Validation of Vehicle Fuel Consumption

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Abstract

The state of environmental degradation demands that factors contributing to it be looked into. A chief cause of environmental degradation is exhaust emissions from vehicles, especially passenger cars. This paper attempts to quantify the relationship between vehicle fuel emissions and the various factors that contribute to it such as speed, acceleration, throttle position etc. The central contention was to come up with anempirical correlation that could be used to reliably tabulate the fuel consumption of a passenger vehicle. The derivation of an empirical correlation between vehicle fuel consumption and the factors contributing to it would allow an optimisation of vehicle fuel consumption to reduce greenhouse gas emissions.

Using a comparison of different driving cycles, the New European Driving Cycle (NEDC) was taken as the basic framework for testing. The research was carried out in two different phases i.e. laboratory testing and real life drive tests. Laboratory testing was utilised to generate the major parameters that affected vehicle fuel consumption. This was then used to derive an empirical correlation that was then tested in the field to determine its validity. The proposed empirical correlation was tested against real life driving conditions which proved the reliability of the empirical correlation.

A number of different driving conditions were simulated including urban driving, extra urban driving and highway driving. The varied testing scheme ensured that the empirical correlation was valid for various driving situations at the same time. The derivation of such an empirical correlation through this work removed one of the chief defects of different driving cycles which was the lack of standardisation for

testing. With the application of this tested model it would be easier and convenient to control pollution considerably through additional research in the future.

Declaration

No portion of this work presented in this thesis has been submitted in support of an application for another degree or qualification of this or any other university or other institute of learning.

Dedication

I dedicate this work to my dear parents for the lifelong and boundless love that I received from them as well their unwavering support. This work is also dedicated to my wife for her unfaltering encouragement throughout my study and my son Abu Bakr and daughters Yakootha and Remas and Mohameed. Without their support reaching this point would not have been possible.

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Copyright

List of Abbreviations

Through the thesis abbreviations have been defined. The abbreviations and descriptions with units (where required) have been listed below.

ARTEMIS- Assessment and Reliability of Transport Emission Models and Inventory System

APTFBSFC- Advanced Power Train Facilities

BSFC- Break Specific Fuel Consumption

BDC- Bottom Dead Centre

CO- Carbon Monoxide

CARB- California Air Resource Board

CVS- Constant Volume Sampling

CAFE- Corporate Average Fuel Economy

CVT- Continuously Variable Transmission

CRDI- Common Rail Diesel Injection

EUDC- Extra Urban Driving Cycle

EUC- Elementary Urban Cycle

EPA- Environmental Protection Agency

FWD- Front Wheel Drive

FUDS- Federal Urban Driving Schedule

FHDS- Federal Highway Driving Schedule

GDI- Gasoline Direct Injection

HSDI- High Speed Driving Injection

HWFET- Highway Fuel Economy Test

IC- internal Combustion

NOX- Nitrogen Oxide

NEDC- New European Driving Cycle

OBD- On Board Diagnostic

PSAT-PNGV System Analysis Toolkit

PWM- Pulse Width Modulation

PID- Proportional, Integral, and Differentiation

PFI- Port Fuel injection

TDC- Top Dead Centre

TPS- Throttle Position Signal

UDDS-Urban Dynamometer Driving Schedule

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1. Alghadhi,M. Ball, A., Kollar,L., Mishra ,R and Asim T (2014) Fuel Consumption Tabulation in Laboratory Conditions. International Journal of Recent Development in Engineering and Technology, 2(4),pp.29-38.ISSN2347-6435
2. Alghadhi,M. Ball, A., Kollar, L., Mishra , R. and Asim T (2015) Drive Cycle Optimation Reduction. International Journal of Environmental Science and Development. Vol.6,No.10,October,2015, DOI:10.7763/IJESD.2015.V6.688. pp.727.ISSN 2010-0264

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CHAPTER-1: INTRODUCTION

1. Introduction

This chapter will look into the concept of fuel economy and the various factors that affect the fuel economy of a vehicle through an exploration of available literature on the matter. In addition, the various methods being used for fuel economy improvements such as alternative power plants, Hybrid Electric Vehicles (HEV) etc. will also be explored in detail. The different methods employed around the world for measuring fuel economy will be investigated with an emphasis on standardized driving cycles such as the New European Drive Cycle (NEDC), the Asian drive cycles and the Australian drive cycle. The limitations offered by these standardized drive cycles will also be evaluated and their applicability to the current research will be highlighted.

1.1. Fuel Economy

The fuel economy (FE) of any vehicle can be calculated as a ratio of distance travelled per unit volume of fuel consumed or as the ratio of fuel consumption per distance travelled (GFEI, 2013). Fuel economy standards can be of various forms such as litres of fuel consumed per hundred kilometres of distance travelled or kilometres travelled per litre of vehicle fuel (An, Robert, & Lucia, 2011, p. 4). The global average vehicle fuel consumption hovers around 8 litres for every 100 km corresponding to 29.4 mpg. A global drive under the aegis of GFEI has been launched to bring global fuel consumption down to 4 litres for every 100 km corresponding to 58.8 mpg by 2050 (GFEI, 2013).The regulations pertaining to fuel economy followed by the four largest automobile markets, namely, the US, the EU, Japan and China differ significantly from each other leading to a lack of global standards on the issue (An, Robert, & Lucia, 2011, p. 4).

1.2. Importance of fuel economy

From the dual perspectives of both energy conservation as well as carbon dioxide emission reduction efforts, fuel economy norms are urgently required to be implemented. On the one hand, the global oil needs have been consistently increasing despite the ongoing economic recession (An, Robert, & Lucia, 2011, p. 1). Developing countries such as Brazil, India and China are spearheading this ever-increasing global demand for oil. For example, the passenger car sector in India has been registering a steep hike in sales as shown in the figure below (Pundir, 2008, p. 6).

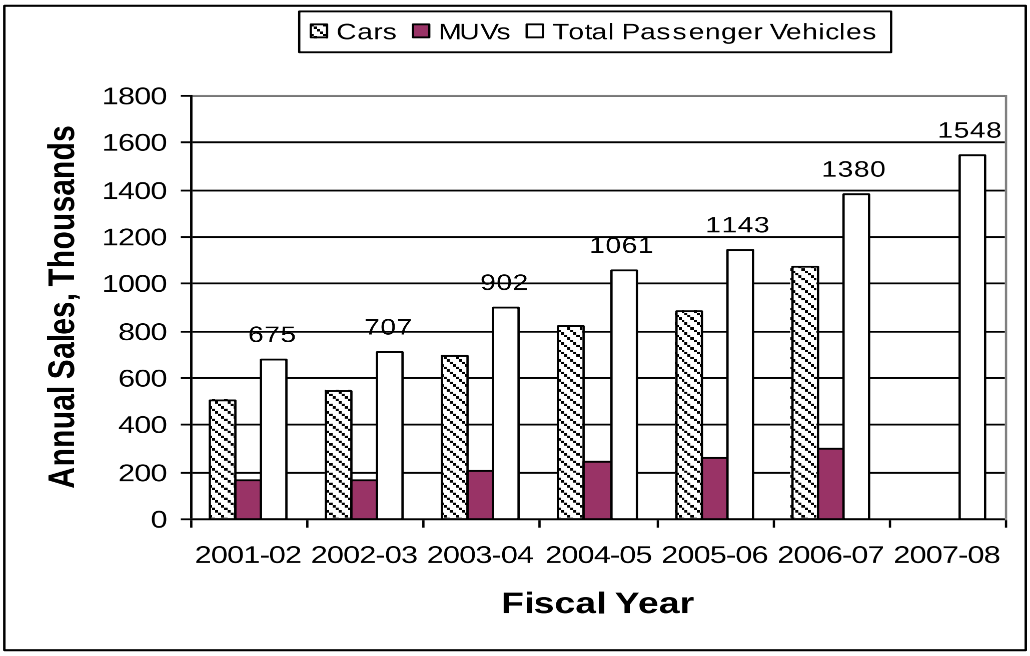


Figure 1.1 – Growth of the passenger car sector in India sourced from (Pundir, 2008, p. 6)

Car sales saw a 16% increase during the period 2000-2007in India which corresponded to an increase in petrol consumption from 6.61 million tonnes to 10.33 million tonnes as shown in Figure 1.4 below(Pundir, 2008, p. 7).The world may presently be at the peak of oil production but this condition may not last for long as can be deduced from Figure 5 below (Mi, Abdul, & Wenzhong, 2011, p. 5) which shows the future projections of demand versus production of oil. Oil is set to become a rare commodity as is evident from a glance at the extrapolated demand and supply figures below.

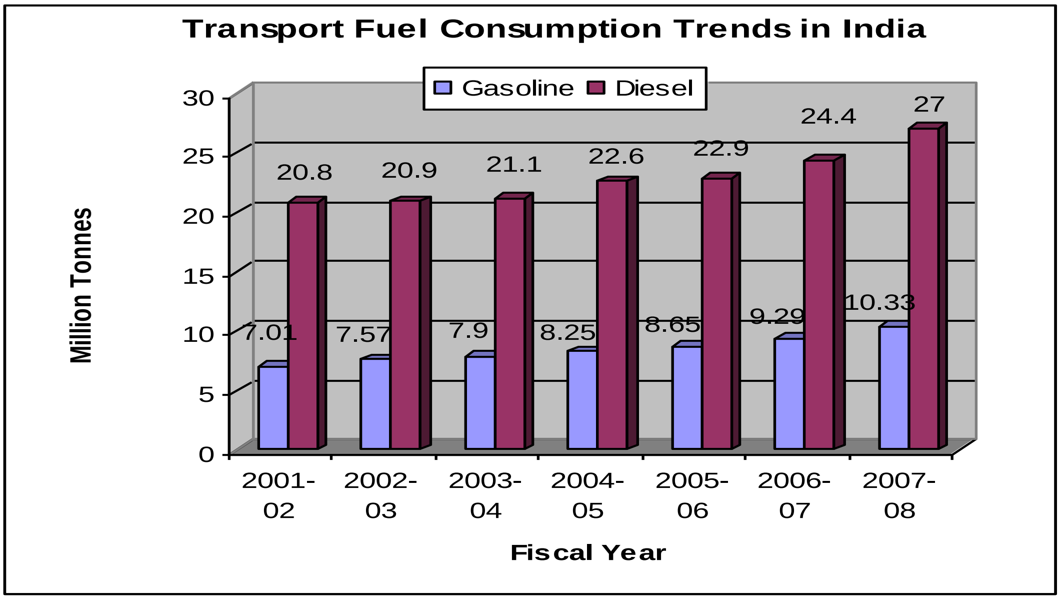


Figure 1.2 - Petrol consumption in India sourced from (Pundir, 2008, p. 7)

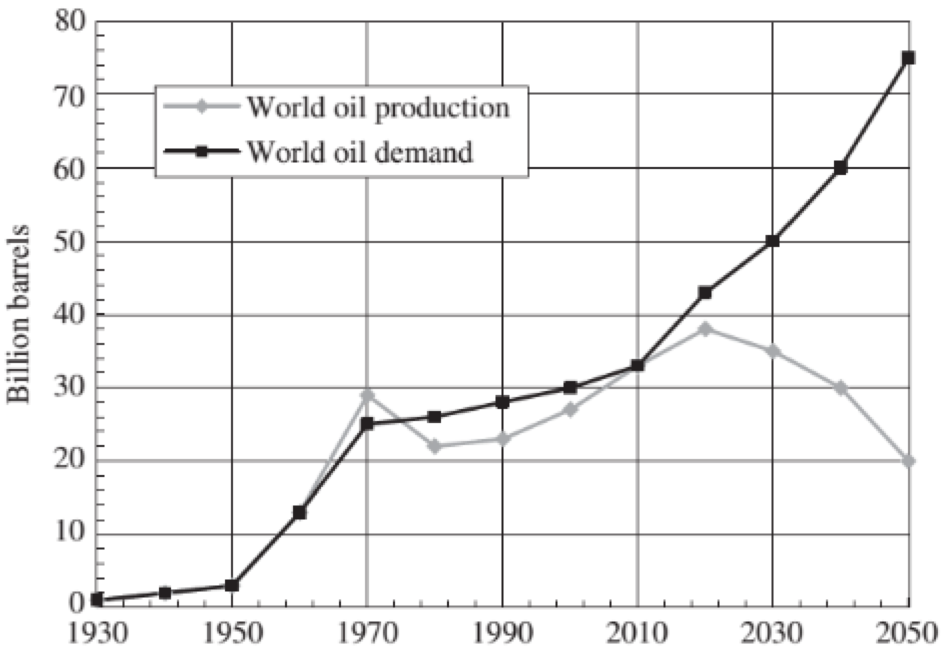


Figure 1.3 - The future projections of demand versus production of oil sourced from (Mi, Abdul, & Wenzhong, 2011, p. 5)

On the other hand, the planet earth is in the very throes of an irreversible climate change precipitated by a sudden rise in anthropogenic carbon dioxide levels in the earth's atmosphere generated due to unprecedented levels of fossil fuel burning. For the first time in recorded human history, the carbon dioxide level has raced past the 400 ppm mark, which was for long considered to be a symbolic threshold and is the highest in the past three million years (BBC, 2013). Climate change has begun to cause a wide range of irreversible and deleterious greenhouse effects such as global warming, reduction of ice cover at polar regions, increase in the acidity levels of the ocean (Harrabin, 2013), extinction of several species of flora and fauna, accelerated emission of methane from peat bogs and the consequent additional damage to the already fragile ecological and environmental balance on earth. The greenhouse effect is caused by the trapping of the outgoing infra-red radiation by the gaseous molecules in the earth's atmosphere such of carbon dioxide, water vapour, methane, nitrous oxide, chlorofluorocarbons and other gases with a resultant rise in global temperatures (Office of Technology Assessment, 1991).

The trends in the increasing global emissions of man-made carbon dioxide created due to burning of fossil fuel such as oil and coal are shown in Figure 6 below (OECD, 2004, p. 43). The recent dramatic and unprecedented sighting of plumes of methane (Connor, 2011), which is a Green House Gas (GHG) about 20 times more potent than carbon dioxide, indicates that the tipping point may well have been reached in climate change, and that immediate action is required to get the manmade carbon dioxide emissions under control. It is becoming clearer that there is a need for implementing more stringent emission control measures.

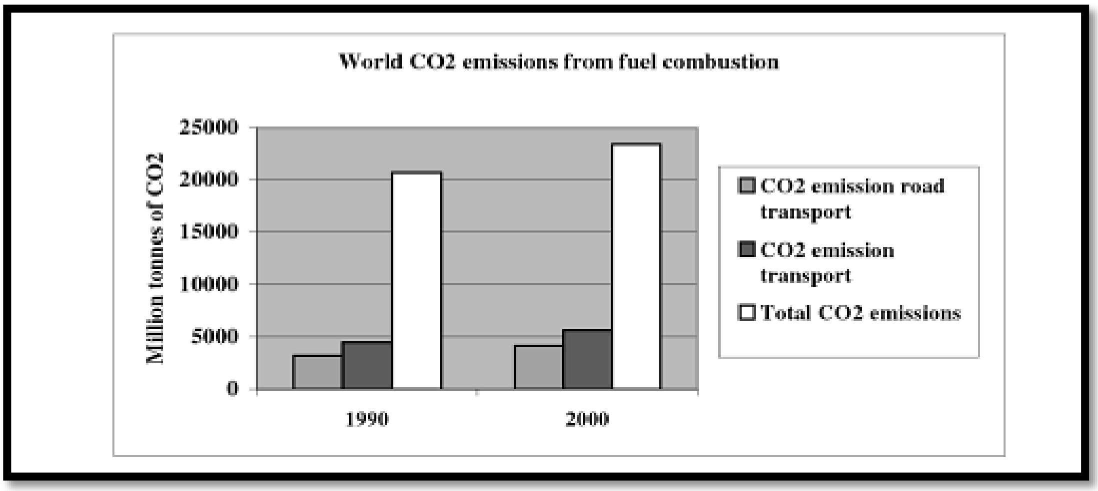


Figure 1.4 – Global carbon dioxide emissions from fuel combustion sourced from (OECD, 2004, p. 43)

Emphasis is shifting from improving the fuel economy to reducing the greenhouse gas emissions of vehicles which are one of the major causes of the ongoing climate change. Fuel economy standards are being revamped in all the major countries of the world such as the US, China, the EU and Japan (An, Robert, & Lucia, 2011, p. 3). A major challenge facing mankind is in getting a decisive control over both the spiralling oil demands and the GHG emissions (An, Robert, & Lucia, 2011, p. 1). The three crucial steps which can curb oil demand are minimizing the vehicle population growth, bringing down the travel demand and improving the fuel efficiency of vehicles.

The fuel consumption of a vehicle is controlled by the loads on the vehicle and the efficiency with which fuel is converted into work to overcome the loads (Office of Technology Assessment, 1991, p. 3). Hence by reducing the loads and by improving the efficiency of conversion of fuel into work, the fuel efficiency can be increased. The loads can be reduced by reducing the weight of the vehicle, reducing its tyre-rolling resistance and by improving its aerodynamic shape. The efficiency of conversion of energy from burning of fuel into work can be increased by reducing friction in the drive-train, reducing auxiliary loads with improved air conditioning, by improved power steering, by reducing pumping losses and by adoption of other technologies. The table below lists out the main proven and emerging technologies of the nineties for improving the fuel economy of automobiles and light trucks. In order to achieve higher vehicle fuel economy of a vehicle, improvements have to be undertaken for conversion of fuel energy to power and power transmission to wheels along with reduction in power requirement for that vehicle (Pundir, 2008, p. 16). Accordingly, engine, transmission, vehicle body and accessories have seen rapid advancements in technology and design aimed towards improvement of fuel economy which culminated in the development of the hybrid electric vehicle in the nineties. According to (OECD, 2004, p. 124) significant efforts have been made by car manufacturers towards optimizing engine efficiency since the nineties.

Table 1.1 - Fuel economy technologies for automobiles and light trucks sourced from (NRC, 2011, p. 41)

Proven Technologies	Emerging Technologies
Engine technologies	Lean burn engine
Transmission technologies	Two stroke engine
Accessories	Active noise control
Rolling resistance	Lean nitrous oxides catalyst
Inertia	
Aerodynamic drag	

1.3. Alternative Power Plants

Petrol car engines sometimes operate under partial-load conditions, the efficiency of which can be enhanced by the following technological improvements to obtained better fuel efficiency (OECD, 2004, p. 130):

(1) Variable Valve Actuation: The adoption of this technology enables the Miller cycle, which curbs throttle losses and also carbon dioxide emissions.

(2) Variable Compression Ratio: Efficiency losses caused by incomplete charges can be minimized by adopting this technology.

(3) Direct Injection on Stoichiometric Engines: By enabling fuel to vaporize in the combustion chamber by absorbing heat from the intake air, the adoption of this technology makes possible, a lowering of the combustion temperature, reduction in thermal losses and reduced fuel consumption.

(4) Downsizing: The average load can be increased by using smaller capacity engines along with turbo charging or supercharging.

(5) Cylinder Disconnection: Efficiency and load can be increased by this process which is suitable for larger engines and which shuts off cylinders at light loads.

(6) Integrated Starter Alternator (ISA): A start-stop mode is enabled by adoption of this technology which facilitates fast shut down and start operations resulting in considerable reduction in fuel consumption during city driving.

Direct injection in diesel engines enables fuel efficiency, but causes increasing emissions of nitrous oxides and particulate matter (PM) (OECD, 2004, p. 131). Emissions of carbon monoxide and volatile organic compounds (VOC) are low in diesel engines but nitrous oxides emissions register high values which cannot be significantly decreased even by exhaust gas recirculation. Since three-way catalysts cannot be used under lean conditions, the following options are employed in diesel engine cars to bring down nitrous oxides emissions (OECD, 2004, p. 131):

(1) Use of Passive de-nitrous oxides Catalyst: This technology makes use of engine output VOCs to bring down nitrous oxides emissions, after increasing the concentration of VOCs by post injection on a common-rail system.

(2) Active de-nitrous oxides Catalyst: In this technology, nitrous oxides emissions are curbed by separately adding VOCs to exhaust gases.

(3) Selective Catalytic Reduction Catalyst: In this technology, suitable for heavy duty applications, injection of selective reducing agents such as urea into the exhaust gas is undertaken to achieve reductions in nitrous oxides emissions.

(4) Nitrous oxides Storage Catalyst: The adoption of this technology enables temporary storage of nitrous oxides during lean conditions and removal of the stored nitrous oxides during short rich conditions by post-injection of fuel through advanced electronically controlled diesel-injection system though it is accompanied by the resultant fuel consumption penalty. Particulate matter emission in diesel engines can be reduced by use of filters specially adapted for regeneration (OECD, 2004, p. 133).The modern diesel engines have a fuel consumption advantage of 25% over modern petrol engines corresponding to a 14% reduction in carbon dioxide emissions.

Power need by a vehicle can be brought down by reducing the vehicle weight, minimizing the air drag, reducing the rolling resistance and by improving the efficiency of the vehicle accessories. Trends in weight in the passenger vehicle categories in the EU indicate an increase in weight of this class of vehicles by around 15% during 1980-2000 followed by a reversion back to the original weight by 2000 (Pundir, 2008, pp. 17-18). The increase in weight was caused by increased use of accessories for passenger comfort in the form of electrically actuated windows, seats, mirrors, etc., stereo-music systems and additional safety enhancing equipment such as air bags and stronger chassis and body structural parts. Weight reduction was made possible through use of light materials such as aluminium and magnesium alloys and by turbo-charging in diesel vehicles. A reduction of 100kg weight would curb fuel consumption by 0.2 L/100km which is equivalent to 0.45 km/L corresponding to a 3% improvement in fuel economy (Pundir, 2008, p. 18).

1.4. Conclusions

From the discussion above, it becomes clear that vehicle fuel efficiency is an issue of growing concern based on economic and environmental considerations. Although there has been a large amount of work done to determine and control vehicle fuel efficiency but there is a lack of standardisation that still persists. Various driving cycles discussed above exist around the world but measures of vehicle fuel efficiency from these cycles are not comparable. Moreover, the particular methods of testing for vehicle fuel efficiency differ between various driving cycles which makes derivation of a single empirical correlation impossible.

1.5. Motivation and Main Aims

1.5.1. Motivation

Fuel economy measures have become indispensable globally due to exigencies of climate change and rising oil demand. Technological advancements enable increasingly higher levels of fuel efficiency in automobiles. Vehicles powered by petrol engines appear to have far more potential than those with diesel engines for achieving improvements in fuel economy. Test drive cycles used for type approval tests emission tests and fuel economy are specific to each country or region but are based on the NEDC of EU, CAFE of USA or either 10-15 mode or JC08 of Japan. The official test drive cycles presently undertaken for type approval of vehicles do not measure or take into consideration the energy consumption requirements of auxiliary equipment or their effect on vehicle emissions (OECD, 2004, p. 128). Consumer comparisons based on such type approval data obtained while auxiliary equipment such as air conditioners in switched off condition are misleading or erroneous since such data do not reflect the environmental performance of vehicles in real use. This has resulted in a situation wherein manufacturers tend to develop automobile systems tailor-made for type approval tests than for real-life conditions. It is suggested that drive cycles for type approval of vehicles should reflect the actual environmental performance of the automobile and should be performed while the air conditioners are in switched on condition. If such realistic conditions are adopted, development of more optimal engine calibration strategies for real-life use by manufacturers would provide more realistic estimates of fuel economies and emissions. Till that time, these drive cycle tests can continue to be used for making fair comparisons between the performances and fuel economies of different types of vehicles but may provide only erroneous values of these parameters in absolute terms.

1.5.2. Aims and Objectives

This thesis aims to contribute to the understanding of the effects of drive cycle parameters on fuel consumption of passenger cars, which is essential to reduce fuel consumption in future vehicle design. The aims and objectives of the current research are:

1. Studying experimentally fuel consumption of passenger cars and their dependence on drive-cycle parameters by applying an experimental test rig
    - Constructing an experimental model to simulate NEDC;
    - Measurement of drive-cycle parameters (velocity, acceleration, throttle position) and fuel consumption using the experimental model
2. Development of anempirical correlation between drive-cycle parameters and fuel consumption

- Comparison between various drive cycles to recognise what combination of drive cycle components needs to be studied;
- Deconstructing various drive cycles into short phases in order to understand their composition and principles behind their formulation;
- Discerning which drive cycle parameters are the most significant in terms of fuel consumption;
- Rationalising the relationship between drive cycle parameters and fuel consumption by fitting functions on measured data
- Studying sensitivity of the proposed empirical correlation, and validate it via laboratory testing

3. Development of a method to predict fuel consumption in any real drive cycles

- Constructing drive cycles using short drive phases, then predict consumption in each phase and in entire drive cycle by using the proposed empirical correlation
- Application of the method in road testing
- Recognising current shortcomings and finding future research direction.

1.6. Summary

In this chapter, a number of important concepts such as the concept of fuel economy, factors which are affecting the fuel economy of a vehicle, importance of fuel economy, its design and technology, alternative power plants, management of fuel economy, measuring fuel economy, the concept of drive cycles, corporate standard of fuel economy, new European drive cycles, Asian and Australian drive cycles and problems with drive cycles are discussed. This chapter also conducts a critical discussion of the motivations, aims and objectives of this paper.

CHAPTER-2: LITERATURE REVIEW

2. Introduction

The previous chapter built on the concept of fuel economy while this chapter will delve into fuel economy measurement and the various standardized drive cycles used to tabulate fuel economy. This chapter will look into the more important research parameters and on the simulation of drive cycles to classify how they can be used for this research including dynamometers. In addition, a standardized drive cycle will be chosen to carry out the current lab and road testing research. The theoretical framework of the chosen drive cycle, its simulations, experiments to study the drive cycle and software support for these methods will also be explored.

2.1. Factors affecting fuel economy of a vehicle

The six parameters enumerated by Hilliard & Springer (1984, p.9) as influencing the fuel consumption of any vehicle are:

(1) engine characteristics;

(2) drive-train characteristics;

(3) weight, aerodynamics;

(4) rolling resistance;

(5) driving cycle;

(6) Driver habits.

The various forces which resist the movement of the vehicle are shown as a function of vehicle speed in the figure below (Hilliard & Springer, 1984, p. 8).

