EFFICIENCY ANALYSIS OF OPTIMIZED HEV AGAINST CONVENTIONAL VEHICLES, IN A SRI LANKAN DRIVE CYCLE

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Degree of Master of Science

By

I. W. D. R. S. KARUNARATNE

Supervised by Dr. Lanka Udawatta

Department of Electrical Engineering
University of Moratuwa

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DECLARATION

The work submitted in this dissertation is the result of my own investigation, except where otherwise stated.

It has not already been accepted for any degree, and is also not being concurrently submitted for any other degree.

UOM Verified Signature

I. W. D. R. S. Karunaratne

Date: 30/01/2009

We/I endorse the declaration by the candidate.

UOM Verified Signature

Dr.Lanka Udawatta

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ABSTRACT

Due to the constant increase of fuel prices and environmental concerns, researchers were pushed to thinking more about fuel-efficiency and reduction of emission on vehicles. As a result there was great enthusiasm for researchers to look into and introduce hybrid technology to the field of automobiles. For example in hybrid electric power trains, an internal combustion engine (ICE) together with an electric motor (EM) is used as two energy sources. The use of an electrical motor in place of the internal combustion engine during different stages of driving resulted in a definite saving in fuel consumption.

In this study, a conventional vehicle and a HEV with varying traffic conditions & flow were compared in relation to fuel economy.

The main aspect was to compare & evaluate HEV and conventional vehicles in the Sri Lankan environment. With that in mind, developing a drive cycle in the Sri Lankan environment was essential. The Colombo drive cycle (CDC) was developed to fulfill that aspect using GPS protocol.

The HEV and conventional vehicles were simulated in following models using Colombo drive cycle.

- Parallel HEV
- Series HEV
- Conventional vehicle with CVT
- TOYOTA Prius

Simulation Models developed in MATLAB was used and to verify that QSS TB simulation model and ADVISOR simulation software was adapted.

Results showed that, with Colombo drive cycle, the two extremes come with maximum efficiency model and conventional vehicle. It proves that the optimized Parallel HEV with future data gives far better fuel economy in a real world drive cycle like CDC. Optimized HEV with prediction is so efficient in drive cycles which has so many sudden changes in acceleration, decelerating, cruse control and idle during the drive. Results were proven by comparison with simulating of above models and other available standard drive cycles. The optimized TOYOTA Prius performed far superior in the current HEV market. It's performance was excellent especially in vulnerable drive conditions.

DEDICATION

I dedicate this dissertation to my loving parents.

ACKNOWLEDGEMENT

Firstly, I wish to thank Dr. Lanka Udawatta for guiding me in this research and helping me to complete it within the given time frame. As the Research Supervisor, he directed me in finding all the necessary literature and to research the work to a high standard.

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I would be failing in my duty if I do not convey my sincere thanks to my two colleagues Mr. Sudath Wimalendra and Mr. Chaminda Edirisinghe. These two batch mates encouraged me from the very beginning to successfully complete the work to the very end.

My heartfelt thanks go to my Parents, Brother and Sister and my wife for their love, understanding and encouragement throughout this study.

Last but not least, I wish to thank all those numerous persons who are too many to mention and in their small way gave me great support to complete this thesis.

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CHAPTER 01

Introduction

A hybrid vehicle is an automobile that has two or more major sources of propulsion power. Most hybrid cars currently marketed to consumers have both conventional gasoline and electric motors, with the ability to power the vehicle by either one independently or in tandem. Those are called as Hybrid Electric vehicles (HEV) Other power sources may include hydrogen, propane, CNG, and solar energy. The technology used depends on the utilization of the vehicle, whether it should be fuel efficient, powerful, driving range, or reduced greenhouse gas emissions. The HEVs currently available in the market till today are usually developed for reduced emissions and driving range. Corporate and government fleets that have been in service for twenty years or more are usually tuned for fuel efficiency, often at the cost of driving range, power, and hydrocarbon emissions.

Newly produced hybrid electric vehicles prolong the charge on their batteries by capturing kinetic energy via regenerative braking, and some HEVs can use the internal combustion engine (ICE) to generate electricity by spinning motor-generator to either recharge the battery or directly feed power to an electric motor that drives the vehicle. Many HEVs reduce idle emissions by shutting down the ICE at idle and restarting it when needed (start-stop system). An HEV's engine is smaller than a non-hybrid petroleum fuel vehicle and may be run at various speeds, providing more efficiency.

HEVs became widely available to the public in the late 1990s with the introduction of the Honda Insight and Toyota Prius. HEVs are viewed by some automakers as a core segment of the future automotive market.[Automotive hybrid technology became successful in the 1990s when the Honda Insight and Toyota Prius became available. These vehicles have a direct linkage from the ICE to the driven wheels, so the engine can provide acceleration power.

The Prius has been in high demand since 2004. Newer designs have more conventional appearance and are less expensive, often appearing and performing identically to their non-hybrid counterparts while delivering 40% better fuel efficiency. The Honda Civic Hybrid appears identical to the non-hybrid version, for instance, but delivers about 50 miles per US gallon. The redesigned 2004 Toyota Prius improved passenger room, cargo area, and power output, while increasing energy efficiency and reducing emissions. The Honda Insight, while not matching the demand of the Prius, stopped being produced after 2006 and has a devoted base of owners. According to many marketing researches the prediction for sales of hybrids is increasing yearly.

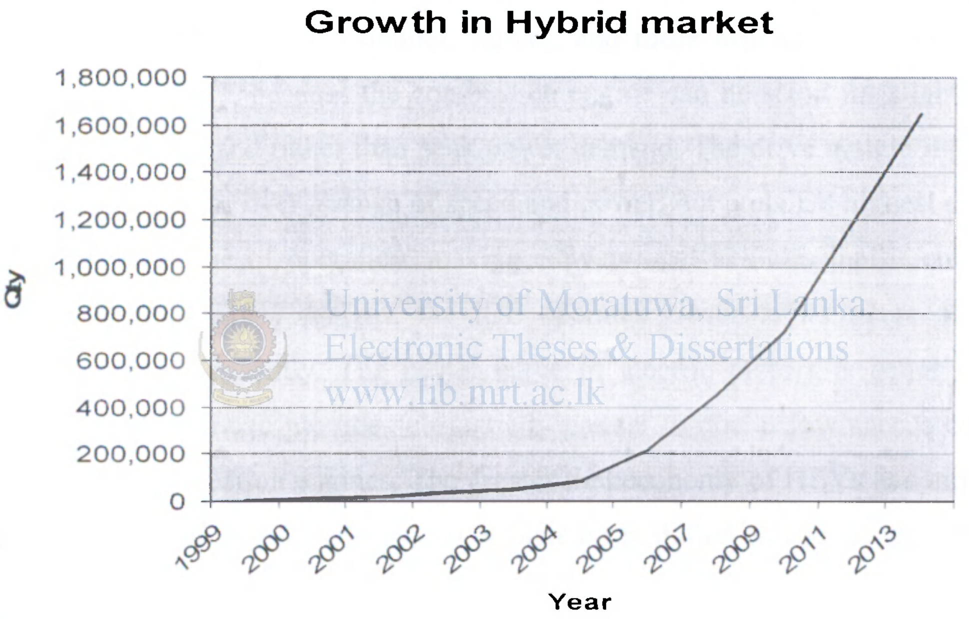


Figure 1.1 Hybrid car sales

The black line shows hybrid sales continuing at their current pace since hybrids were introduced in year 2000.

1.1 Hybrid Electric Vehicles

1.1.1 Fuel consumption

Hybrid vehicles are the best bet to get the most out of each tank of fuel during city driving Current HEVs reduce petroleum consumption under certain circumstances, compared to otherwise similar conventional vehicles, primarily by using three mechanisms

1. Reducing wasted energy during idle/low output, generally by turning the ICE off
2. Recapturing waste energy (i.e. regenerative braking)
3. Reducing the size and power of the ICE, and hence inefficiencies from under-utilization, by using the added power from the electric motor to compensate for the loss in peak power output from the smaller ICE.

Any combination of these three primary hybrid advantages may be used in different vehicles to realize different fuel usage, power, emissions, weight and cost profiles. The ICE in an HEV can be smaller, lighter, and more efficient than the one in a conventional vehicle, because the combustion engine can be sized for slightly above average power demand rather than peak power demand. The drive system in a vehicle is required to operate over a range of speed and power, but an ICE's highest efficiency is in a narrow range of operation, making conventional vehicles inefficient. On the contrary, in most HEV designs, the ICE operates closer to its range of highest efficiency more frequently. The power curve of electric motors is better suited to variable speeds and can provide substantially greater torque at low speeds compared with internal-combustion engines. The greater fuel economy of HEVs has implication for reduced petroleum consumption and vehicle air pollution emissions worldwide.

1.1.2 Noise

Reduced noise emissions resulting from substantial use of the electric motor at idling and low speeds, leading to roadway noise reduction,[in comparison to conventional gasoline or diesel powered engine vehicles, resulting in beneficial noise health effects (although road noise from tires and wind, the loudest noises at highway speeds from the interior of most vehicles, are not affected by the hybrid design alone).

Reduced noise may not be considered an advantage by some; for example, some people who are blind or visually-impaired consider the noise of combustion engines a helpful aid while crossing streets and feel quiet hybrids could pose an unexpected hazard.

1.1.3 Pollution

Reduced air pollution emissions, due to lower fuel consumption, lead improved human health with regard to respiratory problems and other illnesses.

Better fuel efficiency means less use of fossil fuels and the energy and pollution associated with refining them, while lower emissions mean less air pollution from exhaust. However, better fuel efficiency does not necessarily go hand-in-hand with lower emissions.

Pollution reduction in urban environments may be particularly significant due to elimination of idle-at-rest Battery toxicity is a concern, although today's hybrids use NiMH batteries, not the environmentally problematic rechargeable nickel cadmium. "Nickel metal hydride batteries are benign. They can be fully recycled," says Ron Cogan, editor of the Green Car Journal. Toyota and Honda say that they will recycle dead batteries and that disposal will pose no toxic hazards. Toyota puts a phone number on each battery, and they pay a $200 "bounty" for each battery to help ensure that it will be properly recycled.

This is considered as a major advancement that came with HEVs and it used as a marketing tool effectively.

1.2 Literature review

HEV is a revolutionary concept to the modern world and carries great potential for the future. Therefore it has been able to stimulate the world of engineers' researchers and inventors. It is inevitable to stop them going after this revolution.

HEV concept impacts and the benefits of HEVs are discussed and compared with those of conventional vehicles in[2] Current status, design and selection of HEV components are presented in [2] [3] [4]

Due to the complex nature of hybrid electric vehicles, control strategies are of high interest. Extensive studies have been conducted over the past two decades. In particular, several logic-based control strategies and fuzzy logic-based energy management strategies for distributing power demand have been suggested [1] [12]

Recent changes in the technology of modern vehicles and revolutionary development in telematics industry have created the possibility for a vehicle to gather online information about the road infrastructure and the traffic environment in which it is in operation. This information can be used by the HEV power management system to predict its future speed trend in order to decide optimum power split between the two sources more effectively. Several algorithms have been proposed to predict the future speed trends, with the use of preview information provided by the telematics. A methodology of combining two technologies, hybrid and telematics together to create "intelligent vehicle" which provides improved fuel economy with traffic preview is discussed in[15]

Most of these concepts are in a developing stage and there is room for more developments. Therefore vehicle simulation is playing a major role in this scenario. For vehicle simulation and modeling drive cycles are a very important aspect. All models are tested and certified by simulating in drive cycle. Study of drive cycles and learning about developing drive cycles is a very important aspect as well in vehicle modeling and simulation [15]

1.3 Objective

The main objective of this study is to develop a drive cycle on Sri Lankan road- ways which have frequent variable road conditions. This will be referred to as Colombo Drive Cycle (CDC).

When developing or evaluating vehicle performance, most developers use existing drive cycles in US, Europe or Japan. Therefore we cannot expect the same performance when driving those vehicles in Sri Lankan context. This developed drive cycle gives the opportunity to researchers to simulate their vehicles in such conditions.

Secondary objective is to simulate following models with above mentioned developed drive cycle.

- Parallel HEV with maximum efficiency can be achieved
- Optimized PHEV with future predictions
- Series HEV
- Conventional vehicle with CVT
- Conventional vehicle

The efficiency of above vehicle models will be analyzed in terms of fuel economy. All simulations were done in MATLAB / Simulink software , QSS toolbar and ADVISOR software also used in developing the models.
Thereafter these models were compared between NEDC, Japan 10-15, US 06 drive cycles and CDC for analysis and efficiency was analyzed on the basis of fuel economy.

Behavior of those models in CDC is analyzed and compared at the end.

CHAPTER 2

HEV Classifications

There are many ways to classify HEVs. One of the most common ways to classify HEV is based on configuration of the vehicle drive train. Based on this, three major hybrid vehicle architectures introduced are parallel, series and series-parallel.

2.1 Parallel HEVs

In parallel configurations, both the engine and the motor provide traction power to the wheels, which means that the hybrid power is summed at a mechanical node to power the vehicle. As a result, both of the engine and the motors can be downsized, making the parallel architecture more viable with lower costs and higher efficiency [11],[12].

The parallel HEVs usually use the same gearboxes of the counterpart conventional vehicles, either in automatic or manual transmissions. Based on where the gearbox is introduced in the powertrain, there are two typical parallel HEV architectures, named pre-transmission parallel and post-transmission parallel, as shown in Figure 2. 1 and Figure 2. 2, respectively.

In a pre-transmission parallel HEV, the gearbox is located on the main drive shaft after the torque coupler. Hence, gear speed ratios apply on both the engine and the electric motor. The power flow is summed at the gearbox.

On the other hand, in a post-transmission parallel hybrid, the gearbox is located on the engine shaft prior to the torque coupler. The gearbox speed ratios only apply on the engine.

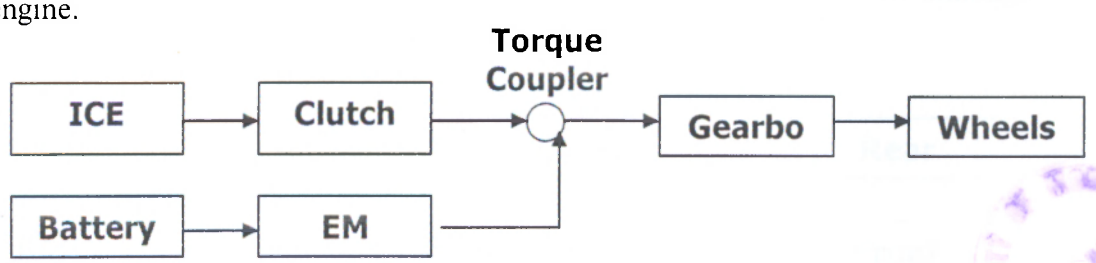


Figure 2.1: Block Diagram of Pre – Transmission Parallel HEV

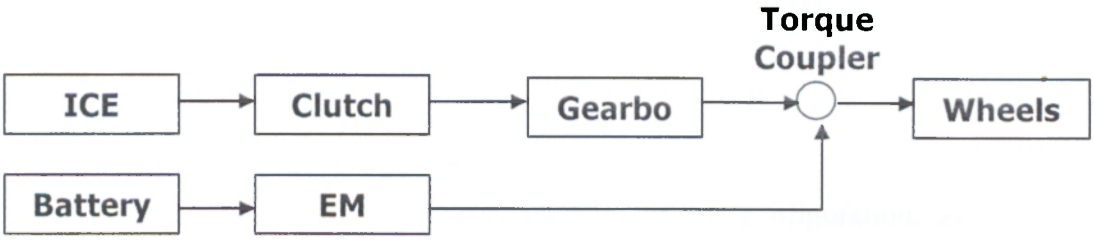


Figure 2. 2 : Block Diagram of Post – Transmission Parallel HEV

In a pre-transmission configuration, torque from the motor is added to the torque from the engine at the input shaft of the gearbox. In a post-transmission, the torque from the motor is added to the torque from the engine delivered on the output shaft of the gearbox. A disconnect device such as a clutch is used to disengage the gearbox while running the motor independently.

There are attempts from different perspectives to improve the operation of a parallel HEV. One possibility is to run the vehicle on electric machine alone in city driving while running engine power alone on highways. Most contemporary parallel vehicles use a complex control system and special algorithms to optimize both vehicle performance and range.

One unique implementation of the parallel hybrid technology is on an all wheel drive vehicle as shown in Figure 2. 3. The design is most beneficial if the ICE powers the rear wheels while the electric motor powers the front wheels. The more weight borne by the front wheels during braking will result in more power captured during regenerative braking. The design is also effective on slippery surfaces by providing vehicle longitudinal stability control that is not as easy with other types of hybrid designs. The power to each axle is manipulated by a single controller, although this requires a fast data communication.

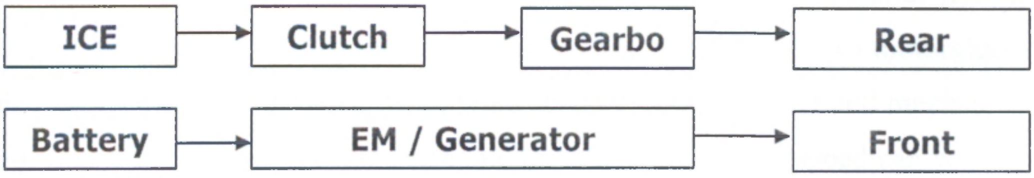


Figure 2. 3 : Block Diagram of all wheel drive Parallel HEV

The flexibility in power train design, in addition to the elimination of the need for a large motor, of parallel hybrids has attracted more interest in HEV development than the series hybrids.

2.2 Series HEVs

One of the basic types of HEV is series hybrid. In this configuration, as shown in Figure 2.4, the ICE is used to generate electricity in a generator. Electric power produced by the generator goes to either the motor or Battery. The hybrid power is summed at an electrical node, the motor.

Despite the early research and prototypes, the possibility for series hybrids to be commonly used in vehicular applications seems to be remote. The series hybrid configuration tends to have a high efficiency at its engine operation. However, the summed electrical mode has tied up the size of every component. The weight and cost of the vehicle is increased due to the large size of the engine and the two electric machines needed. The size of the power electronic unit is also excessive.

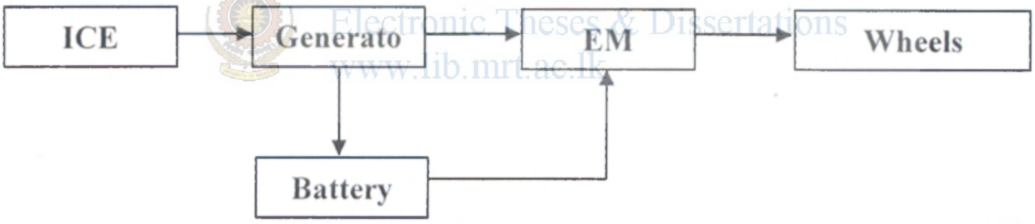


Figure 2.4 : Block Diagram Series HEV

2.3 Parallel - Series (Dual) HEVs

This system combines the series hybrid system with the parallel hybrid system in order to maximize the benefits of both systems [11],[12]. In the series-parallel configurations, the vehicle can operate as a series hybrid, a parallel hybrid, or a combination of both. This design depends on the presence of two motors/generators and the connections between them, which can be both electrical and mechanical. One advantage of a series-parallel configuration is that the engine speed can be decoupled from the vehicle speed. This advantage is partially offset by the additional losses in the conversion between mechanical power from engine and electrical energy.

CHAPTER 3

Drive cycle

A 'Drive cycle' can be expressed as a series of data gathered during a vehicle drive. The data is completed with Speed of that vehicle verses time.
Why a drive cycle? The answer to this question is this speed vs. time profile can be used to evaluate a vehicles behavior especially in the process of vehicle modeling and simulation for various aspects such as energy efficiency, fuel consumption, stability certification testing.

3.1 Drive cycle Classification

There are many developed drive cycles to utilize in above purposes. Basically we can categorize drive cycles in to two main categories.

- Transient Drive cycle
- Model drive cycles

Transient drive cycles

Test drive cycles are derived by collecting actual data in the real world. Those are very realistic and taken using a real vehicle in actual conditions and data recorded in a live environment with actual disturbances. Those drive cycles are considered as very effective when using for simulation of certification activities. Most of the US based drive cycles are transient drive cycles.

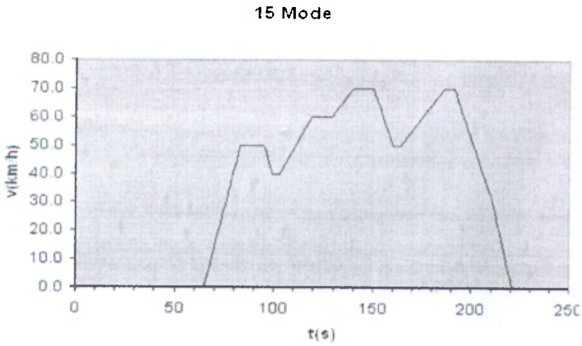
Model drive cycles

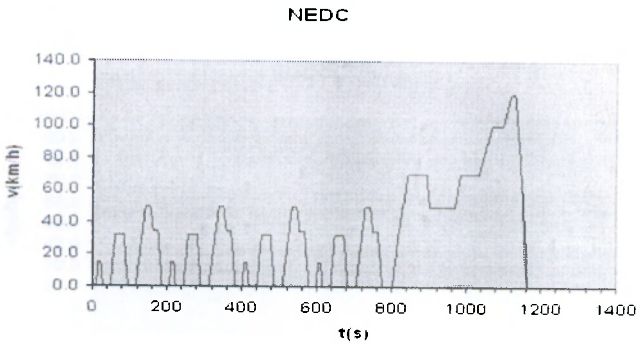
Model drive cycles are the cycles which derived by mathematical modeling with the help of statistics. In those drive cycles they have included some conditions where it is difficult to achieve in real world such as maximum speed and operate in a constant speed over time duration. Most of the European standard drive cycles and Japanese drive cycles are belongs to this category

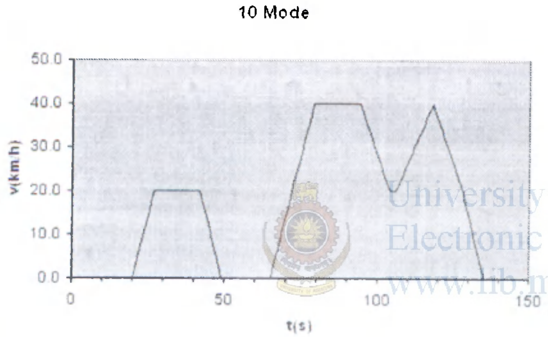
3.2 Available standard drive cycles

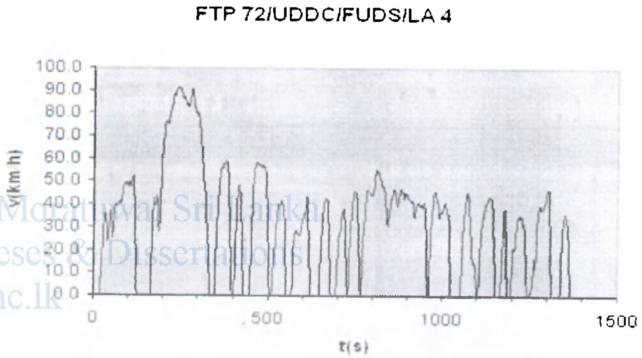
Model drive cycles

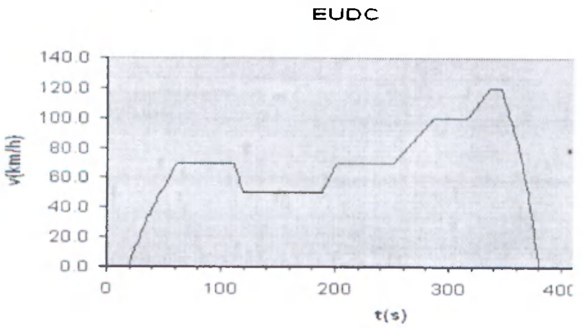
NEDC	JAPAN 10MODE
FUDS	JAPAN 15 MODE
ECE 15	JAPAN 10-15 MOD
EUDC	

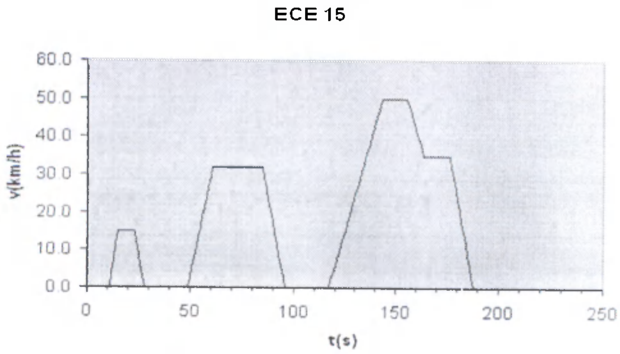












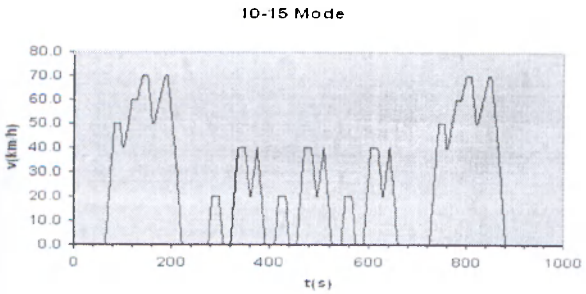


Figure 3. 1 Standard Model drive cycles

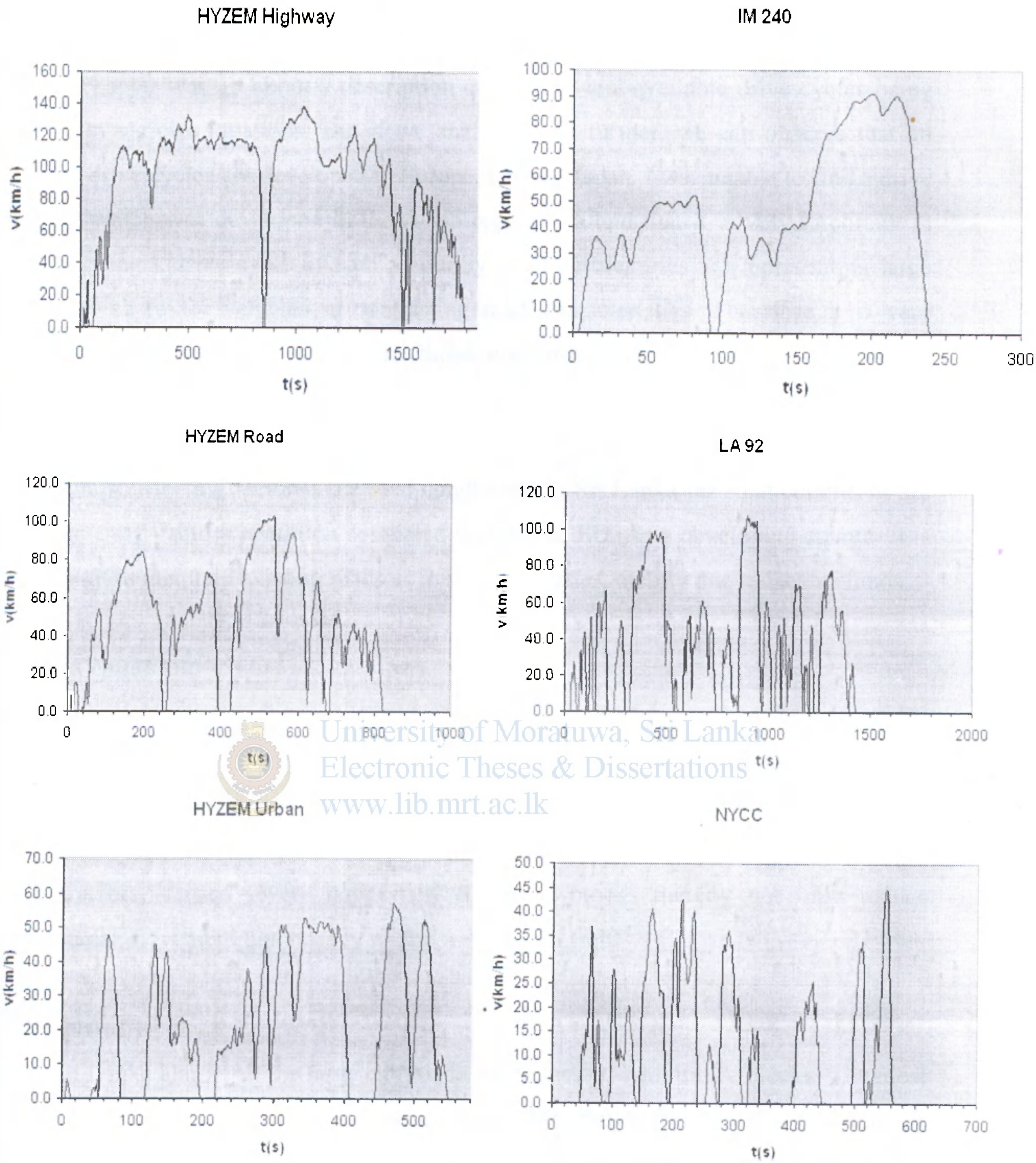


Figure 3.2 Standard Transient Drive cycles

3.3 Colombo Drive Cycle

Last chapter was all about a description of existing and available drive cycles being used in various situations. But if we analyze them further, we can observe that all those drive cycles are developed in Europe, US and Japan. I was unable to find a drive cycle which was developed in the Asian region. I found that it is very important in developing a drive cycle in such a country as those countries are representing large market share for vehicles in contrasting road characteristics. Therefore it is very important to simulate vehicles in those conditions also, to analyze the vehicle behavior.

The most affecting factor is the road conditions. In Sri Lanka the road conditions are not in a satisfactory condition compared with US or EU. As a developing country it is difficult to maintain existing roads as in those countries, mainly due to lack of funds.

Road condition:

As a tropical country the monsoon rainfall is high in Sri Lanka. Poor drainage vis-à-vis flooding of roads is the main reason road surfaces are being damaged frequently. Sub standard construction and poor quality material used and half completion are the main reasons for damage to roads. A badly constructed road, mainly by local contractors, causes severe congestion & traffic blocks thereby not only reduce vehicular movement but a heavy toll on the vehicle itself.

High traffic:

In Sri Lanka almost all the large city roads are congested with traffic blocks! The most critical times are early morning and evenings. Morning hours between 6.30 a.m. & 9.00 a.m. are much worse especially because of people traveling to schools and/or offices. The same occurs in the afternoon at 1.30. – 3.00 p.m. when Schools close and at 5.00 p.m. and 7.30 p.m. when most offices close.

High vehicle density:

In urban areas too the numbers of vehicles traveling along the roads are very high. All modes of transport such as Busses, Motor cycles, Trishaws, Lorries, Vans use the same roads, and there is no discipline on the roads like in other countries where there are strict lanes for use by each category of vehicle.

Indiscipline driving behaviors:

Unfortunately in Sri Lanka there is a total lack of discipline by all motorists and pedestrians alike! We observe various degrees of reckless driving by especially Buss & Trishaw drivers. Most of them are very undisciplined and aggressive! However on the good side is that motorists are very careful nowadays with the introduction of the breathalyzer by the Police to stop drunken drivers of all categories.

Speed limits:

Normally within the urban areas the speed limit is 50 km/h. and on certain roads out station it is on average. 60 -70km/h. Speed limit within most Cities are restricted to 40km/h.

Many unexpected obstacles:

There are many unexpected obstacles when driving on roads in Sri Lanka. People jay walking on the roads and the crossing the road at non pedestrian crossing locations, Road constructions works are frequent with no proper warning to motorists. Cattle, dogs, goats and others animals crossing the roads due to unprotected road boundaries. Buss drivers not adhering to stopping at regulated bus stops, causing traffic blocks. Narrowness of roads in the country which have not been widened and un graded for several decades.

3.4 Developing Methodology

When developing the drive cycle following are considered as the main aspects.

- Route
- Data collection.

3.4.1 Route

When developing Colombo drive cycle I selected two routes. First one is Maharagama to Kirulapona and second one is Kirulapona to Dematagoda(Base line). Those two routes are very different from each other.

First one is going through a road which is condition is not good. Also there are so many traffic situations and so many unexpected stoppages. Most of places only one track can be used to one direction. Figure 3.3

Comparatively second Route is one of the best roads we can find in Colombo. Road condition is good. Tarred well and carpet finish with colas. Comparatively to route 1 less traffic, except in traffic lights. Also two tracks are available from beginning to end for one direction. Figure 3.4

Table 3. 1 Colombo Drive Cycle Details

	Route 1		Route 2	
Terminating points	Maharagama- Kirulapona		Kirulopona to Dematagoda	
	Up ***CDC 1U***	Down ***CDC 1D***	Up ***CDC 2U***	Down***CDC 2D***
Distance	5900m	5150m	6500m	6480m
Time Duration	903 s	845 s	783 s	836 s
No of traffic lights	3	3	9	9

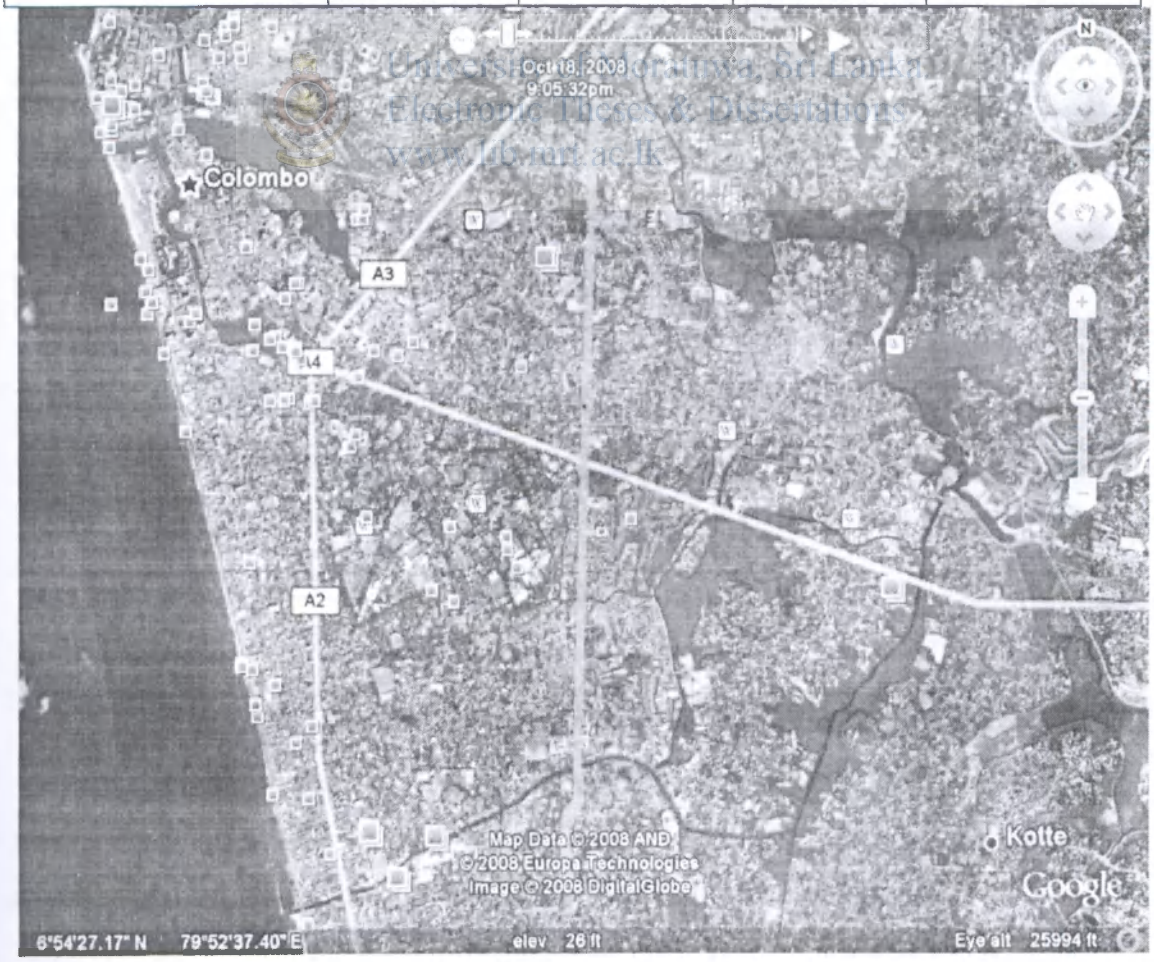


Figure 3.3 CDC Route 2

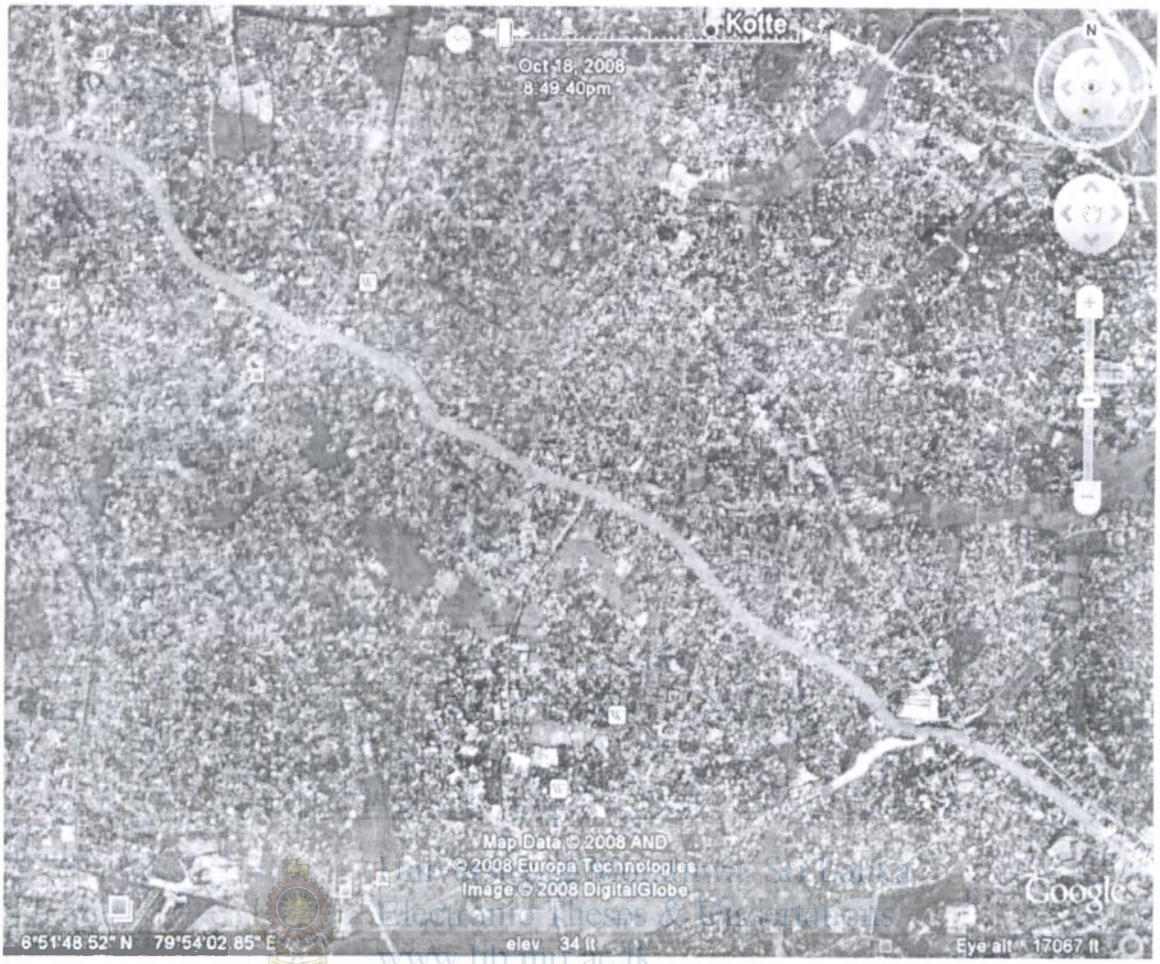


Figure 3.4 CDC Route 1

3.4.2 Data Collection

The Global Positioning System (GPS) protocol was the preferred method to use in data collection. A GPS unit was fixed to the roof of the vehicle and the laptop computer was connected to the unit.

Sample time : 2 Sec

Antenna : External antenna connected to roof top of the vehicle.

During the road rips all data was collected to the computer for analysis. The hardware interface for GPS units is designed to meet the NMEA requirements. This is compatible with serial ports using RS232 protocols.

3.4.3 GPS Performance

GARMIN GPS 76 was the GPS receiver used for data collection. Following are the specification of the unit.

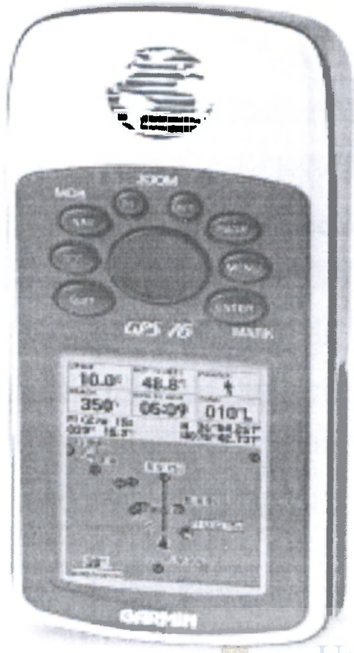


Figure 3.5 GPS Receiver Used

Receiver: WAAS enabled, 12 parallel channel GPS receiver continuously tracks and uses up to 12 satellites to compute and update your position

Acquisition times:

Warm: Approximately 15 seconds
Cold: Approximately 45 seconds
AutoLocate™: Approximately 5 minutes

Update rate: 1/second, continuous

GPS accuracy:

Position: < 15 meters, 95% typical*
Velocity: 0.05 meter/sec steady state

DGPS (USCG) accuracy:

Position: 3-5 meters, 95% typical
Velocity: 0.05 meter/sec steady state

DGPS (WAAS) accuracy:

Position: < 3 meters, 95% typical
Velocity: 0.05 meter/sec steady state

Dynamics: 6 g's

Interfaces: RS232 with NMEA 0183, RTCM 104 DGPS data format and proprietary GARMIN

Antenna: Built-in quadrifilar, with external antenna connection (MCX)

3.4.4 Data Collection Protocol

The National Marine Electronics Association (NMEA) has developed a specification that defines the interface between various pieces of marine electronic equipment. The standard permits marine electronics to send information to computers and to other marine equipment.

GPS receiver communication is defined within this specification. Most computer programs that provide real time position information understand and expect data to be in NMEA format. This data includes the complete PVT (position, velocity, time) solution computed by the GPS receiver. The idea of NMEA is to send a line of data called a sentence that is totally self contained and independent from other sentences. There are standard sentences for each device category and there is also the ability to define proprietary sentences for use by the individual company. All of the standard sentences have a two letter prefix that defines the device that uses that sentence type. (For gps receivers the prefix is GP.) which is followed by a three letter sequence that defines the sentence contents. In addition NMEA permits hardware manufactures to define their own proprietary sentences for whatever purpose they see fit. All proprietary sentences begin with the letter P and are followed with 3 letters that identifies the manufacturer controlling that sentence. For Garmin sentence is start with PGRM.

Each sentence begins with a '$' and ends with a carriage return/line feed sequence and can be no longer than 80 characters of visible text (plus the line terminators). The data is contained within this single line with data items separated by commas. The data itself is just ascii text and may extend over multiple sentences in certain specialized instances but is normally fully contained in one variable length sentence. The data may vary in the amount of precision contained in the message. For example time might be indicated to decimal parts of a second or location may be show with 3 or even 4 digits after the decimal point. Programs that read the data should only use the commas to determine the field boundaries and not depend on column positions. There is a provision for a checksum at the end of each sentence which may or may not be checked by the unit that reads the data. The checksum field consists of a '*' and two hex digits representing an 8 bit exclusive OR of all characters between, but not including, the '$' and '*'. A checksum is required on some sentences.

When considering the hardware connection the NMEA standard is not RS232. They recommend conformance to EIA-422. The NMEA standard for interface speed is 4800 b/s with 8 bits of data, no parity, and one stop bit. All units that support NMEA are supporting this speed. Note that, at a b/s rate of 4800, you can easily send enough data to more than fill a full second of time.

The NMEA standard has been around for many years (1983) and has undergone several revisions. The protocol has changed and the number and types of sentences may be different depending on the revision. Most GPS receivers understand the standard which is called: 0183 version 2

Generally the cable is unique to the hardware model and the cable made specifically for the brand and model of the unit.

