DEVELOPMENT AND REFINEMENT OF A HYBRID ELECTRIC VEHICLE SIMULATOR AND ITS APPLICATION IN "DESIGN SPACE EXPLORATION"

A thesis presented in partial fulfillment of the requirements for the degree of Master of Science in the Graduate School of The Ohio State University

by

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* * * * * * *

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ABSTRACT

Hybrid Electric Vehicle (HEV) have become an active research area for both the academia and the automotive industry. The goal of HEV development is to improve fuel efficiency and reduce harmful emissions. With these motivations, an HEV simulator was developed for the FutureCar student project at The Ohio State University. The simulator was designed to predict the vehicle performance with respect to maximum acceleration, top vehicle speed and fuel economy. This simulator was then chosen as a generic model to be used in the project of "Design-Space Exploration" sponsored by the Department of Defense Advanced Research Projects Agency (DARPA).

During the course of the DARPA project, some limitations and raistakes of the existing HEV simulator were found through repeated runs on the simulator. At the same time, several modules in the HEV simulator were rewritten to accommodate the need of the DARPA project. The key improvements include: rewriting the S-function blocks in Simulink code to allow the HEV simulator to be converted to C code; refining the control logic to realize the correct modeling of charge-sustaining and charge-depleting cases; and improving the control logic to enable the HEV simulator to handle multiple combinations of vehicle powertrain configuration. The HEV simulator is explained in detail in terms of development philosophy and Simulink implementation in this thesis.
The improved HEV simulator allowed participants of the "Design-Space Exploration" project to study numerous combinations of the HEV design. The Design-Space Exploration concept can provide optimum design configurations to the designers based on the HEV design criteria. By doing so, the product development cycle and cost can be greatly reduced. An OSU-CML (Composable Modeling Language) is developed for the design space exploration project. In this thesis, demonstration of how to use CML language to describe the HEV model is given.

Finally, simulation results of the improved HEV simulator are provided. The searching results by using the Design-Space Exploration software – "Seeker" are also included.
To my wife and my parents for their love and support
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NOMENCLATURE

a - Vehicle Acceleration (m/sec^2)
A - The Cross-sectional Area of The Vehicle
ADVISOR - Advanced Vehicle Simulator
Ah_{Cap} - The Total Capacity (Ah) of the Battery
Ah_{Res} - The Residual of the Battery
APU - Auxiliary Power Unit
BSFC - Brake Specific Fuel Consumption
C_D - Coefficient of Drag of The Vehicle in The Direction of Travel
CML - Composite Modeling Language
C_{n0} - The Coefficient of Rolling Resistance
C_{f1} - The Coefficient of Rolling Resistance
DARPA - Defense Advanced Research Projects Agency
DOE - U.S. Department of Energy
EM - Electric Motor
EV - Electric Vehicle
F - Force (N)
F_a - The Aerodynamic Force (N)
F_I - The Inertia Force (N)
\( F_{rf} \) - The Rolling Resistance (N)
\( F_{rr} \) - The Rolling Resistance (N)
\( F_t \) - The Rolling Resistance (N)
\( F_{Tr} \) - The Tractive Force (N)
\( F_{Tr} \) - The Tractive Force (N)
\( F_T \) - The Tractive Force (N)
FCC - FutureCar Challenge
FUDS - Federal Urban Driving Cycle
g - Local Acceleration of Gravity
GUI - Graphical User Interface
HEV - Hybrid Electric Vehicle
HV - Hybrid Vehicle
\( I_{avg} \) - The Average Battery Current
\( I_b \) - Battery Current
\( I_d \) - Rotational Inertia of The Driveshaft
\( I_e \) - Engine Rotational Inertia
\( I_{max} \) - Maximum Current
\( I_i \) - Rotational Inertia of the Transmission
\( I_w \) - Rotational Inertia of the Wheels and Axles Shafts
ICE - Internal Combustion Engine
LAIR - Laboratory for Artificial Intelligence Research of OSU
m - Mass
\(m_r\) - Mass Factor

\(M\) - Mass of The Vehicle

\(M_e\) - The Equivalent Mass of The Rotating Components

MARVEL -

MPG - Miles Per Gallon

\(n_o\) - The Number of The Gear Attached to Output Shaft

\(n_i\) - The Number of The Gear Attached to Input Shaft

\(N_f\) - Numerical Ration of The Final Drive

\(N_t\) - The Gear Ratio of The Transmission

\(N_{fr}\) - Combined Ration of Transmission and Final Drive

NREL - National Renewable Energy Laboratory

OSU - The Ohio State University

\(P\) - Brake Power Output

\(P_{ba}\) - Auxiliary Loads

\(P_{br}\) - Regeneration Power

\(P_{bt}\) - The Total Battery's Power

\(P_{br}\) - The Traction Power at the Battery Interface

PNGV - Partnership for A New Generation of Vehicle

\(r\) - Tire Radius

\(r_f\) - Ratio of the Flow Rate

\(R\) - Internal Resistance of Battery

SFUDS - Simple Federal Urban Driving Cycle
SIMPLEV - Simple Electric Vehicle Simulation
SOC - State of Charge
\( T_{\text{brake}} \) - The Output Brake Torque
\( T_e \) - Engine Torque at A Given Speed
\( T_{\text{Engine}} \) - Engine Output Torque
\( T_{\text{Max brake}} \) - The Maximum Brake Torque
\( T_{\text{WOT}} \) - Engine WOT Torque
USCAR - US Council for Automotive Research
V - Velocity of The Vehicle in The Direction of Travel
\( V_{\text{actual}} \) - Actual Vehicle Velocity
\( V_{\text{desired}} \) - Desired Vehicle Velocity
\( V_{\text{error}} \) - Velocity Error
\( V_{\text{high}} \) - High Threshold Value of The Velocity in Controller
V-Elph - Versatile Electrically-Peaking Hybrid
\( V_{\text{low}} \) - Low Threshold Value of The Velocity in Controller
\( V_b \) - The Battery Output Voltage under Load
\( V_{\text{min}} \) - The Minimum Voltage
\( V_{\text{oc}} \) - Battery Source Voltage
\( V_{\text{shift point}} \) - Shift Point Velocity (m/s)
VW - Volkswagen
\( W \) - The Weight of Vehicle (N)
$W_f$ - The Weight of Front Wheels (N)
$W_r$ - The Weight of Rear Wheels (N)
WOT - Wide Open Throttle
ZEV - Zero Emission Vehicle
$\alpha$ - The Throttle Angle
$\alpha_{brake}$ - The Brake Pedal Angle
$\rho$ - Density of the Ambient Air
$\eta_t$ - Combined Efficiency of Transmission and Final Drive
$\delta$ - Angle of inclination of the road surface
$\omega_{ncx}$ - The Engine Speed (RPM)
CHAPTER 1

INTRODUCTION

In recent years, global warming and exhaustion of natural resources have become serious problems worldwide. At the same time, a large number of vehicles is considered to be a major source of these problems. In order to reduce air pollution caused by automobiles, the amount of harmful emissions produced by automobiles must be reduced. Fuel consumption must be reduced in view of the limited oil reserves remaining.

These serious problems have made us to seek a new type of clean and energy-efficient vehicle to provide city transportation in the twenty-first century. Theoretically, electric vehicles can take this job, because of the enormous progress made in electric motors, motor controllers and storage batteries. However, the energy storage density of an electric battery remains to be poor compared with that of hydrocarbon fuels. A fully charged battery pack can only provide a driving range of approximately 76 miles, and the battery needs 6-8 hours to recharge. Therefore, an electric vehicle has limited interior space due to the volume of batteries; and it has a very short range of operation compared with a combustion engine vehicle.
It is essential that we find cost-effective solutions to the issues of fuel efficiency and exhaust emissions. The U.S. government realized the need for concentrated effort to develop solutions to these problems. The Partnership for a New Generation of Vehicle (PNGV) was formed to find these solutions. Development of these concept vehicles is expected by approximately the year 2000. PNGV is a cooperative research and development program between the U.S. government and the U.S. Council for Automotive Research (USCAR), which is made up of the three major U.S. auto manufacturers — Ford, Chrysler, and General Motors. The PNGV addresses the following three specific, interrelated technological goals:

1) Significantly improve national competitiveness in manufacturing.

2) Implement commercially viable innovation from ongoing research on conventional vehicle.

3) Develop a vehicle to achieve up to three times the fuel efficiency of today's comparable vehicle (approximately 34 km/l (80 mpg)), and ultra-low emissions.

The vehicles should include near-term technology such that the vehicles can be mass-produced by 2004 [1].

These PNGV's goal can't be realized at present in commercially available vehicles, but a feasible solution to these problems is to develop hybrid vehicles (HVs), which have the potential of utilizing alternative energy sources, improving fuel economy, and reducing harmful emissions. A hybrid vehicle is a vehicle with two distinct energy
sources that can be separately converted to useful motive energy. This energy may be
stored in a number of forms including batteries (electrical) and fuel (chemical).

With the existing technology, the most common form of a hybrid vehicle is that of
a hybrid electric vehicle (HEV). Most existing HEVs use batteries for electrical energy
storage, which is converted to mechanical work at the wheels of the vehicle. Fuel is also
stored on-board and is usually converted through an internal combustion engine (ICE) to
produce mechanical work, which can be used to drive the wheels of the vehicle and also
can generate electrical power to charge the batteries. The hybrid propulsion concept
combines the advantages of electric vehicle (efficiency, smoothness, elegance) with the
vast operating range of combustion engines. For short distances, the electric motors get
the propulsion energy entirely from the batteries (thus having zero emission in short range
traffic). For long distances, the hybrid module (internal combustion engine coupled with a
generator) produces the mean required driving power, while batteries support peak power
requirements. This is become, as a combustion engine runs in its optimal rotational speed
range, the energy consumption is significantly lower than that of conventional propulsion
system. Figure 1.1 shows a comparison of power and energy storage capabilities of
different devices [2]. In this figure, we can see that the advantage of HEVs is that they
can use the high specific energy (energy per unit mass) of liquid fuel to provide the
vehicle with long range capabilities, and the high specific power (power per unit mass)
of electrical energy storage to provide the peak power requirements.
In summary, HEVs provide the benefits of both electric vehicles (EVs) and traditional internal combustion engine vehicles. Several advantages of HEVs over traditional internal combustion engine vehicles are as follows:

- Regenerative braking capability, which helps minimize energy loss when driving an urban cycle.
- Engine is sized for average load, not peak load, which reduces the weight of the engine.
- Fuel efficiency is greatly increased, while emissions are greatly decreased.
• HEVs can be operated using alternative fuels, so, they need not be
dependent on fossil fuels.

1.1 Literature Review

In order to fully realize the benefits of hybrid electric vehicles, HEV models are
used as the first steps in the design procedures to study and improve fuel economy, top
speed and maximum acceleration. Therefore, accurate and flexible simulation tools,
which will expedite the design processes for HEVs, are important. The simulation results
will enable engineers to compare relative performances and come up with the better
designs. In addition, computer modeling and simulation can be used to reduce the
expense and length of design cycle of HEVs by testing configurations and energy
management strategies before prototype construction begin.

Interest in simulating hybrid electric vehicles began to increase in the 1970's along
side the development of several prototypes which were used to acquire a large amount of
test data on the performance of hybrid drivetrains [3]. Through a search of the relative
papers dealing with computer software simulations for HEVs, we found that these
simulation tools had varying capabilities in predicting vehicle performance in one or
more areas, such as fuel economy, emissions, acceleration, and grade sustainability.
Several computer simulation tools have been developed to predict hybrid drivetrain
performance, including: Simple Electric Vehicle Simulation (SIMPLEV) from the DOE's
Idaho National Laboratory [4], MARVEL from Argonne National Laboratory [4], V-Elph
from Texas A&M University [6], and the Advanced Vehicle Simulator (ADVISOR) from the National Renewable Energy Laboratory [7].

