; however, current technologies have not matured yet to provide a safe storage of hydrogen.

In search for a working solution, a hybrid vehicle system which combines the advantages of both power sources (IC engine and battery), was proposed. By definition, a hybrid vehicle is one that employs two or more power sources to improve the overall efficiency of the vehicle. By combining an internal combustion engine with an electric battery-motor system, the goal of fuel portability can be solved. In addition to achieving low emission and fuel consumption requirement, hybrid electric vehicle can recapture the otherwise lost kinetic energy during the braking cycle, thus further improving the efficiency of the vehicle system. Hybrid vehicle systems can also be utilized for military application. By using the electric power source during vehicle idling, minimal thermal signature is released, thus lowering the chances of enemy detection.

In order to increase the efficiency and accuracy of automotive design, Computer Aided Engineering (CAE) has been playing an ever increasing role throughout the process of vehicle design. With the increase of computing power, manufacturers are now able to perform design, testing, and optimization of a vehicle through computer simulation, all prior to the actual manufacturing of a vehicle. Similar to other areas of automotive research such as vehicle dynamics and crash worthiness, numerous software packages were developed in order to evaluate the energy efficiencies of the hybrid electric vehicle. One particular example is a software originally developed by the U.S. Department of Energy (DOE) and the National Renewable Energy Laboratory (NREL) called ADVISOR (Advanced Vehicle Simulator), which was later acquired by AVL Powertrain Engineering, Inc. ADVISOR is a software based on MATLAB/Simulink that can be used to simulate and analyze light and heavy vehicles, including hybrid and fuel cell vehicles, where it allows the user to customize the power components such as internal combustion engines and electric motors to study the effect on fuel efficiency and vehicle performance.

The purpose of this thesis is to create a MATLAB/ADAMS hybrid vehicle model that demonstrates the fuel efficiency advantage of a hybrid vehicle. Current hybrid vehicle simulation software such as ADVISOR can only simulate vehicle performances from an energy standpoint and does not consider the complexity of multi-body dynamics of a vehicle system. Similarly, vehicle dynamics simulation software tends to focus on the dynamic performance of a vehicle, and does not consider the energy efficiency of the vehicle’s powertrain components. The MATLAB/ADAMS simulation platform of this thesis will combine the capabilities of both fields to allow the user to perform powertrain design studies on a hybrid electric vehicle in a multi-body dynamic environment.

The MATLAB/ADAMS simulation platform of this thesis consists of a simple hybrid electric vehicle system based on the mechanical and powertrain components of the Honda Insight using its IMA (Integrated Motor Assist) architecture, where the electric motor will act as an assisting device to complement the engine. The Honda IMA system was chosen since it was the least complex of all hybrid systems. The mechanical components of the vehicle body were created in MSC ADAMS, while the power components and the power management logic were modeled in MATLAB/Simulink. Chapter 2 will further discuss various configurations of hybrid electric vehicles, and also provide an overview of existing hybrid vehicle designs available on the market. Chapter 3 will present the overall structure of the hybrid vehicle and its components in detail. Chapter 4 will discuss the software structure of the simulation platform used to simulate the hybrid vehicle. Comparison of simulation results obtained from the MATLAB/ADAMS simulation platform and ADVISOR will be presented. Chapter 5 will contain comparative analysis of hybrid and conventional vehicle simulation based on the ADAMS/MATLAB vehicle model. City and highway standard drive cycles will be used to simulate the performance and the fuel efficiency of the hybrid and conventional vehicles. Finally, Chapter 6 will conclude the modeling and simulation of the MATLAB/ADAMS hybrid vehicle model, and provide recommendations for further improvement of the vehicle system.

Chapter 2

Literature Review and Background

The most successful hybrid configuration currently utilized by various vehicle manufacturers consists of a diesel or gasoline engine, coupled with a motor and a generator linked with a battery system. Although there are many different hybrid configurations currently proposed by vehicle manufacturers, most configurations can be categorized into two hybrid systems: Series Hybrid and Parallel Hybrid.

2.1 Series Hybrid

In the series hybrid system, the IC engine drives the generator, and electricity is supplied to the battery. The electrical energy from the battery is then received by the motor, which in turns drives the wheels to propel the vehicle. Figure 2-1 illustrates the system configuration of a series hybrid electric vehicle. [1]

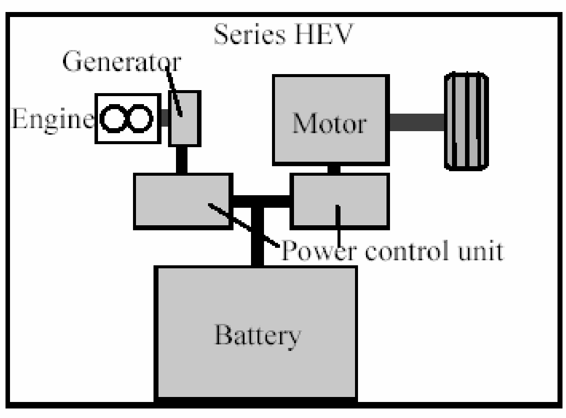

Figure 2-1: Schematic of a Series Hybrid Electric Vehicle [1]

The advantage of the series hybrid is that the engine runs at its best efficiency, thus generating the maximum electrical energy to charge the battery. Since the engine is constantly operating at its optimum efficiency, and the vehicle receives its power solely from the electric motor, this system is most efficient during the stop and go of city driving. In addition, the internal combustion engine of the series hybrid vehicle can be replaced by a fuel cell, thus converting it into a pure electric vehicle. The disadvantage of a series hybrid vehicle is that the efficiency of the system is reduced during highway driving cycles. During highway driving, the engine has to convert fuel energy to electrical energy, which will be converted again to kinetic energy to drive the wheels. Energy loses during conversion in addition to lower torque output of the electric motor at high rotational speeds contributes to the overall lower efficiency of the system.

2.2 Parallel Hybrid

The parallel hybrid configuration switches between the two power sources, i.e., the internal combustion engine and the electric motor drive, where the high efficiency range of each is selected and utilized. Depending on the situation, both power sources can also be used simultaneously to achieve the maximum power output. Figure 2-2 shows the system configuration of a parallel hybrid electric vehicle. [1]

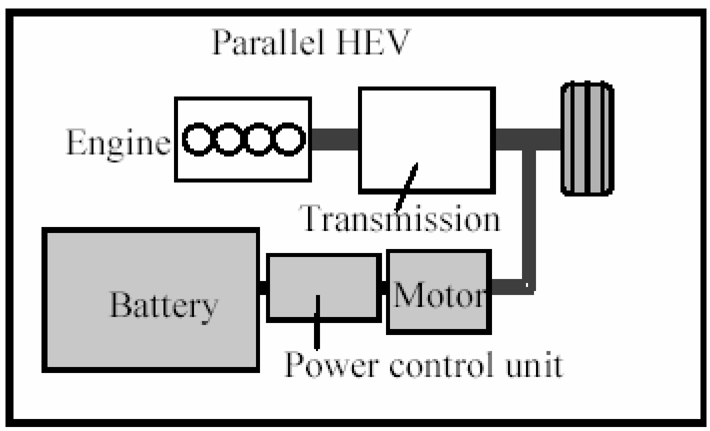

Figure 2-2: Schematic of a Parallel Hybrid Electric Vehicle [1]

The advantage of a parallel hybrid vehicle is that the system has the ability to offer higher efficiency during highway driving condition. During highway driving, the vehicle speed does not vary significantly and therefore it is more efficient to drive the wheels directly from the IC engine. In addition, the electric motor can be used solely during city driving while the IC engine recharges the battery, thus providing higher overall efficiency. In addition, both power sources can be utilized simultaneously to provide maximum performance of the vehicle.

2.3 Existing Design

Various automakers have successfully introduced hybrid electric vehicles into the automobile market. The following sections describe the system configuration of the most popular hybrid vehicles that are currently on the market.

2.3.1 Toyota

Toyota launched the Prius, the world's first mass-produced hybrid vehicle in 1997, and introduced the vehicle to the US and Europe in 2000. The Estima and the Crown Mild hybrid vehicle were placed in the Japanese market following the Prius. Currently, Toyota has over 100,000 hybrid vehicles in the automotive market. Toyota has developed three different Hybrid systems for the vehicles: THS (Toyota Hybrid System) for the Prius, THS-C (Toyota Hybrid System – CVT) for the Estima, and THS-M (Toyota Hybrid System – Mild) for the Crown. [2, 3, 4, 5]

Energy Management Principle

Figure 2-3 shows the energy management principle of the Toyota hybrid vehicles. Due to the fact that the engine has different energy conversion efficiencies at different points in the operating range, a battery is used to store or supply energy to ensure maximum efficiency is achieved during a typical drive cycle. When the vehicle accelerates, the additional energy is supplied from the battery, while the engine runs in the optimum efficiency range to supply the power required by the load. During cruising of the vehicle, the engine is still operating in the maximum efficiency range, and depending on the demand, excess energy is stored back in the battery. Energy can be supplied from the battery if the vehicle needs to operate at a higher load. Finally, during deceleration, the engine is turned off, and the braking energy is recovered by a generator and is returned to the battery. This state of operation is often referred to as regenerative braking. Depending on the state of the charge of the battery, the engine can remain on to charge the battery while still regenerative braking is performed. [3]

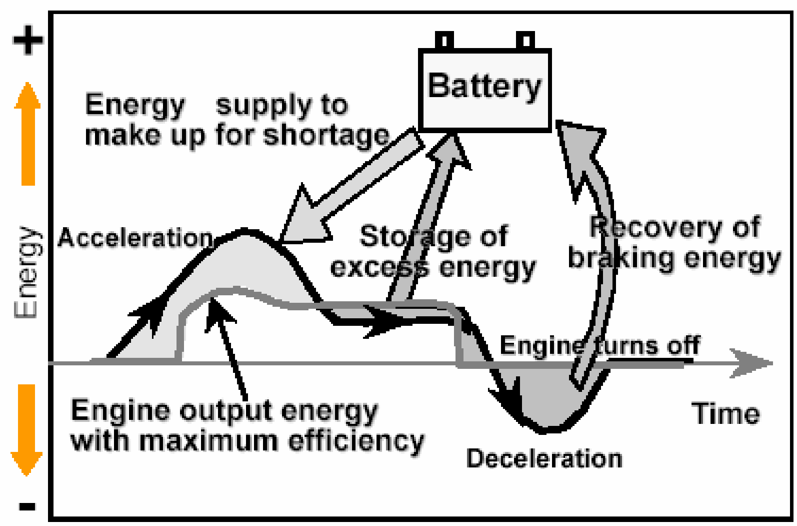

Figure 2-3: Toyota Power Management Principle [3]

THS (Prius) System

The Toyota Prius is the hybrid vehicle marketed by Toyota in the compact sedan segment. Figure 2-4 illustrates the schematic diagram while Table 2-1 summarizes the specification of the Prius THS. This system is a combination of parallel and series hybrid system, thus achieving the advantages of both systems. A gasoline engine and an electric motor are utilized as the power sources, with the gasoline engine remains as the main power source. The power produced by the gasoline engine is distributed to drive the wheels as well as the generator via a set of planetary gears. Depending on the mode of operation, the engine power can be used to solely drive the wheels, be distributed between the wheels and the generator, or be used solely to power the generator. The engine can also be completely shut off if the battery is fully charged. The generated electric power can be used to drive the motor, or is converted into direct current and stored in a high voltage battery. [3, 5]

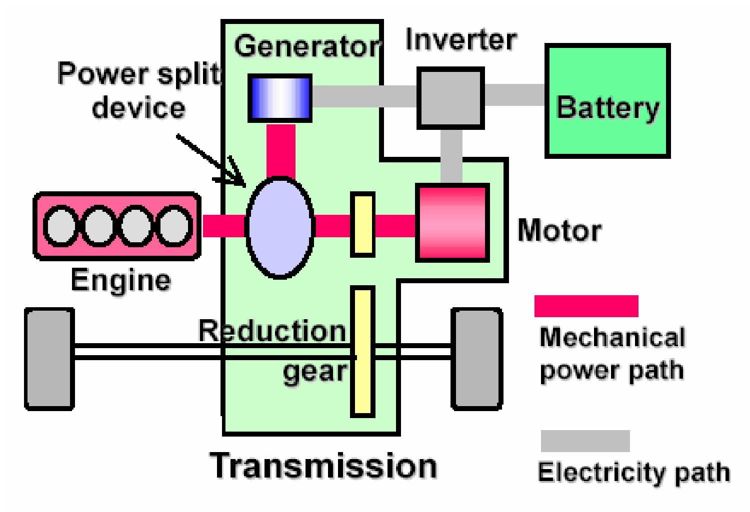

Figure 2-4: Toyota Hybrid System Schematic [3]

Table 2-1: Toyota Prius THS Specification [2]

Curb Weight	1,220kg
Battery	21kW, 274V, 6.5Ah
Motor Generator	33kW
Engine Max Power	53kW @ 4500rpm
Engine Max Torque	115Nm @ 4200rpm

THS-C (Estima) System

The Toyota Estima Hybrid is the hybrid vehicle marketed by Toyota in the mini-van segment in Japan. Figure 2-5 depicts the configuration while Table 2-2 summarizes the specification of the Estima THS-C. This system is based on the THS (Prius) system with the addition of an electric motor to power the rear wheels, thus creating a rear drive unit that is mechanically separated from the front system, eliminating the need for transfers or propeller shafts. The result is the construction of a 4WD system that satisfies the demands of a mini-van. The transaxle of the front drive unit incorporates a CVT (Continuous Variable Transmission) that achieves excellent driving comfort with smooth speed change. [2, 3]

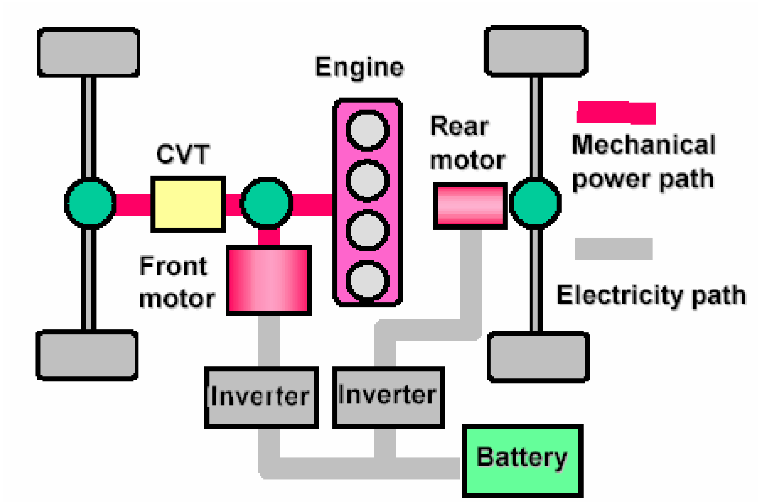

Figure 2-5: Toyota Hybrid System-CVT Schematic [3]

Table 2-2: Toyota Estima THS-C Specification [2]

Curb Weight	1,850kg
Battery	216V, 6.5Ah
Front Motor Generator	13kW
Engine Max Power	96kW @ 4500rpm
Engine Max Torque	190Nm @ 4200rpm
Rear Motor Generator	18kW

THS-M (Crown) System

The Crown mild hybrid is a luxury sedan introduced in the Japanese market. The mild hybrid differs from previous systems in that the motor-generator is not used to drive the wheels. Instead it is used to power the auxiliary devices such as air conditioner and power steering, and is used to recover the otherwise lost energy during deceleration during braking. In addition, it is also used to start the engine during the idle stop operation. In order to maximize the fuel economy of the system, the engine is turned off when the vehicle is at a stop. When the vehicle starts moving, the motor will instantly start the engine, thus allowing the vehicle to start instantly. Figure 2-6 shows the schematic of the THS-M system. The motor-generator in this system is connected to the engine via the engine belt. The motor-generator is connected to the inverter unit, which is then connected to the batteries.

The 42-V power supply system was selected due to the fact that it not only meets the high power requirement unique to the hybrid vehicle, but also the increasing electrical loads of existing vehicles. In addition, since international standardization of the 42-V power supply system has been publicized as the next generation power supply system, it is cost-efficient to incorporate the new system into the hybrid components. [3, 4] Table 2-3 summarizes the motor-generator specification utilized on the Crown mild hybrid vehicle [4].

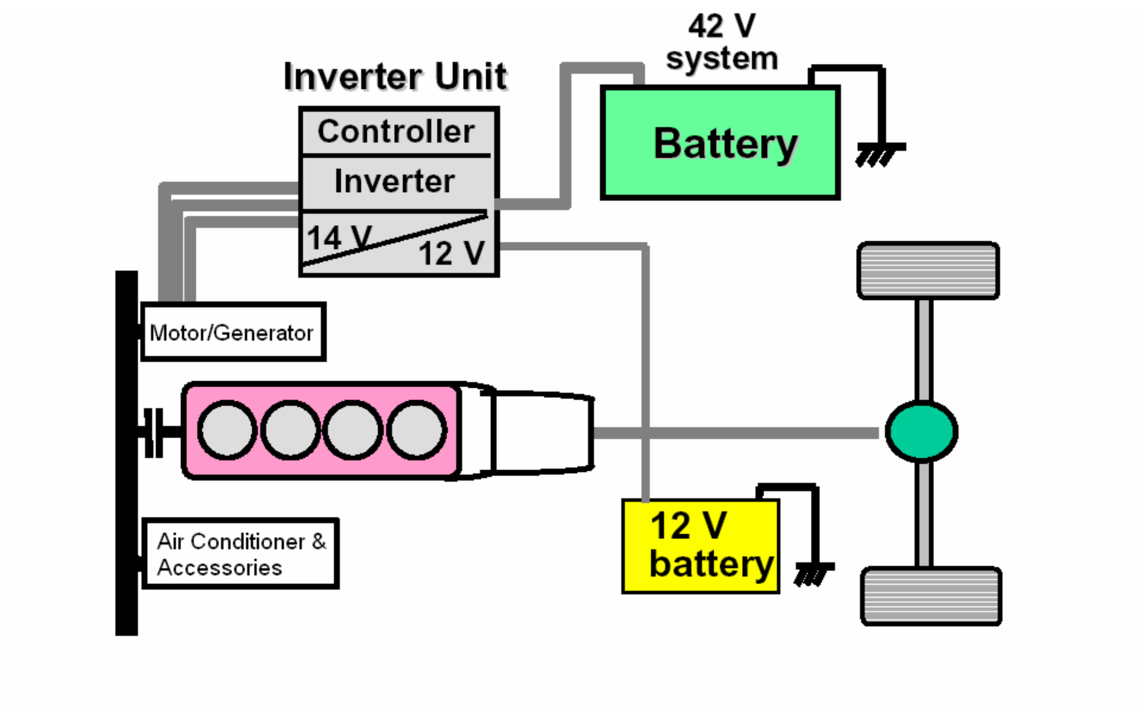

Figure 2-6: Toyota Hybrid System-Mild Schematic [3]

Table 2-3: Toyota Crown THS-M Specification [4]

Motor Type		AC Synchronous Motor
Rated Voltage		36V
Power Rating	Drive	3.0kW
	Generation	3.5kW
Maximum Torque		56.0Nm (0-300rpm)
Permissible Max. Speed		15,000rpm
Cooling Method		Air Cooling

2.3.2 Honda

Currently, Honda has two hybrid electric vehicles on the market: the Insight and the Civic Hybrid. The Insight is a two door coupe that was introduced in 1999, and is the first vehicle to contain the Honda IMA (Integrated Motor Assist) system. The Civic Hybrid was made available in 2002, and has a modified IMA system that is fitted to the Civic's 5-passenger 4-door sedan body. The Insight achieved a fuel consumption rate of 3.4L/100km, while the Civic Hybrid with the manual transmission attained 5.1L/100km and 4.6L/100km in the city and on the highway respectively. [1, 6]

Integrated Motor Assist (IMA) System

The IMA system schematic is shown in Figure 2-7. In this system, a permanent magnet DC brushless motor is placed with direct crankshaft connection between the engine and the transmission. The IMA system uses the engine as the main power source, while the motor acts as an auxiliary power source when accelerating. By using the motor as an auxiliary power source, the overall system is simplified, and it is possible to use compact and light-weight motor, battery, and power control unit, thus reducing the overall weight of the vehicle. [1]

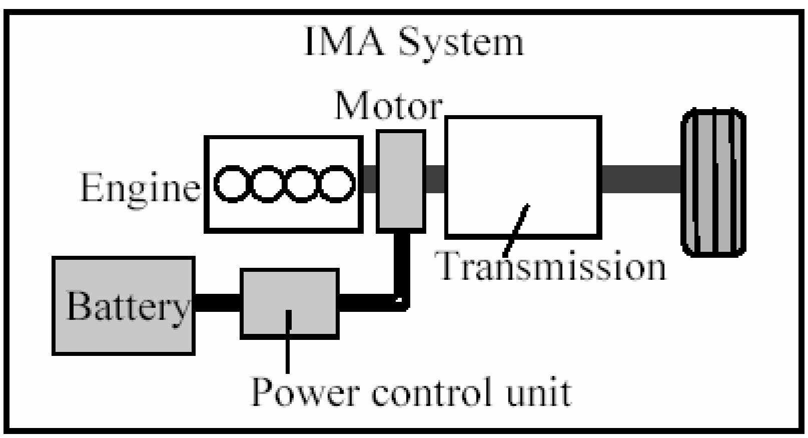

Figure 2-7: Honda IMA Schematic [1]

Figure 2-8 illustrates the vehicle layout of the Civic Hybrid vehicle. The powertrain which includes the engine, motor, and the transmission, is placed in the front of the vehicle. The Intelligent Power Unit (IPU) along with the Power Control Unit (PCU) that controls the motor and the battery is placed in the rear of the vehicle.

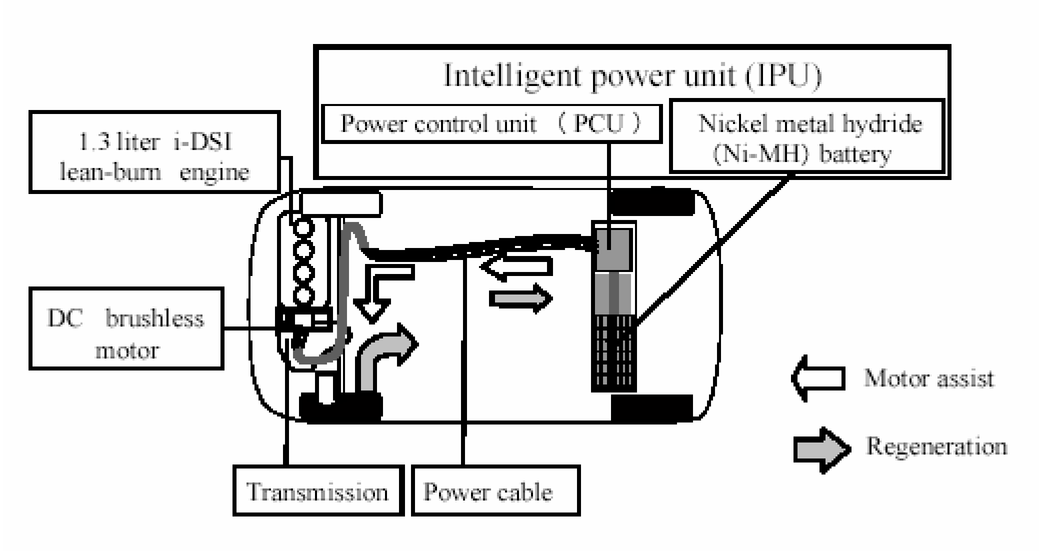

Figure 2-8: Honda Civic Hybrid Schematic [1]

System Description

Three techniques were employed to increase the overall efficiency of the system: [1]

1. Deceleration Energy Regeneration and Acceleration Assist
2. Idle Engine Stop
3. Reduction in Engine Displacement

Conventionally, kinetic energy is lost by braking and engine friction during deceleration. By utilizing the motor as a generator, the otherwise lost energy can be recovered into useful electric energy, and can be used during acceleration, thus increasing the efficiency. Secondly, by shutting off the engine during vehicle idling, fuel is not consumed, therefore reducing unnecessary fuel consumption. Finally, by having a motor for auxiliary power, it is possible to achieve the required dynamic performance through the combination of the engine and the motor. Therefore, it is possible to reduce the engine displacement, which further reduces the fuel consumption. Table 2-4 summarizes the powertrain specification of the Honda Civic Hybrid. [1]

Table 2-4: Honda Civic Hybrid Powertrain Specification [1]

Engine	• Inline 4-cylinder 1.3 liter i-DSI lean-burn SOHC engine • Max Power (kW/rpm): 63/5700 • Max Torque (Nm/rpm): 119/3300
Transmission	Continuous Variable Transmission (CVT) or Manual Transmission (MT)
Motor (Assist)	• DC Brushless Motor • Max Power: 10kW • Max Torque: 62Nm (Starter); 103Nm
Motor (Regeneration)	• Max Power: 12.3kW (MT), 12.6kW(CVT) • Max Torque: 108Nm
Battery	Nickel Metal Hydride (Ni-MH)

2.3.3 Nissan

Nissan developed the Tino hybrid electric vehicle which was launched in Japan in March 2000. The development goal of the Tino hybrid is to achieve a fuel economy twice as good as that of the conventional vehicle. The following measures were used by Nissan to achieve the reduction in fuel consumption: [7]

- Recover braking energy to store in the battery
- Eliminate idling
- Enhance engine efficiency and increase the frequency driven under such efficiency range
- Drive with motor-generated power in low engine load ranges using the power recovered from deceleration energy or generated under high engine efficiency ranges

The comparison of efficiency between the motor and the engine utilized by the Tino Hybrid is shown in Figure 2-9.