3.5 Vehicle parameters

Vehicle specification which used for generating CDC

Suzuki Swift

Figure 3.6 Vehicle used for data collection

Table 3.2: Vehicle specifications

GENERAL	
Body type	Hatch
Drive	FF
Transmission	4 speed automatic
Displacement,	cc1328
Frame	LA-HT51S-CSEA-Z3

SPECIFICATION (SPECS)

EXTERIOR	
Exterior dimensions (LxWxH), mm	3615 x 1600 x 1540
Interior dimensions (LxWxH), mm	1695 x 1345 x 1250
Wheel base, mm	2360
Treads (F/R), mm	1405 / 1385
Ground clearance, mm	165
Curb vehicle weight, kg	910
Gross vehicle weight, kg	
Seating capacity, persons	5
Doors number	5
Min.turning radius, m	4.9
Fuel tank capacity, l	41

ENGINE	
Displacement,	cc1328
Engine	modelM13A
Max.power (Net), kw(PS)/rpm	88 ps (64.72 kw) / 6000 rpm
Max.torque(Net), N*m(kg*m)/rpm	12.0 kg*m (117.68 N*m) / 3400 rpm
Power density	10.34
Engine type	Water cooling serial 4 cylinder DOHC16 valve
Engine information	VVT (variable valve timing mechanism)
Fuel system	EPI (electrically controlled gasoline injection)
Turbocharger	No
Fuel type	Unleaded regular gasoline
LEV system (Low emission vehicle)	Yes
Compression ratio	9.5
Bore, mm	78
Stroke, mm	69.5
Fuel consumption at 10-15 modes, l/100km	5.7

CHASSIS / TRANSMISSION	
Power steering	Yes
Tires size, front	165/70R14 81s
Tires size rear	165/70R14 81s
Braking system, front	Ventilated disk
Braking system, rear	Drum (leading/trailing)
Suspension system, front	McPherson strut type coil spring
Suspension system, rear	IT.L. (isolated trailing link) type coil spring

3.6 Developed Drive Cycle

Route 1 Up

Figure 3.7 is to show the speed Vs time for the CDC 1U drive cycle. The maximum speed is 23.57 kmph. Here we can see the speed is always varying in big margins through out the time scale.

Figure 3.8 is to show the acceleration profile for the CDC 1U drive cycle. The maximum acceleration is 1.67m/s^{-2}. The maximum deceleration is -1.75 m/s^{-2}.

Fig 3.9 is the summery taken from the ADVISOR software after feeding all the relevant data collected during developing Colombo drive cycle. In this screen it provides all the relevant and valuable statistics of this drive cycle.

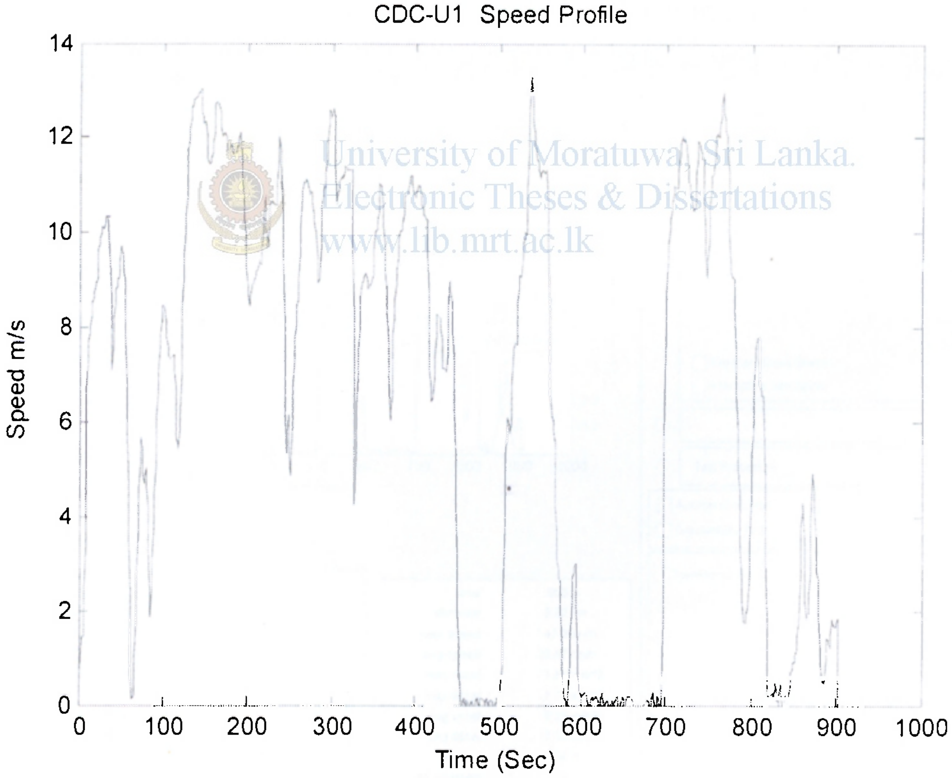


Figure 3.7 Route 1 Up drive Speed profile

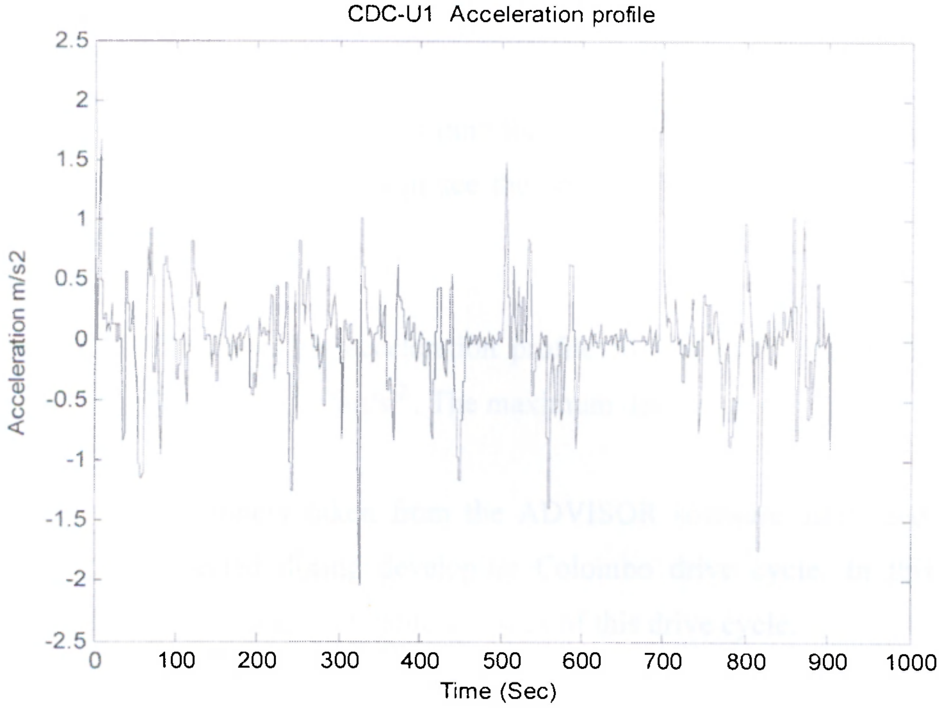
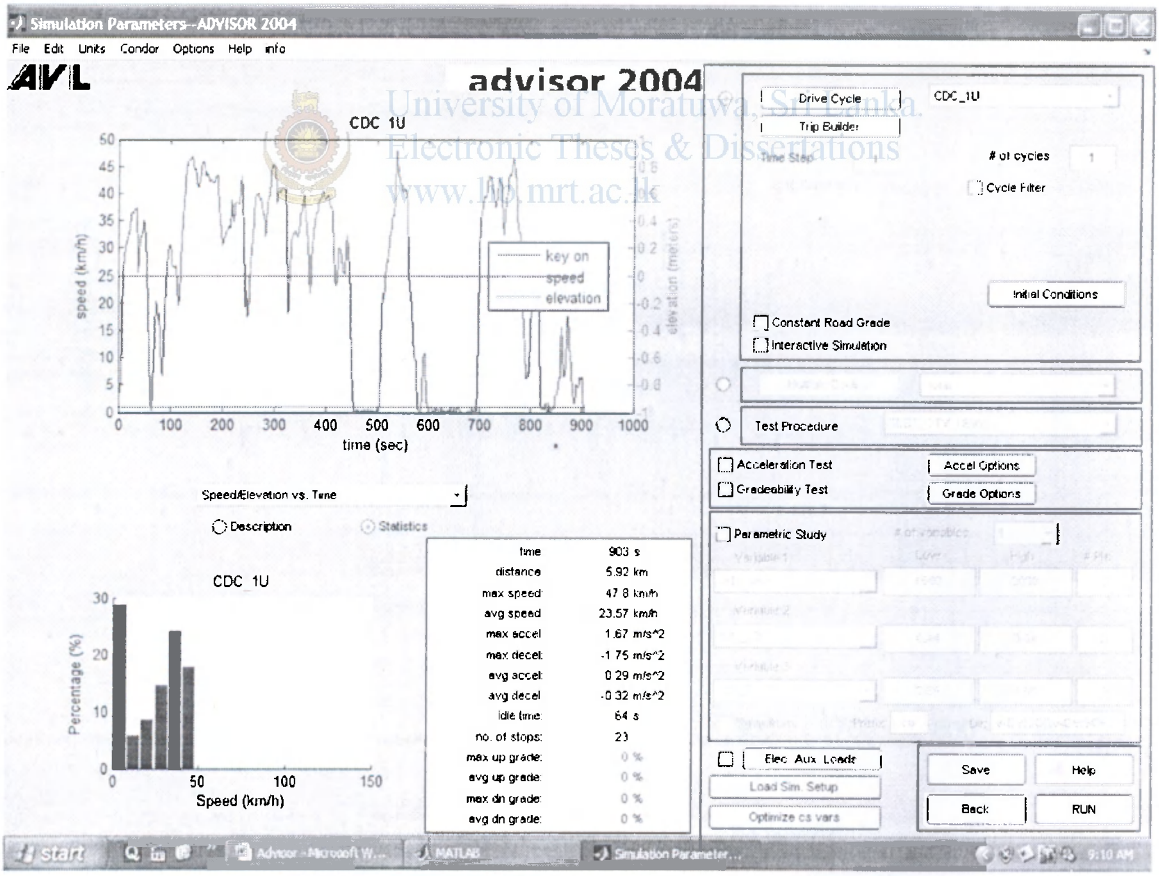


Figure 3.8 Route 1 Up drive Acceleration profile



Drive Cycle: CDC_1U

# of cycles: 1

time	903 s
distance	5.92 km
max speed:	47.8 km/h
avg speed	23.57 km/h
max accel	1.67 m/s^2
max decel:	-1.75 m/s^2
avg accel:	0.29 m/s^2
avg decel	-0.32 m/s^2
idle time:	64 s
no. of stops:	23
max up grade:	0 %
avg up grade:	0 %
max dn grade:	0 %
avg dn grade:	0 %

Figure 3.9 Route 1 Up drive Speed profile

Route 1 Down

Figure 3.10 is to show the speed Vs time for the CDC 1U drive cycle. The maximum speed is 21.91 kmph. Here we can see the speed is always varying in big margins through out the time scale.

Figure 3.11 is to show the acceleration profile for the CDC 1U drive cycle. The maximum acceleration is 1.75m/s^{-2} . The maximum deceleration is -2.03 m/s^{-2}.

Fig 3.12 is the summery taken from the ADVISOR software after feeding all the relevant data collected during developing Colombo drive cycle. In this screen it provides all the relevant and valuable statistics of this drive cycle.

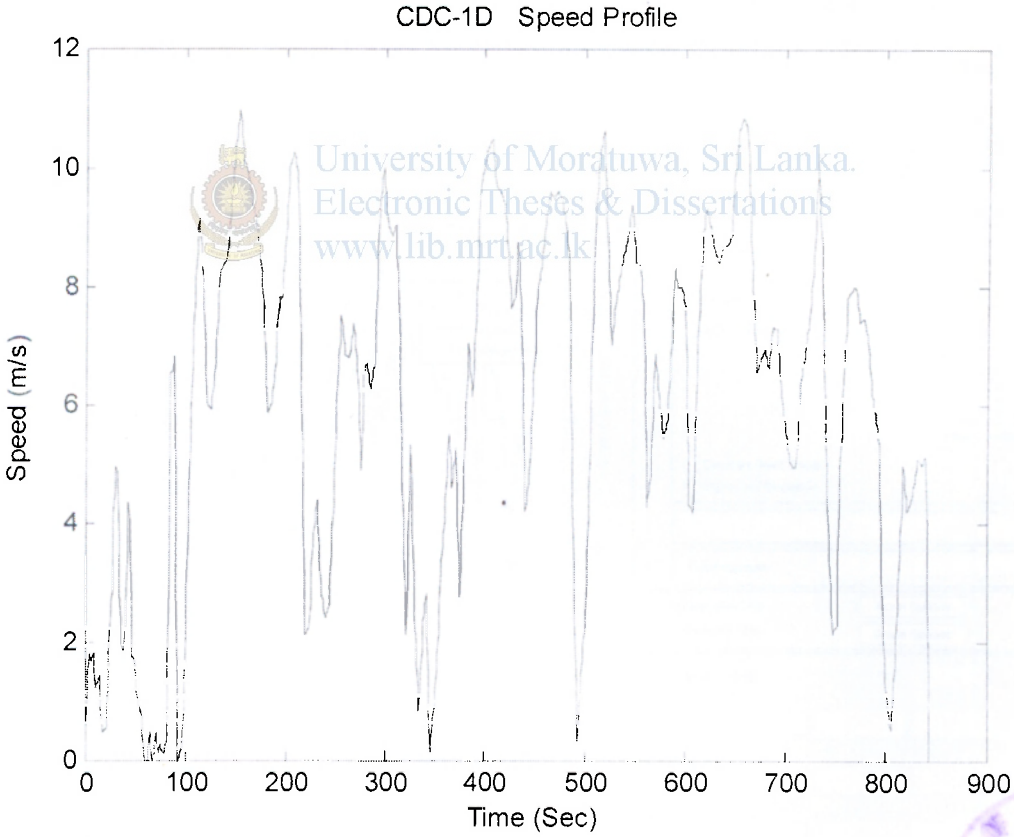


Figure 3.10 Route 1 Down drive Speed profile

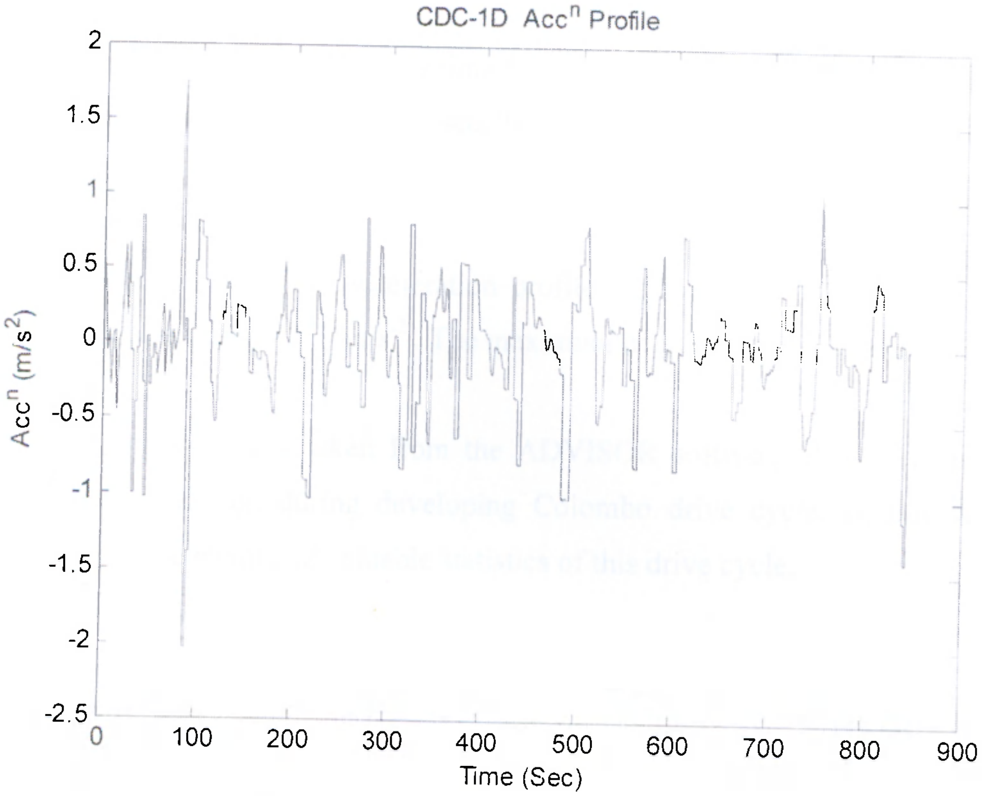
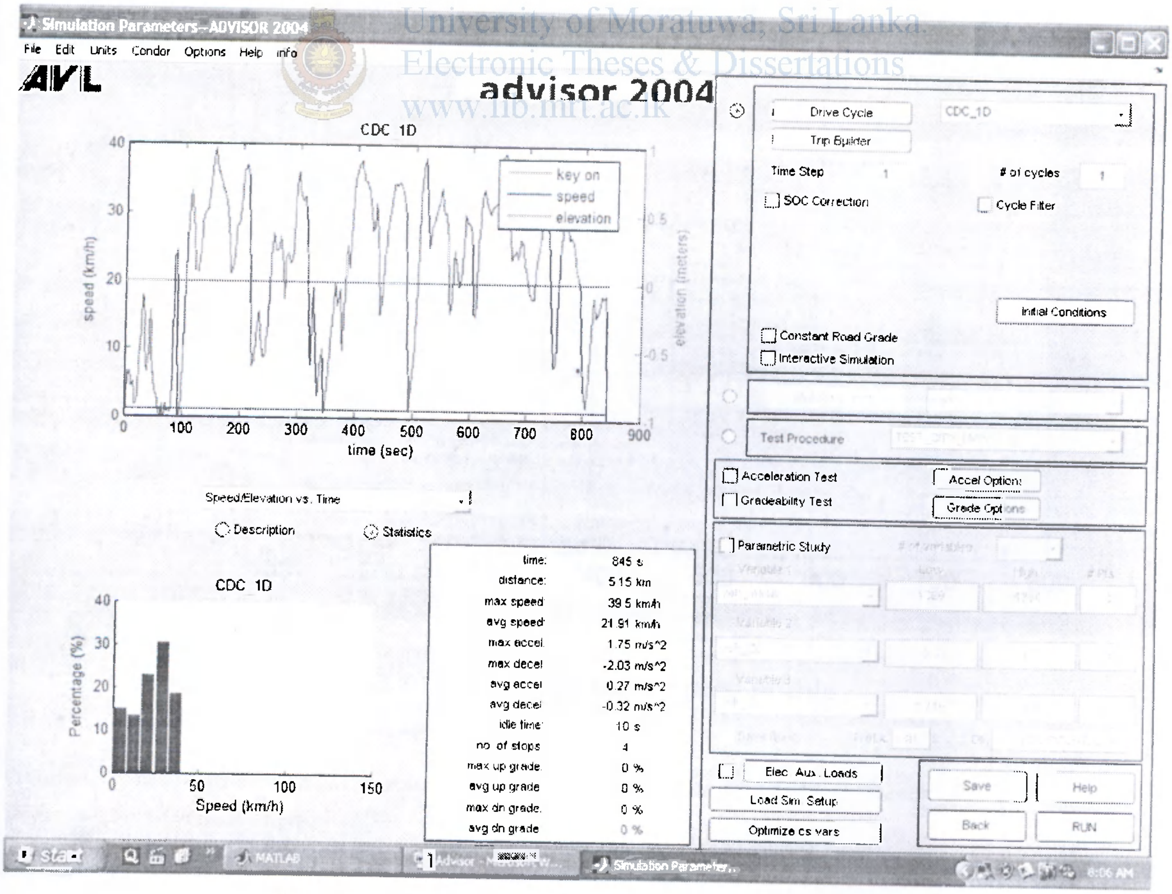


Figure 3.11 Route 1 Down drive Acceleration profile



● Drive Cycle: CDC_1D

Time Step: 1

# of cycles: 1

time: 845 s
distance: 5.15 km
max speed: 39.5 km/h
avg speed: 21.91 km/h
max accel: 1.75 m/s^2
max decel: -2.03 m/s^2
avg accel: 0.27 m/s^2
avg decel: -0.32 m/s^2
idle time: 10 s
no. of stops: 4
max up grade: 0 %
avg up grade: 0 %
max dn grade: 0 %
avg dn grade: 0 %

Figure 3.12 Route 1 Up drive Speed profile

Route 2 UP

Figure 3.13 is to show the speed Vs time for the CDC 1U drive cycle. The maximum speed is 29.85 kmph. Here we can see the speed is always varying in big margins through out the time scale.

Figure 3.14 is to show the acceleration profile for the CDC 1U drive cycle. The maximum acceleration is 1.75m/s^{-2}. The maximum deceleration is -2.04 m/s^{-2}.

Fig 3.15 is the summery taken from the ADVISOR software after feeding all the relevant data collected during developing Colombo drive cycle. In this screen it provides all the relevant and valuable statistics of this drive cycle.

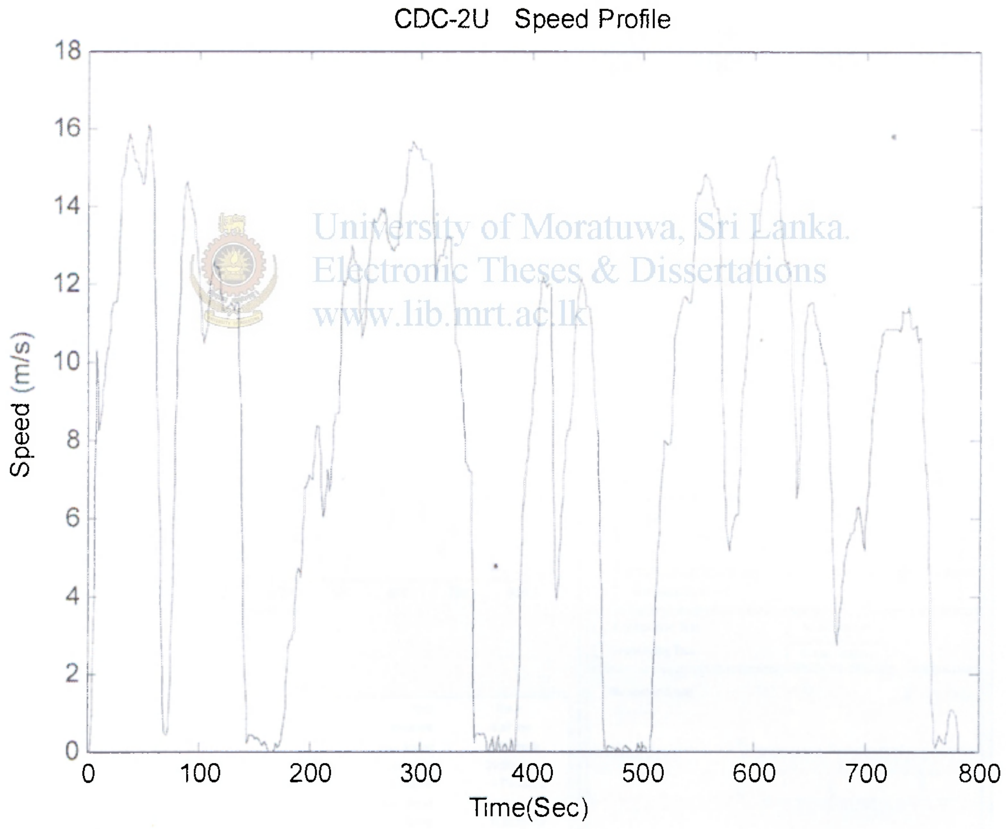


Figure 3.13 Route 2 Up drive Speed profile

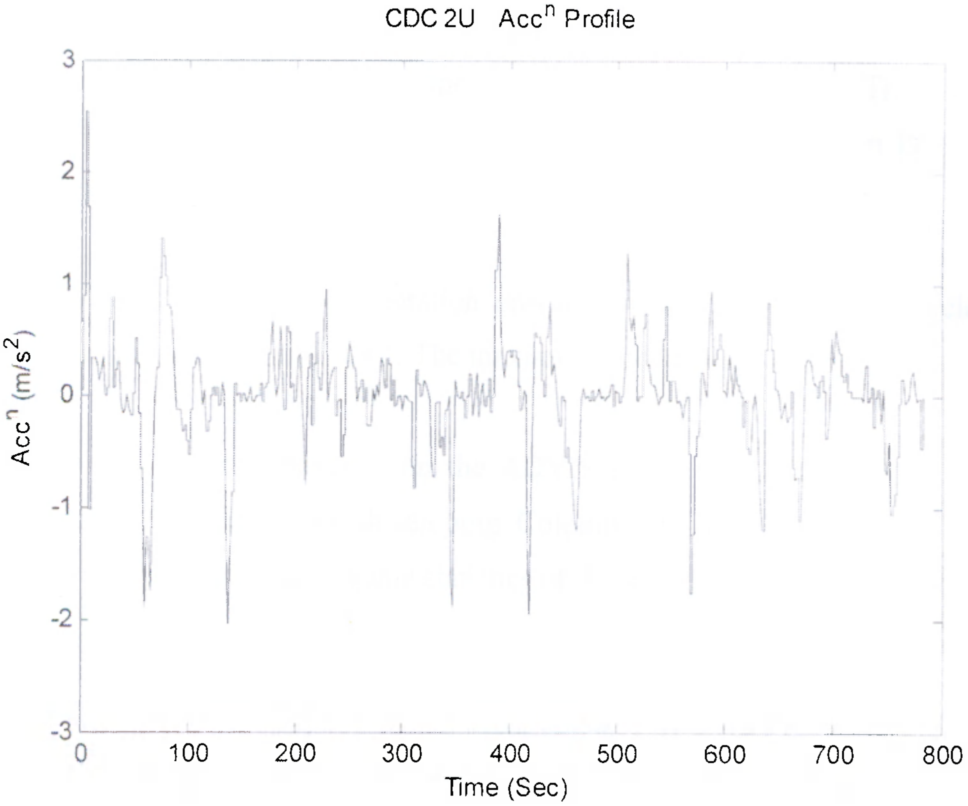
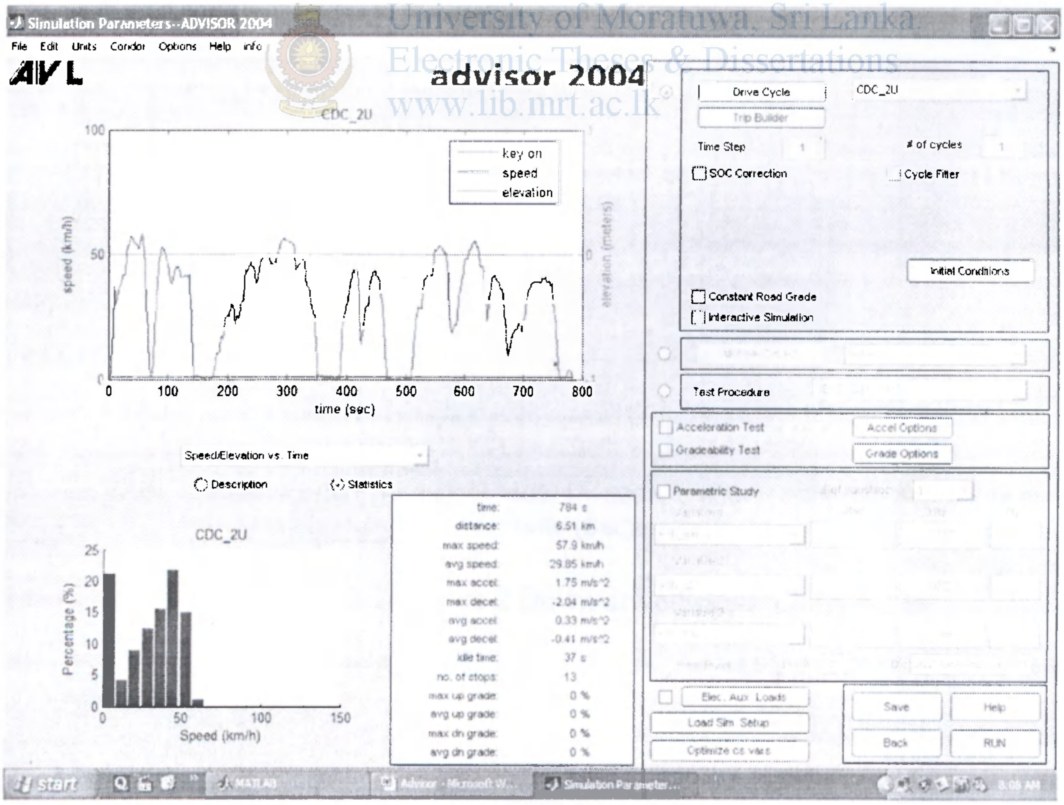


Figure 3.14 Route 2 Down drive Acceleration profile



Drive Cycle: CDC_2U

Time Step: 1

# of cycles: 1

☐ SOC Correction

☐ Cycle Filter

☐ Constant Road Grade

☐ Interactive Simulation

☐ Acceleration Test

☐ Gradeability Test

☐ Parametric Study

time: 784 s
distance: 6.51 km
max speed: 57.9 km/h
avg speed: 29.85 km/h
max accel: 1.75 m/s^2
max decel: -2.04 m/s^2
avg accel: 0.33 m/s^2
avg decel: -0.41 m/s^2
idle time: 37 s
no. of stops: 13
max up grade: 0 %
avg up grade: 0 %
max dn grade: 0 %
avg dn grade: 0 %

Figure 3.15 Route 1 Up drive Speed profile

Route 2 Down

Figure 3.6 is to show the speed Vs time for the CDC 1U drive cycle. The maximum speed is 27.73 kmph. Here we can see the speed is always varying in big margins through out the time scale.

Figure 3.17 is to show the acceleration profile for the CDC 1U drive cycle. The maximum acceleration is 1.67m/s^{-2}. The maximum deceleration is -2.36 m/s^{-2}.

Fig 3.18 is the summery taken from the ADVISOR software after feeding all the relevant data collected during developing Colombo drive cycle. In this screen it provides all the relevant and valuable statistics of this drive cycle.

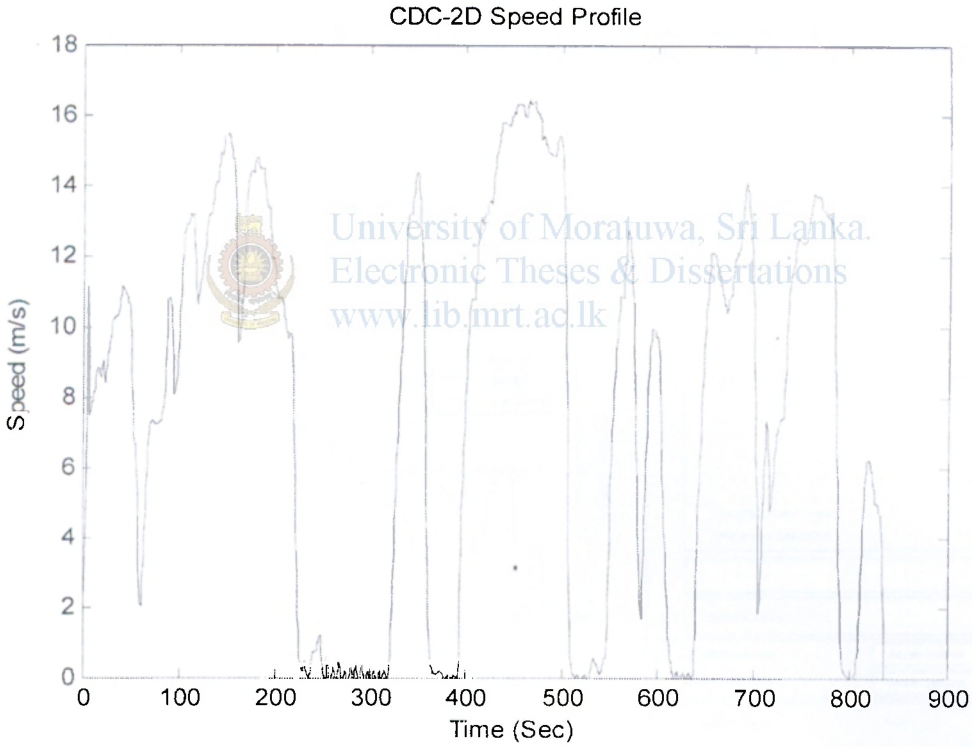


Figure 3.16 Route 2 Down drive Speed profile

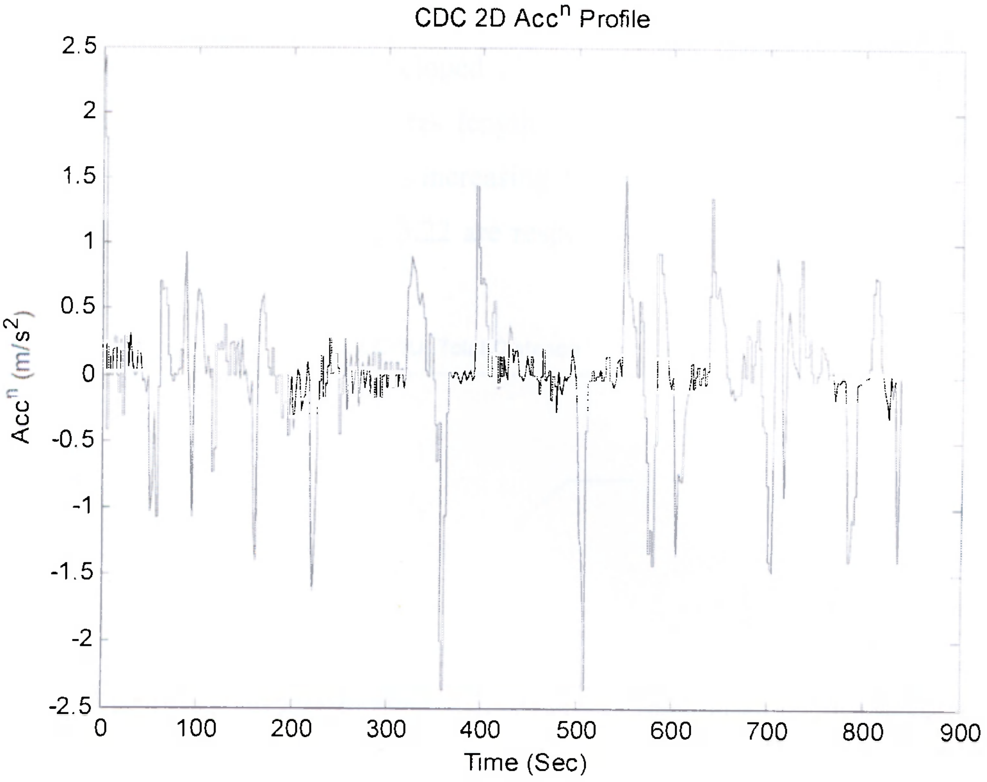
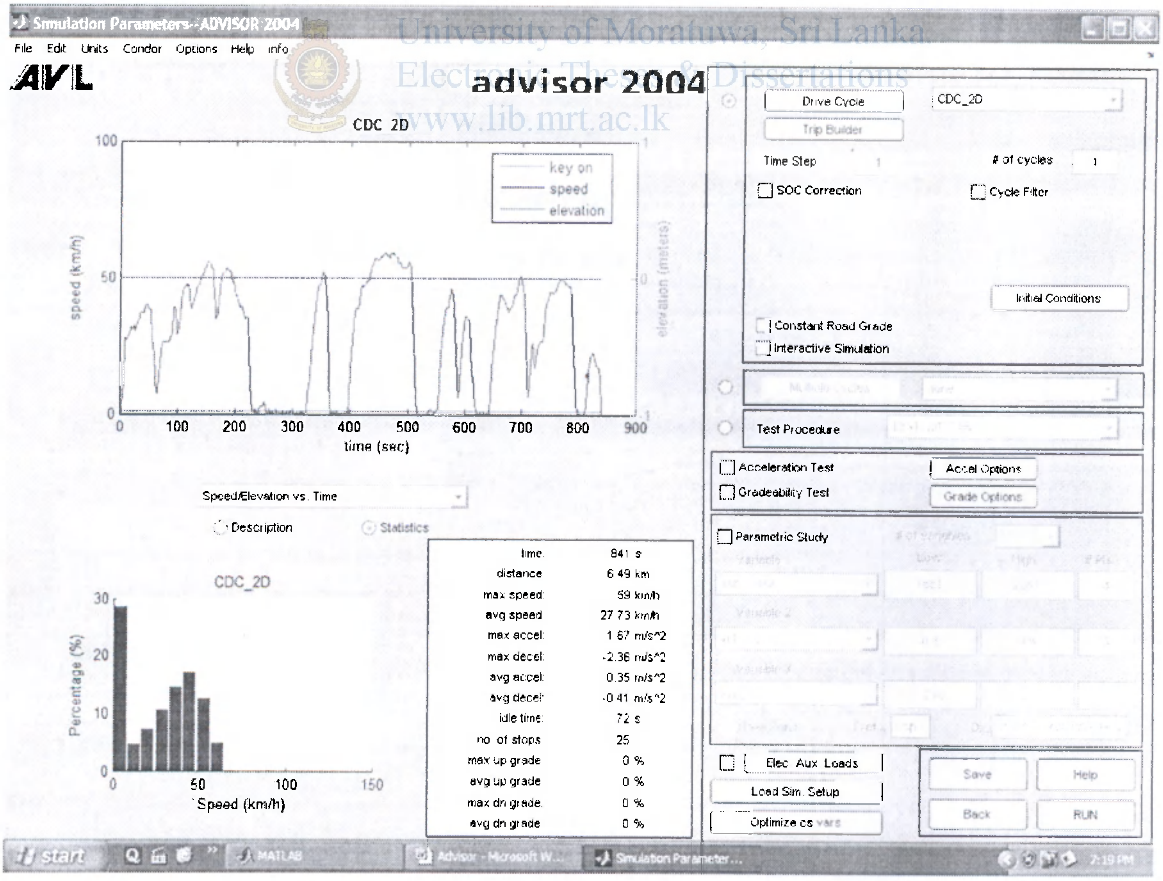


Figure 3.17 Route 2 Down drive Acceleration profile



● Drive Cycle: CDC_2D

Time Step 1

# of cycles 1

☐ SOC Correction

☐ Cycle Filter

☐ Constant Road Grade

☐ Interactive Simulation

○ Test Procedure

☐ Acceleration Test

☐ Gradeability Test

☐ Parametric Study

☐ Elec. Aux. Loads

time:	841 s
distance:	6.49 km
max speed:	59 km/h
avg speed:	27.73 km/h
max accel:	1.67 m/s^2
max decel:	-2.36 m/s^2
avg accel:	0.35 m/s^2
avg decel:	-0.41 m/s^2
idle time:	72 s
no. of stops:	25
max up grade:	0 %
avg up grade:	0 %
max dn grade:	0 %
avg dn grade:	0 %

Figure 3.18 Route 1 Up drive Speed profile

Route Distances

Following four graphs were developed to evaluate the total lengths of four drive cycles respectively. In those figures length in meters were plotted against time in seconds. It shows how the length is increasing cumulatively with the time.

Fig 3.19,fig 3.20,fig3.21 and fig 3.22 are respectively for Colombo drive cycle 1up, 1down, 2up and 2 down.

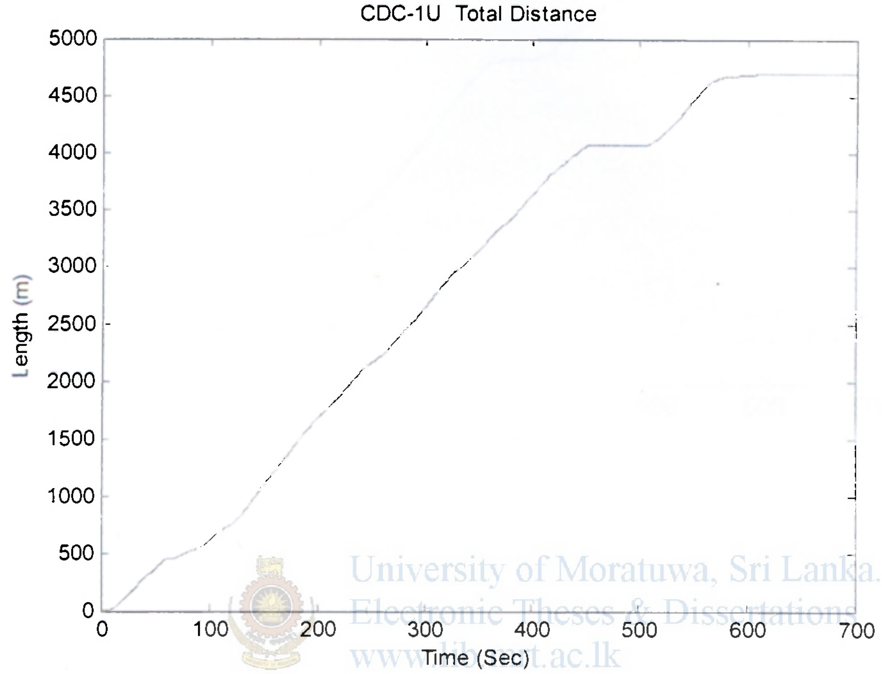


Figure 3.19 Route 1 Up drive distance

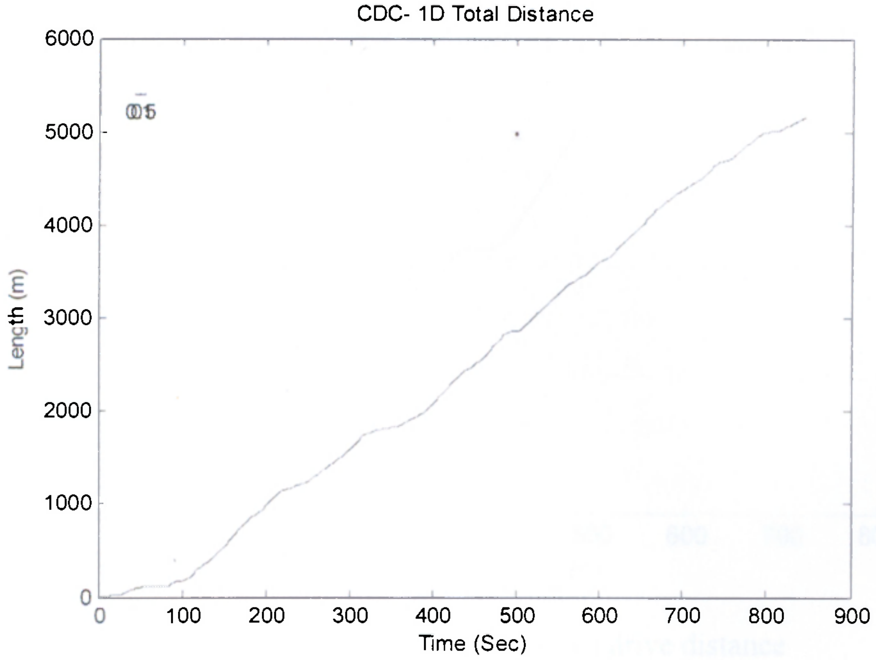


Figure 3.20 Route 1 Down drive distance

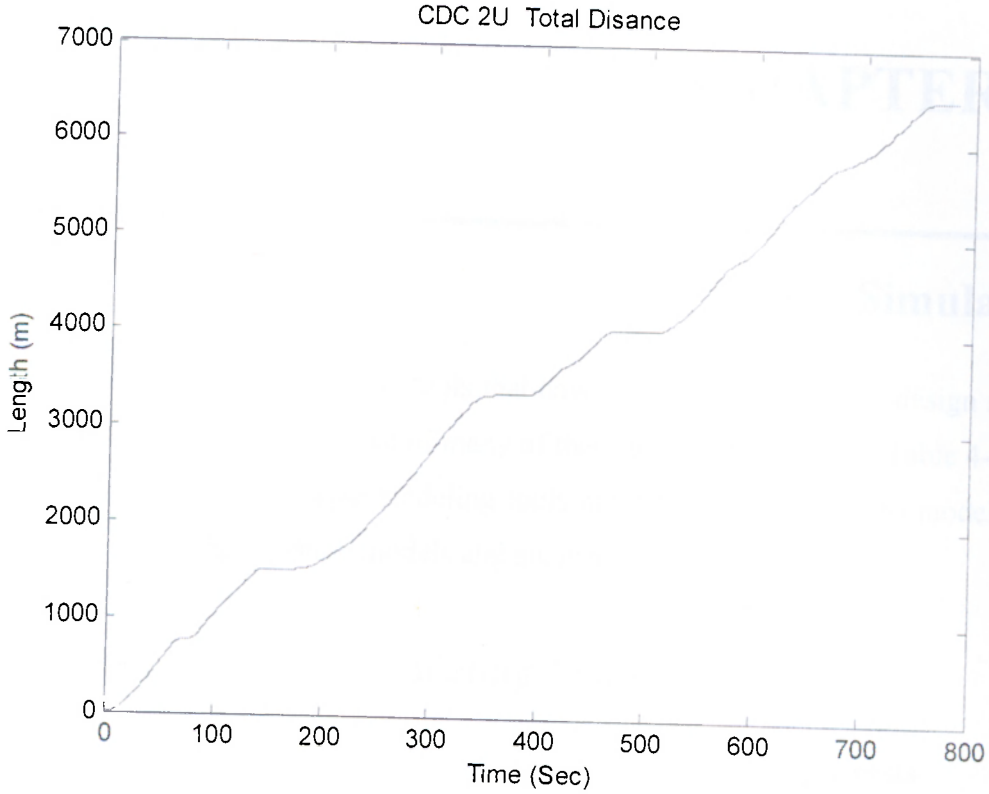


Figure 3.21 Route 2 Up drive distance

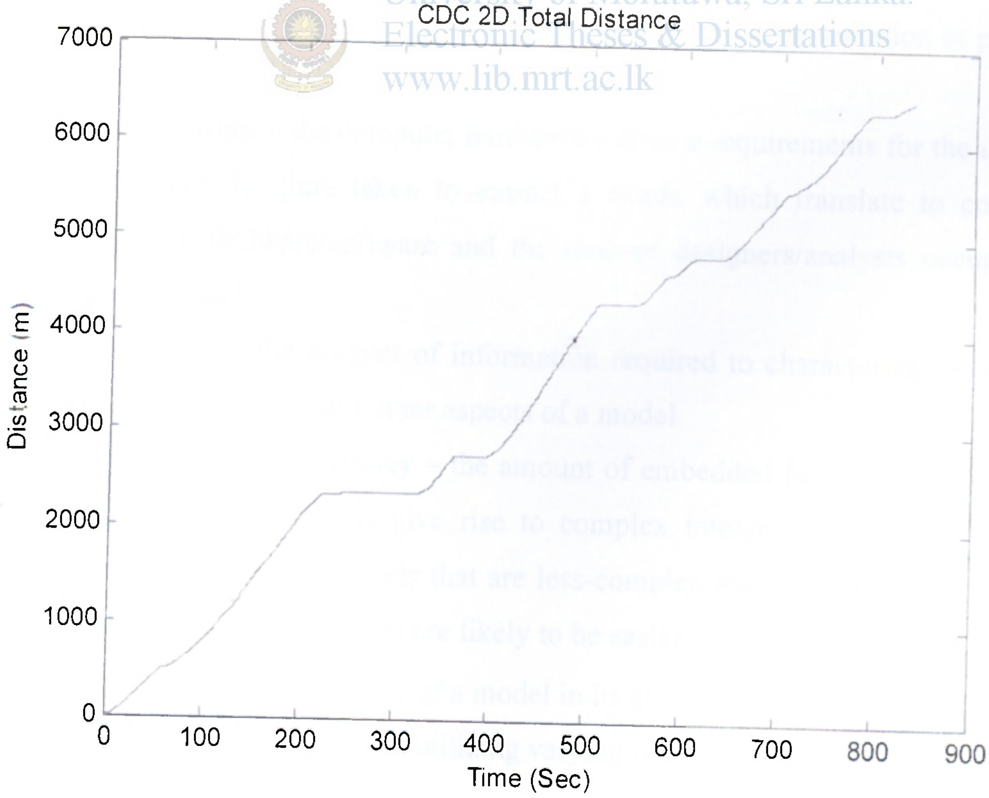


Figure 3.22 Route 2 Down drive distance

CHAPTER 04

HEV Simulation

There are many vehicle modeling tools that have been used for vehicle design studies and technology assessment. A list of many of these tools is provided in Table 4-1. The capabilities of existing vehicle modeling tools are differ from model to model. This chapter is to describe common models and analyze their features.