1.1.1 Simple Electric Vehicle Simulation (SIMPLEV)

A Simple Electric Vehicle Simulation (SIMPLEV) software tool, Version 2.0 [4] was developed at Idaho National Engineering Laboratory for modeling Electric Vehicles and series HEVs. The vehicle powertrain model configuration is based upon conventional component arrangements as shown in Figure 1.2.

![Figure 1.2 Block Diagram of Electric Vehicle Powertrain for SIMPLEV [4]](image-url)
In the configuration, the model includes batteries, motor, inverter/controller, transmission, engine, generator, and catalysts. Although the operation of the series HEV provides an initial estimate of the APU contributions, SIMPELV has a limitation. It does not have the ability to simulate either parallel HEVs or conventional ICE vehicles, and it was not suitable for predicting the behavior of the Ohio State University FutureCar. Because of the nature of the source code of SIMPELV, changing the model to other series and parallel control logic would be very difficult.

In SIMPELV, the vehicle power at the wheel required to meet the driving cycle is calculated, and the power required from the vehicle is determined by using the individual component efficiencies. SIMPELV can simulate vehicle fuel economy, energy usage, emission (HC, CO, NOx) and a number of other vehicle variables.

1.1.2 MARVEL

MARVEL software package [5] was developed at Argonne National Laboratory for analyzing a pure electric vehicle, a pure IC engine (heat engine) vehicle, or a hybrid vehicle that employs both batteries and an IC engine. The ICE/battery MARVEL hybrid system model is shown in the functional block diagram in Figure 1.3. And MARVEL is written in PL/1 language for use on IBM - compatible microcomputers. The MARVEL model is established based on the following general assumptions:

1. Optimization of ICE/battery hybrid system design is based on vehicle life-cycle cost.
2. The performance of an ICE in a hybrid vehicle can be scaled up or down from the reference ICE.

3. No regenerative braking is considered.

![Block Diagram of Electric/Hybrid Vehicle for MARVEL](image)

Figure 1.3 Block Diagram of Electric/Hybrid Vehicle for MARVEL [5]

In MARVEL, a 1.8 liter Pontiac engine is used as the preliminary IC engine model. The main features of MARVEL, which include extensive modeling of the interrelationships among battery characteristics, is to allow tradeoffs and optimization between an IC engine and a battery system. It provides several energy management strategies for analyzing a hybrid vehicle. However, MARVEL cannot simulate vehicle fuel economy, top speed, maximum acceleration and a number of other vehicle performance variables.

1.1.3 V-Elph

V-Elph, or Versatile-Elph, is an extension of the Electrically-Peaking Hybrid (ELPH) simulation model developed at Texas A & M University [6]. The original
simulation model, ELPH, was used to study the viability of an electrically peaking control scheme and to determine the applicability of computer modeling to hybrid vehicle design, and it was limited to one particular HEV control strategy. However, V-Elph expands the capabilities to general series and parallel HEV. The simulation code is written in MATLAB/SIMULINK, and it can be easily converted to represent real world HEVs. A simulation diagram of a hybrid vehicle implemented in the V-Elph modeling system is shown in Figure 1.4.

```
Figure 1.4 System Level and Power Plant Representation of Hybrid Vehicle in V-Elph [c]
```
V-Elph uses visual programming techniques, which allows user to easily change architectures, parameters and to view output data graphically. It includes many detailed models such as electric motor model, internal combustion engine model, battery and vehicle dynamics model. This Matlab/Simulink program package is easily used to design an all electric vehicle, series hybrid and parallel hybrid vehicle.

The Simulink code utilizes a standard data flow for all component models which was shown Figure 1.5.

![Diagram](image)

Figure 1.5 Data Flow Through a Component Model [5]

Data flow means that signal connections are used to send information to and from the power plant controller and the power connections that represent the physical coupling between components which provide a path for transfer of energy.

V-Elph has many useful features, for example, a user can easily select and run the vehicle as series or parallel hybrid mode, and changing the drive cycle and environmental
conditions are easily done. Fuel economy and performance data can be easily plotted. At the same time, users can switch components in and out of the model to try different types of engines, motors, and batteries, and also can change vehicle characteristics such as size and weight, gear ratios, etc. However, it is unclear from the literature whether the current version of V-Elph has the ability to predict emissions output.

1.1.4 The Advanced Vehicle Simulator (ADVISOR)

The Advanced Vehicle Simulator (ADVISOR) is developed by the National Renewable Energy Laboratory (NREL) [7]. The code, like V-Elph, is written in Matlab/Simulink visual block diagram programming environment. Five separate vehicle configurations are modeled which include 3 lightweight vehicles (parallel, series, and conventional drivetrains) and 2 vehicles with 1996 vehicle weights (parallel and conventional drivetrains). This simulator has a significant advantage, which is the flexibility and ease to change the model, such as replacing one control strategy or regenerative braking algorithm with another.

As many other simulation packages mentioned above, ADVISOR can use a variety of custom or standard driving cycles such as the federal urban driving schedule (FUDS), or a speed and grade vs. time driving profile. At the same time, it can predict fuel economy, emissions, accelerations and grade sustainability of a given vehicle.

Another particularly convenient feature of ADVISOR is the well-refined graphical user
interface (GUI) which allows the user to easily select from a list of custom or predefined base vehicle, interchangeable components, driving cycles, and output.

ADVISOR is a primary simulation tool used by PNGV goals. It is used to analyze various theoretical vehicle configurations [7]. The fuel economy of these vehicles is the first item studied in ADVISOR. One result of the study is that both parallel and series HEV configurations show approximately the same sensitivity to all parameters, with the exception of electric drivetrain and battery efficiencies. Figure 1.6 shows the top level of the series hybrid model in ADVISOR.

![Figure 1.6 Top Level of ADVISOR Series Hybrid Model [7]](image)

Simulation software packages can provide convenience and flexibility for designing of the HEVs, and can produce many evaluated results for different configurations of the vehicle drivetrain.
1.2 Conclusion

Simulation model can be generally classified as two types, which are "Forward" model and "Backward" model. From the literature review, we find that most popular type of the models are backward model, such as ADVISOR. In the backward model, the input starts from the required vehicle and wheel speeds to get the required torques and speeds of each component between the wheels and the energy source. A forward model is one in which the engine state is not transferred from the road load calculation but rather is controlled by an input such as the throttle angle.

In this thesis, we use the backward model method to set up the hybrid vehicle model. Four types of vehicles can be described in this model (electric motor only, conventional internal combustion engine only, parallel charge sustaining hybrid and parallel charge depleting hybrid). In addition, driving cycles can be entered in this model: PUDS, SFUDS (Simple PUDS), highway cycle, and city cycle. In this model, we adopt the engine torque-speed curve to represent the engine, and motor torque-speed curve to represent the electric motor model. Both torque-speed curves are given by the manufacturers. More detailed model will be described in the following chapters.
CHAPTER 2

BACKGROUND

A hybrid electric vehicle (HEV) typically uses both an electric motor and internal combustion engine. For short distances, the electric motor can receive the traction energy entirely from the batteries (thus having zero emission in short range traffic). For longer distances, the hybrid module (combustion engine coupled with a generator) is producing the average of the required driving power, while the electric motor supports peak power requirements by using batteries.

HEVs have several advantages over traditional internal combustion engine (ICE) vehicles. Some of these are as following:

1). Regenerative braking capability, which helps minimize the energy lost when driving.
2). Engine is sized to average load, not peak load, which reduces the weight of the engine.
3). Fuel efficiency is greatly increased, while emissions are greatly decreased.
4). HEVs can be driven by using alternative fuels, therefore they do not need to depend on fossil fuels.
Basically, there are two primary coupling methods available when configuring the powertrain of a hybrid electric vehicle: parallel and series.

2.1 Parallel Hybrid Configuration

The configuration of parallel HEVs is such that both the electric motor and ICE are mechanically coupled to drive wheels of the vehicle. Figure 2.1 shows the structure of parallel HEVs.

This configuration allows three possible operating modes. Two modes are that either the electric motor or the internal combustion engine can drive the vehicle independently. The third mode is to drive the vehicle with both engine and electric motor simultaneously. A parallel hybrid vehicle can use the power created from an internal combustion engine for highway driving and the power from the electric motor for accelerating. This allows each power system to be sized for high efficiency in normal operation while still providing high performance in the combined driving mode. Some benefits of a parallel hybrid vehicle configuration include:

1) The vehicle has more power since both ICE and electric motor provide power simultaneously.

2) Most parallel vehicles do not need a separate generator.

3) The power is directly coupled to the road, thus, it can be more efficient.

However, the parallel configuration is more complicated to implement compared with the series configuration, because some mechanical parts are required to connect the combustion engine, the electric motor, and the vehicle’s drivetrain.
2.2 Series Hybrid Configuration

The series hybrid vehicles are similar to pure electric vehicles because only the electric motor is mechanically connected to the drive wheels of the vehicle. The series HEV's configuration is shown in Figure 2.2.
A internal combustion engine drives a generator which provides electrical power to an electric motor, and a battery pack may be used to store electrical energy. Since the ICE is not mechanically coupled to the drivetrain, the mechanical connection is simpler than that of parallel hybrid configuration. The electric motor can easily be sized so that only a single speed transmission is required, and the internal combustion engine also can be sized and works at its optimum speed/ fuel efficiency while supplying the average required power. An auxiliary power unit (APU) is used to manage the input energy from the fuel to the electrical output. The benefits of a series configuration over a parallel configuration are:

1) The engine never idles, which reduces vehicle emissions.
2) The engine drives a generator to run at optimal performance.
3) Some series hybrid vehicles do not need a transmission.

However, because the vehicle is driven by the electric motor directly, the electric motor must be sized to provide appropriate peak power. In the series configuration, it is shown that an internal combustion engine is used to drive a generator. The generator charges battery pack, and drives an electric motor. Thus, using a motor to drive the drivetrain can be less efficient than using an engine to supply power to the drivetrain.

2.3 Control Strategy

An HEV design allows the vehicle to be propelled in three distinct modes, that are EM (electric motor only mode), HEV (hybrid mode), and ICE (combustion only mode).
2.3.1 EM Mode

When the vehicle works in the EM mode, the vehicle is a zero emissions vehicle (ZEV). The ICE controller is disabled, which means that the ICE doesn’t work in this mode. The throttle pedal and electric motor controller (EMC) control the electric motor torque and speed outputs. This control scheme can decide how much power can be generated, when the vehicle is driven at a steady cruise condition or under acceleration. When changing gears, the clutch and throttle pedal are used in the same manner as in a conventional manual or automatic transmission vehicle.

2.3.2 Hybrid Mode

The parallel hybrid mode can be engaged with the vehicle in either electric only or engine only mode. The engine and electric motor are both enabled, and the engine works in the same manner as it does in a conventional vehicle. The control algorithm determines whether the motor or the engine, or both the motor and the engine should be connected to the transmission. If the vehicle can produce all of its required electrical energy to charge the battery pack on board, this kind of vehicle is called a charge-sustaining vehicle. If a vehicle requires an external electrical source to charge the battery pack, the vehicle is called a charge-depleting vehicle. More details about these concepts are described in the next chapter.
2.3.3 Engine Only Mode

Engine only mode of operation is intended for long distance highway driving. The control scheme allows either starting the vehicle in this mode or switching to this mode while the vehicle is moving. The electric motor controller is disabled, and the vehicle is driven as a conventional automobile.