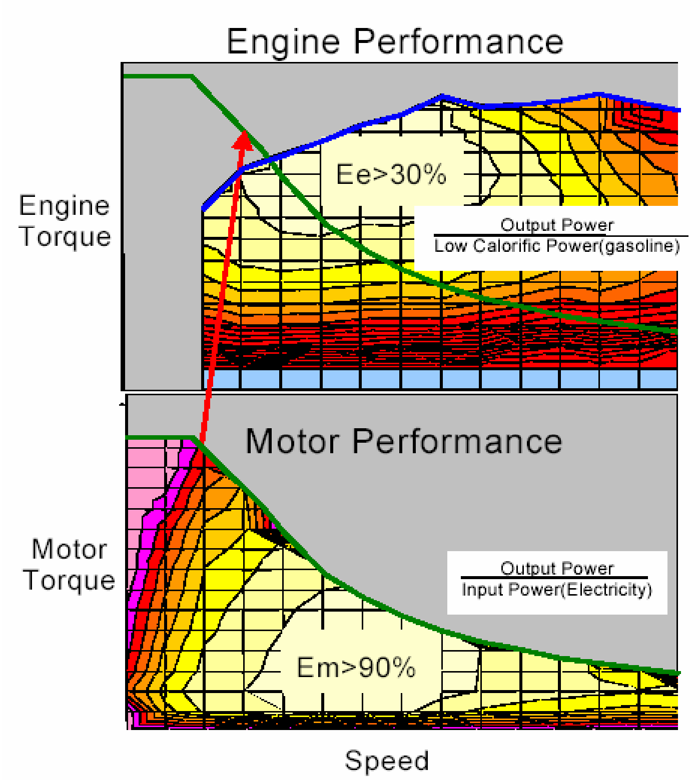

Figure 2-9: Comparison of Engine and Motor Performance Efficiencies [7]

The yellow coloured region shown in Figure 2-9 depicts the higher efficiency areas for both the engine and the motor, while the red coloured areas indicate the low efficiency region of the components. It is shown the motor shows higher efficiency in most areas, while the engine has significantly lower efficiency at the low-load range. Efficiency of the motor was derived by multiplying the charging and the discharging efficiencies of the battery. In hybrid electric vehicles, the power generated by the engine in the high-efficiency range is used to charge the battery, and used to drive the motor at low speed. The efficiency by the motor-powered driving will exceed that of the engine-powered driving, thus increasing the overall vehicle efficiency. [7]

System Specification

The major components of the Tino hybrid propulsion system include: [7]

1. Two power sources: a gasoline engine and a traction motor for propulsion and energy regeneration
2. A Continuous Variable Transmission (CVT)
3. An electromagnetic clutch for transmitting power

4. A motor for generating power and starting the engine
5. Batteries

A schematic of the Tino hybrid propulsion system is shown in Figure 2-10.

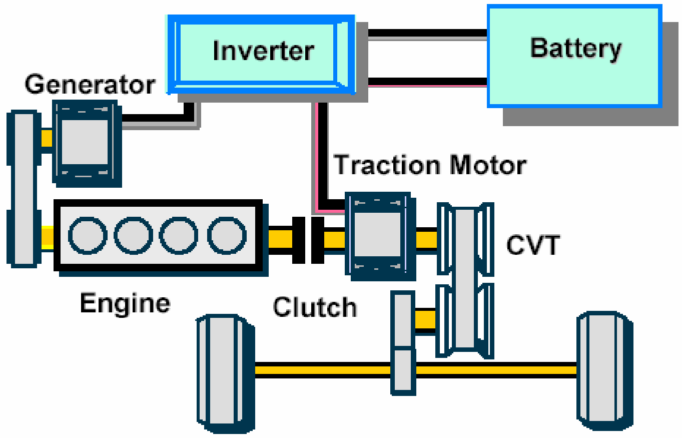

Figure 2-10: Nissan Tino Propulsion System Schematics [7]

As shown in Figure 2-10, the engine and the traction motor are placed upstream of the CVT such that both can transmit power to the wheels directly. An electromagnetic clutch is placed between the traction motor and the engine in order for the engine to be turned on or off independently. Power can then be generated regardless of the driving condition. The generator, which is placed in front of the engine, generates electric power and starts the engine as well. A lithium-ion battery was selected due to its high efficiency even with repeated charging and discharging at high power. The specifications of each component are summarized in Table 2-5. [7]

Table 2-5: Nissan Tino Powertrain Specification [7]

Engine (Gasoline)	• 4-cylinder DOHC, 1.8L, 73 kW • Continuously variable intake valve timing • Electronically controlled throttle
Transmission	Motor-integrated belt CVT with motor-driven oil pump
Traction Motor	Permanent magnetic synchronous motor 17kW
Generator	Permanent magnetic synchronous motor 13kW
Clutch	Electromagnetic Clutch
Battery	Li-ion battery with Mn electrode

2.4 Summary

Presently, two types of hybrid configurations have been proposed and utilized by various manufacturers: Series and Parallel Hybrid. The series hybrid consists of a fuel converter that drives the generator, in which electricity is supplied to the battery and the motor, which subsequently drives the wheels. The parallel hybrid, on the other hand, switches between the two power sources, i.e., the fuel converter and the electric motor drive, where the high efficiency range of each is selected and utilized.

Notable current hybrid vehicle manufacturers are Toyota, Honda, and Nissan. Toyota and Nissan both utilize a combination of parallel and series hybrid architecture on their vehicles, where during city driving the system acts as a series hybrid, and switches to parallel hybrid during highway driving or under hard acceleration. Honda, on the other hand, implements the Integrated Motor Assist (IMA) system, where the engine drives the wheels at all time, while the electric motor provides additional torque when required. The disadvantage of such system is that higher fuel economy would be seen during city driving. All systems however, utilize regenerative braking to recapture the otherwise lost kinetic energy during the braking cycle, thus further improving the efficiency of the vehicle system.

Chapter 3

Hybrid Vehicle Modeling

As previously mentioned, the hybrid vehicle modeled in this project was based on the specifications of the Honda Insight hybrid vehicle's Integrated Motor Assist (IMA) structure. Since the actual engineering data of the Insight was not available directly from Honda, it was decided to use the test data included in ADVISOR, which was provided by the Argonne National Laboratory (ANL) [8, 10, 11, 12, 13, 15]. This chapter describes the overall structure of the hybrid vehicle model and its components in detail.

3.1 Overall Structure

The Honda IMA structure utilizes a DC brushless permanent magnet electric motor that is directly coupled with the engine crankshaft, and is placed in between the engine and the transmission. Figure 3-1 depicts the powertrain configuration of the IMA structure. [1]

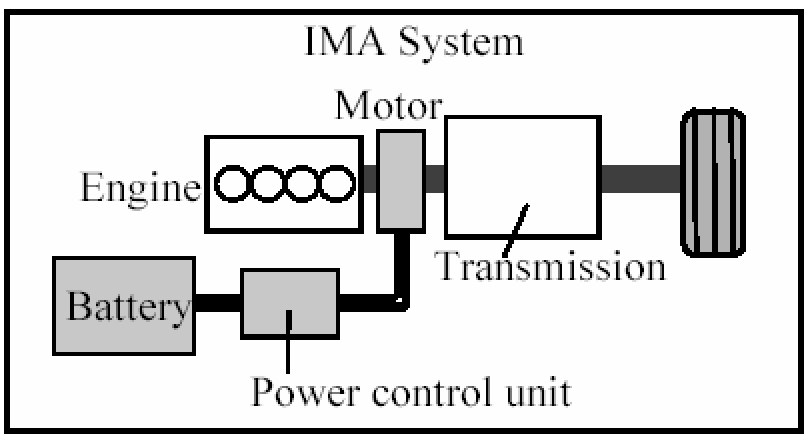

Figure 3-1: Honda's Integrated Motor Assist Powertrain Structure [1]

The battery provides electric power to the motor and stores the electrical energy released by the motor during regenerative braking, and is electrically connected to the motor via a Power Control unit. During vehicle acceleration, the motor assists the engine by providing additional torque into the transmission, and electrical energy is supplied from the battery to the motor. During the vehicle deceleration, the motor acts as a generator and provides a resistive torque to the transmission while slowing the vehicle. During the braking process, kinetic energy of the vehicle is converted into electrical energy, which is then used to charge the battery. This process is commonly referred to as regenerative braking. Since conventional vehicles depend solely on mechanical brakes during deceleration, the stored kinetic energy is converted into heat and lost. On the contrary, regenerative braking captures the energy that would otherwise be lost, leading to an increase in the overall efficiency of the vehicle. Hybrid vehicles however, are still equipped with mechanical brakes in the case when higher braking torque is required.

The hybrid vehicle model in this project utilizes two softwares: MSC ADAMS and MATLAB/Simulink. The mechanical components of the vehicle body are created in MSC ADAMS, while powertrain components and power management logic are modeled in MATLAB/Simulink. Figure 3-2 depicts the overall schematic of the system.

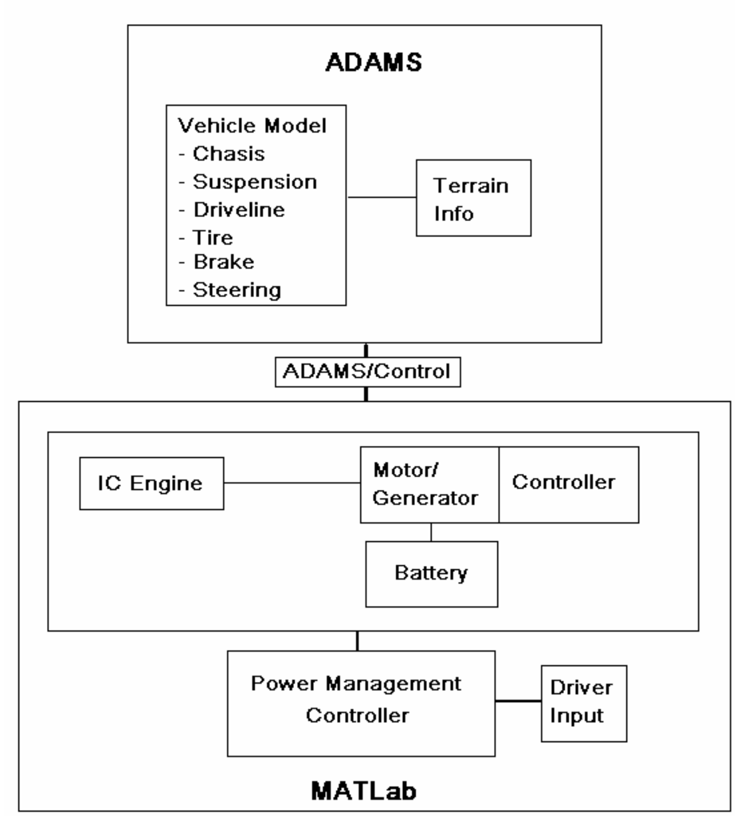

Figure 3-2: Overall Structure of the Hybrid Vehicle Model

The MATLAB/ADAMS hybrid vehicle model utilizes a driver input simulation, where the driver control module compares the actual and the desired speed, and applies a throttle or a braking percent to the powertrain components, which in turns applies the driving or the braking torque to the wheels. Chapter 4 will discuss the software structure in further details.

3.2 Powertrain Components

3.2.1 Engine

The engine utilized in this model is the Honda Insight 1.0L VTEC-E SI Engine. Several characteristics such as Maximum Torque, Closed Throttle Torque, and Fuel Consumption Rate are modeled in the engine as lookup tables [10]. Throttle percent and engine speed are inputs to the engine model, which are used to calculate the corresponding output torque and fuel consumption rate. Figure 3-3 and Figure 3-4 depict the maximum throttle torque and closed throttle torque, respectively.

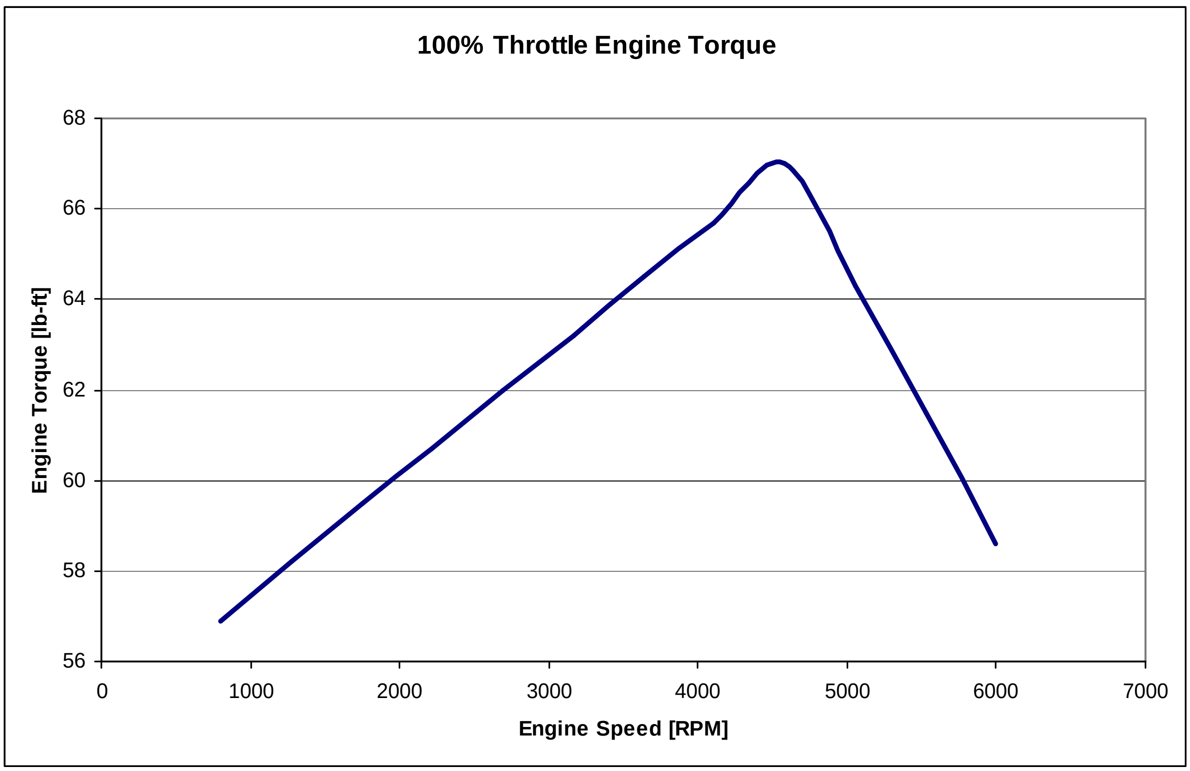

Figure 3-3: Maximum Engine Torque [10]

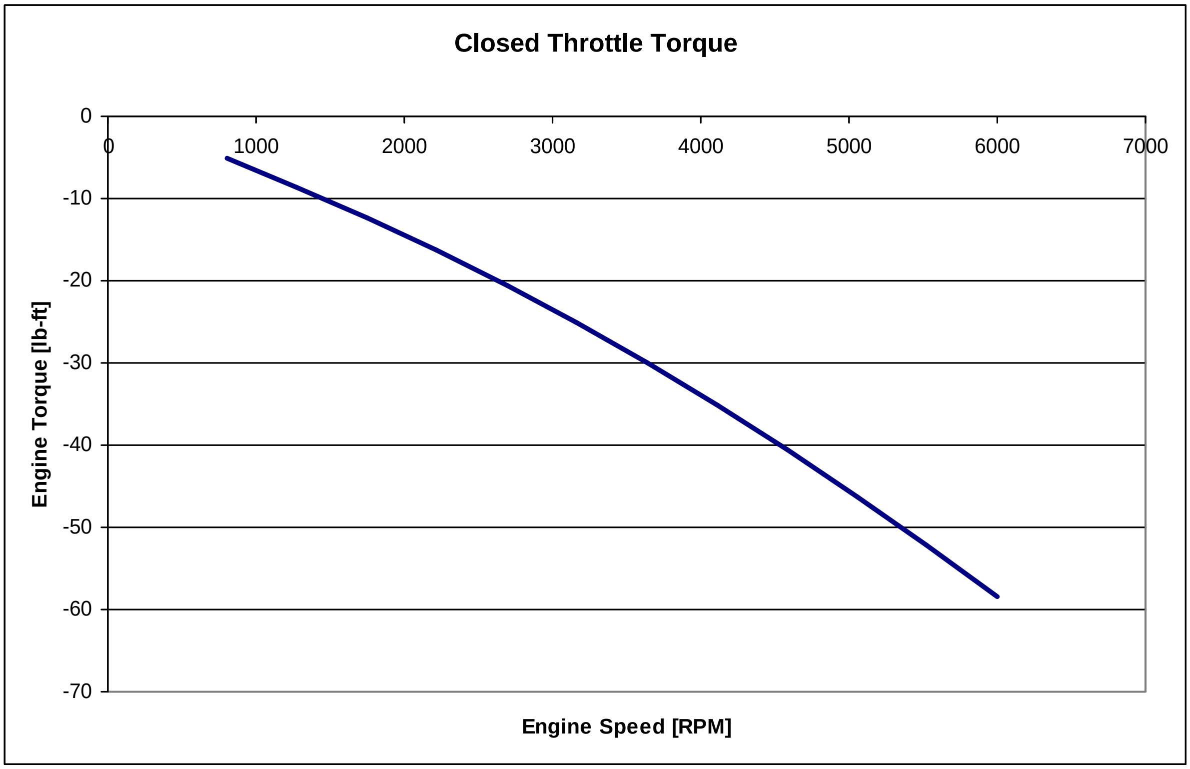

Figure 3-4: Closed Throttle Torque [10]

Maximum engine torque is the maximum amount of torque available when the throttle is wide open at 100%, while the closed throttle torque is the engine resistive torque when the throttle is completely closed. Closed throttle torque is the braking torque felt by the driver from the engine when the gas pedal is completely released while the vehicle is coasting. The relationship between the throttle percent and the maximum engine torque is assumed to be linear; thus, the actual output torque from the engine is calculated by scaling the maximum engine torque at any given engine speed with the throttle percent. The fuel consumption rate of the engine is subsequently calculated by interpolating the fuel rate data map, using the current engine speed and the output engine torque. Figure 3-5 illustrates the fuel consumption rate data map indexed by the engine speed and the engine torque. The engine data is included in Appendix A.

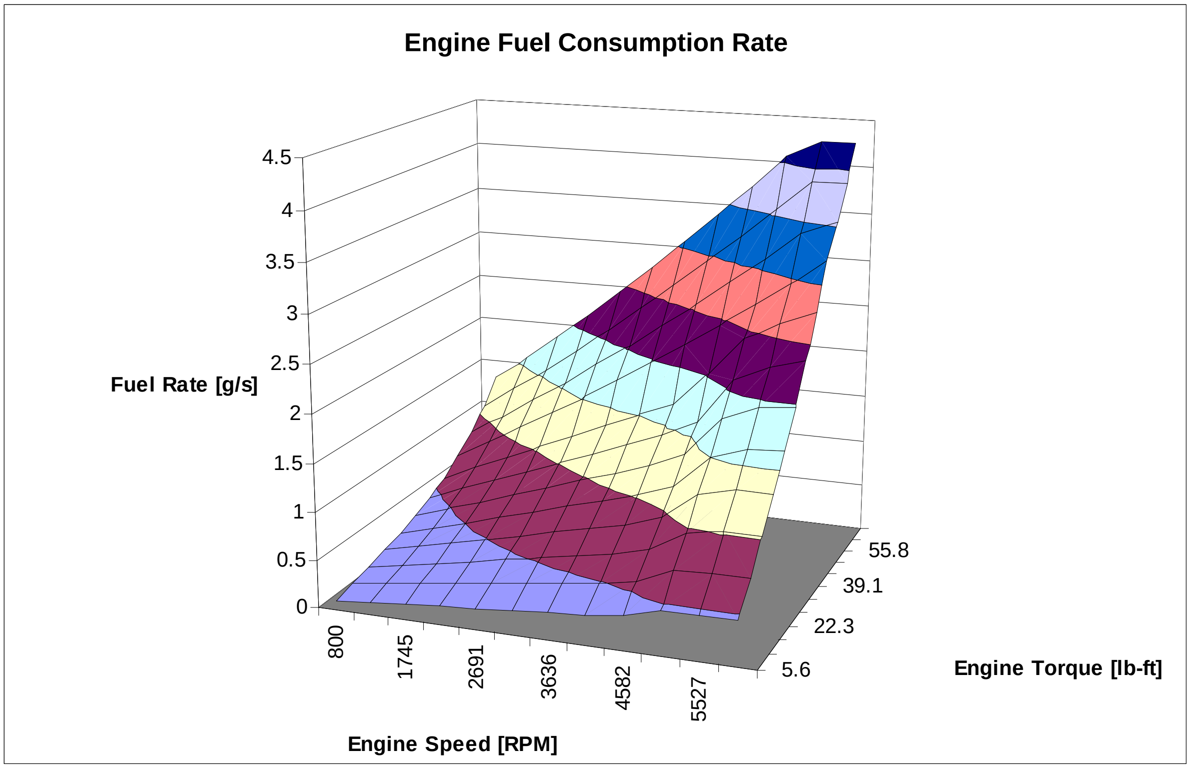

Figure 3-5: Engine Fuel Consumption Rate Data Map [10]

3.2.2 Motor/Generator

The electric motor utilized in this project is a 10-kW DC brushless permanent magnet motor. The unit also functions as a generator during regenerative braking mode. Similar to the engine, the motor/generator is modeled using lookup tables, where the maximum torque of the motor/generator is indexed by the shaft speed. In addition, the efficiency map of the motor/generator is modeled as a three dimensional lookup up table indexed by the torque range and the shaft speed [11]. Since the motor/generator shaft is coupled directly to the engine crankshaft, the speeds of the motor and engine are equal at any given time. Figure 3-6 and Figure 3-7 depict maximum torques of the motor and generator, respectively.

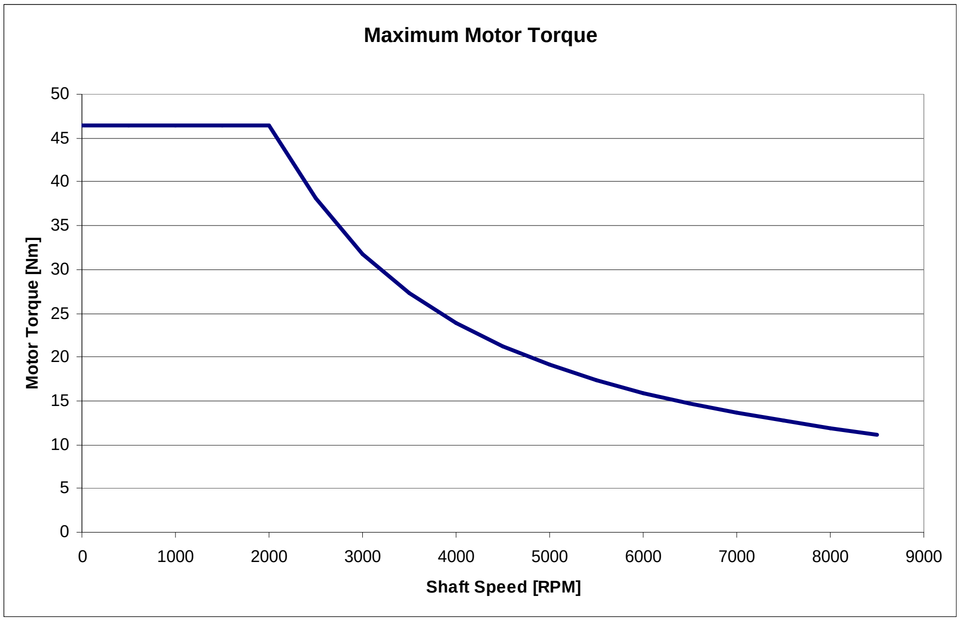

Figure 3-6: Maximum Motor Torque [11]

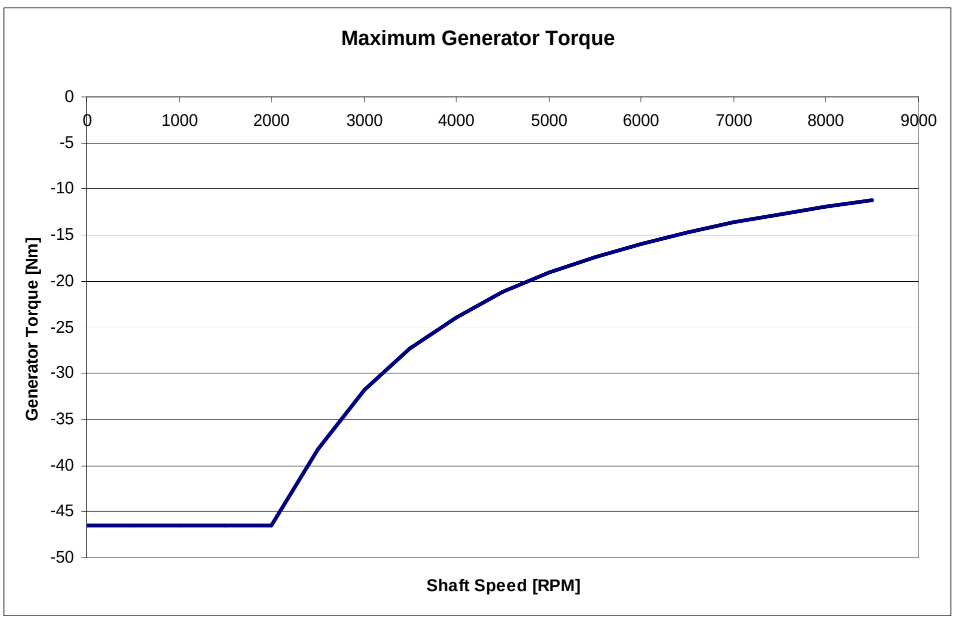

Figure 3-7: Maximum Generator Torque [11]

It should be noted that the positive and negative signs of the motor/generator torque depict the direction of the torque, where positive sign describes torque applied to the transmission from the motor/generator, whereas negative torque signals the transmission is applying torque to the motor/generator. During vehicle acceleration, the output torque of the motor is calculated based on the desired power determined by the power management control and the current shaft speed, up to the maximum available motor torque at the current speed. The output torque is calculated by the following equation.

$$T_{out} = \frac{P_{desired}}{\omega_{engine}} \tag{3.1}$$

During regenerative braking mode, output torque is calculated based on the maximum generator torque scaled by the brake percent received from the driver control logic.

As described earlier, the efficiency map is modeled as a look-up table indexed by the torque range and shaft speed. The power consumed and generated by the motor/generator is calculated by multiplying the current torque and speed and scaling by the corresponding efficiency. The output power value is then used to calculate the energy level of the battery system. Figure 3-8 illustrates the efficiency map of the motor/generator. The motor/generator data are included in Appendix B.