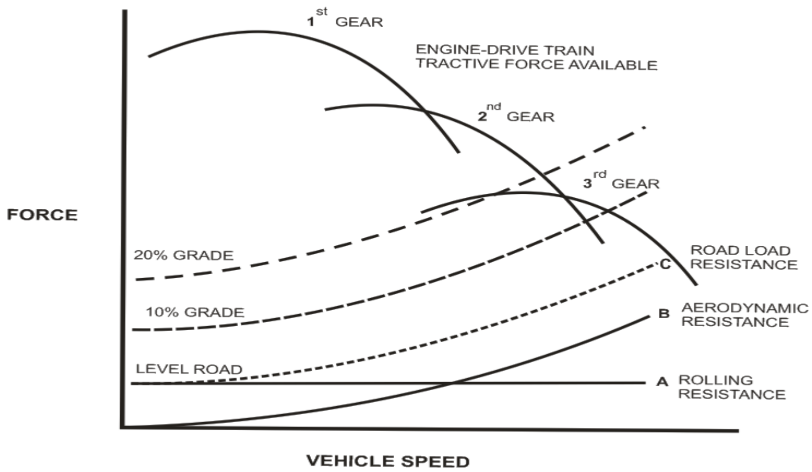


Figure 2.1 - Forces resisting the movement of the vehicle as a function of vehicle speed sourced from (Hilliard & Springer, 1984, p. 8)

In the figure above, the rolling resistance appearing at the tyre-road interface is shown as Curve A and is almost independent of speed. The aerodynamic resistance is shown as Curve B and it is proportional to the square of velocity. Curve C, which is the sum of Curve A and Curve B, is defined as the road load resistance and it represents the total force necessary for maintaining a steady speed on an even road. The product of weight of the vehicle with the sine of the slope of the road is the grade resistant force, different values of which correspond to different values of inclination, as shown in the figure under discussion. The percent slope, called grade is the tangent of the road grade angle. A schematic representation of the tractive force which is generated at the rear wheels of an internal combustion engine powered vehicle with a three-speed standard shift transmission is also shown in the above diagram. When the transmission is changed to a higher gear, there is a decrease in speed reduction ratio and a consequent decrease in transmission output torque and hence the tractive force also comes down. The force available for driving the vehicle forward is the difference between the tractive force and the road load resistance and is called the free- tractive effort. The combination of the vehicle resistance forces along with the combined performance of the engine and power drive train gives the ultimate fuel economy potential of an IC engine powered vehicle while the total of the resistance forces at any operating point has to match the tractive force delivered by the drive train (Hilliard & Springer, 1984, p. 9).

The aerodynamic drag or the air drag of an automobile is decided by the shape of the vehicle and its frontal area and is proportional to the square of its speed. The resistance offered by air can be expressed as (Pundir, 2008, p. 18):

$$F_w = C_w A \frac{\rho V^2}{2} \tag{1.1}$$

Where:

F_w is the air resistance

A is the frontal area of the vehicle

ρ is the air density

V is the vehicle speed

C_w is the air drag coefficient

The air drag coefficients of current cars have been reduced to below 0.30 which enables smooth air flow over the exterior, interior and under body of the vehicle. A reduction in fuel consumption of up to 3.5% can be achieved by a 10% reduction in air drag coefficient and that such reduction in air drag coefficient becomes more pronounced during highway driving (Pundir, 2008, p. 19).

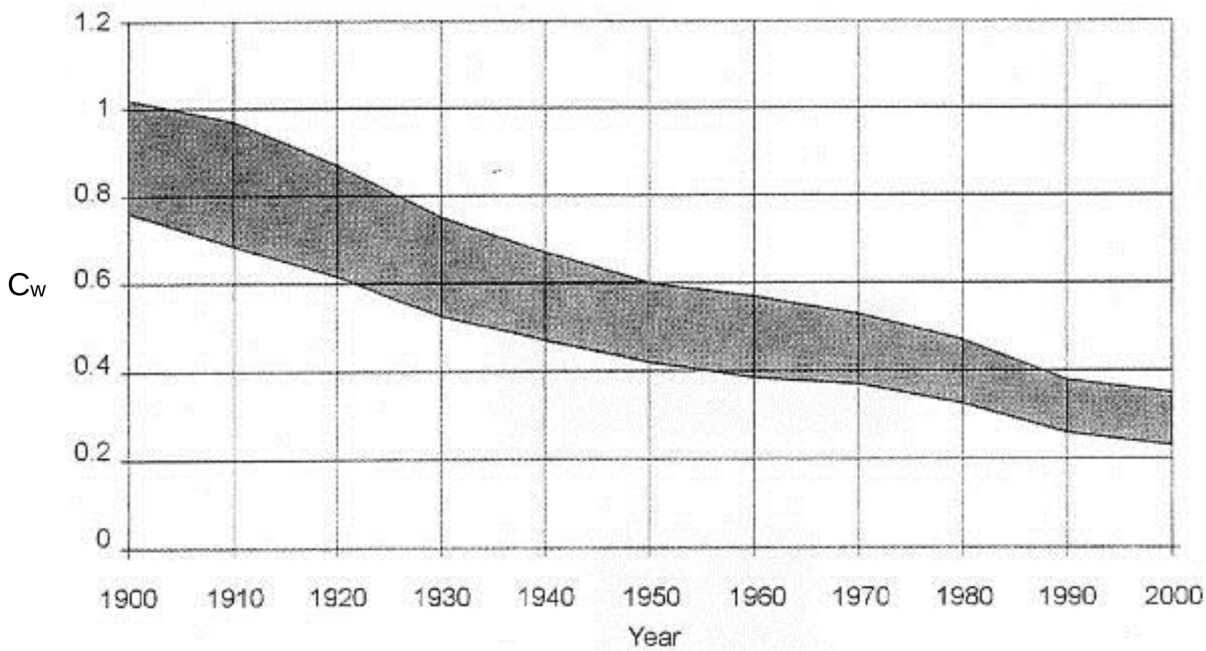


Figure 2.2 - Air drag coefficient in the European countries during the period 1900 to 2000 sourced from (Pundir, 2008, p. 19)

The figure above clearly depicts a reduction in air drag coefficient (C_w) achieved in European countries during the period 1900 to 2000.The effects of fuel consumption due to aerodynamics are more pronounced at higher speeds, generally above 120 km/h. Larger sized cars, though having large frontal areas, are designed to have better aerodynamic efficiency which compensates for their large frontal area and enables reduction in the product of frontal area and drag coefficient. Rolling resistance is decided by various parameters such as temperature, geometry, height / width coefficient and material characteristics of tyre, road surface, tyre pressure, wheel geometry, gravitational force and speed.

The energy breakdown of a traditional standard car is given in the table provided below (OECD, 2004, p. 121). It can be seen that a major part of energy is lost as heat, while a considerable portion of the energy is used for propulsion and by auxiliary systems.

Table 2.1 - The energy breakdown of a traditional standard car sourced from (OECD, 2004, p. 121)

Type of road		Urban	Highway
Energy content of fuel		**100%**	**100%**
Drivetrain losses	Thermodynamic losses	60	60
	Engine losses	12	3
	Transmission losses	4	5
	Total	**76%**	**68%**
Used for components	Auxiliaries	2	1
	Accessories	1	1
	Air conditioning (when in use)	10	10
	Total	**13%**	**12%**
Used for propulsion	Air resistance	2	11
	Roll resistance	4	7
	Kinetic losses / braking, no inclination	5	2
	Total	**11%**	**20%**

While more efficient technologies continue to be adopted, there is trend towards increases in vehicle weight caused by additional power and accessories demand from customers, with the result that fuel economy has not registered any net increase (OECD, 2004, p. 124).

Power for consumption by accessories such as air conditioners and heaters is obtained from fuel consumption. The electric power required for operating an air conditioner in a vehicle can be split up into two components, namely, as the power for the compressor and the power for fans. It was found that there was an average increase in power consumption of around 27% in cars with air conditioners running at full power as compared to cars with air conditioners switched off (OECD, 2004, pp. 124-125).The additional weight of the air-conditioning system by itself results in more fuel consumption due to extra energy required to beat the inertia of the system during acceleration and in turn increases the tailpipe emissions. Auxiliary heaters also contribute to increased fuel consumption and emissions. The ongoing technological developmental work for fuel economy carried out in vehicle air conditioners include reduction in component weight, improvement in compressor efficiency by adopting variable displacement or engine speed independent propulsion, intelligent control accuracy to increase temperature control accuracy, heat pumps, absorption systems, thermal storage, use of refrigerants with lower Global Warming Potential (GWP) with non-conventional system configuration and secondary loop systems (OECD, 2004, pp. 126-127). The power requirement of electrical equipment in a modern car is around 1kW and could go up to 12kW in the near future. The table provided below gives the power consumption of accessories in a typical European car (Pundir, 2008, p. 20). The voltages of the auxiliary electrical systems being developed in vehicles are expected to be changed to around 42V since the advanced range of on-board equipment in cars would comprise of computer controlled systems, mobile internet, fax, Global Positioning Satellite (GPS), television (TV) and video systems which need enhanced power input. Highly efficient engines are required to be equipped with alternators or Auxiliary Power Unit (APU) to supply the required power (OECD, 2004, p. 127).

Table 2.2 - The power consumption of accessories in a typical European car sourced from (Pundir, 2008, p. 20)

Accessory	Power consumption (kW)
Wipers	0.1
Exterior lights	0.16
ECU	0.2
Fuel pump	0.15
Instrument panel	0.15
Stereo system	0.2
Ventilation fan	0.1
ABS	0.6

2.2. Design and Technology for Fuel Economy

The main areas which have undergone design improvements are as follows (Pundir, 2008, pp. 16-17):

(1) Vehicle Power Requirements

a. vehicle weight reduction;
b. air drag reduction;
c. more efficient accessories like alternators, air conditioner and electrical modules.

(2) Engine

a. Engine type:
    i. petrol;
    ii. diesel.
b. Valve gear design;
c. Diesel combustion systems:
    i. Direct injection (DI);
    ii. Indirect injection (IDI);

(3) Fuel System

a. Port fuel injection (PFI);
b. Gasoline direct injection (GDI);
c. Electronic High Pressure Injection.

(4) Turbo charging;

(5) Under-sizing;

(6) Supercharging of gasoline engines;

(7) Variable swept volume

(8) Intelligent engine stop and start.

(9) Transmission

a. Manual transmission;
b. Automatic transmission;

c. Front wheel drive;

d. Six-gear to seven-gear transmission;

e. Elimination of torque converter.

2.3. Managing Fuel Economy

Though the costs of engineering technology for increasing the fuel efficiency of vehicles will increase the cost of the new automobile, the resultant improvements in fuel efficiency will bestow economic benefits to both the customers and manufacturers of the vehicle (Heinrichs, Graf, & Koeppl, 2008, pp. 1-2). The customer will get savings on fuel expenses and gains by avoiding taxation while the manufacturers would save on his potential expenses by avoiding penalties which he should have paid for his failure in meeting fuel efficiency standards. Since carbon dioxide emission is the unavoidable by product of the combustion of the fuel which gives the energy for traction, it follows that an emission reduction in gm/km can be shown as an improvement in mpg. (Heinrichs, Graf, & Koeppl, 2008) goes on to describe the additional areas being considered to improve vehicle fuel efficiency such as using variable power control systems such as pulse width modulation (PWM) system, replacing light bulbs with light emitting diodes (LED) and reducing the operating current of electronic control units (ECU) which will reduce the usage of electric power with resultant increase in fuel efficiency. Introducing variable control of motors and power train systems is another fuel efficiency improving technique. For example using PWM to variably control a fuel pump can save up to 40% of its power consumption. Similarly, a PWM controller for the air conditioning fan in place of the linear controlled series resistor can save up to 80W per km. Alternators with active and low-loss rectification or introduction of Electric Power Steering (EPS) in place of the conventional hydraulic power steering system can also cut the fuel expenses. By replacing the conventional engine-driven water pump with variable controlled electric water pump fuel savings of up to 0.6 l/100km are possible. The table below shows an overview of the different potential savings in terms of fuel efficiency, CO2 reduction, cost increase and payback period.

Table 2.3 - The different potential savings in terms of fuel efficiency sourced from (Heinrichs, Graf, & Koeppl, 2008, p. 7)

Year	New car fleet average	Approximate equivalent fuel economy (km/l) of gasoline
1995	185	12.6
2003	165	14.1
2008	140	16.6
2012	120	19.4

The use of exhaust gas recirculation and improved carburettor settings were two of the first measures taken to increase the fuel efficiency of cars using petrol as fuel (OECD, 2004). This was followed by introduction of catalytic converters and later on, lead-free fuel to prevent damage to catalytic converters. In the eighties, a closed loop system with an oxygen sensor, an engine management system and electronic fuel injection was introduced in gasoline cars, which heralded the exit of the carburettor. More refined engine control systems and more reactive catalysts were progressively introduced in response to further tightening of emission limits. The United States was way ahead of Europe in introducing the technological advancements till the 1992 Euro 1 legislation necessitated adoption of these technologies in Europe. There has been a dramatic drop in the emissions of nitrous oxides, carbon oxides and VOC in gasoline cars in Europe after the introduction of three-way catalysts with Euro 3 standards, whereas in diesel cars, the introduction of oxidation catalysts enabled reduction in carbon oxides and VOC emissions (OECD, 2004, pp. 119-120).

2.3.1. Passenger Cars

Compared to the diesel engine, the technology of petrol/gasoline engine possesses more potential for improvement in areas such as multiple valves, variable valve timing and lift systems, gasoline direct injection, variable swept volume, downsizing of the engine and supercharging (Pundir, 2008, pp. 20-21). Currently, the fuel economy of diesel engines is higher than that of petrol engines due to un-throttled and lean operation, and the characteristic higher compression ratio of diesel engines. The indirect injection (IDI) diesel engines have 15%-20% more fuel economy than petrol engines. The high speed direct injection (HSDI) diesel engines have 25%-30% more fuel economy than petrol engines of the standard port fuel injection (PFI) category. The figure below gives a comparison of fuel consumption of gasoline, IDI diesel and DI diesel engine cars in Europe.

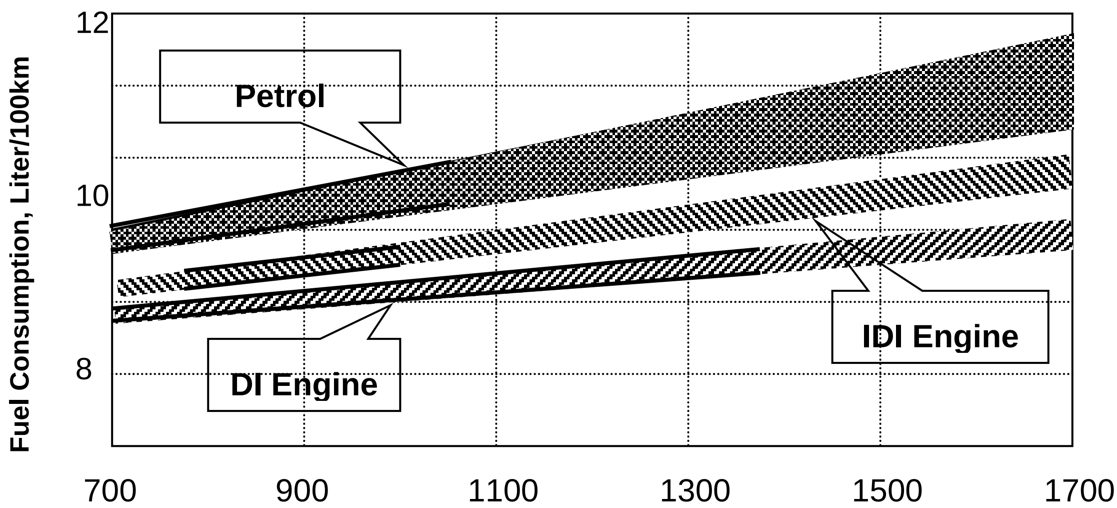


Figure 2.3 - Comparison of fuel consumption of gasoline and diesel engines sourced from (Pundir, 2008, p. 21)

A summary of technological developments for boosting fuel efficiency in gasoline vehicles has been presented by Pundir (2008, p.21-23). These developments are discussed below.

(1) Multiple Valves: This technology enables increasing the flow area through the intake and exhaust valves numbering four, control over valve timings and locating spark plug centrally in the combustion chamber with resultant shorter flame travel, faster combustion and fuel efficiency improvements of 2% to 5% (Pundir, 2008, pp. 21-22).

(2) Variable Valve Actuation: The adoption of this technology with two step valve timing variation, two step valve timing & lift and continuously variable valve timing and lift enables improvements in fuel efficiency of charging engine with fresh mixture. It also reduces pumping work and low speeds, smoother engine operation and recirculation of internal exhaust gas for nitrous oxides emission control. The fuel economy is increased by 3% to 5% by means of this technology (Pundir, 2008, p. 22).

(3) Gasoline Stratified Charge Direct Injection (GDI) Engine: This technology was introduced in 1994 and enables very lean operation of the engine. Stratification of the charge is effected inside the cylinder by design changes in geometry of combustion chamber, injection spray system and motion of the charge. Stoichiometric mixture operation at mid load range is possible with air fuel ratio in the range of 20:1 to 45:1 giving improvements of 10% to 15% in fuel efficiency in but more conservative estimates put fuel efficiency gains at 6% to 7% in real-life situations. The disadvantages are requirements for lean engine nitrous oxides control systems such as nitrous oxides storage

reduction catalysts which are expensive and difficult to operate (Pundir, 2008, pp. 22-23).

(4) Gasoline Stoichiometric Direct Injection Engine: In this technology, the petrol direct injection engines are designed to give stoichiometric operation throughout the complete range of operation which enables use of less rich mixture for cold start, idling etc., resulting in fuel economy gains of 5% to 10% (Pundir, 2008, p. 23).

(5) Engine Downsizing: In this technological advancement, engines with smaller swept volumes are used after boosting them up by turbo charging, with resultant lower values of friction losses. Since turbo charging in conventional engines causes increased incidence of knocking, direct injection petrol engines are used for this purpose. 15%-25% fuel economy gains can be obtained by adopting this process (Pundir, 2008, p. 23).

(6) Cylinder Deactivation: Applicable only to 6-cylinder and 8-cylinder engines, adoption of this technology facilitates shutting off half the number of cylinders when the car is used for very light load applications such as city driving. Such shutting off of half the number of cylinders facilitates the working cylinders to operate at better efficiency due to their working at twice as much load (Pundir, 2008, p. 23).

The areas of technological innovation aimed at improved fuel economy in diesel vehicles are as follows (Pundir, 2008, pp. 23-25).

(1) Multi-valve Technology: The use of four valves instead of two valves in diesel engines enables better volumetric efficiency and also enables locating the injector centrally in the combustion chamber resulting in fuel economy increase of 3% to 5% (Pundir, 2008, p. 24).

(2) Turbo charging: The adoption of this technology, which enables compression of air intake into the engine through a turbine coupled to a compressor facilitates entry of more amounts of air and fuel into the engine cylinders and hence enhanced power output with resultant reduction in friction losses and increased fuel economy of 3% to 7% (Nice, 2013) (Pundir, 2008, pp. 24-25).

(3) Injection Pressure and Common Rail Diesel Injection (CRDI) System: The adoption of this technology along with electronic control of injection timing and quantity enables build-up of injection pressures to the range of 1600 bars to 2000 bars at nearly all engine speeds at far less power consumptions of 20% to 50% than conventional in-line pump, distributor type or electronic injection systems of 600-800 bars. Formation of finer droplets, higher injection velocity, shorter injection duration and better spray penetration are made possible by the use of smaller nozzles and application of high injection pressures resulting in shorter combustion duration and higher efficiencies of combustion. The resultant improvements in fuel economy can be around 5% (Pundir, 2008, p. 25).

Areas with common technological developments for both gasoline and diesel engines can be listed as (Pundir, 2008, pp. 25-26):

(1) Integrated Starter-alternator: This technology consists in replacing the traditional starter and ring gear with an alternator-starter system mounted on crankshaft or driven by a belt. The adoption of this technology raises the fuel economy by 5% (Pundir, 2008, p. 25).

(2) Improved Filters and Pumps: Improved fuel economy of up to 2% can be obtained by using advanced air filters, water pumps and oil pumps with better performances (Pundir, 2008, p. 25).

(3) Reduction of Friction: Technology for reducing engine friction such as improving the design of rings, using rubbing components, lower viscosity oils with friction modifiers also improves the fuel economy.

(4) Smart Stop and Start: When engine is kept idling at traffic lights or traffic jams, it reduced the fuel efficiency. Technology for stopping the engine when the vehicle ceases to move forward and restarting it with a gentle tap on the accelerator pedal, developed especially for hybrid vehicles are now being increasingly adapted to passenger cars with resultant fuel economy savings of 5% to 8%.Smart Idle Stop System (SISS) developed by Mazda stops the engine with all of its pistons near the midpoint of their strokes so that starting torque required to restart the engine is minimized. It has been reported that adoption of SISS has resulted in reduction of fuel economy by 8% on ECE 15 drive cycle (Sherman, 2009) (Pundir, 2008, p. 26).

(5) Improvements in Transmission Technology for Fuel Economy: Continuously variable transmission (CVT) improves fuel efficiency by enabling engine operation near its best efficiency point at all vehicle speeds. The provision of infinite gearing ratios in a vehicle also improves the fuel efficiency. Moreover, the elimination of hydraulic torque converter in favour of manual transmission and use of front wheel drive (FWD) are other transmission technology features which improve the fuel economy (Pundir, 2008, pp. 27-28). The table below shows the various ways in which transmission technology can be used to improve the fuel economy of passenger cars and SUVs.

Table 2.4 - Various way that can be used to improve the fuel economy of passenger cars and SUVs sourced from (Pundir, 2008, p. 28)

Transmission technology improvement	Fuel economy gain (%)
5 gear automatic in place of 4 gear automatic	2-3
6 gear automatic in place of 4 gear automatic	3-5
CVT in small FWDs and SUVs	4-8
Elimination of torque converter	2-3

2.3.2. Hybrid Electric Vehicle (HEV)

A typical Hybrid Electric Vehicle (HEV) uses both an internal combustion (IC) engine and a battery powered electric motor or generator for its power supply. HEVs offer advantages such as regeneration of deceleration energy, stopping the engine with vehicle stop and engine drive condition optimization (OECD, 2004, p. 139). Plug-in hybrid vehicles run on storage batteries which can be recharged by plugging them to the grid. The batteries power the vehicle during low load conditions typical of city driving, saving the engine from operation in the city thus improving the overall fuel economy of the vehicle. On highways, the car is powered by the IC engines. In full-hybrids, the IC engine is not mechanically coupled to the wheel thus facilitating optimization of the engine operation region (Pundir, 2008, p. 28). The full-hybrids can be either series hybrids or parallel hybrids. Their batteries get continuously charged by the IC engine. The fuel economy of series hybrids are better than that of conventional vehicles at low speed or low load conditions but drops to below that of conventional vehicles at high load conditions. As such they are convenient for city driving. Independent of vehicle load conditions, parallel hybrids give better fuel efficiency than conventional vehicles (OECD, 2004, p. 141).

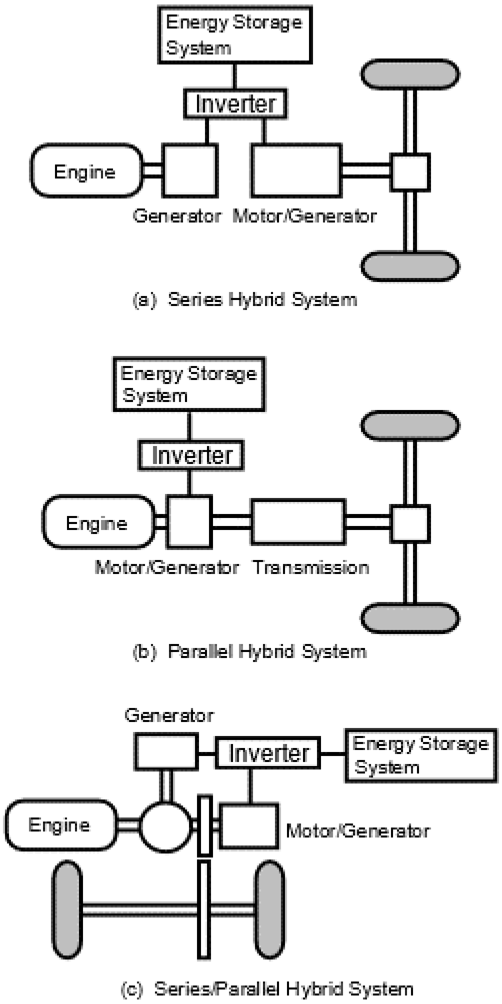


Figure 2.4 - Schematic composition of three different hybrid vehicle drive trains sourced from (OECD, 2004, p. 142)

The fuel economy of full HEVs are higher than that of conventional vehicles due to a variety of reasons such as operation of their IC engine at constant load and speed close to its point of best efficiency, the initial movement of vehicle by electric power, smaller downsized engine, partial recovery of braking energy, and possibility of designing very efficient engines with latest technology such as Atkinson cycle. The figure above schematically illustrates the composition of three hybrid drive train systems.

2.4. Measurement of Fuel Economy

The measurement of fuel economy is regulated according to different standards which can be listed as:

Table 2.5 - Fuel economy and GHG emission standards for vehicles around the world sourced from (An, Robert, & Lucia, 2011, p. 4)

Country/region	Type	Measure	Structure	Test Method	Implementation
United States	Fuel	Mpg	Footprint-based value curve	US CAFE	Mandatory
California	GHG	g/mile	Car/LDT1	US CAFE	Mandatory
European Union	CO_2	g/km	Weight-based limit value curve	EU NEDC	Mandatory
Japan	Fuel	km/L	Weight-bin based	Japan 10-15 JC08	Mandatory
China	Fuel	L/100-km	Weight-bin based	EU NEDC	Mandatory
Canada	Fuel	L/100-km	Cars and light trucks	US CAFE	Voluntary
Australia	Fuel	L/100-km	Overall light-duty fleet	EU NEDC	Voluntary
South Korea	Fuel	km/L	Engine Size	US CAFE	Mandatory

Legislation regarding fuel savings in several countries are based on, or are ultimately traceable to, the fuel economy standards originating from the US, the EU or Japan as listed in the table above. The measurement, stringency and implementation of fuel economy norms vary among the different countries of the world due to historic, cultural and political reasons (An, Robert, & Lucia, 2011, p. 4). Vehicular emissions are highly sensitive to differences in operating conditions necessitating the need for replicable test procedures (Faiz, Weaver, & Walsh, 1996). The measurement of fuel economy is generally performed on a driving cycle as part of testing compliance of the vehicles according to the regulations of the country (Pundir, 2008, p. 13). Test procedures for fuel economy generally measure vehicle emissions along with fuel economy. The driving cycle is designed in such a way as to represent the actual driving pattern specific to that country and takes into consideration the city and highway type of driving patterns prevalent in that country.