The throttle pedal and the engine controller control the engine torque and speed outputs. This control scheme can decide how much power need to be generated, when the vehicle is driven at steady cruise or under acceleration. More details about the control logic will be described in chapter 3.

2.4 Configuration Selection

The series configuration is easier to implement. Its advantages include simplicity of component selection; simplicity of construction and installation; and simplicity of control. Its main disadvantages are the requirement of a very high power electric motor for reliable performance; efficiency loss during hybrid operation; and the need for an additional generator. On the other hand, the parallel configuration requires more specialized components and controls to integrate the two power systems. However, it offers higher efficiency and better peak performance. The predicted reliability is also considered when making the decision. The reliability of a series hybrid vehicle would be the poorer since every component need to remain functional while the vehicle is in operation. Component degrade action will therefore force the vehicle can operate at a level determined by its weakest link. In contrast, either the electric motor or the internal
combustion engine could fail in the parallel hybrid system and the vehicle would still remain functional. The only critical components in the parallel system are the coupler linking the engine and electric motor to the transmission.

Based on the above considerations, the Ohio State University FutureCar team selected a parallel hybrid electric drive system for their vehicle because of the greater efficiency, and better reliability. The implemented schematic of the OSU FutureCar is shown in Figure 2.3 [8].

The FutureCar Challenge is a student engineering research competition sponsored by the U.S. Department of Energy (USDOE) and USCAR, which provide a mechanism for college and university participation in the PNGV program. The focus of this competition is to produce a potential near-term vehicle conversion that reduces emission, improves fuel mileage, and retains all of the performance, safety and convenience features of the original vehicle.

There are relatively few design constraints for the FutureCar Challenge vehicles.
The converted vehicle must meet the following minimum criteria [9]:

1) Standing 200 m (1/8 mile) acceleration < 14.5 seconds,
2) 400 Km (250 miles) range,
3) Curb weight < 1950 Kg (4300 lb.),
4) Seating for five,
5) 100 liters (3.5 cu.ft) luggage capacity,
6) Simultaneous control of NMHC, NOx, CO and emissions, and
7) Superior energy efficiency.
The powertrain implemented in the OSU FutureCar consists of a 66 kW Volkswagen CIDI 1.9 liter engine with turbocharger as the main power plant and a permanent magnet 20 kW brushless DC motor as an auxiliary power unit (APU) which can also regenerate electric energy.

In order to reduce the expense and shorten the design cycle of the hybrid electric vehicle, a computer simulation model of the hybrid vehicle can be used to test the
configurations and energy management strategies before prototype construction begins. An HEV computer simulation model was developed using MATLAB/SIMULINK for the FutureCar Challenge (FCC) team at the Ohio State University [10] [11]. This model is used to simulate conventional parallel / series hybrid electric vehicle or electric vehicle configurations, and to study vehicle performance in terms of maximum acceleration, top speed, and fuel economy and range. However, there are some limitations of the model. This thesis work focuses on improving and expanding the capabilities of the existing model.

2.5 Contributions of This Work

Since the hybrid vehicle may be the main transportation means in the next century, the design and manufacturing of hybrid vehicles become important issues in automotive industry. The simulator of hybrid vehicle will help us to predict the performance of hybrid vehicles so as to reduce the design and development cycle. The simulator developed can predict the vehicle performances including maximum acceleration, fuel economy, and top speed [10], [11]. The FutureCar team at the Ohio State University successfully used this simulator in its design studies for the 1996 and 1997 competitions. At the same time, the earlier version simulator was also used as a design tool for a design-space search project sponsored by Department of Defense Advanced Research Projects Agency (DARPA), which is supported by the Office of Naval Research under the Grant No. N00014-96-1-0701. In the DARPA project, researchers at LAIR (Laboratory for Artificial Intelligence Research of OSU) use the
earlier version HEV simulator in their exploration design space software "Seeker". 

"Seeker" makes use of the original simulator as a generic model to explore an extremely large design space (1.03 million designs), which considers the combinations of various choices of generic devices, alternative components, and parameter values. According to certain criticism evaluators, the design cases will be reduced from millions to hundreds. However, when the earlier version simulator was used in the DARPA project, researchers found that it had some limitations and its solutions gave unreasonable results. Thus, there is an urgent need to refine the old simulator so as to get more realistic and reliable results. This work becomes part of my thesis. The main limitations and improvements are as follows:

1) The DARPA simulation requires the Simulink code be converted to C code. However, the Matlab Real-Time Workshop package can not generate C code for "S-functions" blocks. Therefore, Simulink blocks are implemented to replace the existing "S-functions" in the model.

2) When the earlier version HEV simulator was exercised over the highway driving cycle, the vehicle velocity output could result in unreasonable values. The vehicle dynamics model is refined to obtain more realistic results.

3) In the old control logic, the hybrid charge sustaining and the charge depleting vehicles do not give correct battery pack responses. For example, even in the charge depleting case, the battery pack does not discharge. The state of charge (SOC) calculation module is revised so as to obtain reasonable results.
4) Using the old control logic of the parallel hybrid vehicle model, we found that the fuel economy (fuel consumption) result was not correct for an average size engine. The fuel economy could reach unreasonably high values, and sometimes it reached negative values. So, the control logic is improved to get realistic results of fuel economy. At the same time, the updated control logic can adapt to changes in the engine and electric motor sizes. Three engine sizes are permitted (Small: GEO 1.0 liter, Middle: VW 1.9 liter, Large: Dodge 3.0 liter), and three sizes of electric motors (small, medium, large). This is very important for DARPA project, because it will generate huge design cases by using "Seeker".

5) A new language CML (Composable Modeling Language) is used to describe the generic engine only vehicle model.
CHAPTER 3

HYBRID ELECTRIC VEHICLE SIMULATOR

The Hybrid Electric Vehicle (HEV) simulator is developed using the simulation package MATLAB/Simulink. The main purpose of the HEV simulator is to predict maximum acceleration, fuel economy and top speed for three different vehicle configurations. The structure of the simulator is modular, so that individual sections can be improved easily. Following is a list of the modules included in the current HEV simulator:

1) Vehicle dynamics
2) Transmission
3) Engine
4) Electric Drive
5) HEV Control Logic
6) Braking and Energy Regeneration
7) Battery Pack
8) Fuel Economy Computation

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This simulator uses a dynamic approach to model parallel and series HEVs, pure EV or ICE vehicles. This HEV simulator adopts the so-called “backward” structure. At each discrete time step, the simulator calculates the required energy at the wheels of the vehicle using a pre-determined vehicle velocity profile such as FUDS. The Simulink block diagram used for parallel HEV modeling is shown in Figure 3.1. The simulator responds to a desired velocity input and attempts to match it at every instant in time. The current vehicle velocity is compared to the desired velocity and an error is calculated. This error is passed to the engine and electric motor blocks where the

Figure 3.1 Simulink simulator diagram
appropriate engine and motor torques are generated based on the control logic. The manual transmission block determines the proper gear ratio based on the current vehicle velocity. The engine torque and electric motor torque are transferred to the wheels through the final drive ratio and the wheel force is calculated. The net force acting on the vehicle is calculated by summing the wheel force, the aerodynamic drag and rolling resistance. The net force acting on the vehicle results in a vehicle velocity through the vehicle dynamics and the cycle continues. A more detailed discussion of the individual blocks is given in the next section.

3.1 Vehicle Dynamics

The vehicle dynamic equations considered in the simulator are derived from Newton's Second Law, as given in Equation 3.1 in its scalar form.

\[ F = ma \]  \hspace{1cm} (3.1)

The free body diagram of a two-axle vehicle is shown in Figure 3.2[12].

![Figure 3.2 Forces acting on a vehicle [12]](image)
The equation of motion along the longitudinal axis is given by

$$F_T = F_d + F_r + F_i + F_a$$  \hspace{1cm} (3.2)

The equation (3.2) can be modified with the specific force $F_T$ which typically act on the vehicle and can be rearranged into the form of equation (3.3)

$$M \cdot a = F_T - \frac{1}{2} \rho C_d A V^2 - (C_{n0} + C_{n1} V^2) M \cdot g - M \cdot g \cdot \sin(\theta)$$  \hspace{1cm} (3.3)

The tractive force $F_T$ can be obtained from the engine [12]:

$$F_T = \frac{T_r N_e n_e}{\eta_T} - \left[ (I_r + I_1) N_1^2 + I_3 N_1^2 + I_4 L_1 a \right] \rho$$  \hspace{1cm} (3.4)

where $F_T$ is the total tractive force, $F_{T1} = F_{I1} + F_{H1}$

$F_d$ is aerodynamic drag

$F_r$ is rolling resistance, $F_r = F_{I2} + F_{H2}$

$F_i$ is inertia force

$F_{g}$ is gravitational force

$\rho$ is density of the ambient air.

$C_d$ is the coefficient of drag of the vehicle in the direction of travel.

$A$ is the cross-sectional area of the vehicle.

$V$ is the velocity (i.e., speed) of the vehicle in the direction of travel.
M is mass of the vehicle.

\( C_\alpha \) and \( C_1 \) are the coefficient of rolling resistance between the tires and the road surface.

\( a \) is the acceleration of the vehicle.

\( g \) is local acceleration of gravity.

\( \theta \) is the angle of inclination of the road surface upon which the vehicle is traveling.

\( T_e \) is the engine torque at a given speed.

\( I_e \) is the engine rotational inertia.

\( I_t \) is the rotational inertia of the transmission.

\( I_d \) is the rotational inertia of the driveshaft.

\( I_w \) is the rotational inertia of the wheels and axles shafts.

\( N_t \) is the numerical ratio of the final drive.

\( N_d \) is the combined ratio of transmission and final drive.

\( \eta \) is the combined efficiency of transmission and final drive.

\( r \) is the tire radius.

\( F_t \) includes the engine torque and rotational inertia terms. As a convenience, the rotational inertias from Eq. (3.4) are often lumped with the mass of the vehicle to get a simplified form:

\[
(M + M_e)a = \frac{T_e N_d \eta}{r} - \frac{P}{2} C_p A V^2 - (C_\alpha + C_1) Mg - Mg \sin(\theta)
\]

(3.5)
where $M_i$ is the equivalent mass of the rotating components, that is

$$M_i = \frac{(I_u + I_v)N_f^2 + I_d N_f^2 + I_z}{r^2} \quad (3.6)$$

The combination of the two masses $M+M_i$ is an "effective mass", and the ratio of

$$m_f = \frac{M + M_i}{M}$$

is the "mass factor". A representative number of $m_f$ is often taken as [12]:

$$m_f = 1 + 0.04 + 0.0025 N_0^2 \quad (3.7)$$

Thus, the general vehicle dynamics model is

$$m_f M V = \frac{T_e N_0 \eta_r}{r} - \frac{\rho}{2} C_D AV^2 \cdot (C_{\alpha_0} + C_{\alpha_1}) Mg - Mg \sin(\theta) \quad (3.8)$$

Figure 3.3 shows the Simulink block diagram of the vehicle dynamics model. This model assumes $\delta = 0$ and $C_{\alpha_0} = 0$.

![Simulink Block Diagram of Vehicle Dynamics Model](image)
In a previously developed simulator, a simple integrator is used to numerically evaluate the vehicle velocity. However, some unreasonable velocity value could occur due to numerical problems, two methods are used to solve this problem. First, the minimum step size of simulation is reduced. Second, a limited integrator is used to replace the simple integrator so as to force the velocity value to be positive.