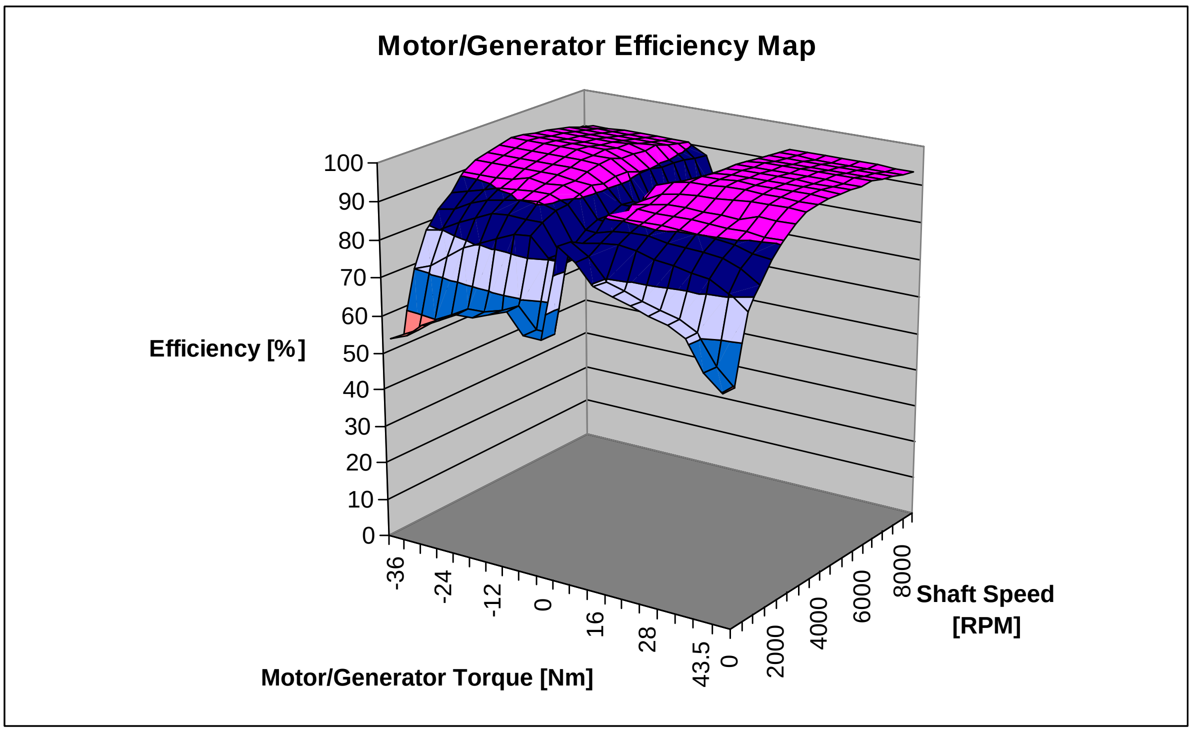

Figure 3-8: Motor/Generator Efficiency Map [11]

3.2.3 Battery System

The battery of this vehicle system is modeled using simple energy calculations. At each time step, the energy consumed or generated is governed by the following equation:

$$\varepsilon = \int P_{mogen} dt \qquad (3.2)$$

where ε = Energy consumed or generated

P_{mogen} = Power consumed or generated

The energy consumed or generated by the motor/generator is calculated at each time step, and would be added to or subtracted from the available energy in the previous time step. The new energy value would then be stored in memory to be used for the next time step. The battery state of charge (SOC) is calculated by dividing the current energy value by the maximum energy capacity of the battery. An initial state of charge of the battery must be specified at the start of the simulation.

Several important assumptions were made to simplify the modeling of the battery. First, it was assumed that the no-load voltage of the battery at various states of charge was constant. This eliminates the need for look-up tables and simplifies the energy calculation. Second, it was assumed that the internal resistance of the battery was zero, and the no-load voltage was equal to the rated voltage. In reality, the internal resistance of the battery would be different during the charge and the discharge cycle, and again varies depending on the state of charge of the battery. At this stage, a simple energy storage system would suit the need of the battery system, and can be further refined if necessary. The maximum energy capacity of the battery is calculated by multiplying the rated capacity (6.5 Ah) and the rated voltage (144V) of the Insight's battery.

3.2.4 Transmission

This model is assumed to have a five-speed manual transmission, and is modeled using a look-up table that defines the gear ratio based on the current vehicle speed. The overall ratio is the sum of the transmission's gear ratio and the final drive ratio. The final drive ratio is a further gear reduction ratio between the transmission and the wheels. Table 3-1 summarizes the transmission's gear ratio and the corresponding vehicle speed. [12]

Table 3-1: Transmission Gear Ratio and Corresponding Vehicle Speed [12]

Gear Number	Gear Ratio	Vehicle Speed [km/h]
1	3.46	0 - 24
2	1.75	24 - 40
3	1.1	40 - 64
4	0.86	64 - 75
5	0.71	75+
Final Drive	3.21	

The input torque to the transmission is the sum of the engine and the motor/generator torque, and the output torque is applied to the wheels. The output torque is calculated by multiplying the input torque and the overall ratio. The output shaft speed of the transmission will also be multiplied by the overall ratio to calculate the input shaft's speed, which will be used as the speed of the engine and the motor/generator.

3.3 Controller Logic

As previously mentioned, both driver logic and power management algorithms are modeled in MATLAB/Simulink. This section describes the controller logic in details.

3.3.1 Driver Logic

The goal of the driver controller is to create a module that mimics the response of a real-life driver. On real road, the driver decides the intended speed of the vehicle, and controls the throttle and the brakes accordingly. If the driver wishes to accelerate the vehicle, one will press on the gas pedal as hard or as light as is one's desire for acceleration. Similarly, one will press the brake pedal according to how quickly or slowly one likes to decelerate. To model such behaviour, the driver controller monitors the differences between the desired and the actual vehicle speeds, and the error value is fed into a proportional controller. Two proportional controllers are used to generate the percent throttle and the percent braking, as illustrated in Figure 3-9 and Figure 3-10, respectively.

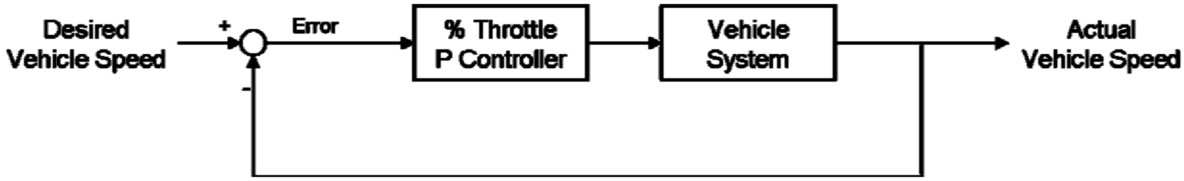

Figure 3-9: Percent Throttle Closed-Loop Proportional Controller

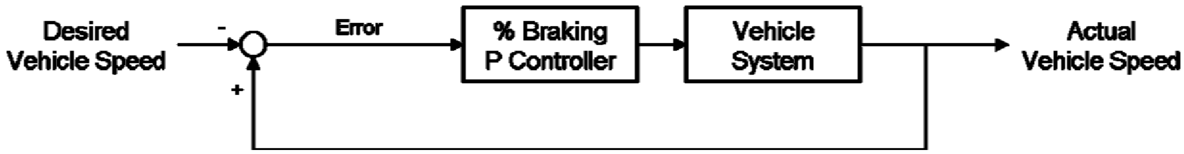

Figure 3-10: Percent Braking Closed-Loop Proportional Controller

It should be noted that during vehicle braking, the desired vehicle speed will be lower than the actual vehicle speed, and therefore it is necessary to negate the error signal in order to generate a positive braking percent. Percent throttle is then used by the engine to output engine torque, and by the power management controller to activate motor assist mode. Similarly, the percent braking is outputted to the mechanical brake controller to activate the mechanical brakes, and to the power management controller to activate the regenerative braking mode.

The benefit of modeling the driver controller logic as a separate module is that if desired, hardware-in-the-loop interface can replace the proportional controller allowing the user to control the throttle and braking directly in real time. For the scope of this project, the proportional controllers will be used to model the driver's input.

3.3.2 Power Management Logic

The goal of the Power Management Controller is to control the power components to achieve the desired vehicle power while increasing the vehicle's overall efficiency. Since the objective of the software model is to provide an overall structure of a hybrid vehicle simulation platform, a simple power management logic will satisfy the purpose of this project at the present time.

The simple power management logic deploys an intuitive approach where the desired power is in direct relation with the driver's throttle input. The desired power equals the maximum power available multiplied by the percent throttle, where the maximum power available is assumed to be the sum of the maximum power available from the engine and the electric motor. Thus at each time step:

$$P_{desired} = P_{\max} \times \%_{throttle} \tag{3.3}$$

The purpose of the coupled motor/generator unit of this system is to provide motor assist during acceleration and regenerative braking during deceleration. Therefore, it is desired that the motor assists the acceleration when the total desired power is greater than the maximum power available from the engine. It is arbitrarily assigned that the motor assist mode is activated when the percent throttle is greater than 50%, while the regenerative braking mode is activated while the percent braking is greater than 5%. Additionally, it was observed from testing that in ADVISOR, the motor assist occurs only in second gear and above, and regenerative braking is activated only if the vehicle speed is greater than 16 km/h (10mph). The control logics of the motor assist and regenerative braking modes are summarized in Table 3-2 and Table 3-3 respectively.

Table 3-2: Control Logic for Activating Motor Assist Mode

Motor Assist Mode
Desired Power > Maximum Engine Power Available
Desired Speed > Actual Speed
Percent Throttle > 50%
Transmission Gear > 1

Table 3-3: Control Logic for Activating Regenerative Braking Mode

Regenerative Braking Mode
Desired Power < Maximum Engine Power Available
Desired Speed < Actual Speed
Percent Throttle = 0%
Percent Braking > 5%
Vehicle Speed > 16 km/h

The power management logic employed in this system is a simple and straight forward logic that activates the motor assist mode during acceleration, and regenerative braking during deceleration. Optimization of the power management logic is recommended for future work to improve the overall vehicle efficiency.

3.3.3 Mechanical Brake Logic

As mentioned in the previous section, regenerative braking occurs only when the vehicle speed is greater than 16 km/h. Therefore for vehicle speeds less than 16km/h, braking of the vehicle is solely based on the mechanical brakes. In addition, to increase the amount of kinetic energy recovered during regenerative braking, it is desired that the generator provides the majority of the braking torque prior to the mechanical braking. It is therefore defined that the mechanical brakes are only activated when the percent braking is greater than 90%. Figure 3-11 illustrates the control logic of the mechanical brakes.

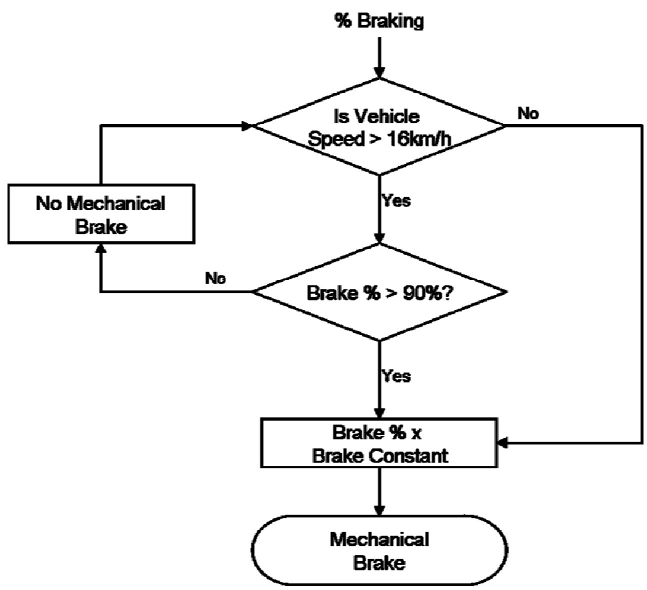

Figure 3-11: Control Logic for Activating Mechanical Brakes

The brake constant for this model is arbitrarily set as 200Nm, and can be modified if additional test data are available. Modeling the mechanical brake interface with the wheels will be further discussed in Chapter 4.

3.4 Mechanical Components

The mechanical components of the vehicle system are modeled in MSC ADAMS, where it performs the vehicle dynamics analysis simulation. This section will present a brief overview of the mechanical components of the vehicle system, and detailed modeling description of the components will be discussed in Chapter 4.

3.4.1 Vehicle Body

The vehicle body utilized in this model is a simple 4x2 Front Wheel Drive (FWD) vehicle with McPherson suspensions for both front and rear axles. The vehicle assumes the characteristic of an open differential, where the input torque to the differential is split equally between the left and the right wheels. Drive torque and regenerative torque from the powertrain are applied to the input of the differential, while mechanical braking torque is applied to the wheels individually. The speed of each wheel is equal to the input speed to the differential. A simple rack and pinion steering system is used to steer the front wheels, where a simple closed loop proportional controller maintains the vehicle in a straight line. P165/65 R14 tires are used for both front and rear axles. [13]

3.4.2 Operating Environment

In reality, various factors of the environment such as road grade, surface condition, and wind forces would affect the vehicle's overall operating efficiency. For the sake of simplicity and consistency in order to study the efficiency of the hybrid vehicle, the vehicle is assumed to be operating in a perfect environment, where the road is assumed to be perfectly flat with a friction coefficient of 1. In addition, it is assumed that there is no additional wind force affecting the vehicle except for the drag force due to the velocity of the vehicle. The drag force equation is given by equation 3.4. [14]

$$F_d = \frac{1}{2} C_D A \rho_{air} v_{act}{}^2 \tag{3.4}$$

The drag coefficient of the vehicle is assumed to be 0.25, and the frontal area of the vehicle is assumed to be 1.9m^2 [15].

Chapter 4

Software Structure

The hybrid vehicle model utilizes two simulation software packages: MATLAB/Simulink and MSC ADAMS. As previously mentioned, the powertrain components and the control logics are modeled in MATLAB/Simulink, and the mechanical components are modeled in MSC ADAMS. ADAMS/Control module is used to provide the communication link for data transfer between the two softwares. This Chapter will describe the software modeling in detail, and provide validation results of the MATLAB/ADAMS model against the ADVISOR simulation data.

4.1 MATLAB/Simulink Model

The powertrain components and control logics are modeled in MATLAB/Simulink R2006a operating on Windows XP Professional SP2. Figure 4-1 depicts the overall structure of the MATLAB/Simulink model.

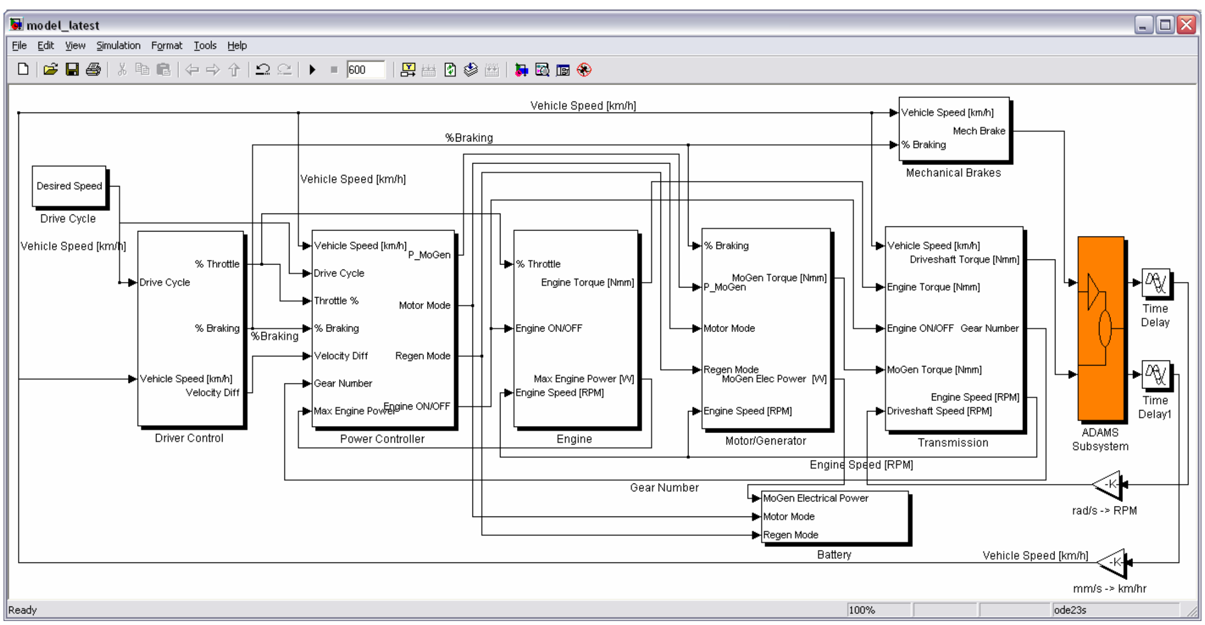

Figure 4-1: Overall Model Structure in MATLAB/Simulink

The MATLAB model components are setup in the chronological order of data flow starting from the left with the drive cycle data, ending to the right with the ADAMS model subsystem. Input data ports of each component block are on the left hand side of the block, while the output data ports are placed on the right of each block. The output data ports are then connected to the input ports of the appropriate component block. This section will present each of the data blocks in details.

4.1.1 Drive Cycle

The drive cycle subsystem contains the time history data for the desired vehicle speed, where several standard drive cycles are modeled as look-up tables. The block outputs the desired vehicle speed based on the current simulation time. Figure 4-2 depicts the drive cycle subsystem.

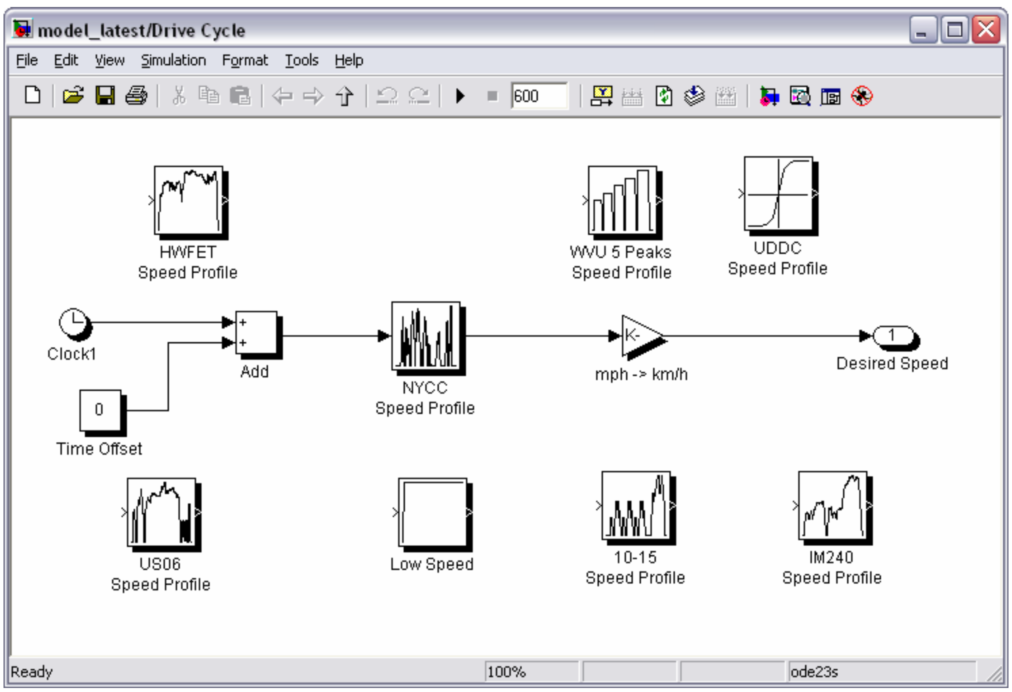

Figure 4-2: Drive Cycle Subsystem

Details of the standard drive cycles used to perform simulations will be discussed in the results section.

4.1.2 Driver Control

The purpose of the driver control subsystem is to mimic the driver's response in controlling the vehicle. As mentioned in the previous Chapter, a simple closed-loop proportional controller is used to simulate the percent throttle and the percent braking to the vehicle system. Figure 4-3 illustrates the driver controller subsystem.

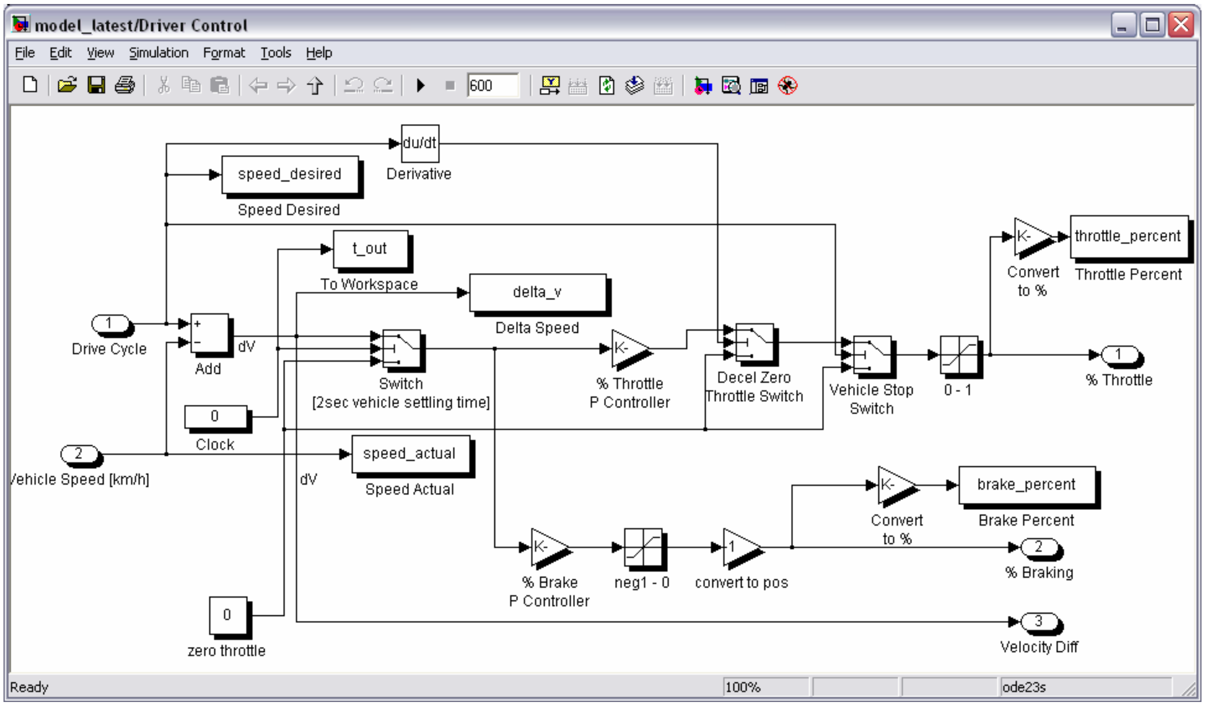

Figure 4-3: Driver Controller Subsystem

The input to the driver controller subsystem is the desired drive cycle speed and the actual vehicle speed. The outputs of the subsystem are percent throttle, percent braking, and the velocity difference. For modeling purposes, the vehicle is allowed to settle for two seconds prior to any throttle or braking calculation. This is to allow the dynamic model in ADAMS to settle to its zero velocity state prior to the actual driving of the vehicle. In addition, the desired vehicle acceleration and speed are monitored via two switches to ensure that the throttle output is zero when the vehicle slows down and when it is stationary. Finally, the braking and throttle percent are both limited between zero and a hundred percent via saturation function blocks.

4.1.3 Power Management Controller

The purpose of the power management controller subsystem is to implement the power management logic discussed in section 3.3.2, and to turn the engine off when the vehicle is stationary. The subsystem also calculates the net power requirement to the motor/generator, where a positive power output value implies additional power is requested for the motor assist mode. Figure 4-4 depicts the power management subsystem.

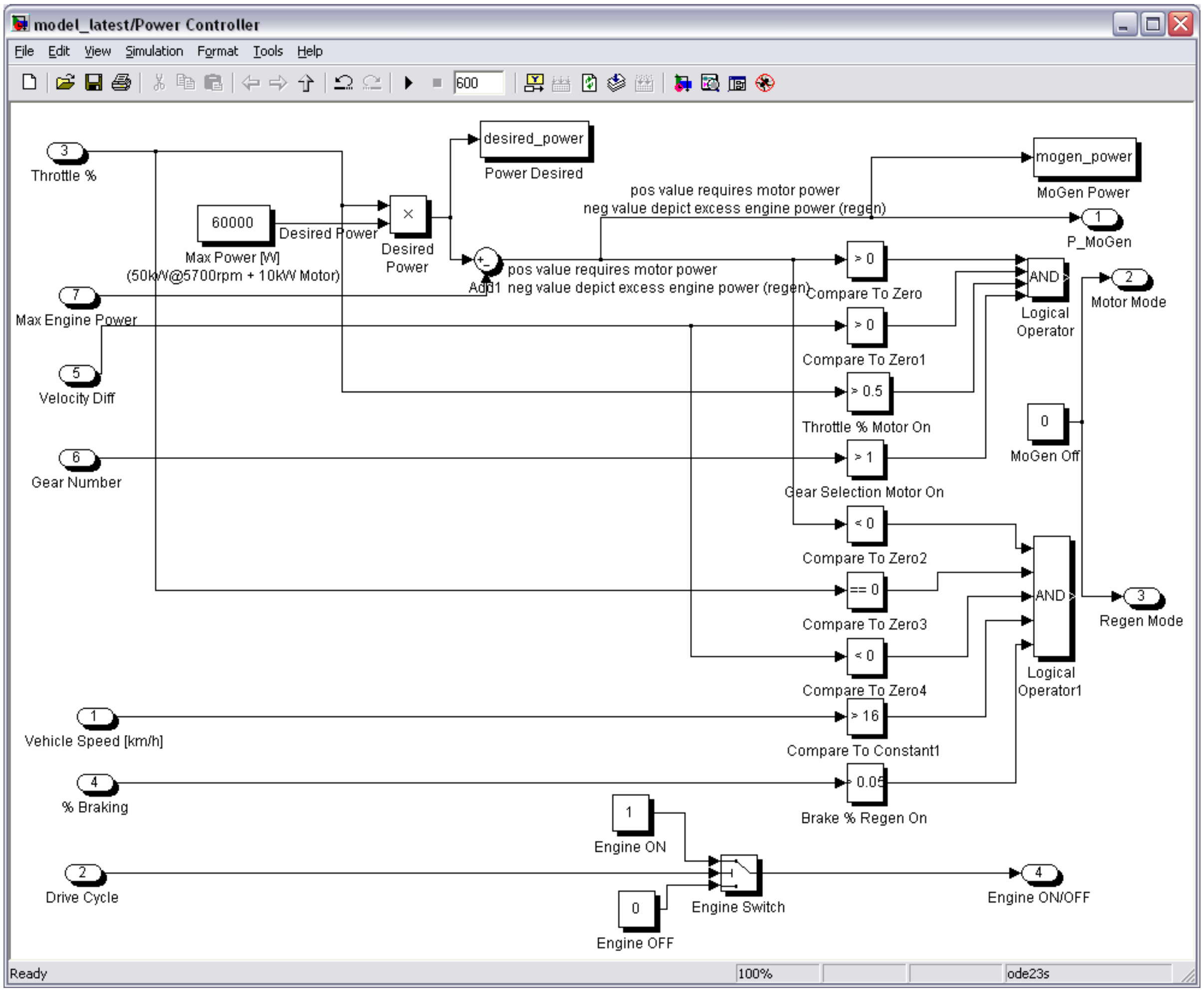

Figure 4-4: Power Management Subsystem

The desired power of the vehicle at any simulation time is the product of the maximum power available and the percent throttle. The maximum power is modeled as a constant, and calculated by summing the peak power output of the engine and the electric motor. The Boolean function blocks perform the logic calculations for the motor and the generator as described in section 3.3.2, and activates the motor and generator modes accordingly. If all Boolean logic is satisfied for the motor or the generator, the AND gate outputs value 1 to activate the operating mode, and returns to zero to turn the motor or the generator mode off. Finally, the engine switch monitors the drive cycle speed, and switches the engine off if the vehicle is to be stationary.