Figure 9 below illustrates the driving cycles used in the US, EU and Japan whereas Figure 10 compares the 10-15 drive cycle of Japan with the new JC08 drive cycle which replaces it from the year 2015.

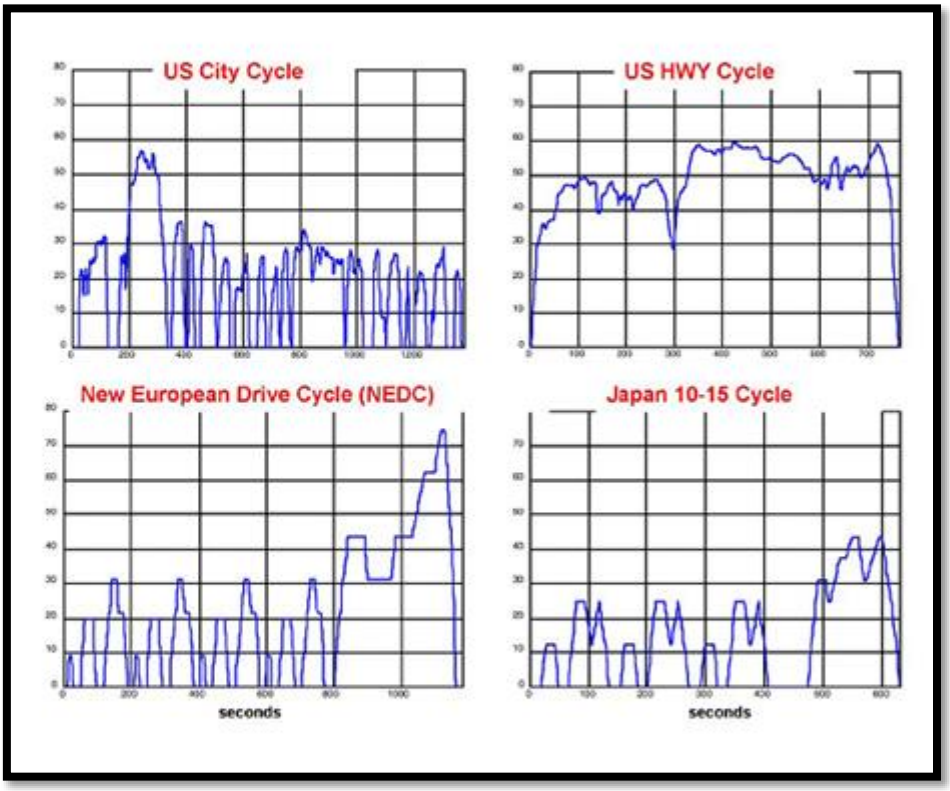


Figure 2.5 - The driving cycles used in the US, EU and Japan sourced from (Pundir, 2008, p. 14)

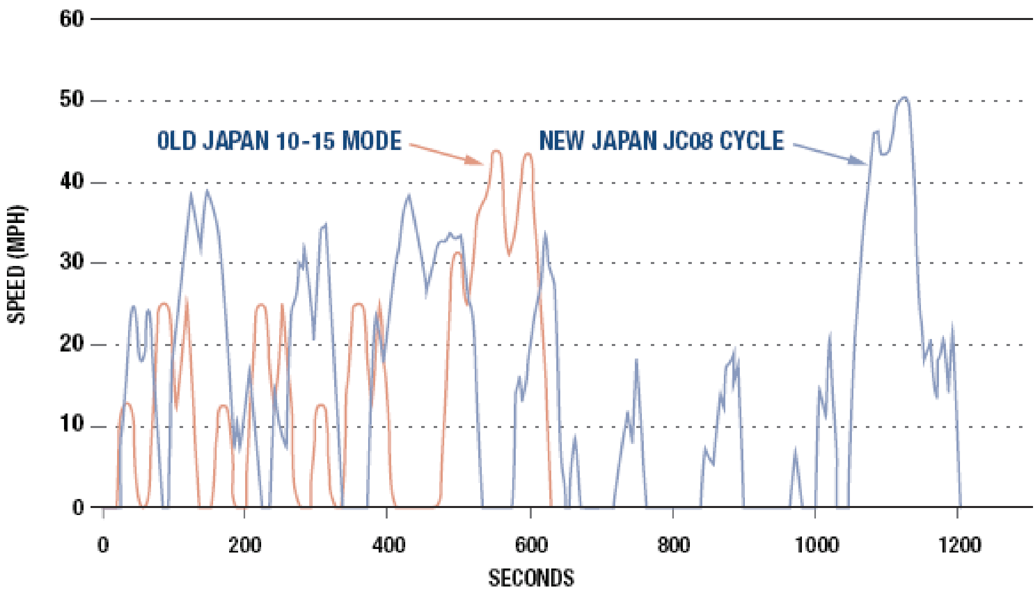


Figure 2.6 – Comparison to the 10-15 drive cycle used in Japan sourced from (Pundir, 2008, p. 14)

The level of carbon dioxide which is the main constituent of vehicular emission is linked to consumption of fuel by the vehicle. Taking this into consideration, in the US, the state of California has proposed a rule that all GHG emissions would be regulated in terms of carbon dioxide equivalent emissions (An, Robert, & Lucia, 2011, p. 16). The US, which is not a party to the Kyoto Protocol, appears all set to be just falling short of meeting its 17% target announced by President Obama in 2009 (Scientific American, 2012). The EU's current share of around 11% of global emissions of GHG gases is also registering a downward trend thanks to the rapid progress in the implementation of Kyoto targets by the EU member countries and due to escalating emissions coming in from the developing countries of the world (European Commission, 2012). China, the world's most populous nation which is also the largest contributor of GHG gases, has not announced any plans for curbing its current GHG emissions, but has set future limits to be reached through its five year plans, while India, another developing country, and the second most populous nation has not yet decided to accept any target to reduce its greenhouse emissions citing its developmental needs (Reuters, 2009).

2.5. Drive cycles

2.5.1. Corporate Average Fuel Economy standard

The fuel economy test drive cycles of the US and the EU consist of two driving schedules, one representing the city driving pattern and the other schedule representing the highway driving pattern. The US CAFE standards give 55% weight age to the city driving cycle and 45% to the highway driving cycle during fuel economy testing (Pundir, 2008, p. 13). The standard drive cycle test is performed on a chassis dynamometer for light duty vehicles and on an engine dynamometer for heavy duty vehicles (Faiz, Weaver, & Walsh, 1996, p. 25). A trained driver undertakes the driving cycle on a chassis dynamometer along with a 'driver's aid' (Barlow, Latham, McCrae, & Boulter, 2009, p. 2). A schematic representation of the test method for light-duty vehicle is illustrated in the figure below.

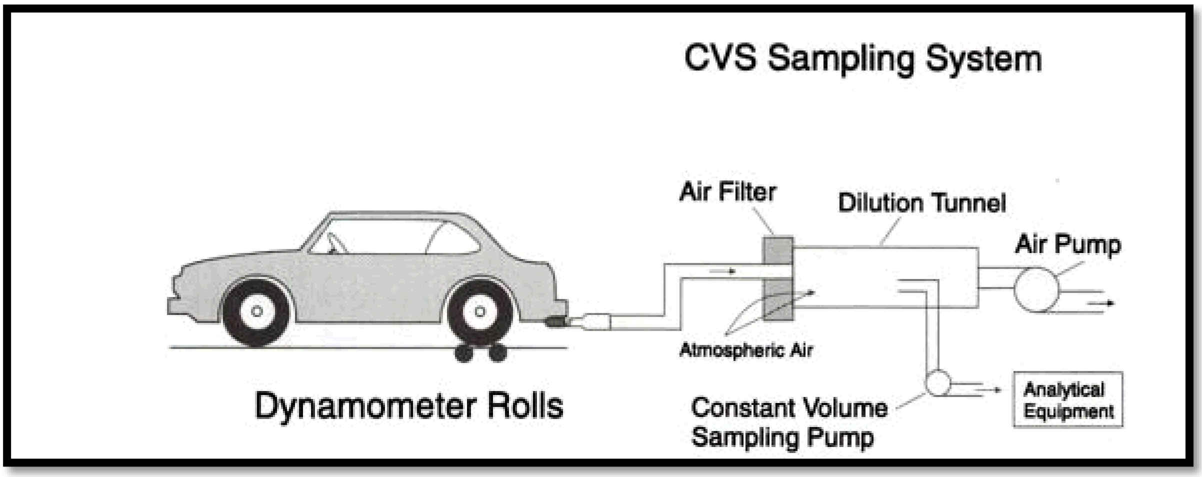


Figure 2.7 - The test method for light-duty vehicles sourced from (Faiz, Weaver, & Walsh, 1996, p. 26)

A typical US drive cycle FTP-75 test procedure is described as follows by the author. The test begins with a 12-hour soak period followed by a cold start at 20-30^{0}C. While the vehicle is being subjected to the chassis-dynamometer test for the predetermined time and speed, emission samples from its exhaust are collected in a constant volume sampling (CVS) system, after diluting and cooling. The FTP-75 driving cycle lasts for 2475 seconds and is patterned on the varying nature of urban operation. The average driving speed for the duration of the test excluding the ten-minute hot soak engine shut-off between 1370 and 1970 seconds is 31.4 km/hr. The test does not cover the full range of conditions of speed and acceleration and hence emissions under off-cycle conditions are left unmeasured. Many manufacturers utilize this unmonitored off-cycle part of the drive cycle to increase the power output and performance of their vehicles resulting in dramatic increases of up to 2500 times in emissions of CO associated with high power and load conditions (Faiz, Weaver, & Walsh, 1996, p. 26).

The US pioneered the setting up of the first-ever fuel economy standard called the Corporate Average Fuel Economy (CAFE) standard after passing the Energy Policy and Conservation Act of 1975 during the 1973 oil crisis. The table below illustrates that the CAFE program generated two separate standards, one each for passenger cars and light trucks.

Table 2.6 - Historical US corporate average fuel economy under CAFE standards (mpg) sourced from (Pundir, 2008, p. 8)

Model year	Passenger cars	Light trucks combined	Light trucks (2WD)	Light trucks (4WD)
1978	18	-	-	-
1979	19	17.2	17.2	15.8
1980	20	14	16	14
1982	24	17.5	18	16
1984	27	20	20.3	18.5
1986	26	20	20.5	19.5
1988	26	20.5	21	19.5
1990	27.5	20	20.5	19
1991	27.5	20.2	20.7	19.1
	Unrevised to 2008	Revised in 2005		

The CAFE standard for passenger cars called for 27.5 mpg and remained unchanged during 1991-2007. In the US, vehicles were being regulated on the basis of two specified fuel economy fleet average levels for cars and trucks, which are now being replaced by a new footprint-based approach which categorizes the required fuel economy targets based on the area between the four wheels called the footprint (An, Robert, & Lucia, 2011, pp. 4-5). The CAFE standards have been revised, on the basis of the footprint, for each manufacturer's vehicle size and are being followed from model year(MY) 2011 (Pundir, 2008, p. 8) (An, Robert, & Lucia, 2011, p. 4). Figure 12 below shows the footprint-based US fuel economy standards for 2011 for trucks, which all manufacturers have to comply with from MY 2011. Figure 13 below shows the evolution of fuel economy in the US.

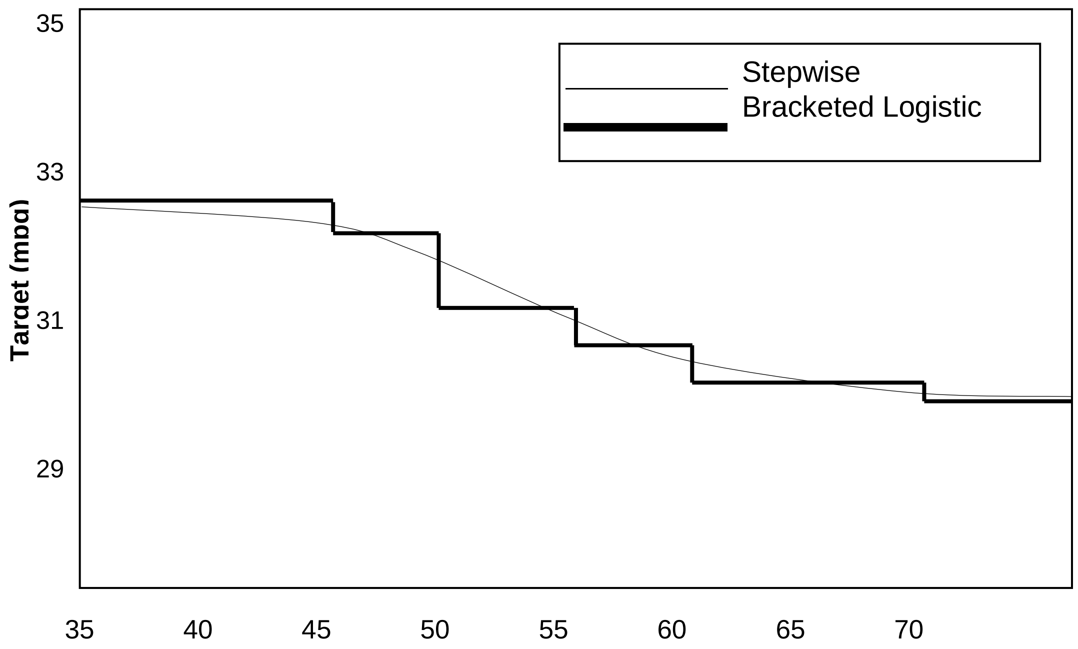


Figure 2.8 - The footprint-based US fuel economy standards for 2011 sourced from (Pundir, 2008, p. 9)

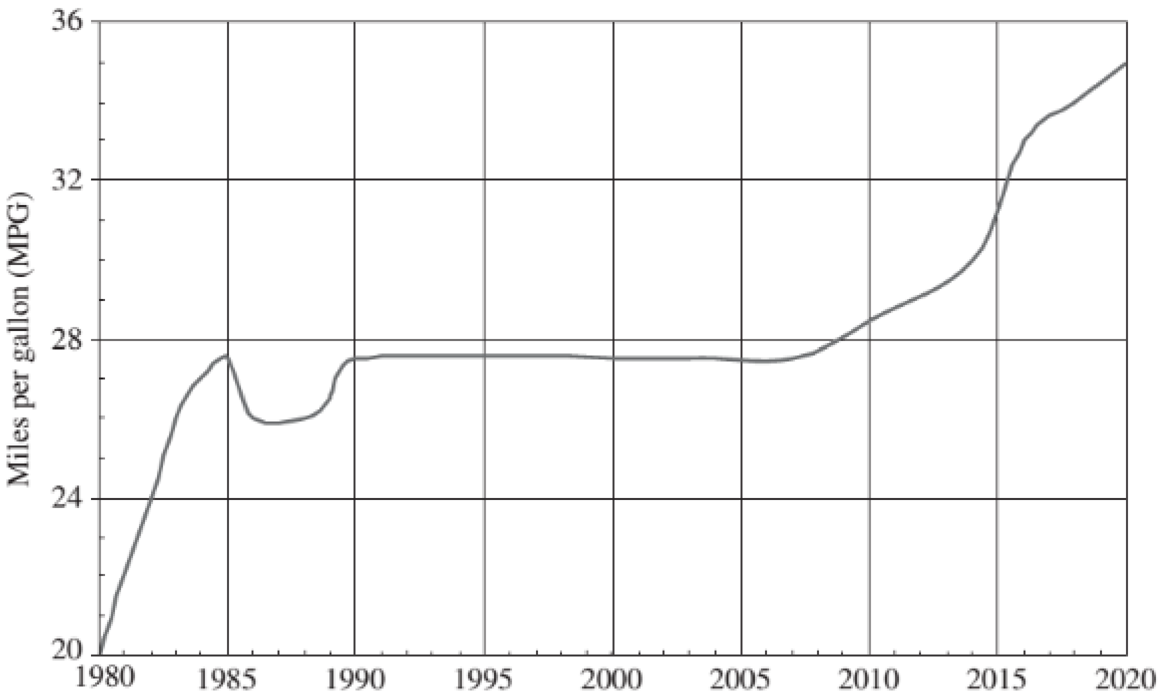


Figure 2.9 - The evolution of fuel economy in the US sourced from (Mi, Abdul, & Wenzhong, 2011, p. 8)

As distinct from the federal CAFE standard, the state of California passed in 2002 its own legislation to ensure the maximum feasible and cost-effective reduction of GHGs in its territory (An, Robert, & Lucia, 2011, pp. 6-8). This legislation has authorized the California Air Resources Board (CARB) to incorporate GHG emission limits into the current low emission vehicle (LEV) programme and other similar emission monitoring drives. Consequently, vehicles have been categorized into two groups for each of which currently two separate GHG emission fleet-average requirement norms have been established. Other states such as New York, Massachusetts, New Jersey, Maine, Connecticut, Rhode Island etc., to name a few, have approved the adoption of the California regulation for use in those states. The California Standards are expected to enable reduction of GHG emissions from the light-duty vehicle fleet by 17% in 2020 and by 25% in 2030. The Obama administration in 2010 announced plans for the merger of federal and California standards with the help of EPA, Department of Transportation and NHTS and in 2011 announced a new fuel economy target of 54.5mpg to be achieved by US vehicles by 2025 (Christian Science Monitor, 2012). It is estimated that light-duty vehicles sold during 2012-2016 would, over their lifetimes, reduce carbon dioxide emissions to the tune of 950 million metric tonnes and save 1.8 billion barrels of oil.

2.5.2. New European Drive Cycle

In the EU, one and the same cycle is used for both fuel economy and vehicle emission measurement tests (Pundir, 2008, p. 13). The New European Driving Cycle (NEDC) which was adapted in 1989 and made applicable since 1993 to passenger cars in EU weighing less than 2500 kg is a drive cycle which corresponds to the US FTP-75 cycle and is shown in the figure below. An alternative version of the NEDC cycle is shown in Figure 15 for comparison.

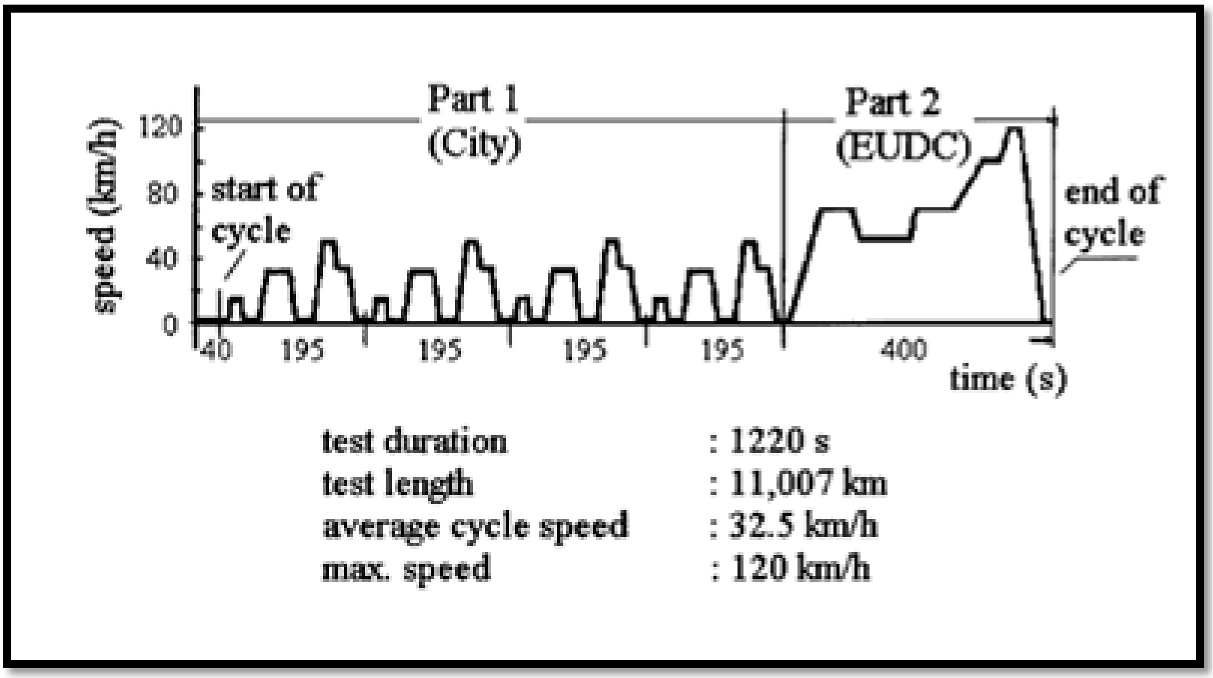


Figure 2.10 - The New European Driving Cycle (NEDC) sourced from (Sideris, 1998, p. 4)

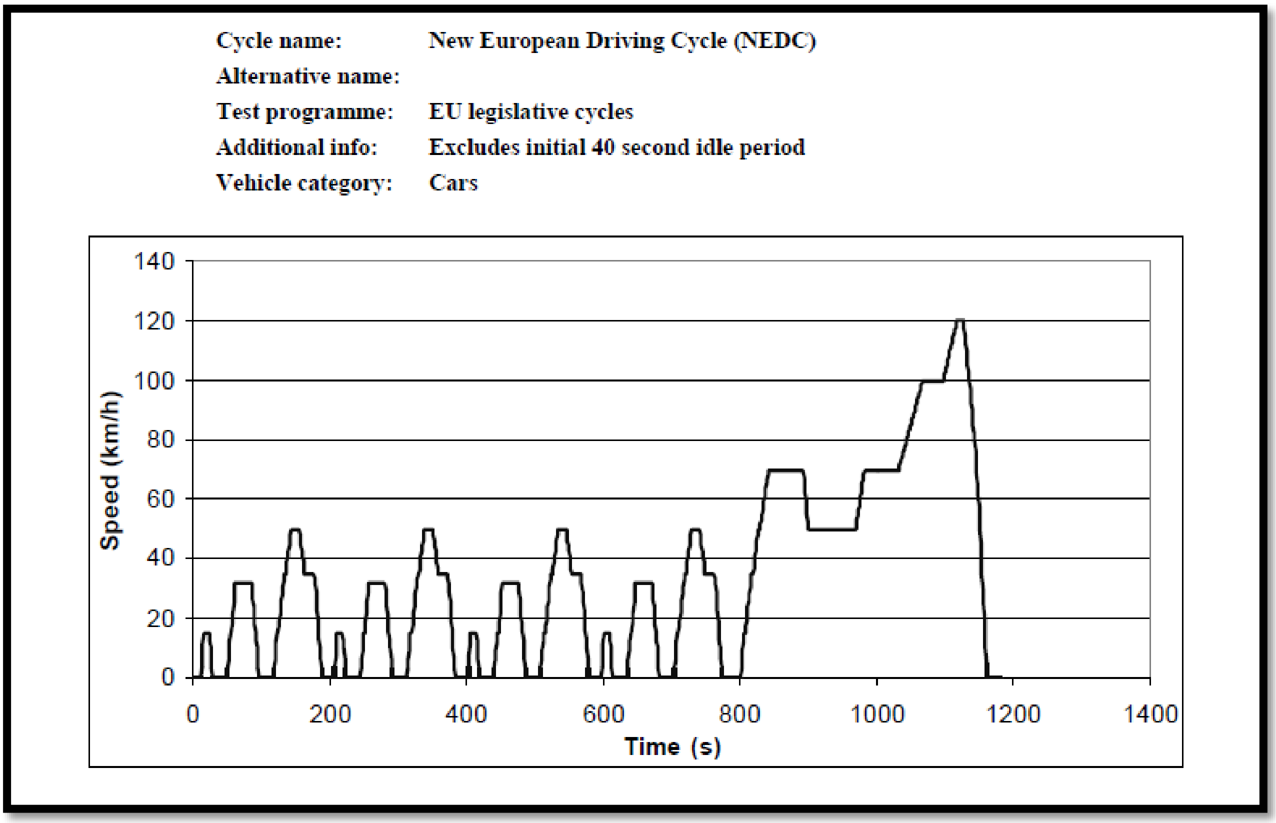


Figure 2.11 - The alternative NEDC sourced from (Barlow, Latham, McCrae, & Boulter, 2009, p. 25)

As shown in Figure 14, the NEDC driving cycle is made up of two parts, namely Part 1 and Part 2. Part 1 of the NEDC is the city driving part with a very high idling time of 31% and engine braking with mean speed of 19 km/h while Part 2 is the Extra Urban driving Cycle (EUDC) with speeds up to 120 km/h (Sideris, 1998, p. 4). The NEDC does not represent a full range of conditions of speed or accelerations of city driving and instead covers only a part of it. On the other hand, Figure 16 below compares the NEDC with FTP-75 (Sideris, 1998, p. 5).

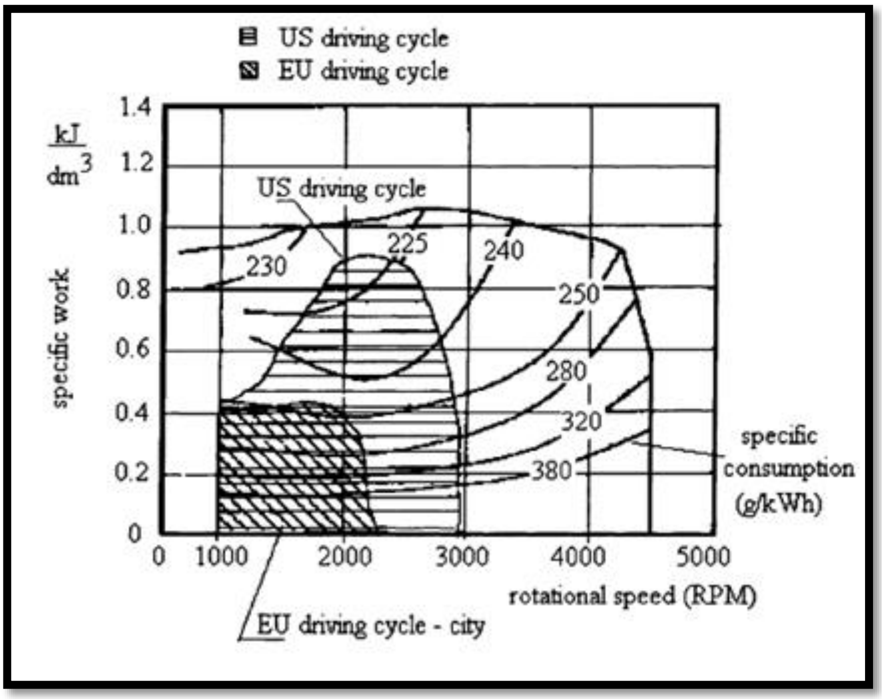


Figure 2.12 – Comparison of the NEDC with FTP-75 (Sideris, 1998, p. 5)

It is observed that the FTP-75 cycle covers a higher range load and speed conditions than the NEDC during city driving. In Europe a combination of Elementary Urban Cycle (EUC or ECE15) and the Extra Urban Drive Cycle (EUDC) is used for emission certification of passenger cars (Holder, 2008, p. 94). The author notes that the entire cycle consists of four ECE15 cycles followed by EUDC without interruption. The urban drive cycle ECE 15 represents the driving situation in big cities characterized by low values of vehicle speed, engine load and exhaust gas temperatures. The more aggressive high speed driving modes are represented by the extra urban drive cycles. The duration of the NEDC is 1180s with an average speed of 33.58 km/h with a travelled distance of 11.007 km. The test commences with a soak period of 6 hours at a temperature of 20^0 C to 30^0 C. This is followed by an engine starting and idling for 40 seconds. The requirement for cold start was removed for model year 2000 and the test cycle has been renamed as the New European Drive Cycle (NEDC). The NEDC's maximum speed of 120 km/h and low average speed of 33.6 km/h have to be seen in the context of speed limited and congested highways which are a common sight in Germany, which is a dominant member of the EU (Edinger & Kaul, 2003).