4.1 Factors of Vehicle Modeling Tools

The vehicle modeling tools can be analyzed according to following aspects.

1. **Accuracy** – the error in a model's simulation output of vehicle energy consumption and actual data
2. **Precision** – the level of detail analysis in a model's representation of physical effects in the vehicle
3. **Computation** – the computer hardware/software requirements for the use of a model and the time taken to extract a result, which translate to costs for computer hardware/software and the time of designers/analysts occupied in using a model.
4. **Input data** – the amount of information required to characterize the vehicle and its components and other aspects of a model
5. **Complexity/transparency** – the amount of embedded functions and "hidden layers" in a model that give rise to complex interactions that may not be obvious to the user. Models that are less-complex/more-transparent are easier to "debug" and their results are likely to be easier to analyze and interpret
6. **Versatility** – the flexibility of a model in its ability to model different vehicles with different performances utilizing varying technologies.

4.2 Existing vehicle modeling tools

Table 4.1. Available modeling tools

Modeling Tool	Type
ADVISOR (Wipke et al, 1999)	Dynamic simulator (backward/forward)
Åhman (2001)	Lumped parameter model
Delucchi (2000)	Dynamic simulator (backward)
EVSIM (Chau et al, 2000)	Dynamic simulator (backward/forward)
HPSP (Weber, 1998)	Dynamic simulator (backward)
Louis (1999)	Lumped parameter model
MARVEL (Marr and Walsh, 1992)	Dynamic simulator (backward)
Moore (1996)	Lumped parameter model
OSU-HEVSIM (Wasacz, 1997)	Dynamic simulator (forward)
Plotkin et al (2001)	Lumped parameter model
PSAT (ANL, 2004)	Dynamic simulator (forward)
QSS Toolbox (Guzella and Amstutz, 1999)	Dynamic simulator (backward)
Ross (1997)	Lumped parameter model
SIMPLEV (Cole, 1993)	Dynamic simulator (backward)
Sovran and Blaser (2003)	Lumped parameter model
Sovran and Bohn (1981)	Lumped parameter model
Steinbugler (1998)	Dynamic simulator (backward)
Thomas et al (1998)	Dynamic simulator (backward)
V-ELPH (Butler et al, 1999)	Dynamic simulator (forward)
VSP (Van Mierlo and Maggetto, 1996)	Dynamic simulator (backward)

4.3 Modeling types

Basically we can categorize two modeling types by considering the system and approach as follows.

1. Dynamic vehicle simulators
2. Lumped parameter models.

The most widely used approach is dynamic modeling. Most popular types are ADVISOR and PSAT. In those tools they use hypothetical drive cycle to simulate dynamic vehicle operation and the corresponding dynamic power flows and energy losses within the vehicle.

The secondary approach is lumped parameter models. Those are very simple models which uses estimated parameters variables for a particular drive cycle. Therefore they are less complex and much easier to apply and interpret. However the main drawback in lumped parameter models is its lack of precision and loss of accuracy. This inaccuracy can cause from the assumptions taken in developing a simple model.

However both types of models are used widely for various purposes depending upon the application.

4.4 Models to be used in this Study

To fulfill the objective of the project that is to simulate HEVs and conventional vehicles in a real Sri Lankan drive cycle and analyze fuel consumption three separate models were used.

The Backward approach was preferred than the forward approach when selecting the technique used for vehicle modeling.

Forward approach

Inputs = "efforts" (e.g. force at wheel)

Outputs = "flows" (e.g. vehicle speed)

Backward approach

Inputs = "flows" (e.g. vehicle speed)

Outputs = "efforts" (e.g. force at wheel)

4.4.1Optimized HEV for maximum efficiency (Known drive cycle)

Sudath Wimalendra developed a mathematical model to calculate the maximum efficiency of the parallel HEV. This calculation was done considering the complete drive Cycle as an input.

This model is done for a known drive cycle, the power requirement of the vehicle to achieve the known speed profile can be calculated using equations. In HEV, this power requirement is supplied by the two power sources; ICE and EM. There are infinite numbers of combinations of power contributions from these two sources to meet the power requirement. This model is developed to find out the optimum power split between the two sources, which make the total fuel consumption a minimum during the period of the drive cycle. The modeling was done the MATLAB platform using dynamic formulas as a base. GA techniques were used for optimization process.

4.4.2 Optimized HEV for Future predictions.

EPMC Edirisinghe developed a mathematical model to calculate the efficiency of the parallel HEV. The specialty and novelty of this model was it considers 5 Sec future data of drive cycle as an input. A 5 sec period is considered as a cluster and that particular cluster is optimized. GA techniques were used for optimization process.
The modeling was done the MATLAB platform using dynamic formulas as a base.

4.4.3 QSS Tool Box

The QSS TB which was developed in Swiss Federal Institute of technology Zurich by L.Guzzella, A.Amstutz June 2005.

The QSS TB makes it possible for powertrain systems to be designed quickly and in a flexible manner and to calculate easily the fuel consumption of such systems.

The key idea behind the QSS TB is to reverse the usual cause-and-effect relationships of dynamic systems. Rather than calculating speeds from given forces, based upon given speeds (at discrete times), the toolbox calculates accelerations and determines the necessary forces.

The step size of the QSS simulation is protected and cannot be redefined. If the accuracy is to be increased, the step size may be decreased. However, not only will the calculations take longer, but there are more efficient ways to solve these problems numerically.

On the basis of given values for speed and force, fuel consumption is calculated using so-called engine maps. Surprisingly enough, this approach is valid for a number of different structures and elements, such as IC engines, electric motors, intermediate storage devices, drive trains, etc.

Series Hybrid vehicle model

The series Hybrid vehicle model used in this study is shown in Fig4.1 as Simulink blocks. When simulating all the parameters in each block were set as specified in Table 4.1

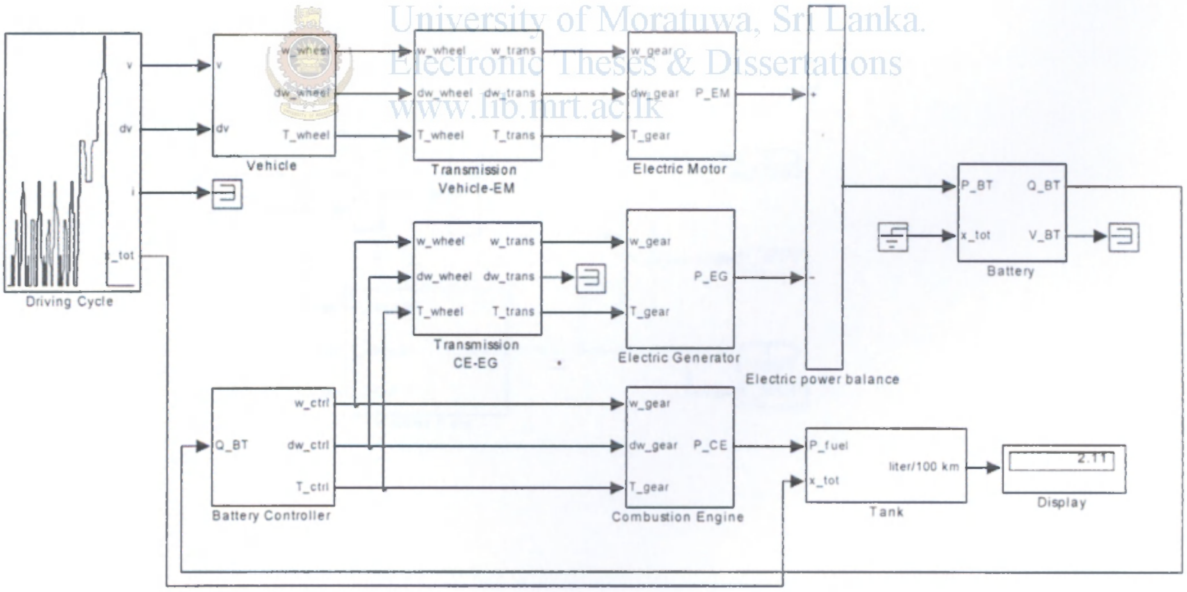


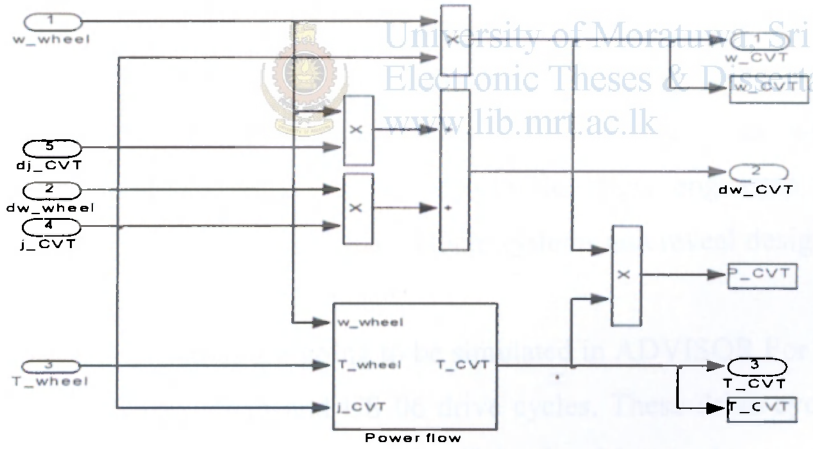
Fig 4. 1 Series HEV QSS_TB block diagram

Conventional vehicle model with CVT

The Conventional vehicle model used in this study is shown in Fig4.5-2 as Simulink QSS _TB blocks. When simulating all the parameters in each block were set as specified in Table 4.6 The physics of CVTs in the "forward" formulation are somewhat more complicated. In a QSS formulation, however, the structure shown in Fig. 2.4.7 arises. This rather surprisingly straightforward model structure is a consequence of the QSS approach.

The online control of CVTs demands that it be "predictive". One of the ways to achieve this is to transmit the desired speed generated by the block "Driving Cycle" directly to the control unit, but to delay its transmission to the block "Vehicle" by one step (this means that the unit delay blocks in Simulink are set to a sample time equal to the step size *h*).

This would be easy to implement in practice, i.e., with a drive-by-wire engine, the step size (being the artificial delay) would be on the order of one tenth of a second.



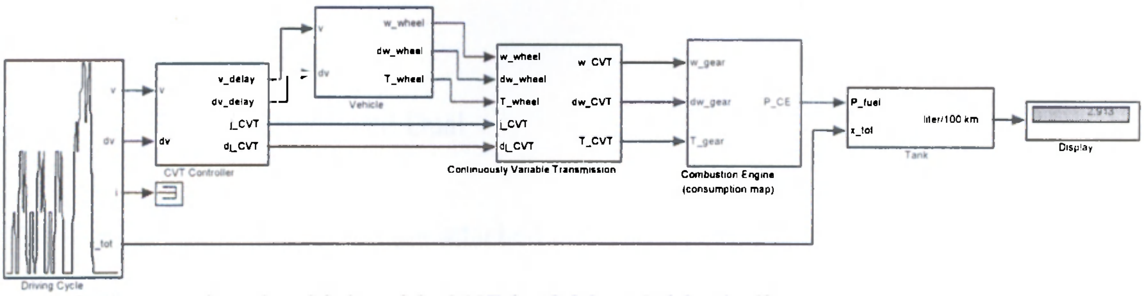


Figure 4. 2 Conventional vehicle with CVT in QSS_TB block diagram

4.5 ADVISOR simulation software

ADVISOR by AVL is the most common simulation software which is used by the developers in all over the world. It is very complex and very sophisticated application which has developed targeting this vehicle simulation only.
ADVISOR is designed for rapid analysis of the performance and fuel economy of conventional and advanced, light and heavy-duty vehicle models as well as hybrid electric and fuel cell vehicle models. It tests the effect of parameter changes in vehicle components (such as motors, batteries, catalytic converters, climate control systems, and alternative fuels) and other modifications that might affect fuel economy, performance or emissions.

Accurate component and vehicle simulation are crucial for efficient development of advanced vehicles, particularly for making intelligent choices regarding energy management. Simulating vehicle and component performance helps engineers determine how to increase the life of components, improve vehicle performance, optimize vehicle system designs, and reduce development times, all for a fraction of the cost of vehicle testing. As an analysis tool with the auto-size capability and various incorporated energy management strategies as well as the Design of Experiments capability, AVL ADVISOR offers engineers the ability to analyze effectively various conceptual vehicle systems and reveal design solutions.

Following Models are going to be simulated in ADVISOR For Colombo Drive cycles, NEDC, Japan 10-15 and US 06 drive cycles. These drive cycles are combination of transient and model drive cycles. Colombo drive cycles are developed here and all relevant data regarding to this drive cycle are fed in to ADVISOR software.

- Parallel HEV
- Conventional Vehicle
- Toyota Prius – Optimized Dual

All the relevant Data and results are attached in the Chapter 5.

4.5.1 Parallel HEV in ADVISOR

Following is the simulink model used for Parallel HEV. All the set parameters are shown in the figure below.

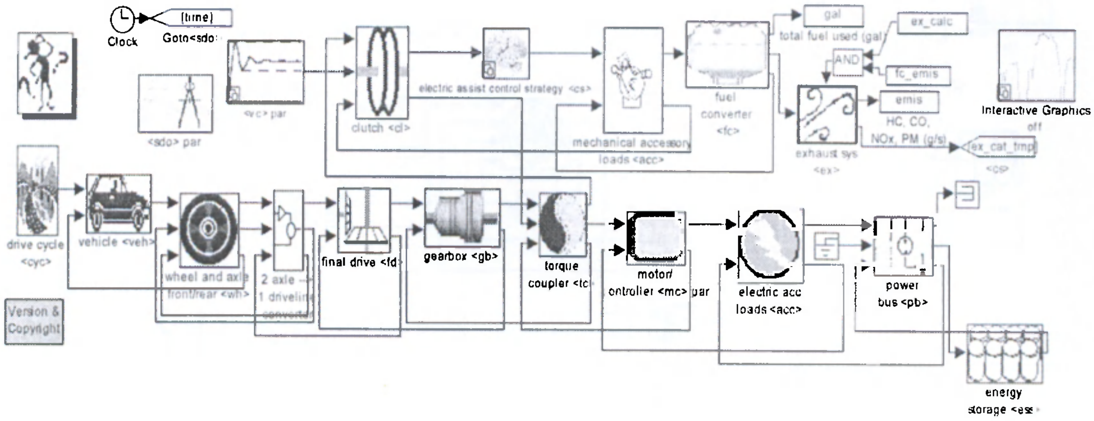
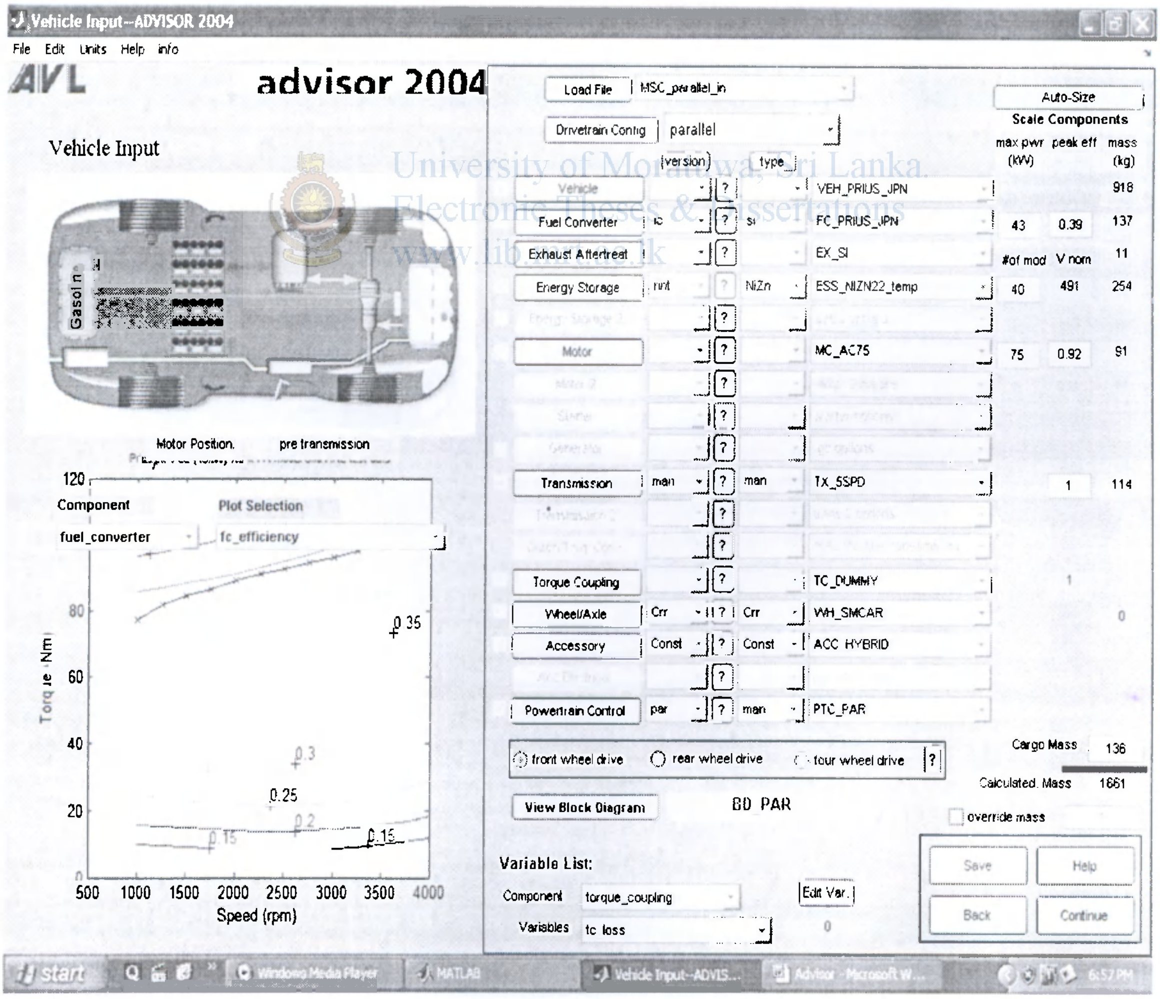


Figure 4.3: Block diagram for parallel HEV in ADVISOR



Load File: MSC_parallel_in

Drivetrain Config: parallel

	version	type		max pwr (kW)	peak eff	mass (kg)
Vehicle			VEH_PRIUS_JPN			918
Fuel Converter	ic	si	FC_PRIUS_JPN	43	0.39	137
Exhaust Aftertreat			EX_SI			11
				#of mod	V nom	
Energy Storage	rint	NiZn	ESS_NIZN22_temp	40	491	254
Motor			MC_AC75	75	0.92	91
Transmission	man	man	TX_5SPD		1	114
Torque Coupling			TC_DUMMY		1	
Wheel/Axle	Crr	Crr	WH_SMCAR			0
Accessory	Const	Const	ACC_HYBRID			
Powertrain Control	par	man	PTC_PAR			

● front wheel drive ○ rear wheel drive ○ four wheel drive

Cargo Mass 136

Calculated Mass 1661

☐ override mass

BD_PAR

Variable List:

Component: torque_coupling

Variables: tc_loss 0

Figure 4.4: Parameter setting for parallel HEV in ADVISOR

4.5.2 Toyota Prius -Japan car on ADVISOR

Following is the simulink model used for Parallel HEV. All the set parameters are shown in the figure

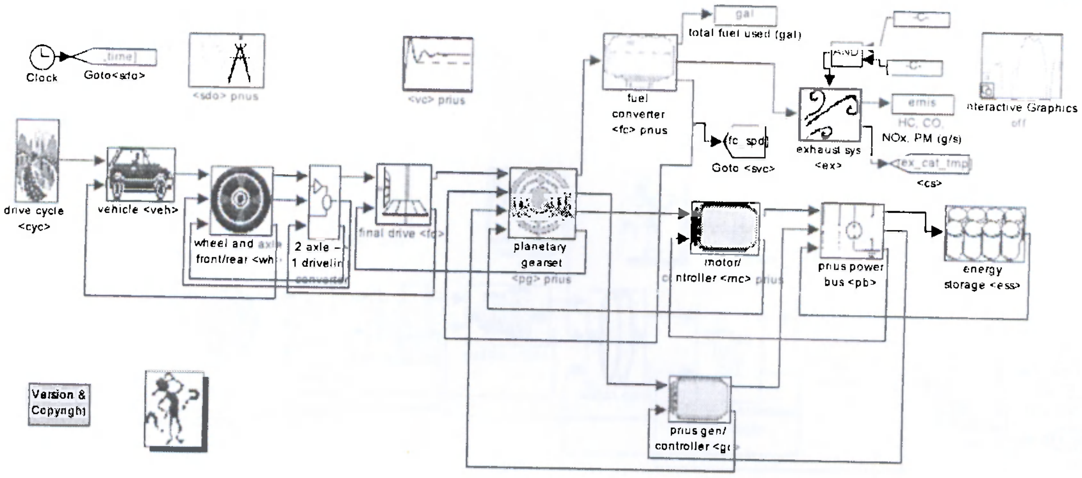
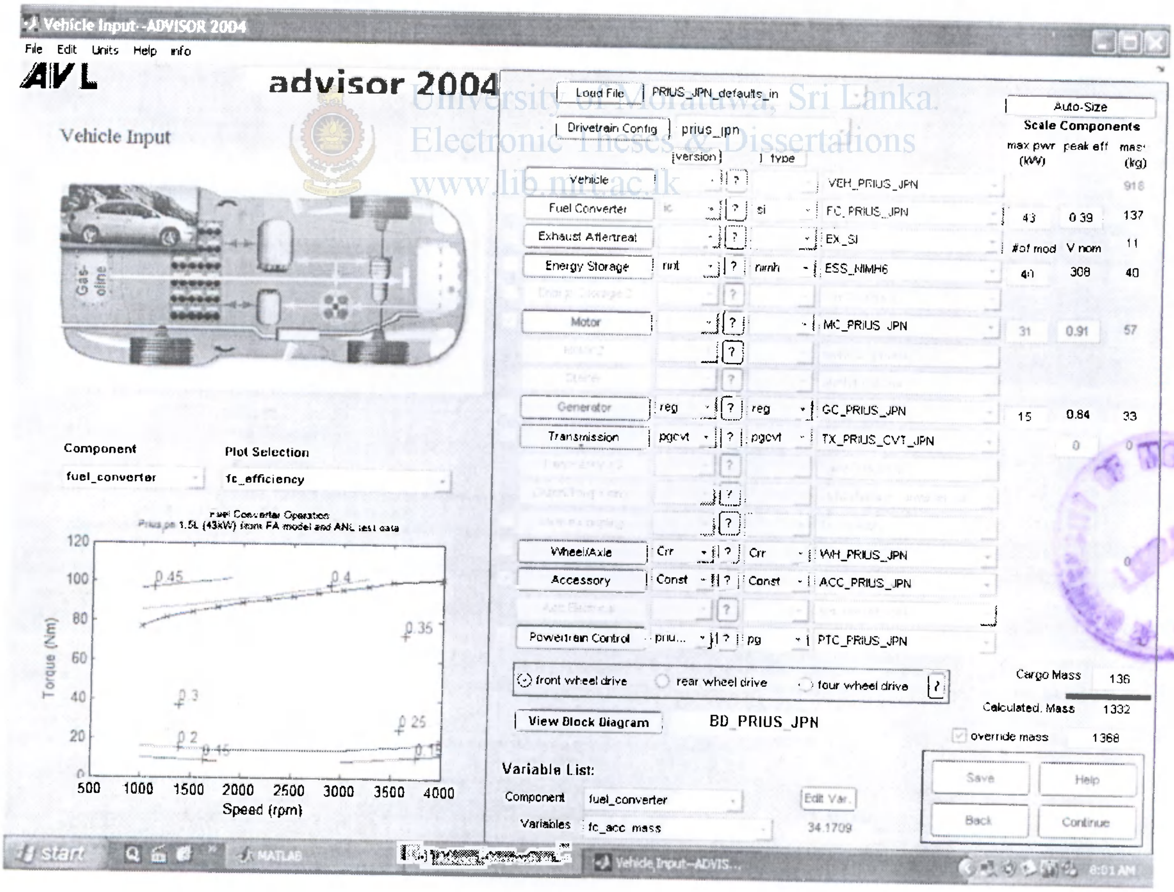


Figure 4.5: Block diagram for Toyota Prius in ADVISOR



Load File: PRIUS_JPN_defaults_in

Drivetrain Config: prius_jpn

Component: fuel_converter

Plot Selection: fc_efficiency

	version	type		max pwr (kW)	peak eff	mass (kg)
Vehicle			VEH_PRIUS_JPN			918
Fuel Converter	ic	si	FC_PRIUS_JPN	43	0.39	137
Exhaust Aftertreat			EX_SI	#of mod	V nom	11
Energy Storage	rint	nimh	ESS_NIMH6	40	308	40
Motor			MC_PRIUS_JPN	31	0.91	57
Generator	reg	reg	GC_PRIUS_JPN	15	0.84	33
Transmission	pgcvt	pgcvt	TX_PRIUS_CVT_JPN		0	0
Wheel/Axle	Crr	Crr	WH_PRIUS_JPN			0
Accessory	Const	Const	ACC_PRIUS_JPN			
Powertrain Control	priu...	pg	PTC_PRIUS_JPN			

● front wheel drive ○ rear wheel drive ○ four wheel drive

View Block Diagram: BD_PRIUS_JPN

Cargo Mass 136

Calculated. Mass 1332

☑ override mass 1368

Variable List:

Component: fuel_converter

Variables: fc_acc_mass 34.1709

Figure 4.6: Parameter setting for Toyota Prius in ADVISOR

4.5.3Conventional vehicle on ADVISOR

Following is the simulink model used for Parallel HEV. All the set parameters are shown in the figure

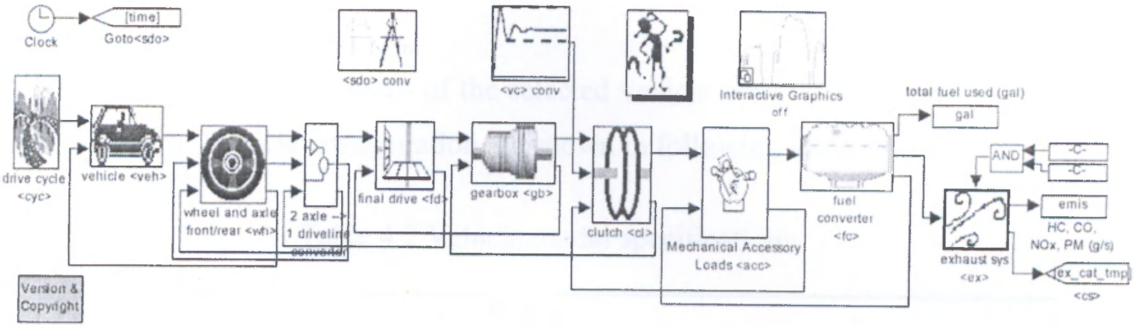
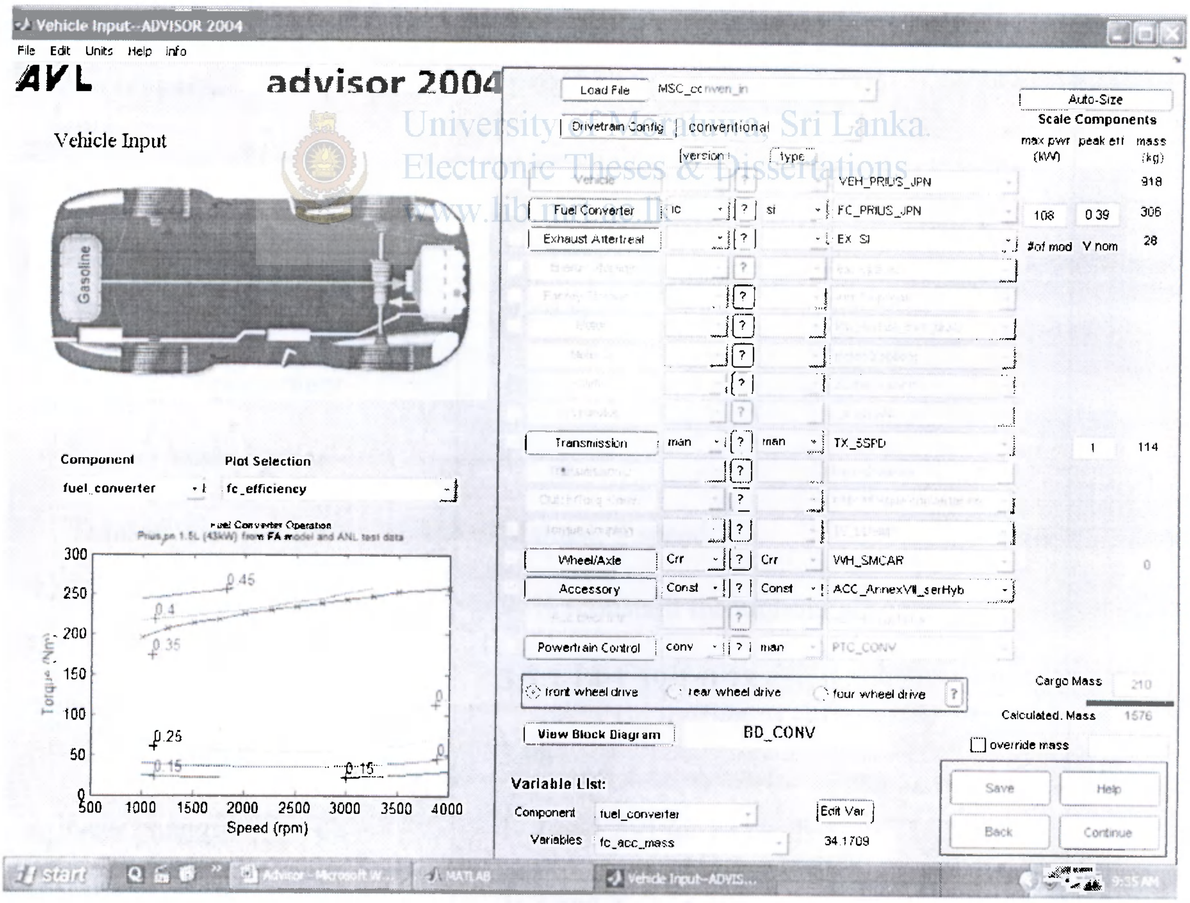


Figure 4.7: Block diagram for conventional vehicle in ADVISOR



Load File: MSC_conven_in

Drivetrain Config: conventional

	version	type		max pwr (kW)	peak eff	mass (kg)
Vehicle			VEH_PRIUS_JPN			918
Fuel Converter	ic	si	FC_PRIUS_JPN	108	0 39	306
Exhaust Aftertreat			Ex_SI	#of mod	V nom	28
Transmission	man	man	TX_5SPD	1		114
Wheel/Axle	Crr	Crr	WH_SMCAR			0
Accessory	Const	Const	ACC_AnnexVII_serHyb			
Powertrain Control	conv	man	PTC_CONV			

● front wheel drive ○ rear wheel drive ○ four wheel drive

Cargo Mass 210

Calculated. Mass 1576

☐ override mass

View Block Diagram: BD_CONV

Component: fuel_converter

Plot Selection: fc_efficiency

Variable List:

Component: fuel_converter

Variables: fc_acc_mass 34.1709

Figure 4.8: Parameter setting for conventional vehicle in ADVISOR

4.6 Specifications of the Selected Vehicle.

The core vehicle used for this study has been a 4 - 1 production family sedan a decision made since similar size vehicles are more popular and which has been used throughout the study

Specification of the components of the selected vehicle which are in specific Parallel Hybrid Electric Vehicle configuration are shown in following table 4.6,

Table 4.2 Vehicle model specifications

Parameter	**Value**
Total weight	1642 kg
Chassis weight	1000 kg
Frontal area	1.92 m^2
Coefficient of Drag	0.32
Vehicle length	5.00 m
Wheel Radius	0.29 m
Engine Displacement	1.5
Engine Scale Factor	1
Transmission	Manual, 5 speed
Transmission efficiency	95% (constant throughout all gears)
Gear ratios	3.5:2.14:1.39:1:0.78
Final drive ratio	3.98
Gear changes	1- 2 and 2 -1 @ 24 km/h 2- 3 and 3 -2 @ 40 km/h 3- 4 and 4 -3 @ 64 km/h

	4- 5 and 5 -4 @ 75 km/h
Motor/Generator	Permanent Magnet Motor, 20kW continuous, 40kW peak
Battery	Advanced Battery, 40kW, 4kWh
Battery Efficiency	85%

The characteristics of the engine of the selected vehicle are represented by the following fuel consumption map and engine torque map which is derived based on the empirical data.

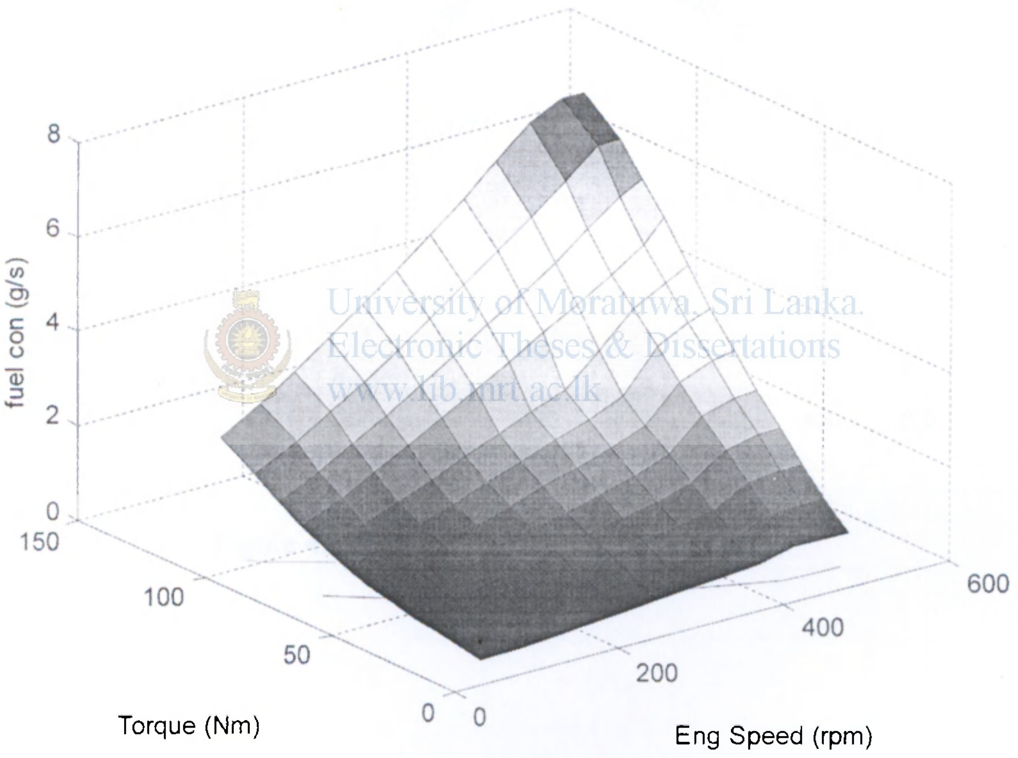


Figure 4.9 Fuel consumption map of the ICE of tested HEV

Figure 4.9 and 4.10 shows the Engine efficiency map and efficiency contours of the tested vehicle.

Motor efficiency of the selected vehicle as a function of speed and torque is represented by the Figure 4.10. Motor model in the vehicle simulation uses these empirical data for calculating motor input power and hence to calculate the power extract from the battery.

In this study, Battery efficiency during both charging and discharging is considered as constant and is taken as 85%.

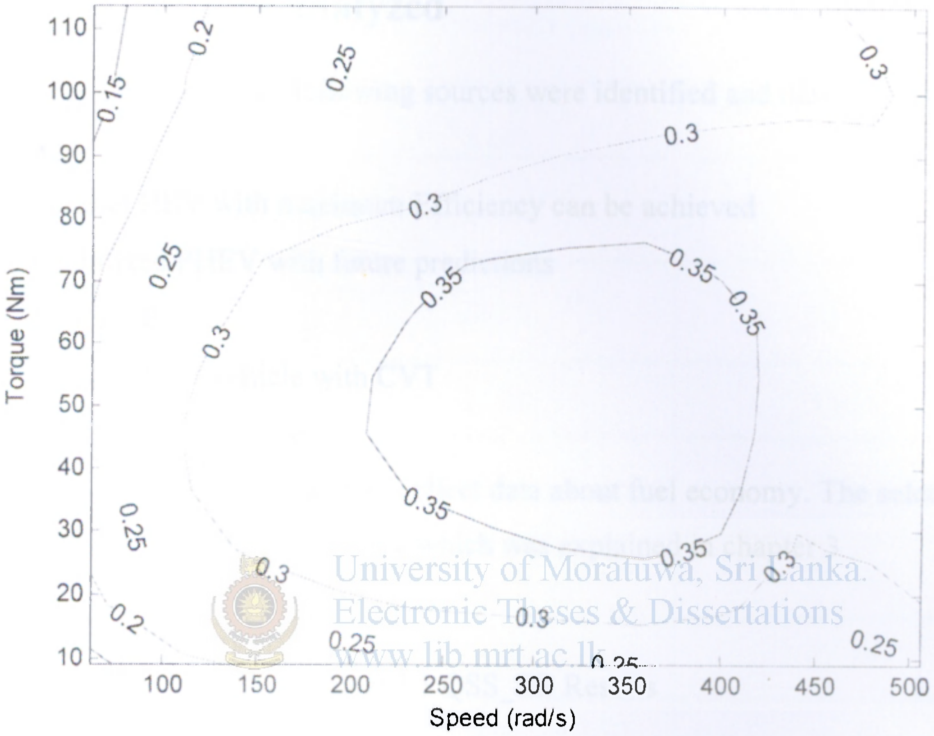


Figure 4.10 Engine fuel efficiency contours

CHAPTER 05

5.1 Results and Analysis

5.1.1 Sources to be analyzed

For the efficiency analysis, following sources were identified and data has gathered by simulations.

- Parallel HEV with maximum Efficiency can be achieved
- Optimized PHEV with future predictions
- Series HEV
- Conventional vehicle with CVT
- Conventional vehicle

All those sources were simulated to collect data about fuel economy. The selected drive cycle was Colombo drive cycle which was explained in chapter 3

5.1.2 Results

Table 5.1 QSS_TB Results

Km/L	**CDC Route 1**		**CDC Route 2**	
	Up	Down	Up	Down
Conventional wit CVT	39.20	41.77	37.71	47.62
Series HEV	19.52	56.18	21.80	20.53

Km/L	**CDC**	**NEDC**
Conventional	11.62	13.04
Maximum Optimization	17.12	18.55
Optimized HEV with Future prediction(8sec)	15.71	14.83

5.1.3 Analysis
Analysis of Drive Cycles with vehicle models

Then this data can be analyzed with existing most common model drive cycles NEDC

Table 5.2 Economy analysis

	Series HEV km/l	**Conventional with CVT Km/l**
CDC 1U	19.52	39.20
CDC 1D	56.18	41.77
CDC 2U	21.80	37.71
CDC 2D	20.53	47.62
Europe NEDC	38.24	35.21
USA FTP Highway	37.86	41.79
Japan 10-15 mode	80	34.33

When considering the Conventional vehicles with CVT in standard drive cycles we can see that fuel efficiency is low in model drive cycles. (NEDC and Japan 10-15).

We observed that conventional vehicle with continuous variable transmission is much more efficient than series HEV. The most probable reason is within the existing components the numbers of energy conversions are high in Series HEV. During these conversions there is always an energy loss. Cumulatively this leads to reduce the efficiency.

If we compare the average over these drive cycle's the data will be as below.

Series HEV	**39.161 km/l**
Conventional with CVT	**39.661 km/l**

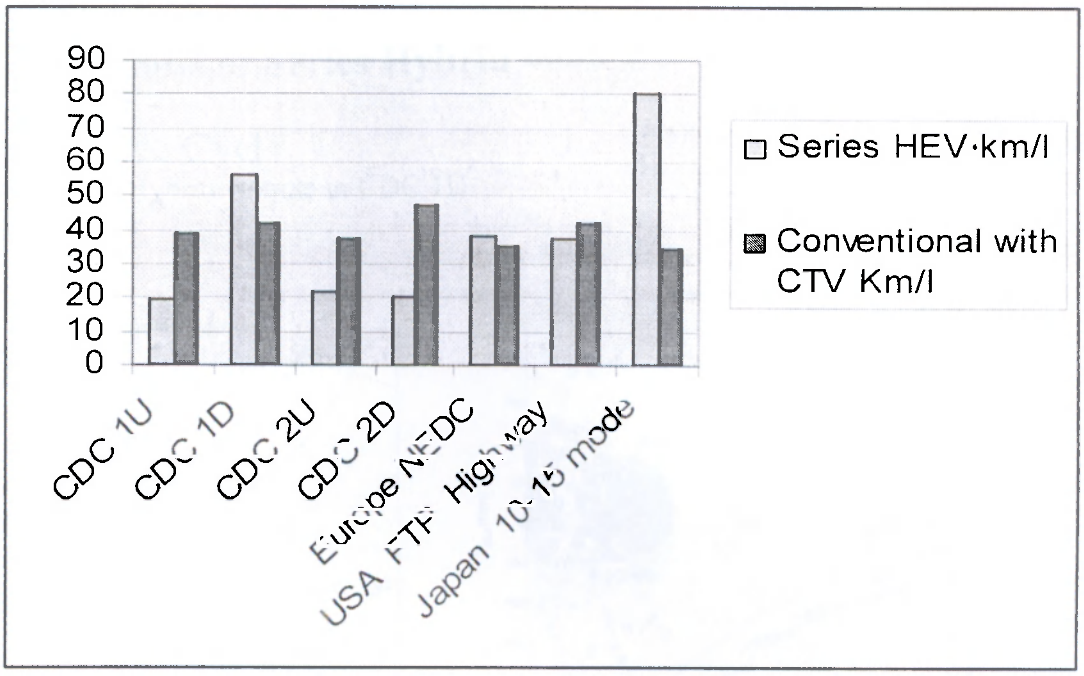


Figure 5.1: Analysis of QSS_TB Model results

Following Table 5.3 is tabulated in order to evaluate two drive cycles

Table 5.3 Analysis of CDC

	Series HEV Economy(km/l)	Conventional Economy(km/l)	Avg. Speed m/s
CDC 1	37.85	40.48	6.32
CDC 2	21.17	42.67	8.01

CDC2 is the good road when considering all aspects in evaluating a road compared to CDC1. This fact is proved by the average speed in CDC2 which is 8.00 m/s. It is observed that when the average speed is high fuel economy is also high. That is because the vehicle is operating on a higher gear for most of the time in CDC2 and the vehicle model is conventional with CVT.