4.1.4 Engine

The main function of the engine subsystem is to perform the engine output torque calculations based on the current throttle percent and the engine speed. Open and closed throttle torque is modeled using look-up tables indexed by the current engine speed. Figure 4-5 illustrates the engine subsystem block.

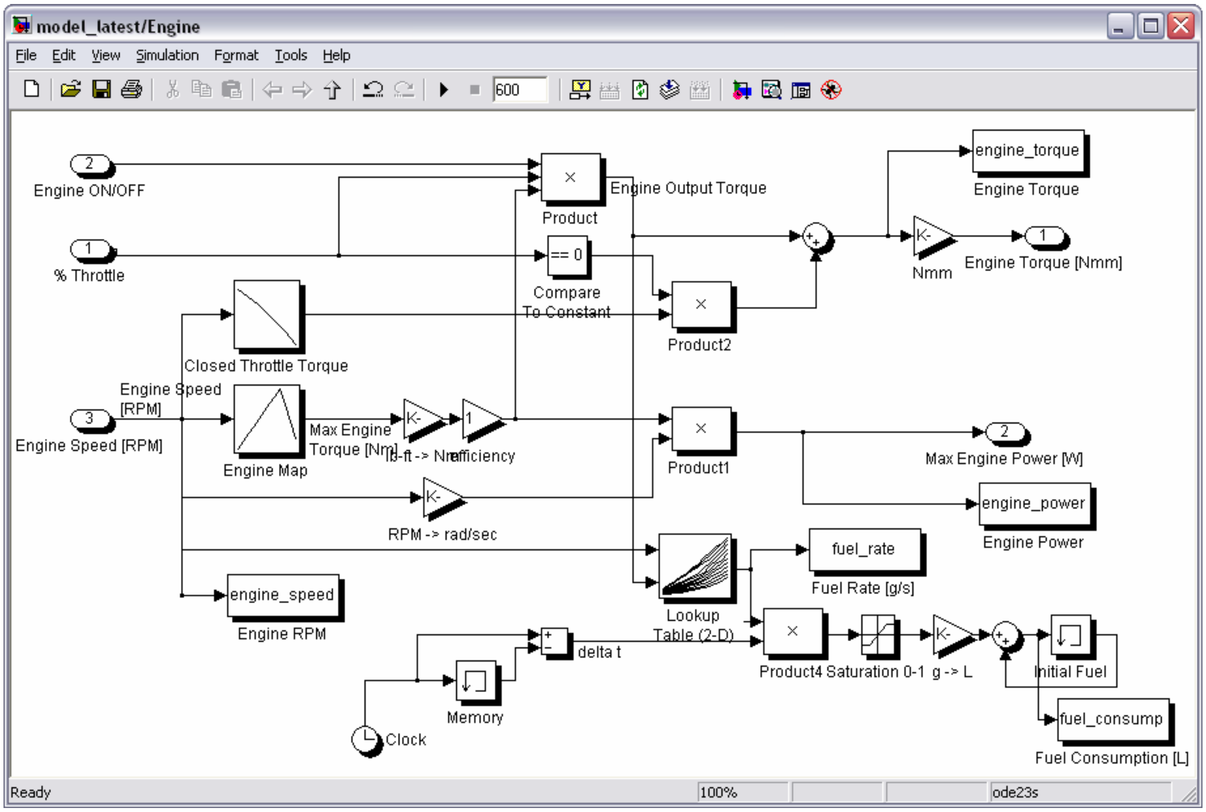

Figure 4-5: Engine Subsystem

In addition to outputting the engine torque, the engine subsystem also calculates the maximum engine power available and the engine's fuel consumption. The maximum engine power available is the product of the current engine speed and the maximum engine torque. The engine fuel consumption rate is modeled using a look-up table indexed by the current engine speed and torque. The fuel consumption rate is then integrated to calculate the total fuel consumed.

4.1.5 Motor/Generator

Similar to the engine model, the motor/generator output torque is modeled using look-up tables indexed by the shaft speed. Since the motor/generator shaft is directly coupled with the engine shaft, the shaft speed of the motor/generator equals that of the engine. Figure 4-6 illustrates the motor/generator subsystem block.

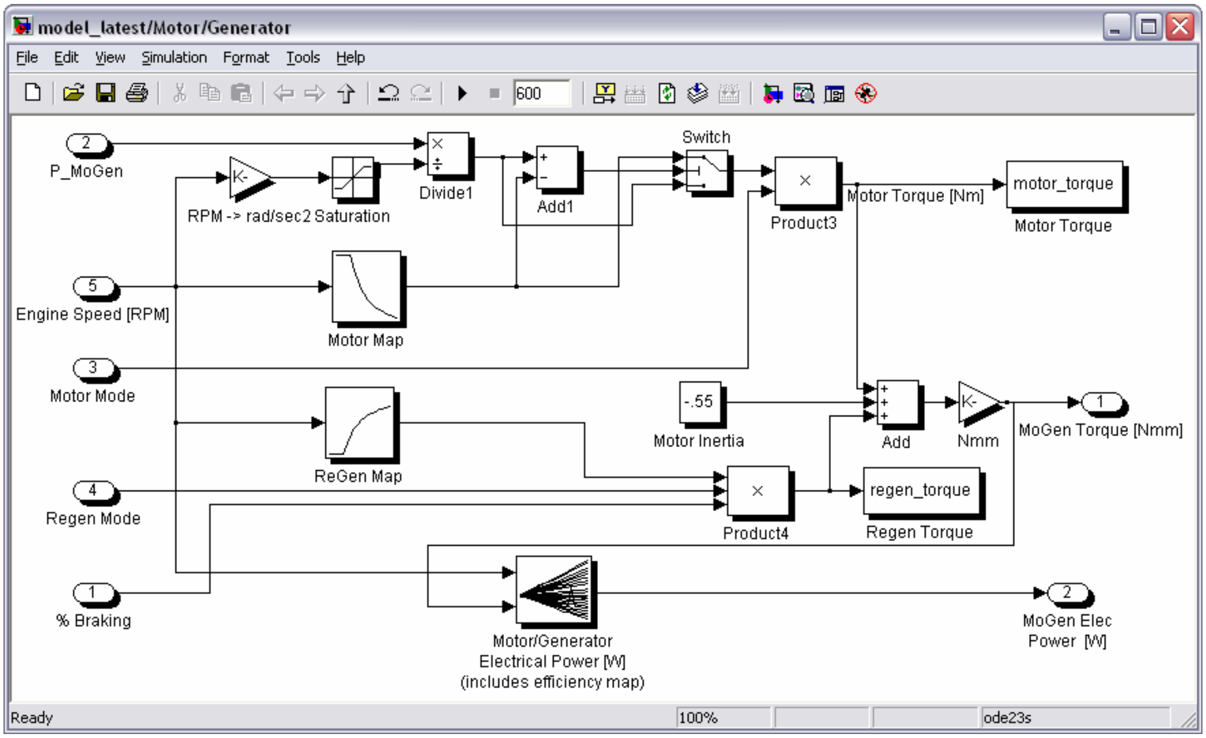

Figure 4-6: Motor/Generator Subsystem

The power management controller decides whether the motor/generator subsystem performs as a motor or as a generator. During motor assist mode, the motor mode signal becomes 1. The power output of the motor is decided by the required power calculation which is performed by the power management controller. In the case where the required power exceeds the maximum power available from the motor, the maximum power available is outputted from the motor. During the regenerative braking mode, the braking torque is the product of the maximum available braking torque of the generator and the percent braking from the driver. Finally, similar to the engine fuel consumption calculation, the motor efficiency is modeled using a look-up table indexed by the shaft speed and torque. The consumed or generated power is subsequently outputted to the battery to perform energy calculations.

4.1.6 Transmission

The transmission utilized in this model is a five-speed manual transmission. A simple logic is used for gear shifting, where the gear ratio is determined by the actual vehicle speed. Figure 4-7 depicts the transmission subsystem.

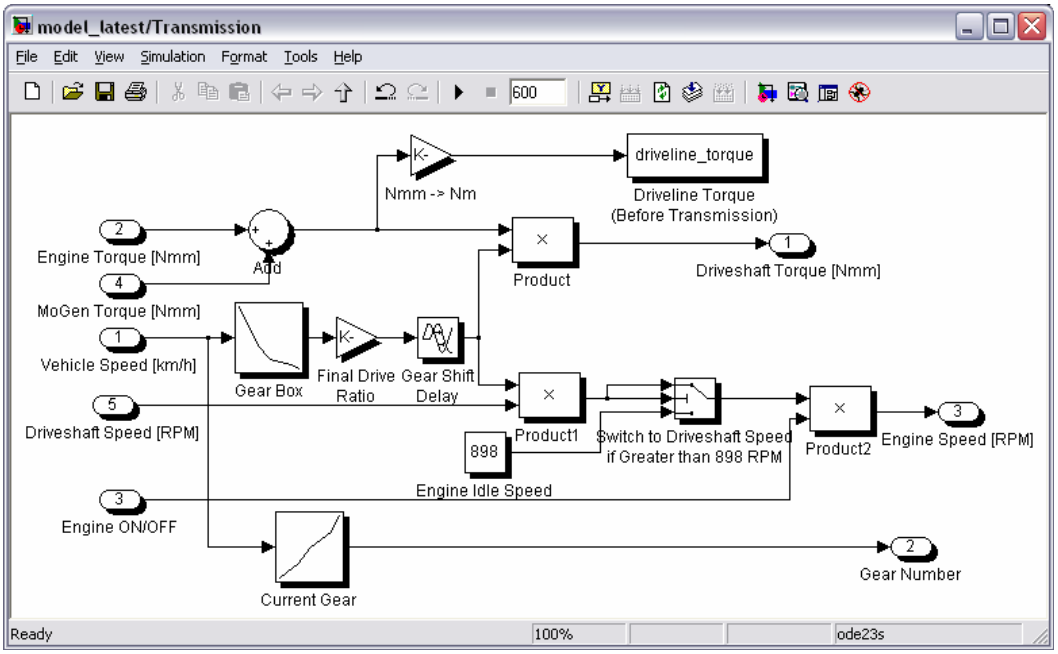

Figure 4-7: Transmission Subsystem

A look-up table is used to output gear ratio indexed by the vehicle speed, and is multiplied with the sum of engine and motor/generator torque to calculate the final driveshaft torque to ADAMS. Similarly, the driveshaft speed from ADAMS is multiplied by the gear ratio to determine the engine speed. Finally, the engine idle speed is defined as a constant at 900 RPM, where the driveshaft would be decoupled from the engine if the driveshaft speed falls below the engine idle speed. Similarly, the transmission would be disconnected from the engine if the engine is turned off.

4.1.7 Mechanical Brake

As mentioned in section 3.3.3, the mechanical brakes supply the entire vehicle braking torque when the vehicle speed is less than 16 km/h, while acting as supplementary braking torque to the regenerative braking when the vehicle speed is higher than 16km/h. Figure 4-8 illustrates the mechanical brakes subsystem.

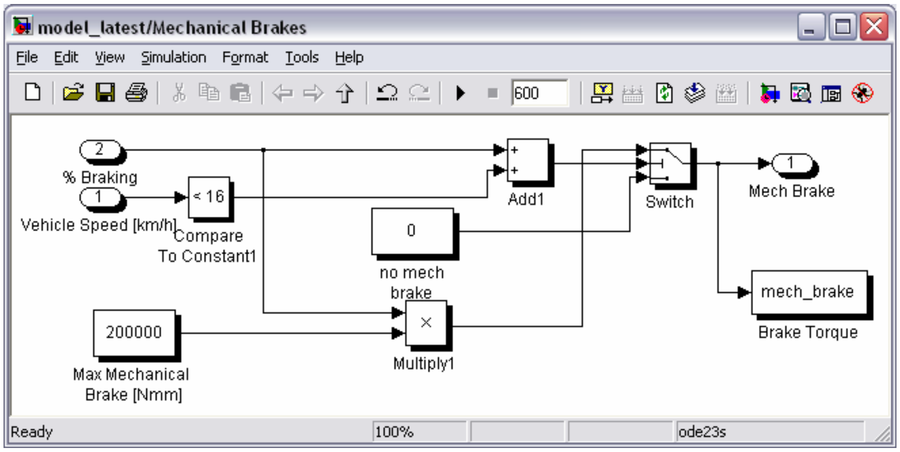

Figure 4-8: Mechanical Brake Subsystem

A switch is used to activate the mechanical brake torque, which is determined by the mechanical brake logic. Once active, the actual mechanical braking output torque is the product of the maximum braking torque and the percent braking. The maximum braking torque currently is arbitrarily set to 200Nm, and can be further modified if test data is available.

4.1.8 Battery System

The battery system in this model utilized a simple energy calculation, where the generated or consumed power is integrated over time to calculate the energy level in the battery. The initial energy level and State of Charge (SOC) of the battery is defined at the beginning of the simulation and subsequently updated based on the power consumption or generation of the motor/generator throughout the simulation. Figure 4-9 depicts the battery subsystem in the MATLAB/Simulink model.

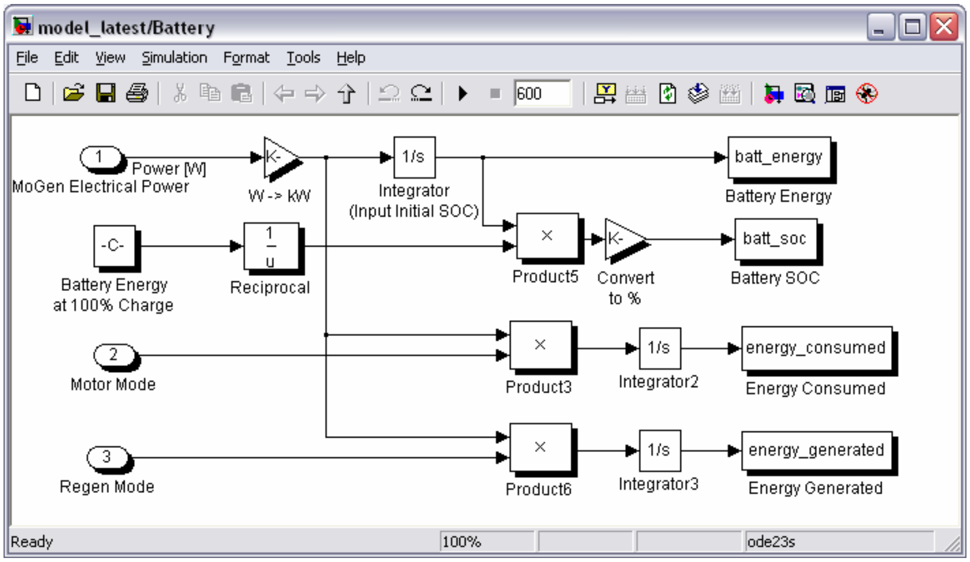

Figure 4-9: Battery Subsystem

4.1.9 ADAMS Subsystem

The ADAMS subsystem block is the standard ADAMS/Control subsystem that is required for MATLAB/Simulink to communicate with ADAMS. The input and output variables of the ADAMS subsystem are defined within ADAMS, and will be further discussed in detail later in the chapter. Figure 4-10 illustrates the ADAMS subsystem block.

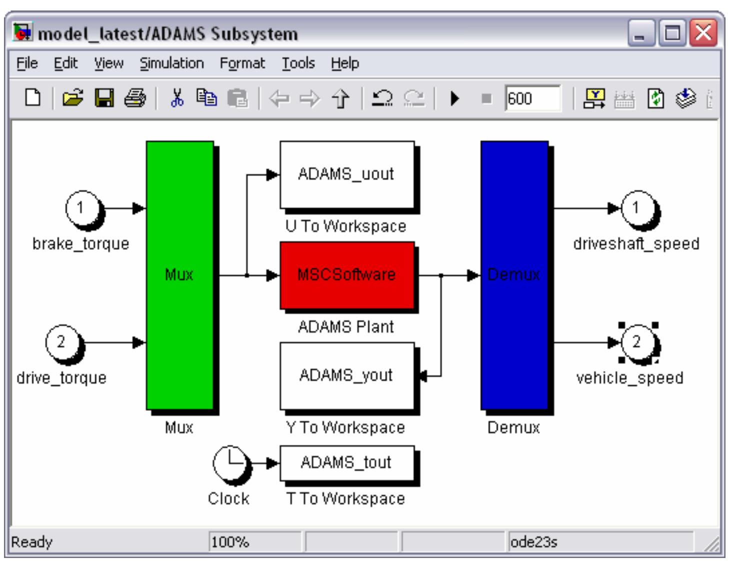

Figure 4-10: ADAMS Subsystem

4.2 ADAMS Model

The mechanical components of the hybrid vehicle system are modeled in MSC ADAMS/View 2005a operating on Windows XP SP2. The vehicle model includes vehicle chassis, suspension, driveline, steering linkages and control, brakes, and tires. The mechanical components are assumed to be rigid bodies, with the exception of the suspension and tires. Figure 4-11 shows an isometric view of the vehicle model in ADAMS/View.

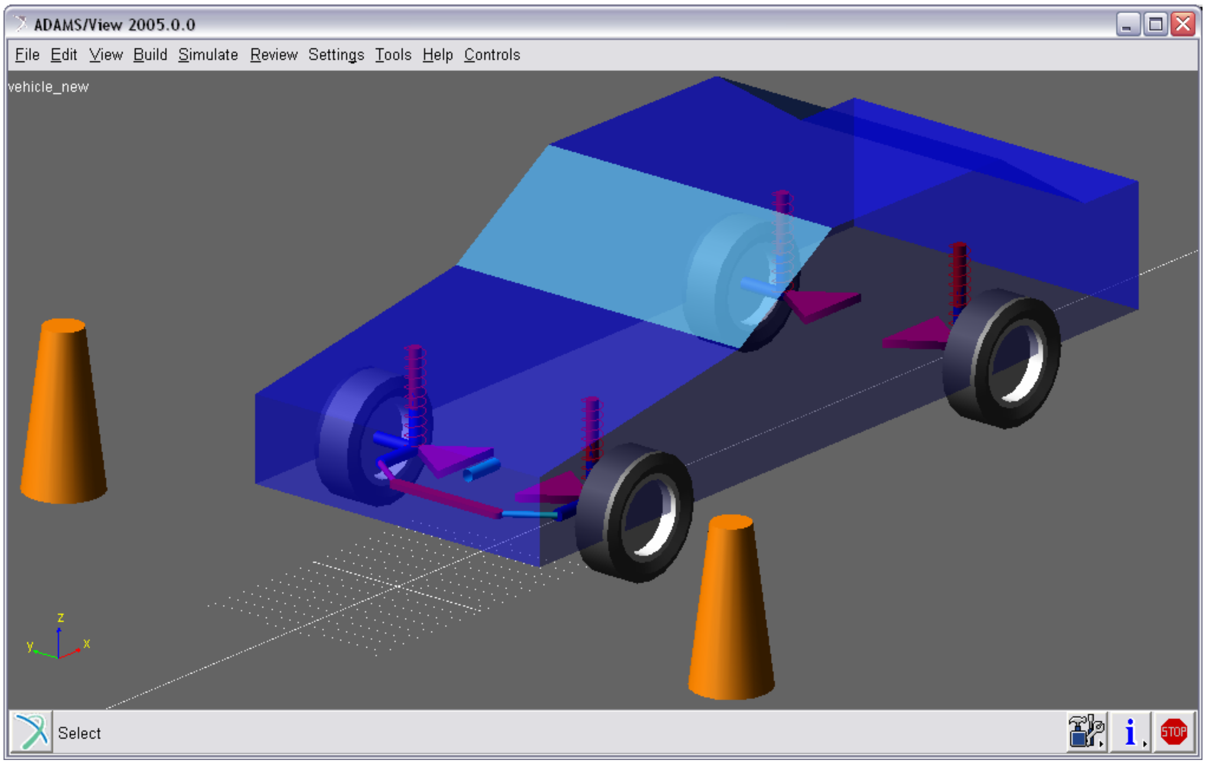

Figure 4-11: Mechanical Components of the Vehicle Model in ADAMS/View

As shown in the diagram, the global sign convention used in this model assumes that positive x points rearwards of the vehicle, positive y points towards the right, and positive z points upwards. As a result, gravity defaults to the negative z-direction. The mass and the inertia properties of the mechanical components are summarized in Appendix C. The following sections will discuss the aforementioned components in detail.

4.2.1 Vehicle Chassis

The vehicle body is modeled using a simple rigid body mass, connects to the suspension at the control arms (A-Frame) via revolute joints, and to the upper struts through spherical joints. The driveshaft connects to the vehicle chassis via a revolute joint, while the steering rack connects to the chassis via a translational joint. Details of the vehicle mechanical subsystem will be further discussed in the subsequent sections. Figure 4-12 depicts the front suspension, the driveline, and the steering system in ADAMS.

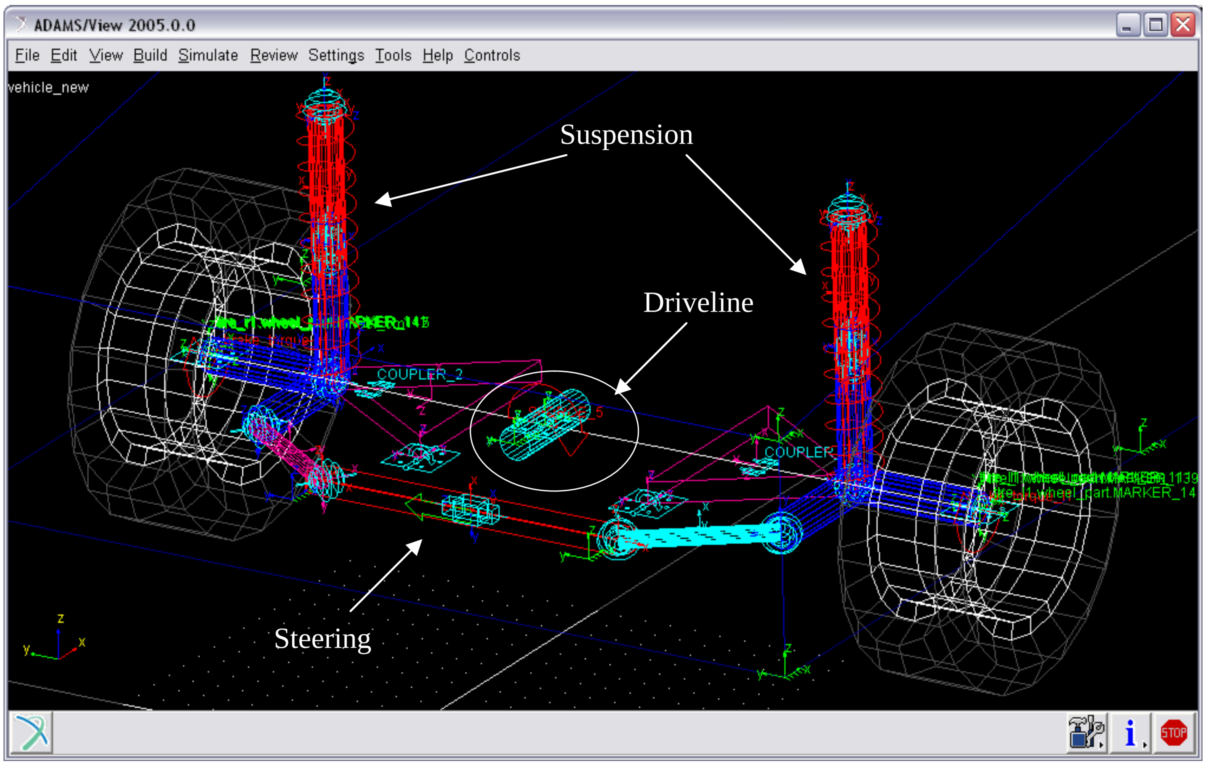

Figure 4-12: Close Up View of the Front Suspension, Driveline and Steering System

A single component force is used to model the drag force due to vehicle velocity as depicted by equation (3.4), and is applied opposite to the vehicle velocity at the vehicle's center of gravity.

4.2.2 Suspension

The suspension utilized in this model is a simple McPherson suspension, which includes a control arm, a lower strut, and an upper strut. As mentioned earlier, the control arm and the upper strut are connected to the vehicle body via a revolute joint and a spherical joint, respectively. The lower strut is connected to the control arm through a spherical joint, and connected to the upper strut via a translational joint. Finally, the tire is connected to the lower strut through a revolute joint. For steering purposes, spherical joints at the upper_strut-chassis and the lower_strut-control_arm locations allow rotation of the struts about the z-axis. The steering motion of the suspension is controlled via the tie rod, where it is connected to the lower strut via a spherical joint. The rear suspension is essentially the same as the front suspension, with the only difference being a revolute joint used at the upper strut-chassis location to restrict the rotational movement about the z axis.

4.2.3 Driveline

A simple driveline system is created to drive the front wheels. As depicted in Figure 4-12, a driveshaft is created and attached to the vehicle body via a revolute joint. A set of couplers are created that constrains the rotation of the wheels to the rotation of the driveshaft. This is achieved by creating a coupler constraint that linked the revolute joint of the driveshaft and the tires together. Since the final drive ratio is modeled in the transmission model in MATLAB/Simulink, the ratio of the couplers is assumed to be 1. A single component torque is created at the driveshaft, where the action body is the driveshaft, and the reaction body is the vehicle body. The magnitude of the drive torque is the state variable ‘drive_torque’, which is used to receive the driveline torque value from MATLAB.

4.2.4 Steering System

A rack and pinion steering system is utilized in the vehicle model. However, due to the requirement of this project, the steering wheel and the subsequent pinion gears are not actually modeled. It is sufficient at this stage to only model the actual movement of the steering rack and tie rods. As mentioned earlier, the steering rack is connected to the vehicle chassis to allow the rack to move in the y-direction with respect to the chassis. A set of tie rods are connected to either end of the rack via spherical joints. To steer the vehicle, a closed loop position controller is used to control the lateral movement of the steering rack, which in turn steers the wheels accordingly. Figure 4-13 illustrates the simple closed loop controller of the steering system.