The European Union entered into voluntary agreements with associations of vehicle manufacturers to curb vehicle exhaust emissions of carbon dioxide during the 1990s (Pundir, 2008, pp. 9-11). This was done in view of its commitments under the Kyoto Protocol to achieve an 8% reduction in its GHG emissions in all sectors of the economy during 1990 to 2012 (Sigit, 2012) (An, Robert, & Lucia, 2011, p. 9). The EU standard laid emphasis on reduction of carbon dioxide emissions rather than on measurement of mileage and had set an all industry target of 140 g/km of carbon dioxide to be achieved in 2008, taking 1995 as the base year. The EU emission standards are mandated through a series of EU directives implementing the increasingly stringent standards from Euro I to Euro VI. Of these the Euro I to Euro IV emission limit for gasoline cars and light duty vehicles are shown at Appendix 1 of DEFRA (2008). The Euro V emission limits and Euro VI emission limits of Regulation (EC) No. 715/2007 are shown in the appendix as Appendix 'A' (OJEU, 2007, pp. 12-13).

In 2006, the all-industry fleet average in the EU was 160 g/km. The EU had been promoting a voluntary standard till 2009, after which year it has been made mandatory. The 2012 EU target was 120 g of carbon dioxide per km, which was adopted through an EC regulation No. 443/2009 of the European Parliament and the Council. This was to be achieved through an integrated approach. Firstly, the fleet average of 130 g/km would be achieved by all cars registered in the EU. After that, another 10 g/km would be achieved by making use of bio fuels, gear shifting reminders, efficient air conditioning, low rolling resistance tyres, tyre pressure monitoring and a limit curve for light commercial vehicles (An, Robert, & Lucia, 2011, p. 10). The current EU standards regulate the emissions of nitrogen oxides (NO_x), total hydrocarbon (THC), non-methane hydrocarbons (NMHC), carbon monoxide (CO) and particulate matter (PM) from the vehicles being newly registered, but currently there are no standards for emissions limits of carbon dioxide in the EU (Sigit, 2012). The EU has also made obligatory labelling of vehicles a legal requirement, through Directive No.19099/94/EC and of the Council to ensure that information relating to the availability of consumer information on fuel economy and carbon dioxide emissions of new passenger cars are made available to customers (Sigit, 2012).

2.5.3. Asian drive cycles

In Japan, the fuel economy standards are based on weight class and were first set up in 1999 for light-duty passenger and commercial vehicles fuelled by gasoline and petrol (Pundir, 2008, p. 11). The government of Japan allowed manufacturers of these vehicles to conditionally accumulate credits in one weight class for use in another but levied penalties in case targets were not met. Strong disincentives levied on customers in the form of progressively higher taxes based on the gross vehicle weight and its engine displacement enabled the successful implementation of these standards. Japanese standards pertaining to passenger cars, light commercial vehicles and medium commercial vehicles are shown in the tables below respectively (Pundir, 2008, pp. 11-12).

Table 2.7 - Japanese fuel economy standards for cars (km/1) sourced from (Pundir, 2008, pp. 11-12)

Vehicle mass (kg)	Gasoline cars	Diesel cars
< 702	21.2	18.9
703 – 827	18.8	18.9
828 – 1015	17.9	18.9
1016 – 1265	16	16.2
1266 – 1515	13	13.2
1516 – 1765	10.5	11.9
1766 – 2015	8.9	10.8
2016 – 2265	7.8	9.8
> 2266	6.4	8.7

Table 2.8 - Japanese gasoline LCV and MCV fuel economy standards for the year 2010 (km/1) sourced from (Pundir, 2008, pp. 11-12)

Vehicle mass (kg)	Light commercial vehicles				Medium commercial vehicles	
	Car derivative		Others		Car derivative	
	A/T	M/T	A/T	M/T	A/T	M/T
< 702	18.9	20.2	16.2	17		
703 – 827	16.5	18	15.5	16.7		
828 – 1015			14.9	15.5		
1016 – 1265			14.9	17.8	12.5	14.5
1266 – 1515			13.8	15.7	11.2	12.3
> 1516					10.3	10.7

Table 2.9 - Japanese diesel LCV and MCVs fuel economy standards for the year 2005 (km/1) sourced from (Pundir, 2008, pp. 11-12)

<table>
<tr><th>Vehicle mass (kg)</th><th>MCV (A/T)</th><th>MCV (M/T)</th><th>LCV (A/T)</th><th>LCV (M/T)</th></tr>
<tr><td>> 1265</td><td>12.6</td><td>14.6</td><td rowspan="4">15.1</td><td rowspan="4">17.7</td></tr>
<tr><td>1266 – 1515</td><td>12.3</td><td>14.1</td></tr>
<tr><td>1516 – 1765</td><td>10.8</td><td>12.5</td></tr>
<tr><td>> 1766</td><td>9.9</td><td>12.5</td></tr>
</table>

Since the majority of the Japanese gasoline passenger vehicles met or exceeded the 2010 standards, these standards were revised in Dec 2006 for implementation from 2015, increasing the number of weight categories from nine to sixteen, as shown in the figure below (Pundir, 2008, p. 13).

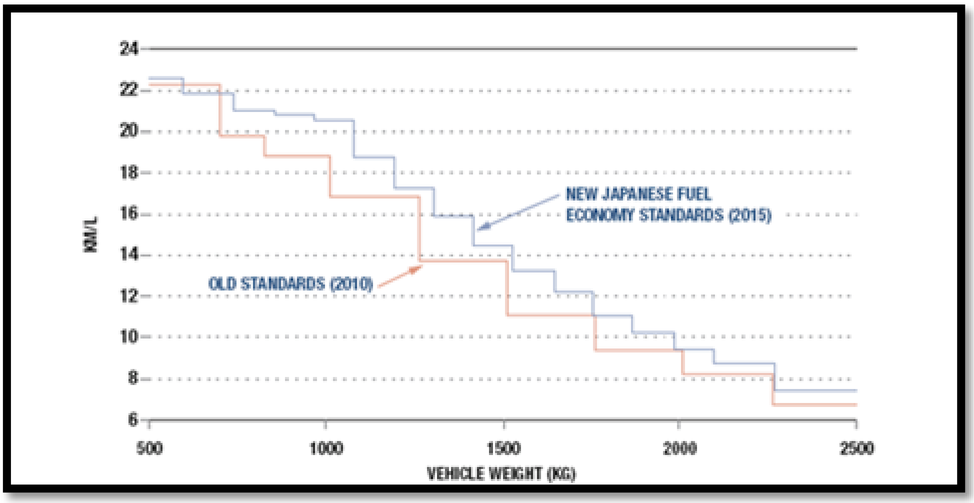


Figure 2.13 - The Japan vehicle FE standards effective from the model year 2015 sourced from (Pundir, 2008, p. 13)

For current standards, 10-15 mode test cycle would be used. The new test cycle JC08 with faster acceleration rates and higher average and maximum speeds replaces the shorter 10-15 mode test cycle from the model year 2015 in Japan. The progress made towards the year 2015 fuel economy targets would be measured by the newly introduced and more stringent JC08 test cycle (Pundir, 2008, p. 12).

In China, fuel economy standards are based on 16 weight classes of vehicles ranging from less than 750 kg to more than 2500 kg, which cover all types of vehicles except commercial vehicles and pick-up trucks (An, Robert, & Lucia, 2011, p. 10). These standards were set in 2005 followed by formulation of more stringent standards in 2008 which is claimed to have improved SUV fuel economy from 11 km/L in 2002 to 12.1 km/L in 2006 (Pundir, 2008, p. 13).

A draft regulation to curb GHG emissions of passenger cars and trucks during model year 2011-2016 has been issued by Canada. The footprint based approach recently introduced in the US CAFE standard is being adopted by Canada for measuring its fuel economy.

In the Republic of Korea also called South Korea, fuel economy standards are based on engine size classification system and the test methods followed are similar to those of the CAFE of the US (Pundir, 2008, pp. 4,14). Only the city driving cycle of the US CAFE test procedure has been adopted for fuel economy drive cycles by South Korea.

India has not yet initiated any fuel economy programme since its fuel economy norms are still under discussion (Pundir, 2008, p. 13). Fuel economy standards were to be established in India under the "Integrated Energy Policy" of 2008, with emphasis on more efficient vehicle air conditioning systems with low greenhouse gas emissions (Pundir, 2008, p. 14). Test data from the Automotive Research Association of India would be released by manufacturers to introduce a labelling system of vehicles. Meanwhile, India has adopted the European emission test procedure with a modification in the EUDC in Part 2. The modification is that the maximum speed of 120 km/h in the EUDC has been substituted with a maximum speed of 90 km/h. India calls the revised cycle as the modified Indian driving cycle (MIDC).

2.5.4. Australian Drive Cycle

Australian driving cycles are those developed for the well-known cities of the country namely Sydney, Perth, and Melbourne. All three cycles used a chase car method to collect on-road data. The cycles were primarily developed to measure carbon dioxide emissions (Tong and Hung, 2010). The New South Wales Environment Protection Agency (NSW EPA) recently develops a driving cycle that targets six specific types of diesel vehicles that are popularly used in the urban setting. The Sydney cycle uses micro-trips that best fit the assessment criteria, while the Perth cycle is based on the 'Knight's Tour' which is based on the driving characteristics and dynamics that are observed in the urban setting (Lyons *et al*., 1986). The Melbourne cycle adopts a two-tier random selection process that is based on speed-time parameters.

2.5.5. Problems with standard drive cycles

The discrepancy between type-approval values and "real-world" fuel consumption/carbon dioxide values has increased from about 8% in 2001 to around 21% in 2012 (Mock, German, Bandivadekar, & Riemersma, 2012, pp. 1-3). This discrepancy is due to various reasons such as (a) an increasing tendency to use existing tolerances and loopholes in the determination of road load, vehicle weight, laboratory test temperatures, and transmission shifting schedules for type approval and (b) Increasing manufacture of vehicles fitted with air conditioning system. In the EU, the current NEDC does not represent the 'real-life' driving conditions because it is associated with low accelerations, constant speed cruises and many idling events (Mock, German, Bandivadekar, & Riemersma, 2012). This has resulted in a situation where in the carbon dioxide emissions measured over the NEDC will not be representative of the real-life driving conditions. In addition, many manufacturers capitalize on the fact that the values of fixed speeds, gear shift points and accelerations of the NEDC cycle are already known to them and then optimize their vehicular CO_2 emissions specifically to suit the corresponding operating points of their engines so as to obtain deceptively lower emission values for their type-approval drive cycle and type approval tests, which may not represent the actual real-world emissions of their vehicles.

Research by two German Technology Institutes showed that “real-world” nitrous oxides emissions from diesel vehicles are much above the corresponding values recorded during type approval using NEDC drive cycles in the European Union (T&E Bulletin, 2006, p. 1). The two research institutes also discovered that the nitrous oxides emissions did not register any significant reduction in the preceding thirteen years.

2.6. An Overview

Motor vehicles are emerging as the largest source of urban air pollution globally, because of their steadily increasing numbers concurrent with insufficient emission control strategies (Kamble, Mathew, & Sharma, 2009, pp. 132-140). These emissions constitute a major share of air pollution and contribute to global warming (Al Zaidi, 2013, p. 13).The emissions from automobiles are combustion products such as carbon monoxide, volatile organic compounds and oxides of nitrogen and particulate matter which are mandated for control in the EU by EU Directives (Barlow, Latham, McCrae, & Boulter, 2009, p. 1). Industrialized nations have embarked on various programmes to monitor and regulate automobile GHG emissions and improve fuel economy realizing their potential in controlling oil demand (An, Robert, & Lucia, 2011, p. 1). Emission tests are conducted by means of driving cycles. A driving cycle is a fixed schedule of operation which enables the performance of an emission test under reproducible conditions (Barlow, Latham, McCrae, & Boulter, 2009, p. 2).

2.6.1. Classifying Research Parameters

In order to study the engineering characteristics of a vehicle, an artificial or hypothetical situation or profile can be developed which can cover typical road profiles and terrains expected to be faced by the particular type of vehicle in real-life use. Various arbitrary road profiles can be synthesized using such profiles which can simulate conditions of driving in a city, on a highway or on other types of terrain which can be plain, sloped, rugged or mountainous. Such arbitrary drive profiles are called drive cycles and they provide only the time and speed fluctuations, though they may be variously named, as city drive cycle or highway drive cycle etc. We can generate time versus speed data to simulate conditions faced by a vehicle being driven through a terrain having characteristics of a city and highway by synthesizing the corresponding drive cycles specific to such terrain. Now, if we want to compare the fuel economy of two passenger cars, A and B, while being driven through that terrain, this synthesized drive cycle can be very handy. The synthesized conditions of time versus speed constitute drive cycles and can be replicated under laboratory conditions of the standard drive cycle to which vehicle A and vehicle B can be tested. Thus drive cycles enable us not only to make a fair comparison between the performances of different vehicles to which they are subjected, but also between their fuel economies (Mi, Abdul, & Wenzhong, 2011, pp. 30-31).

Drive cycles have been defined by various authors in different methods such as:

(a) "a representation of a speed-time sequenced profile developed for a specific area or city", (Al Zaidi, 2013, p. 14)and

(b) "a speed-time sequence developed for a certain type of vehicle in a particular environment to represent the driving pattern with the purpose of measuring and regulating exhaust gas emissions and monitoring fuel consumption", (Barlow, Latham, McCrae, & Boulter, 2009, p. 1).

It must be noted that driving cycles are generally defined in terms of vehicle speed and gear selection expressed as a function of time.

Various testing protocols have been developed by many countries of the world to measure fuel economy and vehicle emissions (An, Robert, & Lucia, 2011, p. 15). Selection of a driving cycle which is ideally designed to represent on-road vehicle driving patterns in the particular country is a crucial element of any testing protocol. Thousands of driving cycles have been used in the measurement of emissions though only the legislated driving cycles monopolize the tests (Barlow, Latham, McCrae, & Boulter, 2009, p. 1). The Chinese Academy of Engineering (2003) notes that the standard driving cycles of Japan and EU, in which they observe that more time is spent with vehicle being in stopped or idling condition, are more similar to the US urban driving cycle than to the US highway driving cycle. The table below compares some typical US, European and Japanese driving Cycles in the context of their duration, time stopped/decelerating, speed, distance and accelerations encountered (IEA, 2005).

Table 2.10 - Comparisons of US, European and Japanese driving cycles sourced from (IEA, 2005)

	Time (s)	Percent of time stopped	Distance (miles)	Average speed (mph)	Maximum speed (mph)
Japanese 10/15 mode	631	52.3	2.6	14.8	43.5
NEDC	1181	24.9	6.8	20.9	74.6
EPA City	1372	43.2	7.5	19.5	56.7
EPA Highway	765	9.3	17.8	48.2	59.9
US average	2137	27.9	10.3	29.9	59.9

2.6.2. Simulation of Drive Cycles

The simulation of fuel consumption and emissions under a standard driving cycle in effect provides the vehicle performance of several possible driving situations due to the fact that the standard driving cycle consists of a series of data points which represent the velocity and acceleration of a vehicle versus time (Feng, 2007).

Chan and Chau (2001, pp.46-48) describe several standard driving cycles for EVs and ICEVs which are used to characterize different driving cycles in different regions or countries. According to the authors, Federal Urban Driving Schedule (FUDS), the most common driving cycle in the US was synthesized by studying statistically the trend of traffic patterns in Los Angeles and was developed to assess toxic emissions of ICEVs. On the other hand, Federal Highway Driving Schedule (FHDS) simulates rural cross-country driving in the US. The SAE J227 Cycle developed by the Society of Automotive Engineers developed for EVs has the same road load energy demand as the FUDS but has a lower peak road-load power. European cycles such as the ECE cycle which were developed to evaluate both fuel economy and emissions and its reduced version called the ECE 15 Urban Cycle , and the Japanese 10-15 Mode cycle for evaluating EVs have been described (Chan & Chau, 2001, p. 48).

NRC (2011, p.17) describes the fuel economy tests of the US. These tests use a driving cycle or test schedule originally developed for testing emissions based on simulated urban-commute driving in Los Angeles in the end of 1960s and beginning of 1970s.This cycle had different names such as LA-4, the urban dynamometer driving schedule (UDDS), or the city cycle. Another cycle known as the highway fuel economy test (HWFET) was added to the schedule by the EPA. The Federal Test Procedure FTP is a combination of the above two test procedures with weighting of 55% city cycle and 45% highway cycle respectively. NHTSA’s CAFE regulation compliance is based on vehicle dynamometer tests being conducted on both city and highway cycles with 55% and 45% weighting respectively for emission values by the EPA. In the first stage, vehicle manufacturers self-certify their preproduction prototype vehicles. In the second stage, EPA tests 10% to 15% of the production vehicles to verify the manufacturers’ claims. The EPA edits the fuel economy values of the manufacturer based on their own tests. From model year 2008, three additional tests called respectively US06, SC03 and Cold UDDS have been supplemented to the two FTP tests to capture the effects of higher speed and acceleration, air conditioning and cold weather.

2.7. Drive cycle dynamics

The force required at the wheels during driving is called the Tractive Force (F_{TR}) and is given by the formula (Berry, The effects of Driving Style and Vehicle Performance on the Real-World Fuel Consumption of US Light Duty Vehicles, 2010, p. 47):

$$F_{TR} = \left(C_\gamma M g\right) + \left(\frac{C_D A_F v^2 \rho}{2}\right) + (Mg \sin\alpha) + (M\delta a) \quad (2.1)$$

Where:

$C_\gamma$is the coefficient of rolling resistance for the vehicle

$M$is the vehicle test mass

$g$is the acceleration due to gravity

$C_D$is the coefficient of drag

$A_F$is the frontal area of the vehicle

$\rho$is the density of air

$v$is the vehicle speed

α is the angle of the road grade

sin α is the grade

δ is the mass correction factor

According to Berry (2010, p.47) an alternate equation which is applicable, if grade does not exit is as follows:

$$F = (A + Bv + Cv^2) + +(M\delta a) \quad (2.2)$$

In this case, the coefficient A is contributed by rolling resistance of the tyres, from accessory loads, drag from brake pads and wheel bearings. On the other hand, coefficient B represents partly rolling resistance of tyres, and power consumed by pumps of the vehicle. Moreover, coefficient C represents aerodynamic drag from vehicular frontal area and density of air. The coefficients can be determined by a simple test called the coast down test.

The sum of A, B and C equals the road load and is according to Berry (2010, p.48) described by the equation:

$$Roadload = (A + Bv + Cv^2) \qquad (2.3)$$

The tractive power is the product of tractive force with vehicle speed and is, according to Berry (2010, p.48) explained by the equation:

$$P = (Av + Bv^2 + Cv^3) + (M\delta av) \qquad (2.4)$$

According to Berry (2010, p.48), the average positive tractive power is the mean of the tractive power when the tractive power is positive and is given by the equation:

$$\bar{P} = \frac{\int (Av+Bv^2+Cv^3)^+ dt}{\int t^{P>0} dt} = \frac{\int (P)^{P>0} dt}{\int t^{P>0} dt} \qquad (2.5)$$

The positive energy or work required at the wheels is called the wheel work. It is obtained by dividing the total positive tractive power by the total distance travelled and is, according to Berry (2010, p.49) is governed by the equation:

$$W_{wheel} = \left(\frac{E}{t}\right) = \frac{\int (Av^3+Bv^2+Cv+Mav)^+ dt}{\int vdt} = \frac{\int (P)^{P>0} dt}{\int vdt} \qquad (2.6)$$

The wheel work consists of two components: the *velocity* or *road-work* component and the *acceleration* or *inertia-work* component. Out of these, the *velocity* or *road-work* component is the sum of the road load power when power is positive and is, as per Berry (2010, p.49) given by the equation:

$$W_{wheel,velocity} = \frac{\int (Av^3+Bv^2+Cv)^{P>0} dt}{\int vdt} \qquad (2.7)$$

The inertia summed when total power is positive is the *acceleration* or *inertia-work* component and it is given by Berry (2010, p.50) to be as per the equation:

$$W_{wheel,inertia} = \frac{\int (Mav)^{P>0} dt}{\int vdt} \quad (2.8)$$

Berry (2010, p.50) describes the total wheel work, as the sum of the road-work and inertia-work components of the wheel work and provides its equation as:

$$W_{wheel} = W_{wheel,velocity} + W_{wheel,inertia} \quad (2.9)$$

Steady-speed wheel work is the positive tractive energy per unit distance during steady speed driving. Berry (2010, p.51) notes that if there is no acceleration, tractive power is always positive and hence steady-speed work will be the instantaneous road-work at a specific velocity, proportional to road load and is given by the equation:

$$W_{wheel,steady} = \frac{\int \left(Av+Bv^2+Cv^3\right)}{\int vdt} \quad (2.10)$$

Berry (2010, p.52) describes the "acceleration wheel work" as the difference between the actual wheel work and steady speed wheel work at average speed reflecting the role of acceleration in wheel work and also the impact of variations and fluctuations in speed and as given by the equation:

$$\left(\frac{E}{x}\right)_{acceleration} = \frac{\int \left(Av^3+Bv^2+Cv+Mav\right)^{+} dt}{\int vdt} - roadload(\bar{v}) \quad (2.11)$$

2.8. Dynamometer Testing

Dynamometers are load based devices that are utilised in order to test engine performance. The loading conditions of the engine being tested are varied by manipulating the power output against the engine speed. The behaviour of most internal combustion engines is not linear so it is imperative to determine the optimal output of the engine and the engine speed at which this occurs. In the simplest terms, the dynamometer is arranged to connect the engine's output shaft to a dyno that is configured to measure the input torque. Both speed sensors and torque sensors are available on the testing arrangement in order to measure both as a function of each other. A simplified dynamometer arrangement is shown below (Gitano-Briggs, 2008, p. 5):

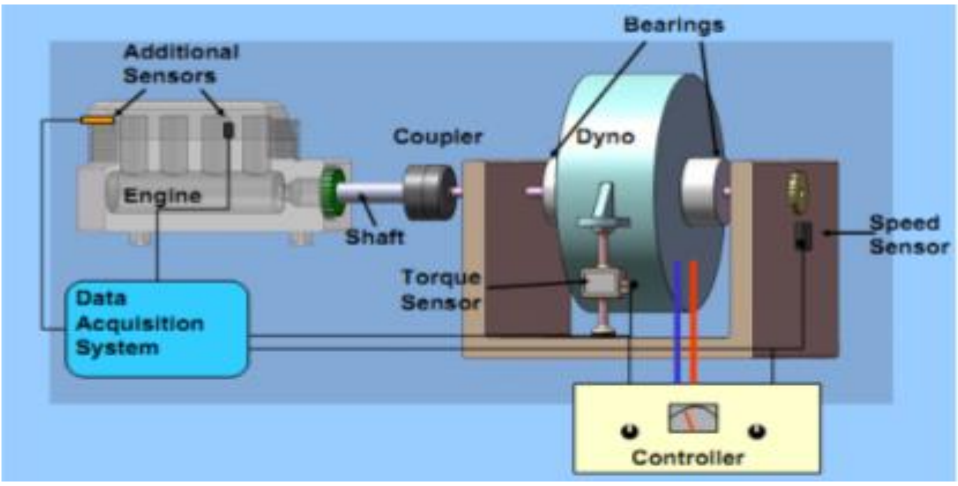


Figure 2.14 - Typical dynamometer arrangement shown diagramatically simplified, sourced from (Gitano-Briggs, 2008, p.5)

2.8.1. Relating Engine Torque and Engine Speed

The relationship between engine torque and engine speed is curvilinear in nature so testing is required to decipher engine behaviour over a range of speeds. Engine torque output tends to increase with engine speed to a certain threshold after which it tends to reduce. The dynamometer arrangement functions by equating dynamometer torque with torque produced by the engine. As the testing proceeds, the engine speed is varied by changing the engine throttle settings as well as the applied load. This allows a determination of the engine output in terms of torque at any given point under the engine's maximum torque curve.

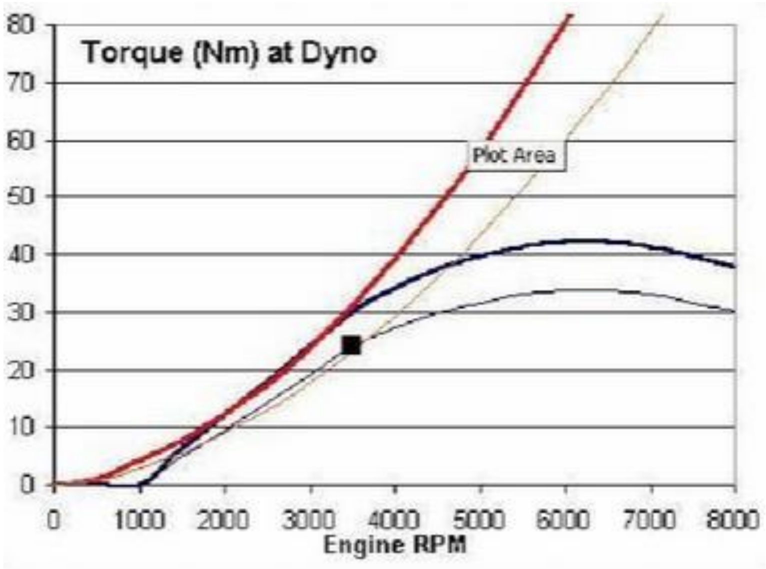


Figure 2.15- Typical dynamometer engine testing curve sourced from (Gitano-Briggs, 2008, p.7)

The figure presented above depicts a typical engine testing curve that plots the engine torque output against the engine speed output. The bolder curves depict the engine's performance at full throttle settings while the leaner curves represent the engine's performance at varying throttle settings.