Modeling results of Series Hybrid vehicle

CDC 1U Drive Cycle

Results of Series Hybrid vehicle in CDC 1U

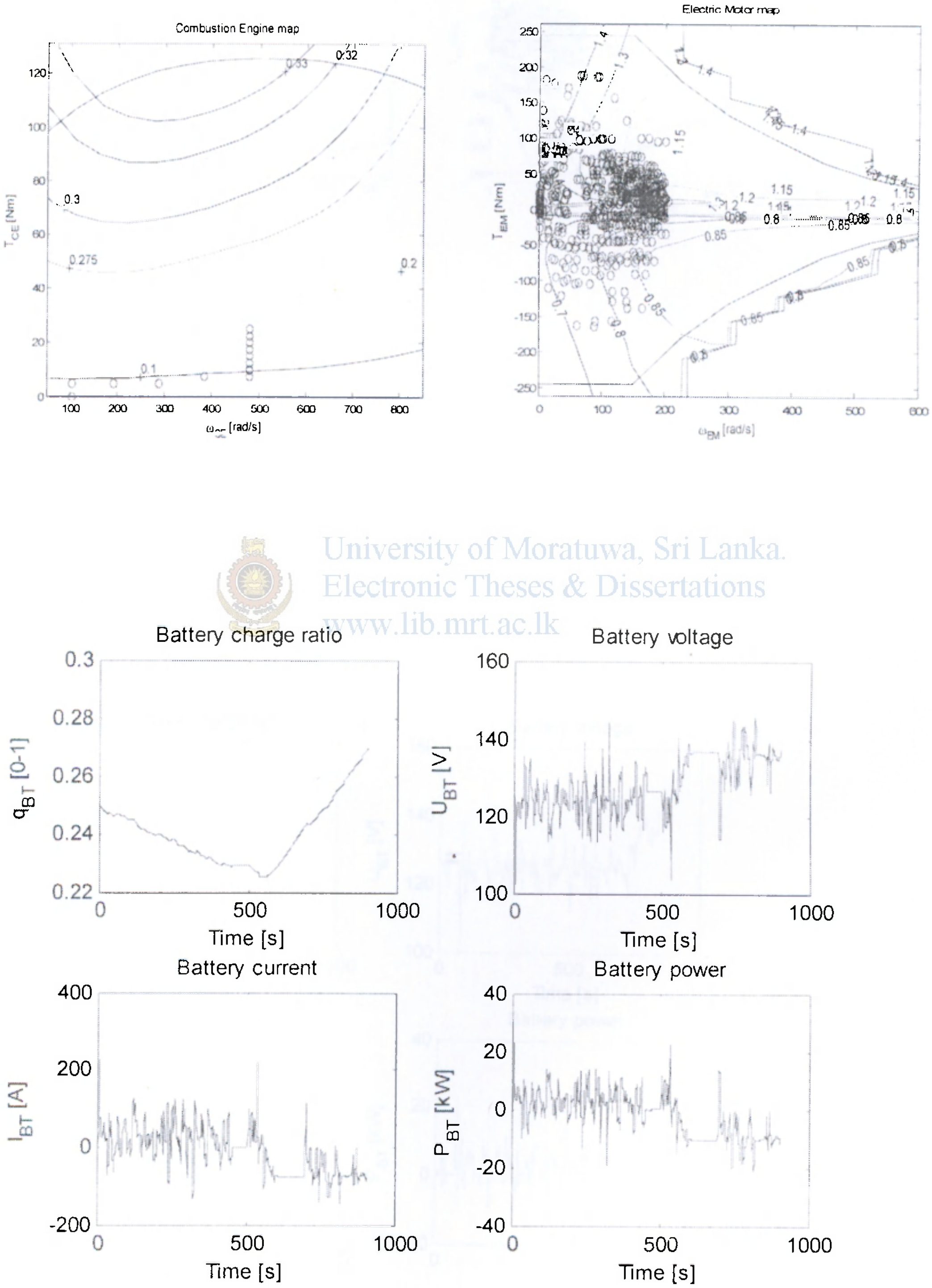


Figure 5.2: Results of Series HEV in CDC 1U

CDC 1D Drive Cycle

Results of Series Hybrid vehicle in CDC 1D

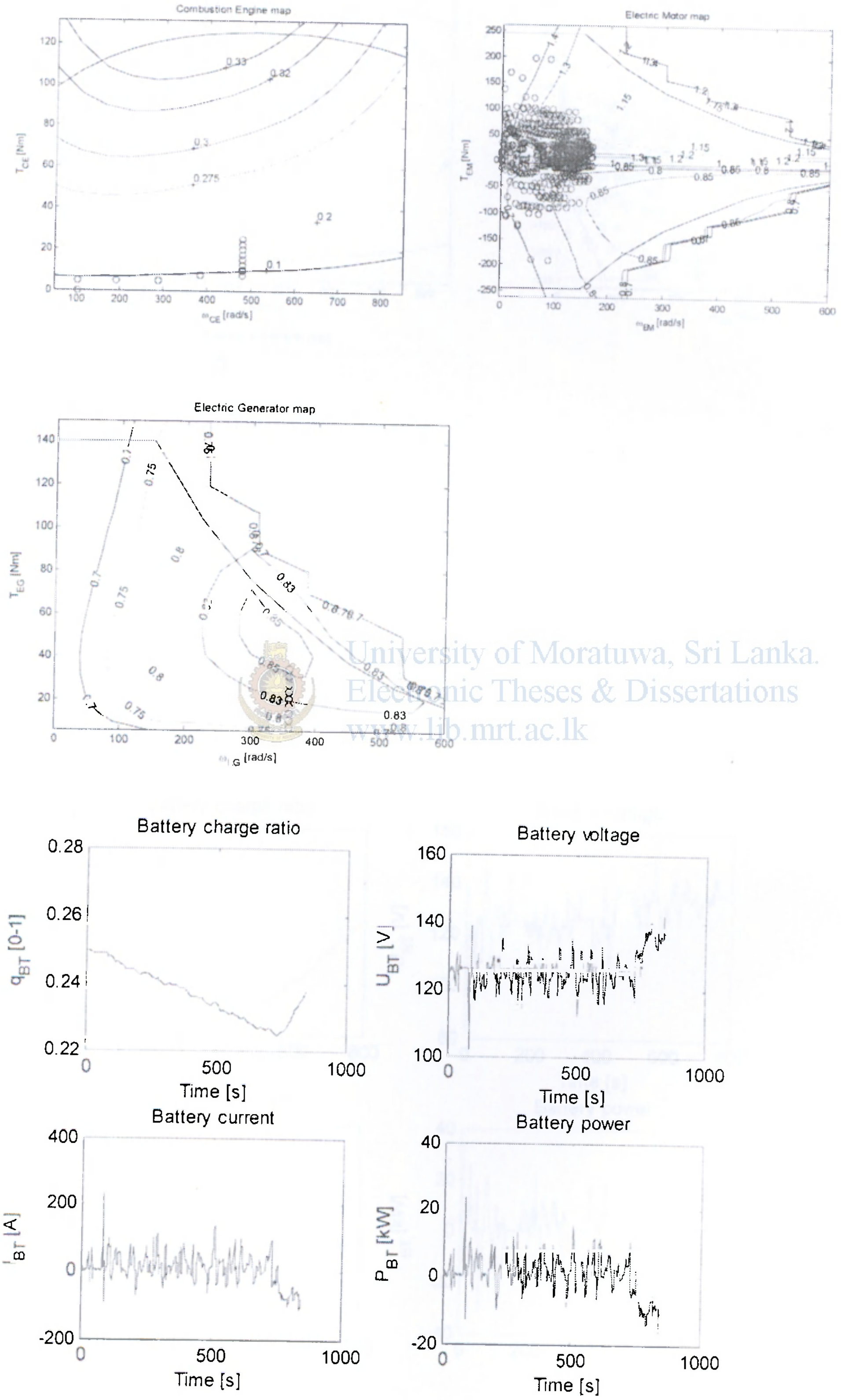


Figure 5.3: Results of Series HEV in CDC 1D

CDC 2U Drive Cycle

Results of Series Hybrid vehicle in CDC 2U

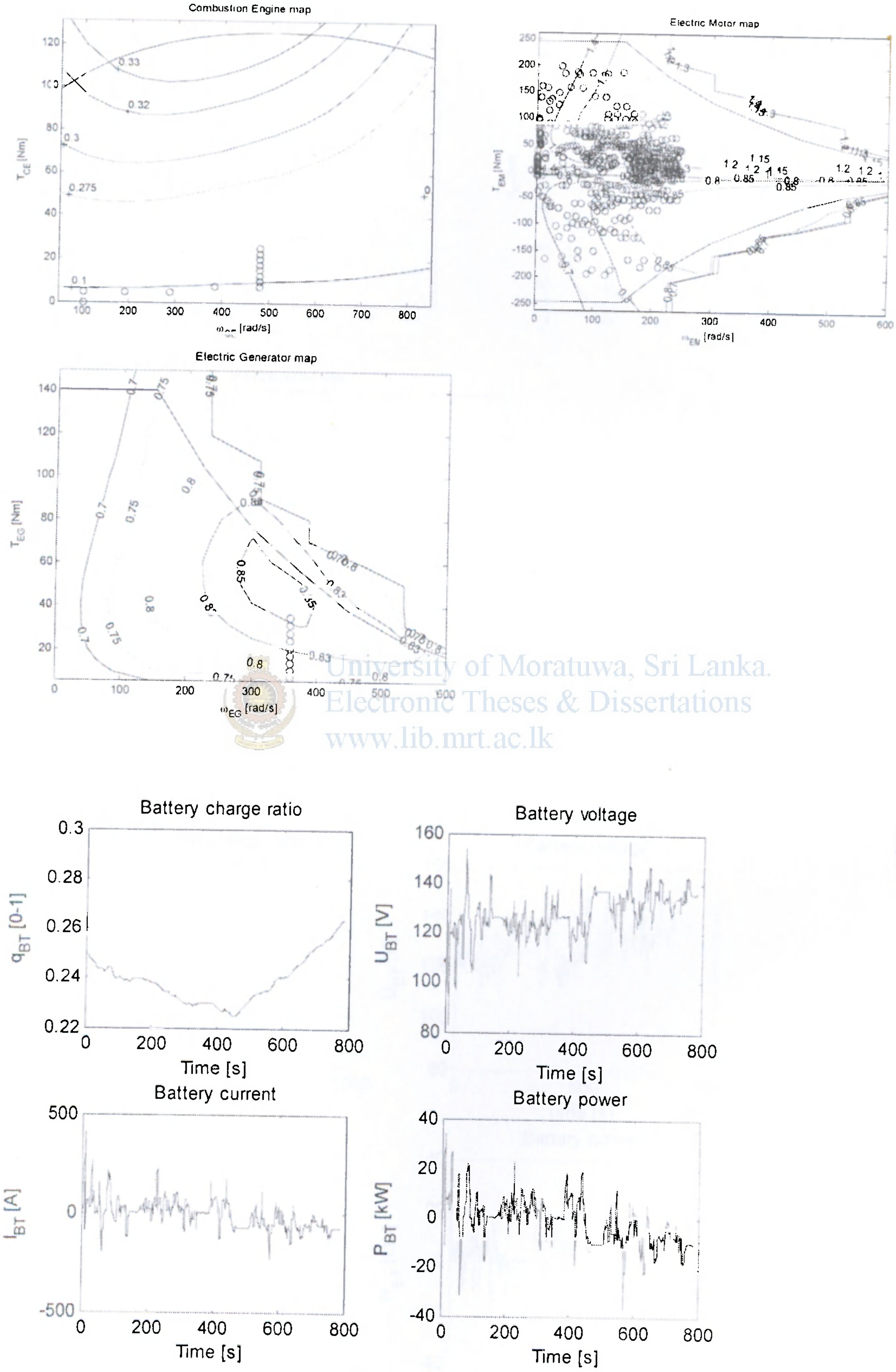


Figure 5.4: Results of Series HEV in CDC 2U

CDC 2D Drive Cycle

Results of Series Hybrid vehicle in CDC 2D

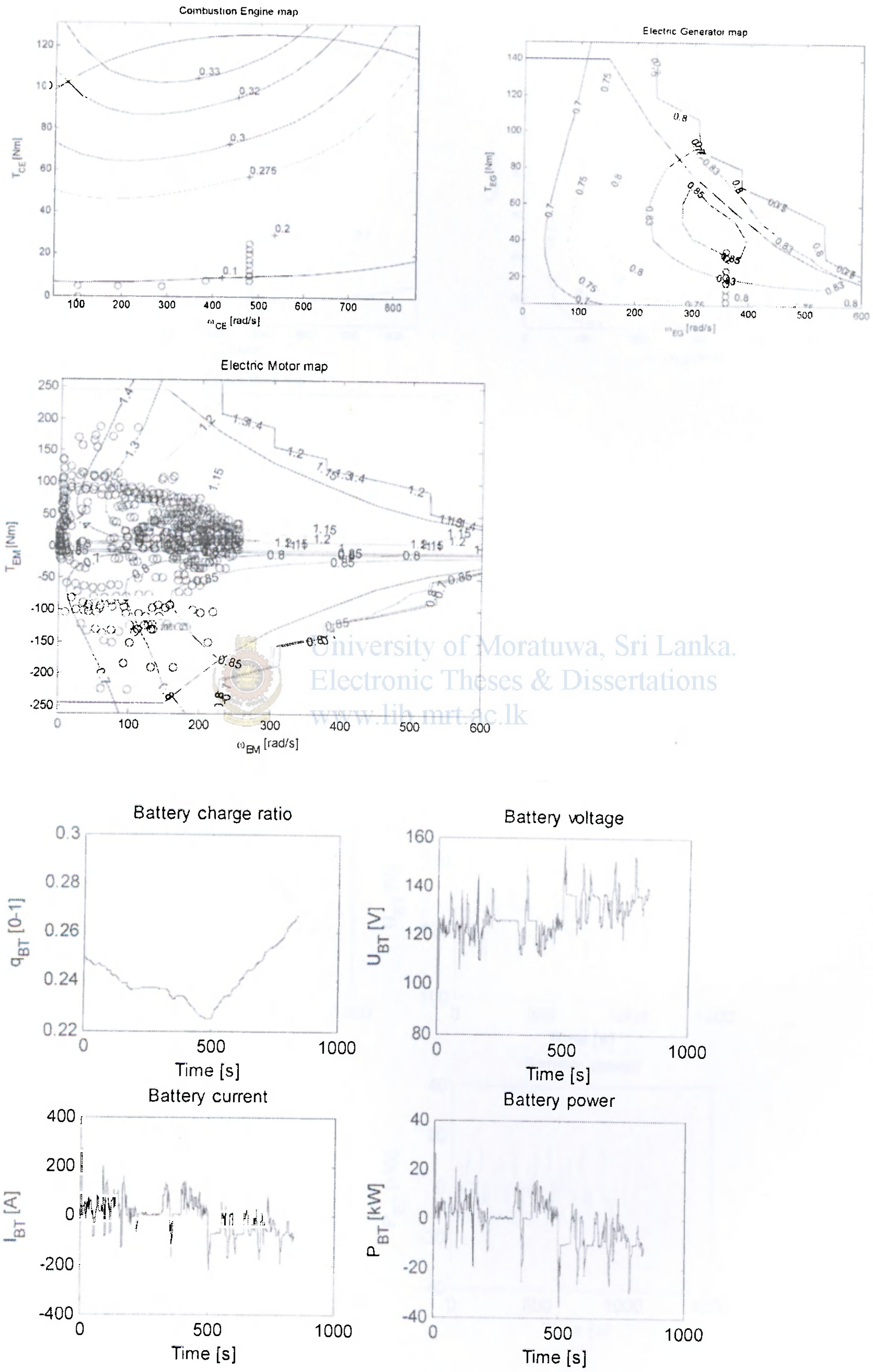


Figure 5.5: Results of Series HEV in CDC 2D

European NEDC

Results of Series Hybrid vehicle in NEDC

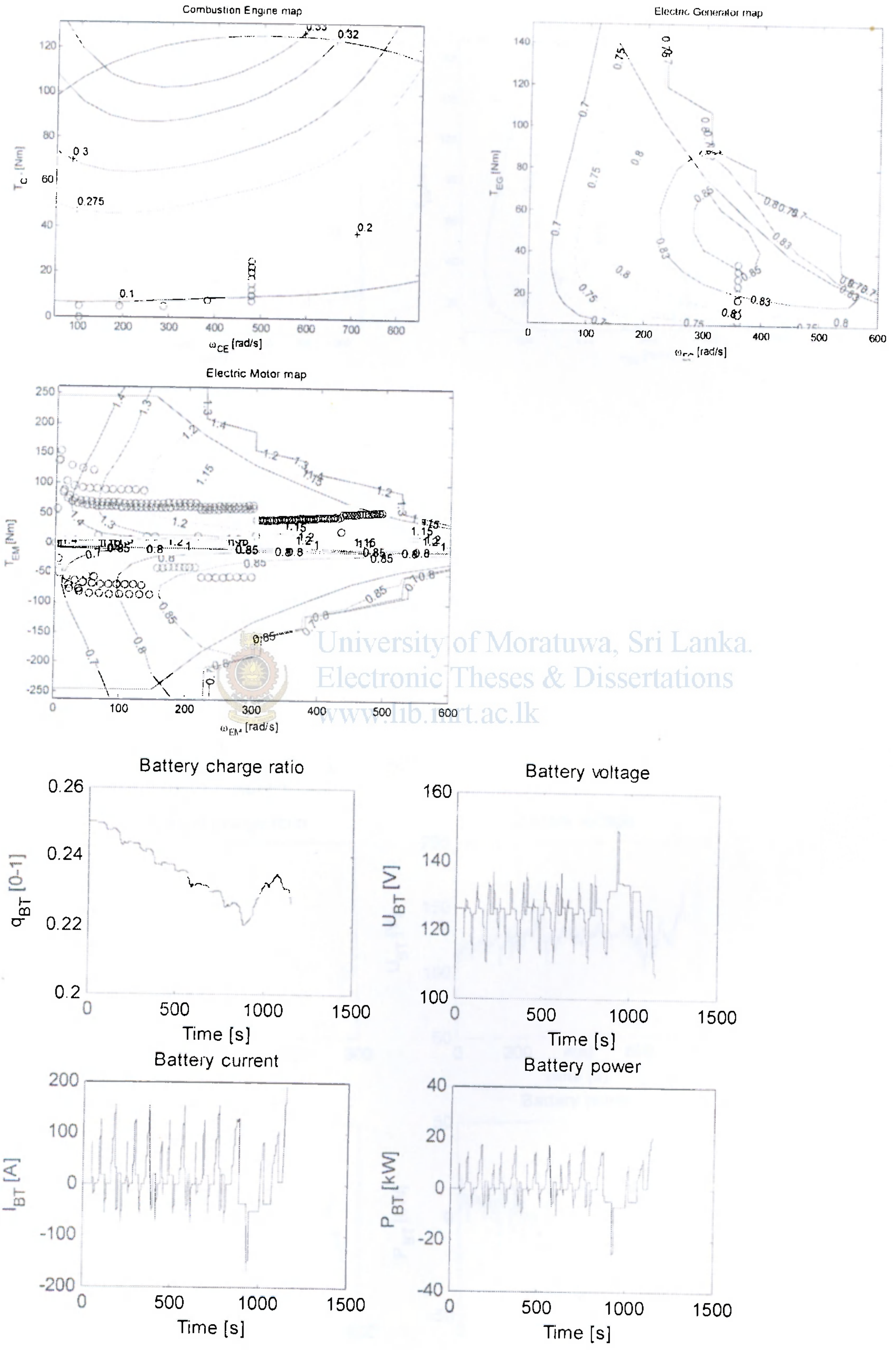


Figure 5.6: Results of Series HEV in NEDC

US FTP High way

Results of Series Hybrid vehicle in US FTP highway

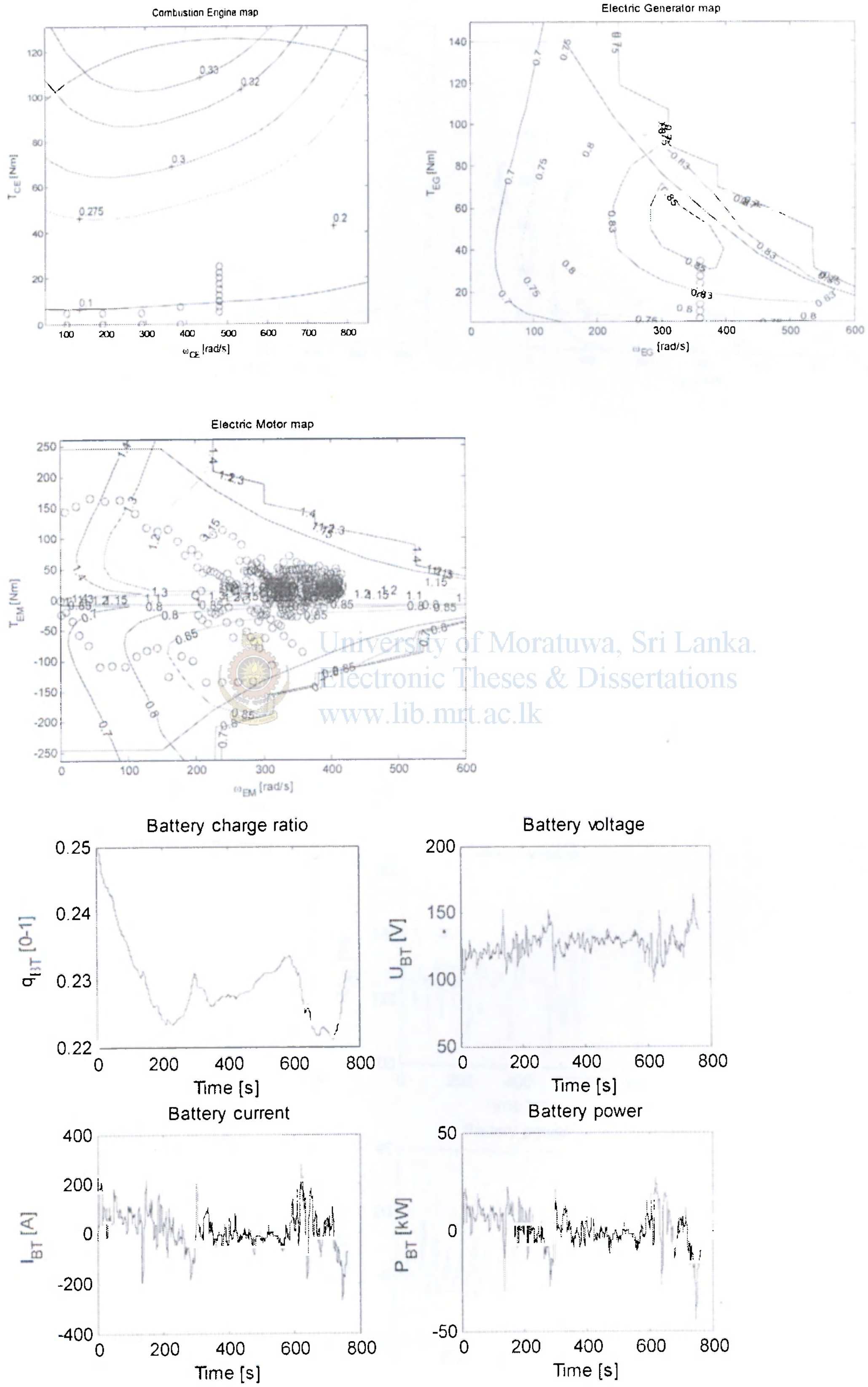


Figure 5.7: Results of Series HEV in FTP Highway

Japan 10-15

Results of Series Hybrid vehicle in Japan 10-15

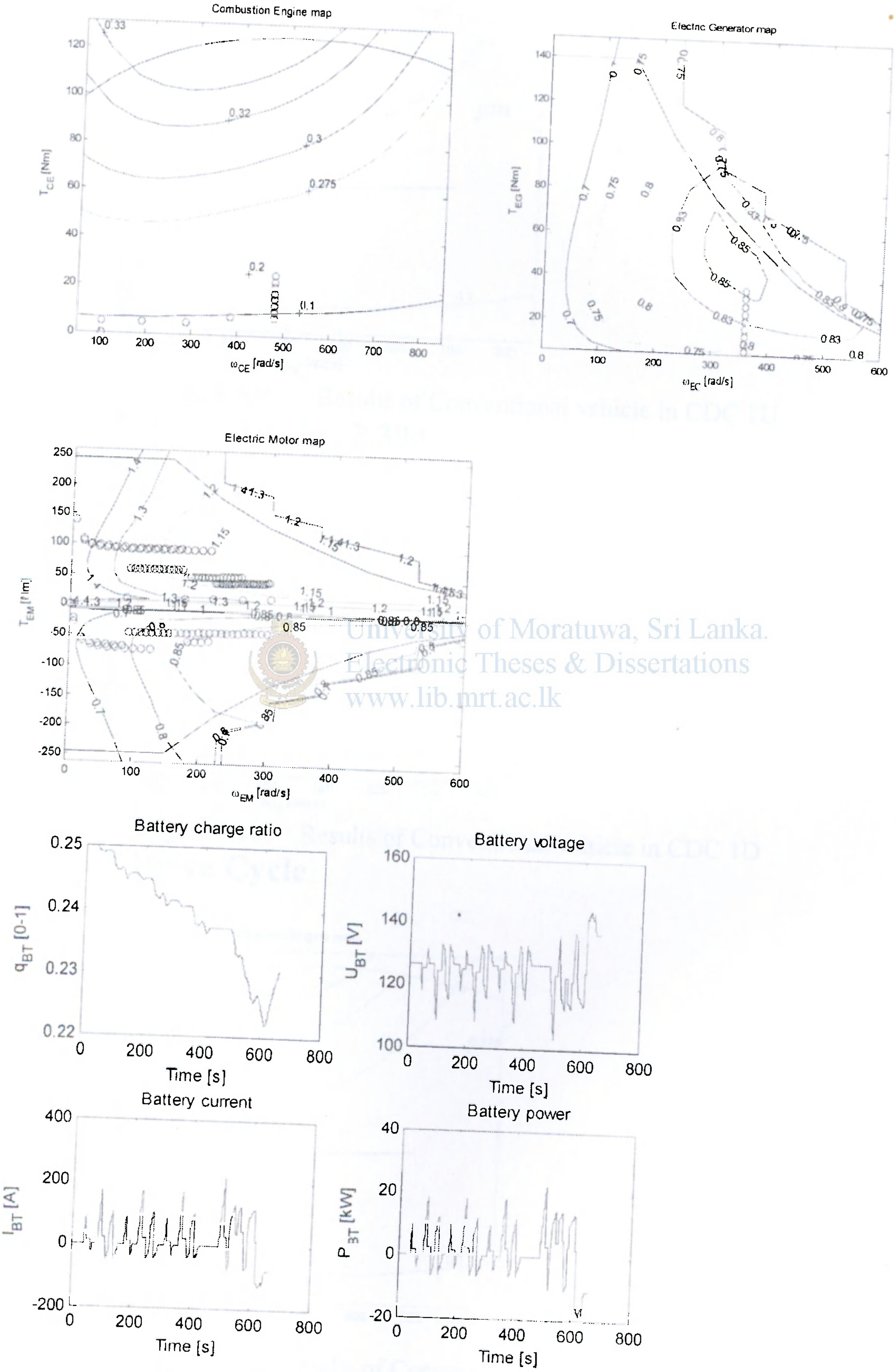


Figure 5.8: Results of Series HEV in Japan 10-15

Modeling results of Conventional Vehicle with CVT

CDC 1U Drive cycle

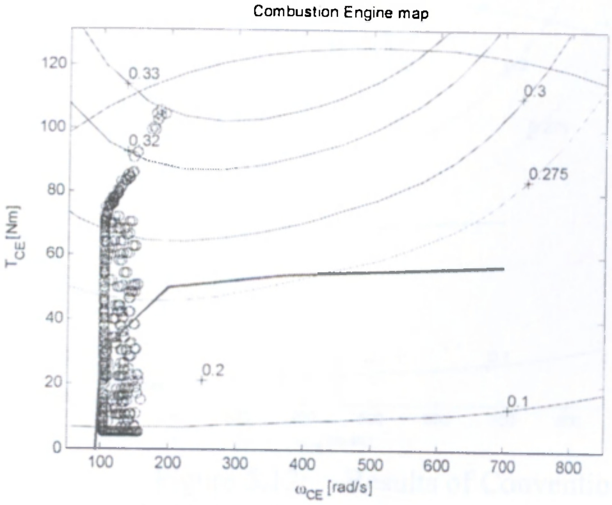


Figure 5.9: Results of Conventional vehicle in CDC 1U

CDC 1D Drive Cycle 2.394

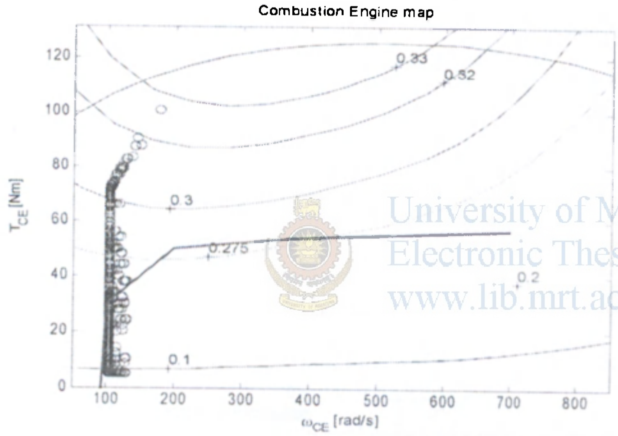


Figure 5.10: Results of Conventional vehicle in CDC 1D

CDC 2U Drive Cycle

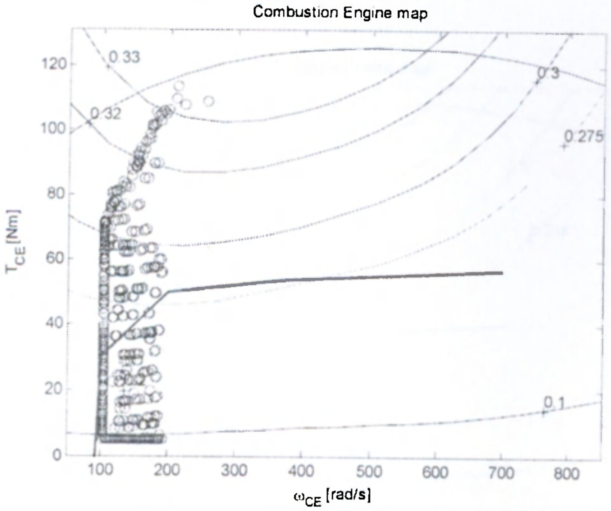


Figure 5.11: Results of Conventional vehicle in CDC 2U

CDC 2D Drive cycle

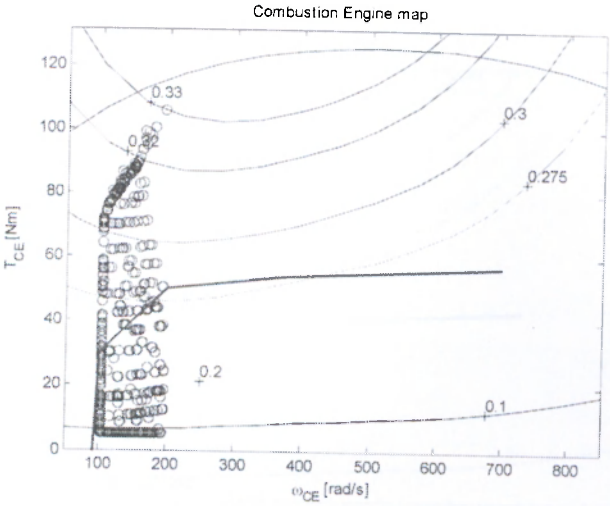


Figure 5.12: Results of Conventional vehicle in CDC 2D

European NEDC

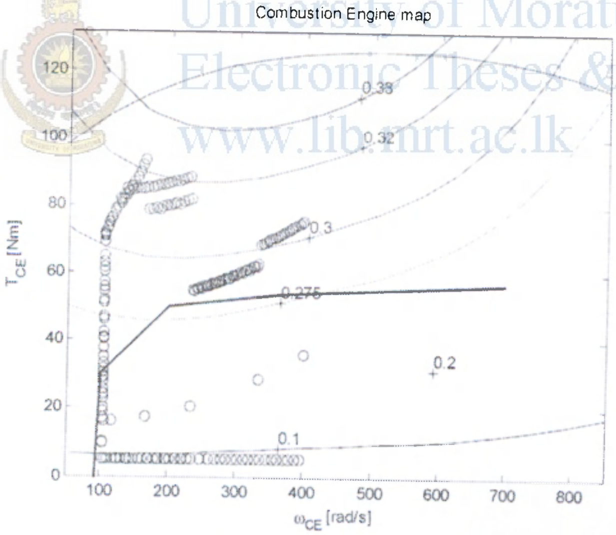


Figure 5.13: Results of Conventional vehicle in NEDC

US FTP Highway

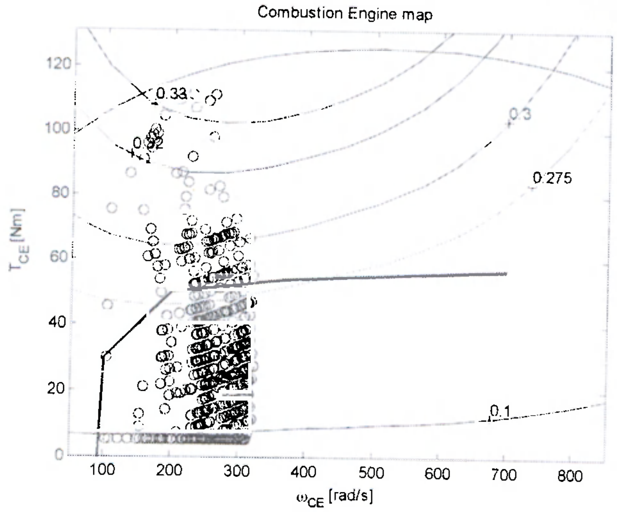


Figure 5.14: Results of Conventional vehicle in FTP HIghway

Japan 10 15

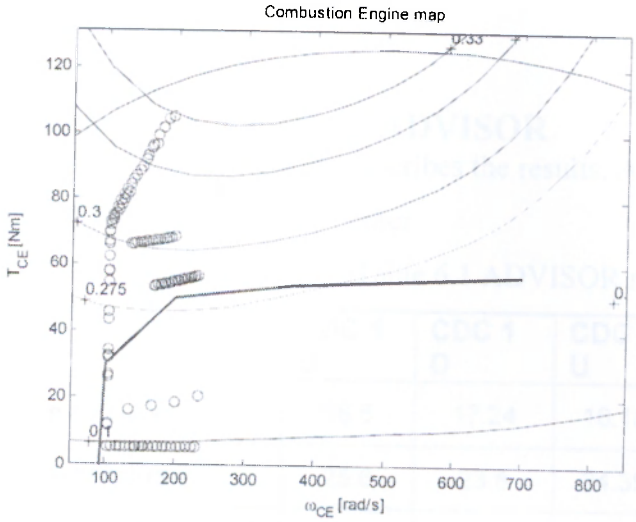


Figure 5.15: Results of Conventional vehicle in Japan 10-15

CHAPTER 06

ADVISOR Results

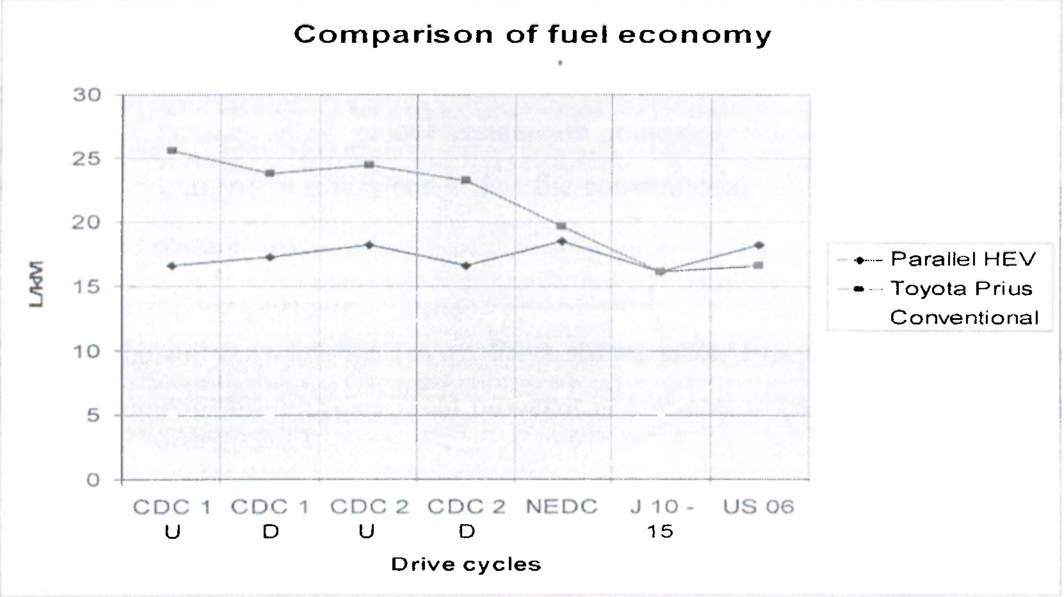
6.1Simulation Results in ADVISOR

In summery following table describes the results. All the relevant result sheets are attached to the end of this chapter

Table 6.1 ADVISOR results

kM/L	CDC 1 U	CDC 1 D	CDC 2 U	CDC 2 D	NEDC	J 10 - 15	US 06
Parallel HEV	16.6	17.24	18.18	16.6	18.51	16.129	18.18
Toyota Prius	25.6	23.8	24.39	23.25	19.6	16.12	16.6
Conventional	5.12	5.12	6.21	5.68	6.711	4.97	9.34

Distance (kM)	5.9	5.1	6.5	6.5	10.9	4.2	12.9
Time(Sec)	930	845	784	841	1184	660	600
Max. Speed(km/h)	47.8	39.5	57.9	59	120	69.97	129.23
Avg. Speed (km/h)	23.57	21.91	29.85	27.73	33.21	22.68	77.2
Avg. Acc^n (ms^-2)	0.29	0.27	0.33	0.35	0.54	0.57	0.67
Avg. dec^n (ms^-2)	-0.32	-0.32	-0.41	-0.41	-0.79	-0.65	-0.73
Idle time(Sec)	64	10	37	72	298	215	45



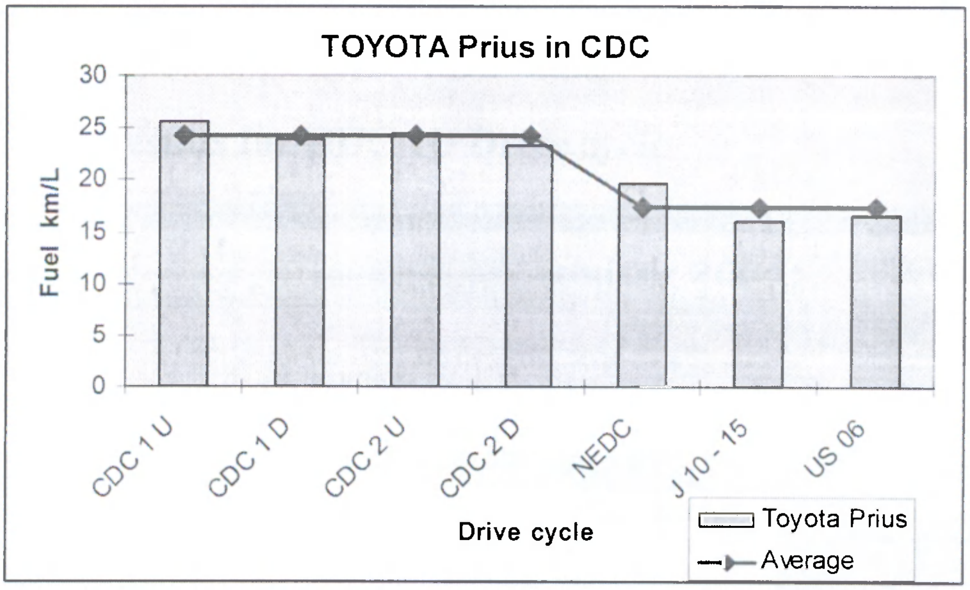


Fig 6.1 Graph of fuel economy

When studying the Table 6.1 and the chart 6.1 it is obvious that the optimizing process is essential and very effective to improve fuel economy. The best example is Toyota Prius car. The optimized duel mode HEV is showing a real edge over other models. Even in Toyota Prius the most significant is it is more economical in complex or irregularly varying drive cycles such as CDC. This difference is clearly visible in the chart in figure 6.1.

According to the simulation results the conventional vehicle shows maximum fuel economy only when the speed variation is very minimum. That means the vehicle is cruising without any acceleration or deceleration. The simulation results for US 06 highway drive cycle is an example.

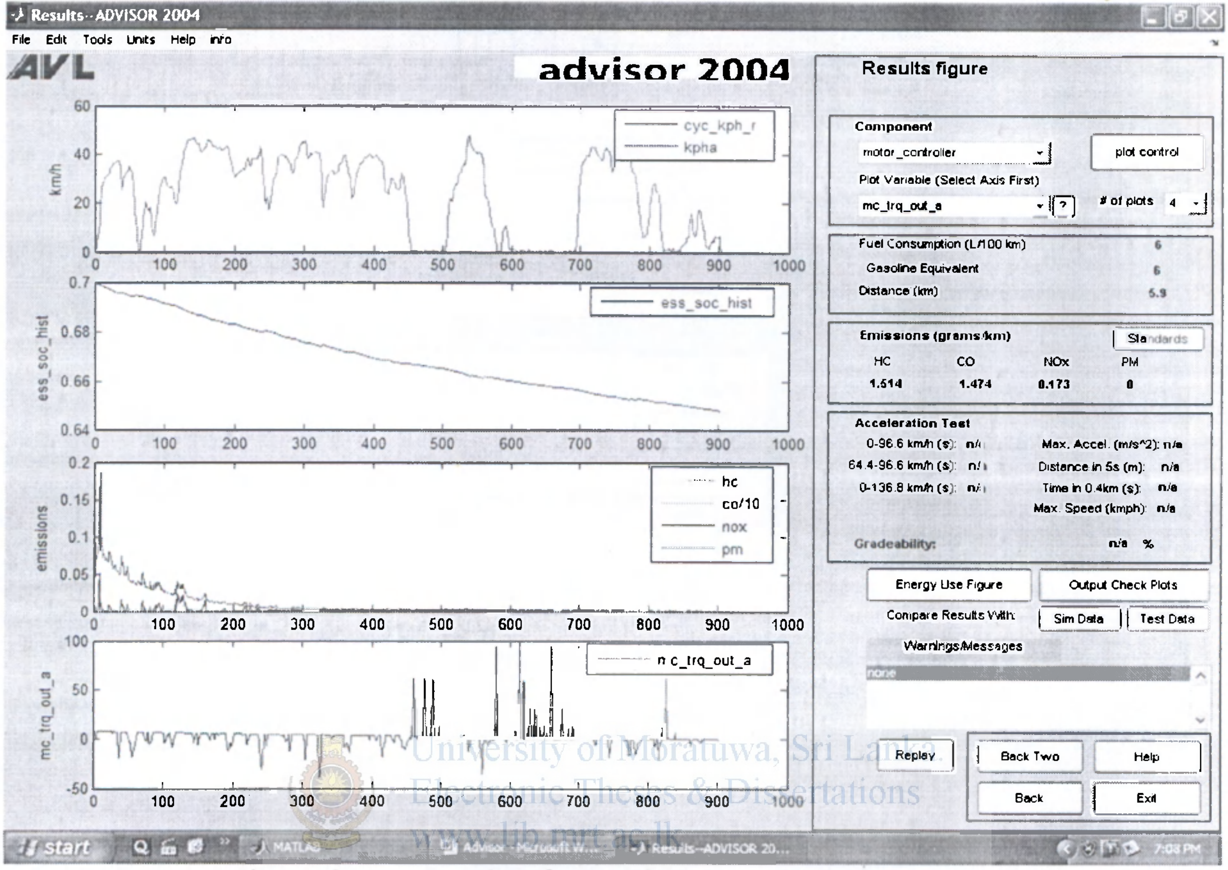
The dfault parallel HEV model results are indicated between the two extremes explained above. Always it is better than the conventional vehicle and not so close to optimized Toyota Prius.

In Colombo drive cycles the Toyota Prius shows better fuel economy than in other selected standard drive cycles. That proves it is essential to cater those unpredictable and always changing factors in drive cycles.

It is very important to simulate all vehicles in such drive cycles as CDC for performance evaluating. Also in HEV optimization it is essential to consider these situations in their optimization processes to obtain better performances.