3.2 Transmission

The function of an automotive transmission is to convert mechanical power input (input torque $T_i$, input shaft speed $\omega_i$) to mechanical power output (output torque $T_o$, output shaft speed $\omega_o$). Ideally, such conversions should be without loss, but in practice, energy is lost due to friction, etc. Equations (3.9) to (3.11) show the gear ratio relationships with an assumed given transmission efficiency $\eta_i$.

$$N_i = \frac{n_o}{n_i} \quad (3.9)$$

$$\frac{\omega_o}{\omega_i} = \frac{1}{N_i} \quad (3.10)$$

$$\frac{T_o}{T_i} = \eta_i \cdot N_i \quad (3.11)$$

where $n_o$ is the number of teeth of the gear connected to output shaft,

$n_i$ is the number of teeth of the gear connected to input shaft,

$N_i$ is the gear ratio of the transmission.
From the transmission to the drive train, there is another speed reduction component which is the final drive gear (differential gear) with a gear ratio $N_f$. Thus the overall gear reduction ratio is $N_{eq} = N_i \cdot N_f$, and the relationship between the vehicle speed $V$ (m/s) and the engine speed $\omega_{ICE}$ (RPM) is

$$\omega_{ICE} = \frac{V \cdot N_{eq} \cdot 60}{2\pi \cdot r} \quad (3.12)$$

Three broad families of transmissions are used in passenger vehicles: manual, automatic and continuously variable transmission (CVT).

3.2.1 Manual Transmission

A manual transmission is a gearbox with multiple gear sets. A typical manual transmission has gear ratios from 1st gear to 5th gear. The driver selects gear ratio by changing the shift stick. Among the three types of transmissions, the manual transmission has the highest efficiency. Therefore, the OSU future car team uses a manual transmission in the car.

The current transmission model is developed to simulate the general shift characteristics, i.e. the gear ratio change. Therefore, certain dynamics such as transient phenomena, vibration modes etc., are not considered. During a shift, it takes a finite amount of time to disengage the clutch, change gears, and reengage the clutch. This is described by a time delay block. The function of the time delay block is that, when the gear shift occurs, the time flag is delayed by 0.4 seconds. This represents the time it takes
to perform a gear shift. During a shift, the throttle is set to its idle condition, thus there is no torque and speed being transmitted to the wheels from the engine, causing the vehicle to decelerate. The flow chart of the gear selection sequence is shown in Figure 3.4.

Figures 3.5 and 3.6 are the corresponding Simulink block diagrams for the gear selection.

Figure 3.4 Flow Chart of Gear Selection of Transmission
Figure 3.4 (continued)

(c)

Figure 3.4 Flow Chart of Gear Selection of Transmission

Figure 3.5 Gear Selection Block
The gear ratio selection block shown in Figure 3.6 determines the gear ratio based on the current gear and velocity, and a series IF - THEN condition switches are used in this block. By examining which gear the transmission is currently in, one of the switches labeled "Shift Point #" is selected. For example, suppose the transmission is currently in the 1st gear, then switch Shift Point 1 is selected. The switching condition is based on the vehicle velocity. The switch takes the path to the 1st gear when the velocity input is less than the velocity threshold and takes the path to the 2nd gear otherwise. It was mentioned earlier that shifting occurs as a function of engine RPM, but here it is referred to velocity in m/s. The relationship between shift point velocity and engine RPM is as follows:

\[ V_{\text{shift point}} = \frac{\text{RPM}_{\text{engine}} \times 2 \pi \times r}{\text{gear ratio} \times \text{final drive} \times 60} \]  

(3.13)
Once the velocity becomes greater than the shift point, it selects the higher gear ratio. At
the same time, the time delay block goes into effect. The combined efficiency for the
manual transmission is $\eta_m = 0.95$.

3.2.2 Automatic Transmission

An automatic transmission is an assembly of different planetary gear sets coupled
through hydraulically actuated band or plate clutches. Shifting is performed automatically
by a controller which engages and disengages the clutches or bands in a defined order.

To make the simulation more generally useful, the automatic transmission is
modeled similarly to that of the manual transmission. The differences are in the gear
ratios and the overall efficiency. The combined efficiency is chosen as $\eta_e = 0.85$. The
gear ratios are listed in the appendix. The Simulink block diagram is shown in Figure 3.7.

![Figure 3.7 Transmission Block](image)

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3.2.3 Continuously Variable Transmission (CVT)

A continuously variable transmission (CVT) is the most desirable type of transmission. Its design does not limit the gear ratio to discrete numbers. The most common form of CVT has a belt or chain running between two wheels of adjustable radius.

To model a CVT, the CVT gear ratio is obtained from the vehicle velocity and the specified shift point as described by equation (3.14).

\[
\text{gear\_ratio} = \frac{1}{\frac{\text{Velocity} \times \text{final\_drive} \times 60}{\text{RPM\_engine} \times 2\pi \times r}} \tag{3.14}
\]

The CVT Simulink block diagram is shown in Figure 3.8.

![CVT Simulink block diagram](image)

**Figure 3.8 CVT Model Block**

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3.3 Engine

An engine is an energy converter that converts the chemical energy contained in a fuel into mechanical energy. In practice, the fuel energy supplied to the engine is not fully released by the combustion process since combustion is incomplete. In addition to the incomplete combustion, there are also losses due to friction, gas exchange etc. Therefore, the peak efficiency of gasoline engines is about 38%, and the peak efficiency of modern diesel engines can reach 40% [8] [14].

3.3.1 Engine Model

There are different levels of engine models depending on the applications. Table 3.1 lists several levels of engine models. As shown in the table, an engine can be modeled from a high level torque-speed curve to a detailed model including the combustion chemical process.

<table>
<thead>
<tr>
<th>Engine Model Levels</th>
<th>Time Scale</th>
</tr>
</thead>
<tbody>
<tr>
<td>Torque-speed (T·ω) curve</td>
<td>seconds (s)</td>
</tr>
<tr>
<td>Multiple MAPs from throttle to torque (static MIMO model)</td>
<td>seconds (s)</td>
</tr>
<tr>
<td>System dynamics MIMO model</td>
<td>10 to 100 milliseconds (ms)</td>
</tr>
<tr>
<td>Individual combustion system dynamics MIMO model</td>
<td>milliseconds (ms)</td>
</tr>
<tr>
<td>Basic combustion chemistry, fluid mechanics, etc.</td>
<td>microseconds (µs)</td>
</tr>
</tbody>
</table>

Table 3.1 Different Levels of Engine Models
In our case, the engine is modeled using a torque-speed curve. A wide open throttle (WOT) torque-speed curve obtained from the manufacturer is used to model the engine. For example, the WOT torque-speed curve for the VW engine is shown in Figure 3.9.

The maximum engine output torque is determined by the given engine speed (RPM) and the throttle angle \( \alpha \). The relationship between WOT torque and throttle angle is:

\[
T_{\text{Engine, max}} = T_{\text{WOT}} \cdot \alpha
\]

(3.15)

where the range of throttle opening is defined from 0 (idling) to 1 (wide open throttle).

Figure 3.10 shows the structure of the engine model. The Simulink block diagram of this module is shown in Figure 3.11.
3.3.2 Throttle Control Logic

The throttle opening is determined by a control logic based on the velocity error and shift delay trigger.

When no shifting occurs, the throttle opening output is controlled by the velocity error, which is given by:
\[ V_{error} = V_{desired} - V_{actual} \] (3.16)

The velocity error is then passed onto the throttle controller, where decisions are made. During a shift, the delay trigger is held, or delayed for 0.4 seconds, and the throttle opening is set to 0 (idling position).

The throttle control logic is implemented by using proportional and integral control. The flow chart of the control logic is shown in Figure 3.12. The Simulink block diagram of the throttle control module is shown in Figure 3.13.

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**Figure 3.12 Flow Chart of the Throttle Control Logic**
In the Simulink implementation, a "resettable integrator" is needed. However, when the "resettable integrator" is converted to C code in Simulink version 1, there are some bugs in the C code generator. Therefore, we tried using the Simulink version 2.0 to solve these problems. But the "resettable integrator" in the older version of Simulink is no longer supported by Simulink 2.0. Hence, a new "resettable integrator" block is built by
using Simulink 2.0 to replace the older version one. The Simulink block diagram of the new "resettable integrator" is shown in Figure 3.14.

![Figure 3.14 New Resettable Integrator Block](image)

3.4 Electric Drive

Like engine models, electric motors can also be modeled at different levels depending on the application. A complex electric motor model can use vector-control theory, and the motor can also be modeled by simply using a torque-speed curve. For our application, we are interested in the overall performance of the HEV system. Therefore, we choose the torque-speed curve representation to model the electric motor used in the HEV system.

The electric motor chosen in this simulator is SR 218G motor made by Unique Mobility, Inc.[15]. The motor specifications are given in Table 3.2.
Table 3.2 SR218G Motor Specifications [15]

The maximum system performance for the SR218G motor is shown in Figure 3.15 [15]. In the current HEV model, the maximum motor output torque is determined by the given motor speed (RPM) and the throttle opening $\alpha$. The relationship between torque and throttle opening is the same as in equation (3.15). The Simulink block diagram is shown in Figure 3.16.

![Figure 3.15 Maximum System Performance of SR218G Motor [15]](image-url)
3.5 HEV Control Logic

In the parallel Hybrid Electric Vehicle (HEV) model, the key issue is how to optimally arrange the engine and the electric motor for load sharing.

Here, we need to define two concepts: charge sustaining and charge depleting vehicles. If the vehicle can produce all of its required electrical energy on board, this kind of vehicle is called a charge-sustaining vehicle. On the other hand, if the vehicle requires external electrical energy, or in other words, if the vehicle needs to be recharged, this vehicle is called a charge-depleting vehicle since it can not maintain its own state of charge (SOC). The concept of SOC will be discussed in detail in section 3.7.3.

The characteristics of charge-sustaining and charge-depleting vehicle are as follows:

1) A charge-sustaining HEV will keep the battery's SOC on approximately the same level during the whole driving cycle. The energy used to charge the
battery packs comes from the fuel tank, which means that the engine produces the extra power to convert to the electrical energy by using generator.

2) A charge-depleting HEV will use as much energy stored in the battery pack as possible. When the SOC value approaches the minimum value, the internal combustion engine provides the extra energy to compensate the power drop. In the charge-depleting case, there is no generator in the vehicle.

Figure 3.17 shows the SOC characteristics for both charge-sustaining and charge-depleting cases.

![Figure 3.17 SOC for Charge-sustaining and Charge-depleting](image)

When the parallel HEV is driven in urban area, the vehicle runs at relatively low speed. In such cases, the electric motor is more efficient and it can take over as the prime mover. When the parallel HEV is driven on highways, the engine is more efficient source.
Thus, the engine will take over the driving. When the vehicle needs to accelerate on highways, it needs extra power to drive the vehicle. In such situations, the electric motor can provide the extra power to accelerate the vehicle. At the same time, when the battery pack’s state of charge (SOC) value reaches the minimum value in the charge sustaining case, the engine can provide energy to charge the battery until the value of SOC reaches the maximum value. In such case, the electric motor works as a generator. Therefore, the control logic becomes the key issue of the whole HEV system. The operating schedule of the control logic for the IC engine and EM is shown in Figure 3.18 [11].

Figure 3.18 The Operating Schedule of HEV [11]

In Figure 3.18, we can see that when starting, the electric motor is the primary power source until the vehicle speed reaches $V_{high}$. When the velocity is above $V_{high}$, the engine will be the primary power source until the velocity drops below $V_{low}$. When the
velocity is below \( V_{\text{low}} \), the electric motor takes over again. However, between \( V_{\text{low}} \) and \( V_{\text{high}} \), there is a hysteresis region.