Internal combustion engines need to be investigated thoroughly for their performance to classify them for better use. Moreover, engine load testing is required in order to optimise engine design to optimise the levels of fuel consumption and emissions. Increasing focus on emissions control means that engines need to be tested thoroughly to comply with stringent emissions laws.

The data generated from engine test runs provides the primary measure and scale that is utilised to achieve the aforementioned objectives. Unless reliable data is available, there could be little chance to improve engine design. The operating characteristics of internal combustion engines can only be fine-tuned using data obtained from engine test runs using dynamometers. In addition, the same data serves as proof to both customers and government regulatory agencies that the engine performs at certain minimum fuel consumption and certain maximum emissions levels.

2.8.2. Road Testing for Data Extraction

Another possibility must be examined in this regard – engine data may also be obtained through on road testing of engines (Gitano-Briggs, 2008, p. 8). Installing an engine on a vehicle and road testing it may seem a better testing idea at first but it may not be possible to execute such ideas practically. It could be argued that laboratory conditions would provide an oversimplification of on ground realities; however, these differences are accounted for using simple empirical correlations. On the other hand, it needs to be kept in mind that during road testing of an engine it may not be possible to ascertain the engine's complete operating characteristics. On a road, the road conditions would continue to vary and a stable baseline for comparison could almost never be reached. For example, traffic conditions would continue to vary and this in turn would affect the testing vehicle's speed and hence the engine speed. Moreover, it may not also be possible to test the engine over a desired range of speeds since the engine speeds would depend directly on the vehicles on road speed. In a similar manner, weather conditions would tend to vary and hence the quality of the input air would vary too. This would also not provide for a stable baseline for comparison at various throttle settings. These problems would be further compounded by the fact that sensitive laboratory equipment such as sensors would require meticulous configuration but still such equipment might not produce the required results reliably enough.

2.8.3. Limitations of Testing with Dynamometers

On the other hand, testing engines with dynamometers becomes much easier. The testing procedures with dynamometers are greatly simplified but not over simplified. It is arguable that when testing engines with dynamometers, a number of dynamic input parameters experience in the real world are absent. For example, it might not be possible to accommodate wind loading, temperature variations in actual driving conditions, varying formation of water at the exhaust, accounting vibrations and a number of other losses. A realisation of the differences between actual driving conditions and laboratory testing must be well understood in order to utilise laboratory results to deal with practical engine optimisation.

A generator type dynamometer will be used for the purposes of this research to measure speed, acceleration, throttle position, fuel consumption. Further parameters can also be measured as discussed later in this chapter, but these parameters will be used in Chapter 4 to construct an empirical correlation to predict fuel consumption. These measures will be treated as parameters obtained from testing in laboratory conditions under the NEDC framework for engine load testing.

2.9. Various drive cycles and air quality

Driving cycles are *the tests*, which are utilised in estimating the emission of vehicles, fuel consumption, fuel economy, and vehicular performance and certification. Duoba*et al* (2005) in a paper presented at Electric Vehicle Symposium 21 showed that there is a wide gap between laboratory testing for fuel economy using present and previous Environmental Protection Agency (EPA) methods and actual real-world observations and that this gap is widest in hybrid vehicles. The research used four types of conventional vehicles (Toyota Prius, Honda Insight, Toyota Echo, Ford Focus, Ford Escape, and Jaguar XJ8). These vehicles were tested using various driving cycles. Duoba et al. (2005) used Urban Dynamometer Driving Schedule (UDDS) cycles to quantify and test the robustness of vehicle fuel consumption and intensive driving. Using various multiples (0.8; 1.0; 1.2; and 1.4), the research showed the trend of fuel consumption for each vehicle through scaled results.

In the results of US06 cycles and Ford STDS, it has been observed that hybrids have significant decrease in fuel consumption. However, Duoba*et al* (2005) have found that fuel consumption have less impact on driving intensity changes and that hybrid vehicles are more sensitive to driving aggressiveness. André, Rapone, and Jounard (2004 a, b) developed another form emission testing with the aim of creating test procedures that closely resembles real-world driving cycles. Using available data from Switzerland and Italy and reviewing various cycles , André *etal* (2004) were able to create a new driving cycle called as ARTEMIS (Assessment and Reliability of Transport Emission Models and Inventory System). This system was able to present the conception that vehicles, which are using diesel, are more sensitive to speed, stop, and go parameters whereas petrol cars are sensitive to accelerations.

Moreover, by using ARTEMIS, they were able to observe that a good fit between vehicle and CO_2 emissions has been attained, but concerning other air pollutants, there are insufficient variables to establish the fit. More significantly, ARTEMIS was able to develop a database that can be used to address issues regarding emissions of low spatial scale like traffic situation approach.

In another study, Dai, Niemeier, and Eisinger (2008) assert that models such as EMFAC in California, MOBILE, FTP, and California Unified Cycle show that construction of cycle methods that are representative of real-world scenario is possible. With this, the study suggested that instead of using traffic classifications, actual driving patterns should be first identified and used vis-à-vis emission related variables. They also claimed that cycle construction methods should consider actual activities and its direct link with emissions instead of just looking at the activities on specific road link. In addition, this study claims that Speed-Acceleration Frequency

Distributions should be combined with mode modal events so that it can be representative of real-world driving conditions.

Similarly, Yu, Wang, and Shi (2008) conducted a study regarding the assessment pertinent to air quality and driving cycles. In their study, they have raised the point that many driving cycles measure emission as corollary to vehicle performance. This is significant because they assert that most of the existing driving cycles are primarily focused in knowing vehicular efficiency and as such, interests given to greenhouse gas emission are insufficient. In this regard, it results to the fact that some of the existing driving cycles are inadequate to account for or measure greenhouse gas emissions.

In order to support their claim, they have subjected Japan driving cycle, New European Driving Cycle, and other driving cycles to experimentation using the chase car method. They have come up with the finding that these driving cycles are unable to capture the characteristics and profile of gas emissions. This is critical, especially for New European Driving Cycle, since the European Union as signatory to Kyoto Protocol, have shifted the focus of their fuel policies from fuel consumption to greenhouse gas emission, particulate matter, Nitrogen Oxide, and other air pollutants. Furthermore, the study presents the idea that New European Driving Cycle and Japan driving cycle do not capture the characteristics and profile of emission activities.

In effect, this study proposes to go beyond existing driving cycles and develop new cycles that are more in tuned with the issue of emission. They assert that although traditional driving cycles like the Japan driving cycle and New European Driving Cycle cover a variety of road conditions, it is still insufficient in addressing the issue of emission within the condition of current real-world driving condition.

Finally, Tong and Hung (2010) conducted a literature review of the various driving cycles that have been developed across the globe. By reviewing 101 transient cycles, they have established categories that will help identify the various driving cycles used around the globe. They assert that driving cycles are basically made up of three important components and these are test route selection, data collection, and cycle construction methods. This is included in the literature review to highlight the fact that

(1) Various driving cycles are developed in order to address the issue of gas emissions. This signifies the fact that there is no unilateral agreement in adopting and using driving cycles.

Since, what is essential is to be able to come up with driving cycle constructs that can come close to real world scenarios. Hence, driving cycles can authentically describe the connection between gas emissions and engine performance of vehicles.

(2) There are many factors to be considered in understanding the connection between fuel economy and vehicle. Road conditions, weight, type of vehicle, friction, driving behaviour, air drag, power accessory systems, and adequate parameters describing conditions should be properly accounted in order to gain better understanding of their connection.

(3) In the presence of numerous driving cycles present, researchers should be able to find the proper driving cycle that fits their requirements (Manuel, Biona, and Cubana 2006).

These studies show that the continued effort in arriving at the appropriate driving cycle to test gas emissions and vehicular performance is crucial as it provides the means, which will ensure high performance of vehicles, protection of environment, and satisfy customers' demands. From this perspective, it can be inferred that driving cycles are critical tools and procedures in the automobile sector in particular and in the society in general.

2.10. Analysis of New European Drive Cycle

With this perspective of plurality in driving cycles, this research has chosen to use the New European Driving Cycle (NEDC). Recognising the change in the quality of life style, increased preference to personal transport, and increased mobility (Uherek*et al*., 2010); the European Commission has entered into agreement with automobile manufacturers regarding the reduction of CO_2 emissions in passenger cars (Commission Recommendation 1999/125/EC). In this regard, significant CO_2 reduction has been achieved by vehicle manufacturers in light of the target 140g/km for the year 2008/2009 and moving towards 120g/km target for 2015 (Regulation 443/2009). Regulation 443/2009 mandates that all vehicular manufacturers in EU must achieve a 130g/km emission target by 2015 for all new cars registered in EU. A further reduction of 10g/km will be attained using other approaches such use of bio fuel. This is in line with longer target of reducing CO_2 emissions in EU by 95g/km in the year 2020. These limits have been set using New European Driving Cycle. In this context, as this research intends to determine the CO_2 emission of a Nissan Patrol in European cities, it is appropriate to use New European Driving Cycle as it provides driving cycle for urban condition and extra urban condition. This is possible because New European Driving Cycle is the combination of Urban Driving Cycle (ECE) and Extra-Urban Driving Cycle (EUDC or EUDCL). *Urban driving cycle* represents urban driving conditions. It is characterised by low vehicle speed (max of 50 km/h), low engine load, and low exhaust gas temperature (*Driving Cycles*, 2013). On the other hand, *extra-urban driving cycle* describes the suburban driving conditions and cycle. At the end of the cycle, the vehicle accelerates as it enters highway-speed. In Extra-Urban Driving Cycle, both the acceleration and speed are higher than urban driving cycle, but it is still a modal cycle (*Driving Cycles,* 2013). Another possible cycle that can be used in New European Driving Cycle is the EUDCL. EUDCL is similar with extra urban driving cycle but the maximum speed is 90km/h. With this viewpoint, by using New European Driving Cycle, a wider perspective regarding urban cycle and extra-urban cycle in European cities is achieved.

2.10.1. Breakup of the NEDC

The New European Driving Cycle (NEDC) is the standard testing procedure for certification that is used in passenger cars and light duty vehicles in Europe (Li et al., 2013). New European Driving Cycle is performed in a chassis dynamometer (EEC Directive 90/C81/01). The testing procedure consisted of four urban driving cycle segments that are repeated without interruption and followed by one extra urban driving cycle (EUDC).

As noted earlier, the urban driving cycle is a driving cycle that is representative of urban setting. It is characterised by low vehicle speed, soft acceleration, and low engine loads. These are the typical driving conditions that are encountered in most European cities. On the other hand, the EUDC segments are added to account for highway, sub-urban, and motorway driveway. Initially, the vehicle is allowed to 'soak' before the test for at least 6 hours at a temperature of 20–30 °C. It was then started and allowed to idle for 40 s. From 2000, the idling period was eliminated, i.e., engine is cold started and the emission sampling process begins immediately. The New European Driving Cycle (NEDC) is used for CO_2 emission measurement. Emissions are sampled during the cycle, using the constant volume sampling technique, analysed, and expressed in grams per kilometre for each pollutant (Giakoumis and Lioutas 2010, p 137).

The “duration of the cycle is 19m 40s (1180 seconds) for Euro III and later certification, with the two phases being 13m and 6m 40s long, respectively. The Euro III test differs from the Euro II and earlier certification procedure (specified in directive 98/69/EC) in that the earlier test started with a 40-second idling period that preceded the start of gaseous emissions sampling (*Review of Test Procedures* 2013, p. 12). Consequently the earlier test:

• was 40 seconds longer, i.e. 20m 20s, although emissions were only collected for the last 19m 40s and

• Vehicles were idling for 51 seconds, rather than 11 seconds, before the start of the first acceleration.

Source: *Review of Test Procedures* 2013, p. 13

These changes are implemented to quantify, and control, the high level of emissions(especially carbon monoxide) occurring during the first part of a journey before the three way catalyst of a gasoline fuelled car is fully operational, thus, it reduces polluting emissions to a very low level. In this context, New European Driving Cycle provides an image of real-world driving condition in most European cities.

2.10.2. Limitations of the NEDC

However, New European Driving Cycle has been criticised as not truly representative of real-world driving condition in Europe. This is based on the supposition that variables integral in New European Driving Cycle does not necessarily depict real-world conditions. These are (1) New European Driving Cycle consisted of slow accelerations and decelerations and that there are several steady states. (2) it does not take into account other factors such as air-conditioning, vehicle accessories, reduced tyre pressure have an impact in the reduction of CO_2 in real world driving conditions (Fontaras and Dilara, 2012; Yu *et al*., 2010). Nonetheless, these limitations do not deter the fact that New European Driving Cycle is the driving cycle that is used for certification of passenger cars in Europe. As such, as a tool for measuring CO_2 emissions, it can be maintained that it is the standard procedure to be followed by passenger cars in Europe. In addition, it clearly manifest that existing driving cycles have limitations. As such, there is no one perfect driving cycle that can cover all of the real-world driving conditions. In case there is one, it will be *the* panacea for the issues of driving. Unfortunately, there is none. In this regard, this researcher holds as this study intends to know the greenhouse gas emission of Nissan Patrol in urban and extra-urban setting, New European Driving Cycle provides the most efficient procedure. Since, the two road routes and conditions under New European Driving Cycle are the primary focus of this study. Likewise, as the research seeks to understand the driving conditions of some cities in Europe and since, New European Driving Cycle is representative of it, and it is assumed that the New European Driving Cycle is the most appropriate driving cycle suitable in attaining the aims and objectives of this study.

2.10.3. Theoretical Framework and the NEDC

In this context, this research adopted New European Driving Cycle as the driving cycle to be used in the analysis of the Nissan Patrol engine, the identified vehicle.

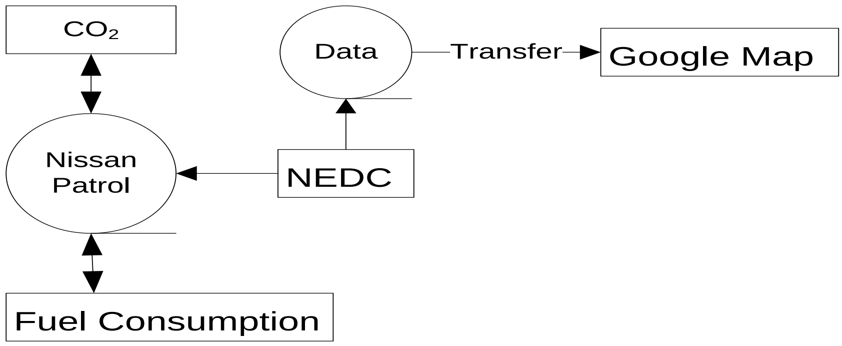


Figure 2.16 - Theoretical Framework

This figure presents the framework that presents what the research intends to attain. By using New European Driving Cycle, fuel consumption and CO_2 emission of Nissan Patrol engine can be measured. The information that will be gathered from this step will be used in three ways. First, it will be used to compare the difference between urban driving cycle and extra-urban driving cycle with Nissan Patrol as the identified vehicle. This is significant as there limited information regarding this matter. Second, the data that will be gathered in the simulation can be used as the benchmark for the on–road test that will be conducted in order to cover some of the observable gaps in New European Driving Cycle. The on-road test is critical, as the information that will be gathered is the data that will be transferred to Google Map. The third step deals with the development of pathways that will allow for the gathering of data while the vehicle is on-road travel. This means developing mechanisms that will allow for the collection, storage, and transfer of CO_2 emissions of Nissan Patrol to Google and thus, create a live feed of actual CO_2 emission of Nissan Patrol when it is used, wherever it is used.

In this context, this researcher holds that there are three essential phases in the methodology. This ensures that all the necessary data needed for the study will be gathered. Since, the information that will be gathered are critical in the attainment the aims of this research.

2.10.4. Simulations

At this phase, the research employs the PNGV System Analysis Toolkit (PSAT) for the validation of the model system. PSAT is a powerful tool that is used for analysing hybrid electric vehicles. PSAT allows users to evaluate realistically not only fuel consumption and CO_2 emission, but also vehicular performance (Pasquier, Duoba, and Rousseau, 2013). Moreover, PSAT is forward looking in the sense that it simulates vehicle system from the driver to wheels, with realistic control commands (Pasquier*etal*, 2013).

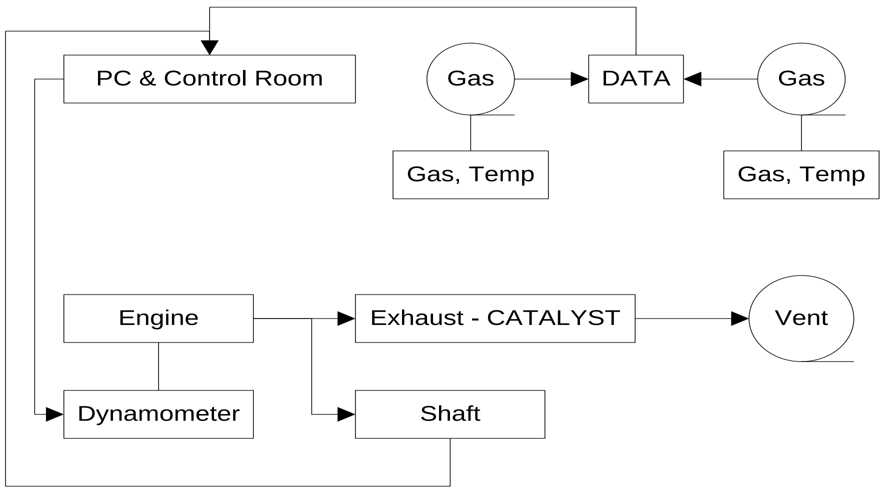


Figure 2.17 - The schematic diagram of Phase 1

The engine under observation is Nissan Patrol. Nissan Patrol has been chosen because it is considered as one of the 'greenest' vehicles (www.nissanpatrol.com.au). The engine was coupled to a McClure 215 kW transient dynamometer, and it was controlled with the aid of CP Cadet V14 control. The exhaust was modified so that it could accommodate the catalyst that was used.

For the powertrain, the PSAT-PRO software was used, as it was not required to test all the components. The part of the drive train that needed to be validated was controlled. Other simulated components were already validated by this researcher.

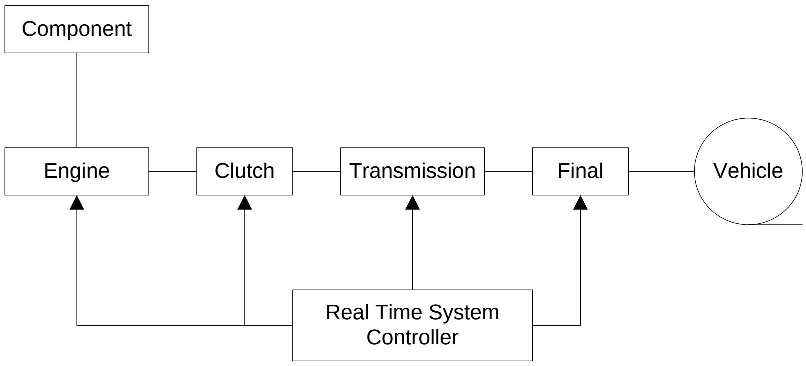


Figure 2.18 - Schematic Diagram of Powertrain Adopted from Pasquier et al.,2013

The model reacts to a command by providing a speed output when the inertia of the component is simulated, or a torque output when both inertia and stiffness of the shaft are taken into account in the model. (Pasquiera*et al* 2013, p.8). To obtain good validation results, we must use only validated component models to simulate the part of the vehicle that is not being tested. Component models that have been validated through a traditional test using our Advanced Powertrain Facilities (APTF) can be used to validate other component models. As the powertrain is assembled, we can validate the control that has been developed in simulations using PSAT. During vehicle testing, we cannot control all of the components; but using PSAT-PRO and the assembled powertrain, we can reproduce the PSAT controller for validation (Pasquiera*et al*2013, p. 9).

2.10.5. Experiments

For the experimental method, the researcher will conduct the chase car method. The chase car method or protocol is one of the recognised approaches in collecting data. This method has been briefly discussed in the previous sections. This researcher holds that this is crucial, as it will allow the researcher to get descriptions, data, and information regarding real-world driving conditions, which are all vital for this project.

At the same time, by using the chase car method, the researcher can factor in driver behaviour in the study. This is crucial, as this is one of the descriptors that have often been excluded in the analysis of driving cycles (Wildevanck, 1996). As already mentioned, there are some concerns that are observable with the chase car method and these are confusion and deviant behaviour of drivers (Tong and Hung, 2010).

However, these concerns can be limited. This can be done by:

(1) By employing trained driver so that the erratic behaviour of drivers when chased can be eliminated and at the same time the confusion regarding as to what is the target car can be significantly reduced (Tong and Hung, 2010).

(2) By working out an appropriate protocol that is suitable for the research (Tong and Hung, 2010).

In the chase car method, the chase car becomes an instrumented vehicle that records second-by-second data as it follows a predetermined route within a selected city (Yu, Wang, Qiao, and Qi, 2008). A laser is used in chase car to record the relative distance between itself and a target vehicle. With this information, it is possible to estimate second-by-second speed and acceleration data for the target vehicle. The advantage of this method is that it can simulate regular driving behaviours, but it is very difficult to chase the target car in practice (Yu *et al*. 2008). Another problem with this method is when the target car is lost, and then the collected data pertinent to the tester's driving behaviour shows irregular driving behaviour because the tester had to drive aggressively to catch the target car (Yu *et al*. 2010).

In this regard, for this study, this researcher will be working with a professional driver. In addition, owners of Nissan Patrols (the target vehicle) will be invited. This researcher will contact outdoor clubs and Nissan showrooms to invite possible participants for the study. All the necessary information will be given to the participants and that they will not be forced to join the research if they do not want. Respect for the integrity and dignity of the invited participants will be observed in all phases the research. This approach may be irregular in the chase car method, since the chase car method works on the premise that the target vehicles are not aware that they are under study. Nonetheless, this researcher thinks that it is appropriate to adopt the qualitative approach since, (1) the vehicle under study is identified – Nissan patrol and, (2) the route is identified – urban and extra urban. As such, this researcher holds that with these parameters, it is suitable that the participants be invited and informed pertinent to the research.

2.10.6. Software

This phase of the research deals directly with one of the aims of the research and that is, to develop a program that will provide live feed information regarding greenhouse gas emission of the vehicle. The ethos behind this aim is the reality that computer is already an integrated and integral part of the automotive world. The inclusion of specific software, which is specifically designed to measure greenhouse gas emission, will definitely help build a solid database anchored on real world driving conditions.

It is essential to note that there are other software already developed that are aimed in handling the issue of greenhouse gas emission and other air pollutants. The first of its kind is MOBILE, which was first created on 1978. Currently, MOBILE is now on its sixth version of the series (Kousoulidou, Ntziachristos, Hausberger, and Rexeis, 2010). Its most current version, *MOBILE6.1/6.2*, “calculates average in-use fleet emission factors for hydrocarbons, CO, NO_X, exhaust particulate matter (which consists of several components), tyre wear particulate matter, brake wear particulate matter, sulphur dioxide (SO_2), (NH_3,) six hazardous air pollutants (HAP), and CO_2 for gasoline-fuelled and diesel highway motor vehicles and for certain specialized vehicles such as natural-gas-fuelled or electric vehicles that may replace them. It bases these emission factors on vehicles from the 25 most recent model years, and is capable of developing factors for calendar years from 1952 to 2050" (Kousoulidou*et al*. 2010, p. 24).

Another important emission inventory tool is the Motor Vehicle Emission Simulator (MOVES). This system will estimate emissions for both on-road and non-road sources. It "covers a broad range of pollutants, and allows multiple scale analysis, from fine-scale analysis to national inventory estimation" (Kousoulidou*et al*. 2010, p. 24). In effect, MOVES is not just a simple software program, but it is a combination of algorithm, "underlying data and guidance necessary for use in all official analyses associated with regulatory development, compliance with statutory requirements, and national/regional inventory projections" (Kousoulidou*et al*. 2010, p. 25).

The last software to be given consideration is COPERT 4. This software is developed primarily to measure air pollutants coming from road transport. COPERT is part of the EMEP/CORINAIR Atmospheric Emissions Inventory Guidebook (AEIG) and it is used by several European member states in their official reporting of national emission inventories for road transport (Kousoulidou*et al*. 2010, p. 26).

What is significant with COPERT 4 is that it "estimates emissions of all regulated air pollutants (e.g., CO, NO_X, volatile organic compounds (VOC), and particulate matter) produced by different vehicle categories (passenger cars, light-duty vehicles, heavy-duty vehicles, mopeds, and motorcycles) as well as CO_2 emissions on the basis of fuel consumption. Emissions are also calculated for other nonregulated pollutants, including CH_4, N_2O, NH_3,SO_2, heavy metals, polycyclic aromatic hydrocarbons (PAHs) and persistent organic pollutants (POPs)" (Kousoulidou*et al*. 2010, p. 26).

Moreover, the models "are estimated from three general processes: emissions produced during thermally stabilized engine operation (hot emissions), emissions occurring during engine start from ambient temperature (cold-start and warming-up effects) and NMVOC emissions due to fuel evaporation" (Kousoulidou*et al*. 2010, p. 26). Finally, COPERT 4 "distinguishes between urban, rural and highway driving to account for variations in driving performance. Different activity data and emission factors are attributed to each driving situation" (Kousoulidou*et al*. 2010, p. 26).

In this regard, the emission inventory tool that is envisioned is to be integrated in the computer and communication system of the vehicle is COPERT 4 with provision for MOVES. These two software programs have been chosen because they touch on ordinary concerns and experience of people. These software programs do not abstract the issue of greenhouse gas emission, but they bring to reality the gravity of the issue. From this perspective, these two software are essential in understanding, from user's perspective, greenhouse gas emission levels.

These programs can be integrated in the Controller Area Network (CAN) system of vehicles. CAN is the latest communication system in the automotive world (*OBD II Network Systems*, 2013). CAN is a "means of linking all of the electronic systems within a car together to allow them to communicate with each other. As on-board computers increase, so does the number of different electronic Systems" (*OBD II*, 2013).