6.2 Parallel HEV in ADVISOR

6.2.1 Results for CDC 1U Drive cycle



Results figure

Component: motor_controller

plot control

Plot Variable (Select Axis First): mc_trq_out_a

\# of plots: 4

Fuel Consumption (L/100 km): 6

Gasoline Equivalent: 6

Distance (km): 5.9

Emissions (grams/km)

HC	CO	NOx	PM
1.514	1.474	0.173	0

Standards

Acceleration Test

0-96.6 km/h (s): n/a

64.4-96.6 km/h (s): n/a

0-136.8 km/h (s): n/a

Max. Accel. (m/s^2): n/a

Distance in 5s (m): n/a

Time in 0.4km (s): n/a

Max. Speed (kmph): n/a

Gradeability: n/a %

Energy Use Figure

Output Check Plots

Compare Results With: Sim Data | Test Data

Warnings/Messages

none

Replay | Back Two | Help | Back | Exit

Figure 6.2: Results of parallel HEV in CDC 1U

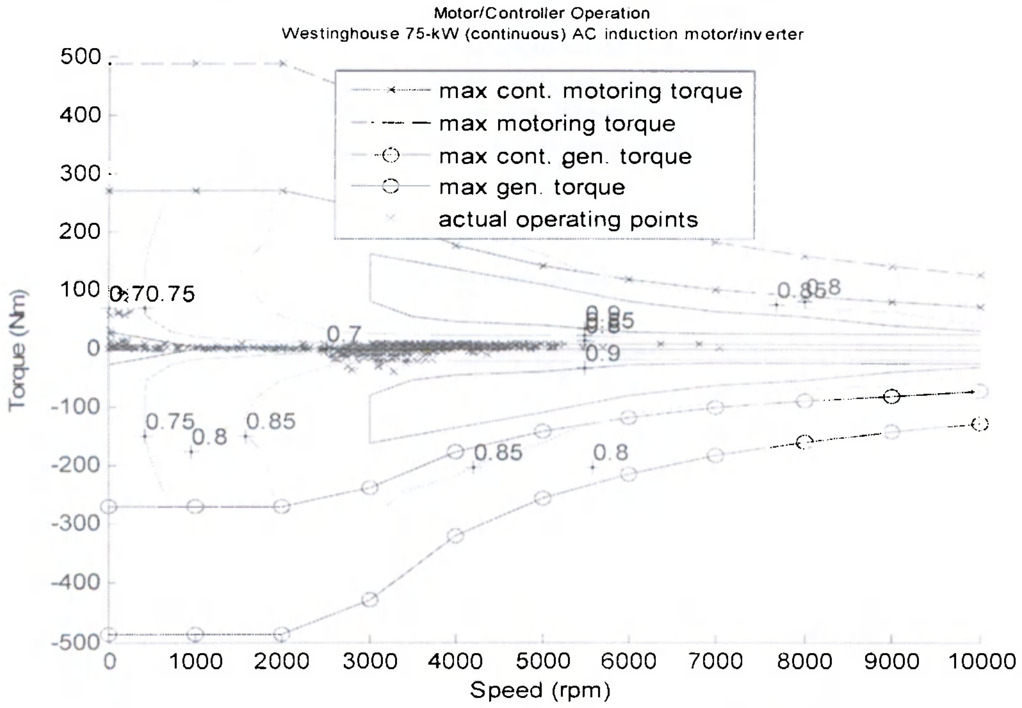
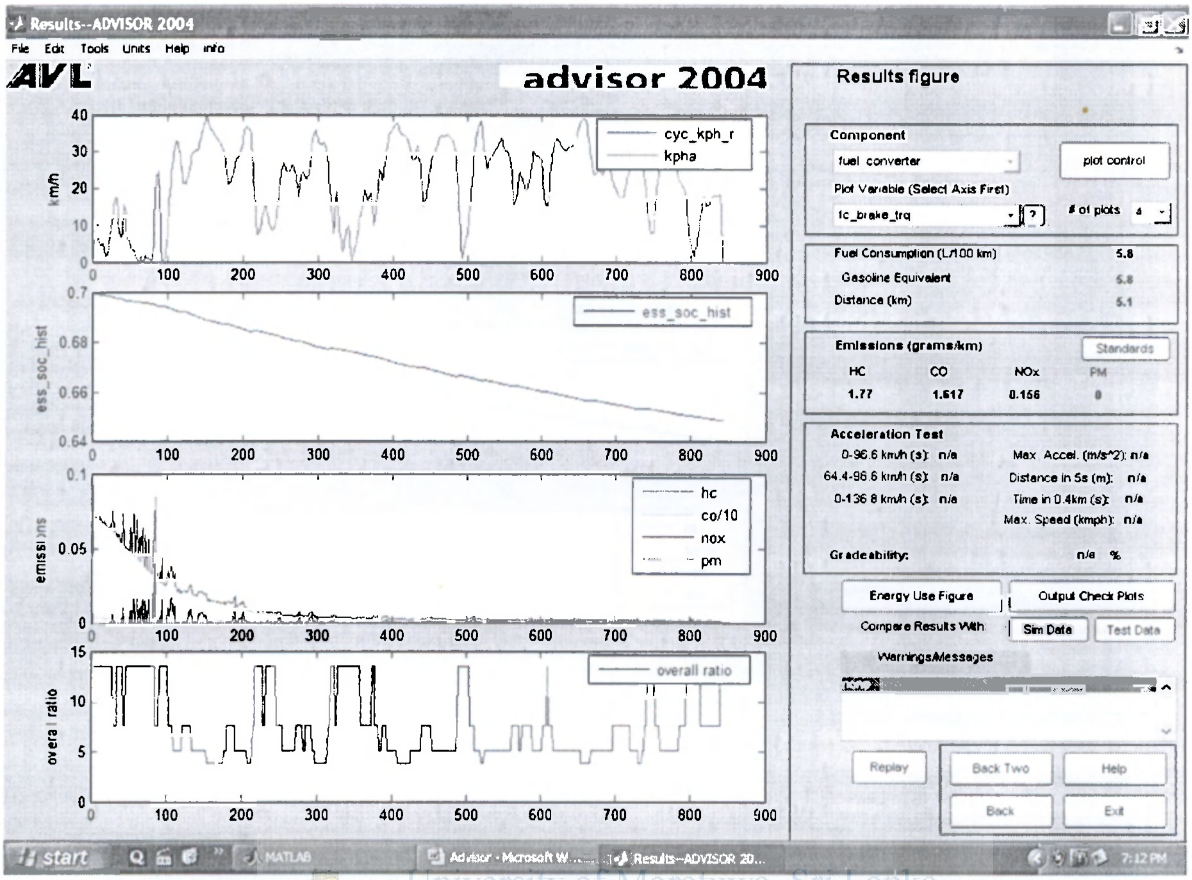


Figure 6.3: Motor efficiency of parallel HEV in CDC 1U

6.2.2 Results for CDC 1D Drive cycle



Component

fuel converter

Plot Variable (Select Axis First)

fc_brake_trq

# of plots 4

Fuel Consumption (L/100 km)	5.8
Gasoline Equivalent	5.8
Distance (km)	5.1

Emissions (grams/km)

HC	CO	NOx	PM
1.77	1.617	0.156	0

Acceleration Test

0-96.6 km/h (s): n/a

64.4-96.6 km/h (s): n/a

0-136.8 km/h (s): n/a

Max. Accel. (m/s^2): n/a

Distance in 5s (m): n/a

Time in 0.4km (s): n/a

Max. Speed (kmph): n/a

Gradeability: n/a %

Figure 6.4: Results of parallel HEV in CDC 1D

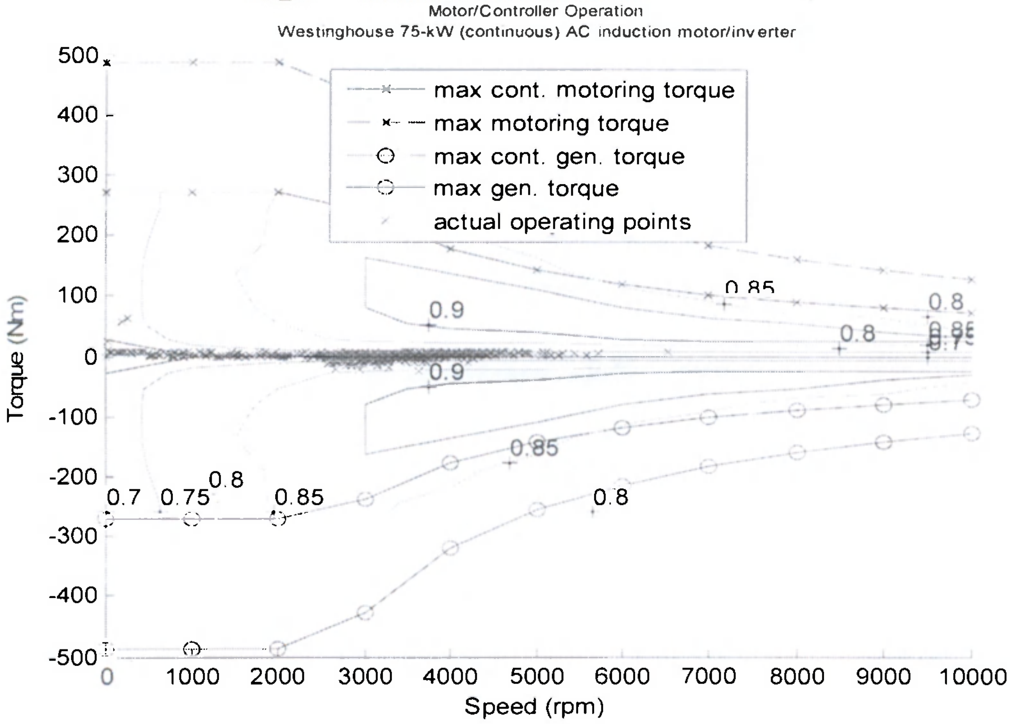
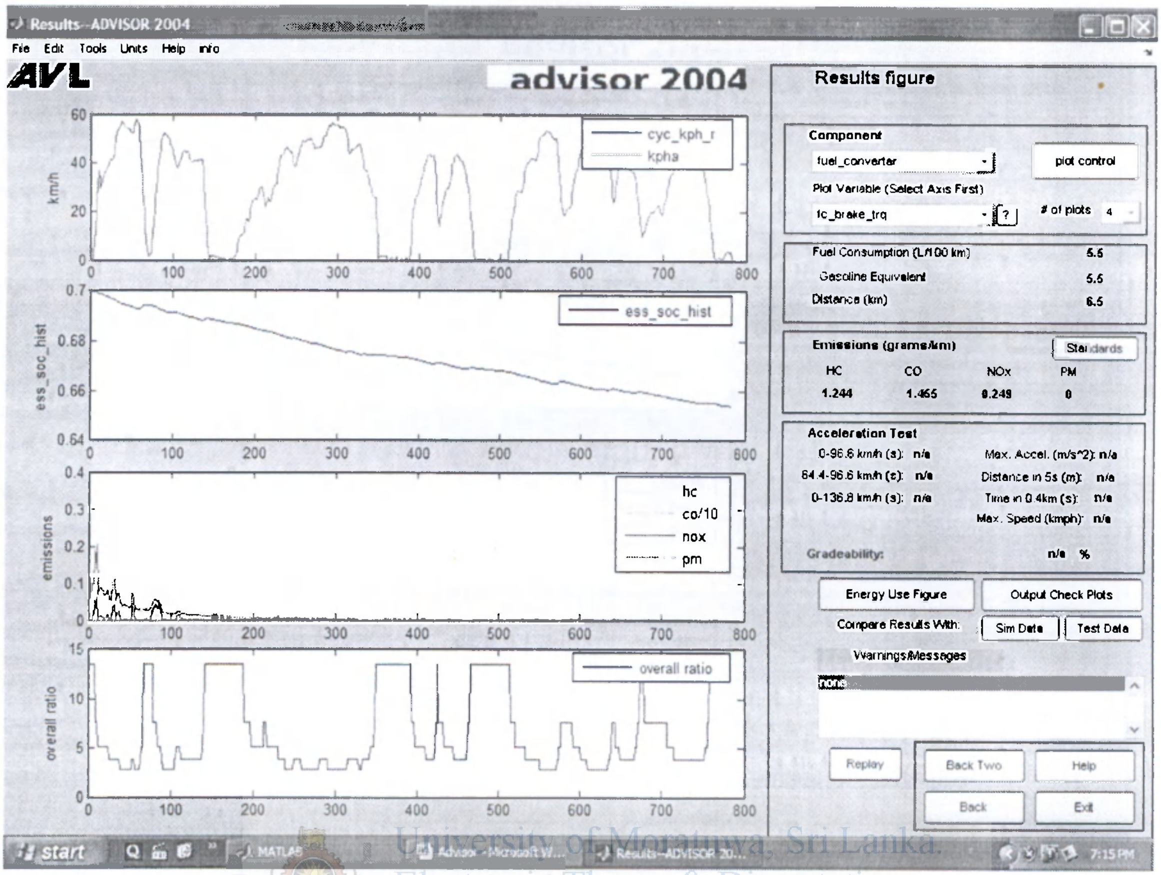


Figure 6.5: Motor efficiency of parallel HEV in CDC 1D

6.2.3 Results for CDC 2U Drive cycle



Component: fuel_converter

Plot Variable (Select Axis First): fc_brake_trq

# of plots: 4

Fuel Consumption (L/100 km): 5.5

Gasoline Equivalent: 5.5

Distance (km): 6.5

Emissions (grams/km)

HC	CO	NOx	PM
1.244	1.465	0.249	0

Acceleration Test

0-96.6 km/h (s): n/a

64.4-96.6 km/h (s): n/a

0-136.8 km/h (s): n/a

Max. Accel. (m/s^2): n/a

Distance in 5s (m): n/a

Time in 0.4km (s): n/a

Max. Speed (kmph): n/a

Gradeability: n/a %

Compare Results With:

Warnings/Messages

none

Figure 6.6: Results of parallel HEV in CDC 2U

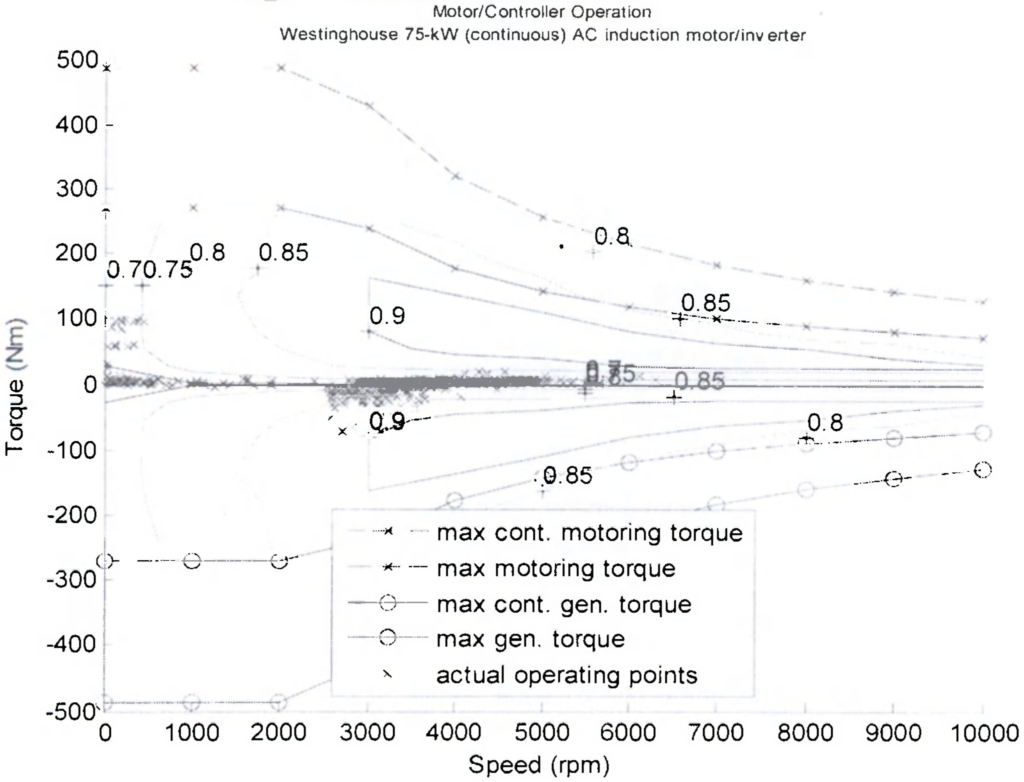
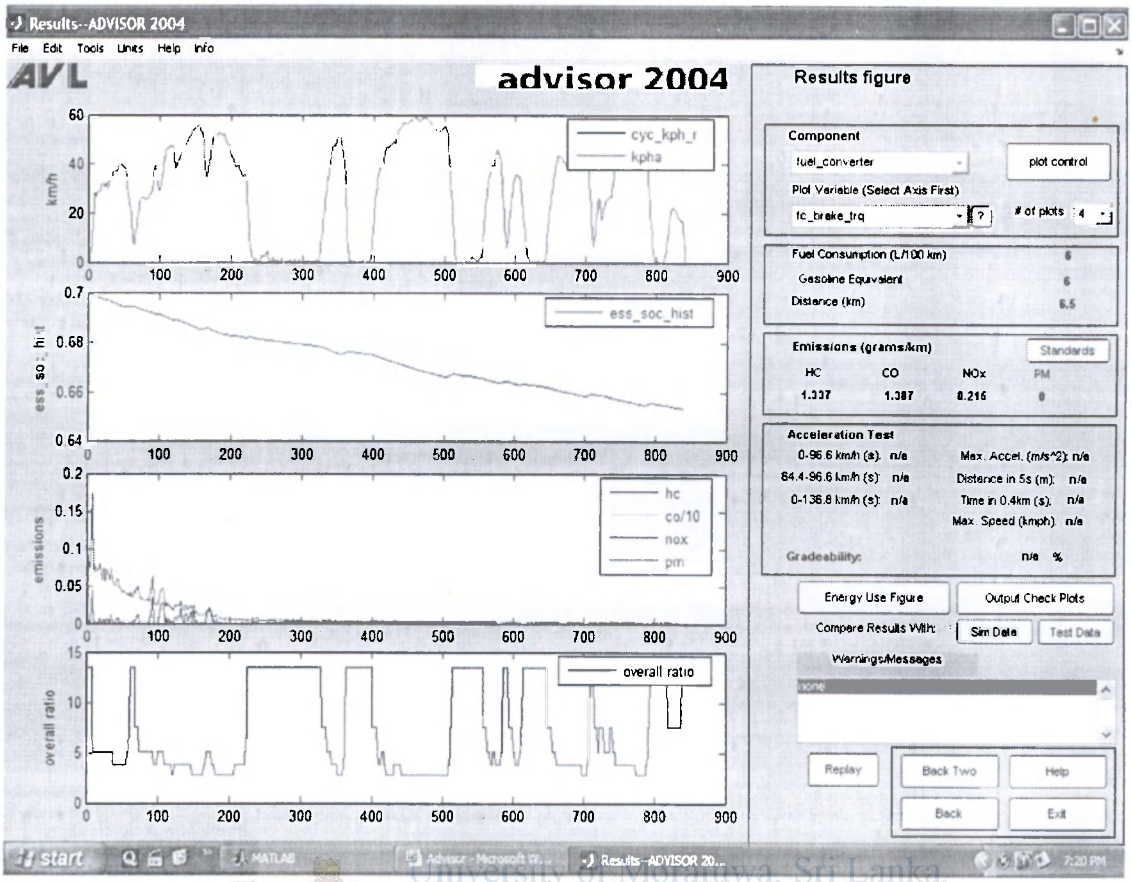


Figure 6.7: Motor efficiency of parallel HEV in CDC 2U

6.2.4 Results for CDC 2D Drive cycle



Results figure

Component: fuel_converter

plot control

Plot Variable (Select Axis First): fc_brake_trq

# of plots: 4

Fuel Consumption (L/100 km) 6

Gasoline Equivalent 6

Distance (km) 6.5

Emissions (grams/km)

HC	CO	NOx	PM
1.337	1.387	0.216	0

Acceleration Test

0-96.6 km/h (s): n/a

64.4-96.6 km/h (s): n/a

0-136.8 km/h (s): n/a

Max. Accel. (m/s^2): n/a

Distance in 5s (m): n/a

Time in 0.4km (s): n/a

Max. Speed (kmph): n/a

Gradeability: n/a %

Warnings/Messages

none

Figure 6.8: Results of parallel HEV in CDC 2D

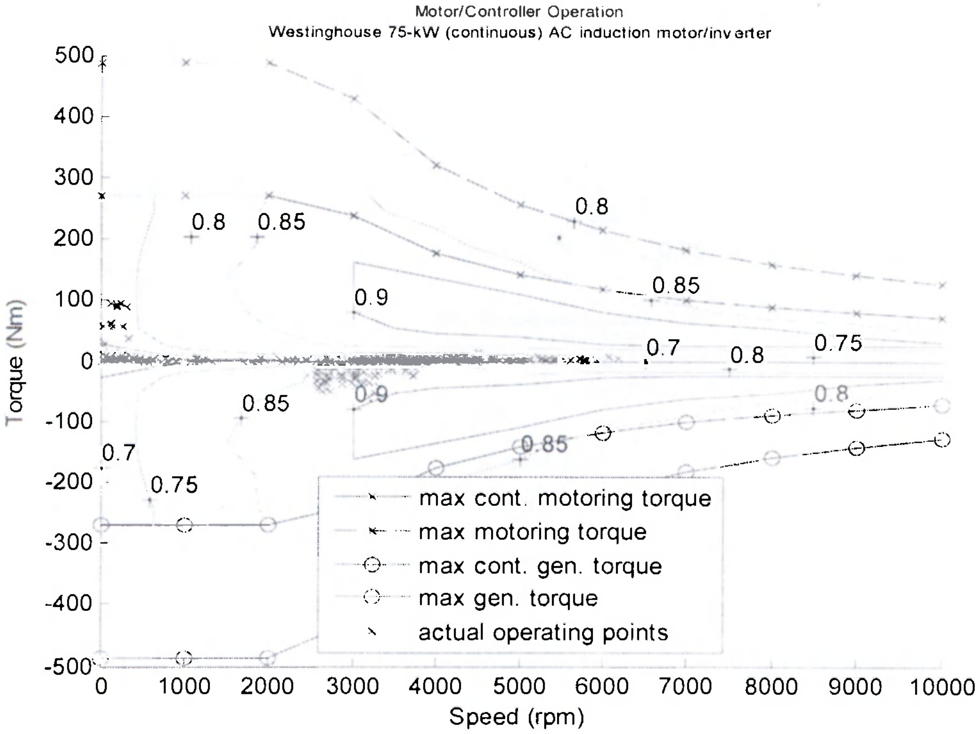
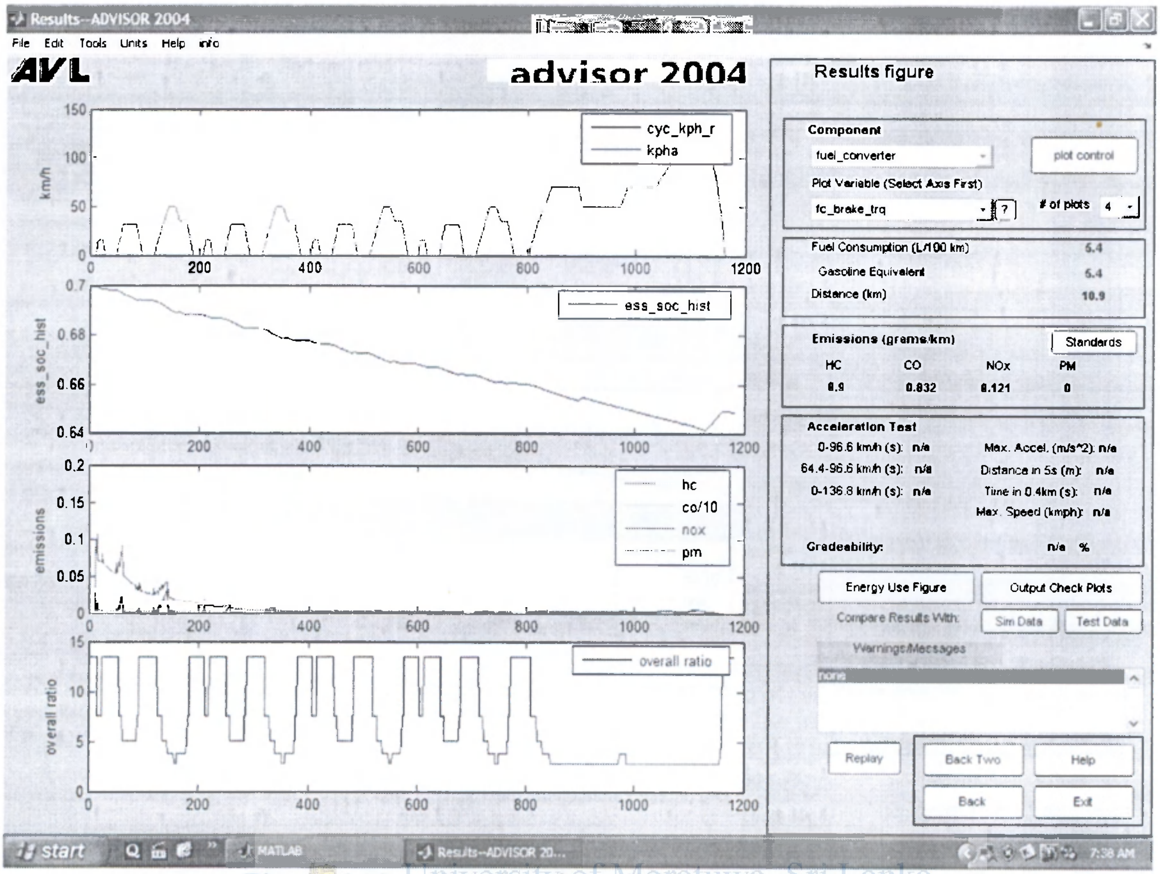


Figure 6.9: Motor efficiency of parallel HEV in CDC 2D

6.2.5 Results for NEDC Drive cycle



Results figure

Component

fuel_converter

Plot Variable (Select Axis First)

fc_brake_trq

# of plots 4

Fuel Consumption (L/100 km)	6.4
Gasoline Equivalent	6.4
Distance (km)	10.9

Emissions (grams/km)

HC	CO	NOx	PM
0.9	0.832	0.121	0

Acceleration Test

0-96.6 km/h (s): n/a

64.4-96.6 km/h (s): n/a

0-136.8 km/h (s): n/a

Max. Accel. (m/s^2): n/a

Distance in 5s (m): n/a

Time in 0.4km (s): n/a

Max. Speed (kmph): n/a

Gradeability: n/a %

Warnings/Messages: none

Figure 6.10: Results of parallel HEV in NEDC

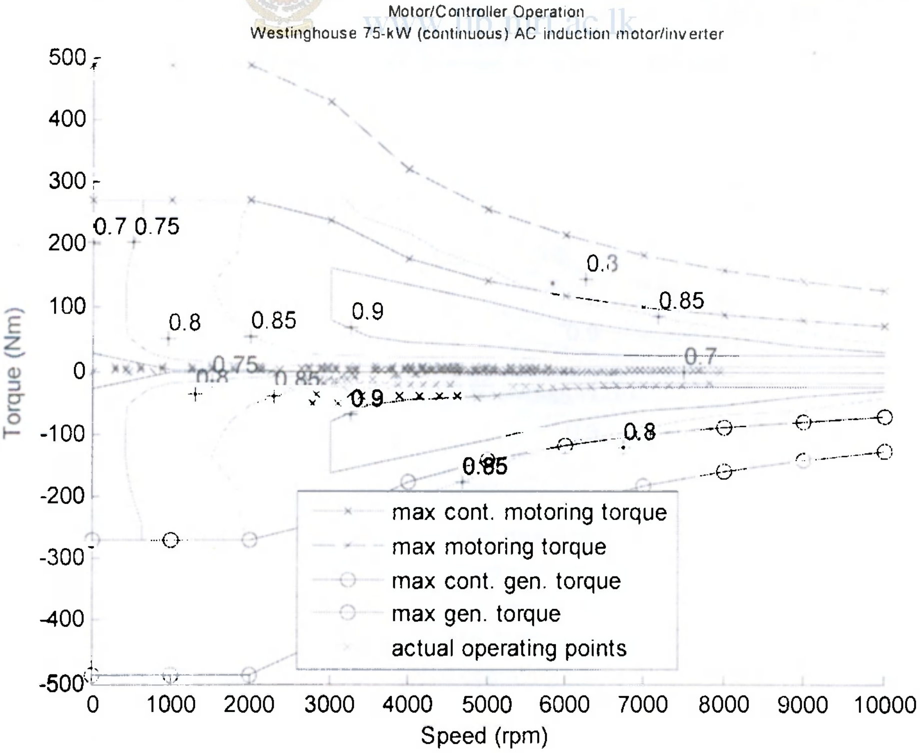
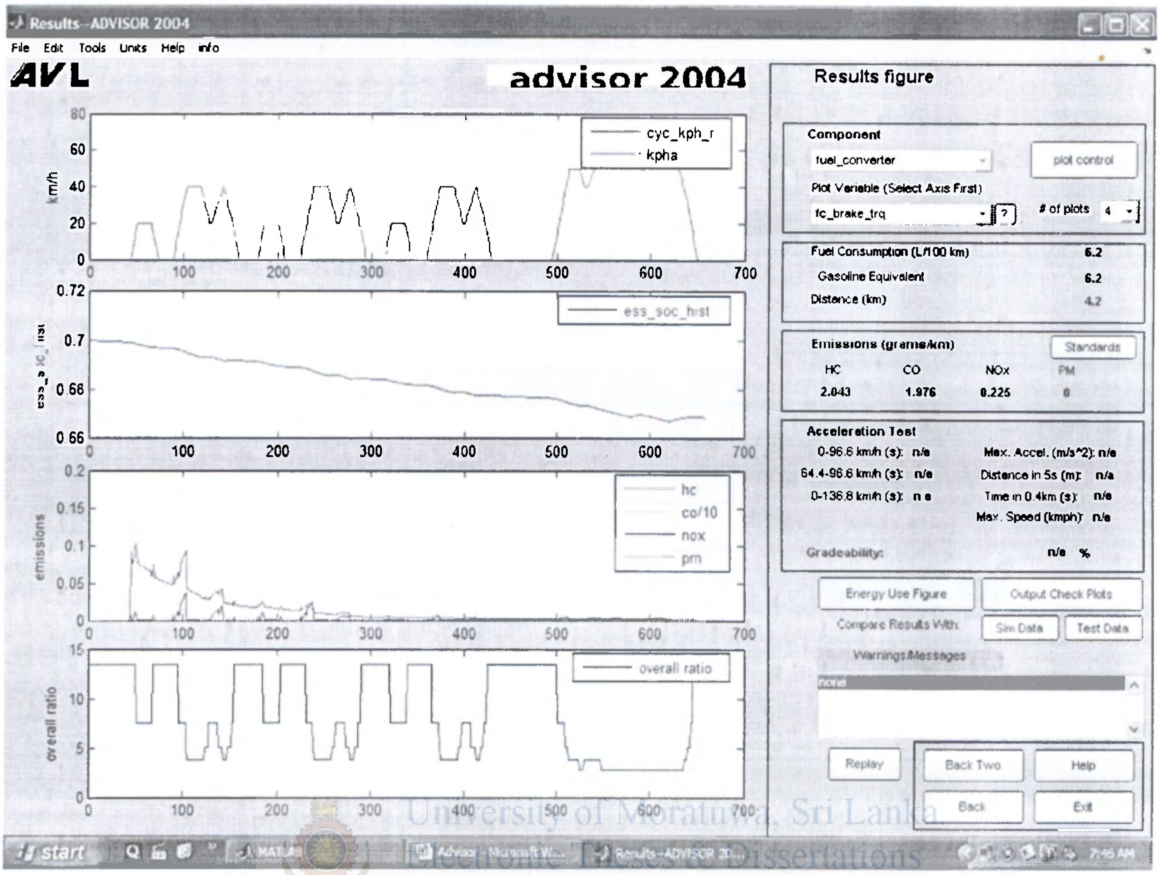


Figure 6.11: Motor efficiency of parallel HEV in NEDC

6.2.6 Results for JAPAN 10-15 Drive cycle



Results figure

Component: fuel_converter

Plot Variable (Select Axis First): fc_brake_trq

# of plots: 4

Fuel Consumption (L/100 km) 6.2
Gasoline Equivalent 6.2
Distance (km) 4.2

Emissions (grams/km)

HC	CO	NOx	PM
2.043	1.976	0.225	0

Acceleration Test
0-96.6 km/h (s): n/a
64.4-96.6 km/h (s): n/a
0-136.8 km/h (s): n/a
Max. Accel. (m/s^2): n/a
Distance in 5s (m): n/a
Time in 0.4km (s): n/a
Max. Speed (kmph): n/a
Gradeability: n/a %

Warnings/Messages: none

Figure 6.12: Results of parallel HEV in Japan 10-15

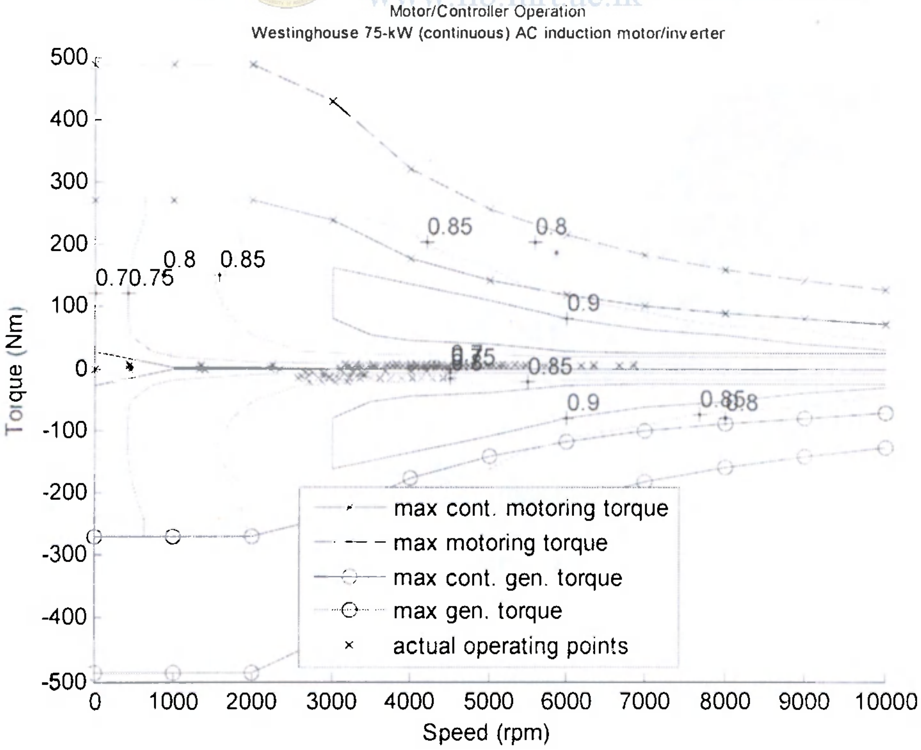
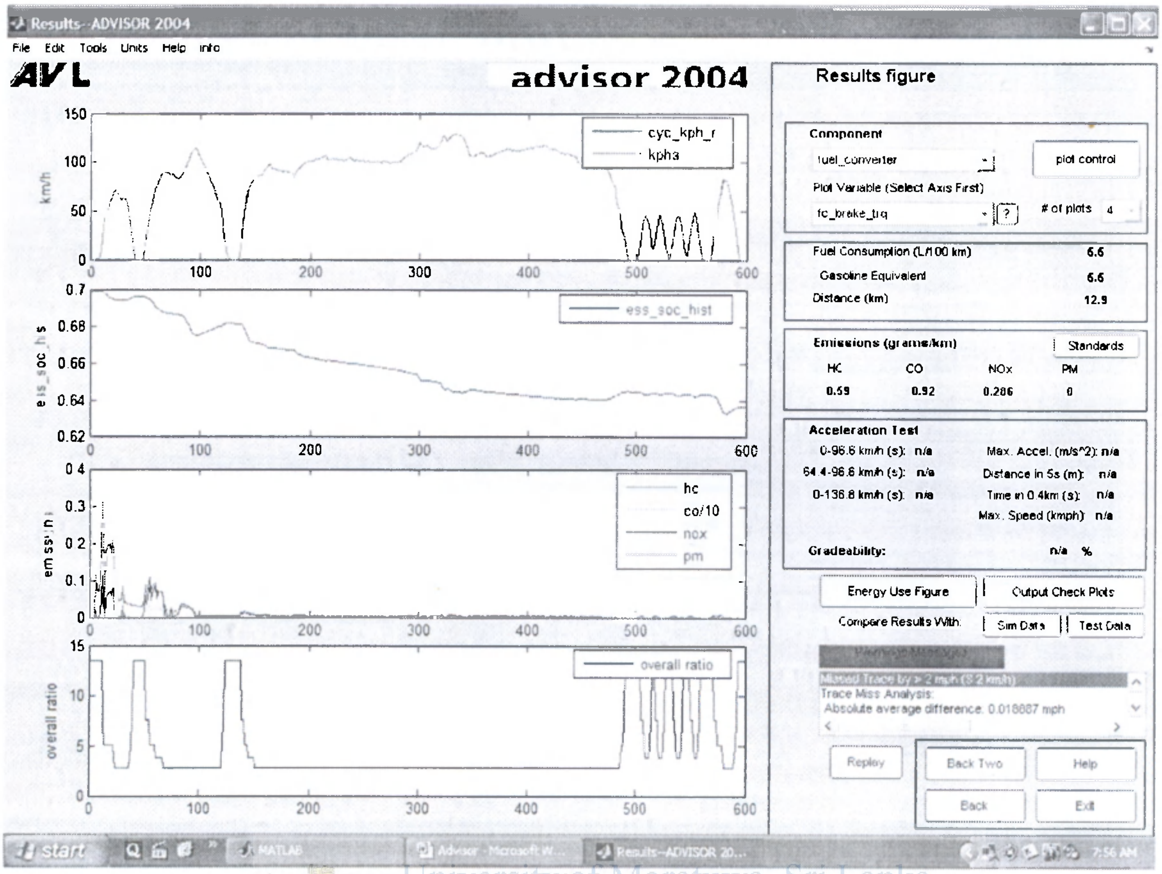


Figure 6.13: Motor efficiency of parallel HEV in Japan 10-15

6.2.2 Results for US 06 Drive cycle



Results figure

Component: fuel_converter
Plot Variable (Select Axis First): fc_brake_trq
# of plots: 4

Fuel Consumption (L/100 km) 6.6
Gasoline Equivalent 6.6
Distance (km) 12.9

Emissions (grams/km)

HC	CO	NOx	PM
0.59	0.92	0.206	0

Acceleration Test
0-96.6 km/h (s): n/a
64.4-96.6 km/h (s): n/a
0-136.8 km/h (s): n/a
Max. Accel. (m/s^2): n/a
Distance in 5s (m): n/a
Time in 0.4km (s): n/a
Max. Speed (kmph): n/a
Gradeability: n/a %

Compare Results With:

Missed Trace by > 2 mph (3.2 km/h)
Trace Miss Analysis:
Absolute average difference: 0.018887 mph

Figure 6.14: Results of parallel HEV in US 06

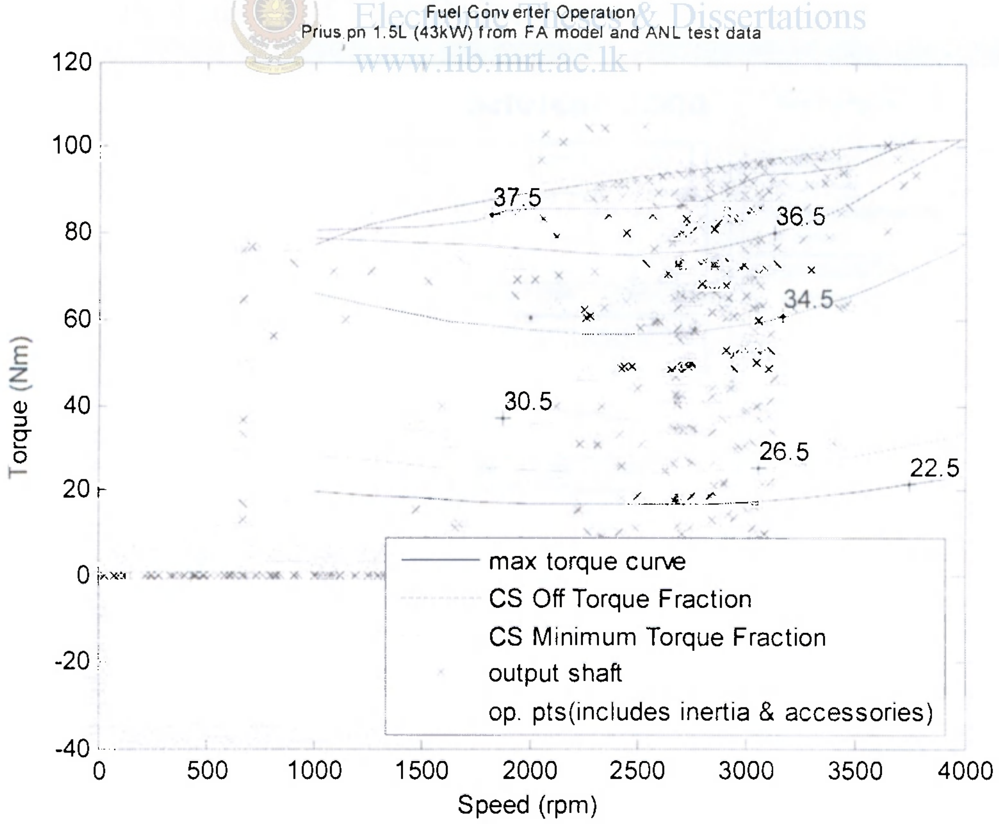
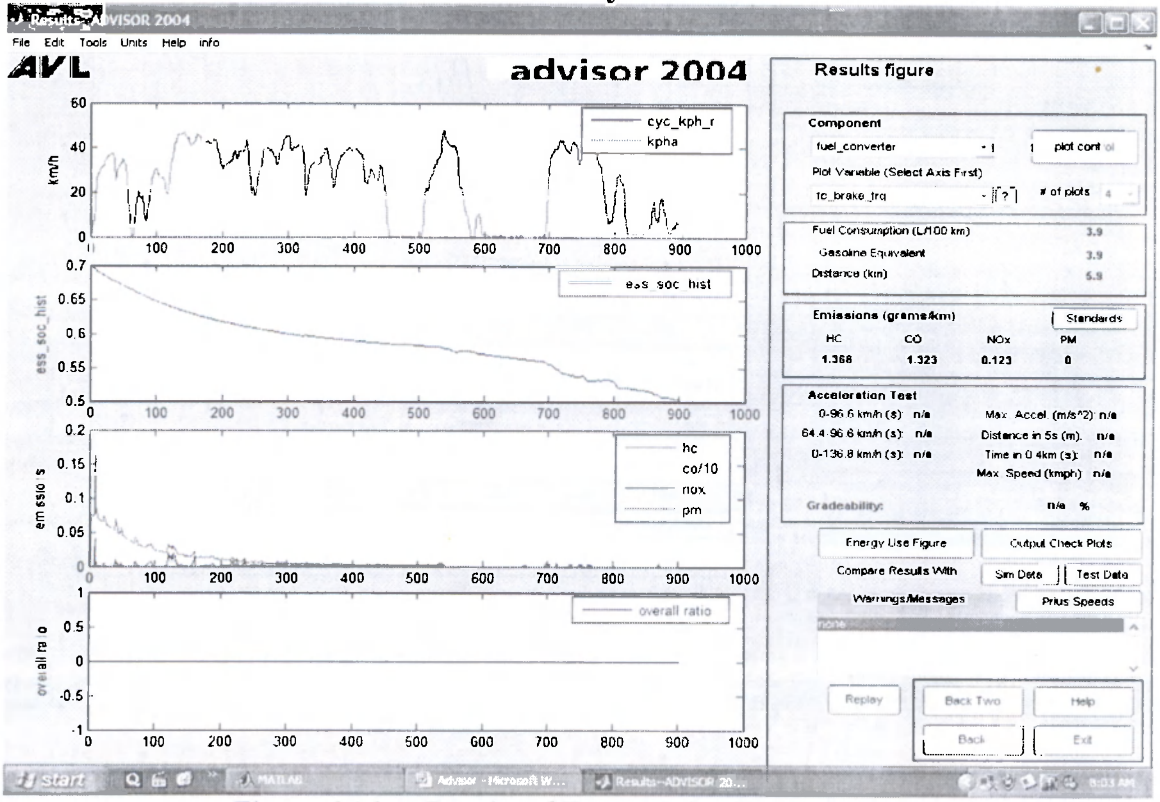


Figure 6.15: Motor efficiency of parallel HEV in US 06

6.3 Toyota Prius -Japan car on ADVISOR

6.3.1 Results for CDC 1U Drive cycle



Results figure

Component: fuel_converter

Plot Variable (Select Axis First): fc_brake_trq

\# of plots: 4

Fuel Consumption (L/100 km) 3.9

Gasoline Equivalent 3.9

Distance (km) 5.9

Emissions (grams/km)