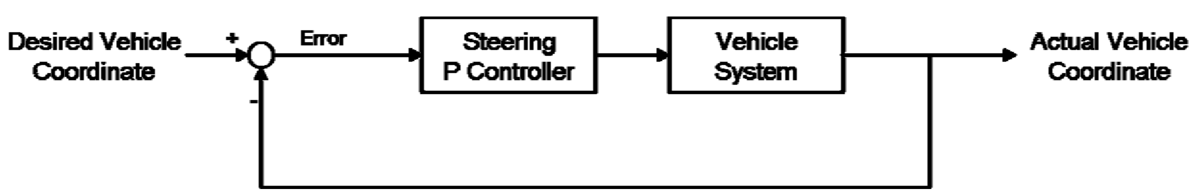

Figure 4-13: Closed Loop Steering Controller

The closed loop position controller is created using ADAMS built-in controls toolkit, where the input and the output variables are defined. For the purpose of this project, it is only required for the vehicle to maintain a straight path along the x-axis, thus the desired vehicle coordinate is set to y = 0. The following equation defines the steering input and output of the steering controller.

$$Steering_{ouptut} = (Steering_{desired} - Steering_{actual}) \times Steering_{gain} \tag{4.1}$$

To control the movement of the steering rack, a general motion is applied to constrain the steering rack in the local y-direction with respect to the vehicle chassis, where the actual value of the general motion is defined by the steering output variable. The variables of the steering controller used in the ADAMS controls toolkit as well as the general motion definition are included in Appendix D.

4.2.5 Mechanical Brakes

The mechanical brakes are defined as a single-component torque element applied at each wheel. It is assumed that the actual torque values of each wheel are equal, and are received from the MATLAB/Simulink's mechanical brake logic via ADAMS/Control. Detailed description of ADAMS/Control will be discussed later in the chapter, and the mechanical brake torque element in ADAMS is illustrated in Figure 4-14.

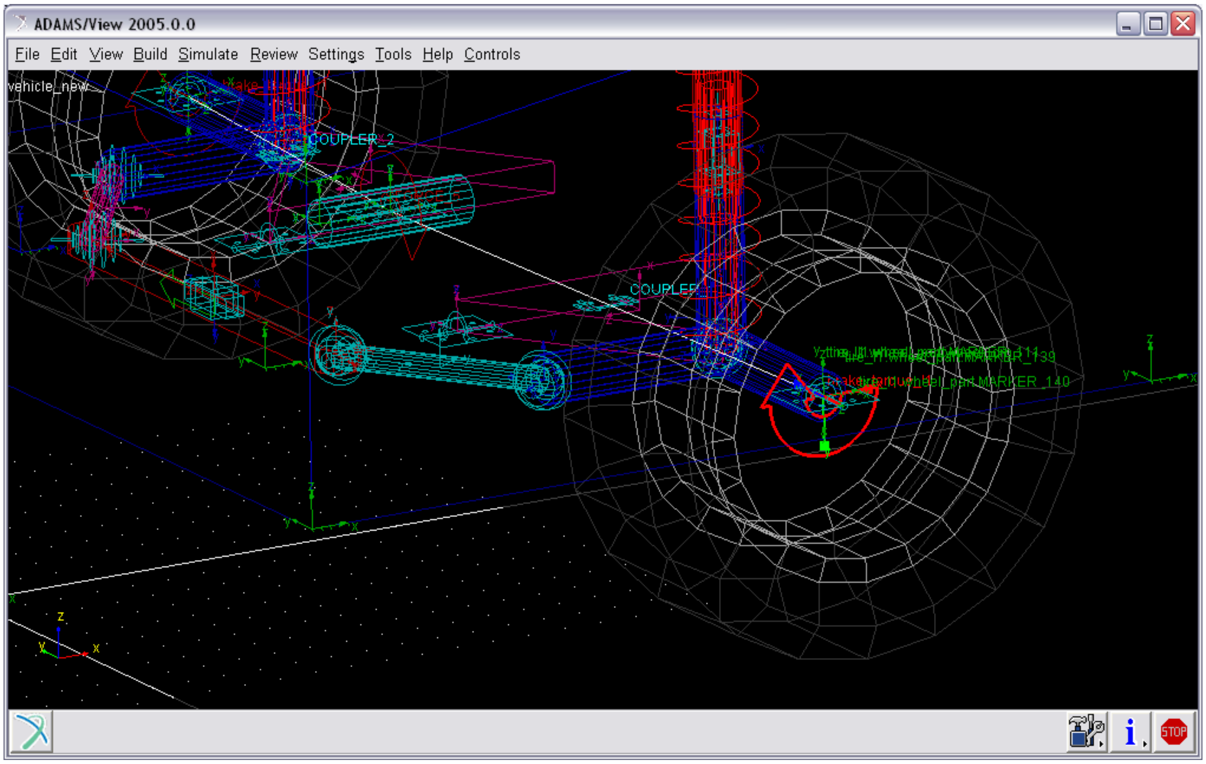

Figure 4-14: Mechanical Brake Torque Element in ADAMS

4.2.6 Tires and Road

Various tire modules are available in ADAMS, where different tire modules can be used for different purposes, such as handling, durability, two dimensional, or three dimensional roads. More information of the different tire modules available in ADAMS can be found in the ADAMS/Tire documentation [9]. For the purpose of this model, where the vehicle travels straight on a flat ground, it is decided the durability tire model on a 2D road will satisfy the purpose of this vehicle model. A Pacejka 94 tire model is used to simulate the P165/65 R14 tire utilized by the Honda Insight. The tire and road interface is created through the ADAMS tire element as shown in Figure 4-15.

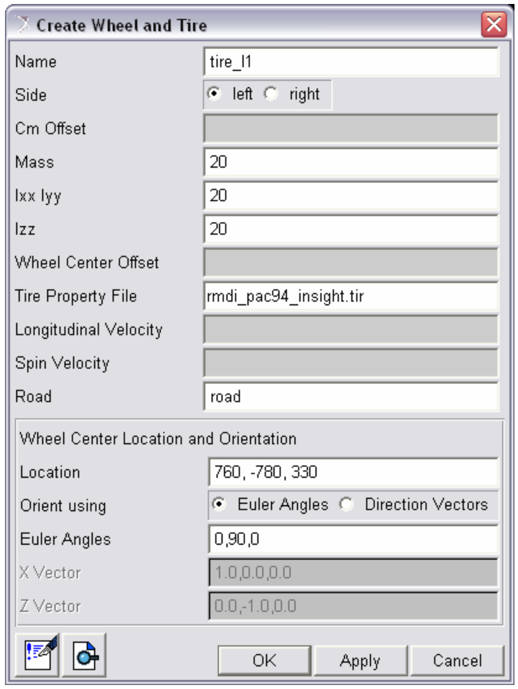

Figure 4-15: Defining Front Left Tire Element in ADAMS

To define all four tires, it is necessary to create the tire elements at each of the four tire locations while referencing the same tire and road property file. The tire and road property files are attached in Appendix E and Appendix F, respectively.

4.3 Co-Simulation

In order to interface ADAMS and MATLAB via ADAMS/Control, a series of steps are necessary to invoke ADAMS/Controls and to ensure a proper co-simulation between the two softwares. ADAMS/Control is accessed through ADAMS/View, where a set of files are generated for communicating with MATLAB. To perform a simulation, the files created by ADAMS must first be called in MATLAB. Once the simulation command is executed in MATLAB or Simulink, ADAMS/Control will then activate ADAMS/Solver to perform the co-simulation.

4.3.1 ADAMS Plant Export

To perform an ADAMS/Controls Simulation, the ADAMS model that contain a set of state variables, which specifies the input and the output parameters from MATLAB, must first be created. To invoke ADAMS/Controls, the controls plug-in must be loaded in ADAMS in order to export the plant systems to MATLAB. Plant input and output variables are created where plant input specifies the input state variables of the system, while the plant output variable specifies the output variable, or the sensor variable that will be monitored in MATLAB. Figure 4-16 illustrates the plant export window for ADAMS/Control.

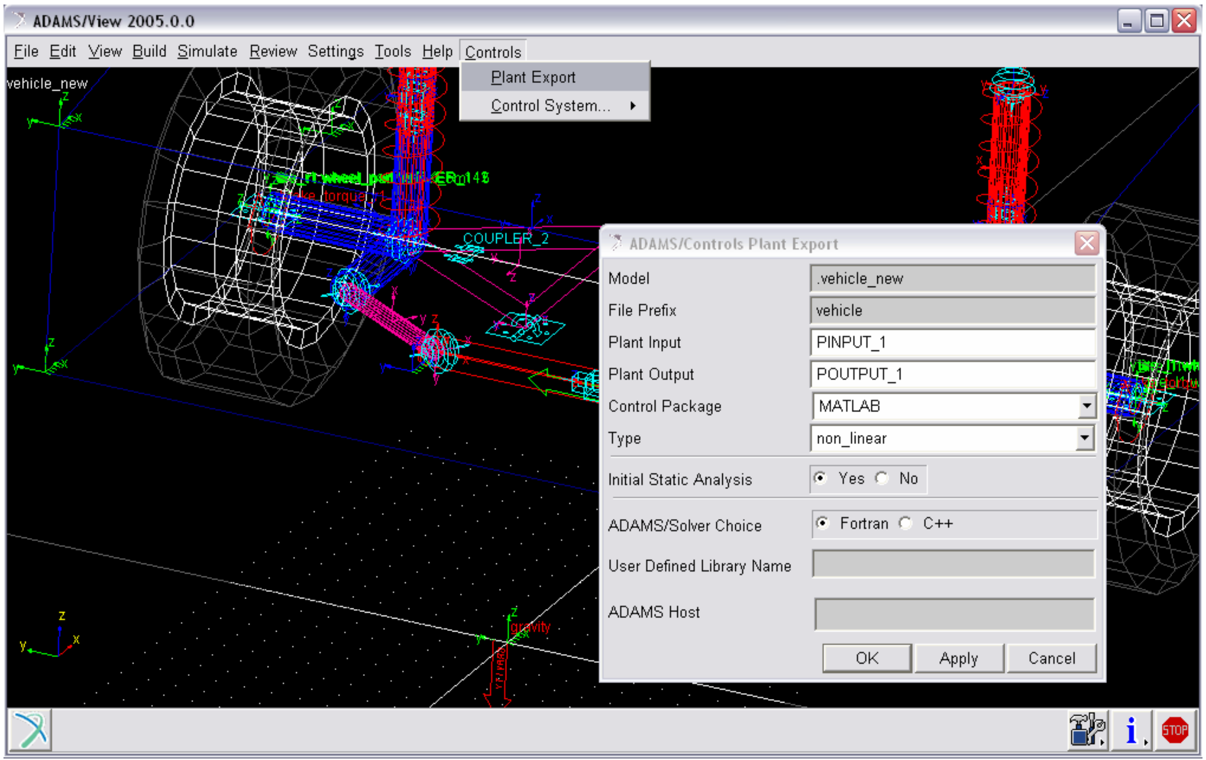

Figure 4-16: Defining Plant Export for ADAMS/Control

Plant input defines the input variables into the ADAMS model from MATLAB, and vice versa for plant output definition. For the hybrid vehicle model, the MATLAB control logic computes the driveshaft torque and the mechanical brake torque for the vehicle; therefore, the driveshaft torque and the mechanical brake torques are defined as plant input variables in ADAMS/Control. Similarly, ADAMS outputs the vehicle's current state for MATLAB to perform control logic calculation; thus, the vehicle speed and the driveshaft speed are defined as plant output variables in ADAMS/Control. The plant input and output definitions are attached in Appendix G.

Once the plant input and output variables have been specified, exporting the plant will generate .m, .adm, and .cmd files. The .m file is the initialization file that must be executed in MATLAB, where the ADAMS setup parameter would be read into the MATLAB workspace memory. The .adm file is the ADAMS solver dataset file used by the solver when performing simulations in the ADAMS solver mode, while the .cmd is the command file that would be used to solve the model in the interactive mode. The difference between the two modes is that the solver mode performs the simulation without updating the graphical interface at each time step, while the interactive mode provides the user a visual update at each time step. To save time and computing power, the simulations for the hybrid vehicle model are executed in the solver mode.

4.3.2 ADAMS/Control in MATLAB

Once the input and output plants have been exported, the next step is to call the .m file in MATLAB, which will define the necessary variables in order to execute the ADAMS solver. The .m file for the hybrid vehicle model is attached in Appendix H. Once the .m file is executed in MATLAB, a subsystem named ADAMS_sys will be created, and will contain a subsystem block as described in section. 4.1.9, which is needed to establish the connectivity between the MATLAB/Simulink model and ADAMS vehicle model. Figure 4-17 depicts the simulation parameters for ADAMS/Control in MATLAB/Simulink.

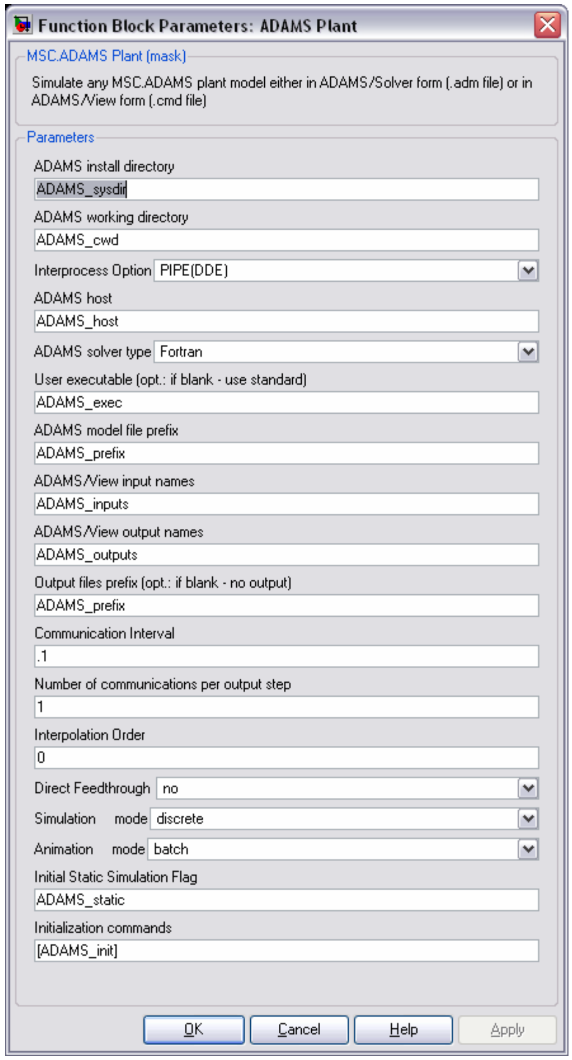

Figure 4-17: Simulation Parameters for ADAMS/Control in MATLAB/Simulink

To perform an analysis, simulation command is executed in Simulink, in which ADAMS/Controls will invoke the ADAMS/Solver to perform co-simulation with MATLAB, completing the process.

4.4 Model Validation with ADVISOR

ADVISOR (ADvanced VehIcle SimulatOR), a software originally developed by the U.S. Department of Energy (DOE) and the National Renewable Energy Laboratory (NREL), is based on MATLAB/Simulink that can be used to simulate and analyse light and heavy vehicles, including hybrid and fuel cell vehicles, where it allows the user to perform rapid analysis of the performance and fuel economy of conventional, electric, and hybrid vehicles [8]. Initially developed as a shareware, where it allowed free download for industries, it has since been commercialized by AVL Powertrain Engineering, Inc., in 2003. The ADVISOR version used for comparison purpose in this thesis was ADVISOR 2002, which is the shareware version prior to its commercialization by AVL.

ADVISOR was initially developed as an analysis tool, rather than a detailed design tool. Its components are created as a quasi-static model; therefore, it cannot be used to perform dynamic analysis. ADVISOR utilizes a backwards facing vehicle simulation architecture, where it uses the required/desired speeds as inputs, and determines what drivetrain torque, speed, and power would be required to meet that vehicle speed. For more information on ADVISOR, refer to the documentation help file of the software. [8] Figure 4-18 depicts the startup window of the ADVISOR 2002 in MATLAB/Simulink.

Figure 4-18: ADVISOR 2002 Startup Window

This section will provide a result comparison between the MATLAB/ADAMS hybrid vehicle model and ADVISOR. A standard drive cycle and common powertrain components will be used for the two models, and the simulation results of various components will be presented.

4.4.1 Model Setup

As mentioned previously, the major difference between ADVISOR and the MATLAB/ADAMS model is that ADVISOR utilizes backwards-facing vehicle simulation architecture, while the

MATLAB/ADAMS model performs a forwards-facing vehicle simulation. For comparative purpose, common drive cycle and component characteristic are used for the ADVISOR and the MATLAB/ADAMS models.

The standard drive cycle used for the simulation is the West Virginia University (WVU) Five Peaks drive cycle, where the vehicle is accelerated to a constant speed from standstill, and decelerated back to stationary. The cycle is repeated five times at increasing constant speed. The MATLAB/ADAMS hybrid vehicle model utilizes the power management control logic where the motor assist is active when the throttle percent is over 50%, and the regenerative braking occurs when the braking percent is 5% and over. Figure 4-19 illustrates the time history of the WVU 5 Peaks drive cycle.

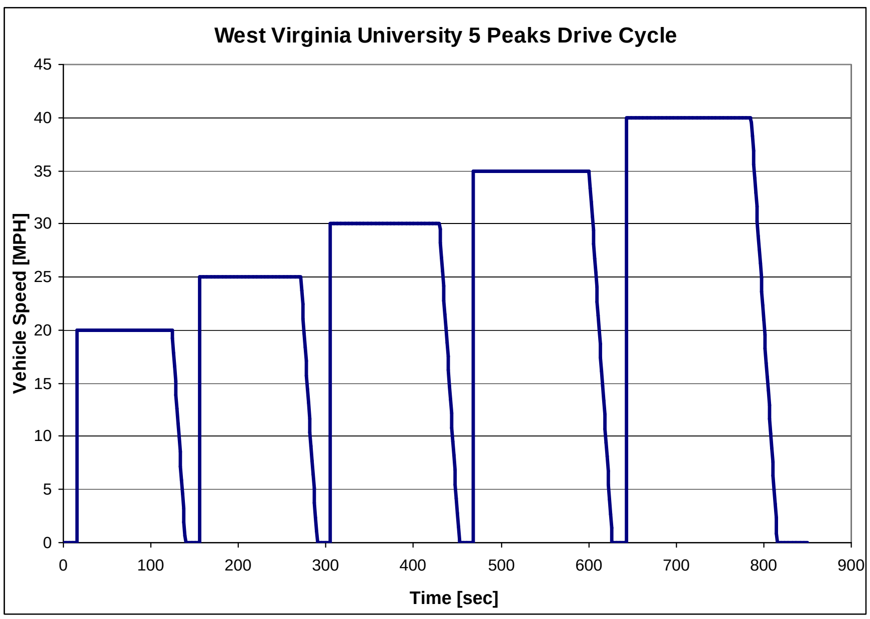

Figure 4-19: West Virginia University 5 Peaks Drive Cycle

4.4.2 Results Comparison

The MATLAB/ADAMS hybrid vehicle model simulation was performed for 850 seconds over the West Virginia University 5 Peaks drive cycle, and the results are as follows.

Vehicle Speed

The actual vehicle speeds of both models are presented in Figure 4-20. There is a close match between the results, as expected.

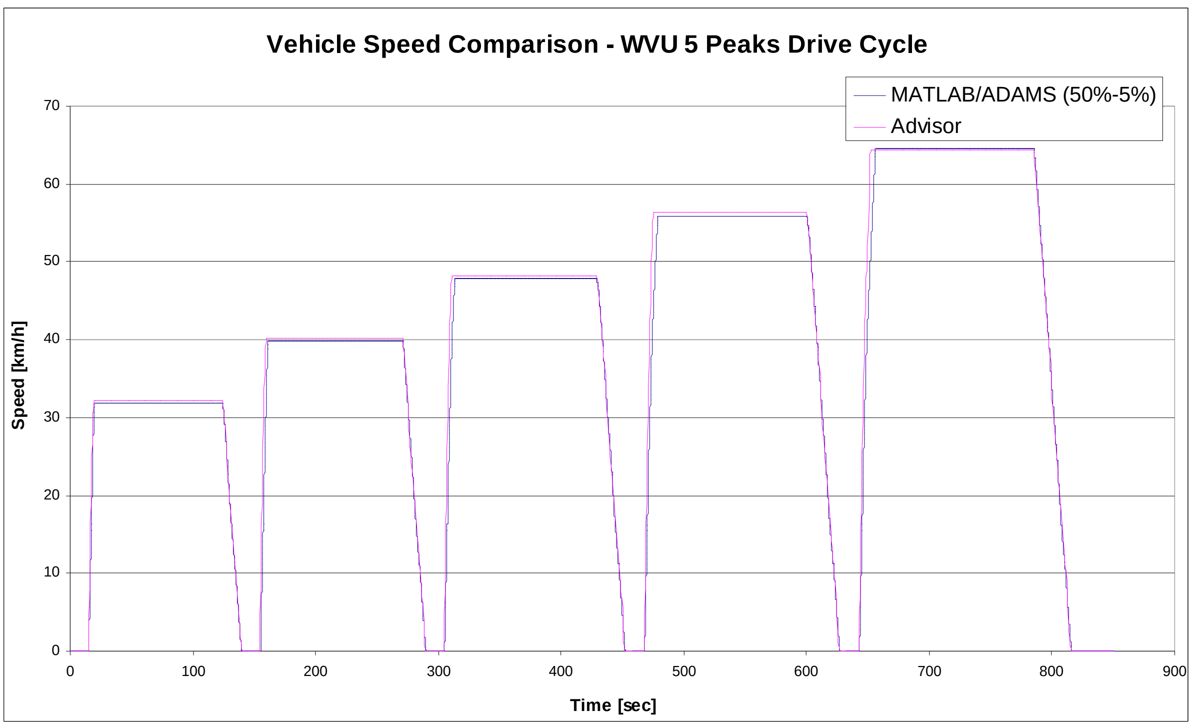

Figure 4-20: WVU 5 Peaks Drive Cycle Vehicle Speed Comparison

Engine Speed

Figure 4-21 depicts the engine speed of the two models. The overall results match very closely. Since both vehicles have manual transmission, and the vehicle speeds of the two models match, it should be expected for the engine speed to correlate well. However, it is observed that during the acceleration phase, the engine speeds of the two models differ. The main difference is due to the transmission modeling. MATLAB/ADAMS utilizes a simple gear change logic and the gear number is dependent on the vehicle speed. However, in ADVISOR, a clutch logic is implemented and it seems that during every up-shift, the engine is accelerated to an unusually high speed. This does not seem to be reasonable, and therefore is disregarded in validating the MATLAB/ADAMS vehicle model.

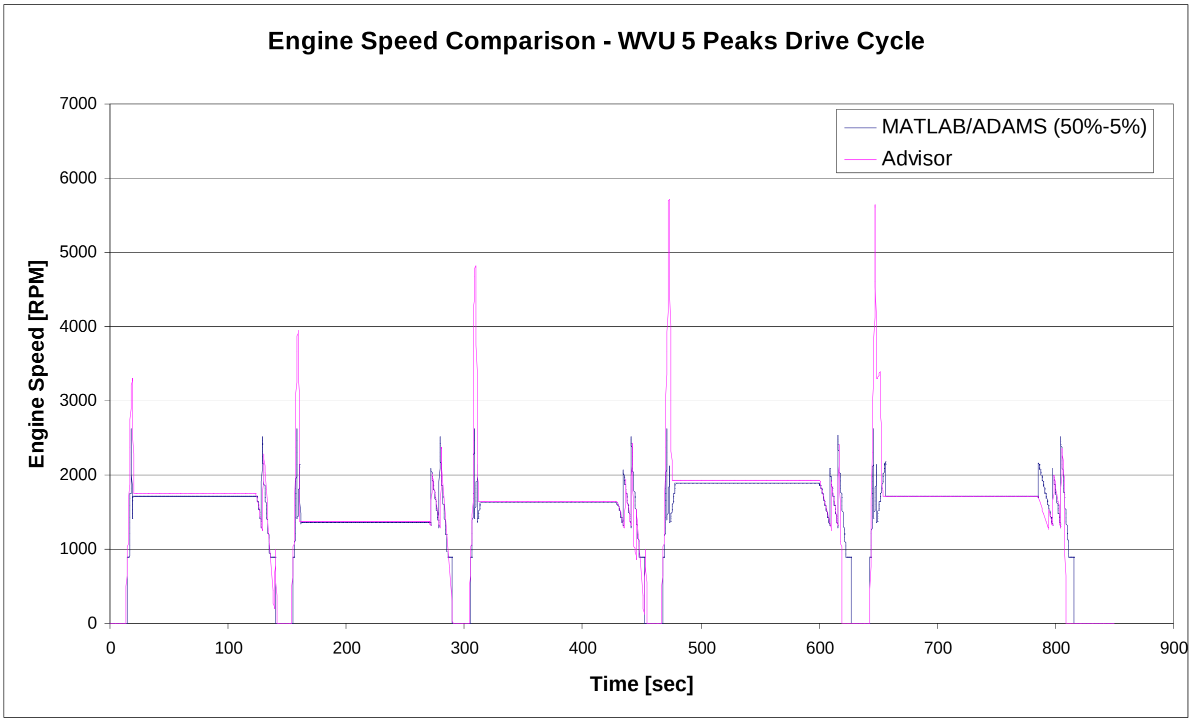

Figure 4-21: WVU 5 Peaks Drive Cycle Engine Speed Comparison

Engine Torque

Figure 4-22 depicts the engine torque comparison of the two models and, as seen, the trends match very closely. However, it is noted that there are several differences between the magnitudes of the engine torque, specifically during the closed throttle (negative) torque region. During deceleration, both models calculate the negative torque from the engine due to the closed throttle characteristic of the engine. However, it is noted that when the vehicle is stationary, the engine model in ADVISOR still exhibits a negative engine torque value, while the engine torque of the MATLAB/ADAMS model returns to zero. Since both models turn the engine off when the vehicle is stationary, such that there is no engine idling when the vehicle is stopped, it is not possible for the engine to output any torque values. It seems that in ADVISOR, when the vehicle is stopped and the engine is shut off, the engine still outputs a closed throttle torque at the engine idle speed. It is concluded that this might be due to a modeling glitch in ADVISOR, and thus, can be disregarded in the validation of the MATLAB/ADAMS model.