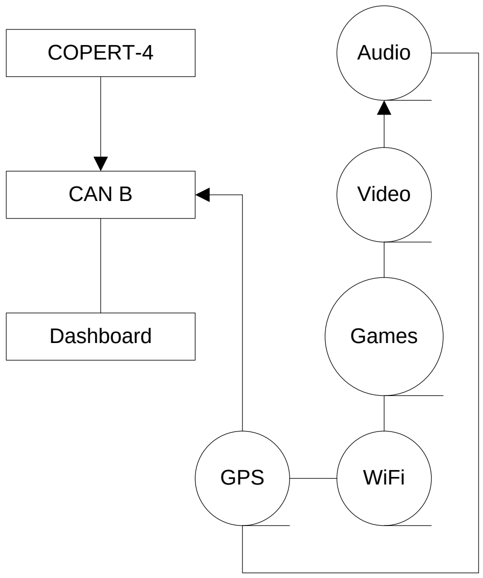


Figure 2.19 - The Schematic Diagram of CAN

This figure shows the CAN that will be integrated into the vehicle. The system will be integrated in the dashboard of the Nissan Patrol. It will contain the program that will allow the vehicle to collect the needed input or data relevant to gas emissions. This data can be stored and retrieved in the computer. Furthermore, the data can be sent to Google Map for actual live feed of data.

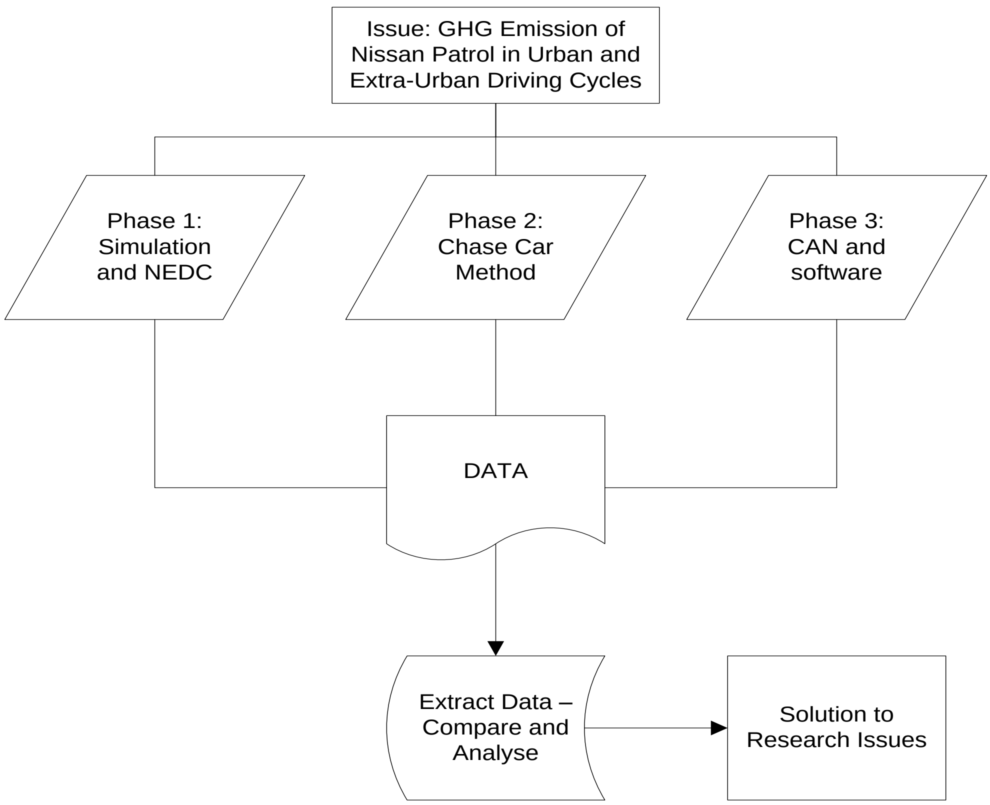


Figure 2.20 - Research Design

Figure 24 presents the methodology that is adopted in the conduct of this research. In recognising the issue pertinent to greenhouse gas emissions of Nissan Patrol in urban driving cycle and extra-urban driving cycle, there is a need to undertake the research in three phases. As such, it is fundamental that at Phase 1 of the research, New European Driving Cycle is the driving cycle that will be used. Since, New European Driving Cycle directly deals with the concern of the research – Nissan Patrol greenhouse gas emission in urban and extra-urban driving cycles.

In Phase II, a Chase car method is to be conducted. This is to provide a picture of the real-world driving condition that is said to be lacking in New European Driving Cycle. In effect, Phase II fills in the gap that is said to be missing in New European Driving Cycle. For this reason, this researcher decided to include the chase car method. Aside from the fact, that as an alternative method of collecting data, the chase car method is less costly than on board measurements. Finally, Phase III pertains to the integration of emission inventory tools to the CAN system of the vehicle. This is crucial as this phase does not only provide data from real-world driving conditions and scenario but that it can also be used as a dataset and a live feed for the vehicle's greenhouse gas emission in real world. This information can be sent to Google Map and with this, help create a better and more authentic picture of the greenhouse gas emissions that are coming from road transport in urban and extra urban setting. With this research design, we will be able to collect the relevant information that will adequately address the issue of the research.

2.11. New European Drive Cycle – Phases in a drive cycle

When compared to other drive cycles, such as the EUDC and the Japan 15 cycles, the NEDC is a more aggressive drive cycle (Berry, 2007, p.93). This allows the use of the NEDC to model real world driving situations better but this does not suggest that the NEDC is truly representative of all factors required for real world driving.

As noted earlier, the urban driving cycle is a driving cycle that is representative of urban setting. It is characterised by low vehicle speed, soft acceleration, and low engine loads. These are the typical driving conditions that are encountered in most European cities. On the other hand, the EUDC segments are added to account for highway, sub-urban, and motorway driveway (Mi, et al, 2011).

The NEDC is seen to override all previous engine testing directives issued by the European Commission such as 70/220/EC. NEDC testing methods are now the primary means of evaluation for approval of engines and are specified as the Type I testing methods in the original directive. The NEDC has been modified as gasoline engine technology has evolved over recent years. This has been done in an effort to make the testing method more reliable and valid, not merely for real world driving conditions but also to account for changes to gasoline engine technologies, which were previously being ignored. The test is composed largely around urban driving techniques such that two major testing sections are present that are:

- Urban driving cycle;
- Extra urban driving cycle.

2.11.1. Urban Driving Cycle

The urban driving cycle is composed of consecutive accelerations, steady speed patches, decelerations as well as idling patches. The contention is to simulate average daily road conditions in any large European city. It needs to be kept in mind that this methodology has been implemented to simulate typical driving conditions based on traffic stops, low speed driving and frequent stops as is typical of any urban driving cycle (NRC, 2011). However, it would be unrealistic to expect that urban driving alone would suffice for testing purposes, especially for fuel consumption testing purposes, so an extra urban driving mode has also been incorporated for testing. The diagram provided below shows the NEDC graphically in terms of the speed against the testing time.

2.11.2. Extra Urban Driving Cycle

The EUDC portion of the test, occurring at roughly after 800 seconds of testing is composed roughly half of steady speed driving. The steady speed for testing is maintained between 75 km/hr and 120 km/hr but the testing speed is not pushed any further to accommodate for legal speed restrictions. Moreover, the other half of the EUDC testing cycle is composed of accelerations, decelerations as well as some idling patches (DEFRA, 2013, p.12).

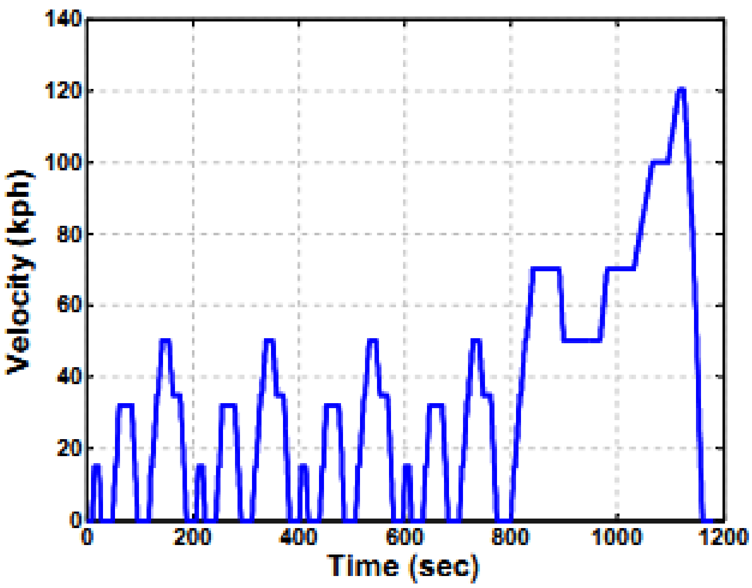


Figure 2.21 - The New European Drive Cycle sourced from (Berry, 2007, p.132)

2.11.3. Soaking

Initially, the vehicle is allowed to 'soak' before the test for at least six hours at a temperature between 20ºC and 30 °C. The soaking process is allowed to continue until the engine oil temperature and the coolant temperatures are within ±2ºC of the ambient temperature (DEFRA, 2013, p.12). The contention behind soaking is to allow engine lubricating oil to come to a steady state before testing is realised. Losses resulting from cold engine oil and the lack of engine oil recirculation to all parts of the engine cause an increase of fuel consumption figures that would tend to offset the balance of the overall test. In order to ensure that the engine would produce consistent results throughout the various phases of the test, it is essential to have a steady engine oil temperature before testing would begin. Moreover, if soaking were not allowed, there are large chances that the cold sections of the cold engine block would take up heat as the engine is being warmed up. A cold engine would allow for higher efficiencies to emerge during the start of the test while the performance efficiency would fall off as the engine block were to assume more temperature since engine efficiency depends on the engine's lowest temperature directly. Engine soaking has been allowed for six hours in order to ensure that the entire engine compartment of the tested vehicle is at the same temperature level before testing begins.

2.11.4. Idling

Initially, the engine is allowed to idle after the soaking period before being worked up. The engine is allowed to idle for 40 seconds of the test. After the year 2000, the idling period was eliminated for carbon dioxide sampling purposes, i.e., engine is cold started and the emission sampling process begins immediately. The New European Driving Cycle (NEDC) is used for CO_2 emission measurement. Emissions are sampled during the cycle, using the constant volume sampling technique, analysed, and expressed in grams per kilometre for each pollutant (Giakoumis & Lioutas, 2010).

However, it needs to be kept in mind that such directives are not applicable for fuel consumption testing. The idling process is still included for fuel consumption testing as shown in the diagram above. A number of different idling cycles have been emulated for the urban driving mode of the NEDC testing regime to allow for countenance of traffic stops, routine pullovers etc. This is expected to make the overall testing regimen as realistic as practically possible but is not expected to account for all forms of driving situations such as long traffic stops etc.

2.11.5. Cycle Duration

The “duration of the cycle is 19m 40s (1180 seconds) for Euro III and later certification, with the two phases being 13m and 6m 40s long, respectively. The Euro III test differs from the Euro II and earlier certification procedure (specified in directive 98/69/EC) in that the earlier test started with a 40-second idling period that preceded the start of gaseous emissions sampling (DEFRA, 2013, p.12). Consequently the earlier test:

• was 40 seconds longer, i.e. 20m 20s, although emissions were only collected for the last 19m 40s and

• Vehicles were idling for 51 seconds, rather than 11 seconds, before the start of the first acceleration.

(DEFRA, 2013, p.13)

These changes are implemented to quantify, and control, the high level of emissions (especially carbon monoxide) occurring during the first part of a journey before the three way catalyst of a gasoline fuelled car is fully operational, thus, it reduces polluting emissions to a very low level. In this context, New European Driving Cycle provides an image of real-world driving condition in most European cities.

However, New European Driving Cycle has been criticised as not truly representative of real-world driving condition in Europe. This is based on the supposition that variables integral in New European Driving Cycle does not necessarily depict real-world conditions. These are (1) New European Driving Cycle consisted of slow accelerations and decelerations and that there are several steady states. (2) it does not take into account other factors such as air-conditioning, vehicle accessories, reduced tyre pressure have an impact in the reduction of CO_2 in real world driving conditions (Fontaras & Dilara, 2012) (Yu et al., 2010).

2.11.6. Critique

Nonetheless, these limitations do not deter the fact that New European Driving Cycle is the driving cycle that is used for certification of passenger cars in Europe. As such, as a tool for measuring CO_2 emissions, it can be maintained that it is the standard procedure to be followed by passenger cars in Europe. In addition, it clearly manifest that existing driving cycles have limitations. As such, there is no one perfect driving cycle that can cover all of the real-world driving conditions. In case there is one, it will be *the* panacea for the issues of driving. Unfortunately, there is none. In this regard, this researcher holds as this study intends to know the greenhouse gas emission of Nissan Patrol in urban and extra-urban setting, New European Driving Cycle provides the most efficient procedure. Since, the two road routes and conditions under New European Driving Cycle are the primary focus of this study. Likewise, as the research seeks to understand the driving conditions of some cities in Europe and since, New European Driving Cycle is representative of it, and it is assumed that the

New European Driving Cycle is the most appropriate driving cycle suitable in attaining the aims and objectives of this study (Yu, et al, 2010).

In this context, this research adopted New European Driving Cycle as the driving cycle to be used in the analysis of the Nissan Patrol engine, the identified vehicle.

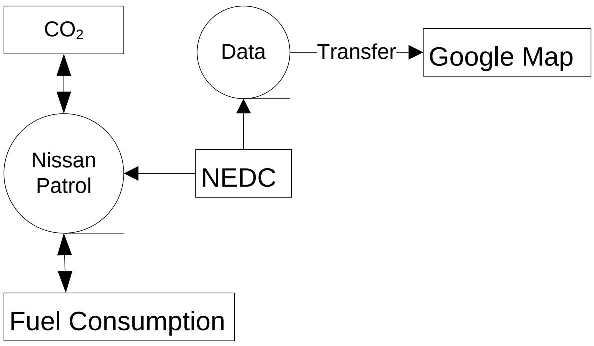


Figure 2.22 - Theoretical Framework

This figure presents the framework that presents what the research intends to attain. By using New European Driving Cycle, fuel consumption and CO_2 emission of Nissan Patrol engine can be measured. The information that will be gathered from this step will be used in three ways. First, it will be used to compare the difference between urban driving cycle and extra-urban driving cycle with Nissan Patrol as the identified vehicle. This is significant as there limited information regarding this matter. Second, the data that will be gathered in the simulation can be used as the benchmark for the on–road test that will be conducted in order to cover some of the observable gaps in New European Driving Cycle. The on-road test is critical, as the information that will be gathered is the data that will be transferred to Google Map. The third step deals with the development of pathways that will allow for the gathering of data while the vehicle is on-road travel. This means developing mechanisms that will allow for the collection, storage, and transfer of CO_2 emissions of Nissan Patrol to Google and thus, create a live feed of actual CO_2 emission of Nissan Patrol when it is used, wherever it is used (Yu, et al, 2010).

In this context, this researcher holds that there are three essential phases in the methodology. This is to ensure that all the necessary data needed for the study will be gathered. Since, the information that will be gathered are critical in the attainment the aims of this research.

2.12. Methodology of Experimental Study

The issue of fuel consumption especially by vehicles emitting carbon and other dangerous gases is one of the biggest that the world is facing. Recognising the contribution of the transport sector to the issue, governments across the globe have come up with their own specific approach in reduce the fuel consumption to an extent that will reduce greenhouse gas emission especially for vehicles consuming more fuel than required and emitting more gases than expected. In this regard, they have developed the idea of the driving cycle, which can be used to measure not only the efficiency of the vehicle but also its carbon emissions.

However, in the course of developing the research methodology, it has been observed that there is no specific driving cycle that covers all driving conditions. In fact, numerous driving cycles have been developed in order to satisfy the specific conditions that are encountered by each particular country. In addition, geographical conditions, politics, history, economics, and culture have been determinative in the existing differences among the developed driving cycles.

It has been observed that for those countries that do not have their own driving cycles, they follow the driving cycles of other countries. One of the approaches adopted in knowing driving cycles is by categorising each cycle according to the region where it was developed. This categorisation has been observed in this chapter. Likewise, it has been observed that aside from the different driving cycles that have been developed, different methods in the collection of data, and construction approach have been adopted by those who develop driving cycles.

A three-phase collection of data scheme was developed and implemented. The first phase is simulation method. Under this phase, using PSAT software, a test rig, and New European Driving Cycle software the research will attempt to determine the fuel consumption of the identified vehicle Nissan Patrol in two driving cycles, namely: urban and extra urban. Then, this is followed by a chase car method in order to get data that are closer to real-world conditions with minimal costs. This researcher deems this is necessary in order to fill in the gap of the New European Driving Cycle knowledge base. It is claimed that although New European Driving Cycle manifests the strategic stable points of the vehicle, it fails to present real-world driving conditions. As such, it is considered weak on that point. Hence, this researcher decided to conduct the chase car method for the second phase of the study. This phase brings the research closer to real world scenario.

The last phase of the research is the integration of COPERT 4 and some aspects of MOVES in the computer system of the vehicle. This phase deals directly with the aim of the research, which will develop a software program that will collect real-time data and then transfer it as live-fed to Google Map so that car owners, drivers, researchers, and all stakeholders of greenhouse gas emission may have access to current and live data. In addition, this is vital as it provides actual driving condition data that is essential in understanding real-world driving condition. The program capitalises on recent technological developments that are integrated in the electrical system of the vehicle. CAN is the part of the vehicle is to be used for this facet of the research.

With these approaches designed to collect the data for the research, this researcher intends to cover and gather as much data as possible in order to arrive at a more holistic and accurate picture of the fuel consumption of the Nissan Patrol. The gathered information will be further analysed in order to provide a clearer perspective of the issue raised in this research.

In this regard, this research does not only present the methodology adopted in the conduct of this research but it also showed the trends and issues that are addressed in the continuous development of driving cycles in order to respond to real world driving conditions and deal with the issues of greenhouse gas emission, particulate matter, and other air pollutants that immensely contribute to the dwindling air quality experience of people across the globe.

2.6: Summary

In this chapter, a wide study of the literature is carried on. Through the study of the literature, the research parameters are classified; simulation of drive cycles, the dynamics of drive cycles, different types of drive cycles and the quality of the air, an analysis of European drive cycles, and methodology of experimental study of the paper is also stated in this chapter.

CHAPTER-3: EXPERIMENTAL SETUP AND PROCEDURE

3. Experimental Setup and Procedure

The previous chapter looked into the theoretical framework used for the current research and derived the New European Drive Cycle (NEDC) as the preferred method to carry out this research. This chapter will look into the testing methods within lab conditions used to simulate the NEDC. The choice of equipment vis a vis dynamometers will be investigated. Various types of dynamometers will be compared and this would be used to choose the most suitable type of dynamometer for the current research. Lab testing will be utilised to develop an empirical correlation that would utilize parameters from Chapter Two to define the relationship between fuel consumption and the chosen parameters. The testing scheme of the chosen dynamometer will be evaluated in detail including the methods being used.

Drive cycles are simulated under laboratory conditions, and the measured results are used to study the relationship between different drive-cycle parameters and fuel consumption. Simulations are carried out by dynamometer testing. The related experimental setup together with the procedure of measurement is described in detail in this chapter.

3.1. Dynamometer Types and Comparisons

In the simplest terms, a dynamometer is a load based device that is utilised to measure engine speed and corresponding torque output. In addition, the dynamometer is also used to measure the fuel consumption as well as emissions levels inter alia other operating and output parameters. Dynamometer configurations allow engine speed control as well which is achieved by varying the load provided to the engine. The primary dynamometer testing regimens are designed to test various engine designs at the same operating point that is engine speed and engine torque output. This allows reliable comparisons to be formed regarding various engine designs. The contention is to test the engine in conditions as close as possible to actual driving conditions. The dynamometer's ability to vary engine loading is utilised in order to simulate actual driving cycles as well (Gitano-Briggs, 2008, p. 9).

Broadly put, dynamometers could be classified as either absorption type or transmission type. The absorption type dynamometer, as the name implies, rely on the absorption of the engine's output power as a means of measuring required parameters. In contrast, transmission type dynamometers are simple measurement devices that are incorporated in the transmission's power transmission element which is typically a shaft. The measurement device allows tabulation of the other output engine torque as well as the output engine speed which in turn allows the tabulation of output engine power (Gitano-Briggs, 2008, p. 10).

The current research is more concerned with absorption type dynamometers since this kind of dynamometer was used for testing purposes. In the simplest terms, an absorption type dynamometer is composed of a rotor that is housed inside the stator. The shaft of the dynamometer is in the rotor assembly. The rotor and stator are connected through some form of coupling mechanism that may include (but are not limited to) the following kinds:

- Mechanical;
- Aerodynamic;
- Fluid;
- Electromagnetic;
- Hydraulic.

The basic principle of absorption type dynamometers is to induce equal but opposite torques on the rotor and the stator. The resulting torque is measured through a load cell employed at the stator end. The most common type of load cell employed is force type load cells. A simple absorption type dynamometer is shown below:

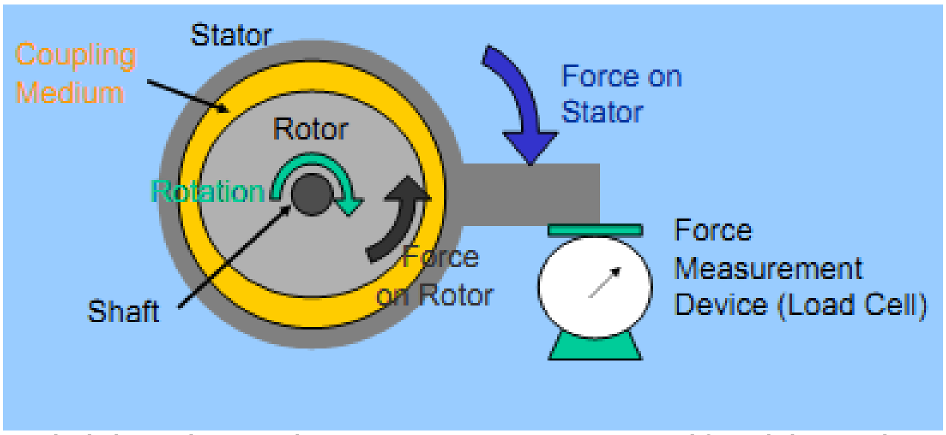


Figure 3.1 - Typical absorption type dynamometer arrangement sourced from (Gitano-Briggs, 2008, p.11)

3.1.1. Absorption Type Dynamometer

The current research employed a generator type absorption dynamometer that employs a generator whose output is resisted by an electrical supply. In such an arrangement, the engine's output shaft is utilised to rotate the rotor of the generator. The output of the generator is countered by a power supply applied to the generator's output. The resulting electromagnetic forces tend to resist the rotor's motion. Load is provided using a resistor bank that could be either air cooled or water cooled. Typically, current based control of the generator is utilised to vary engine load by varying the field winding current.

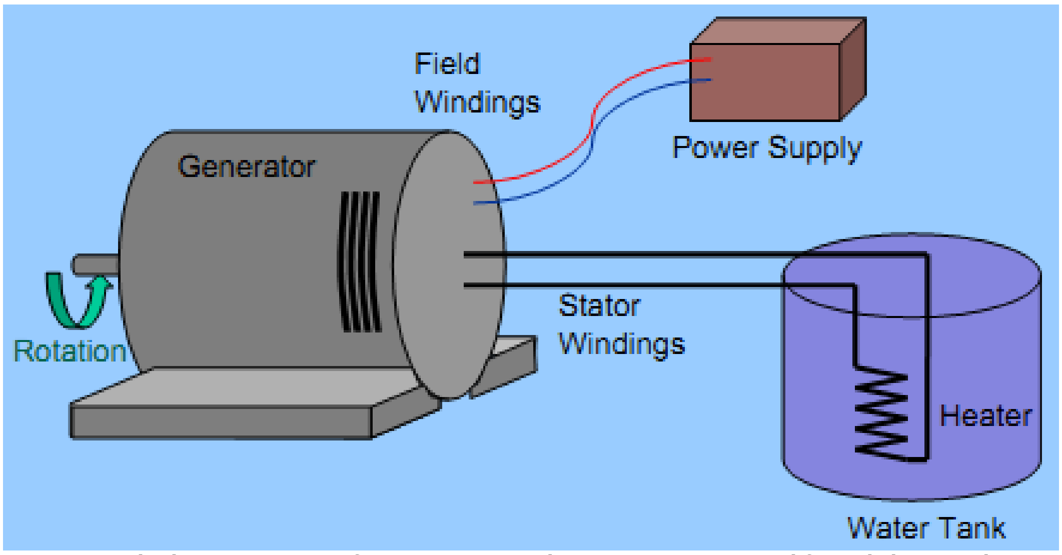


Figure 3.2 - Typical arrangement of generator type dynamometer sourced from (Gitano-Briggs, 2008, p.15)

3.1.2. Vehicle Type Dynamometer

Vehicle type dynamometers offer the distinct advantage of allowing on road measurements in actual driving conditions. The vehicle utilized is weighed and then instrumentation is added in order to measure both vehicle speed and acceleration. In turn, the measurement of vehicle speed and acceleration along with the gear ratio employed allows the calculation of engine speed and engine torque. It must be kept in mind that this type of testing cannot claim much accuracy and can only be used for rather crude measurements. The application of this technique needs a large testing area which cannot always be provided. In addition, this technique has found greater application to rough measurements for maximum engine speed and engine torque. Mathematically, the measurements can be explained as under:

$$a = \frac{v_2 - v_1}{t_2 - t_1}$$

$$F = ma$$

$$T = R.F \tag{3.1}$$

Where:

a is the vehicle acceleration

v_2 is the vehicle velocity after acceleration

v_1 is the vehicle velocity before acceleration

t_2 is the time after acceleration

t_1 is the time before acceleration

F is the force applied on the vehicle

m is the vehicle's mass

T is the torque

R is the distance through which the force has been applied

3.1.2.1 Torque Sprocket Type Vehicle Dynamometer

The torque type vehicle dynamometer is constructed to have separate inner and outer races. When torque is applied by the engine, the outer race and the inner race develop some slip. The relative motion of the inner race and the outer race can be measured using pickup sensors. Typically, the pickup sensor is positioned near the sprocket not inside it. This arrangement provides for simultaneous measurement of both the sprocket speed and sprocket torque levels. Since the sprocket is placed inside a moving vehicle for testing, it is categorized as a vehicle type dynamometer.