HC	CO	NOx	PM
1.368	1.323	0.123	0

Acceleration Test

0-96.6 km/h (s): n/a

64.4-96.6 km/h (s): n/a

0-136.8 km/h (s): n/a

Max. Accel. (m/s^2): n/a

Distance in 5s (m): n/a

Time in 0.4km (s): n/a

Max. Speed (kmph): n/a

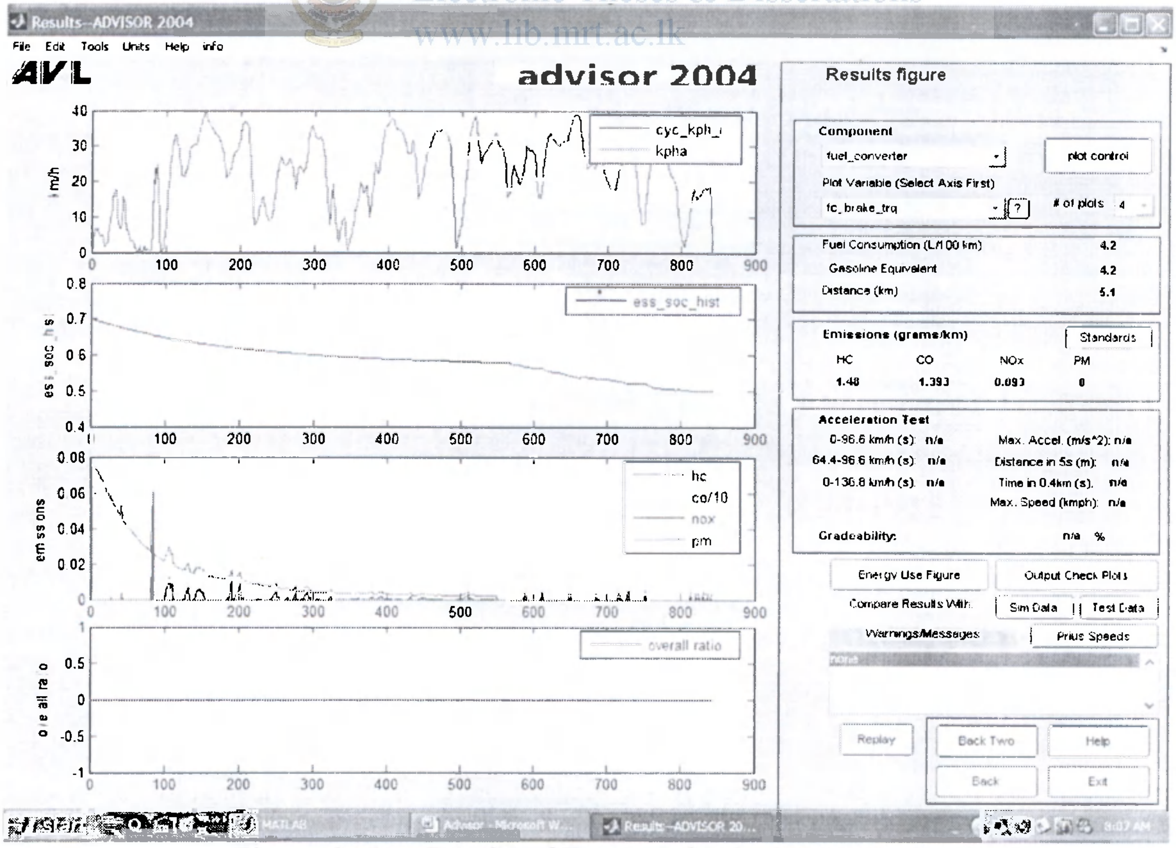
Gradeability: n/a %

Compare Results With

Warnings/Messages: none

Figure 6.16: Results of Toyota Prius in CDC 1U

6.3.2 Results for CDC 1D Drive cycle



Results figure

Component: fuel_converter

Plot Variable (Select Axis First): fc_brake_trq

\# of plots: 4

Fuel Consumption (L/100 km) 4.2

Gasoline Equivalent 4.2

Distance (km) 5.1

Emissions (grams/km)

HC	CO	NOx	PM
1.48	1.393	0.093	0

Acceleration Test

0-96.6 km/h (s): n/a

64.4-96.6 km/h (s): n/a

0-136.8 km/h (s): n/a

Max. Accel. (m/s^2): n/a

Distance in 5s (m): n/a

Time in 0.4km (s): n/a

Max. Speed (kmph): n/a

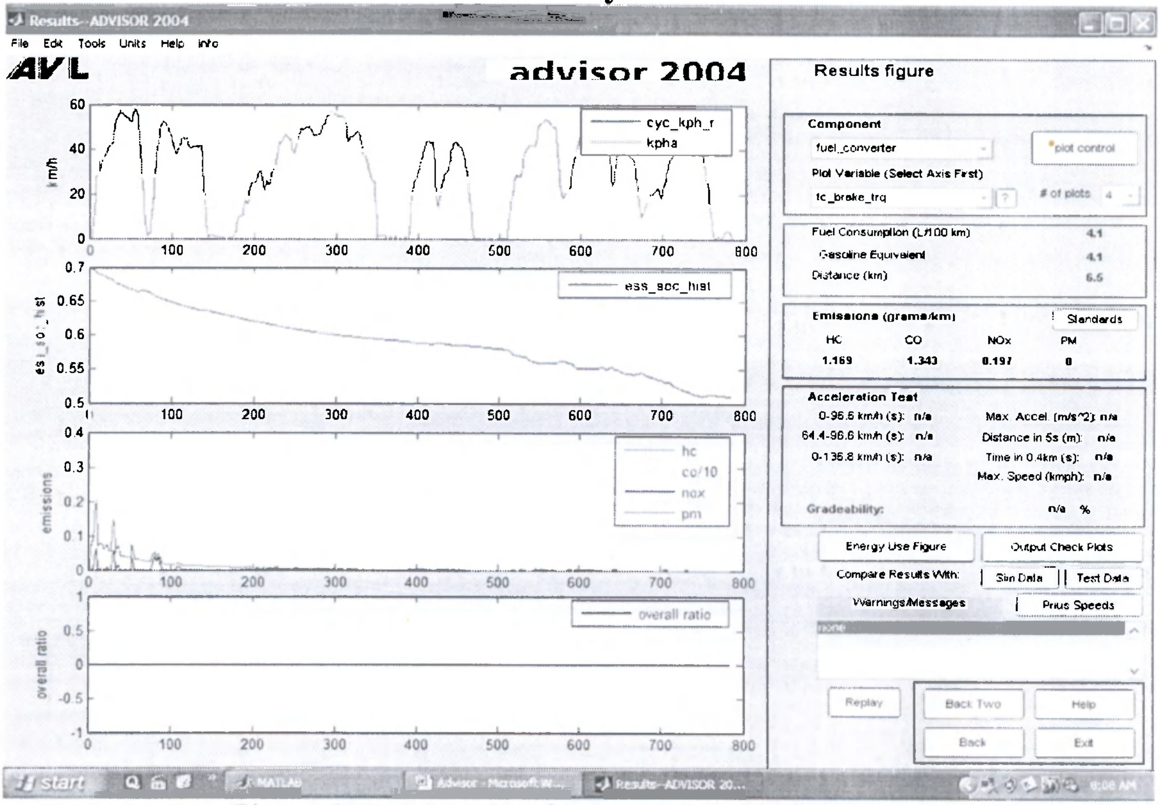
Gradeability: n/a %

Compare Results With

Warnings/Messages: none

Figure 6.17: Results of Toyota Prius in CDC 1D

6.3.3 Results for CDC 2U Drive cycle



Component: fuel_converter
Plot Variable (Select Axis First): fc_brake_trq
# of plots: 4

Fuel Consumption (L/100 km): 4.1
Gasoline Equivalent: 4.1
Distance (km): 6.5

Emissions (grams/km)

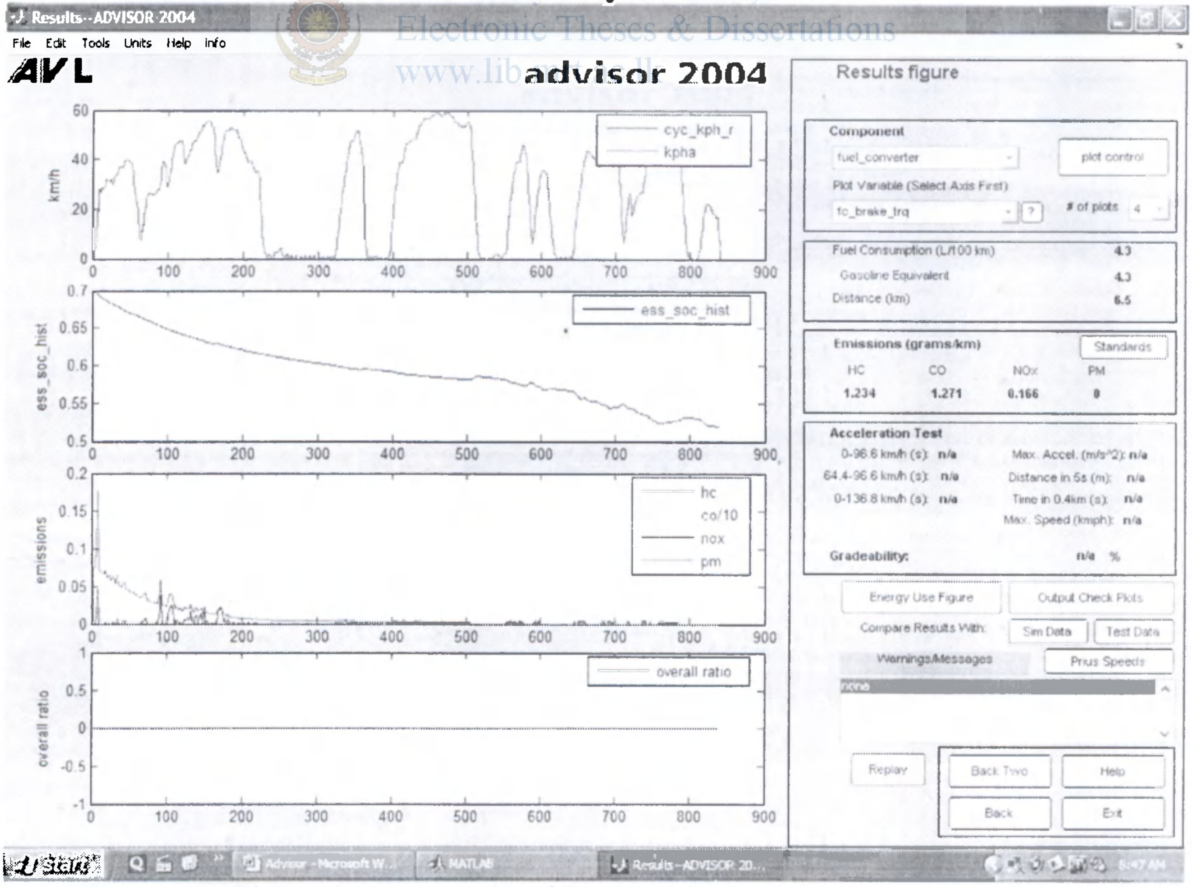
HC	CO	NOx	PM
1.169	1.343	0.197	0

Acceleration Test
0-96.6 km/h (s): n/a
64.4-96.6 km/h (s): n/a
0-136.8 km/h (s): n/a
Max. Accel. (m/s^2): n/a
Distance in 5s (m): n/a
Time in 0.4km (s): n/a
Max. Speed (kmph): n/a
Gradeability: n/a %

Compare Results With:
Warnings/Messages: none

Figure 6.18: Results of Toyota Prius in CDC 2U

6.3.4 Results for CDC 2D Drive cycle



Component: fuel_converter
Plot Variable (Select Axis First): fc_brake_trq
# of plots: 4

Fuel Consumption (L/100 km): 4.3
Gasoline Equivalent: 4.3
Distance (km): 6.5

Emissions (grams/km)

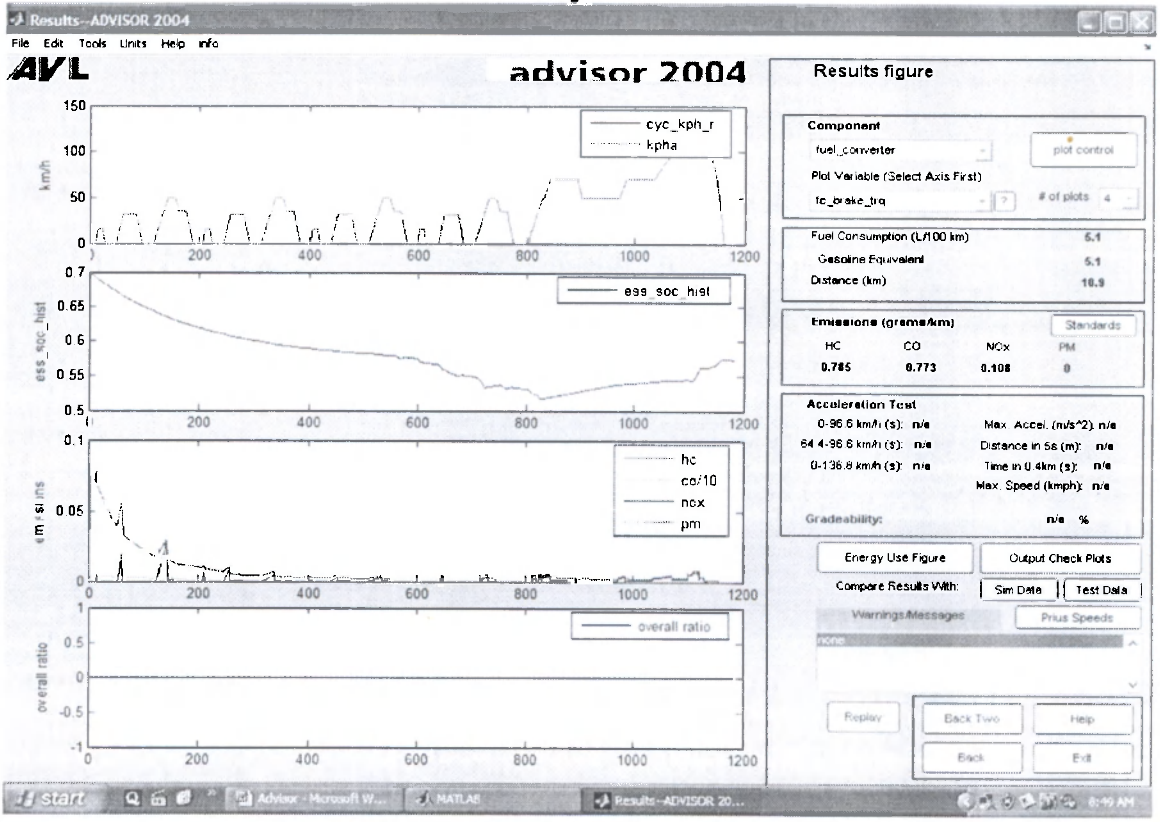
HC	CO	NOx	PM
1.234	1.271	0.166	0

Acceleration Test
0-96.6 km/h (s): n/a
64.4-96.6 km/h (s): n/a
0-136.8 km/h (s): n/a
Max. Accel. (m/s^2): n/a
Distance in 5s (m): n/a
Time in 0.4km (s): n/a
Max. Speed (kmph): n/a
Gradeability: n/a %

Compare Results With:
Warnings/Messages: none

Figure 6.19: Results of Toyota Prius in CDC 2D

6.3.5 Results for NEDC Drive cycle



Component: fuel_converter
Plot Variable (Select Axis First): fc_brake_trq
# of plots: 4

Fuel Consumption (L/100 km) 5.1
Gasoline Equivalent 5.1
Distance (km) 10.9

Emissions (grams/km)

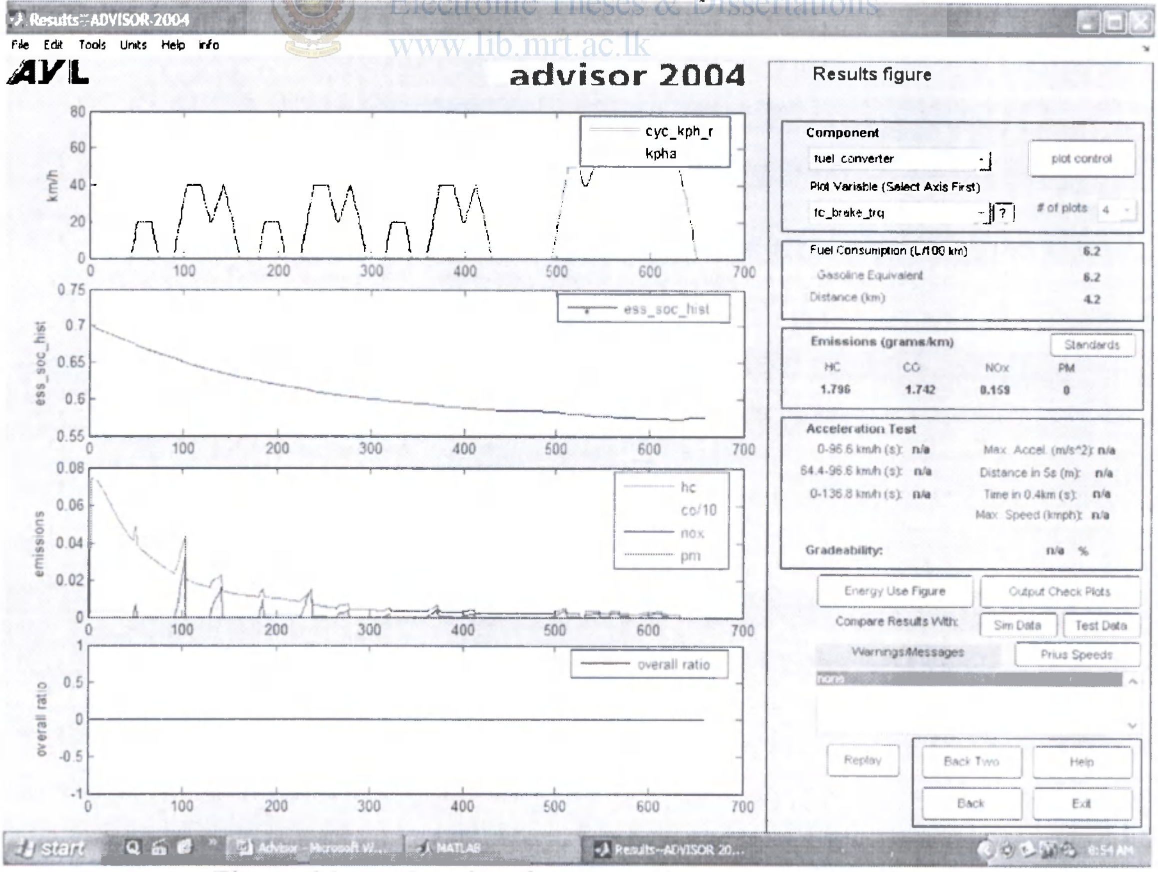
HC	CO	NOx	PM
0.785	0.773	0.108	0

Acceleration Test
0-96.6 km/h (s): n/a
64.4-96.6 km/h (s): n/a
0-136.8 km/h (s): n/a
Max. Accel. (m/s^2): n/a
Distance in 5s (m): n/a
Time in 0.4km (s): n/a
Max. Speed (kmph): n/a
Gradeability: n/a %

Compare Results With:
Warnings/Messages: none

Figure 6.20: Results of Toyota Prius in NEDC

6.3.6 Results for JAPAN 10-15 Drive cycle



Component: fuel_converter
Plot Variable (Select Axis First): fc_brake_trq
# of plots: 4

Fuel Consumption (L/100 km) 6.2
Gasoline Equivalent 6.2
Distance (km) 4.2

Emissions (grams/km)

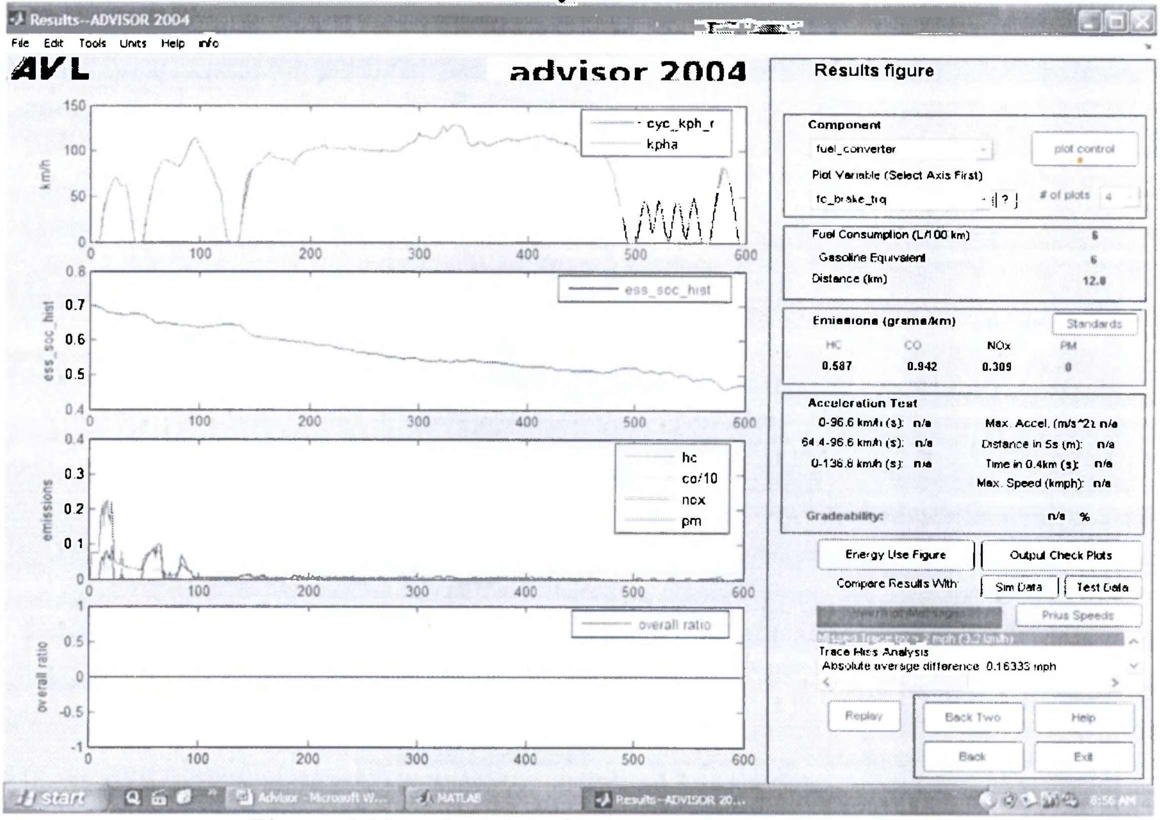
HC	CO	NOx	PM
1.796	1.742	0.159	0

Acceleration Test
0-96.6 km/h (s): n/a
64.4-96.6 km/h (s): n/a
0-136.8 km/h (s): n/a
Max. Accel. (m/s^2): n/a
Distance in 5s (m): n/a
Time in 0.4km (s): n/a
Max. Speed (kmph): n/a
Gradeability: n/a %

Compare Results With:
Warnings/Messages: none

Figure 6.21: Results of Toyota Prius in Japan 10-15

6.3.7 Results for US 06 Drive cycle



Results figure

Component: fuel_converter

Plot Variable (Select Axis First): fc_brake_trq

# of plots: 4

Fuel Consumption (L/100 km): 6

Gasoline Equivalent: 6

Distance (km): 12.8

Emissions (grams/km)

HC	CO	NOx	PM
0.587	0.942	0.309	0

Acceleration Test

0-96.6 km/h (s): n/a

64.4-96.6 km/h (s): n/a

0-136.8 km/h (s): n/a

Max. Accel. (m/s^2): n/a

Distance in 5s (m): n/a

Time in 0.4km (s): n/a

Max. Speed (kmph): n/a

Gradeability: n/a %

Compare Results With:

Missed Trace by > 2 mph (3.2 km/h)

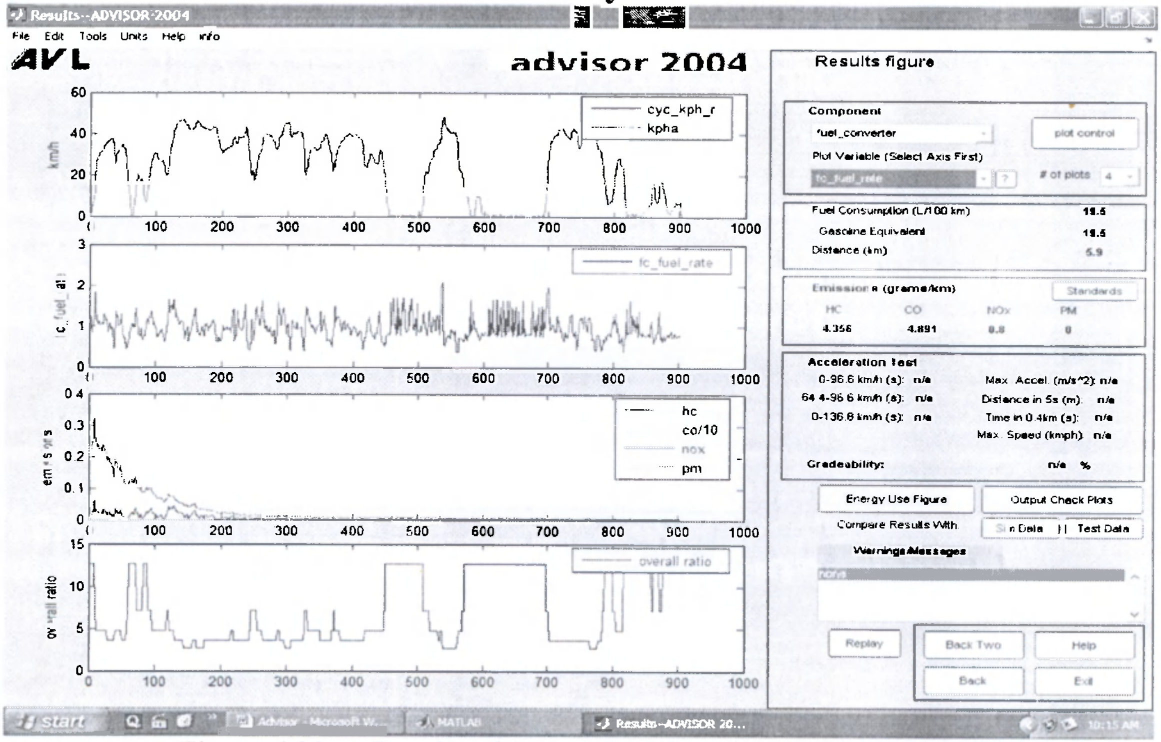
Trace Miss Analysis

Absolute average difference 0.16333 mph

Figure 6.22: Results of Toyota Prius in US 06

6.4Conventional vehicle on ADVISOR

6.4.1 Results for CDC 1U Drive cycle



Results figure

Component: fuel_converter

Plot Variable (Select Axis First): fc_fuel_rate

# of plots: 4

Fuel Consumption (L/100 km) 19.5
Gasoline Equivalent 19.5
Distance (km) 5.9

Emissions (grams/km)

HC	CO	NOx	PM
4.356	4.891	0.8	0

Acceleration Test
0-96.6 km/h (s): n/a
64.4-96.6 km/h (s): n/a
0-136.8 km/h (s): n/a
Max. Accel. (m/s^2): n/a
Distance in 5s (m): n/a
Time in 0.4km (s): n/a
Max. Speed (kmph): n/a
Gradeability: n/a %

Compare Results With: Sim Data || Test Data

Warnings/Messages: none

Figure 6.23: Results of Conventional vehicle in CDC 1U

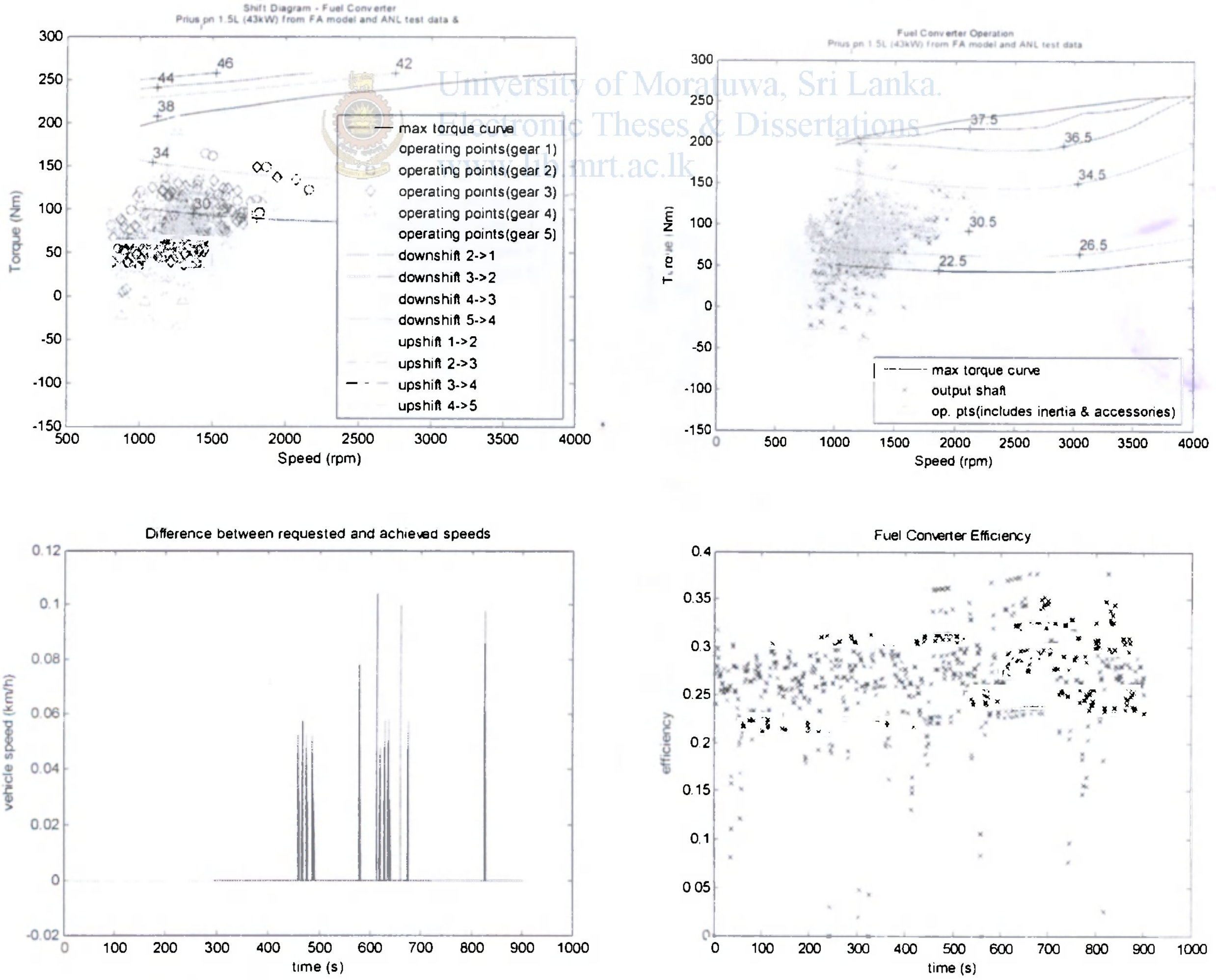
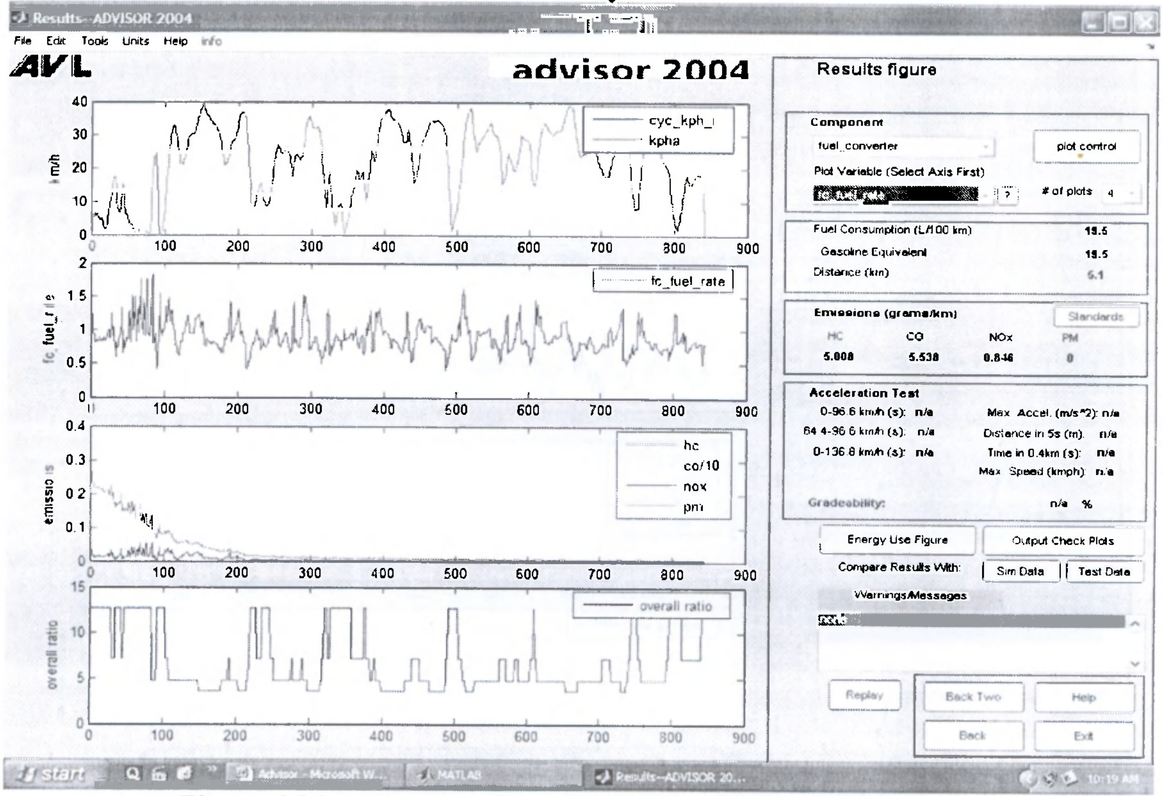


Figure 6.24: Motor efficiency of Conventional vehicle in CDC 1U

6.4.2 Results for CDC 1D Drive cycle



Results figure

Component: fuel_converter

Plot Variable (Select Axis First): fc_fuel_rate

plot control

# of plots: 4

Fuel Consumption (L/100 km): 19.5

Gasoline Equivalent: 19.5

Distance (km): 5.1

Emissions (grams/km)

HC	CO	NOx	PM
5.008	5.538	0.846	0

Acceleration Test

0-96.6 km/h (s): n/a

64.4-96.6 km/h (s): n/a

0-136.8 km/h (s): n/a

Max. Accel. (m/s^2): n/a

Distance in 5s (m): n/a

Time in 0.4km (s): n/a

Max. Speed (kmph): n/a

Gradeability: n/a %

Energy Use Figure

Output Check Plots

Compare Results With: Sim Data | Test Data

Warnings/Messages

Figure 6.25: Results of Conventional vehicle in CDC 1D

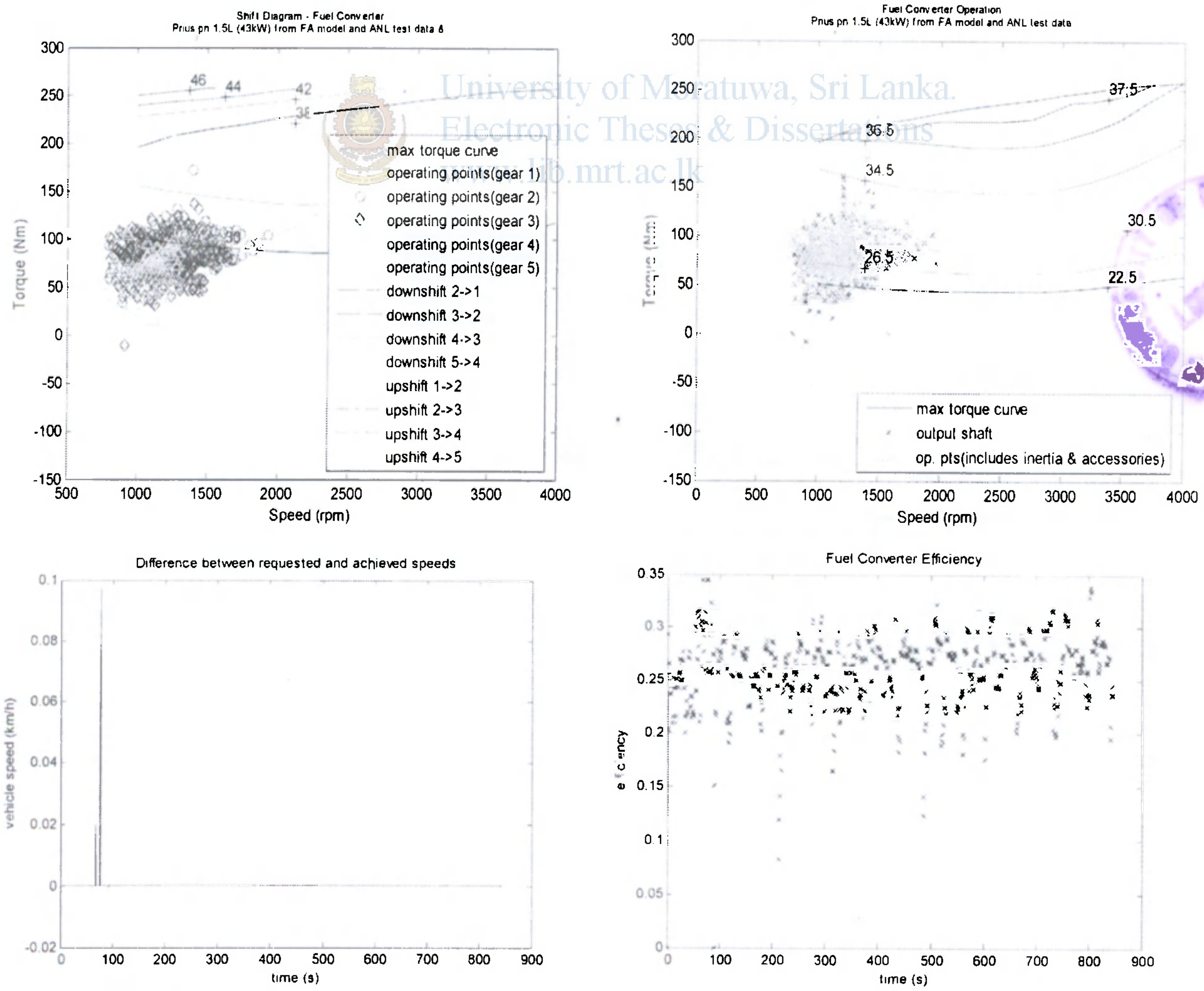
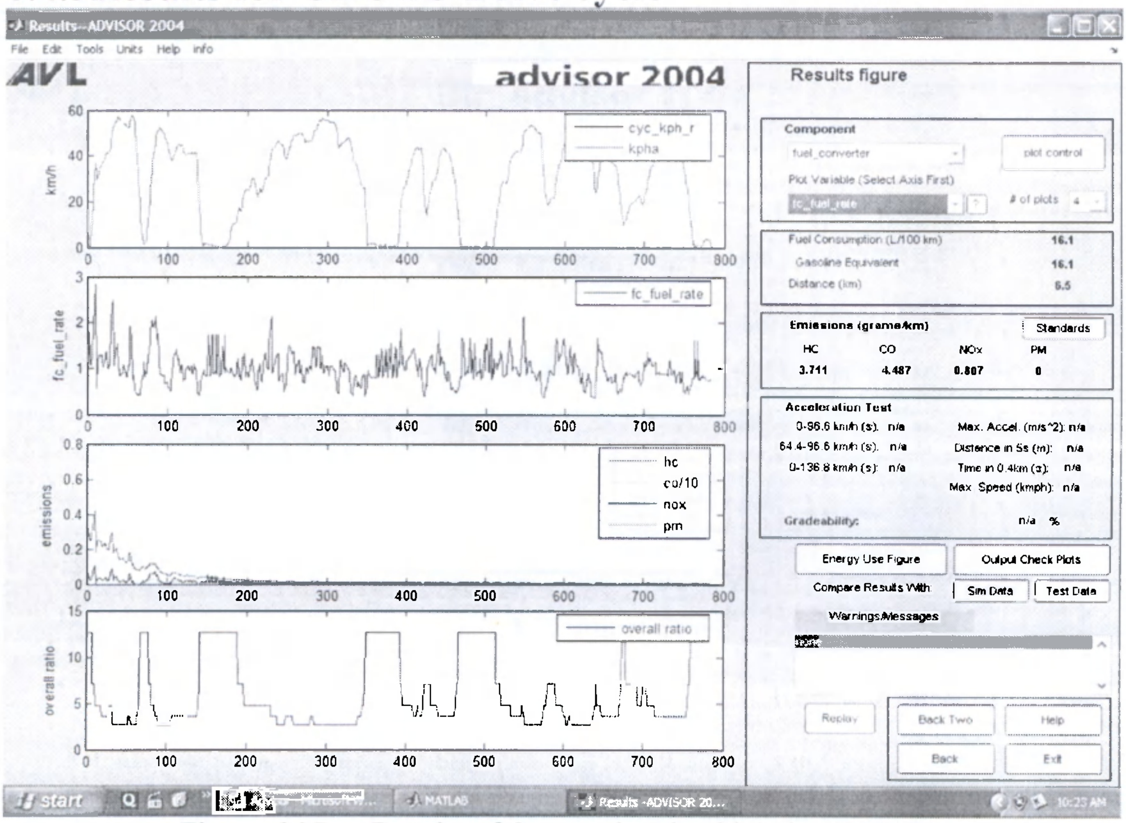


Figure 6.26: Motor efficiency of Conventional vehicle in CDC 1D

6.4.3Results for CDC 2U Drive cycle



Results figure

Component: fuel_converter

Plot Variable (Select Axis First): fc_fuel_rate

# of plots: 4

Fuel Consumption (L/100 km) 16.1

Gasoline Equivalent 16.1

Distance (km) 6.5

Emissions (grams/km)