In the hysteresis range, both power sources will be used with the default power source providing 100% of its output and the secondary power source attempting to supplement with the required power difference. For example, let's assume a hard acceleration is required at low speed where the electric motor is the primary power source. If there is a difference between the torque requirement and the torque output, the engine will be turned on and provides the extra power to the wheels since the electric motor can not provide the requested performance. The control logic of ICE and EM is clearly demonstrated by the control logic flow chart shown in Figure 3.19 and Figure 3.20.

**Electric Motor Control Logic**

**Input Data**

- Velocity, \( T_{\text{yaw}} \), \( T_{\text{req}} \), GR, SOC

```
N

SOC > 0.2

EM OFF

Y

N

VEL < V_{\text{low}}

EM OFF

Y

N

VEL > V_{\text{high}}

EM OFF

AND

AND

EM ON

Figure 3.19 Flow Chart of EM Control Logic
```
From Figure 3.19, we can see that the SOC value is very important for the control logic of the electric motor. The controller monitors the current SOC value to make sure that there is sufficient power and energy remaining in the battery packs to run the electric motor. If the SOC value is lower than the minimum value, the electric motor will shut down and the engine will act in. At the same time, if the battery works in the charge sustaining case, the battery will be charged by the engine and the brake power regeneration, until the SOC value returns to the maximum value. The Simulink block diagram of the SOC controller is shown in Figure 3.21.
Figure 3.21 State of Charge Controller

(Note: in the earlier version of the simulator, there was one problem in the SOC controller. When the battery works in the charge depleting case, the SOC value is always constant which is not correct. This problem results in some mistakes in the EM and ICE control logic. The improved model block diagram is shown in Figure 3.21.)

3.6 Braking and Energy Regeneration

In HEVs, the braking energy is used to recharge the battery pack, this is referred as regenerative braking. Regenerative braking uses some of the energy normally discarded as heat during braking to recharge the battery. In such situations, the electric motors are used as generators to convert the kinetic energy of the vehicle to the electrical energy which can be stored in the battery packs.

The brake model block diagram is shown in Figure 3.22. The control logic is chosen as follows:
When the velocity error is greater than -0.4 m/s, the brake pedal is at zero position. If the velocity error is less than -0.4 m/s, it means the brake pedal needs to be stepped on. The brake pedal angle is $\alpha_{\text{brake}}$. The brake output torque is given by:

$$T_{\text{brake}} = T_{\text{max,brake}} \cdot \alpha_{\text{brake}} \quad (3.17)$$

The brake is controlled by a PI controller with a similar structure as that used in the throttle module.

![Brake Block Model](image-url)

Figure 3.22 Brake Block Model

For the brake energy regeneration case, the motor controller switches the mode from driving to generating when the driver releases the throttle pedal, and steps on the brake pedal. The angle of the brake pedal determines the amount of regeneration which varies from no regeneration ($\alpha_{\text{brake}} = 0$ pedal not pressed) to maximum regeneration ($\alpha_{\text{brake}} = 1$ pedal fully pressed). The brake regeneration model block diagram is shown in Figure 3.23.
3.7 Battery Pack

Accurate indication of the state of charge (SOC) of the battery is essential in the development of the HEV model, since SOC affects the HEV performance (MPG) and control logic directly. Thus, based on battery discharging process, a dynamic state empirical battery model, derived from electrical behavior of a lead acid battery system, is used in the HEV simulator.

During the discharging process, only a fraction of the total chemical energy of the battery can be converted to electrical energy. This can be seen in the simple battery model shown in Figure 3.24. The lead-acid battery during the discharging process can be represented by a circuit consisting of voltage source $V_{oc}$, the e.m.f. of the battery, and the internal resistance $R$. The internal resistance $R$ acts as the source for the voltage drop.
during the discharging process and it varies according to the discharging current \( I \) and power.

![Electrical Circuit Representing the Battery During Discharge](image)

Figure 3.24 Electrical Circuit Representing the Battery During Discharge [16]

The traction power at the battery interface \( P_m \), comes from the motor output. And the total battery’s power \( P_{nb} \) is determined by algebraically adding any power contributed by regeneration power \( P_m \), and auxiliary loads \( P_{sa} \) as follows:

\[
P_{nb} = P_m + P_r + P_{sa}
\]

By convention, battery power and current are positive out of the battery (discharge) and negative into the battery (charge). So \( P_{sa} \) is positive and \( P_m \) is negative as shown in Figure 3.25.

From the calculated total battery power \( P_{nb} \), and the battery characteristics (i.e., open circuit voltage \( V_{oc} \), and resistance \( dV/dIc \) at the current depth-of-discharge) is found
by linear interpolation of the data via the battery data file, the battery current \( I_b \) is determined by solving for the real root of the quadratic equation:

\[
P_a = \frac{dV}{dt} \cdot I_s^2 + V_{oc} \cdot I_s
\]

and \( I_b \) is given by:

\[
I_b = \frac{-V_{oc} + \sqrt{V_{oc}^2 - 4 \cdot P_a \cdot (dV/dt)}}{2 \cdot (dV/dt)}
\]

The battery voltage under load \( V_s \) is calculated from the following relationship:

\[
V_s = V_{oc} - I_s \cdot R
\]
3.7.1 Minimum Voltage

The calculated battery voltage, $V_b$, is compared to the minimum voltage $V_{mn}$. If $V_b < V_{mn}$, $V_b$ is set equal to $V_{mn}$, and the maximum battery current is given by

$$I_{V_{mn}} = (V_{mn} - V_{cc}) \times \left(\frac{dV}{dt}\right)$$  \hspace{1cm} (3.22)

3.7.2 Maximum Current

The calculated current $I_b$ is used as a control signal. If $I_b > 0$, the current is equal to $+I_{mn}$. If $I_b < 0$, the current is equal to $-I_{mn}$.

3.7.3 Battery Capacity and SOC

In order to describe a reliable “fuel gauge” for electric traction, the concept of state of charge (SOC) of battery is very important. A general definition of SOC for a lead-acid battery is:

$$SOC = \frac{Ah_{res}}{Ah_{cap}} \times 100\%$$  \hspace{1cm} (3.23)

where $Ah_{res}$ and $Ah_{cap}$ are the residual and the total capacity (Ah) of the battery at a certain moment. $Ah_{res}$ is given by:

$$Ah_{res} = SOC_{ini} \times Ah_{cap} - Ah_{drained}$$  \hspace{1cm} (3.24)

where $SOC_{ini}$ is the initial value of SOC, and $Ah_{drained}$ is the energy drained from the battery.
The average battery current, $I_{\text{avg}}$, is used to calculate the available battery capacity from the Pueckert relationship [17]:

$$ A_{\text{cap}} = K \cdot I_{\text{avg}}^n $$  \hspace{1cm} (3.25)

where $K$ and $n$ are constants.

and

$$ I_{\text{avg}} = \int I_t \cdot dt $$  \hspace{1cm} (3.26)

The Simulink block diagram of the battery model is shown in Figure 3.26.

![Battery Model](image)

Figure 3.26 The Battery SOC Simulink Diagram

3.8 Fuel Economy Computation

One objective of the current model is to predict fuel economy. This can be calculated by integrating the brake specific fuel consumption (BSFC) over the driving cycle. In the current model, fuel economy is described as the ratio of the flow rate ($t$ in gram/hour) to the power output (P in kw), which is known as BSFC [18].
\[ BSFC = \frac{T}{\rho} \]  
(3.27)

The power output of the engine is calculated by

\[ P = T_e \cdot \omega_{j,CE} / 1000 \]  
(3.28)

The BSFC map is a function of the engine RPM and the engine torque and is shown in Figure 3.27.

![VW 1.9 L engine BSFC map](image)

Figure 3.27 Brake Specific Fuel Consumption Map

The engine torque and speed are calculated at every time step. They are also used to determine the fuel consumption from BSFC map. The specific fuel consumption is given in terms of grams per kilowatt-hour, but the fuel economy is calculated in terms of miles per gallon. Thus, it is necessary to convert grams per kilowatt-hour into gallon.

From equation (3.33) and Equation (3.34), we have

\[ r_j = BSFC \cdot (T_e \cdot \omega_{j,CE} / 1000) \]  
(3.29)
So the fuel flow ratio in terms of \( \text{gram/second} \) is \( \frac{r_f}{3600} \), and the fuel consumption in terms of gram is integrated by the fuel flow ratio \( \int \frac{r_f}{3600} \, dt \). In order to convert gram into gallon, we need to know the fuel density. From "Internal Combustion Engine Fundamentals" [13], the densities of gasoline fuel and light diesel fuel are 0.72-0.78 (kg/dm\(^3\)) and 0.78-0.84 (kg/dm\(^3\)), respectively. In the model, the density of fuel is chosen as 0.78 (kg/dm\(^3\)). The conversion from gram to gallon is given by:

\[
fuel_{\text{con}} = 0.78 \frac{\text{kg}}{\text{dm}^3} \cdot \frac{1000 \text{g}}{1 \text{kg}} \cdot \frac{3.7854 \text{dm}^3}{\text{gallon}} = 2953 \frac{\text{g}}{\text{gallon}} \quad (3.30)
\]

Figure 3.28 shows the calculation and conversion procedures of the fuel economy from BSFC map.

![Fuel Economy Diagram](Image)

Figure 3.28 Engine Fuel Consumption Block

So, the fuel consumption of the engine is calculated by

\[
gal_{\text{engine}} = \int \frac{BSFC \cdot (T_r \cdot \theta_{\text{inlet}})}{3600 \cdot 1000} \, dt \quad (3.31)
\]
In the earlier version HEV model, there are some unreasonable results in MPG values. This is due to the unreasonable input given to the BSFC map. The output of the BSFC is interpolated based on the inputs of engine torque and RPM. If the input values are outside the range of the given map, the interpolated BSFC result will be incorrect. Therefore, in order to avoid the incorrect results, the limited saturators are added to the inputs of the BSFC map. This means that if the input values are outside the range of the given map, the boundary values of the inputs to the map are chosen instead of the real inputs.

When the vehicle works in HEV mode, we need to consider whether the energy source of the electric motor comes from the vehicle itself or from outside. In the charge depleting case, the battery has already been charged by a wall outlet. In such situations, we need to add the energy used by the electric motor to the total energy. Thus, the total energy is the sum of the engine input energy and the stored electric motor energy. This total energy is then converted into an equivalent amount of reformulated gasoline.

In the charge sustaining case, the battery is recharged by the brake energy regeneration and the engine, which means more fuel is burned to produce the extra energy. Therefore, the total energy, in such case, should not include the electric motor energy.

The electric driving system efficiency map, which is shown in Figure 3.29, is used to calculate the electric motor energy. By using this efficiency map, the required energy for the electric motor can be calculated. This required energy is then used as an input to
the battery block. The Simulink block diagram for the required motor energy calculation is shown in Figure 3.30.