Figure 3.3 - Sprocket utilised for torque testing of engines under loading sourced from (Gitano-Briggs, 2008, p.22)

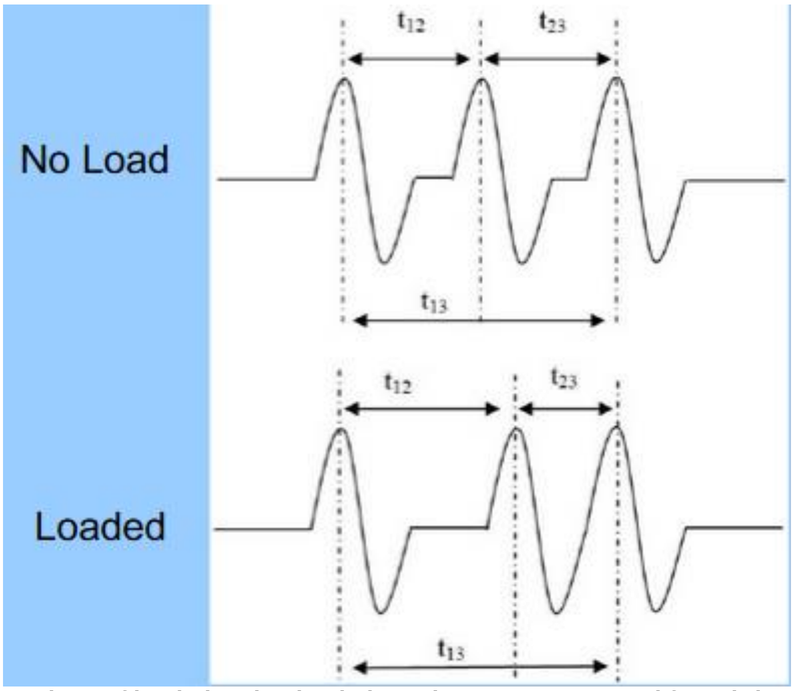


Figure 3.4 - Comparison of loaded and unloaded sprokect output sourced from (Gitano-Briggs, 2008)

3.1.3. Motored Dynamometers

Certain types of dynamometers are capable of driving the engine being tested. This allows a measurement of the engine's internal friction resulting from contact as well as hydraulic losses. The use of motored dynamometers requires that the engine should not fire during testing. A motor is used to spin the engine and the torque on the motor is measured. In turn, the motor driving the engine could be incorporated with a load based device such as a generator. The combined train could be used as either an absorption type dynamometer or like a frictional dynamometer (Gitano-Briggs, 2008, p. 23).

3.1.4. Dynamometer Comparisons

The oldest dynamometers relied on friction for testing by trying to equate the engine's output power with friction through contacting surfaces. However, friction type dynamometers were not only hard to control but also provided constant wear on contacting surfaces.

Hydraulic type dynamometers utilize hydraulic pumps to counter engine output. These dynamometers provide the greatest amount of power in the smallest possible space that they occupy.

In contrast, generator type dynamometers are fairly large and require a lot of space for housing and testing. On the positive side, such dynamometers provide easier control and are rather inexpensive.

Eddy current type dynamometers are utilized for engine testing too. These dynamometers offer the easiest control methods. Moreover, they provide a low inertia and hence bearing losses are low. However, the cost of eddy type dynamometers is significant when compared to other types.

Fan type dynamometers offer the distinct advantage of being cheap to construct and operate. However, on the down side, these dynamometers are not highly accurate and require meticulous calibration for measurement.

Vehicular dynamometers are used for engine speed and torque determinations by attaching measuring instruments on board vehicles. These dynamometers need to determine the vehicle's mass in order to function. Moreover, the element of air drag is eliminated when using such dynamometers. On the positive side, these dynamometers can be used for determining vehicle behaviour in actual driving conditions.

3.1.4.1 Assembly Features of Dynamometers

It is common for dynamometers to be connected to the output shaft of an engine through a coupling. Conversely, dynamometers may also be connected to the output shaft of the transmission such as a gear box, planetary gear arrangements etc. This allows variation of the engine speed and engine torque by varying the transmission gearing ratios. This allows a determination of engine behaviour as well as coupling behaviour through dynamometer measurements (Gitano-Briggs, 2008, p. 27).

On the other hand, chassis dynamometers can also be used. These dynamometers employ large rollers that are driven by the vehicle's wheels. The vehicle is positioned such that it wheels are on the driven rollers. The vehicle's wheels are locked down so that the vehicle is unable to move when testing proceeds. The roller is in turn connected to the dynamometer for taking down measurements. The connection between the driven rollers and the dynamometer could be direct or indirect (Gitano-Briggs, 2008, p. 28). It is common to utilize constant velocity (CV) joints in order to transmit power from the engine or transmission to the dynamometer. CV joints are preferred because they do not require precision alignment of the engine or transmission and the dynamometer.

3.2. Empirical correlation

The engine testing regimen through a dynamometer can be explained mathematically as shown below;

$$T = F.R$$

$$P = T\omega$$

$$\omega = \frac{engine\ angular\ velocity(2\pi)}{60} \qquad (3.2)$$

For the transmission:

$$T_2 = T_1(gearing\ ratio) \quad (3.3)$$

$$\omega_2 = \omega_1(gearing\ ratio) \quad (3.4)$$

Where:

T_2 is the torque developed by the engine after applying power

T_1 is the torque developed by the engine before applying power

F is the force developed by the engine as measured by the load cell

R is the distance through which the engine developed force has been transmitted

P is the power developed by the engine

ω_2 is the engine's angular velocity (in revolutions per minute) after applying power

ω_1 is the engine's angular velocity (in revolutions per minute) before applying power

In addition, empirical correlationing for engine testing requires taking into account other losses from transmission and measurement components. The spur gear losses on every stage amount to nearly 2%. In contrast, tire losses amount to around 10% of total power. In addition, chassis and vehicular dynamometers tend to produce measurements that are around 15-25% lower than measurements produced by other types of dynamometers due to the effect of transmission losses (Gitano-Briggs, 2008, p. 36).

3.3. Dynamometer Testing Scheme

A typical dynamometer testing scheme is presented below for explanation. As shown below, the dynamometer and engine are connected together for testing purposes.

The engine is regulated through the variation of the throttle. The dynamometer is connected to the load cell and is regulated using the current provided to the stator. A controller is provided to stabilize the entire system and to deal with data measurement. The controller receives inputs from the engine's fuel meter, from the coupling connecting the engine and dynamometer as well as the coil current and the load cell. An operator is required to manipulate the engine torque output while the controller regulates the dynamometer at stable levels during testing. The final output is received through display devices that are dealt with by another technician.

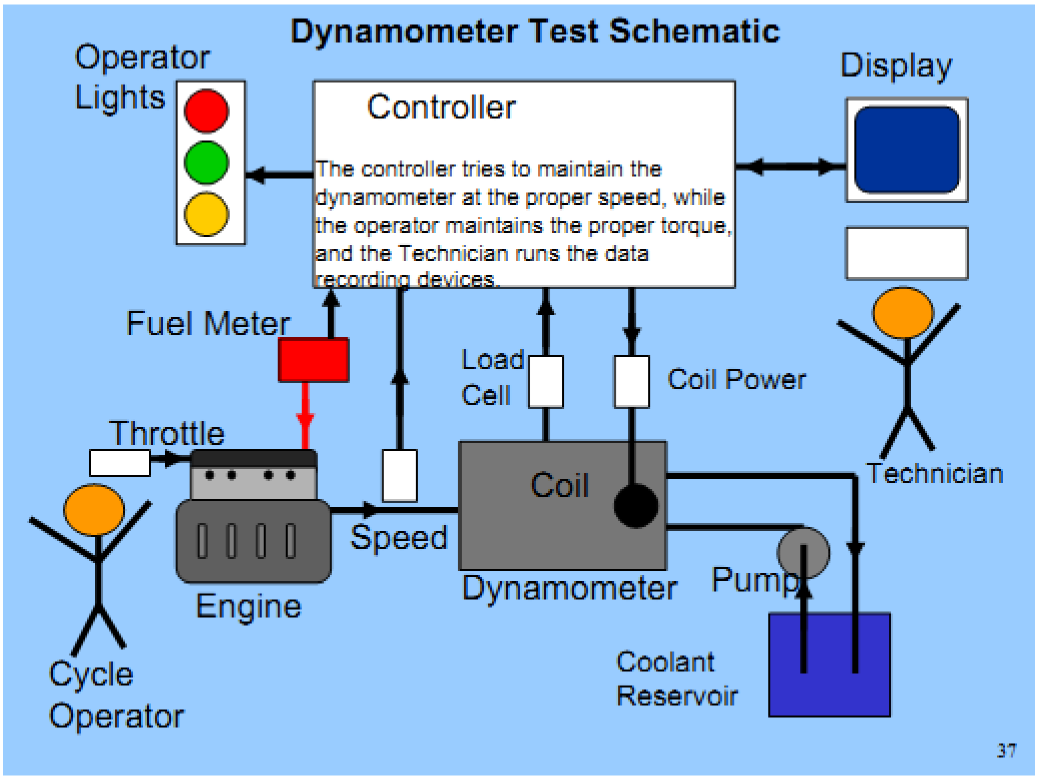


Figure 3.5 - Typical dynamometer testing schematic sourced from (Gitano-Briggs, 2008, p.37)

3.3.1. Testing Parameters

Engine testing has engine speed and engine torque determination as its primary objectives. However, a number of different input and output parameters need to be measured as well to ensure that the engine is operating within safe limits and within optimal levels of operation. The most commonly measured parameters during testing include (but are not limited to):

- Engine torque;
- Engine speed;
- Fuel emissions;
- Fuel consumption;
- Temperatures:
    - Head temperature;
    - Exhaust temperature;
    - Coolant temperature.

In addition to the commonly measured parameters listed above, a number of other parameters may need measurement at times. These parameters include (but are not limited to):

- Combustion pressure;
- Engine dynamics:
    - Acceleration of components;
    - Vibration levels;
    - Stress produced in various components.
- Intake pressure;
- Exhaust pressure;
- Engine acoustics;
- Ignition timing;
- Engine knocking;
- Valve lifts.

The various commonly measured and occasionally measured parameter listed above can be measured using either automatic or manual means though automatic measurements are preferred (Gitano-Briggs, 2008, p. 40).

3.3.2. Parameter Manipulation

Parameter measurements arrive as both discrete and continuous variables. This requires manipulation of the data in order to make it more legible for processing. Moreover, entire data series of the measured parameters cannot be utilized since it would require tremendous computing power. Often, it is advisable to treat measured parameters for tabulation purposes. The simplest technique is to average the measured parameters. The most commonly average parameters include the engine speed, load on engine, throttle opening and various temperature measurements. These parameters are typically averaged over a number of different cycles for further processing. In addition, the signals from measurement are treated with low pass filters in order to remove higher frequencies that act as outliers and aberrations on the measured data (Gitano-Briggs, 2008, p. 41).

As an example, torque measurements can be either positive or negative. Measured torque values are positive during the power stroke while they are negative during the compression stroke. The final tabulation requires the average torque produced by the engine and hence it is typical to average the torque produced in a complete cycle. Averaging of torque and other such parameters can be carried out using electronic means or through using coding in the data acquisition system (Gitano-Briggs, 2008, p. 41).

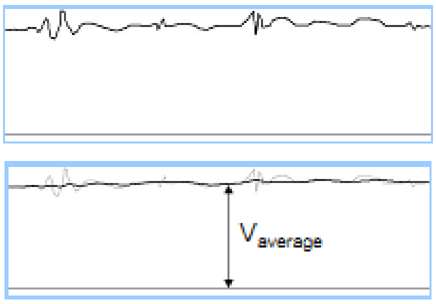


Figure 3.6 - Unfiltered measurement waveform (on the left) and its treated average form (on the right) after being processed through low pass filtering and averaging sourced from (Gitano-Briggs, 2008, p.42)

In a similar manner, exponential averaging could be carried out using computer written code. The data acquisition system inputs the measured parameter values and then treats them through code to produce a final averaged output. The diagram shown below provides a 60:40 exponential averaging for torque based on the formula shown below:

$$T_{avg} = 0.6(T_2) + 0.4(T_1) \quad (3.5)$$

Where:

T_{avg} is the exponentially averaged torque

T_1 is the previously measured torque

T_2 is the currently measured torque

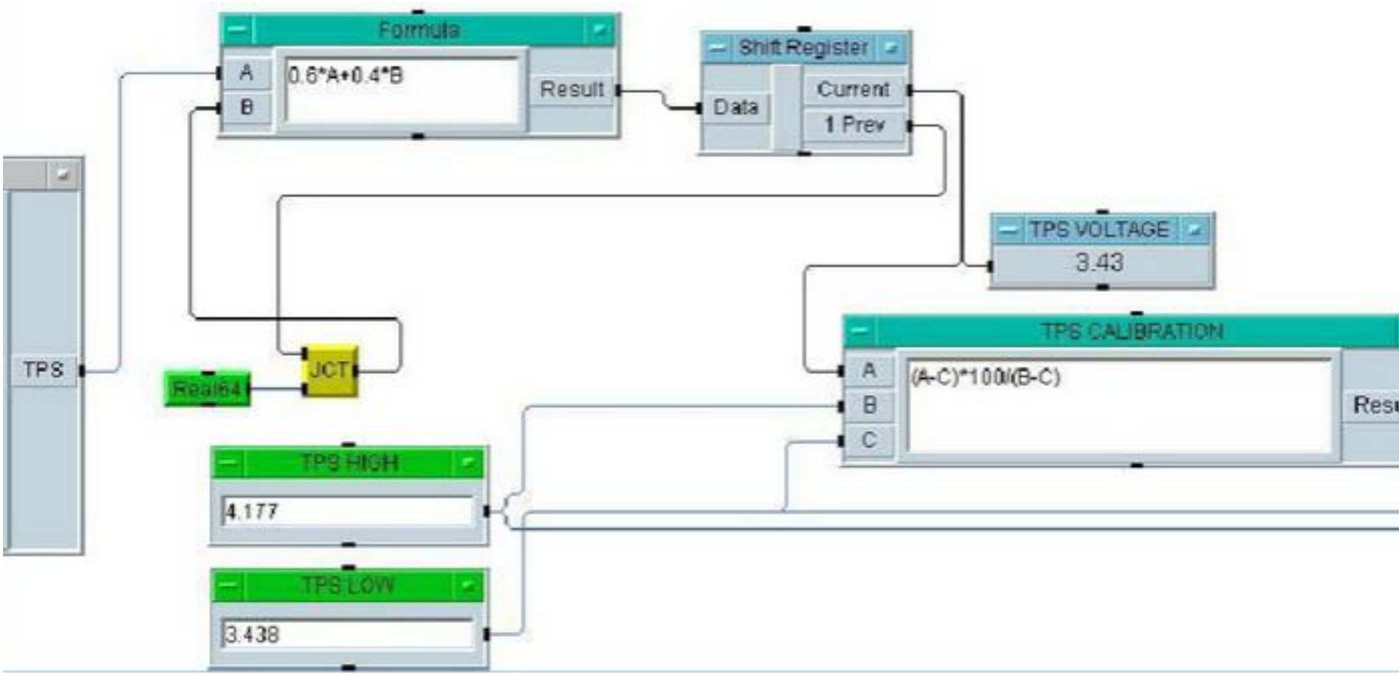


Figure 3.7– Block diagram used for exponential averaging in a data acquisition and processing software (screenshot) Vee sourced from (Gitano-Briggs, 2008, p.43)

3.3.3. Speed Measurement and Manipulation

Speed is typically measured using a variable reluctance sensor that operates on inductive principles. Gear teeth are employed to register speed on an induction type probe. As the teeth of the gear rotate, the inductance registered by the probe changes as the testing proceeds. The output registered from such probes is typically sinusoidal in nature for a given period of time for any number of cycles. For further processing, the time domain is converted into the frequency domain which is then in turn converted to angular velocity. It is common to use gears with sixty teeth to perform measurements since this allows equating the measured frequency to the angular velocity. Mathematically (Gitano-Briggs, 2008, p. 44):

$$RPM = \frac{60}{n(Period)} \tag{3.6}$$

Where:

$RPM$is the angular velocity in revolutions per minute

$n$is the number of teeth read by the induction probe

$Period$is the distance between the same points on two consecutive sinusoidal waves

Figure 3.8 - Typical gear tooth used for engine speed measurement sourced from (Gitano-Briggs, 2008, p. 44)

3.3.4. Acceleration Measurement

Acceleration measurements are not carried out directly on the dynamometer since it would tend to complicate the overall sensor interface by employing too many sensors in a limited space. A more convenient approach would be to use derived measurements such as speed to calculate the acceleration as required. The acceleration is obtained using the empirical correlation for speed as follows:

$$Acceleration = \frac{RPM}{Time\ Step} = \frac{60}{n(Period)(Time\ Step)}$$

Where:

$Time\ Step$is the amount of time for which the acceleration requires computation

It should be noted that acceleration may be calculated using the number of teeth employed in the speed measurement gear or otherwise. The time step used for acceleration measurement would depend on the resolution required. A smaller time step would lead to low resolution and vice versa.

3.3.5. Throttle Position Measurement

The throttle position is changed in order to vary engine speed and needs to be monitored continuously during testing. A variable resistor is used in order to sense the throttle position. The potentiometer is mounted on the throttle itself at one end of the throttle shaft controlled by the throttle cable. A simple 5V DC power supply is used to perform these measurements that respond to changes in resistance at the potentiometer as the throttle cable changes the throttle position. The final output parameter is the throttle position signal (TPS) that directly measures the throttle position as a distinct voltage level when the throttle changes its state. A throttle and throttle sensor arrangement is shown below:

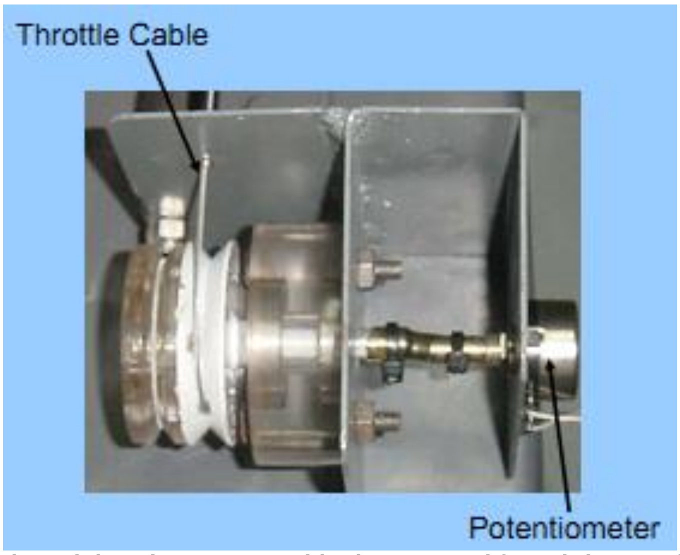


Figure 3.9 - Throttle and throttle sensor positioning sourced from (Gitano-Briggs, 2008, p. 46)

3.3.6. Torque Measurement and Manipulation

Torque measurements are carried out through the use of a Wheatstone bridge arrangement. The various resistors of the Wheatstone bridge tend to change their resistance as load is applied to them and produce resistance readings that can be interpreted into torque values. The arrangement of the resistors in the Wheatstone bridge is known better as a load cell. In the absence of any torque application, the load cell is balanced while the application of torque produces an imbalance in the load cell.

The resistors used for the load cell are not typical electrical resistors but mechanical elements that show deformation when placed under stress. When torque is applied to such resistors, a noticeable strain is produced that allows a change of resistance. The mechanical elements are constructed out of semiconductors or wire foil strain gauges. When torque is applied, these mechanical elements tend to either stretch or compress as a means of indicating strain (Gitano-Briggs, 2008, p. 47). This tends to alter the resistance and processing the changes resistance allows a computation of the torque. Or the purposes of measurement, the excitation voltage of the load cell is kept between 5V and 10V. In addition, an amplifier is also included in the load cell which allows zeroing the applied load as well as adjusting the load cell for calibration (Gitano-Briggs, 2008, p. 47).

3.3.7. Fuel Consumption Measurement and Manipulation

The fuel consumption of vehicles is measured using gravimetric means. Even for engine testing, gravimetric means are employed. The weight of the fuel available in the fuel tank is weighed before and after an engine testing run. It is common for the engine to be run at constant speed between one minute and ten minutes to produce a stable, averaged reading of fuel consumption. The fuel consumption for such procedures can be expressed mathematically as:

$$FC = \frac{Wt_1 - Wt_2}{\Delta t} \quad (3.7)$$

Where:

FC is the fuel consumption

Wt_1 is the fuel weight before the test run

Wt_2 is the fuel weight after the test run

Δt is the time for which the engine was run

The fuel consumption of engines is measured typically in either grams per minute or grams per second depending on the time measurement units. Additionally, cheap but reliable digital scales can be used to interface with the data acquisition and processing system via the serial port. This allows automated measurements of the engine fuel consumption (Gitano-Briggs, 2008, p. 49). Furthermore, this interfacing allows a differentiation of engine fuel consumption during ignition and during stable running periods that can differ significantly for large engines.

The fuel consumption of engines is tabulated as the weight of fuel consumed per unit time but this method of measurement fails to account for other differences such as the size of the engine, the fuel used etc. In order to create a fair comparison between engines, it is common to express fuel consumption as break specific fuel consumption (BSFC). The BSFC measure allows a tabulation of the fuel consumption against the power output of the engine being tested (Gitano-Briggs, 2008, p. 50). Mathematically, BSFC can be expressed as:

$$BSFC = \frac{FC}{BP} \tag{3.8}$$

Where:

$BP$is the brake horse power realized at the measurement point of the testing rig

The typical units for the BSFC are grams per kilo watt hours. It must be kept in mind that the BSFC depends directly on the engine's operating speed and torque. The BSFC tabulation allows a comparison of the relative inefficiencies of various kinds of engines and their designs. As a rule of thumb, the lower the BSFC realized, the more efficient the engine under consideration (Gitano-Briggs, 2008, p. 50).

3.3.8. Temperature Measurement and Manipulation

Engine temperature measurements are conducted through the use of thermocouples since they provide a largely linear output and are compact in terms of installation space. One problem associated with thermocouples is their low voltage output (typically in milli volts) which requires the installation of an amplifier to bolster output signals. Engine temperature measurements are aided by certain data acquisition systems that allow direct temperature readings.

3.3.9. Crank Angle (Resolved) Data and Manipulation

A number of different parameters during engine testing depend on the crank position as specified by the crank angle. These parameters are also labelled as “high speed” parameters and include (but are not limited to) (Gitano-Briggs, 2008, p. 52):

- Ignition timing;
- Combustion pressure;
- Knock;
- Valve lift.

The speed of the engine itself is measured as an averaged value since engine speed varies within each cycle. For example, the compression stroke sees slower engine speeds compared to the exhaust stroke. To make things simpler, the engine speed is taken as a cycle averaged value. The engine speed must be denoted in terms of the crank shaft position for synchronization purposes. Shaft encoders are attached to the crankshaft in order to carry out such processing (Gitano-Briggs, 2008, p. 52).

The crank’s position is denoted through the crank angle. The data for the crank angle could be uni-channel or multi-channel. In either case, the data received from the encoder channel can be synchronized with the crank position (Gitano-Briggs, 2008, p. 54). The crank angle’s resolved data is used to record a pressure value into an array at each LSB transition / timing signal. The array is arranged so that the array index is zeroed at the TDC position at the index transition / MSB (Gitano-Briggs, 2008, p. 55).

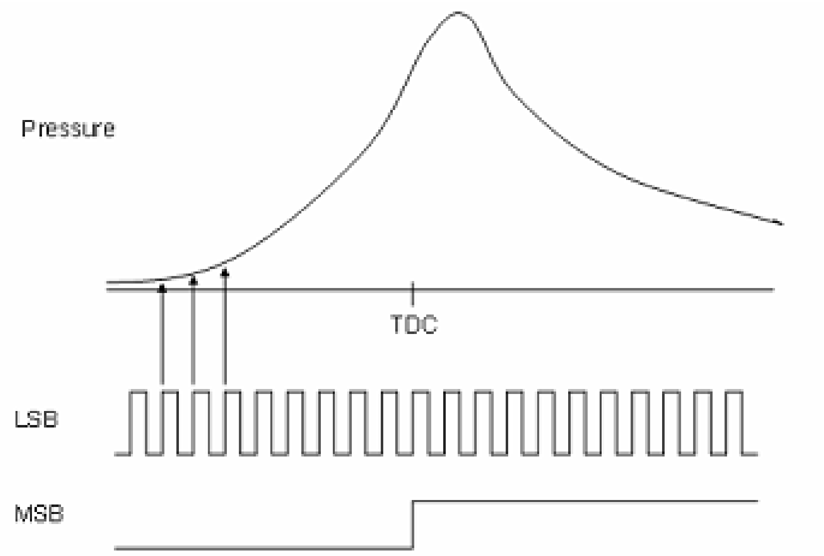


Figure 3.10 - Re-indexing pressure data from time base to crank shaft angle sourced from (Gitano-Briggs, 2008, p. 55)

3.3.10. Shaft Position Data and Manipulation

Crankshaft encoders are used to synchronise engine speed with crank position. Typically missing teeth encoders are used that are composed of a few teeth less than sixty. The missing teeth are used to indicate the index such as that for the top dead centre (TDC). The index tooth areas are bereft of any teeth while the rest of the encoder has teeth.

In a similar manner, the index is also synchronized with the timing channel that operates at 256, 512 or 1,024 pulses in each revolution and is set at either the TDC or the bottom dead centre (BDC). On the other hand, absolute encoders may also be used that are settled at 8, 9 or 10 bits depending on the testing situation (Gitano-Briggs, 2008, p. 53).

3.4. Experimental Facility

The test rig utilised to test vehicles is a transmission dynamometer located in the advanced Automotive Laboratory at Huddersfield University. The test rig is equipped with two AAB 132Kw AC Dynamometers; with a 4 axis robot gear shift all controlled by sierra CP Engineering's V14 software.

In order for the correct load to be applied to the vehicle as if it were in the vehicle the system runs in Road law which enables the Dynamometers to change dependent on aerodynamic and tyre frictional forces that would be experienced. The system in integrated with speed, pressure, fuel and Temperature transducers to enable all aspects of the power train to be measured accurately. The engine utilised in the testing is a 2005 Nissan Micra 4 cylinder 1.4L16v engine that is attached to a standard 5 speed manual gearbox. The engine and its drive train are instrumented with various sensors and the required drive cycles were programmed using the Cadet V14 software.