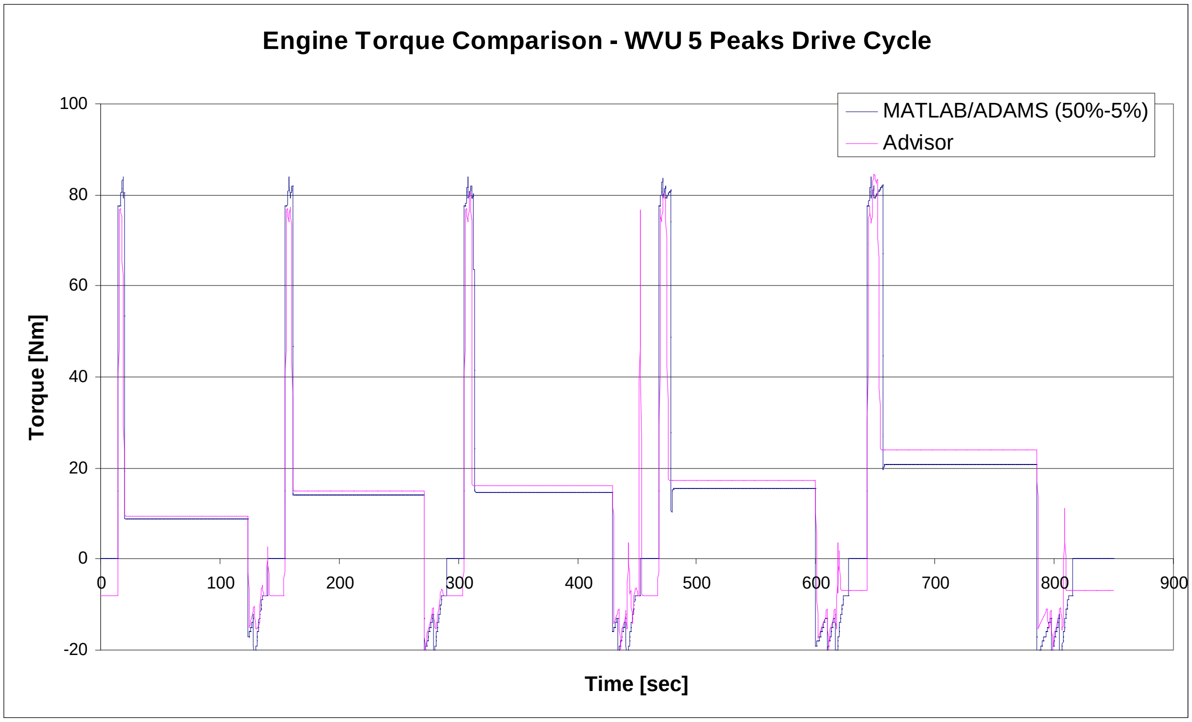

Figure 4-22: WVU 5 Peaks Drive Cycle Engine Torque Comparison

Motor/Generator Torque

The motor/generator torques of ADVISOR and MATLAB/ADAMS vehicle models are included in Figure 4-23. The torque results from the two models matched reasonably well. However, the ADVISOR model exhibited some motor torque spikes just when the vehicle comes to a rest, especially around 453 seconds. Again, this is disregarded when compared with the MATLAB/ADAMS vehicle model.

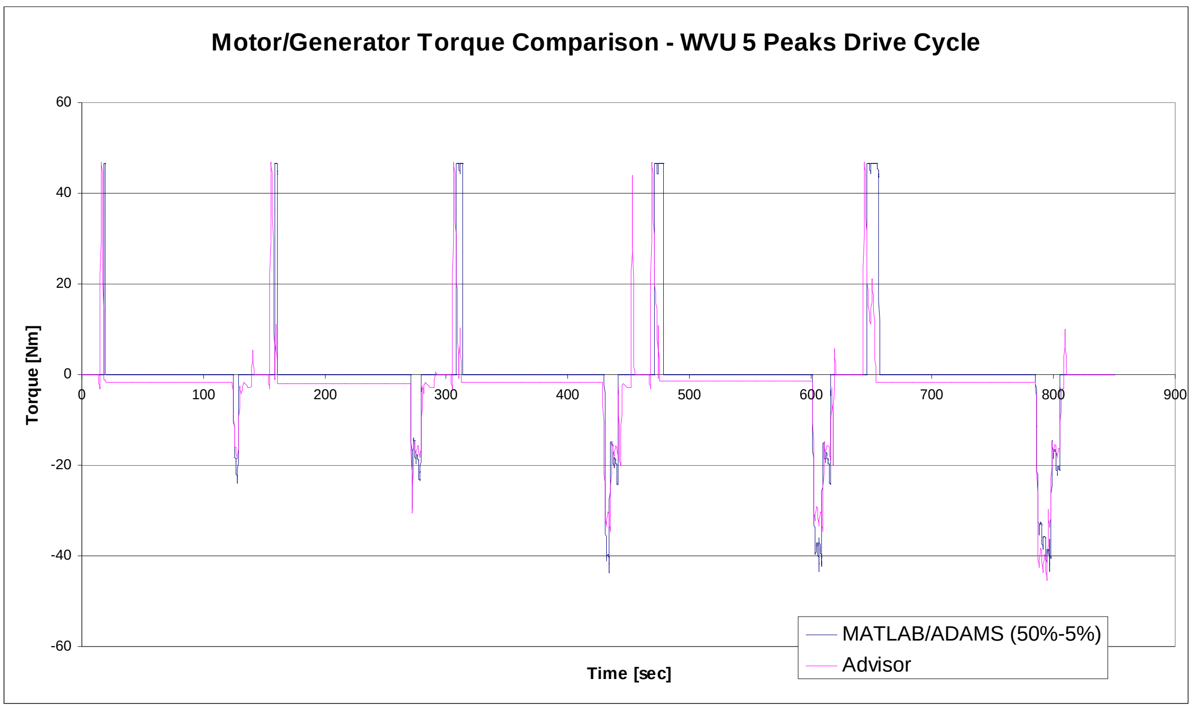

Figure 4-23: WVU 5 Peaks Drive Cycle Motor/Generator Torque Comparison

Fuel Consumption Rate

Figure 4-24 depicts a comparison of the engine fuel consumptions of the two models. Similar to the engine speed curve in Figure 4-21, ADVISOR exhibits values higher than that of MATLAB/ADAMS model at the beginning of each acceleration cycle. Such phenomenon is again due to the high engine speed during the clutch logic of ADVISOR, and therefore can be disregarded. Other than the initial spikes, the fuel rate results for the two models matched reasonably well.

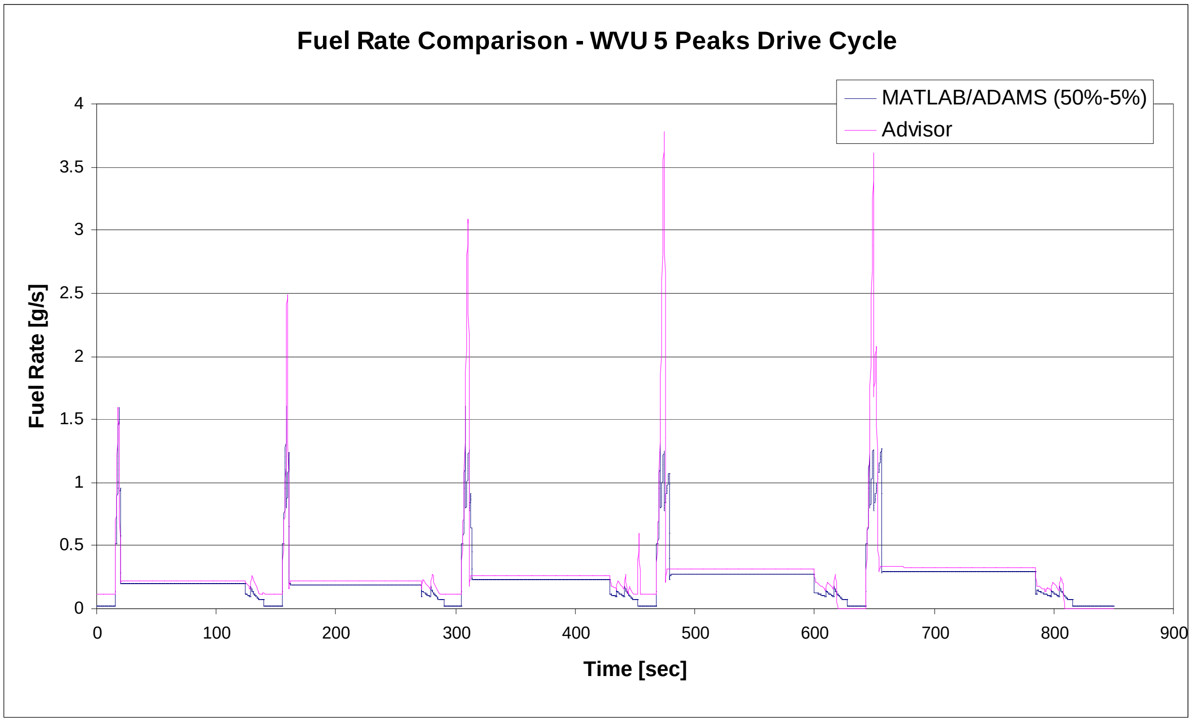

Figure 4-24: WVU 5 Peaks Drive Cycle Fuel Rate Comparison

Battery State of Charge (SOC)

Figure 4-25 illustrates the state of charge (SOC) of the battery system of the two models. The overall trend of the energy consumption and generation of the two models matches reasonably well. However, since the battery model used in the MATLAB/ADAMS model utilizes a simple energy calculation for the battery, some discrepancies existed between the magnitudes of the results. However, since the magnitude differences are within 2% of the overall SOC, the MATLAB/ADAMS battery model is considered satisfactory for the purpose of this thesis. Detailed battery modeling can be further implemented should the user require it.

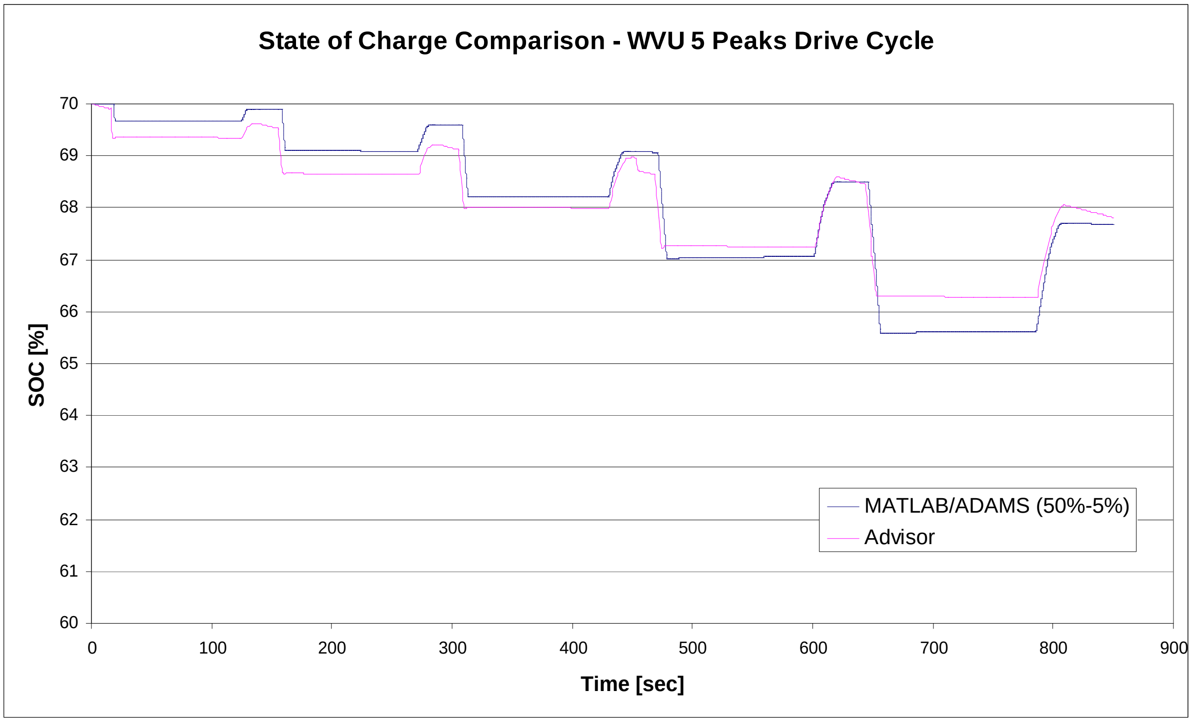

Figure 4-25: WVU 5 Peaks Drive Cycle State of Charge Comparison

Results Conclusion

It is concluded that the MATLAB/ADAMS hybrid vehicle results matched very well with the ADVISOR data. The overall torque values of the engine and the motor/generator system correlated well between the two models, for the exception of a few torque spikes from the ADVISOR motor torque and the negative engine torque while the vehicle is stationary. The vehicle speeds and the engine speeds of the two models also compared well, with the exception that ADVISOR implemented a clutch logic causing the engine speed to increase to an unusually high value, in turn causing the fuel consumption rate to increase. The negative torque during engine shut off and the high engine speed during acceleration of the ADVISOR model both seem unreasonable, and are therefore disregarded for the purpose of comparative evaluation of the MATLAB/ADAMS model. Finally, since the battery model utilized in the MATLAB/ADAMS model is based on a simple energy calculation, it is recommended that further work be performed to increase the accuracy of the battery model should the user require it.

Chapter 5

Simulation Results and Efficiency Comparison

The purpose of a hybrid vehicle is to provide better fuel efficiency over a conventional vehicle. As shown in the previous chapter, the MATLAB/ADAMS hybrid vehicle model provided results that correlated well with the published ADVISOR simulation data. Using a validated vehicle model, it is essential to show that the hybrid vehicle model indeed provides better fuel efficiency over a conventional vehicle. The purpose of this chapter is to provide an efficiency performance comparison of the MATLAB/ADAMS hybrid vehicle over a conventional vehicle.

The conventional vehicle model will be based on the same hybrid vehicle model developed for this thesis, but without the motor assist and the regenerative braking. It is also assumed that the conventional vehicle is 100kg[1] less than the hybrid vehicle. The vehicle performance of the hybrid and the conventional vehicle models will be compared over the same standard drive cycles. Two standard U.S. EPA (Environmental Protection Agency) drive cycles will be used to simulate city and highway driving. The EPA NYCC (New York City Cycle) will be used to simulate the city driving, while the EPA HWFET (Highway Fuel Economy Cycle) will be used to determine the highway fuel economy. Figure 5-1 and Figure 5-2 depict the NYCC and the HWFET standard drive cycles.

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[1] Assumed mass of the motor/generator and batteries, based on the mass difference of the conventional and hybrid model of the Honda Civic [17, 18]

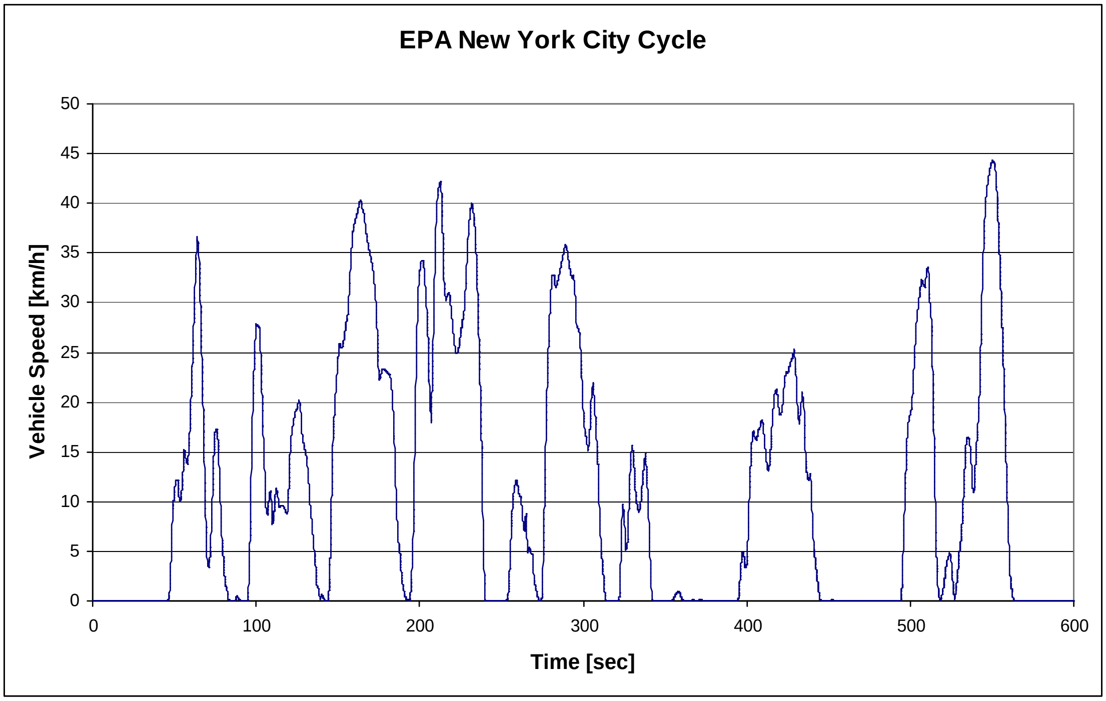

Figure 5-1: EPA New York City Cycle (NYCC) Standard Drive Cycle

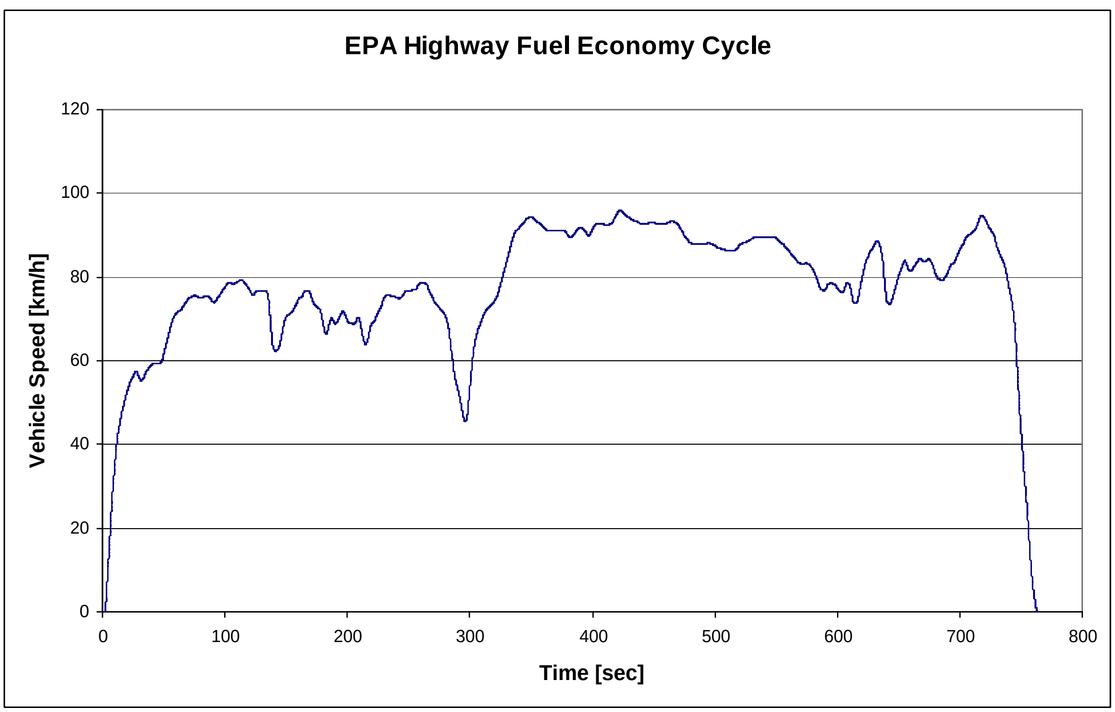

Figure 5-2: EPA Highway Fuel Economy (HWFET) Standard Drive Cycle

5.1 New York City Cycle (NYCC)

As previously mentioned, the New York City Cycle is used to simulate city driving. Figure 5-3 depicts the results of comparison between the hybrid and the conventional vehicle models.

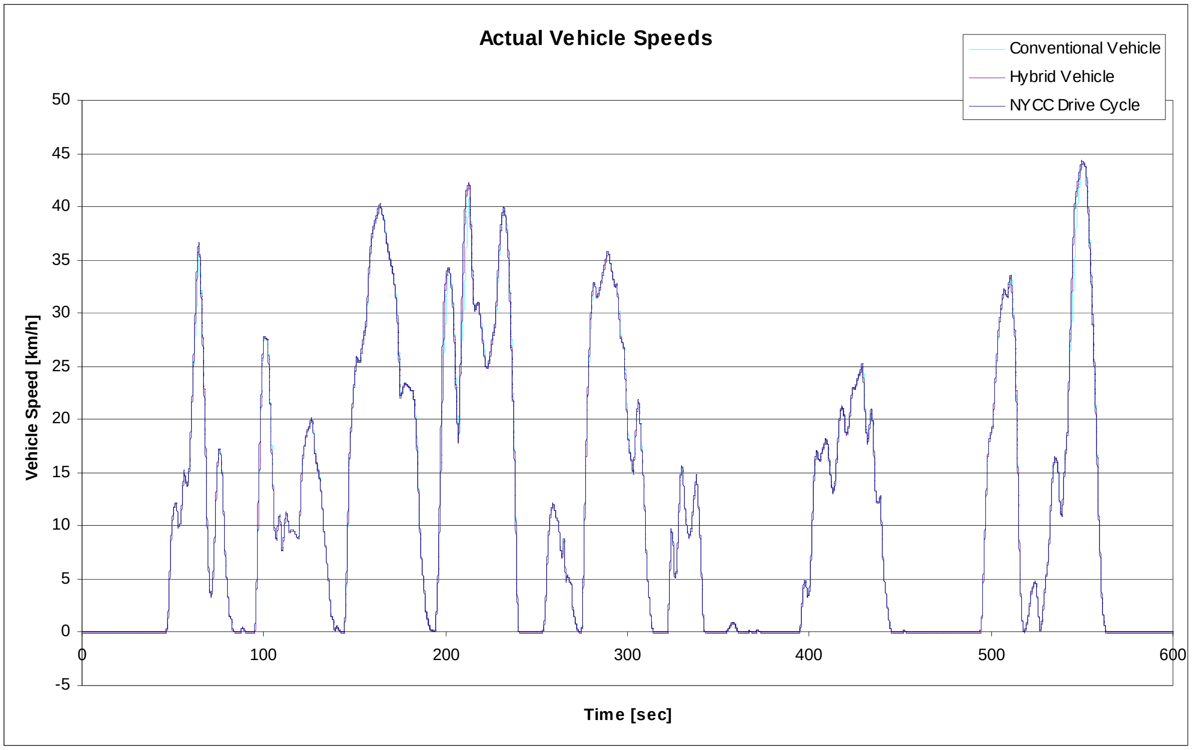

Figure 5-3: NYCC Hybrid and Conventional Vehicle Speed Comparison

It can be seen that both the hybrid and the conventional vehicle model followed the desired drive cycle speed very well. The actual driving behaviour of the vehicle and the efficiency comparison will be presented in the subsequent sections.

5.1.1 Driving Behaviour

In order for the vehicle to achieve the desired speed profile, the driver control logic applies the appropriate percent throttle and braking accordingly. Since the conventional vehicle model does not utilizes motor assist and regenerative braking, only the engine torque and the mechanical brakes are available throughout the drive cycle. Figure 5-4 and Figure 5-5 depict, respectively, the throttle and braking percent comparison throughout the New York City Cycle.

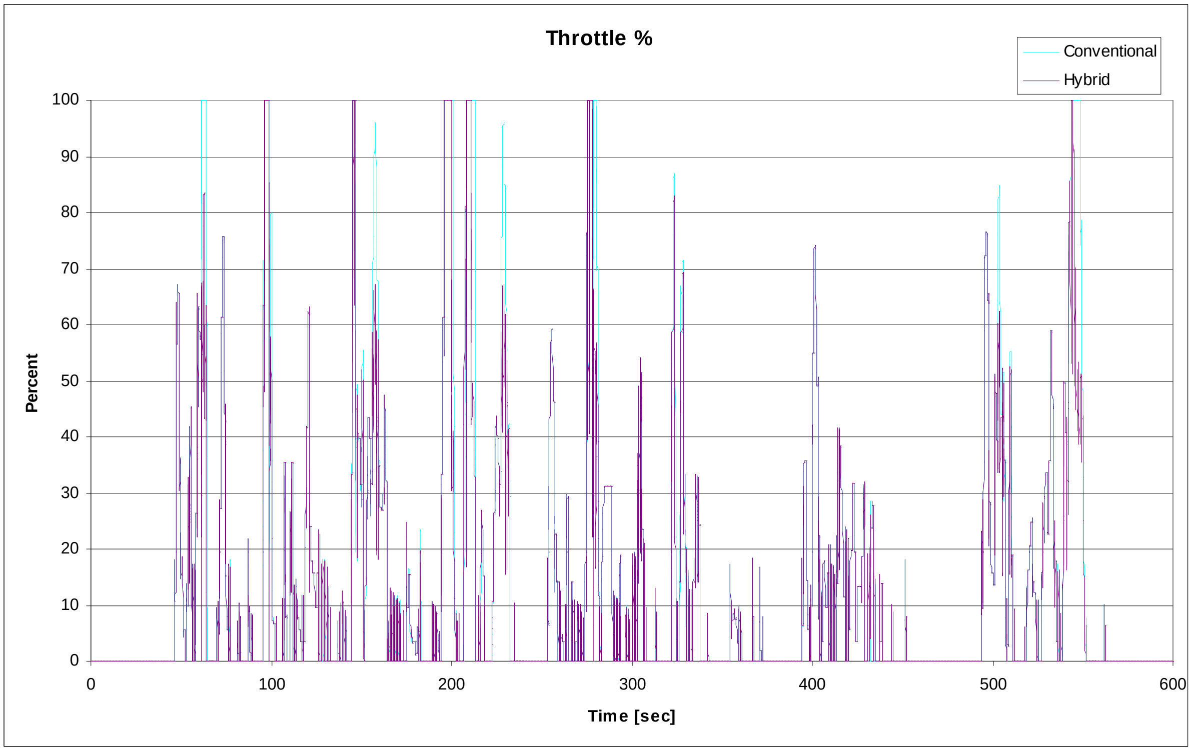

Figure 5-4: NYCC Hybrid and Conventional Vehicle Throttle Percent Comparison

As illustrated in Figure 5-4, the conventional vehicle model applied more throttle than the hybrid vehicle model, which is logical since the conventional vehicle does not have the additional motor torque of the hybrid vehicle, and thus additional engine torque is required for the vehicle to achieve the desired speed.

Figure 5-5 depicts the braking percent of the hybrid and the conventional vehicle models throughout the NYC cycle. Similar to the throttle percent, the conventional vehicle model applied more braking percent than the hybrid vehicle model. Since the conventional vehicle does not have regenerative braking available, higher braking percent is required from the mechanical brakes to decelerate the vehicle.