![Electric Drive Efficiency Map](image)

**Figure 3.29 Electric Drive System Efficiency Map**

![Motor Required Energy Simulink Diagram](image)

**Figure 3.30 Motor Required Energy Simulink Diagram**

60
According to the required motor energy and the brake power regeneration, the battery can produce the corresponding output voltage $V_b$ and the output current $I_b$. Thus, the electric motor energy is calculated by

$$\text{Energy}_{\text{motor}} = \int (V_b \cdot I_b) \cdot dt$$  \hspace{1cm} (3.32)

The Energy_{motor} is then converted to gasoline fuel by

$$\text{gal}_{\text{motor}} = \frac{\text{Energy}_{\text{motor}}}{115400 - 10551 \cdot \text{efficiency}_{\text{motor}}}$$  \hspace{1cm} (3.33)

The total fuel consumption is calculated by:

$$\text{gal}_{\text{total}} = \begin{cases} \text{gal}_{\text{engine}} & \text{charge\_sustaining} \\ \text{gal}_{\text{engine}} + \text{gal}_{\text{motor}} & \text{charge\_depleting} \end{cases}$$  \hspace{1cm} (3.34)

Thus, the total fuel consumption is divided by the travel distance in miles to get the fuel economy in miles/gallon (MPG). The Simulink block diagram of the fuel economy calculation is shown in Figure 3.31.

![Figure 3.31 Fuel Economy Diagram](image-url)
3.8 Conclusions

In this chapter, the HEV model is described in detail. The implementation philosophy of each module in the whole system is discussed, followed by the Simulink block diagrams. The HEV model developed is generic. Therefore, it can be used to model any combinations of parallel HEV configurations.

The simulation results and the application of the developed HEV simulator in the project of "Design Space Exploration" sponsored by DARPA will be presented in the next chapter.
CHAPTER 4

SIMULATION RESULTS AND APPLICATION OF DESIGN-SPACE EXPLORATION

This chapter has two parts. The first part includes the simulation results by using the HEV simulator. The second part reports the application of the HEV simulator in "Design-Space Exploration". To demonstrate the capabilities of the OSU HEV simulator, the simulation is run under various driving cycles such as Urban (or City) Driving Schedule and Highway Driving Cycle. The main objective of this simulator is to accurately predict vehicle performance in three aspects, which are maximum acceleration, top speed and fuel economy. For the cases of maximum acceleration and top speed, a speed step is used as the input. The concept of maximum acceleration is to evaluate how much time the vehicle takes when the vehicle reaches 60 MPH, which is called T60 in this thesis. The concept of top speed is defined as the vehicle maximum steady-state speed. The HEV simulator can simulate three types of vehicle configurations such as Engine only, EM only and HEV. The simulation results for these cases are discussed in the following sections.

As mentioned in the introduction chapter, the Design-Space Exploration project sponsored by Defense Advanced Research Projects Agency (DAPRA) is to consider and evaluate a very large number of potential designs. The HEV simulator is chosen as a
domain test for this design concept. The results of the application of HEV simulator in this Design-Space Exploration project are reported.

HEV simulator is based on the gross vehicle dynamics of the OSU FutureCar, which is a modified Chevy Lumina. The simulator can simulate four types of vehicles. It is listed in Table 4.1.

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>IC Only</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
</tr>
<tr>
<td>EM Only</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
</tr>
<tr>
<td>Parallel HEV</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
</tr>
</tbody>
</table>

Table 4.1 Table of Simulated Cases

4.1 Simulation Results by Using HEV Simulator

4.1.1 ICE Only Case

For the ICE only case described in reference [10], it only provides the maximum acceleration and the fuel economy. The simulated T60 and fuel economy results match the measured values perfectly by using FUDS cycle as shown in Figure 4.1 and Figure 4.2 [10]. From these results, we can see that the dynamic behavior of the simulator shows good correlation with the experimental results of T60 and fuel economy. However, reference [10] does not show any results for the top speed value. Therefore, we wanted to show the simulated result using two different methods. First, we run the simulator to get the top speed. A speed step is used as input. Table 4.2 shows the results.
Figure 4.1 Maximum Acceleration Measured and Simulation [10]

Figure 4.2 Measured and Simulated Fuel Economy during FUDS Cycle [10]
<table>
<thead>
<tr>
<th>$f_d$</th>
<th>$M$ (L.b.)</th>
<th>$C_{0}$</th>
<th>$C_{D}$</th>
<th>$r$ (m)</th>
<th>Shift point (RPM)</th>
<th>top speed (m/h)</th>
</tr>
</thead>
<tbody>
<tr>
<td>2</td>
<td>3300</td>
<td>0.00677</td>
<td>0.3433</td>
<td>0.31685</td>
<td>2000</td>
<td>96.11</td>
</tr>
<tr>
<td>4</td>
<td>3300</td>
<td>0.0067</td>
<td>0.3433</td>
<td>0.31685</td>
<td>2000</td>
<td>99.17</td>
</tr>
<tr>
<td>6</td>
<td>3300</td>
<td>0.0067</td>
<td>0.3433</td>
<td>0.31685</td>
<td>2000</td>
<td>66.84</td>
</tr>
</tbody>
</table>

Table 4.2 Top Speed at Different Differential Gear Ratio $f_d$

In order to verify the above results, another method is used to calculate the top speed [20]. The IC only vehicle is assumed to work at steady-state point, and run at wide open throttle with the transmission in the 5th gear. When the engine torque is exactly equal to the road load, it means that the two torque curves intersect at one point; the corresponding speed is the top speed. The top speed results of the comparison method is shown in Figure 4.3. The Matlab program written for this comparison method is in the Appendix 1.

![Figure 4.3 Comparison of Engine Torque and Road Load to Maintain Top Speed at Different $f_d$](image)

66
From Figure 4.3, we can see that when \( f_d \) is increased, for example when \( f_d \) is 4 or 6, the cross points are out of the "red line" (4000RPM) range, this does not make sense for the real engine. Hence, if the cross point exceeds the "red line", the top speed will be set as the "red line" value. Table 4.3 shows the top speed at different \( f_d \).

<table>
<thead>
<tr>
<th>( f_d )</th>
<th>( M ) (Lb)</th>
<th>( C_{d0} )</th>
<th>( C_D )</th>
<th>( r ) (m)</th>
<th>shift point (RPM)</th>
<th>Top speed (m/h)</th>
</tr>
</thead>
<tbody>
<tr>
<td>2</td>
<td>3300</td>
<td>0.0067</td>
<td>0.3433</td>
<td>0.31685</td>
<td>2000</td>
<td>96.07</td>
</tr>
<tr>
<td>4</td>
<td>3300</td>
<td>0.0067</td>
<td>0.3433</td>
<td>0.31685</td>
<td>2000</td>
<td>98.38</td>
</tr>
<tr>
<td>6</td>
<td>3300</td>
<td>0.0067</td>
<td>0.3433</td>
<td>0.31685</td>
<td>2000</td>
<td>65.59</td>
</tr>
</tbody>
</table>

Table 4.3 Comparison of ICE Torque and Road Load to Maintain Top Speed at Different \( f_d \)

From Table 4.2 and Table 4.3, we can see that by using different method to calculate the top speed performance, the results obtained from both methods are very close. In the pure IC only case, the battery energy is kept constant. Figure 4.4 shows the battery SOC response for pure IC only case.

![Figure 4.4 Battery SOC Response for Pure ICE Case](image_url)
4.1.2 EM Only Case

To simulate the EM only case, we select a medium size UQM motor to drive the vehicle. For an EM vehicle, it totally depends on the battery packs to provide the electric power. Therefore, the battery works in the discharge mode (charge depleting). Equation (3.38) is used to calculate the fuel economy. Assuming the battery is fully charged, i.e., SOC value is equal to one. Figure 4.5 (a), (b), (c) and Figure 4.6 (a), (b), (c) show the vehicle speed, the fuel economy and the SOC results of highway (10.26 miles) and city cycle (11.09 miles), respectively.

From the simulation results, we can see that the vehicle can follow the profile perfectly, and the fuel economy is almost the same for both cases.

4.1.3 HEV Case

For the hybrid electric vehicle case, we choose a medium size diesel engine (VW 1.9L), a medium electric motor (UQM SR218G), a manual transmission and 15 battery cells. Their masses are listed in Table 4.4.

<table>
<thead>
<tr>
<th>Mass (Kg)</th>
<th>Vehicle Body</th>
<th>VW Engine</th>
<th>Motor</th>
<th>Transmission</th>
<th>Battery Cell</th>
</tr>
</thead>
<tbody>
<tr>
<td>1210</td>
<td>135</td>
<td>50</td>
<td>69</td>
<td>375</td>
<td></td>
</tr>
</tbody>
</table>

Table 4.4 Masses of Vehicle
Figure 4.5 Highway Cycle Vehicle Performance
Figure 4.6 City Cycle Vehicle Performance
Therefore, the total weight of the medium size vehicle is 1839Kg. For our simulator, prior to running the simulator, a Matlab program must be run. First, in this program, the user can select the engine and the electric motor sizes, the transmission type, the battery SOC working function (charge sustaining/depleting) and the initial parameters, such as SOC_{initial}, SOC_{max}, SOC_{min} values, and the user also needs to select $V_{\text{high}}$ and $V_{\text{low}}$ values for the control logic. Finally, the user needs to choose the driving cycle profile. The selected parameter values are as follows:

Charge sustaining/depleting:

$\text{SOC}_{\text{initial}} = 0.4 \text{ and } 0.8, \text{ SOC}_{\text{max}} = 0.8, \text{ SOC}_{\text{min}} = 0.4$

$V_{\text{high}} \approx 22 \text{ miles/hour, } V_{\text{low}} = 20 \text{ miles/hour}$

Driving cycle profile:

Highway and City cycle.

For highway cycle charge sustaining case the results are shown Figure 4.7. Since the battery packs need to be charged when $\text{SOC}_{\text{initial}} = \text{SOC}_{\text{min}}$, which means the engine needs to produce extra energy to charge the battery until the SOC value reaches $\text{SOC}_{\text{max}}$, so it consumes more fuel. We can see that the fuel consumption is 19.72 miles/gallon in Figure 4.7 (c). However, when $\text{SOC}_{\text{initial}} = \text{SOC}_{\text{max}}$, the battery packs discharge until the SOC value reaches $\text{SOC}_{\text{min}}$, which indicates that the battery can provide extra power to drive the vehicle. The fuel consumption is 71.1 miles/gallon in Figure 4.7 (d). This battery charge and discharge process is shown in Figure 4.8.
Figure 4.7 Highway Cycle HEV Responses for Charge Sustaining Case
Figure 4.8 Battery Charge and Discharge Process for Highway Cycle

To calculate the accurate fuel economy, we need to consider the extra power when SOC drops from \( \text{SOC}_{\text{max}} \) to \( \text{SOC}_{\text{min}} \). It is calculated by a Matlab code program, which is attached in Appendix 2.

Based on the above program, we get the highway cycle fuel economy as 53.1 miles/gallon.

Using the same method, we can obtain the fuel economy results for all these cases shown in Table 4.5.

<table>
<thead>
<tr>
<th></th>
<th>Highway Cycle</th>
<th>City Cycle</th>
</tr>
</thead>
<tbody>
<tr>
<td>Charge Sustaining</td>
<td>53.1</td>
<td>37.99</td>
</tr>
<tr>
<td>Charge Depleting</td>
<td>58.95</td>
<td>53.94</td>
</tr>
</tbody>
</table>

Table 4.5 Fuel Economy of HEV (miles/gallon)
From Table 4.5, we can see that the fuel economy of the charge depleting case is higher than that of the charge sustaining case, because there is no charging process in the charge depleting case. The top speed and T60 time are 135.4 miles/hour and 11.5 seconds (reaching 63.17 miles/hour) respectively.

According to the data given in the reference [19][21], we use the simulator to run the HEV simulation again. The comparison results are shown in Table 4.6. This table indicates that the simulation results are very close to the measured data.