HC	CO	NOx	PM
3.711	4.487	0.807	0

Acceleration Test

0-96.6 km/h (s): n/a

64.4-96.6 km/h (s): n/a

0-136.8 km/h (s): n/a

Max. Accel. (m/s^2): n/a

Distance in 5s (m): n/a

Time in 0.4km (s): n/a

Max. Speed (kmph): n/a

Gradeability: n/a %

Figure 6.27: Results of Conventional vehicle in CDC 2U

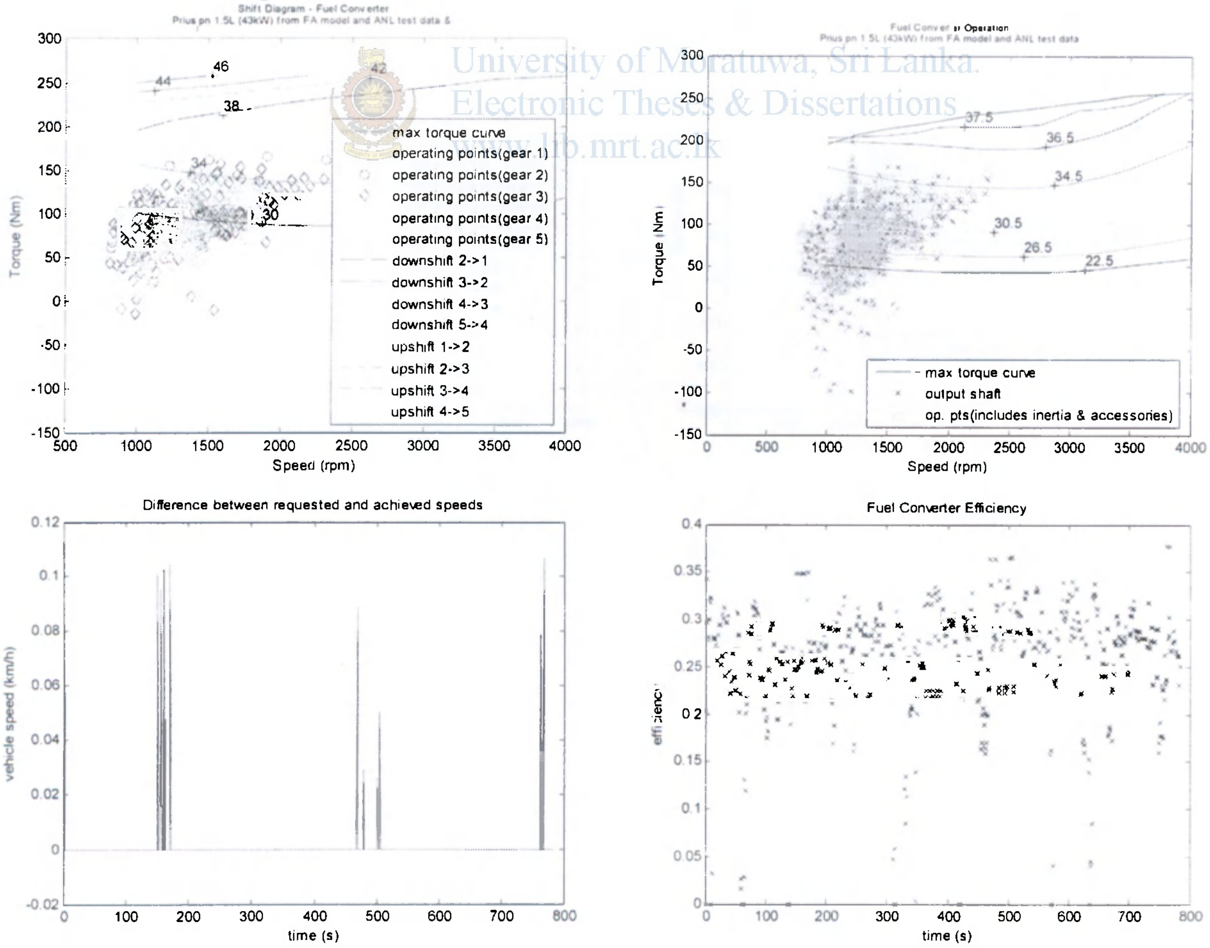
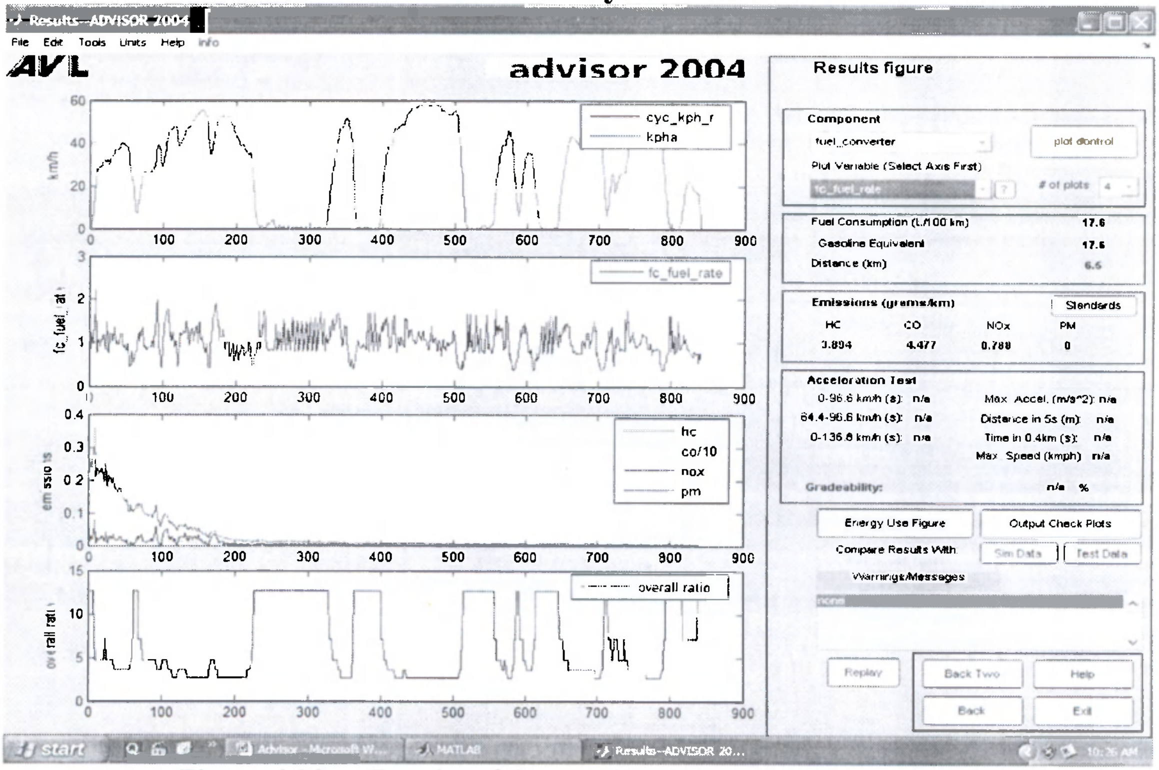


Figure 6.28: Motor efficiency of Conventional vehicle in CDC 2U

6.4.4 Results for CDC 2D Drive cycle



Component: fuel_converter

Plot Variable (Select Axis First): fc_fuel_rate

# of plots: 4

Fuel Consumption (L/100 km) 17.6

Gasoline Equivalent 17.6

Distance (km) 6.5

Emissions (grams/km)

HC	CO	NOx	PM
3.894	4.477	0.788	0

Acceleration Test

0-96.6 km/h (s): n/a

64.4-96.6 km/h (s): n/a

0-136.8 km/h (s): n/a

Max Accel. (m/s^2): n/a

Distance in 5s (m): n/a

Time in 0.4km (s): n/a

Max Speed (kmph) n/a

Gradeability: n/a %

Compare Results With

Warnings/Messages

none

Figure 6.29: Results of Conventional vehicle in CDC 2D

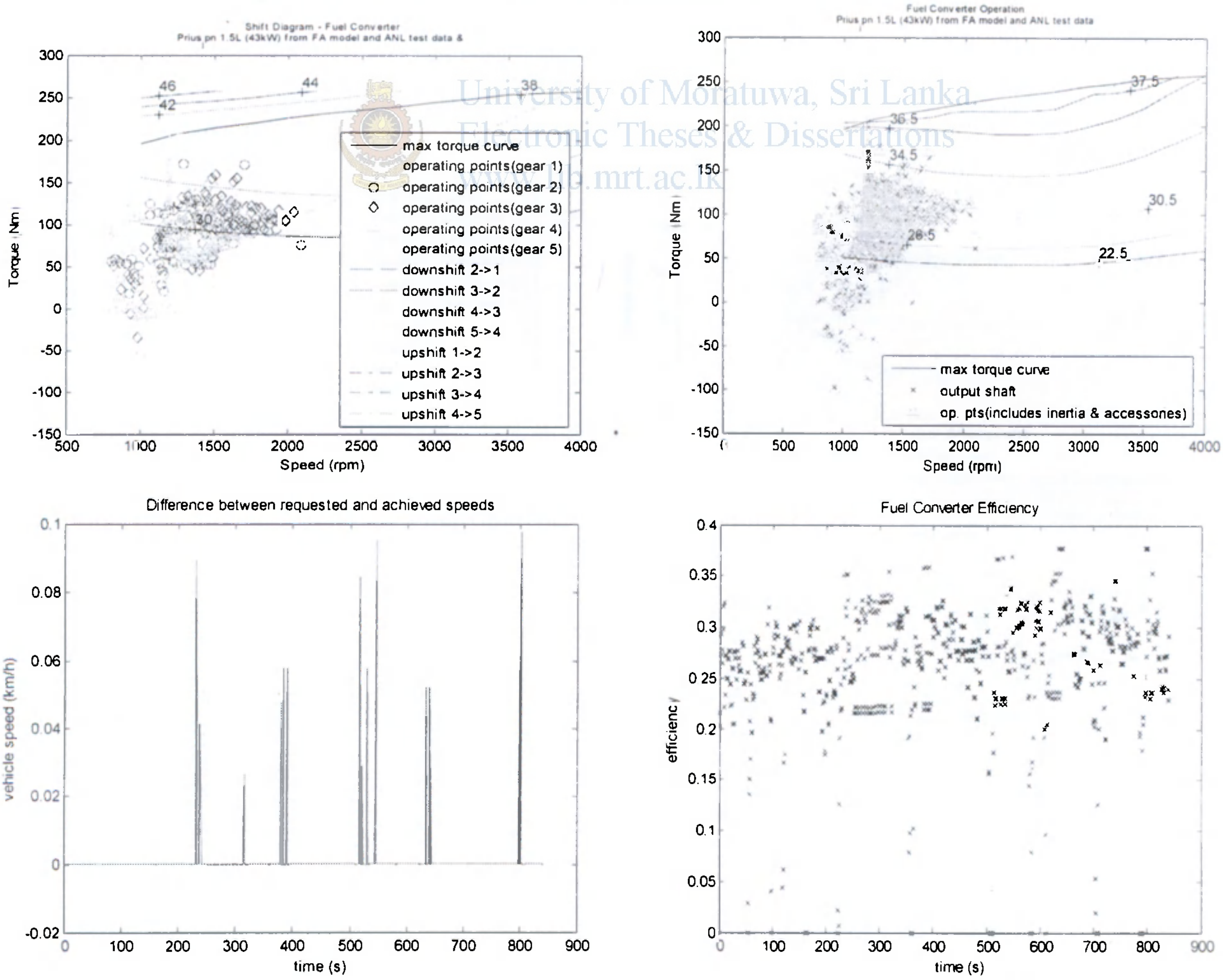
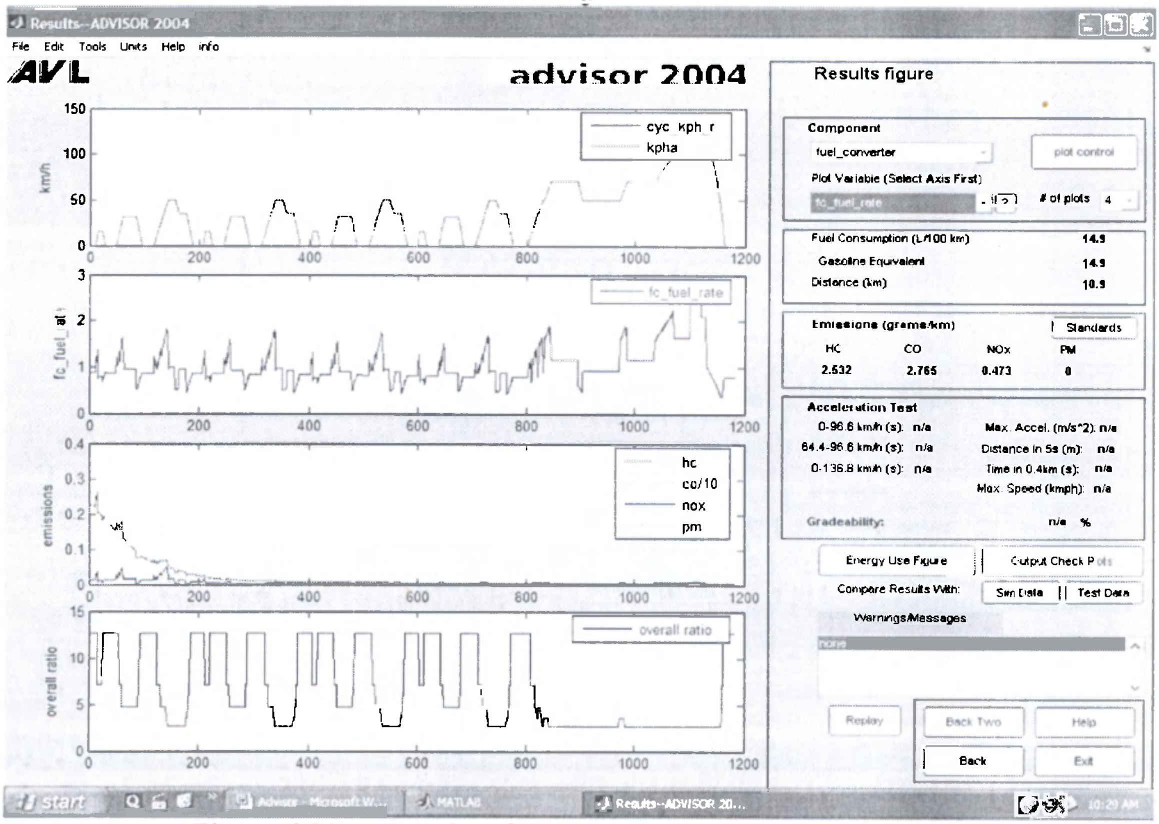


Figure 6.30: Motor efficiency of Conventional vehicle in CDC 2D

6.4.5 Results for NEDC Drive cycle



Results figure

Component: fuel_converter

Plot Variable (Select Axis First): fc_fuel_rate

# of plots: 4

Fuel Consumption (L/100 km): 14.9

Gasoline Equivalent: 14.9

Distance (km): 10.9

Emissions (grams/km)

HC	CO	NOx	PM
2.532	2.765	0.473	0

Acceleration Test

0-96.6 km/h (s): n/a

64.4-96.6 km/h (s): n/a

0-136.8 km/h (s): n/a

Max. Accel. (m/s^2): n/a

Distance in 5s (m): n/a

Time in 0.4km (s): n/a

Max. Speed (kmph): n/a

Gradeability: n/a %

Warnings/Messages: none

Figure 6.31: Results of Conventional vehicle in NEDC

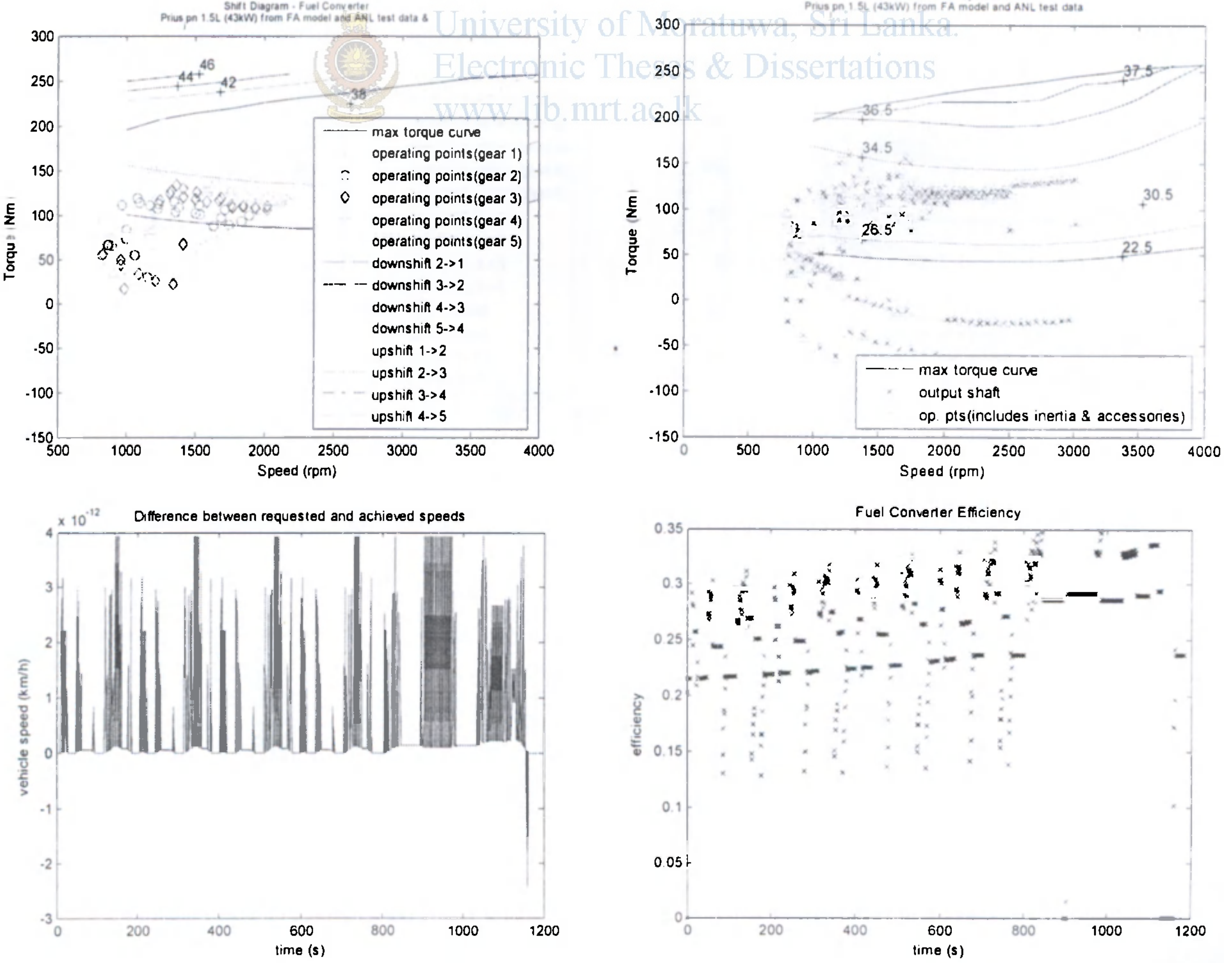
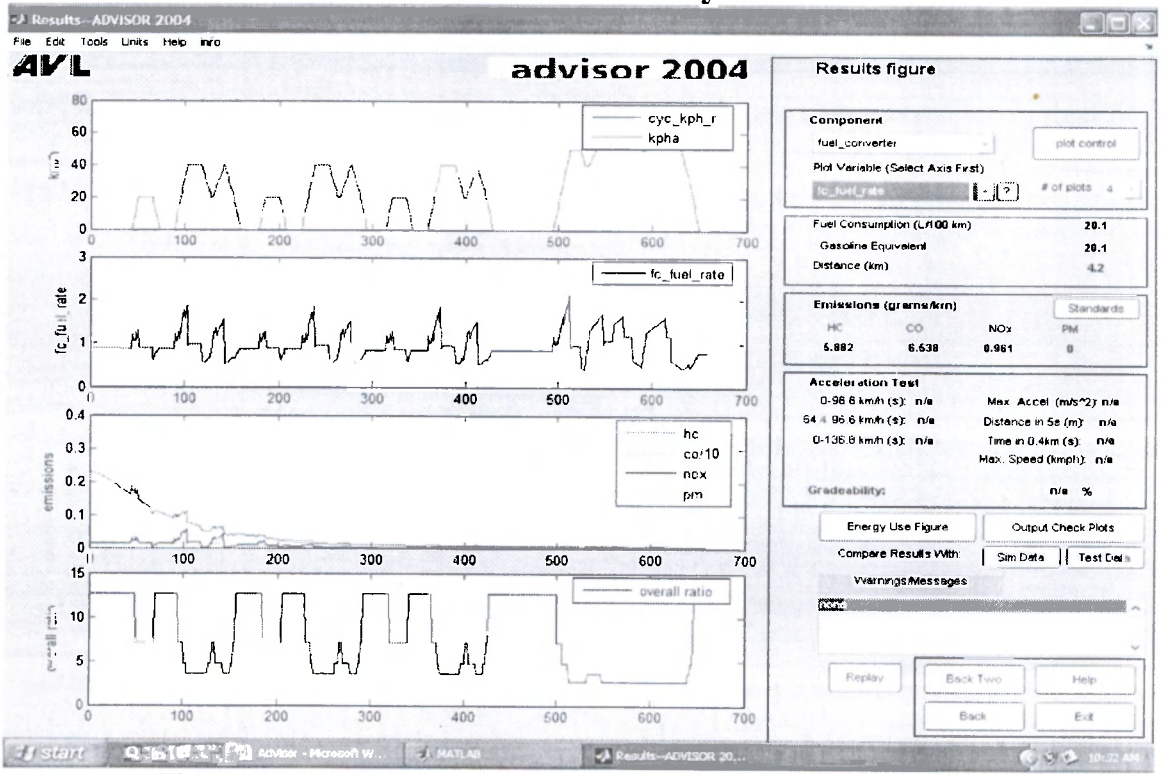


Figure 6.32: Motor efficiency of Conventional vehicle in NEDC

6.4.6 Results for JAPAN 10-15 Drive cycle



Results figure

Component: fuel_converter

Plot Variable (Select Axis First): fc_fuel_rate

# of plots: 4

Fuel Consumption (L/100 km) 20.1
Gasoline Equivalent 20.1
Distance (km) 4.2

Emissions (grams/km)

HC	CO	NOx	PM
5.882	6.638	0.961	0

Acceleration Test
0-96.6 km/h (s): n/a
64.4-96.6 km/h (s): n/a
0-136.8 km/h (s): n/a
Max. Accel (m/s^2): n/a
Distance in 5s (m): n/a
Time in 0.4km (s): n/a
Max. Speed (kmph): n/a
Gradeability: n/a %

Compare Results With:

Warnings/Messages

Figure 6.33: Results of Conventional vehicle in Japan 10-15

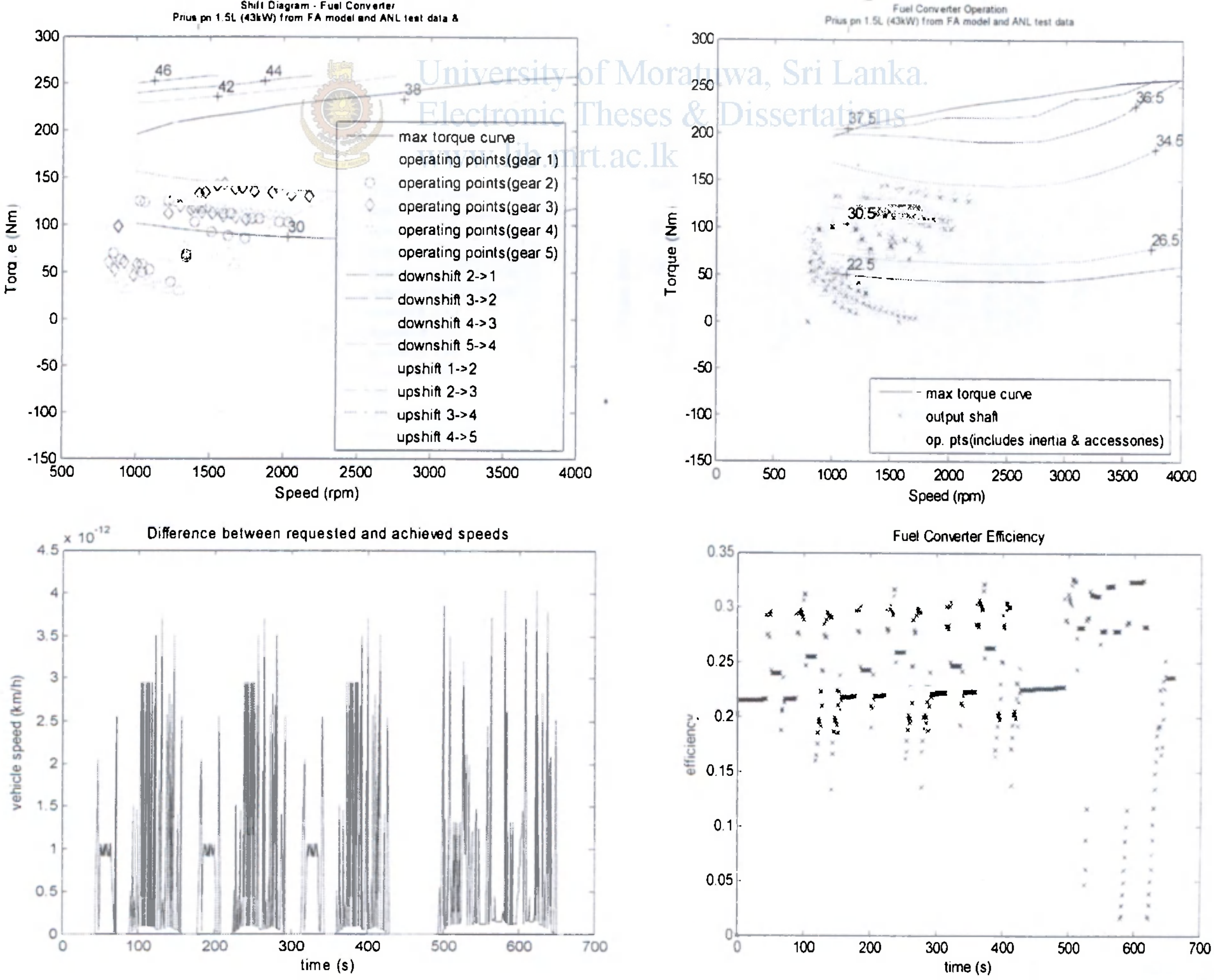
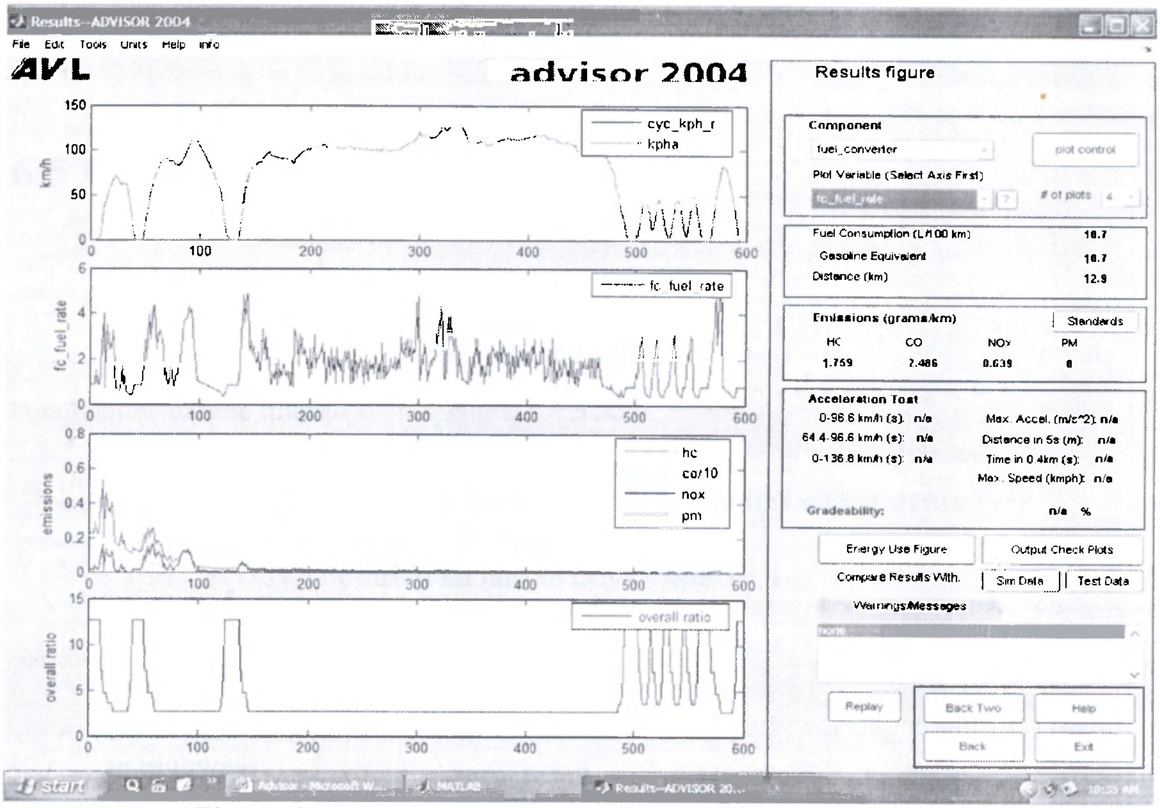


Figure 6.34: Motor efficiency of Conventional vehicle in Japan 10-15

6.4.7 Results for US 06 Drive cycle



Results figure

Component: fuel_converter

Plot Variable (Select Axis First): fc_fuel_rate

# of plots: 4

Fuel Consumption (L/100 km) 10.7

Gasoline Equivalent 10.7

Distance (km) 12.9

Emissions (grams/km)

HC	CO	NOx	PM
1.759	2.486	0.639	0

Acceleration Test

0-96.6 km/h (s): n/a

64.4-96.6 km/h (s): n/a

0-136.8 km/h (s): n/a

Max. Accel. (m/s^2): n/a

Distance in 5s (m): n/a

Time in 0.4km (s): n/a

Max. Speed (kmph): n/a

Gradeability: n/a %

Compare Results With:

Warnings/Messages

none

Figure 6.35: Results of Conventional vehicle in US 06

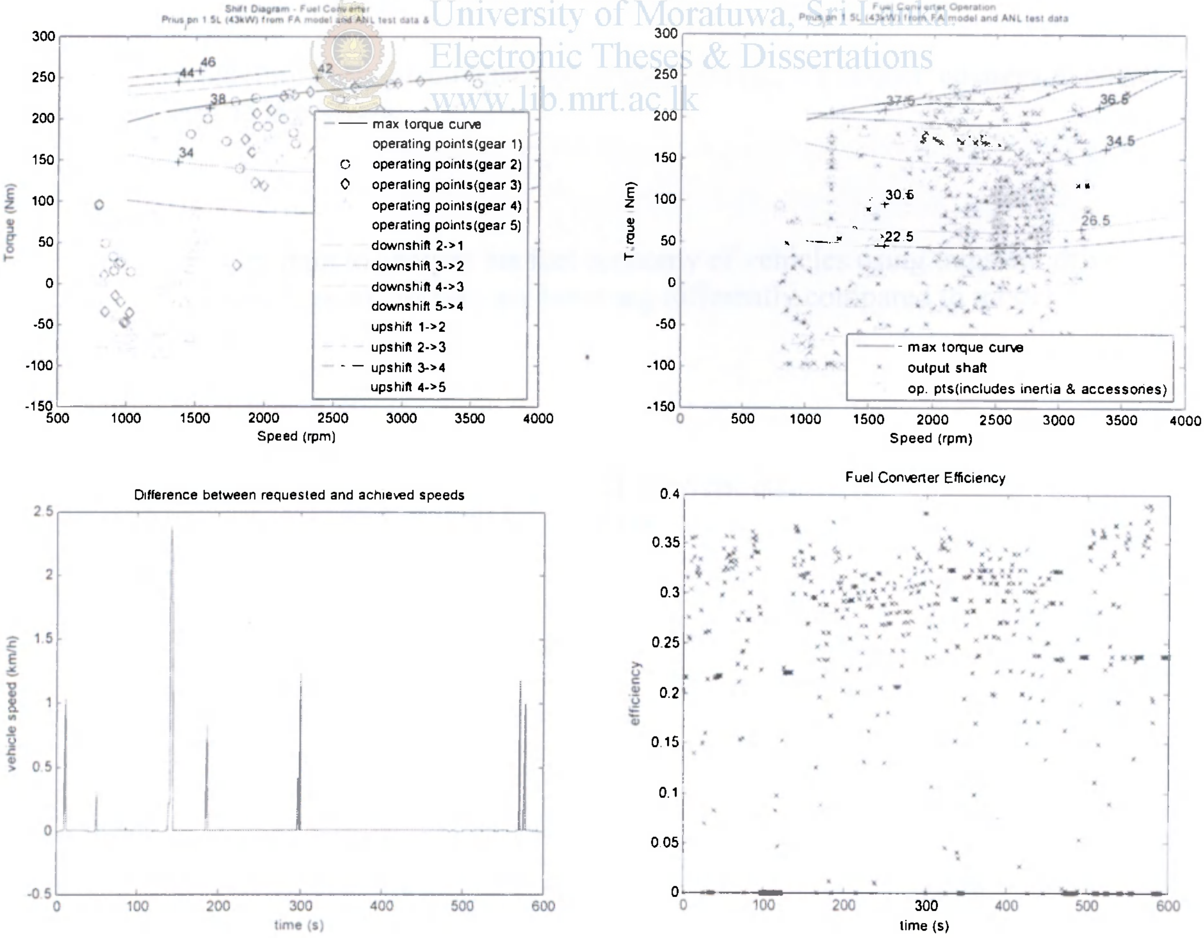


Figure 6.36: Motor efficiency of Conventional vehicle in US 06

6.5 Conclusion

After analyzing all the simulation results and collected data during the study following conclusions can be made.

- The optimization is really effective in road conditions which shows very irregular variation in speed vs. time
    - ex: toyota prius in sri lankan drive cycle

- Optimized hybrids are more economical in irregularly varying conditions than in highways.

- To maximize the effectiveness of concept hybrid, the sudden changes in power demand is essential.

- It is important to analyze the fuel economy of vehicles using transient drive cycles such as cdc as they are behaving differently compared to model drive cycles.

- Series hybrids performing worse than conventional vehicles in such drive cycles due to many energy conversions

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Appendix A:

Published research papers

Determination of Maximum Possible Fuel Economy of HEV for Known Drive Cycle: Genetic Algorithm Based Approach

R. Sudath Wimalendra[*], Lanka Udawatta[+], E. M. C. P. Edirisinghe and Sudarshana Karunarathna
Department of Electrical Engineering, Faculty of Engineering
University of Moratuwa, Sri Lanka

[*]Emails: rs_wimalendra@yahoo.com,
[+]Email: lanka@ieee.org

***Abstract*— This paper describes a methodological approach to investigate the maximum fuel economy that could be achieved by a hybrid vehicle with parallel configuration for a known drive cycle. A backward looking hybrid vehicle model is used for computation of fuel economies. The optimization process represents a constrained, multi-domain and time-varying problem, which is highly nonlinear. Here, genetic algorithm (GA) based approach was used to find out optimum power split between two power sources over their driving cycles that make maximum possible overall fuel economy for the given drive cycle by the vehicle. In this approach using Parallel Hybrid Electric Vehicle (PHEV) configuration, optimization problem is formulated so as to minimize the overall fuel consumption. The whole set of electric motor power contribution along the drive cycle is then coded as the chromosomes. These results represent the maximum fuel economy that could be ever achieved by any power management system of a Hybrid Electric Vehicle, with the tested HEV configuration and shall allow setting a benchmark against which the fuel economy is measured.**

***Keywords*— Hybrid Electric Vehicles, Optimization, Genetic Algorithm**

I. INTRODUCTION

As a result of the endless interest of the society for improved fuel economy & reduced emission without sacrificing vehicle performance, safety, reliability, cost of ownership and other conventional vehicle attributes, Hybrid Technology came in to the world of automobiles, leaving lot of research topics to the researchers living all over the globe. The pressing environmental concerns and skyrocketing price of fuel oils are highly responsible factors for the rapid development of this technology within the past two decades.

Hybrid Electric Vehicles (HEV) have a great potential as new alternative means of transportation. The specific benefits of HEVs, compared to conventional vehicles, include improved fuel economy and reduced emissions.

Hybrid systems involving a combination of an Internal Combustion Engine (ICE) and electric motors (EM) have the potential of improving fuel economy. by operating the Internal Combustion Engine in the optimum operating range while making use of regenerative braking during deceleration.

An extensive set of studies have been conducted over the past two decades. In particular, several *logic*-based control strategies and fuzzy logic-based energy management strategies for distributing power demand have been suggested [1], [2] & [3]. These approaches have been adopted mainly due to their effectiveness in dealing with the problems appear in the complexity of hybrid drive train via both heuristics (human expertise) and mathematical models.

Recent changes in the technology of modern vehicles and revolutionary development in telematics industry have created the possibility for a vehicle to gather online information about the road infrastructure and the traffic environment in which it is in operation. Several algorithms have been proposed to predict the future speed trends, with the use of preview information provided by the telematics. Two technologies, hybrid and telematics are combined together to create "intelligent vehicle" which provides improved fuel economy with traffic preview [4].

The aim of this study is to find out the maximum fuel economy that a PHEV can achieve with any type of HEV energy management system. Here, genetic algorithm (GA) has been used as the technique for optimization which will lead to find a global optimum. In fact, though it is needed to find the maximum possible theoretical best, in actual practice it might not be reachable. However, knowing the maximum possible best fuel economy, it can be used as a benchmark value which might be useful in setting the standards of HEV.

Rest of the paper has been organized as follows; In Section II, it explains the vehicle model used in this study and briefly describes the driving cycle used. Evolutionary computational algorithm to find out the maximum fuel economy has been presented in Section III, followed by the analysis of the results of this study in Section IV. Finally, the Conclusion is presented in Section V.

II. VEHICLE MODEL AND DRIVE CYCLE

A. Modeling the hybrid vehicle

A parallel hybrid configuration has been taken in Fig. 1 to account for modeling the hybrid electric vehicle in this study. This configuration consists of an electric motor and internal combustion engine that can simultaneously or individually drive the transmission (and subsequently propel the vehicle). The split is determined by the vehicle's hybrid control strategy [subject to constraints on the battery state of charge (SOC)]. Normally, the EM is used to assists the engine for peak acceleration, hill climbing, and extremely fast highway driving conditions. Furthermore, the EM can act in reverse mode to become a generator during regenerative braking and consequently used to recharge the batteries.

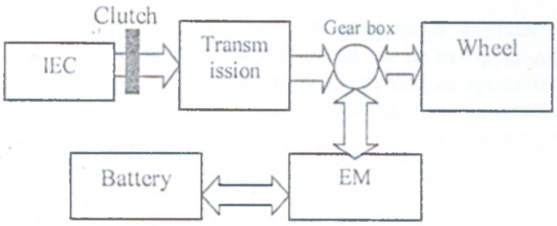


Fig. 1 Block diagram of the parallel hybrid vehicle

The city driving test standard starts from ambient initial conditions (known as "cold starts"). However, in this analysis, the engine has been assumed to be warm.

Another constraint during the optimization process is the change in, state of battery charge at the beginning and end of the cycle in order to prevent misleading fuel economy results, arising from excessive use of the electric motor (this would result increased fuel usage during the next vehicle run, for battery replenishment).

The baseline vehicle chosen for this study has been a 4 - 1 production family sedan with a specific Parallel Hybrid Electric Vehicle (PHEV) configuration, which has been used throughout the study. Following table gives details of its' specifications;

TABLE I
VEHICLE MODEL SPECIFICATIONS

Parameter	Value
Total weight	1642 kg
Chassis weight	1000 kg
Frontal area	1.92 m2
Coefficient of Drag	0.32
Vehicle length	5.00 m
Transmission	Manual, 5 speed
Transmission efficiency	95% (all gears)
Gear ratios	3.5:2.14:1.39:1:0.78
Final drive ratio	3.98
Gear changes	1- 2 and 2 -1 @ 24 km/h 2- 3 and 3 -2 @ 40 km/h 3- 4 and 4 -3 @ 64 km/h 4- 5 and 5 -4 @ 75 km/h

(Permanent Magnet Motor 20kW continuous, 40kW peak, Advanced Battery 40kW, 4kWh, 100V)

It is important to note that the simulation essentially works in a reverse direction to what happens in the real scenario – i.e. the drive cycle is the input to the vehicle model, and the required changes to the vehicle speed are calculated based on the drive cycle. This change in vehicle speed is then converted in to engine speed and torque requirements by taking into account the current gear ratio (a shifting map is given for the model) and the efficiencies of the transmission. The fuel consumed is then calculated from a look-up table of fuel rate against engine operating point (defined by engine speed and torque). The fuel usage map as a function of operating point has been evolved from steady state maps and is illustrated in Fig. 2.

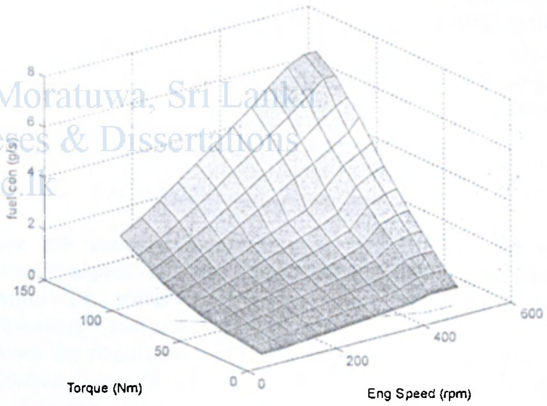


Fig. 2. Fuel consumption map of the ICE of tested HEV

B. Drive cycles

Driving cycles are defined as the test cycle used to standardize the evaluation of vehicle fuel economy and emissions. Driving cycles are speed time sequences that represent the traffic conditions and driving behavior in a specific area.

In this optimization study, New European Driving Cycle (NEDC), which is commonly used in regulatory work has been used and is shown in Fig-3.

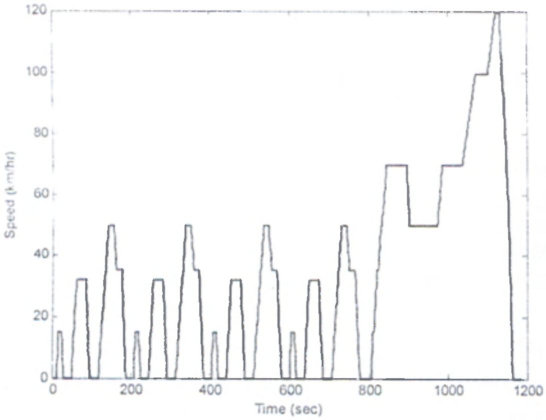


Fig. 3 New European Drive Cycle

The optimization process now represents a constrained multi-dimensional problem that could not be easily solved. In order to find a solution to the problem and to optimize fuel economy of the Parallel HEV configuration indicated in Figure 1, the Genetic Algorithm approach could be employed over the above drive cycle as mentioned below;

III. OPTIMISATION USING GA

In this section an Evolutionary Computational algorithm has been developed to find out the optimum fuel trajectory for a known drive cycle using Genetic Algorithm (GA). The GA is a stochastic global search method that mimics the metaphor of natural biological evolution. GAs operate on a population of potential solutions, applying the principle of survival of the fittest to produce (hopefully) better and better approximations to a solution [5]. In the following sub-section, the architecture of GA applied to the fuel economical operation of PHEV is presented.

A. Domain and Constraints

Fig. 1 presents a block diagram of a PHV with an EM and an ICE. For this particular configuration the ICE and EM power are combined downstream of the transmission. Alternatively the power could also be combined upstream of the transmission. There are five different ways to operate the system depending on the flow of energy: 1) provides power to the wheel with only ICE, 2) provides power to the wheel with only EM or, 3) provides power to the wheel with both ICE and EM simultaneously, 4) charges the battery, using part of the ICE power and generated power by EM running as a generator 5) slow down the vehicle by letting the wheel to drive the EM as a generator.

In this analysis, since the drive cycle is known, corresponding power demand to achieve the speed trajectory is calculated using dynamic equations [6], taking sampling period as one second.

The power at the wheel is given by,

$$P_{wheel} = \sum force \times v = (F_{acc} + F_{incline} + F_{rr} + F_{drag}) \times v$$
$$= (m \times a + mg \sin C_{rr} \cos A + 1/2 \rho_{air} C_D A_f v^2) \times v$$

where m is the total mass, a is the vehicle acceleration, v is the vehicle velocity, A is the angle of slope. C_{rr} is the coefficient of tire rolling resistance, C_D is the drag coefficient, ρ is the density of air and A_f is the frontal cross section area of the vehicle.

Power demand corresponding to each sampling period is split between two power sources. Here, it is also assumed that the ICE is in continuous operation throughout the drive cycle, even when the motor is providing the total power requirement for moving of the vehicle and also when the vehicle is at stand still.

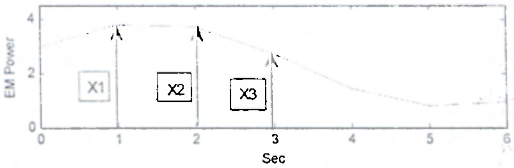
The SOC of the battery pack decides whether the required power contribution of the EM is possible or not. If the batteries are completely charged EM cannot be allowed to operate as a generator and on the other hand if the batteries are completely discharged, positive power contribution from EM is not possible. It is also required to keep the SOC within a certain upper and lower limit in order to avoid damage to the battery pack. In this analysis initial SOC is considered as 50%. In order to have meaningful result (fuel economy), SOC at the end of the cycle should not vary much from the initial value and at any time of operation, the battery SOC should not go outside the specified minimum and maximum limits (40% & 80%).

B. Population and Individuals

There are variables equivalent to the total number of operating seconds of the drive cycle and each variable represents the power contribution from EM during the corresponding sampling period. The individuals which composes the population of the current generation consists of contribution from EM at each second. EM power can have any value between maximum motor power and maximum generator power (generation is represented by negative sign).

C. Chromosomes

Chromosome composes of string of binary numbers corresponding to EM power at each second.



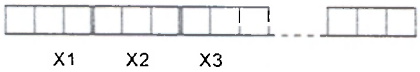


Fig. 4. Example of EM contribution (Top), Chromosome (Bottom). This composes of string of binary numbers which represent EM power at each seconds of the drive cycle.

X1, X2 ….are the binary representation of EM power at each second. In this approach, for New European Drive Cycle, there are 1200 variables to be optimized. The precision of variables depend on the size of binary coding of the variables. In this study, each variable has been represented by a binary value of 06 (six) bits.

D. Fitness Function

The fitness function calculates the total fuel consumption with respect to ICE power trajectory. Here, the EM power at each second is taken as the decision variable. Since the power demand is known the ICE power can be calculated. For negative power request (braking), the ICE power is considered zero and the sum of motor and mechanical braking power would be taken as equal to power demand. However for positive power demand, the sum of ICE and EM power should be equal to the power demand.

Once the ICE power is known, the corresponding engine torque and speed can be calculated taking gear ratios and efficiencies of transmission in to account. Then empirical model based on test data is used for fuel consumption calculation. Two look up maps are in this model, engine torque and fuel consumption. Engine torque map decides engine torque limit at each speed, while fuel consumption map (Fig. 2) decides fuel rate (g/s) of engine speed and torque.

In this study, the objective function is defined as follows:

$$J(x)=\sum_{i=1}^{n} FCi + M^{k}W(N_{B}+N_{P})$$

Where, FCi is the fuel consumption during i^{th} second and $J(x)$ is the total fuel consumption plus the penalty.
M is the number of generation and W is the weighting coefficient. N_B and N_P quantify magnitudes of constraints.

Some of the chromosomes which represent the EM power trajectory in the problem space are invalid, as the battery SOC and the rate of change of power at some instants may exceed the limits. To represent the poorness of the chromosome in such a situation, a penalty is introduced in to the objective function $J(x)$, similar to that used in constrained optimizations treated under penalty function concept in evolutionary computational techniques. Here, N_B and N_P are the number of instants that the battery SOC and the rate of change of power exceed the limits within the drive cycle corresponding to a chromosome. Here, 10 and 1.2 have been used for 'W' and 'k' respectively.