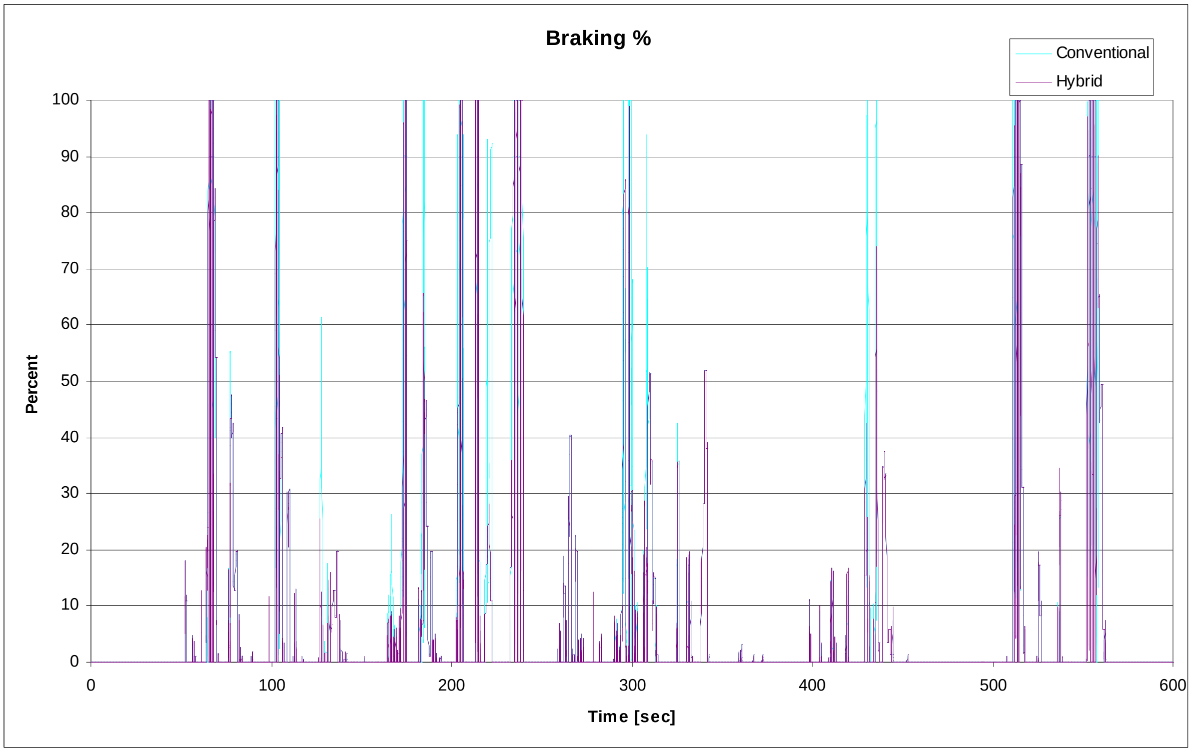

Figure 5-5: NYCC Hybrid and Conventional Vehicle Braking Percent Comparison

5.1.2 Efficiency Comparison

To demonstrate the advantages of a hybrid vehicle over a conventional vehicle, it is essential to analyze the energy consumptions of the vehicle. The fuel and the electrical energy consumption of the hybrid and the conventional vehicles will be presented in this section.

Figure 5-6 depicts the fuel consumptions of the hybrid and the conventional vehicle models over the NYC cycle. As expected, the total amount of fuel consumed by the conventional vehicle is higher than that of the hybrid vehicle.

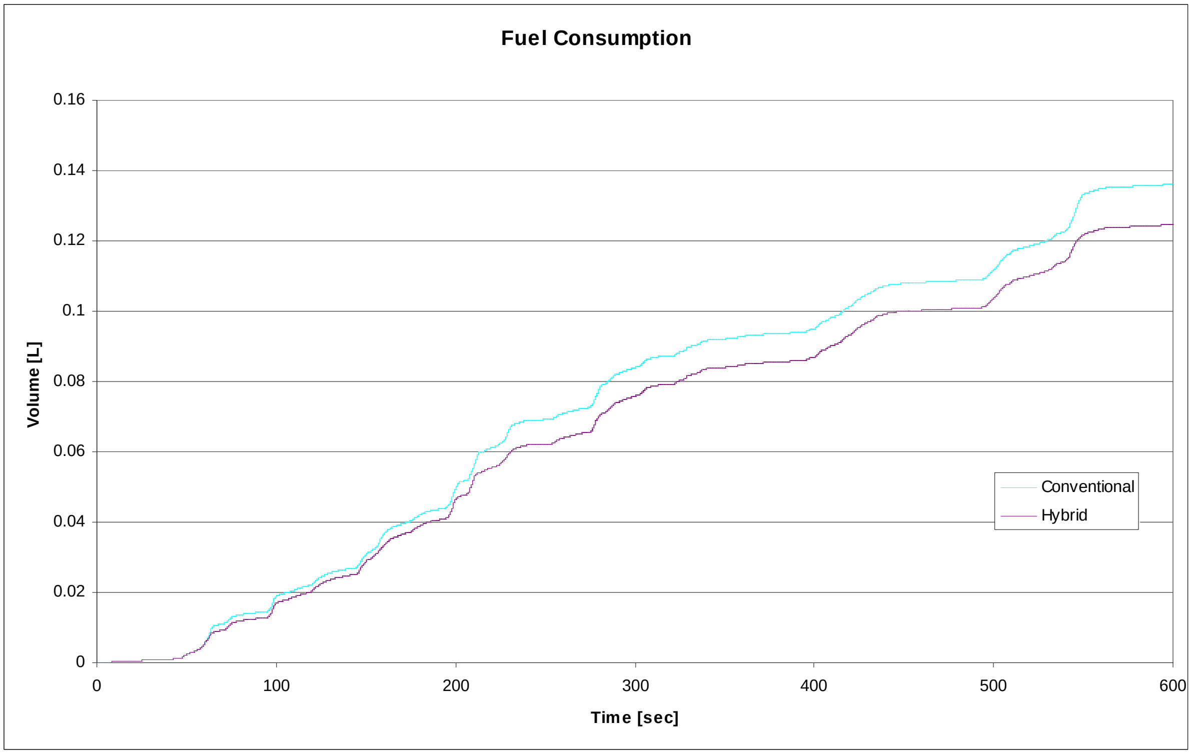

Figure 5-6: NYCC Hybrid and Conventional Vehicle Fuel Consumption Comparison

Table 5-1 summarizes the actual fuel consumption comparison of the conventional and the hybrid vehicle models.

Table 5-1: NYCC Fuel Consumption Summary of the Hybrid and the Conventional Vehicle Model

Vehicle Model	Fuel Consumption [L]	Distance Traveled [km]
Conventional	0.13609	1.89
Hybrid	0.12464	1.89

Figure 5-7 illustrates the battery state of charge of the hybrid vehicle throughout the drive cycle. Due to the stop and go nature of city driving, the regenerative braking of the hybrid vehicle was able to recover the kinetic energy, which would otherwise be lost to the mechanical brakes, back into electrical energy to recharge the battery. The recovered electrical energy can then be used to provide additional power to the motor during the assist mode, and further reduce the amount of fuel consumed. The process of recovering lost kinetic energy into electrical energy for later use is essentially the major advantage of a hybrid vehicle over a conventional vehicle.

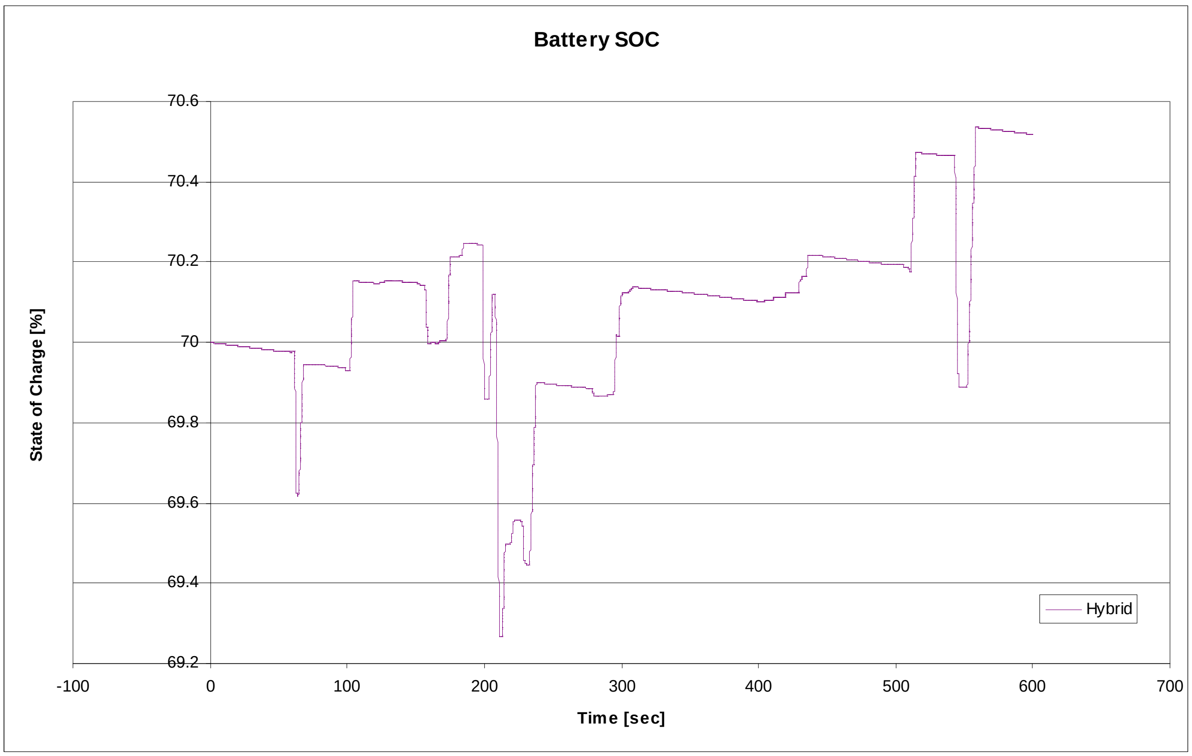

Figure 5-7: NYCC Hybrid and Conventional Vehicle Battery State of Charge Comparison

To understand the amount of energy savings provided by the hybrid vehicle model from a different perspective, the energy consumed or generated can be used to calculate an equivalent fuel amount using the following equation.

$$Fuel_{equiv} = \frac{\varepsilon_{elec}}{\rho_{fuel} \times lhv_{fuel}} \tag{5.1}$$

where $Fuel_{equiv}$ = Equivalent fuel of the motor/generator's electrical energy [L]

ε_{elec} = Electrical energy of the motor/generator [J]

ρ_{fuel} = Density of gasoline [g/L]

lhv_{fuel} = Lower heating value (does not contain water vapour energy) of gasoline [J/g]

The following table summarizes the electrical energy consumption and its equivalent fuel amount for the hybrid vehicle.

Table 5-2: NYCC Electrical Energy Consumption Summary of the Hybrid Vehicle

	Electrical Energy [kJ]	Equivalent Fuel [L]
Energy Consumed	83.61	2.620e-3
Energy Generated	105.49	3.306e-3

By combining the equivalent fuel consumption of the motor/generator with the actual fuel usage of the hybrid vehicle as indicated in Table 5-1, the overall fuel economy of the hybrid vehicle can be calculated. The following table summarizes the fuel economy of the conventional and the hybrid vehicle over the NYCC drive cycle.

Table 5-3: NYCC Fuel Economy Summary of the Hybrid and the Conventional Vehicle Model

Vehicle Model	Fuel Consumption [L]	Distance Traveled [km]	Fuel Economy [L/100km]
Conventional	0.1361	1.89	7.20
Hybrid	0.1246	1.89	6.56
% Difference	-8.92%		-8.92%

It should be noted that since the actual ADAMS vehicle model and the power management logic of the MATLAB/ADAMS hybrid vehicle model are not validated against the Honda Insight, the fuel economy stated in Table 5-3 may differ from the published value of 3.9L/100km [16] from the manufacturer.

5.2 Highway Fuel Economy Cycle (HWFET)

The Highway Fuel Economy Cycle as previously mentioned is used to simulate highway driving. Figure 5-8 depicts the comparison results between the hybrid and the conventional vehicle model.

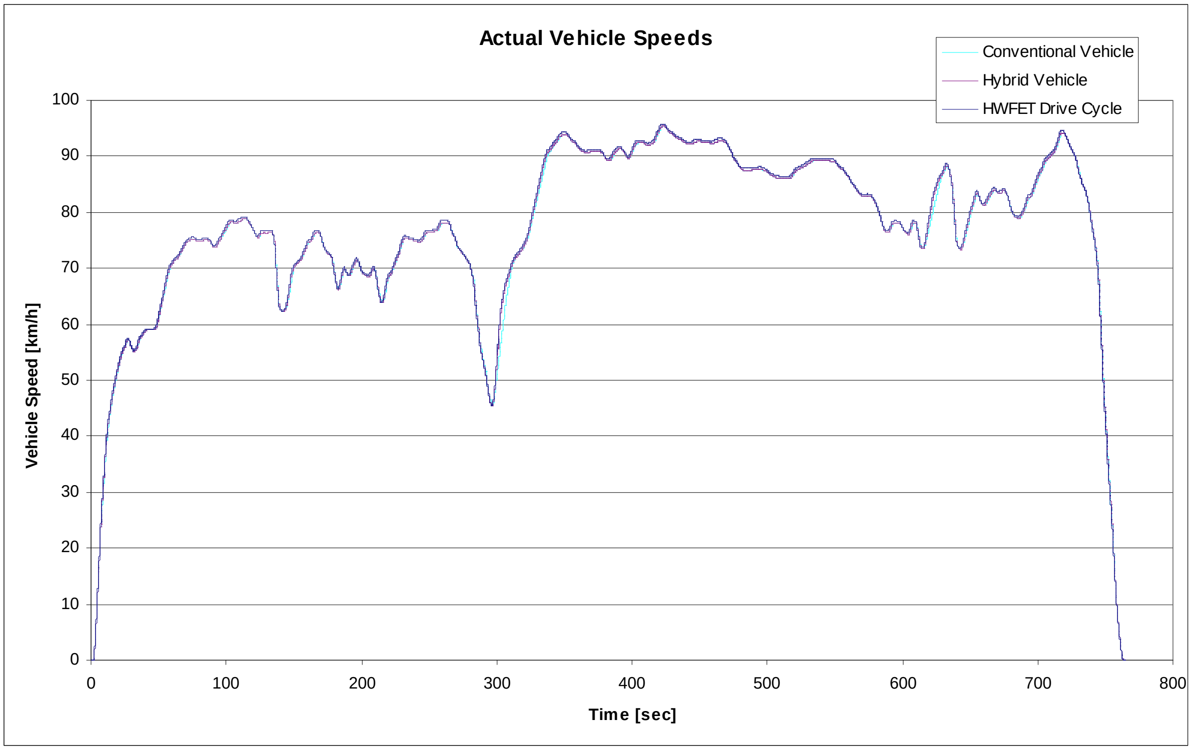

Figure 5-8: HWFET Hybrid and Conventional Vehicle Speed Comparison

Similar to the city driving of the NYCC, it can be seen that both the hybrid and the conventional vehicle model followed the desired drive cycle speed very well. The actual driving behaviour of the vehicle and the efficiency comparison will be presented in the subsequent sections.

5.2.1 Driving Behaviour

Similar to section 5.1.1, Figure 5-9 and Figure 5-10 depict, respectively, the throttle and brake percent comparisons throughout the highway fuel economy cycle.

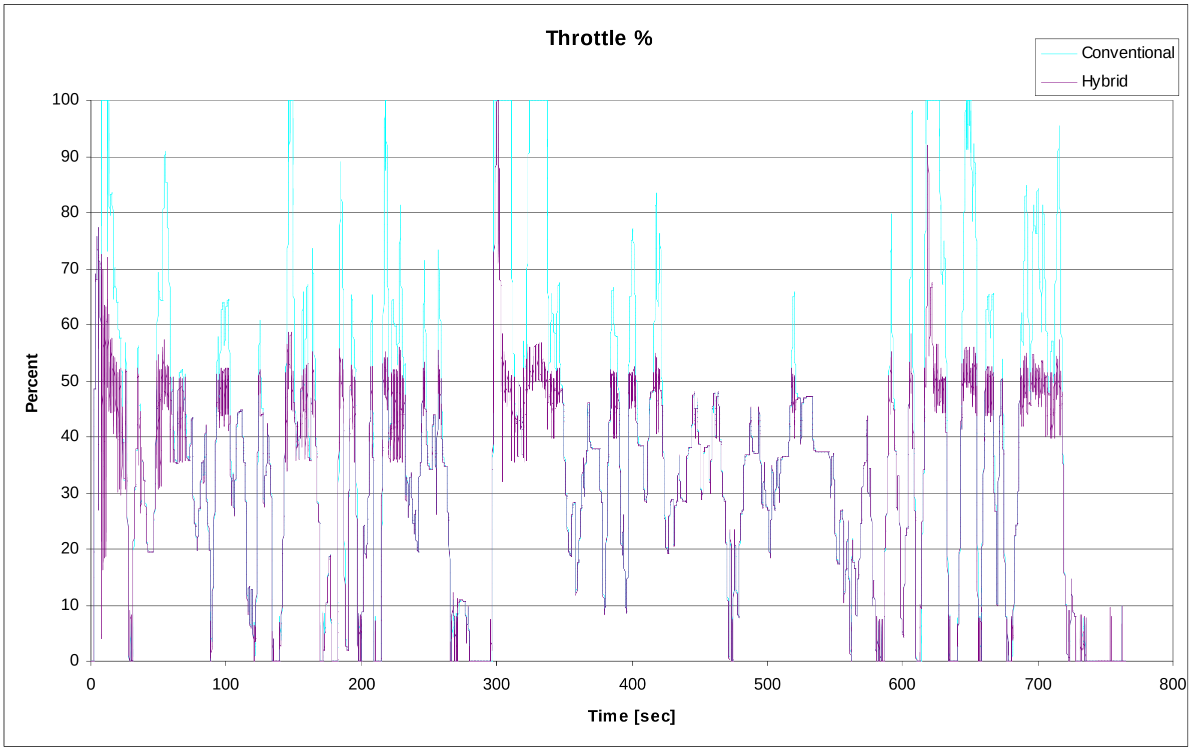

Figure 5-9: HWFET Hybrid and Conventional Vehicle Throttle Percent Comparison

As illustrated in Figure 5-9, it is shown that the conventional vehicle model applied significantly more throttle than the hybrid vehicle model, especially past the 50% throttle threshold. Since the power management logic of the hybrid vehicle depicts the motor to assist the engine when the throttle percent is over 50%, it is not surprising that the hybrid vehicle's throttle percent is maintained around 50% during highway cruising. However, due to the lack of additional motor torque in the conventional vehicle, a higher throttle percent is needed to output the required engine torque in order to maintain the highway cruising speed.

Figure 5-10 depicts the braking percent of the hybrid and the conventional vehicle models throughout the highway drive cycle. Again, since the conventional vehicle does not have regenerative braking available, higher brake percent is required from the mechanical brakes to output the same amount of braking torque. However, due to the nature of highway driving, the brakes were not engaged as frequently as in the case of the New York City Cycle.

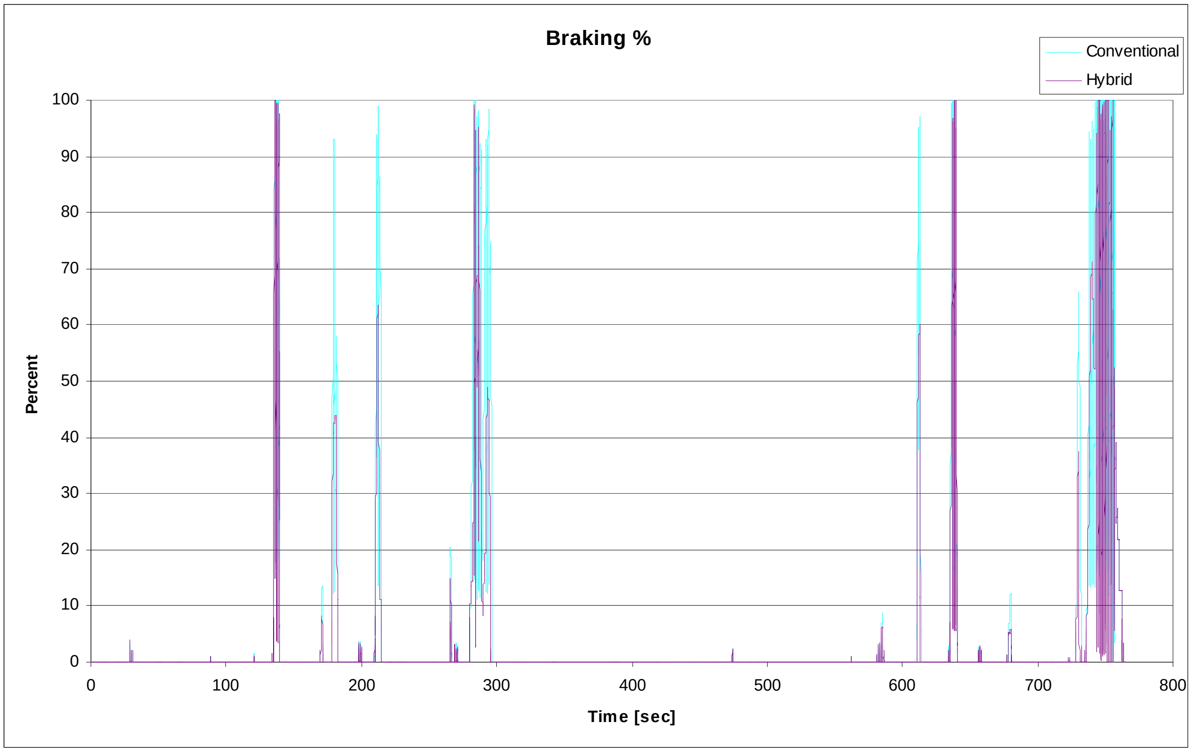

Figure 5-10: HWFET Hybrid and Conventional Vehicle Braking Percent Comparison

5.2.2 Efficiency Comparison

Similar to the city driving results comparison, the fuel and the electrical energy consumption of the hybrid and the conventional vehicles will be presented in this section.

Figure 5-11 depicts the fuel consumption of the hybrid and the conventional vehicle models over the highway fuel economy drive cycle. As expected, the total amount of fuel consumed by the conventional vehicle is higher than that of the hybrid vehicle.

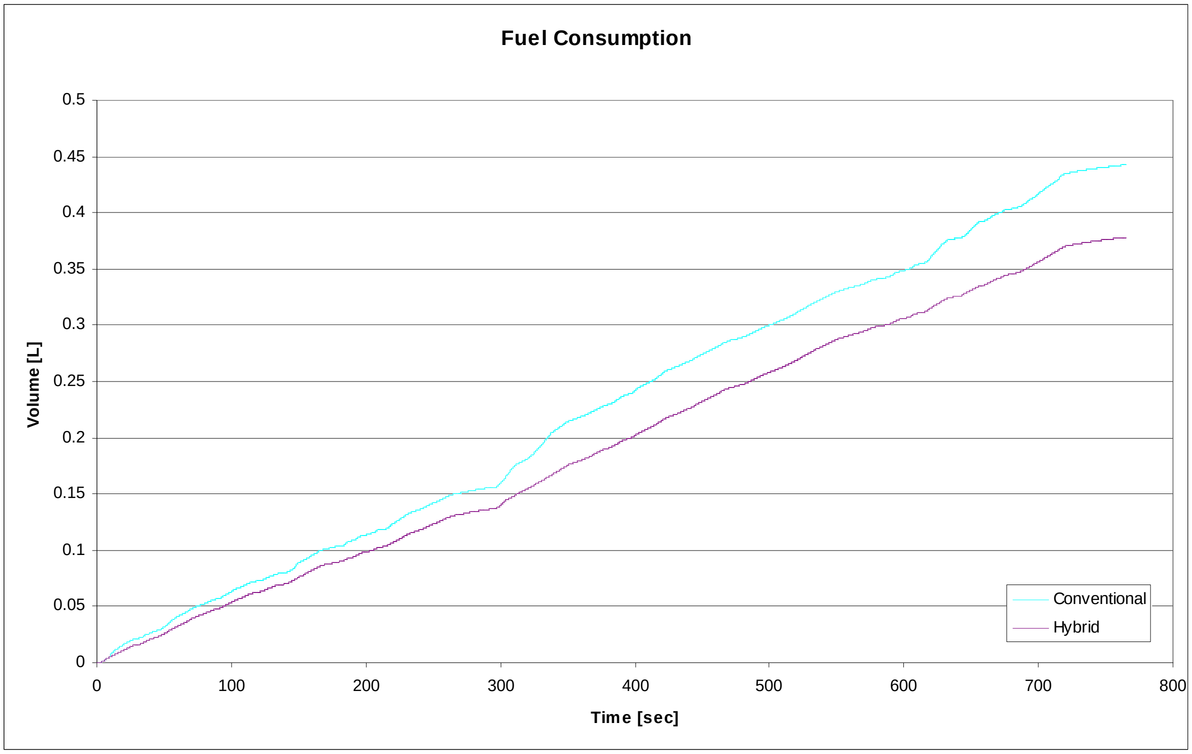

Figure 5-11: HWFET Hybrid and Conventional Vehicle Fuel Consumption Comparison

Table 5-4 summarizes the actual fuel consumption comparison of the conventional and the hybrid vehicle models.

Table 5-4: HWFET Fuel Consumption Summary of the Hybrid and the Conventional Vehicle Model

Vehicle Model	Fuel Consumption [L]	Distance Traveled [km]
Conventional	0.4423	16.45
Hybrid	0.3779	16.45

Figure 5-12 illustrates the battery state of charge of the hybrid vehicle throughout the drive cycle. As discussed in section 5.2.1, due to the nature of highway driving, the brakes were not engaged as frequently as in city driving, and therefore less electrical energy was recovered. As a result of the motor assisting the engine primarily to maintain highway cruising speed, a higher net energy was consumed in the highway driving when compared to the city driving cycle.

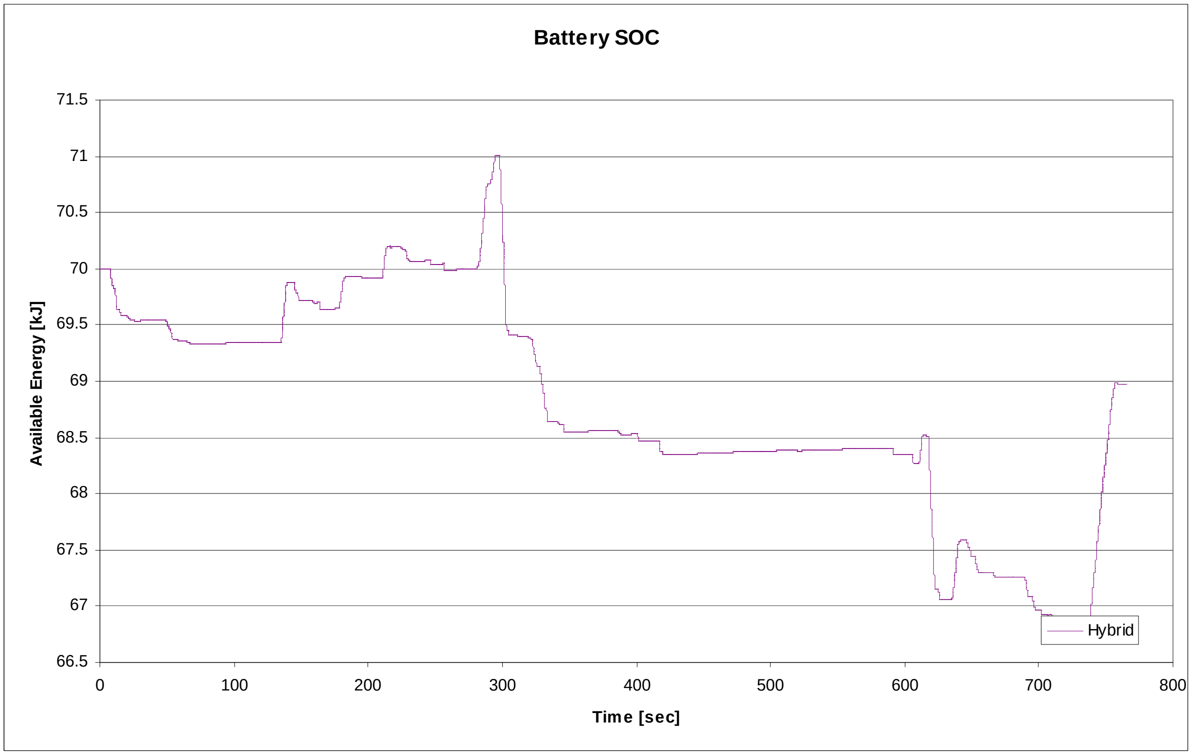

Figure 5-12: HWFET Hybrid and Conventional Vehicle Battery State of Charge Comparison

Using equation (5.1), Table 5-5 summarizes the electrical energy consumption and its equivalent fuel amount of the hybrid vehicle.