<table>
<thead>
<tr>
<th></th>
<th>Mass (Kg/Lb)</th>
<th>( C_D )</th>
<th>( C_m )</th>
<th>T60 Time (sec.)</th>
<th>Speed (mph)</th>
<th>Highway MPG</th>
<th>City MPG</th>
</tr>
</thead>
<tbody>
<tr>
<td>FCC'97 (measured)</td>
<td>1500 (3300)</td>
<td>0.300</td>
<td>0.0067</td>
<td>10.7</td>
<td>65.7</td>
<td>57.5</td>
<td>35.4</td>
</tr>
<tr>
<td>Simulation (C.S.)</td>
<td>1500 (3300)</td>
<td>0.300</td>
<td>0.0067</td>
<td>11</td>
<td>66.6</td>
<td>56.98</td>
<td>40.83</td>
</tr>
</tbody>
</table>

Table 4.6 HEV Dynamic Performance Comparison

The HEV simulator can also be expanded to study different engine and motor combinations. We choose a GEO (1.0L) engine as the small size engine, and a DODGE (3.1L) engine as the large size engine. According to the UQM motor specification [15], we can scale the medium size motor torque-speed curve so as to get the small size (0.6) motor and the large size motor (1.5). The objective of studying these combinations is to apply these simulation cases in the experiments of Design-Space Exploration of DARPA project.
4.2 Application of HEV Simulator in Design-Space Exploration

Exploring very large design spaces is an essential part of DARPA's Rapid Design Exploration and Optimization (RaDEO) program, which has a number of university and industry participants. The long-term vision of RaDEO program is to create a highly flexible and responsive design environment which can be used to evaluate an order of magnitude more design alternatives than that possible today in an attempt to optimize product characteristics (such as performance, manufacture ability, assembly ability, quality, reliability, and maintainability etc.), and quickly prototype complex products and processes.

Researchers at Laboratory for Artificial Intelligence Research (LAIR) of Ohio State University developed a very powerful software "Seeker" to realize the goal of RaDEO. The overall architecture of the software is an interactive decision-support architecture for design, which is shown in Figure 4.9 [22] [23].

A component/configuration library is available for design candidate generation. In the device library, the software can retrieve all the information such as object properties, relationships, instant initial values and the information of environment. Then it composes the individual objects into a new device according to the structure description and various specified constraints made by users. Finally, it produces the new device in the specified environment with initial values. The Good-Design Seeker generates design candidates by selecting components from the library and composing them so as to satisfy the constraints. Each design candidate is evaluated by several design critics, and each critic
evaluates a candidate design from the point of view of a particular aspect. The total number of design candidates can be quite large. Therefore, in order to make effective use of the critical information for the designer, it must have some dominance filters to select the small optimized number of designs which will be examined further. Researchers of LAIR have developed a safe filtering criterion to guarantee no loss of good designs [22].

To demonstrate the experimental results in design-space exploration, the hybrid electric vehicle simulator is chosen as the domain design space exploration experiment.
The hybrid electric vehicle is used as the component library is the experiment. Details of the domain model used are listed in Table 4.7-4.9:

<table>
<thead>
<tr>
<th>Vehicle Type</th>
<th>IC only, Electric only, Parallel HEV (charge sustaining and charge depleting), Series HEV</th>
</tr>
</thead>
<tbody>
<tr>
<td>IC Engine Size</td>
<td>Small (GEO 1.0L), Medium (VW 1.9L), Large (DODGE 3.1L)</td>
</tr>
<tr>
<td>Electric Motor Size</td>
<td>Small, Medium, Large</td>
</tr>
<tr>
<td>Transmission Type</td>
<td>Manual (4, 3 speed), Automatic (3, 4 speed), CVT</td>
</tr>
<tr>
<td>Motor Torque Reduction</td>
<td>Representative Values (0.6 - 1.5)</td>
</tr>
<tr>
<td>Motor Speed Reduction</td>
<td>Representative Values (1.0 - 3.0)</td>
</tr>
<tr>
<td>Battery Cell Number</td>
<td>12, 15, 18, 21, 24</td>
</tr>
<tr>
<td>Shift Speed Point</td>
<td>Representative Values (2000RPM - 4000RPM)</td>
</tr>
<tr>
<td>Differential Gear Ratio ($f_d$)</td>
<td>Representative Values (2.0 - 6.0)</td>
</tr>
<tr>
<td>Parallel HEV Control Policy</td>
<td>Representative Values for $V_{high}$, $V_{low}$, SOC$<em>{ins}$, SOC$</em>{max}$, Charge Sustaining/Charge Depleting</td>
</tr>
</tbody>
</table>

Table 4.7 Component Library Used in DARPA

<table>
<thead>
<tr>
<th>Mass (Kg)</th>
<th>Small</th>
<th>Medium</th>
<th>Large</th>
<th>Manual</th>
<th>Automatic</th>
<th>CVT</th>
</tr>
</thead>
<tbody>
<tr>
<td>IC Engine</td>
<td>68.0</td>
<td>135.0</td>
<td>190.0</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Motor</td>
<td>31.7</td>
<td>50.0</td>
<td>68.0</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Transmission</td>
<td>69.0</td>
<td>101.0</td>
<td>85.0</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Lumina Frame</td>
<td>1210.0</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Battery Cell</td>
<td>25.0</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Table 4.8 Component Weight (Kg)

<table>
<thead>
<tr>
<th>IC Engine</th>
<th>Small</th>
<th>Medium</th>
<th>Large</th>
</tr>
</thead>
<tbody>
<tr>
<td>GEO</td>
<td>VW</td>
<td>DODGE</td>
<td></td>
</tr>
</tbody>
</table>

Table 4.9 Torque-Speed Curve and Efficiency Map
Before we use the HEV simulator written by using Simulink as the design-space exploration experiment, we need to use MATLAB’s “Real-Time Workshop” [25] to convert the Simulink model into C code. Then the design-space exploration software “Seeker” can use the C code as the device library to run in UNIX. When the user supplies a set of realistic choices for these components, the “Good Design Seeker” explores them all. The design space size can be made to grow very large by stepping component changes through very small increments. The design candidates are generated by first selecting a vehicle configuration from the five choices, then systematically going through all relevant combinations of component choices and parameter value choices based on the restrictive condition. The design critics of dominance in the experiments are:

- Maximum acceleration,
- Top speed;
- City driving cycle fuel economy;
- Highway driving cycle fuel economy.

The LAIR design-space exploration software “Seeker” runs the simulation over many combined configurations. Current small size running is 56,025 possible designs.

The total 56,025 design-space's results are:

\[
\begin{align*}
\text{Mpg city} &= 11.70 - 61.049 \text{ MPG} \\
\text{Mpg highway} &= 17.25 - 82.8486 \text{ MPG} \\
\text{Top speed} &= 31.41 - 140.524 \text{ MPH} \\
T60 &= 7.75 - 490.0 \text{ Seconds}
\end{align*}
\]
Finally, through the strict dominance filtering, only 103 (0.184%) designs survive in the strict dominance, they are 16 parallel HEV (charge depleting) and 87 parallel HEV (charge sustaining). The 103 survivor design-space’s results are:

\[
\text{Mpg city} = 26.96 - 61.049 \text{ MPG}
\]

\[
\text{Mpg Highway} = 30.26 - 82.54 \text{ MPG}
\]

\[
\text{Top} \sim 89.555 - 140.524 \text{ MPH}
\]

\[
T_{50} = 7.75 - 9.25 \text{ Seconds}
\]

Figure 4.10 shows six pairwial plots obtained from overall 103 survivor design-spaces.

Figure 4.10 Overall Survived Design-Spaces for Small Size Running Case
Figure 4.10 (continued)

Figure 4.10 Overall Survived Design-Spaces for Small Size Running Case
Figure 4.10 (continued)

Figure 4.10 Overall Survived Design-Spaces for Small Size Running Case
Figure 4.10 Overall Survived Design-Spaces for Small Size Running Case

From Figure 4.10 (c), we can select the lowest T60 and high city MPG (>45MPG), then there are 13 survivor designs as shown in Figure 4.11.
Figure 4.11 Survivor Designs of Lowest T60 and High City MPG
Figure 4.11 Survivor Designs of Lowest T60 and High City MPG

(Continued on the next page)
Figure 4.11 Survivor Designs of Lowest T60 and High City MPG
From Figure 4.10 (a), we can select the high highway MPG and high city MPG as domain criteria, then there are 6 survivor designs as shown in Figure 4.12.

(Continued on the next page)

Figure 4.12 Survivor Designs of High Highway MPG and High City MPG

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Figure 4.2 (continued)

(c) Survivors within window $x_1$.

(d) Survivors within window $x_2$.

(Continued on the next page)

Figure 4.12 Survivor Designs of High Highway MPG and High City MPG

87
Figure 4.2 (continued)

(e)

(f)

Figure 4.12 Survivor Designs of High Highway MPG and High City MPG

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From Figure 4.10 (d), we can select high top speed and high highway MPG as domain criteria, then there are 5 survivor designs as shown in Figure 4.13.

Figure 4.13 Survivor Designs of High Top Speed and High Highway MPG
Figure 4.13 (continued)

(Continued on the next page)

Figure 4.13 Survivor Designs of High Top Speed and High Highway MPG
Figure 4.13 (continued)

Figure 4.13 Survivor Designs of High Top Speed and High Highway MPG

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From Figure 4.10 (f), we can select the lowest T60 and high top speed as domain criteria (sports car), then there are 7 survivor designs as shown in Figure 4.14.

(Continued on the next page)

Figure 4.14 Survivor Designs of the Lowest T60 and High Top Speed
Figure 4.14 (continued)

Figure 4.14 Survivor Designs of the Lowest T60 and High Top Speed
Figure 4.14 (continued)

Survivors within window = 7

(c)

Survivors within window = 7

(f)
Figure 4.14 Survivor Designs of the Lowest T66 and High Top Speed

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4.3 The Concept of OSU-CML

The first step of simulation is to gather all the information in the model, including all the information about objects: properties, inner structures, relationships between objects, initial values of instances, and descriptions of environment. Normally, this kind of information can be retrieved from the device library. We have a language to describe the device library, named OSU-CML (Composable Modeling Language) which was derived from a similar language developed by researchers at Stanford University [27]. The language parser will recognize those well-formatted descriptions (CML grammar) and retrieve them into a database. More precisely, the data retrieved from the model are a bunch of equations. For example, a simple circuit is given in Figure 4.15.

![Figure 4.15 A Simple Circuit with Only One Resistance And A Battery](image)

The CML code is given as follows:

```cml
ENTITY resistor : two_legged

QUANTITIES:
  resistance_dimension: resistance;

COMPONENTS:
  PORTS:
    Resistance: resistance;

CONSTRAINTS:
  CONDITION TRUE
  CONSEQUENCE
    Terminal_2.voltage-Terminal_1.voltage = resistance*Terminal_2.current;

```

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According to the CML concept, a simple IC only vehicle's model is described by using CML. In this model, there are four components which are IC engine, transmission, fuel_Tank, and brake. If the condition is true, the aero-drag, rolling resistance, forward force, acceleration, etc., are calculated as consequence. The main part of CML is represented as follows, and the more detailed program is attached in the Appendix.