E. Selection

Once the individuals have been assigned a fitness value, they could be chosen from the population, with a probability according to their relative fitness, and could be recombined to produce the next generation. Selection is the mechanism for selecting the individuals with greater fitness over the low fitted ones to produce new individuals for the next population. In this study, individuals have been selected from the population using roulette wheel selection, in which the probability to chose a certain individual is proportional to its fitness.

F. Crossover

Crossover is the method of merging the genetic information of two individuals to produce new individuals. Here, multi point crossover which performs multiple-point crossover between pairs of individuals contained in the current population have been used, according to the crossover probability and return of a new population after mating.

G. Mutation

In natural evolution, mutation is a random process where one allele of a gene is replaced by another to produce a new genetic structure. In GAs, mutation is randomly applied with low probability, and modifies elements in the chromosomes. In this study, we have used mutation probability as 0.0001. The positive effect of mutation is the preservation of genetic diversity such that the local maxima can be avoided.

In this study, the population of GA has been initialized with 500 randomly selected individuals around zero (i.e. no contribution from EM throughout the drive cycle) and maximum number of generations have been set to 1000. Further improvement of the accuracy of the variables and the convergence rate can be achieved by increasing the size of the binary coding of variables and the number of individuals in a generation with the penalty of simulation run. The extreme expansion of the individual numbers would tend to a direct search method.

IV. RESULTS AND ANALYSIS

Fig. 5 shows the optimization process history for the driving cycle. As it could be seen in this figure, the rate of convergence is faster for the first 100 generations and then the convergence rate is slower. It has taken almost 1000 generations to converge to the optimum value. This is justified by the fact that this optimization process consists of 1200 variables as EM contributions at each second which is considered as decision variable and each variable has 2^6 different values. Since the battery SOC at any instant should be kept within the desired range, for every individual (i.e. EM power trajectory) the battery SOC at every second is calculated and if the SOC falls outside the limits at any instant, a penalty which represents the amount by which the constraints are violated by the chromosome is added to the fitness value, in order to reduce the probability of selecting it to form the next generation. Therefore, considerable amount of chromosomes in each generation will subject to this constraint and it will also be one of the reasons for slowing down of convergence. As each generation composes of 500 individuals, evaluation of fitness function including the objective function and constraints for one generation may take an average of about 20 minutes for a 3.0 GHz Pentium computer.

In Table II, the optimum fuel economy for the selected drive cycle is compared with that of a conventional vehicle. This indicates that a maximum of about 30% improvement can be achieved by a Parallel HEV, compared to a conventional vehicle. It is obvious that fuel economy varies with the driving cycle and hence the results obtained through this study are valid only for the selected drive cycle.

The Power demand to achieve the given speed profile and the optimum contribution from the EM are indicated in figures 6 and 7 below.

Fig. 8 shows the battery SOC variation throughout the drive cycle. It could be observed that, the SOC at any instant is within the upper and lower limits and the SOC difference at the beginning and the end of the cycle is just 2%.

TABLE II
FUEL ECONOMIES FOR CONVENTIONAL AND OPTIMISED HYBRID VEHICLE

Drive Cycle	NEDC	
Fuel Economy (L/100km)	Conventional Vehicle	10.3
	Parallel HEV	7.23
Improvement with HEV (%)	30	

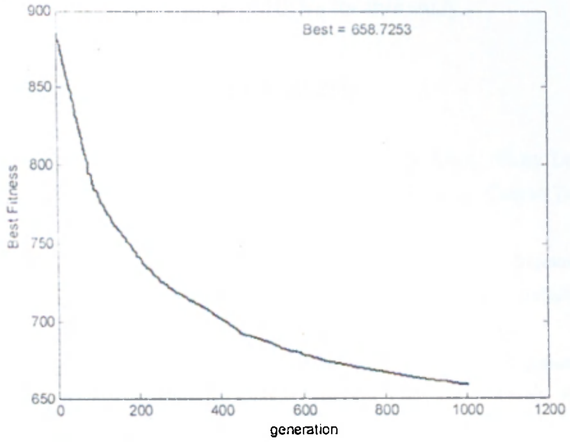


Fig. 5. History of genetic algorithm optimization process.

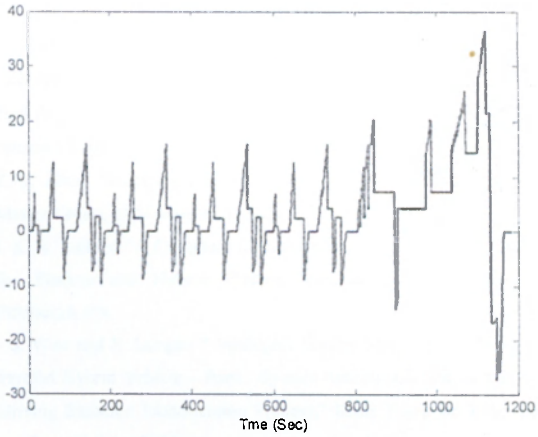


Fig. 6. Power demand to achieve the speed profile.

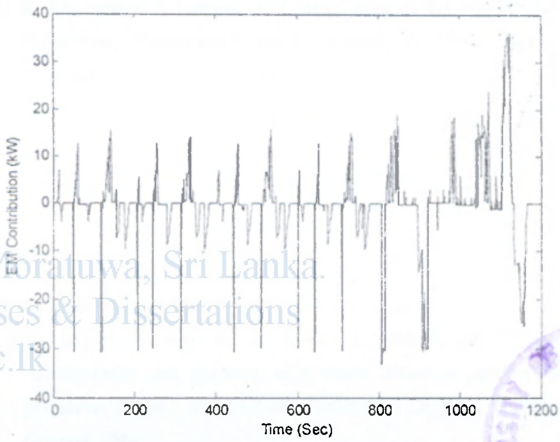


Fig. 7. Contribution from EM over the drive cycle.

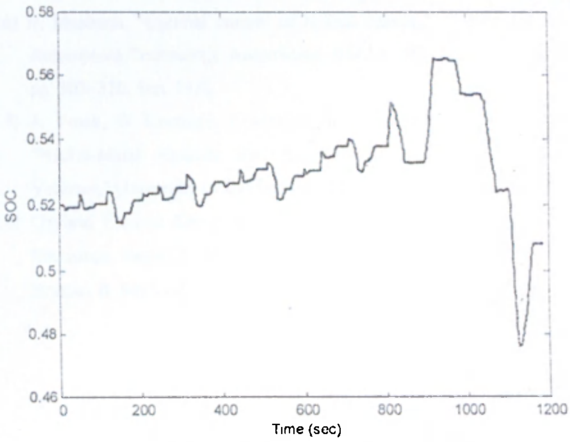


Fig. 8. Battery SOC variation over the drive cycle.

V. CONCLUSIONS AND REMARKS

In this paper, the methodological approach to find out maximum fuel economy of a PHEV for a known cycle is presented. In this approach, an optimization problem is formulated in order to employ genetic algorithm for the best solution. Variables are defined to find out optimum power contribution from EM and ICE. The objective function is defined in order to minimize fuel economy and to keep the battery SOC within the desired range throughout the drive cycle. In this study we do not consider the limitations in switching of electric motor between motor mode and generator mode. The result from the GA optimization is the maximum fuel economy that can be achieved by an HEV with selected configuration for the selected drive cycle.

The results of this GA optimization are useful to measure the effectiveness of a power management system of an HEV.

The development in automobile and telematics industry has enabled the power management systems to be more intelligent. Hybrid technology and telematics have combined together to create "intelligent vehicle" to make more accurate predictions about the possible speed trends well ahead of the current times, enabling more effective decisions on the power split of the two power sources, in order to bring the overall fuel economy of the vehicle close to its' maximum point.

In future, authors wish to research and investigate the possibility of employing real time genetic algorithm with less number of chromosomes and optimum code lengths. This will enable applications to optimize such situations online, to achieve the theoretical maximum possible fuel economy through optimally employed telematics.

AKNOWLADGEMENT

Authors would like to thank Prof. Saman Halgamuge and Sunil Adikari, School of Engineering, University of Melbourne, Australia. for providing the necessary research materials and information of HEVs for this study.

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Appendix B:

Colombo drive cycle data

	CDC 1U	CDC 1D	CDC 2U	CDC 2D
Time (s)	Speed(km/h)	Speed(km/h)	Speed(km/h)	Speed(km/h)
1	0.0	0.0	0.0	0.0
2	2.7	2.0	0.2	0.0
3	5.3	4.0	0.3	2.2
4	5.3	5.3	3.5	5.0
5	5.3	6.5	6.7	8.2
6	8.8	6.3	13.0	10.0
7	12.3	6.0	19.0	16.0
8	18.3	6.3	25.0	22.0
9	24.3	6.5	31.0	28.0
10	26.1	5.5	37.0	27.5
11	27.8	4.4	33.3	27.0
12	28.4	4.6	29.6	27.7
13	29.0	4.7	30.8	28.4
14	29.8	4.9	32.0	28.4
15	30.5	5.1	33.2	28.4
16	30.8	3.4	34.4	29.1
17	31.0	1.7	35.4	29.7
18	31.5	1.7	36.4	30.7
19	32.0	1.7	36.9	31.7
20	32.3	1.9	37.4	31.7
21	32.5	2.0	38.2	31.7
22	33.6	3.3	39.0	31.2
23	34.7	4.5	40.2	30.7
24	35.2	6.8	41.4	31.6
25	35.6	9.1	41.4	32.5
26	36.1	9.7	41.4	31.4
27	36.5	10.3	41.6	30.2
28	36.4	12.7	41.8	31.2
29	36.3	15.0	44.3	32.2
30	36.8	16.4	46.7	33.0
31	37.2	17.7	49.9	33.8
32	37.2	17.5	53.0	34.0
33	37.1	17.2	53.2	34.2
34	37.2	13.6	53.4	35.4
35	37.2	10.0	54.2	36.5
36	34.2	8.5	55.0	36.8
37	31.1	7.0	56.1	37.1
38	28.3	6.8	57.1	37.1
39	25.5	6.6	56.8	37.1
40	27.5	8.1	56.5	37.1
41	29.5	9.6	55.9	37.1
42	30.6	12.6	55.3	37.9
43	31.7	15.6	54.9	38.7
44	32.0	14.6	54.4	39.4
45	32.2	13.6	54.4	40.1
46	32.5	9.9	54.4	39.9
47	32.7	6.2	54.0	39.7
48	33.9	6.3	53.6	39.6
49	35.0	6.3	53.0	39.4
50	34.7	5.3	52.3	38.9
51	34.3	4.2	52.4	38.4
52	33.3	3.8	52.4	38.4
53	32.3	3.3	54.2	38.4
54	30.4	3.2	56.0	34.7
55	28.4	3.1	57.0	31.0
56	24.7	2.8	57.9	27.9
57	21.0	2.4	57.3	24.7
58	16.9	1.6	56.7	23.7
59	12.7	0.7	54.4	22.7
60	8.7	0.4	52.0	19.2
61	4.6	0.0	45.2	15.7
62	2.5	0.0	38.3	11.9
63	0.3	0.0	33.8	8.0
64	0.5	0.9	29.2	7.7
65	0.7	1.7	24.7	7.3
66	3.5	0.9	20.1	9.9
67	6.2	0.0	13.8	12.4
68	8.1	0.2	7.5	14.7
69	9.9	0.3	4.6	17.0
70	13.3	1.0	1.7	19.4
71	16.6	1.7	1.6	21.7
72	18.5	1.1	1.4	23.6
73	20.4	0.5	2.3	25.4
74	19.5	0.8	3.1	25.9
75	18.5	1.0	6.9	26.4
76	17.7	0.8	10.6	26.4
77	16.8	0.5	15.6	26.4
78	17.5	0.5	20.6	26.2
79	18.1	0.5	25.1	26.0
80	16.6	0.9	29.5	26.1
81	15.1	1.2	33.4	26.1
82	11.7	6.1	37.2	26.1
83	8.2	11.0	40.1	26.1
84	7.5	17.3	42.9	26.3
85	6.7	23.6	45.6	26.4
86	9.0	23.6	48.3	27.1
87	11.2	23.6	50.0	27.7
88	13.7	24.1	51.7	27.7
89	16.2	24.6	52.2	27.7
90	18.2	17.3	52.6	29.9
91	20.2	10.0	52.2	32.0
92	22.1	5.0	51.7	35.4
93	23.9	0.0	51.2	38.7
94	25.6	0.3	50.7	38.9
95	27.3	0.5	50.2	39.0
96	28.4	0.8	49.7	37.9
97	29.4	1.0	48.6	36.7
98	30.0	2.9	47.4	32.9
99	30.5	4.8	46.4	29.0
100	30.5	7.7	45.4	29.4
101	30.5	10.6	43.9	29.8
102	29.3	13.5	42.4	31.3
103	28.1	16.3	40.5	32.7
104	27.4	18.9	38.6	35.1
105	26.6	21.4	38.2	37.4
106	26.6	23.9	37.7	39.6
107	26.5	26.4	38.6	41.8
108	26.5	27.9	39.4	43.6
109	26.4	29.4	40.6	45.4
110	26.6	30.9	41.7	45.9
111	26.8	32.3	42.9	46.4
112	25.5	32.8	44.1	46.4
113	24.2	33.2	44.6	46.4
114	22.3	32.2	45.1	46.9
115	20.4	31.2	44.8	47.4
116	20.0	30.2	44.4	47.3
117	19.6	29.2	44.6	47.1
118	20.9	27.3	44.7	47.3
119	22.1	25.4	43.6	47.4
120	25.1	23.5	42.4	44.8
121	28.1	21.6	41.6	42.1
122	30.3	21.6	40.7	40.1
123	32.4	21.5	40.7	38.1
124	34.3	21.4	40.7	38.9
125	36.1	21.3	40.9	39.7
126	37.4	22.0	41.1	40.4
127	38.7	22.7	41.1	41.0
128	40.5	23.4	41.0	41.9
129	42.2	24.0	41.2	42.7
130	43.0	25.4	41.4	43.4
131	43.8	26.8	41.1	44.0
132	44.6	28.2	40.7	45.4
133	45.4	29.6	41.1	46.7
134	45.8	29.8	41.4	47.1

135	46.1	29.9	41.4	47.4
136	46.1	30.1	41.4	47.4
137	46.1	30.2	36.6	47.4
138	46.3	30.3	31.7	48.2
139	46.4	30.4	24.4	49.0
140	46.6	30.5	17.0	49.9
141	46.7	30.5	12.0	50.7
142	46.8	31.4	7.0	50.7
143	46.9	32.3	3.9	50.7
144	46.1	33.2	0.7	51.4
145	45.2	34.0	1.1	52.0
146	44.8	34.9	1.4	52.9
147	44.3	35.7	1.4	53.7
148	44.4	36.5	1.4	53.6
149	44.5	37.3	1.5	53.4
150	43.3	37.9	1.5	54.4
151	42.0	38.4	1.3	55.4
152	41.6	39.0	1.1	55.4
153	41.2	39.5	1.2	55.4
154	41.3	38.8	1.2	55.6
155	41.3	38.0	1.0	55.7
156	41.7	37.2	0.7	55.2
157	42.0	36.4	0.6	54.7
158	42.8	36.2	0.5	53.9
159	43.5	36.0	0.7	53.1
160	44.7	35.8	0.9	52.9
161	45.8	35.5	0.7	52.7
162	45.9	35.1	0.5	48.6
163	45.9	34.7	0.3	44.4
164	45.8	34.3	0.0	39.4
165	45.6	33.8	0.0	34.4
166	45.1	33.6	0.0	34.8
167	44.6	33.3	0.0	35.1
168	44.0	33.1	0.0	36.8
169	43.3	32.8	0.4	38.4
170	43.5	32.5	0.7	40.4
171	43.6	32.1	0.5	42.4
172	43.5	31.8	0.3	44.6
173	43.3	31.4	0.5	46.8
174	42.8	30.6	0.7	48.5
175	42.2	29.7	1.1	50.1
176	42.3	28.8	1.4	50.8
177	42.3	27.9	2.7	51.4
178	42.5	26.2	4.0	51.6
179	42.7	24.5	6.4	51.8
180	42.4	22.8	8.7	51.8
181	42.0	21.0	9.5	51.7
182	42.0	21.2	10.3	52.4
183	41.9	21.4	10.3	53.1
184	42.0	21.6	10.3	53.1
185	42.1	21.7	10.7	53.1
186	42.4	22.4	11.0	52.6
187	42.7	23.0	13.2	52.1
188	43.1	23.6	15.3	52.1
189	43.5	24.2	16.2	52.1
190	43.4	26.1	17.0	52.1
191	43.2	28.0	16.5	52.1
192	41.8	28.1	16.0	50.9
193	40.3	28.1	18.2	49.7
194	38.7	28.1	20.4	48.9
195	37.0	28.1	22.4	48.1
196	36.0	28.9	24.4	48.1
197	34.9	29.6	24.6	48.0
198	33.5	30.4	24.8	46.4
199	32.0	31.1	25.2	44.7
200	31.3	32.4	25.5	43.9
201	30.5	33.6	25.3	43.0
202	31.2	34.9	25.1	43.0
203	31.8	36.1	26.3	43.0
204	31.9	36.3	27.4	41.5
205	32.0	36.5	28.7	40.0
206	32.2	36.7	30.0	39.4
207	32.4	36.9	30.0	38.7
208	32.8	36.6	30.0	38.9
209	33.1	36.2	28.7	39.0
210	33.3	35.8	27.4	39.0
211	33.4	35.4	24.6	39.0
212	33.7	32.2	21.7	38.1
213	33.9	28.9	22.6	37.1
214	33.7	25.6	23.4	36.5
215	33.5	22.3	24.7	35.8
216	34.9	18.7	26.0	35.3
217	36.2	15.0	25.0	34.7
218	37.5	11.3	24.0	35.1
219	38.8	7.6	25.0	35.4
220	37.6	7.8	26.0	35.3
221	36.4	7.9	28.0	35.1
222	35.7	8.1	30.0	30.8
223	34.9	8.2	30.6	26.4
224	36.5	9.4	31.1	20.6
225	38.1	10.6	31.3	14.7
226	38.3	11.8	31.4	10.5
227	38.4	13.0	34.1	6.3
228	38.4	13.7	36.7	4.5
229	38.4	14.4	40.1	2.7
230	38.3	15.1	43.4	1.9
231	38.1	15.7	43.2	1.1
232	38.1	14.5	43.0	0.9
233	38.1	13.2	43.4	0.7
234	39.0	11.9	43.7	1.2
235	39.8	10.6	44.4	1.7
236	41.5	10.1	45.0	1.1
237	43.2	9.6	45.9	0.5
238	42.2	9.1	46.7	0.3
239	41.2	8.6	46.1	0.0
240	37.6	8.8	45.4	0.3
241	33.9	9.0	45.2	0.5
242	29.4	9.2	45.0	1.5
243	24.9	9.4	44.9	2.5
244	22.1	10.9	44.7	2.5
245	19.3	12.4	42.7	2.5
246	20.8	13.9	40.7	2.6
247	22.2	15.4	39.4	2.7
248	19.8	17.5	38.1	3.3
249	17.4	19.6	39.0	3.8
250	17.9	21.7	39.8	4.0
251	18.3	23.8	41.5	4.2
252	21.3	24.6	43.1	2.6
253	24.3	25.4	44.4	1.0
254	26.1	26.2	45.7	0.5
255	27.9	27.0	46.6	0.0
256	29.0	26.4	47.4	0.0
257	30.0	25.8	48.3	0.0
258	30.5	25.2	49.1	1.0
259	30.9	24.6	48.9	1.9
260	32.6	24.6	48.7	1.0
261	34.2	24.6	48.9	0.0
262	36.4	24.6	49.1	0.0
263	38.5	24.5	49.6	0.0
264	39.2	25.0	50.1	0.6
265	39.8	25.5	49.9	1.1
266	39.8	26.0	49.7	0.6
267	39.7	26.5	49.9	0.0
268	39.9	25.8	50.1	0.0
269	40.0	25.1	49.1	0.0
270	39.8	24.4	48.1	0.9

271	39.5	23.7	47.1	1.7
272	39.2	22.2	46.1	0.9
273	38.8	20.6	46.3	0.0
274	39.0	19.1	46.4	0.0
275	39.1	17.5	46.3	0.0
276	38.3	20.5	46.1	0.4
277	37.4	23.5	46.4	0.7
278	36.8	23.7	46.7	0.4
279	36.1	23.9	46.7	0.0
280	36.1	24.1	46.7	0.0
281	36.1	24.2	47.9	0.0
282	34.2	23.8	49.0	0.6
283	32.2	23.4	50.0	1.1
284	32.5	23.0	51.0	0.6
285	32.8	22.5	51.2	0.0
286	35.0	22.9	51.4	0.0
287	37.2	23.3	52.6	0.0
288	38.1	23.7	53.7	0.6
289	38.9	24.1	54.7	1.2
290	39.3	26.5	55.7	0.6
291	39.6	28.8	55.6	0.0
292	40.6	31.1	55.4	0.0
293	41.5	33.4	55.9	0.0
294	42.9	34.1	56.4	0.6
295	44.2	34.7	56.1	1.2
296	44.8	35.3	55.7	0.6
297	45.3	35.9	55.7	0.0
298	45.1	35.1	55.7	0.0
299	44.8	34.3	55.7	0.0
300	45.2	33.5	55.7	0.4
301	45.5	32.6	55.2	0.7
302	44.8	32.5	54.7	0.4
303	44.1	32.3	54.7	0.0
304	41.1	32.1	54.7	0.0
305	38.1	31.9	54.7	0.0
306	38.7	32.1	54.7	0.4
307	39.2	32.2	54.6	0.7
308	39.8	32.4	54.4	0.4
309	40.4	32.5	54.2	0.0
310	40.4	31.6	54.0	0.0
311	40.3	30.6	51.7	0.0
312	40.3	29.7	49.4	0.4
313	40.2	28.7	46.4	0.7
314	40.7	25.8	43.4	0.4
315	41.1	22.8	44.2	0.0
316	41.0	19.8	45.0	0.2
317	40.8	16.8	45.4	0.3
318	40.8	14.6	45.7	0.5
319	40.7	12.3	45.7	0.7
320	40.7	10.0	45.7	0.4
321	40.7	7.7	46.2	0.0
322	40.7	10.6	46.7	0.0
323	40.7	13.4	47.1	0.0
324	35.4	16.3	47.4	2.4
325	30.0	19.1	47.6	4.8
326	24.0	16.5	47.7	7.3
327	18.0	13.9	47.6	9.7
328	19.0	11.3	47.4	13.0
329	22.6	8.7	45.2	16.2
330	24.8	7.3	43.0	19.2
331	27.0	5.9	40.4	22.2
332	28.6	4.5	37.7	25.0
333	30.1	3.0	37.4	27.8
334	31.1	4.2	37.1	30.0
335	32.0	5.4	36.9	32.1
336	32.2	6.6	36.7	34.0
337	32.3	7.8	35.1	35.9
338	32.7	8.4	33.4	38.2

339	33.0	8.9	32.1	40.4
340	33.0	9.5	30.7	42.2
341	33.0	10.0	28.8	44.0
342	32.4	7.7	26.8	45.6
343	31.7	5.3	26.4	47.1
344	31.9	2.9	25.9	47.3
345	32.0	0.5	25.9	47.4
346	32.2	1.2	25.9	47.4
347	32.4	1.9	20.1	47.4
348	32.8	2.6	14.3	48.6
349	33.2	3.2	7.5	49.7
350	34.7	4.3	0.7	50.7
351	36.2	5.4	1.2	51.7
352	36.2	6.5	1.7	51.6
353	36.2	7.6	1.7	51.4
354	36.9	9.5	1.7	50.1
355	37.6	11.3	1.6	48.7
356	38.7	12.1	1.5	46.4
357	39.7	12.9	1.6	44.0
358	39.6	13.7	1.7	42.7
359	39.5	14.5	1.6	41.4
360	38.0	15.9	1.4	34.2
361	36.5	17.2	0.7	27.0
362	35.3	18.5	0.0	18.5
363	34.1	19.8	0.0	10.0
364	33.0	19.0	0.0	6.2
365	31.8	18.2	0.7	2.4
366	29.8	17.4	1.3	1.4
367	27.8	16.5	0.7	0.3
368	24.8	17.1	0.0	0.4
369	21.7	17.7	0.0	0.5
370	22.7	18.3	0.0	0.5
371	23.6	18.9	0.7	0.5
372	25.9	16.7	1.4	0.4
373	28.2	14.4	0.7	0.3
374	29.5	12.2	0.0	0.4
375	30.8	9.9	0.0	0.5
376	32.0	11.9	0.0	0.6
377	33.2	13.8	0.4	0.7
378	34.1	15.8	0.7	0.6
379	35.0	17.7	0.4	0.5
380	35.6	19.6	0.0	0.3
381	36.2	21.5	0.0	0.0
382	36.2	23.4	0.0	0.0
383	36.2	25.3	0.6	0.0
384	36.8	24.5	1.1	0.2
385	37.4	23.7	0.6	0.3
386	38.1	22.9	0.0	0.2
387	38.8	22.0	0.0	0.0
388	38.8	23.6	0.0	0.0
389	38.8	25.2	4.0	0.0
390	39.1	26.8	8.0	0.2
391	39.3	28.3	13.9	0.3
392	39.8	29.9	19.7	0.2
393	40.3	31.5	21.8	0.0
394	40.3	33.1	23.8	0.0
395	40.3	34.6	25.0	0.0
396	39.7	35.0	26.1	1.7
397	39.0	35.3	26.7	3.3
398	38.9	35.6	27.3	8.5
399	38.7	35.9	28.7	13.7
400	39.0	36.3	30.0	17.2
401	39.2	36.6	31.4	20.7
402	39.4	36.9	32.8	23.2
403	39.5	37.2	34.1	25.7
404	39.6	37.4	35.3	28.4
405	39.6	37.5	36.7	31.0
406	38.9	37.6	38.1	33.5

407	38.1	37.7	39.5	36.0
408	37.8	37.0	40.9	37.4
409	37.4	36.3	42.1	38.7
410	37.3	35.6	43.2	38.7
411	37.2	34.8	43.5	38.7
412	37.1	34.8	43.8	38.7
413	36.9	34.7	43.3	38.7
414	34.2	34.7	42.8	40.4
415	31.5	34.6	43.0	42.1
416	28.6	34.4	43.1	44.1
417	25.6	34.2	43.1	46.1
418	24.4	34.0	43.1	46.6
419	23.2	33.8	38.3	47.1
420	23.5	33.3	33.4	46.8
421	23.7	32.7	26.4	46.4
422	25.2	32.2	19.3	46.9
423	26.7	31.6	16.7	47.4
424	28.3	30.6	14.0	47.4
425	29.8	29.6	16.0	47.4
426	29.8	28.6	18.0	47.9
427	29.8	27.5	19.9	48.4
428	29.7	27.7	21.7	48.6
429	29.5	27.9	23.6	48.7
430	28.7	28.1	25.4	48.6
431	27.9	28.2	27.1	48.4
432	26.8	29.9	28.7	49.8
433	25.7	31.5	29.2	51.1
434	25.7	30.3	29.7	52.3
435	25.7	29.0	29.7	53.4
436	25.6	27.7	29.7	53.8
437	25.4	26.4	31.6	54.1
438	27.0	23.6	33.4	54.8
439	28.5	20.8	36.4	55.4
440	30.5	18.0	39.4	56.1
441	32.4	15.1	40.1	56.7
442	31.6	15.7	40.7	56.7
443	30.7	16.2	41.7	56.7
444	28.7	16.7	42.7	56.7
445	26.7	17.2	43.2	56.7
446	24.7	18.8	43.7	56.6
447	22.7	20.3	43.4	56.4
448	19.2	21.9	43.0	56.4
449	15.7	23.4	42.0	56.4
450	11.5	24.7	41.0	56.9
451	7.3	25.9	41.0	57.4
452	4.9	27.1	41.0	57.6
453	2.5	28.3	40.9	57.8
454	1.3	28.8	40.7	57.8
455	0.0	29.2	38.7	57.7
456	0.0	29.6	36.7	58.2
457	0.0	30.0	35.1	58.7
458	0.3	30.7	33.4	58.7
459	0.5	31.4	31.2	58.7
460	0.3	32.1	29.0	58.7
461	0.0	32.7	25.9	58.7
462	0.2	33.2	22.8	58.6
463	0.3	33.6	18.8	58.4
464	0.2	34.1	14.7	57.9
465	0.0	34.5	10.4	57.4
466	0.0	34.4	6.0	57.4
467	0.0	34.3	3.2	57.4
468	0.2	34.2	0.3	58.2
469	0.3	34.1	0.2	59.0
470	0.2	34.3	0.0	58.9
471	0.0	34.4	0.3	58.7
472	0.0	34.5	0.5	58.7
473	0.0	34.6	0.4	58.7
474	0.3	34.5	0.3	58.9
475	0.5	34.3	0.3	59.0
476	0.3	34.2	0.3	58.4
477	0.0	34.0	0.2	57.7
478	0.2	33.7	0.0	57.7
479	0.3	33.4	0.2	57.7
480	0.4	33.1	0.3	57.4
481	0.5	32.8	0.2	57.1
482	0.4	32.2	0.0	56.1
483	0.3	31.5	0.0	55.1
484	0.2	30.8	0.0	55.3
485	0.0	30.1	0.3	55.4
486	0.3	26.5	0.5	55.1
487	0.5	22.9	0.4	54.7
488	0.3	19.3	0.3	54.2
489	0.0	15.6	0.3	53.7
490	0.2	12.0	0.3	53.7
491	0.3	8.4	0.2	53.7
492	0.3	4.8	0.0	53.6
493	0.3	1.1	0.0	53.4
494	0.2	2.2	0.0	53.4
495	0.0	3.2	0.0	53.4
496	0.0	4.2	0.0	53.4
497	0.0	5.2	0.4	53.4
498	0.3	6.1	0.7	54.1
499	0.5	7.0	0.4	54.8
500	0.5	7.9	0.0	55.1
501	0.5	8.7	0.2	55.4
502	0.4	10.7	0.3	55.3
503	0.3	12.6	0.4	55.1
504	1.6	14.6	0.5	53.5
505	2.8	16.5	0.3	51.8
506	8.2	19.2	0.0	46.0
507	13.5	21.8	0.0	42.0
508	16.4	24.5	0.0	37.0
509	19.3	27.1	1.0	32.0
510	20.6	30.0	2.0	27.2
511	21.9	32.8	6.6	25.0
512	21.4	33.8	11.1	18.0
513	20.8	34.8	13.7	12.2
514	21.5	35.8	16.2	8.0
515	22.2	36.7	18.3	3.7
516	24.5	37.1	20.4	2.2
517	26.7	37.5	23.0	0.7
518	27.2	37.9	25.5	0.5
519	27.7	38.2	27.1	0.3
520	27.6	36.4	28.7	0.2
521	27.5	34.6	28.6	0.0
522	29.1	32.8	28.4	0.2
523	30.7	30.9	28.4	0.3
524	31.8	29.5	28.3	0.2
525	32.8	28.1	28.3	0.0
526	32.7	26.7	28.3	0.0
527	32.6	25.2	30.5	0.0
528	33.9	25.9	32.7	0.0
529	35.2	26.6	35.4	0.0
530	35.7	27.3	38.0	0.2
531	36.1	28.0	39.0	0.3
532	36.0	28.3	40.0	0.2
533	35.9	28.6	40.4	0.0
534	39.0	28.9	40.7	0.0
535	42.0	29.2	41.1	0.0
536	44.9	29.6	41.4	0.5
537	47.8	30.0	41.7	1.0
538	47.8	30.4	42.0	1.5
539	47.7	30.7	42.0	2.0
540	46.1	31.0	42.0	1.9
541	44.4	31.3	41.7	1.7
542	43.5	31.6	41.4	1.6

543	42.6	31.9	41.4	1.4
544	42.3	32.4	41.4	1.1
545	41.9	32.9	43.2	0.7
546	41.7	33.4	45.0	0.5
547	41.4	33.8	47.9	0.3
548	40.8	32.9	50.7	0.7
549	40.2	32.0	51.2	1.1
550	40.5	31.1	51.7	1.6
551	40.7	30.2	51.6	2.0
552	40.8	30.2	51.4	2.0
553	40.8	30.2	51.9	2.0
554	40.6	30.2	52.4	5.4
555	40.4	30.1	52.9	8.7
556	40.6	29.3	53.4	14.2
557	40.7	28.5	53.2	19.7
558	37.8	27.7	53.0	22.4
559	34.9	26.9	52.9	25.1
560	29.9	24.1	52.7	27.3
561	24.9	21.2	52.4	29.4
562	23.7	18.3	52.1	31.6
563	22.5	15.4	51.4	33.7
564	22.1	15.9	50.7	35.1
565	21.7	16.3	50.4	36.4
566	20.8	16.7	50.1	37.8
567	19.9	17.1	50.1	39.1
568	17.6	19.0	50.1	39.1
569	15.3	20.9	48.3	39.0
570	13.3	22.8	46.4	39.0
571	11.2	24.7	40.1	39.0
572	10.5	24.1	33.7	41.0
573	9.7	23.4	29.3	43.0
574	9.6	22.7	24.8	44.5
575	9.5	22.0	22.9	46.0
576	7.1	21.4	21.0	45.5
577	4.7	20.8	19.7	45.0
578	2.7	20.2	18.4	43.9
579	0.7	19.5	19.2	42.7
580	0.5	19.8	19.9	40.4
581	0.3	20.1	20.7	38.0
582	0.2	20.4	21.4	33.2
583	0.0	20.7	21.6	28.4
584	0.4	22.0	21.8	24.2
585	0.7	23.2	21.8	20.0
586	3.0	24.4	21.8	14.9
587	5.3	25.6	24.3	9.7
588	7.6	27.8	26.7	7.9
589	9.8	30.0	30.1	6.0
590	10.1	29.7	33.4	9.4
591	10.4	29.4	34.4	12.7
592	10.6	29.1	35.4	16.1
593	10.8	28.8	36.6	19.4
594	7.6	28.8	37.8	22.2
595	4.3	28.8	39.3	25.0
596	2.7	28.8	40.8	27.4
597	1.0	28.7	42.8	29.7
598	1.0	28.4	44.8	31.7
599	1.0	28.0	46.3	33.7
600	0.9	27.7	47.8	34.7
601	0.7	27.3	48.0	35.7
602	0.9	24.4	48.1	35.7
603	1.0	21.4	48.1	35.7
604	1.0	18.5	48.1	35.4
605	1.0	15.5	49.4	35.0
606	0.9	15.4	50.7	35.0
607	0.7	15.3	51.4	35.0
608	0.4	15.2	52.0	32.9
609	0.0	15.0	52.0	30.7
610	0.0	17.7	52.0	25.9
611	0.0	20.4	53.0	21.0
612	0.4	23.1	54.0	18.4
613	0.7	25.7	54.4	15.7
614	0.5	27.3	54.7	12.9
615	0.3	28.9	54.9	10.0
616	0.5	30.5	55.0	7.2
617	0.7	32.0	55.0	4.3
618	0.6	32.4	55.0	3.2
619	0.5	32.8	54.0	2.0
620	0.3	33.2	53.0	1.4
621	0.0	33.6	52.9	0.7
622	0.0	33.3	52.7	0.4
623	0.0	33.0	51.1	0.0
624	0.5	32.7	49.4	0.0
625	1.0	32.4	47.6	0.0
626	0.5	32.1	45.7	0.4
627	0.0	31.7	45.4	0.7
628	0.0	31.3	45.0	0.4
629	0.0	30.9	45.1	0.0
630	0.2	30.8	45.1	0.0
631	0.3	30.6	44.5	0.0
632	0.2	30.4	43.8	0.3
633	0.0	30.2	41.5	0.5
634	0.0	30.5	39.1	0.3
635	0.0	30.7	35.6	0.0
636	0.2	31.0	32.0	0.0
637	0.3	31.2	27.7	0.0
638	0.2	31.3	23.4	0.3
639	0.0	31.3	24.9	0.5
640	0.2	31.3	26.4	0.3
641	0.3	31.3	29.4	0.0
642	0.5	31.5	32.4	0.2
643	0.7	31.6	34.4	0.3
644	0.4	31.8	36.4	2.5
645	0.0	31.9	37.9	4.7
646	0.0	32.8	39.4	9.6
647	0.0	33.7	40.2	14.4
648	0.4	34.6	41.0	17.3
649	0.7	35.4	41.2	20.1
650	0.4	36.1	41.4	22.3
651	0.0	36.8	41.4	24.5
652	0.0	37.5	41.4	26.7
653	0.0	38.2	40.7	28.8
654	0.4	38.4	40.0	31.3
655	0.7	38.6	39.6	33.7
656	0.7	38.8	39.1	35.7
657	0.7	39.0	38.9	37.7
658	0.7	38.9	38.7	39.2
659	0.7	38.7	37.9	40.7
660	0.5	38.5	37.0	42.1
661	0.3	38.3	36.4	43.4
662	0.2	36.7	35.7	43.4
663	0.0	35.0	35.9	43.4
664	0.0	33.3	36.0	43.4
665	0.0	31.6	33.7	43.4
666	0.0	30.1	31.4	42.9
667	0.0	28.6	28.7	42.4
668	0.0	27.4	26.0	42.1
669	0.0	26.1	23.4	41.7
670	0.0	24.9	20.7	41.1
671	0.0	23.6	16.7	40.4
672	0.0	23.8	12.7	39.9
673	0.0	24.0	11.2	39.4
674	0.0	24.2	9.7	38.9
675	0.0	24.3	10.7	38.4
676	0.2	24.5	11.7	37.9
677	0.3	24.6	12.9	37.4
678	0.3	24.8	14.0	38.1

679	0.3	24.9	15.2	38.7
680	0.2	24.7	16.4	39.1
681	0.0	24.4	17.4	39.4
682	0.0	24.1	18.4	39.4
683	0.0	23.8	18.9	39.4
684	0.5	24.5	19.4	40.6
685	0.9	25.1	19.8	41.7
686	0.5	25.7	20.1	42.7
687	0.0	26.3	20.1	43.7
688	0.0	26.3	20.1	43.6
689	0.0	26.3	20.6	43.4
690	0.4	26.3	21.1	43.8
691	0.7	26.2	21.8	44.1
692	0.4	25.4	22.4	45.1
693	0.0	24.5	22.6	46.0
694	0.0	23.6	22.7	47.6
695	5.0	22.7	21.4	49.1
696	8.0	22.2	20.0	49.9
697	13.0	21.6	19.4	50.6
698	19.0	21.0	18.7	50.1
699	25.0	20.4	20.6	49.6
700	30.0	20.0	22.4	48.3
701	33.9	19.5	23.5	46.9
702	35.1	19.0	24.5	45.4
703	36.3	18.5	26.6	43.9
704	36.7	18.3	28.7	40.9
705	37.1	18.1	30.4	37.9
706	37.8	17.9	32.0	32.9
707	38.4	17.7	33.4	27.8
708	39.0	17.8	34.7	22.6
709	39.5	17.8	35.4	17.3
710	39.5	17.8	36.0	12.0
711	39.4	17.8	36.5	6.6
712	39.4	19.1	37.0	8.0
713	39.4	20.4	37.7	9.4
714	40.7	21.7	38.4	12.7
715	42.0	22.9	38.6	15.9
716	42.7	23.4	38.7	18.6
717	43.3	23.9	38.9	21.3
718	43.2	24.4	39.0	23.9
719	43.0	24.9	39.0	26.4
720	43.1	25.4	39.0	25.1
721	43.1	25.9	39.0	23.8
722	42.7	26.4	39.0	20.5
723	42.3	26.8	39.0	17.2
724	41.1	27.8	39.0	18.1
725	39.8	28.7	39.0	19.0
726	39.7	29.7	39.0	20.8
727	39.5	30.6	39.0	22.6
728	39.1	32.2	39.0	23.8
729	38.6	33.8	38.9	24.9
730	38.1	35.4	38.7	25.4
731	37.6	37.0	39.7	25.8
732	37.8	35.6	40.7	26.1
733	38.0	34.2	40.6	26.4
734	39.2	32.8	40.4	26.6
735	40.4	31.3	40.4	26.8
736	41.7	29.0	40.4	26.8
737	42.9	26.6	40.7	26.8
738	42.7	24.2	41.0	29.3
739	42.5	21.8	40.1	31.7
740	42.1	19.8	39.1	34.9
741	41.6	17.7	39.1	38.1
742	41.6	15.7	39.0	39.3
743	41.6	13.6	39.2	40.4
744	38.9	12.2	39.4	41.0
745	36.1	10.7	38.6	41.5
746	34.4	9.2	37.7	42.1

747	32.6	7.7	37.9	42.6
748	34.0	7.9	38.1	43.7
749	35.3	8.0	35.8	44.7
750	36.7	8.1	33.4	44.9
751	38.1	8.2	30.9	45.0
752	39.2	11.9	28.4	44.9
753	40.3	15.6	26.9	44.7
754	40.5	17.7	25.4	44.6
755	40.7	19.8	21.6	44.4
756	41.8	21.9	17.8	44.5
757	42.9	24.0	14.3	44.5
758	43.2	25.1	10.8	44.7
759	43.5	26.1	7.7	44.8
760	43.4	27.1	4.6	45.6
761	43.2	28.1	2.7	46.4
762	44.1	28.3	0.7	47.1
763	44.9	28.4	0.5	47.7
764	45.8	28.5	0.3	48.2
765	46.6	28.6	0.9	48.7
766	45.9	28.7	1.4	49.1
767	45.2	28.7	1.2	49.5
768	44.6	28.8	1.0	49.5
769	43.9	28.8	0.9	49.4
770	43.3	28.3	0.7	49.3
771	42.6	27.7	0.7	49.1
772	40.6	27.2	0.7	49.3
773	38.6	26.6	1.3	49.4
774	36.1	26.7	1.9	48.8
775	33.5	26.7	2.7	48.1
776	33.1	26.8	3.5	48.0
777	32.7	26.8	3.7	47.8
778	32.6	26.5	3.8	47.6
779	32.5	26.2	3.7	47.4
780	31.4	25.9	3.5	47.3
781	30.2	25.5	3.4	47.1
782	27.0	24.7	3.3	47.1
783	23.8	23.9	1.7	47.1
784	21.0	23.1	0.0	47.0
785	18.1	22.2		46.8
786	16.4	21.9		45.2
787	14.7	21.6		43.5
788	12.3	21.3		38.5
789	9.8	21.0		33.5
790	8.1	20.6		28.5
791	6.3	20.1		23.4
792	6.3	19.6		19.6
793	6.3	19.1		15.7
794	6.9	16.5		11.[illegible]
795	7.4	13.9		7.7
796	7.4	11.3		4.5
797	7.4	8.7		1.2
798	9.8	7.4		1.0
799	12.2	6.1		0.7
800	15.7	4.8		0.5
801	19.2	3.5		0.3
802	20.7	3.1		0.3
803	22.2	2.7		0.3
804	24.4	2.3		0.2
805	26.5	1.8		0.0
806	27.3	2.8		0.0
807	28.0	3.8		0.0
808	28.0	4.8		0.0
809	28.0	5.8		0.0
810	26.3	7.5		0.3
811	24.6	9.1		0.5
812	24.1	10.7		1.6
813	23.6	12.3		2.7
814	23.6	13.7		5.0

815	23.6	15.1		7.3
816	17.3	16.5		10.0
817	11.0	17.9		12.7
818	6.1	17.2		15.4
819	1.2	16.5		18.0
820	0.9	15.8		19.7
821	0.5	15.1		21.4
822	0.5	15.3		21.8
823	0.5	15.4		22.2
824	0.8	15.6		22.3
825	1.0	15.7		22.4
826	0.8	16.1		22.0
827	0.5	16.5		21.5
828	1.1	16.9		20.9
829	1.7	17.3		20.2
830	1.0	17.8		19.1
831	0.3	18.3		17.9
832	0.2	18.2		18.0
833	0.0	18.1		18.0
834	0.9	18.0		17.5
835	1.7	17.9		16.9
836	0.9	18.1		16.8
837	0.0	18.2		16.7
838	0.0	18.3		13.4
839	0.0	18.4		10.0
840	0.4	14.3		5.0
841	0.7	10.2		0.0
842	0.9	5.1		
843	1.0	0.0		
844	0.9	0.0		
845	0.7	0.0		
846	1.6			
847	2.4			
848	2.8			
849	3.1			
850	3.2			
851	3.3			
852	3.8			
853	4.2			
854	5.3			
855	6.3			
856	6.3			
857	6.2			
858	9.9			
859	13.6			
860	14.6			
861	15.6			
862	12.6			
863	9.6			
864	8.1			
865	6.6			
866	6.8			
867	7.0			
868	8.5			
869	10.0			
870	13.6			
871	17.2			
872	17.5			
873	17.7			
874	16.4			
875	15.0			
876	12.7			
877	10.3			
878	9.7			
879	9.1			
880	6.8			
881	4.5			
882	3.3			

883	2.0		
884	1.9		
885	1.7		
886	1.7		
887	1.7		
888	3.4		
889	5.1		
890	4.9		
891	4.7		
892	4.6		
893	4.4		
894	5.5		
895	6.5		
896	6.3		
897	6.0		
898	6.0		
899	6.0		
900	6.3		
901	6.5		
902	3.3		
903	0.0		