Table 5-5: HWFET Electrical Energy Consumption Summary of the Hybrid Vehicle

	Electrical Energy [kJ]	Equivalent Fuel [L]
Energy Consumed	213.56	6.69e-3
Energy Generated	171.99	5.39e-3

Again, by combining the equivalent fuel consumption of the motor/generator with the actual fuel usage of the hybrid vehicle as indicated in Table 5-4, the overall fuel economy of the hybrid vehicle can be calculated. The following table summarizes the fuel economy of the conventional and the hybrid vehicle over the HWFET drive cycle.

Table 5-6: HWFET Fuel Economy Summary of the Hybrid and the Conventional Vehicle Model

Vehicle Model	Fuel Consumption [L]	Distance Traveled [km]	Fuel Economy [L/100km]
Conventional	0.4423	16.45	2.69
Hybrid	0.3792	16.45	2.31
% Difference	-14.27%		-14.27%

Again, it should be noted that since the ADAMS vehicle model and the power management logic of the MATLAB/ADAMS hybrid vehicle model are not validated against the Honda Insight; therefore, the fuel economy stated in Table 5-6 differs from the published value of 3.2L/100km [16] from the manufacturer.

5.3 Summary

It is shown that simulations of the hybrid and the conventional vehicles are successfully performed over the EPA New York City Cycle (NYCC) and the Highway Fuel Economy Cycle (HWFET). It is found that the hybrid vehicle model demonstrated 8.92% and 14.27% fuel economy improvement over the conventional vehicle model for the NYCC and HWFET drive cycles, respectively. Due to the stop and go nature of the city driving, it is demonstrated that the regenerative braking recovered sufficient kinetic energy to recharge the battery for motor assist. The motor assist consumed 83.61kJ while the regenerative braking recovered 105.49kJ of electrical energy during the city driving. On the other hand, less energy is recovered during the highway driving due to the less frequent braking throughout the drive cycle. The motor assist consumed 213.56kJ while the regenerative braking recovered 171.99kJ of electrical energy throughout the highway drive cycle.

Chapter 6

Conclusions and Recommendations

The MATLAB/ADAMS hybrid vehicle model was successfully created based on the Honda Integrated Motor Assist (IMA) architecture. The energy components and the vehicle controllers were created in MATLAB/Simulink, while the vehicle body and its inertial components were created in MSC ADAMS. The powertrain components utilized in the hybrid vehicle model were based on the Honda Insight's 1.0L VTEC-SI engine and the 10kW DC brushless permanent magnet motor. Test data of both the engine and the motor/generator were published by the Argonne National Laboratory (ANL), and were used in the MATLAB/ADAMS hybrid vehicle model.

The hybrid vehicle model utilized a driver input architecture, where a driver controller compares the desired and actual vehicle speeds, and outputs throttle or braking percent to the powertrain, which in turn provides a drive torque to the vehicle driveshaft. Communication between the powertrain and the mechanical components was established by ADAMS/Control. To evaluate the accuracy of the MATLAB/ADAMS hybrid vehicle model against the published ADVISOR results, the West Virginia University (WVU) 5 Peaks drive cycle was used. There was a close match between the MATLAB/ADAMS and the ADVISOR vehicle models for the engine and the motor/generator. Minor discrepancies existed where the engine speed of ADVISOR reached an unusually high value during each gear change, and thus directly affected the fuel consumption rate of the engine. In addition, the magnitude of the battery state of charge (SOC) comparison curve exhibited some differences due to the fact that the MATLAB/ADAMS model was based on a simple energy calculation. However, since the trend of the battery SOC curve matched very well, and that the magnitude difference was relatively small, it was concluded that the MATLAB/ADAMS hybrid vehicle model correlated well with the published results of ADVISOR.

In order to demonstrate the fuel efficiency advantages of the hybrid vehicle over the conventional vehicle, a comparison study was performed over standard city and highway drive cycles. The EPA standard New York City Cycle (NYCC) and the Highway Fuel Efficiency Cycle (HWFET) simulations were performed on both the hybrid and the conventional vehicle models. The hybrid vehicle model demonstrated 8.9% and 14.3% fuel economy improvement over the conventional vehicle model for the NYCC and HWFET drive cycles, respectively. Since the Honda Insight is a form of parallel hybrid vehicle, the result is consistent with the consensus that parallel hybrid vehicles are more energy efficient during highway driving than city driving over series hybrid vehicles. In addition, due to the stop and go nature of the city driving, it was demonstrated that the regenerative braking recovered sufficient kinetic energy to recharge the battery for motor assist. The motor assist consumed 83.6kJ while the regenerative braking recovered 105.5kJ of electrical energy during the city driving. On the other hand, less energy was recovered during the highway driving due to the less frequent braking throughout the drive cycle. The motor assist consumed 213.6kJ while the regenerative braking recovered 172.0kJ of electrical energy throughout the highway drive cycle.

The MATLAB/ADAMS hybrid vehicle model offers a simulation platform that is modular, flexible, and can be easily modified for different types of vehicle model. In addition, the simulation results clearly demonstrated the fuel economy advantage of the hybrid vehicle over the conventional vehicle. However, additional work is recommended to further optimize the efficiency of the power management controller. Since the current power management controller utilizes a simple motor assist and regenerative braking logic, it is recommended that a more sophisticated power management controller be implemented to optimize the efficiencies of the engine and the motor/generator. Furthermore, it is recommended that the mechanical portion of the vehicle system be validated against an actual vehicle, in order to fully utilize the multi-body vehicle dynamics that the ADAMS has to offer.

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Appendix A

Engine Data

Maximum Engine Torque

Engine Speed [RPM]	100% Throttle Engine Torque [lb-ft]
800	56.9
1273	58.2
1745	59.5
2218	60.7
2691	62
3164	63.2
3636	64.5
4109	65.7
4582	67
5055	64.3
5527	61.5
6000	58.6

Closed Throttle Engine Torque

Engine Speed [RPM]	100% Throttle Engine Torque [lb-ft]
800	-5.15
1273	-8.58
1745	-12.29
2218	-16.28
2691	-20.57
3164	-25.13
3636	-29.97
4109	-35.11
4582	-40.52
5055	-46.23
5527	-52.2
6000	-58.47

Fuel Consumption Rate [g/s] Data Map

	Engine Speed [RPM]											
Engine Torque [lbs]	***800***	***1273***	***1745***	***2218***	***2691***	***3164***	***3636***	***4109***	***4582***	***5055***	***5527***	***6000***
5.6	0.0962	0.1269	0.1576	0.1883	0.2191	0.2498	0.2805	0.3112	0.361	0.4566	0.4641	0.4641
11.2	0.142	0.1909	0.2398	0.2887	0.3375	0.3864	0.4353	0.4842	0.5584	0.7129	0.7383	0.7383
16.8	0.1871	0.2541	0.3212	0.3882	0.4552	0.5223	0.5893	0.6563	0.7533	0.9683	1.0215	1.0215
22.3	0.2371	0.3223	0.4075	0.4927	0.5779	0.663	0.7482	0.8334	0.9524	1.2297	1.3207	1.3207
27.9	0.2953	0.3987	0.502	0.6053	0.7087	0.812	0.9154	1.0187	1.1591	1.5012	1.6278	1.6399
33.5	0.3656	0.4871	0.6086	0.7301	0.8516	0.9731	1.0946	1.216	1.3777	1.7875	1.9363	1.9839
39.1	0.4521	0.5918	0.7314	0.8711	1.0107	1.1504	1.29	1.4297	1.6124	2.0936	2.2647	2.3577
44.7	0.5591	0.7169	0.8747	1.0325	1.1903	1.3481	1.5059	1.6637	2.0304	2.4249	2.6182	2.7666
50.3	0.7038	0.8993	1.1014	1.3102	1.5255	1.7475	1.976	2.2112	2.453	2.7014	2.9563	3.2156
55.8	0.868	1.0863	1.3123	1.5458	1.7869	2.0356	2.2919	2.5558	2.8272	3.1063	3.393	3.5433
61.4	1.0663	1.3087	1.5596	1.8193	2.0877	2.3647	2.6504	2.9448	3.2479	3.5596	3.8801	3.883
67	1.3032	1.5709	1.8484	2.1357	2.433	2.7402	3.0572	3.3841	3.7208	4.0675	4.2459	4.2459

Appendix B

Motor/Generator Data

Maximum Motor and Generator Torque

Shaft Speed [RPM]	Maximum Motor Torque [Nm]	Maximum Generator Torque [Nm]
0	46.5	-46.5
500	46.5	-46.5
1000	46.5	-46.5
1500	46.5	-46.5
2000	46.5	-46.5
2500	38.2	-38.2
3500	27.3	-27.3
4000	23.9	-23.9
4500	21.2	-21.2
5000	19.1	-19.1
5500	17.4	-17.4
6000	15.9	-15.9
6500	14.7	-14.7
7000	13.6	-13.6
7500	12.7	-12.7
8000	11.9	-11.9
8500	11.2	-11.2

Motor/Generator Efficiency [%] Map

	Motor/Generator Torque [Nm]																			
Speed [RPM]	***-36***	***-32***	***-28***	***-24***	***-20***	***-16***	***-12***	***-8***	***-4***	***0***	***4***	***8***	***16***	***20***	***24***	***28***	***32***	***36***	***43.5***	***46.5***
0	54.17	56.09	59.74	62.16	64.71	64.88	66.49	68.3	63.07	63.07	87.76	84.71	79.49	78.1	76.56	75.09	73.9	71.33	63.88	59.75
500	54.17	56.09	59.74	62.16	64.71	64.88	66.49	68.3	63.07	63.07	87.76	84.71	79.49	78.1	76.56	75.09	73.9	71.33	63.88	59.75
1000	70	71.77	75.2	78.37	80.62	82.73	84.62	85.31	80.23	80.23	85.98	86.96	87.34	86.64	85.45	84.73	84.03	83.26	80.81	77.35
1500	79.08	80.25	82.73	84.76	86.91	87.56	87.27	87.2	80.24	80.24	87.45	88.53	89.23	89.37	88.36	88.08	87.98	87.33	85.65	82.47
2000	83.36	84.27	86.74	88.36	89.34	90.2	90.39	89.14	81.05	81.05	90.54	90.31	90.33	90.42	90.38	90.13	89.86	89.38	87.95	87.25
2500	86.38	87.62	88.89	90.36	90.71	91.07	91.08	89.2	83.52	83.52	88.41	91.83	91.51	91.56	91.43	91.28	91.02	91.23	90.67	90.67
3000	90.83	90.83	91.04	91.41	92.6	91.95	92.22	90.68	84.9	84.9	90.61	91.38	92.36	92.29	92.35	92.16	92.12	93.52	93.61	93.61
3500	92.78	92.78	92.78	92.78	93.06	93.1	92.21	91.79	84.92	84.92	90.37	92.79	93.59	94.31	94.42	94.68	95.24	95.42	95.42	95.42
4000	93.49	93.49	93.49	93.49	93.49	93.74	93.45	91.19	86.24	86.24	93.14	94.56	95.69	95.67	96.02	96.07	95.88	95.88	95.88	95.88
4500	94.37	94.37	94.37	94.37	94.37	94.24	93.97	91.8	85.7	85.7	90.78	93.73	96	96.13	96.39	96.23	96.23	96.23	96.23	96.23
5000	95.03	95.03	95.03	95.03	95.03	94.26	94.29	91.51	82.22	82.22	89.23	93	95.29	96.05	96.05	96.05	96.05	96.05	96.05	96.05
5500	94.75	94.75	94.75	94.75	94.75	94.75	93.06	90.49	81.37	81.37	87.75	92.89	95.47	95.83	95.83	95.83	95.83	95.83	95.83	95.83
6000	94.07	94.07	94.07	94.07	94.07	94.07	93.27	89.98	80.69	80.69	86.69	92.47	95.18	95.4	95.4	95.4	95.4	95.4	95.4	95.4
6500	93.84	93.84	93.84	93.84	93.84	93.84	92.95	89.38	79.83	79.83	86	92.05	95.06	95.48	95.48	95.48	95.48	95.48	95.48	95.48
7000	93.05	93.05	93.05	93.05	93.05	93.05	93.05	89.16	78.99	78.99	85	91.13	94.5	94.7	94.7	94.7	94.7	94.7	94.7	94.7
7500	92.12	92.12	92.12	92.12	92.12	92.12	92.12	88.9	77.41	77.41	84.26	90.75	94.21	94.21	94.21	94.21	94.21	94.21	94.21	94.21
8000	91.27	91.27	91.27	91.27	91.27	91.27	91.27	88.14	76.08	76.08	82.89	90.31	93.49	93.49	93.49	93.49	93.49	93.49	93.49	93.49
8500	90.47	90.47	90.47	90.47	90.47	90.47	90.47	87.8	75.97	75.97	82.22	89.96	93.17	93.17	93.17	93.17	93.17	93.17	93.17	93.17

Appendix C

Mechanical Components Mass Properties

Component	Mass [kg]	Ixx [kg-mm]	Iyy [kg-mm]	Izz [kg-mm]
Vehicle System	1498.89	2.95815E+009	9.15079E+009	7.25796E+009
Vehicle Chassis	1143	2.83059E+009	7.71304E+009	5.77436E+009
Tire (each)	20	1.43460E+007	2.30495E+008	2.40485E+008
Control Arm (each)	18.72	4.17384E+006	1.29802E+007	1.30713E+007
Upper Strut (each)	6.62	4.96956E+006	6.93284E+006	5.68370E+006
Lower Strut (each)	18.58	9.02080E+006	1.26049E+007	1.58652E+007
Steering Rack	9.08	1.30545E+006	2.10352E+006	1.43088E+006
Tie Rod (each)	1.54	4.41253E+005	4.57350E+005	5.61937E+005
Hybrid Components[2]	100	n/a	n/a	n/a

X-direction: towards the rear of the vehicle

Y-direction: towards the passenger side of the vehicle

Z-direction: upwards of the vehicle (opposite of gravity)

[2] Assumed mass of the motor/generator and batteries, based on the mass difference of the conventional and hybrid model of the Honda Civic [17, 18]

Appendix D

Steering System Controller ADAMS Definitions

Steering Rack General Motion

Object Name	: .vehicle_new.general_motion_3
Object Type	: general_motion
Parent Type	: Model
Location	: 0.0, 0.0, 0.0 mm, mm, mm
Orientation	: 0.0, 0.0, 0.0 deg

General Parameters:

i_marker	(MARKER_195 (MARKER_195))
j_marker	(MARKER_196 (MARKER_196))
constraint	(JOINT_24 (JOINT_24))
t1_type	(0)
t2_type	(0)
t3_type	(1)
r1_type	(0)
r2_type	(0)
r3_type	(0)
t1_func	(0 * time)
t2_func	(0 * time)
t3_func	(step(time, 1, 0, 2, .vehicle_new.steering_gain.steering_gain))
r1_func	(0 * time)
r2_func	(0 * time)
r3_func	(0 * time)
t1_ic_disp	(0.0)
t2_ic_disp	(0.0)
t3_ic_disp	(0.0)
r1_ic_disp	(0.0)
r2_ic_disp	(0.0)
r3_ic_disp	(0.0)
t1_ic_velo	(0.0)

t2_ic_velo (0.0)
t3_ic_velo (0.0)
r1_ic_velo (0.0)
r2_ic_velo (0.0)
r3_ic_velo (0.0)

Input Parameters: None

Output Parameters: None

Steering Desired Variable

Object Name : .vehicle_new.steering_d.steering_d_input
Object Type : ADAMS_Variable
Parent Type : controls_input
Adams ID : 129
Active : NO_OPINION
Initial Condition : 0.0
Function : 0

Steering Actual Variable

Object Name : .vehicle_new.steering_a.steering_a_input
Object Type : ADAMS_Variable
Parent Type : controls_input
Adams ID : 131
Active : NO_OPINION
Initial Condition : 0.0
Function : DY(mar1)

Steering Difference Variable

Object Name : .vehicle_new.steering_diff
Object Type : controls_sum
Parent Type : Model
Location : 0.0, 0.0, 0.0 mm, mm, mm
Orientation : 0.0, 0.0, 0.0 deg

General Parameters:
input_obj (.vehicle_new.steering_d, .vehicle_new.steering_a)
gain1 (1.0)
gain2 (1.0)

Input Parameters: None

Output Parameters: None

Steering Gain Variable

Object Name : .vehicle_new.steering_gain.steering_gain_input
Object Type : ADAMS_Variable
Parent Type : controls_gain
Adams ID : 136
Active : NO_OPINION
Initial Condition : 0.0
Function : steering_diff.steering_diff

Appendix E

Tire Property Definition File

```
!:FILE_TYPE:      tir
!:FILE_VERSION:   2
!:TIRE_VERSION:   PAC94
!:COMMENT:        New File Format v2.1
!:FILE_FORMAT:    ASCII
!:TIMESTAMP:      1996/02/15,13:22:12
!:USER:           ncos
$------------------------------------------------------------------------units
[UNITS]
 LENGTH           = 'inch'
 FORCE            = 'pound_force'
 ANGLE            = 'radians'
 MASS             = 'pound_mass'
 TIME             = 'second'
$------------------------------------------------------------------------model
[MODEL]
!          use mode   1          2          3          4
!          -------------------------------------------
!          smoothing                        X          X
!    combined                    X                     X
!
! USER_SUB_ID = 903
 PROPERTY_FILE_FORMAT   = 'PAC94'
 FUNCTION_NAME          = 'TYR903'
 USE_MODE               = 4
$--------------------------------------------------------------------dimensions
[DIMENSION]
 UNLOADED_RADIUS        = 11.222 !Honda Insight tire radius used by Advisor. Wheel dia: 570.1mm
 WIDTH                  = 10.0
 ASPECT_RATIO      = 0.30
$---------------------------------------------------------------------parameter
[PARAMETER]
 VERTICAL_STIFFNESS     = 2500
 VERTICAL_DAMPING       =  250.0
 LATERAL_STIFFNESS      = 1210.0
 ROLLING_RESISTANCE     = 0.0054
$-----------------------------------------------------------------------scaling
[SCALING_COEFFICIENTS]
 DLAT    =  0.10000E+01
 DLON    =  0.10000E+01
 BCDLAT  =  0.10000E+01
 BCDLON  =  0.10000E+01
```

```
$---------------------------------------------------------------------lateral
[LATERAL_COEFFICIENTS]
 A0    =   1.5535430E+00
 A1    =  -1.2854474E+01
 A2    =  -1.1133711E+03
 A3    =  -4.4104698E+03
 A4    =  -1.2518279E+01
 A5    =  -2.4000120E-03
 A6    =   6.5642332E-02
 A7    =   2.0865589E-01
 A8    =  -1.5717978E-02
 A9    =   5.8287762E-02
 A10   =  -9.2761963E-02
 A11   =   1.8649096E+01
 A12   =  -1.8642199E+02
 A13   =   1.3462023E+00
 A14   =  -2.0845180E-01
 A15   =   2.3183540E-03
 A16   =   6.6483573E-01
 A17   =   3.5017404E-01
$----------------------------------------------------------------longitudinal
[LONGITUDINAL_COEFFICIENTS]
 B0    =   1.4900000E+00
 B1    =  -2.8808998E+01
 B2    =  -1.4016957E+03
 B3    =   1.0133759E+02
 B4    =  -1.7259867E+02
 B5    =  -6.1757933E-02
 B6    =   1.5667623E-02
 B7    =   1.8554619E-01
 B8    =   1.0000000E+00
 B9    =   0.0000000E+00
 B10   =   0.0000000E+00
 B11   =   0.0000000E+00
 B12   =   0.0000000E+00
 B13   =   0.0000000E+00
$--------------------------------------------------------------------aligning
[ALIGNING_COEFFICIENTS]
 C0    =   2.2300000E+00
 C1    =   3.1552342E+00
 C2    =  -7.1338826E-01
 C3    =   8.7134880E+00
 C4    =   1.3411892E+01
 C5    =  -1.0375348E-01
 C6    =  -5.0880786E-03
 C7    =  -1.3726071E-02
 C8    =  -1.0000000E-01
 C9    =  -6.1144302E-01
 C10   =   3.6187314E-02
 C11   =  -2.3679781E-03
 C12   =   1.7324400E-01
 C13   =  -1.7680388E-02
 C14   =  -3.4007351E-01
 C15   =  -1.6418691E+00
 C16   =   4.1322424E-01
```

```
 C17   =  -2.3573702E-01
 C18   =   6.0754417E-03
 C19   =  -4.2525059E-01
 C20   =  -2.1503067E-01
$-------------------------------------------------------------------------shape
[SHAPE]
{radial width}
 1.0    0.0
 1.0    0.2
 1.0    0.4
 1.0    0.5
 1.0    0.6
 1.0    0.7
 1.0    0.8
 1.0    0.85
 1.0    0.9
 0.9    1.0
```

Appendix F

Road Property Definition File

```
$---------------------------------------------------------------------MDI_HEADER
[MDI_HEADER]
FILE_TYPE  =  'rdf'
FILE_VERSION  =  5.00
FILE_FORMAT  =  'ASCII'
(COMMENTS)
{comment_string}
'flat 2d contact road for testing purposes'
$--------------------------------------------------------------------------UNITS
[UNITS]
 LENGTH            = 'mm'
 FORCE             = 'newton'
 ANGLE             = 'radians'
 MASS              = 'kg'
 TIME              = 'sec'
$--------------------------------------------------------------------------MODEL
[MODEL]
 METHOD            = '2D'
 FUNCTION_NAME      = 'ARC901'
 ROAD_TYPE          = 'flat'
$-----------------------------------------------------------------------GRAPHICS
[GRAPHICS]
 LENGTH            = 160000.0
 WIDTH             = 80000.0
 NUM_LENGTH_GRIDS   = 16
 NUM_WIDTH_GRIDS    = 8
 LENGTH_SHIFT       = 10000.0
 WIDTH_SHIFT        = 0.0
$---------------------------------------------------------------------PARAMETERS
[PARAMETERS]
 MU                =  1.0
```

Appendix G

ADAMS/Control Plant Definition

PINPUT_1

Object Name	: .vehicle_new.PINPUT_1
Object Type	: Plant_Input
Parent Type	: Model
Adams ID	: 1
Active	: NO_OPINION
Variables	: brake_torque, drive_torque

POUTPUT_1

Object Name	: .vehicle_new.POUTPUT_1
Object Type	: Plant_Output
Parent Type	: Model
Adams ID	: 1
Active	: NO_OPINION
Variables	: driveshaft_speed, vehicle_speed

Appendix H

ADAMS/Control MATLAB .m File

```
% ADAMS / MATLAB Interface - Release 2005.0.0
machine=computer;
if strcmp(machine, 'SOL2')
   arch = 'ultra';
elseif strcmp(machine, 'SGI')
   arch = 'irix32';
elseif strcmp(machine, 'GLNX86')
   arch = 'rh_linux';
elseif strcmp(machine, 'HPUX')
   arch = 'hpux11';
elseif strcmp(machine, 'IBM_RS')
   arch = 'ibmrs';
else
   arch = 'win32';
end
[flag, topdir]=dos('adams05 -top');
if flag == 0
  temp_str=strcat(topdir, arch);
  addpath(temp_str)
  temp_str=strcat(topdir, '/controls/', arch);
  addpath(temp_str)
  temp_str=strcat(topdir, '/controls/', 'matlab');
  addpath(temp_str)
  ADAMS_sysdir = strcat(topdir, '');
else
  addpath( 'install_dir\MSC~1.SOF\MSC~1.ADA\2005\win32' ) ;
  addpath( 'install_dir\MSC~1.SOF\MSC~1.ADA\2005\controls/win32' ) ;
  addpath( 'install_dir\MSC~1.SOF\MSC~1.ADA\2005\controls/matlab' ) ;
  ADAMS_sysdir = 'install_dir\MSC~1.SOF\MSC~1.ADA\2005\' ;
end
ADAMS_exec = '' ;
ADAMS_host = 'host' ;
ADAMS_cwd ='My Documents\thesis\model latest'  ;
ADAMS_prefix = 'vehicle' ;
```

```
ADAMS_static = 'yes' ;
ADAMS_solver_type = 'Fortran' ;
if exist([ADAMS_prefix,'.adm']) == 0
   disp( ' ' ) ;
   disp( '%%% Warning : missing ADAMS plant model file !!!' ) ;
   disp( ' ' ) ;
end
ADAMS_init = '' ;
ADAMS_inputs  = 'brake_torque!drive_torque' ;
ADAMS_outputs = 'driveshaft_speed!vehicle_speed' ;
ADAMS_pinput  = '.vehicle_new.PINPUT_1';
ADAMS_poutput = '.vehicle_new.POUTPUT_1';
ADAMS_uy_ids  = [
                   137
                   125
                   127
                   126
                ] ;
ADAMS_mode   = 'non-linear' ;
tmp_in  = decode( ADAMS_inputs  ) ;
tmp_out = decode( ADAMS_outputs ) ;
disp( ' ' ) ;
disp( '%%% INFO : ADAMS plant actuators names :' ) ;
disp( [int2str([1:size(tmp_in,1)]'),blanks(size(tmp_in,1))',tmp_in] ) ;
disp( '%%% INFO : ADAMS plant sensors   names :' ) ;
disp( [int2str([1:size(tmp_out,1)]'),blanks(size(tmp_out,1))',tmp_out] ) ;
disp( ' ' ) ;
clear tmp_in tmp_out ;
% ADAMS / MATLAB Interface - Release 2005.0.0
```