ENTITY IC_Only_Vehicle SUBCLASS OF Superclass_Vehicle
{
    COMPONENTS:
    IC_Engine : ic_engine;
    Transmission : transmission;
    Fuel_Tank : fuel_tank;
    brake : brake;
    CONDITION: TRUE
    CONSEQUENCE:
    Area_Drag=Air_density*Drag_coefficient*
    Front_area*Velocity^2/2 AND
    Rolling_resistance=Rolling_resistance*
    Total_Vehicle_Mass^0.81 AND
    Forward_Force=(ic_engine_Engine_Torque* transmission.Transmission_Ratio(t)*
    transmission.Transmission_efficiency*
    brake.Brake_Torque)/Tire.Radius-
    AERO_drag - Rolling_resistance AND
   Vel_TERR=Desired_Velocity-Velocity AND
    Mass=Body.Weight + fuel_tank.Initial_Fuel-
    ic_engine.Fuel_consumption*3.0283 AND
    acceleration=d(Velocity)/dt AND
    Forward_Force=Mass_factor*Mass*Acceleration AND
    Mile= integrator(Velocity,t)/269.3 AND
    Fuel_Consumption_MPG=Mile/ic_engine.Fuel_consumption AND
    Material_Flow_Connected(fuel_tank.Fuel_flow_rate,
    ic_engine.Fuel_consume_rate) AND
    Rotationally_Coupled(transmission.input,
    ic_engine.input)
}
Based on the introduction, a generic HEV model can be represented by CML. The generic CML model also can be described as a device in Design-Space Exploration software ("Seeker"). This is work for the future.
CHAPTER 5

CONCLUSIONS AND FUTURE WORK

Hybrid electric vehicles offer the opportunity to combine the advantages of conventional vehicles (such as gasoline engine vehicles) with those of the electrically powered ones. A powerful HEV simulator can be a very helpful tool in the design process. In this thesis, a hybrid electric vehicle simulator based on OSU FutureCar Challenge is described. The work in the thesis is to improve the earlier version simulator developed by Byron Wacac [10], so as to make the simulator to adapt to different HEV configurations. The final goal is to build a generic HEV simulation model. The main contributions are summarized below:

- Simulink code is used to rebuild the "S-function" blocks so that it can be converted into C code by using Matlab "Real-Time Workshop".
- The vehicle dynamics model is described more realistically based on physical law.
- The control policy is improved so as to make the parallel HEV work in both battery charge sustaining and charge depleting cases.
- The control policy is revised so that the parallel HEV obtains realistic fuel economy results.

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• The control policy is improved so as to adapt the changes of engine and motor sizes. The objective is to use the generic HEV model in the application of DARPA project.

• The HEV simulation results are verified by using the results of '97 OSU FutureCar data.

• Using the simulation model, a small size Design-Space Exploration was run in DARPA project. The survived designs are realistic. It will help designers to select the best HEV design.

• A simple IC only vehicle model is described by CML.

From chapter 3, we showed that the current simulator is not yet sufficiently modular, it is not a totally generic simulation model. Therefore, the future work needs to improve its structure to make it more robust for general purpose application and build a generic HEV control logic [26] so as to develop a new generation simulation model. The new generation simulation model block diagram is proposed in Figure 5.1.

Based on the principles of the Simulink HEV simulator, a new HEV simulator based CML model will be developed for DARPA application. Thus, the two new HEV simulation models can either be used in general simulation purposes or used in specific purpose such as DARPA project.
Figure 5.1 General HEV simulation diagram
BIBLIOGRAPHY


Engineers, Inc. 1994.


[21] Web page of Furecar


APPENDIX

Appendix 1: The Manual Transmission Gear Ratio

<table>
<thead>
<tr>
<th>Gear</th>
<th>1st</th>
<th>2nd</th>
<th>3rd</th>
<th>4th</th>
<th>5th</th>
</tr>
</thead>
<tbody>
<tr>
<td>GR</td>
<td>3.30</td>
<td>1.94</td>
<td>1.308</td>
<td>0.971</td>
<td>0.756</td>
</tr>
</tbody>
</table>

The combined efficiency is $\eta_e = 0.95$.

Appendix 2: The Automatic Transmission Gear Ratio

<table>
<thead>
<tr>
<th>Gear</th>
<th>1st</th>
<th>2nd</th>
<th>3rd</th>
<th>4th</th>
</tr>
</thead>
<tbody>
<tr>
<td>GR</td>
<td>2.71</td>
<td>1.54</td>
<td>1.0</td>
<td>0.71</td>
</tr>
</tbody>
</table>

The combined efficiency is $\eta_e = 0.85$. 
Appendix 4:

\[
\begin{align*}
\text{SOC Init} &= \text{SOClo}; \\
\text{dSOCInit} &= \text{SOC}(\text{length}(\text{SOC}) - \text{SOC Init})/\text{length}(\text{gal}); \\
\text{SOC Init} &= \text{SOChi}; \\
\text{dSOCj} &= \text{SOC}(\text{length}(\text{SOC}) - \text{SOC Init})/\text{length}(\text{gal}); \\
\text{k2} &= \text{UMC_e}(\text{length}(\text{UMC_e})); \\
\text{if} \ (\text{dSOC1} - \text{dSOC2}) = 0 \& \text{else} \\
\text{Citymp} &= \text{miles}/((\text{j1} + \text{j2})/2) \\
\text{if} \ (\text{dSOC1} - \text{dSOC2}) = 0 \& \text{else} \\
\text{Total_gal} &= \text{dSOC1} + \text{dSOC2} \\
\text{mpg} &= \text{miles}/\text{Total_gal} \\
\end{align*}
\]

Appendix 5:

```plaintext
ENTITY Superclass_Vehicle
{
    QUANTITIES:
    VARIABLE:
    Velocity : Velocity;
    Acceleration : Acceleration;
    Aero_Drag : Force;
    Forward_Force : Force;
    Fuel_Consumption_MPG : mpg;
    Mile : Distance;
    Mass : Weight;
    Mass_Factor : FLOAT;
    CONSTANT:
    Drag_coefficient : FLOAT;
    Front_area : Area;
    COMPONENTS:
    Body : Body;
    Tire : Tire;
}
ENTITY IC_Only_Vehicle SUBCLASS OF Superclass_Vehicle
{
    COMPONENTS:
    ic_engine : Engine;
    transmission : Transmission;
}
```
Fuel_Tank : fuel_tank;
Brake : brake;

CONDITION:
true

CONSEQUENCE:
Area_drag = Air_density * Drag_Coefficient * Front_Area * Velocity^2/2
Rolling_resistance = Rolling_Coefficient * Total_Vehicle_Mass * 9.81
Vel_EUR_Desired_Velocity_Velocity
Mass = body.body_weight + fuel_tank.Initial_Fuel_ic_engine.Fuel_consumption * 3.018

AND
Acceleration = (Velocity)/dt
Forward_forces = Mass * Acceleration
Miles = integrator(Velocity, t) / 1609.3
fuel_consumption_MPG = Mile / ic_engine.Fuel_consumption

AND
Material_flow_connected(t, fuel_flow_rate, ic_engine.fuel_consume_rate)
Rotationally_Coupled(transmission.input, ic_engine.input)

IC_Engine:
Quantities:
Engine_Torque(t) : float (Nm)
Engine_RPM(t) : float
Throttle_angle(t) : float (°-1)
Fuel_consumption_rate(t) : float (gallon/s)
Fuel_consumption : float(t) (gallon)

Fuel_map(t) = Function1(IC_Engine, Engine_Torque(t), IC_Engine.Engine_RPM(t))
Torque_map(t) = Function2(IC_Engine, Engine_Torque(t), IC_Engine.Engine_RPM)

CONDITION:
true

CONSEQUENCE:
Fuel_consumption_rate(t) = Fuel_map(t) * Engine_Torque(t) * RPM * 0.0570 * 12
Engine_Torque(t) = Torque_map(t) * Throttle_angle(t)
Throttle_angle(t) = Function3(VelEUR(t), PID_algorithm)

AND
Fuel_consumption(t) = integrator(Fuel_consumption_rate(t))

Transmission:

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Quantities:

er.err(t); float (m/s)
Current gear(t); int (1,2,3,4,5)
gear; float (g1,g2,g3,g4,g5)
Differential_gear_ratio; float
out1-5; float
Shift_point; float
(Sp1,Sp2,Sp3,Sp4)
Final_Gear_Ratio(t); float
Transmission_efficiency; float

CONDITION:

Vael ERR>=0 and Current_gear(t)>= 2.5 and Velocity < Sp3
CONSEQUENCE:
out1>=g1

CONDITION:

Vael ERR>=0 and Current_gear(t)>= 2.5 and Velocity < Sp4
CONSEQUENCE:
out3>=g4
out4>=g4

CONDITION:

Vael ERR>=0 and Current_gear(t)>= 2.5 and Velocity >= Sp4
CONSEQUENCE:
out2>=g5
out3>=g5

CONDITION:

Vael ERR>=0 and Current_gear(c) >= 3.5
CONSEQUENCE:
out1>=out2

CONDITION:

Vael ERR>=0 and Current_gear(t) < 3.5
CONSEQUENCE:
out1>=out2

CONDITION:

Vael ERR>=0 and Current_gear(t) < 3.5
CONSEQUENCE:
out1>=out3

CONDITION:

Vael ERR>=0 and Current_gear(t) >= 4.5
CONSEQUENCE:
Final_Gear_Ratio(t)=Sp5

CONDITION:

Vael ERR>=0 and Current_gear(t) < 4.5
CONSEQUENCE:
Final_Gear_Ratio(t)=out1

CONDITION:

Vael ERR>=0 and Velocity < Sp2
CONSEQUENCE:
out5=g1

CONDITION:

Vael ERR>=0 and Velocity < Sp2
CONSEQUENCE:
out1=g2
out4=g2

CONDITION:

Vael ERR>=0 and Velocity >= Sp3
CONSEQUENCE:
out4=g3

CONDITION:

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Vel.ERR=0 and Current.gear(t) > 1.5
CONSEQUENCE: Final.Gear_Ratio(t)=out4
CONDITION: Vel.ERR=0 and Current.gear(t) <= 1.5
CONSEQUENCE: Final_Gear_Ratio(t)=out5

CONDITION:
Vel.ERR=0 and Current.gear(t)> 3.5 and Velocity<=Dep3
CONSEQUENCE: out3=g3
CONDITION:
Vel.ERR<0 and Current.gear(t)> 3.5 and Dep3>Velocity<=Dep4
CONSEQUENCE: out3=g4
out2=g4
CONDITION:
Vel.ERR<0 and Current.gear(t)> 3.5 and Velocity>=Dep4
CONSEQUENCE: out2=g5
CONDITION:
Vel.ERR<0 and Current.gear(t)> 4.5
CONSEQUENCE: Final_Gear_Ratio(t)=out2
CONDITION:
Vel.ERR<0 and Current.gear(t)< 4.5
CONSEQUENCE: Final_Gear_Ratio(t)=out5
CONDITION:
Vel.ERR<0 and Current.gear(t)< 1.5
CONSEQUENCE: Final_Gear_Ratio(t)=g1
CONDITION:
Vel.ERR<0 and 1.5<Current.gear(t)< 3.5 and Velocity<Dep4
CONSEQUENCE: out3=g1
CONDITION:
Vel.ERR<0 and 1.5<Current.gear(t)< 3.5 and Dep4<Velocity<Dep5
CONSEQUENCE: out5=g2
out4=g2
CONDITION:
Vel.ERR<0 and 1.5<Current.gear(t)< 3.5 and Velocity>=Dep5
CONSEQUENCE: out5=g3
CONDITION:
Vel.ERR<0 and 2.5<Current.gear(t)< 3.5
CONSEQUENCE: Final_Gear_Ratio(t)=out4
CONDITION:
Vel.ERR<0 and 1.5<Current.gear(t)< 2.5
CONSEQUENCE: Final_Gear_Ratio(t)=out5

RELATION Rotationally_coupled(input, output)
\{ 
input\_torque = output\_torque AND 
input\_RPM = output\_RPM; 
\}