3.4.1. Water and Air Cooling

In order to run the engine as it would in its original application, excess energy that is absorbed by the coolant and oil to maintain operating conditions needs to be removed. This is done by utilising two Bowman heat exchangers, with a controlled water supply that is cooled via a 500kW air blast cooler outside the building. The cold water supply is regulated using a control pneumatic actuator acting upon a three way ball valve and controlled by a PID loop through Cadet V14 software. The standard thermostat in the engine is removed so full control of temperature can be conducted by the software.

3.4.2. Fuel Flow

The fuel flow is measured using a Coriolis that is situated in the high pressure feed to the engine. The Coriolis allows fuel to be measured transiently and the data is displayed and recorded through the V14 software. The fuel temperature and pressure is also monitored and the necessary adjustments made through PID loops to keep these within preset limits defined by the user. This system gives readings with an accuracy of ±0.7%.

3.4.3. Torque Measurement

The torque output from the engine is measured via torque flanges coupled between the motor. The flange and the output shaft from the gearbox. In the Cadet V14 software, the user defines the rolling radius of the tyre and the system calculates the torque at the output. The torque of the engine ignoring all of the losses is calculated by measuring the differences in speed between the output shaft and the engine.

3.4.4. Temperature Measurement

Two methods for measuring temperature have been utilised in the collection of data. The oil, water and the intake air temperature is measured using PRT sensors due to the high resolution and accuracy at low temperatures. For the exhaust gas temperature measurement K-type thermocouples are utilised as they are suitable for measurement up to 1250^{o}C. The data from these sensors were then passed into the Cadet V14 software for logging use in the PID loops for relevant actuators.

3.4.5. Data Acquisition

The signals produced by the various sensors are in analogue form and are converted in the control tower to a digital form that can be read by the computer and output for data analysis. The on board data acquisition system is capable of logging at up to 50Hz per channel dependent upon user demands. The files are output from the system in a CSV format that can be read by all of the leading software programs used for data analysis.

3.4.6. Sierra CP Engineering V14 Software

CADET V14 is the latest release of engine test systems integrated with a Windows XP operating system. V14 supports many user defined input and outputs to ensure that the operator can tailor the tests to their needs. The tests performed have utilised many of these features as well as the on board data acquisition system.

3.5. Test Rig Overview

The test rig is a complex and expensive piece of equipment and its intended purpose is to simulate a drive train in a vehicle but under laboratory conditions. The Dynamometers are AX **2-Wheel Transmission Dynamometer** 2off AC Transient Dynamometers, 4 Quadrant Regenerative Drive with Motoring and Absorbing Capability.

The dynamometers are connected to the hubs of the vehicle drive shafts and as such this enables very accurate matching of true driving conditions by eliminating the tyre-roller interface.

Figure 3.11 - Test rig employed for engine testing for the current research

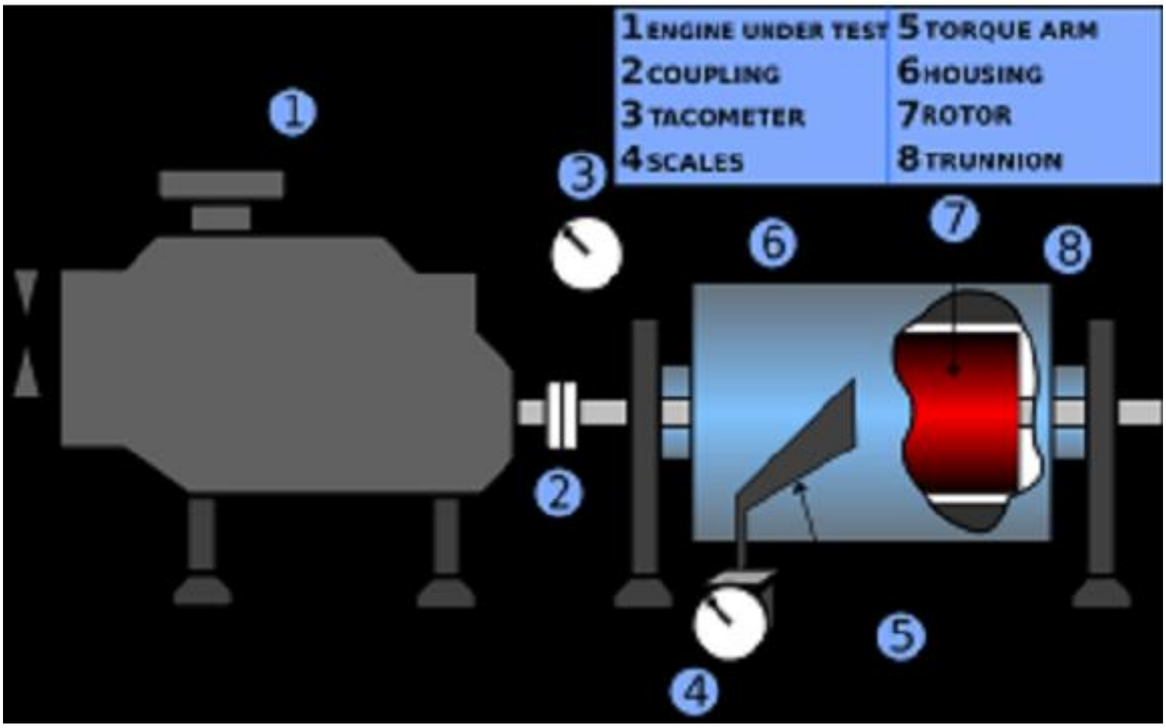


Figure 3.12 - Schematic diagram of test rig used for current research

3.5.1. Dynamometer Description

Table 3.1 - Specifications of the dynamometer used for the current research

Type	2off 132kW AC 4 Quadrant Dyno
Maximum Speed	3000 rpm
Maximum Power	132 kW from 990rpm to 3000rpm
Maximum Torque	1272 Nm from 10 to 990rpm
Rotor Inertia	5.8 kgm^2
Speed Measurement	1024ppr Optical Encoder
Torque Measurement	2off In-line Torque Meter

3.5.2. Control System Description

- CP Cadet V12 Control and Data logging System designed specifically for engine testing.
- Potential Capability of 512 Data Logging Channels and 64 PID loops for secondary control hardware.
- CP Robot Driver
- 4 Axis Robot System Gear Shift Torso Actuators
- Throttle and Clutch Actuators
- Fuel Measurement Coriolis Transient Fuel Meter
- V-Sim, Vehicle Simulation Software allows simulation of vehicle parameters Cooling Post, 3 channels with PID controlled electro-pneumatic actuators for independent temperature control of Oil, Water and Intercooling circuits associated with the engine.

3.6. Procedure

3.6.1. Dynamometer Controllers

Dynamometer controllers are used to control the load on the engine by varying the throttle point. The testing mode determines if the set point for engine testing is generated through manual means or automatically through electronic means. The dynamometer controllers can be operated in three modes that are (Gitano-Briggs, 2008, p. 65):

- *Open loop:* used to settle load manually in order to vary load as the system's overall speed varies;
- *Speed control:* used to manipulate constant engine speed even though the engine load is varied;
- *Torque control:* used to manipulate constant engine torque even though the engine load is varied.

The system under test determines the procedure to be administered. Generating and administering a single set point fails to achieve meaningful results since the system's inertia leads to overshoots, undershoots, hunting and instability of response. Generator type dynamometers are coupled to proportional pulse width modulation (PWM) in order to administer testing but limitations arise out of torque response testing. Since the torque response of such systems is instantaneous, the inertial load of the overall system causes hunting. The better procedure to adopt is to use proportional, integral and differential (PID) controllers but these controllers have to be tuned appropriately before use. In addition, fuzzy logic can be used along with empirical correlationling to simplify system implementation (Gitano-Briggs, 2008, p. 68).

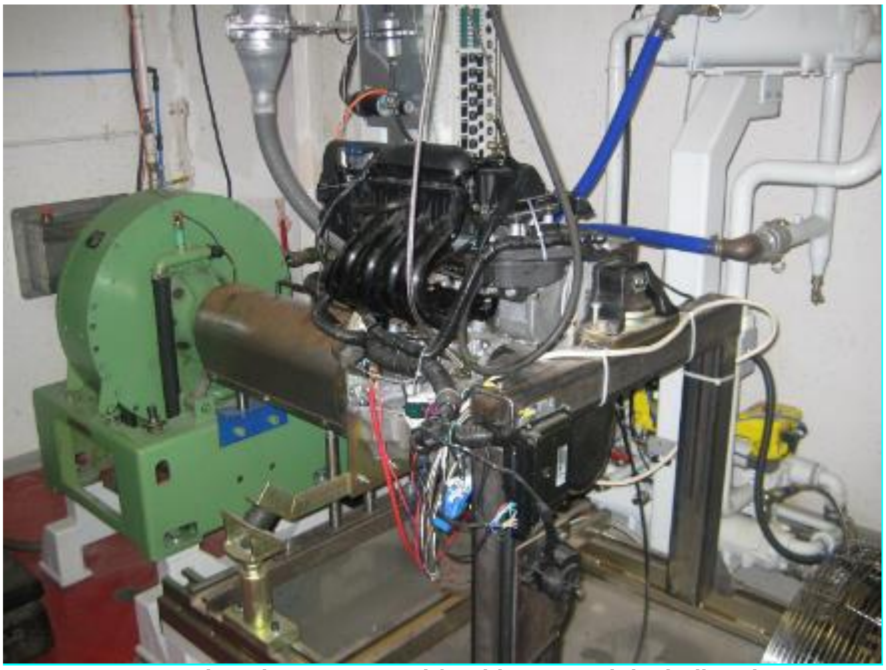


Figure 3.13 - Dynamometer and engine setup used for this research including dynamometer controllers

3.6.2. Dynamometer Calibration

Before testing proceeded, the dynamometer was calibrated through the use of a pre-configured engine and engine loads. The contention behind calibration is to ensure that the dynamometer produces readings that are consistent with actually realised values. Calibration is performed on the sensors and controllers employed in the dynamometer so as to ensure error minimisation. The dynamometer employed in the testing rig was taken to a pre-configured torque value that was used to test how the system measured the provided torque value. This ensured that any errors between measurement through the test rig and actual loads could be avoided. If the testing rig was not calibrated before testing proceeded, there were chances that the produced data would show positive or negative skewness depending on the nature of mis-calibration. Moreover, the sensors and other measurement equipment incorporated in the testing rig was also calibrated to ensure consistency with real life measured data.

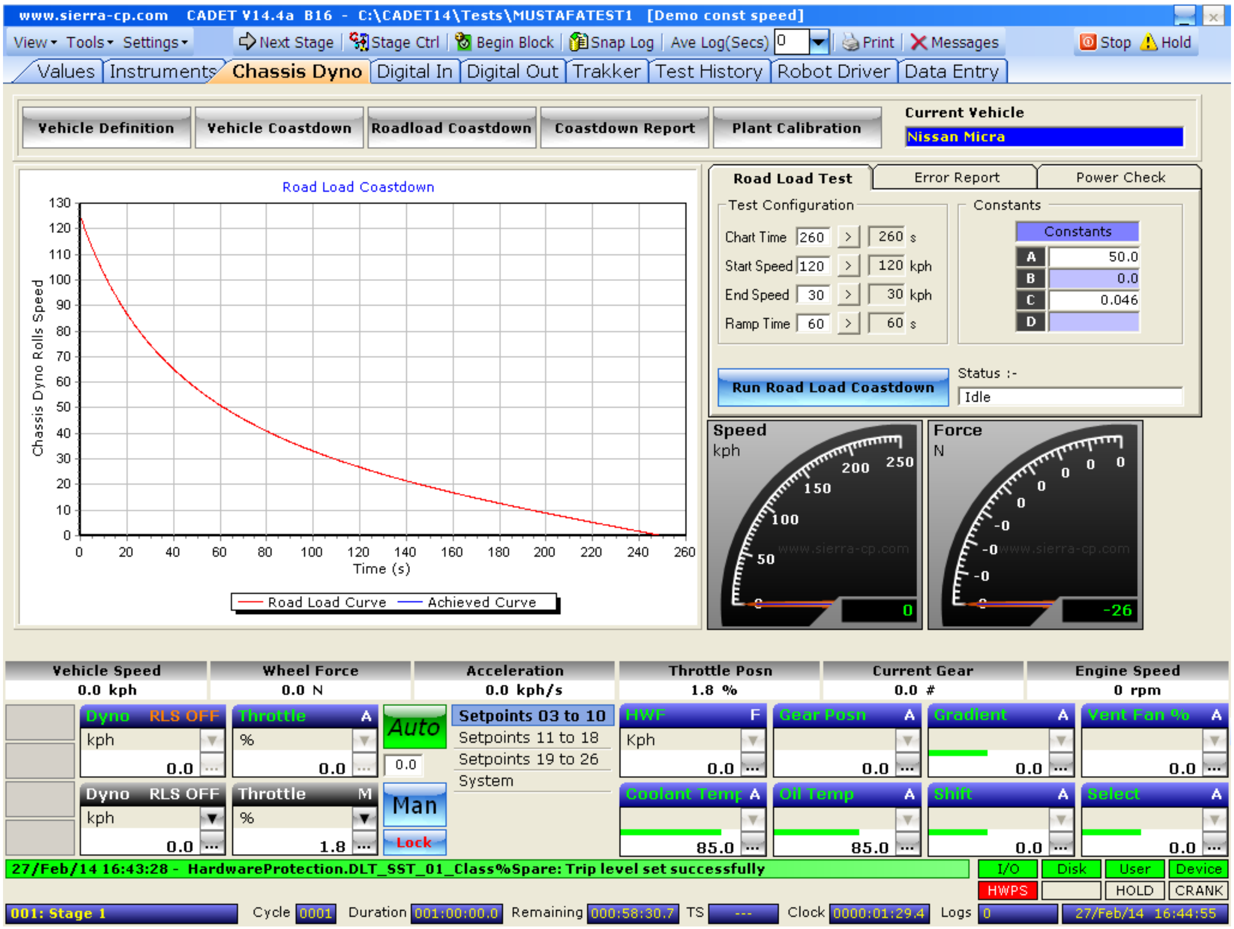


Figure 3.14 – Software used for test rig calibration and testing

3.6.3. Transient Tests

Testing for certain issues such as air fuel ratio, accelerator pumping, engine knocking etc. requires that the engine be operated at more than one specified operating point only. Transient tests for acceleration behaviour, deceleration behaviour, throttle transients etc. also require transient testing. Transient testing requires that detailed cycle resolution is achieved so data acquisition has to be carried out at frequencies greater than 10 kHz (Gitano-Briggs, 2008, p. 70). Transient testing could be carried out using either inertial methods or a combination of inertial and loading methods. Inertial methods rely on adding a large rotating mass to the dynamometer in order to emulate the inertia of the vehicle. In terms of construction, inertial methods are easier to construct but provide limited realism during testing. In contrast, the combination of inertial and loading methods allows greater system stability. In addition, this method allows air resistance to be factored in as well. Thus, the vehicle's load, road resistance and other such factors can be modelled more accurately (Gitano-Briggs, 2008, p. 71).

In addition to the methods mentioned above, better results can be obtained through computer control of the dynamometer. This allows an application of road load as the speed is increased. The computer acquires a vehicle model that allows it to implement the vehicle's weight, the aerodynamic engineering and rolling resistance. As the simulation proceeds and the speed are increased, the applied load is also increased as shown in the diagram below:

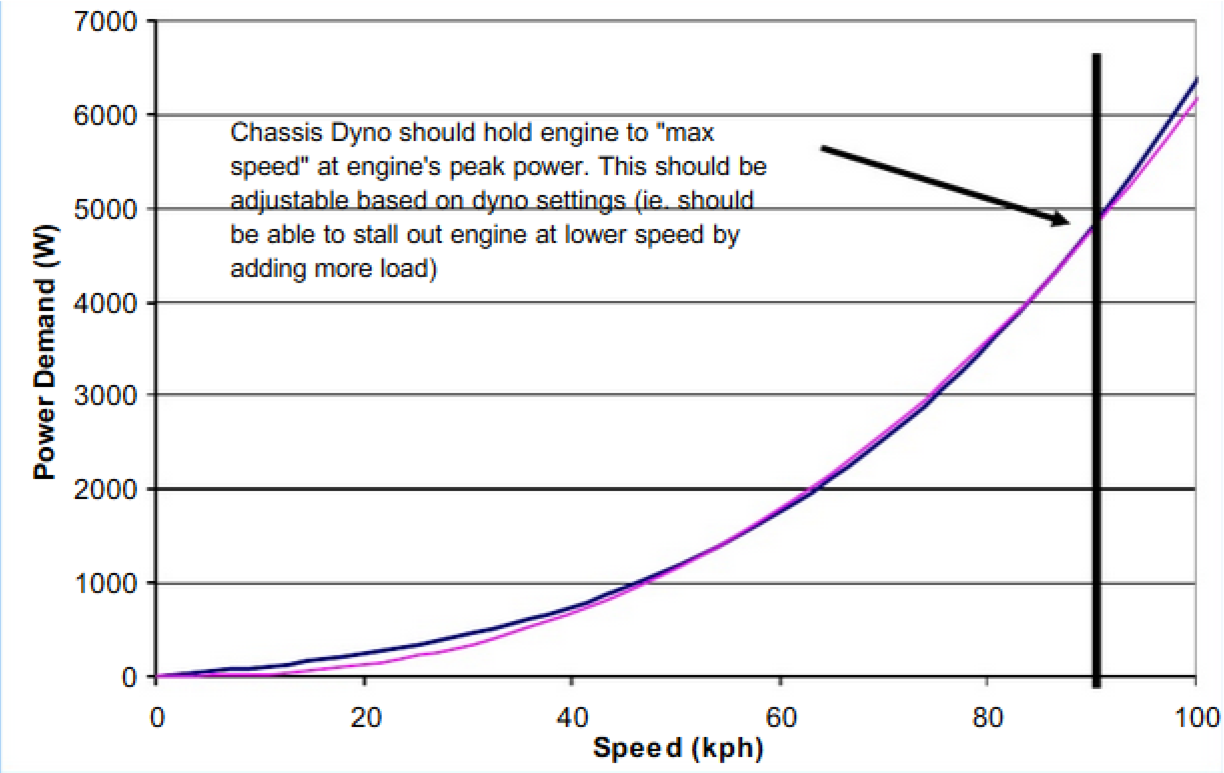


Figure 3.15 - Applied load versus the speed simulation for a small motorcycle and the rider sourced from (Gitano-Briggs, 2008, p. 73)

In addition, when simulating the procedure must make careful consideration to select an apt driving cycle. Additional real world loads such as aerodynamic drag and rolling resistance can also be added in order to ensure more realistic results (Gitano-Briggs, 2008, pp. 74-83).

3.7. Summary

In this chapter different component of experimental set up and procedure is discussed. It discusses the reasons for Dynamometer testing, Dynamometer types and comparisons, the empirical correlation, scheme of Dynamometer testing, experimental facility, test rig overview, and its procedure.

CHAPTER-4: EMPIRICAL CORRELATION FOR PREDICTION OF FUEL CONSUMPTION DURING DRIVE CYCLES

4. Introduction

Anempirical correlation has been developed to predict fuel consumption in passenger cars. The model estimates fuel consumption depending on drive cycle parameters that were measured during the simulation of the New European Drive Cycle (NEDC) under laboratory conditions as was described in Chapter 3.

4.1. Empirical correlationling

The NEDC consists of four differentiated cycles of urban driving and one cycle of extra urban (EUDC) driving that have been discussed above and in Section 2.4.2. The total resultant drive cycle was simulated in laboratory conditions in order to extract quantifiable results for prediction of fuel consumption. Results from laboratory tests were measured and were further used to fit a mathematical function on drive cycle parameters as a means of predicting fuel consumption (DEFRA, 2013).

4.1.1. Mathematically classified phases in a drive cycle

For the purposes of empirical correlationling the NEDC classifications of urban driving and extra urban driving were decomposed into smaller more quantifiable driving phases. A number of different phases were observed in NEDC components that are listed below:

- Constant speed driving;
- Acceleration;
- Deceleration due to gradient with throttle;
- Deceleration without gear engagement;

- Gear changes.

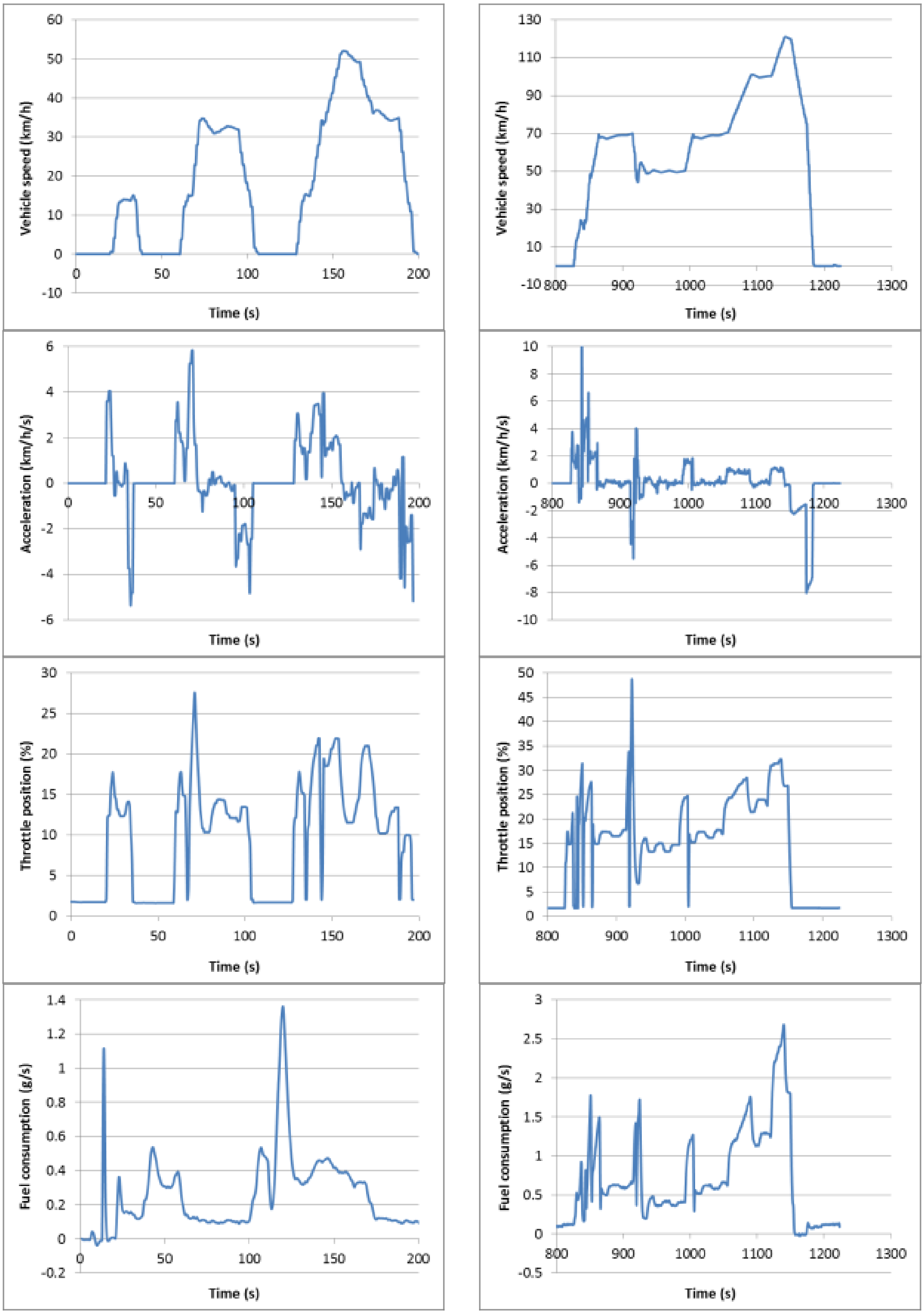
These phases may be used to construct any random driving cycle that emulates the different kinds of driving conditions and driving behaviour experienced on both urban and extra urban roads. The fuel consumption of any vehicle driven in these phases depends on several different parameters that are used to describe the driving cycle. An examination of multiple factors was carried out to classify which factors made the greatest contributions to fuel consumption. Within the examined parameters, the following parameters were observed to exert a large influence:

- Vehicle speed(v);
- Acceleration(a);
- Throttle position(p);
- Gear (G).

The parameters listed above have been used extensively throughout the analysis presented below to propose anempirical correlation that can predict fuel consumption(c) in a variety of different driving conditions.

4.1.2. Driving parameters processing

Laboratory test runs were used to capture parameter data that was then plotted against the time in order to create anempirical correlation. Four different parameters were focused on namely vehicle speed (in kilometres per hour), acceleration (in kilometres per hour per second), throttle position (in percentage opening) and fuel consumption (in grams per second).The vehicle was sped up and decelerated along with idling stops in order to emulate the NEDC criterion as discussed in preceding sections.



(a) (b)

Figure 4.1 - Time history of the drive-cycle parameters during a drive cycle, (a) city driving, (b) extra urban driving

The vehicle was soaked before testing was initiated to ensure that the conditions of the NEDC were met as prescribed. Total running times of two hundred and four hundred seconds were used in order to emulate the driving test for urban driving and extra urban driving, respectively, including driving and idling patches.

4.1.3. Empirical correlations between fuel consumption and drive-cycle parameters

The total driving test run was divided into a number of different phases for simplification of the empirical correlationling. The various drive cycle parameters recorded during test runs were used in terms of their averaged values only. The nature of the driving cycle included constant speed, accelerating, decelerating and idle patches that were not defined by a fixed frequency that could classify each driving cycle as being related to the other. In order to circumvent processing difficulties such as constructing approximated driving cycles, it was chosen to average the captured values. The creation of entire cyclical patterns was seen as promoting errors in the final empirical correlationling relationship since close approximation for differing runs was not a distinct possibility. It could be argued that averaging would produce larger errors in the overall relationship but it cannot be denied that using a simple measure such as averages would provide for simpler processing. The trade-off between accuracy using cyclical empirical correlations and simple averaging to promote processing ease was seen to be in favour of using simple averaging techniques (DEFRA, 2013).

Since the current research is interested in investigating the fuel consumption of the vehicle in relation to the parameters discussed above, so the fuel consumption was expressed in terms of these parameters. To make the empirical correlation more realistic, the fuel consumption was expressed as being functionally related to the various parameters in each driving cycle being tested in laboratory conditions. Since the data obtained from the tests was not linear, quadratic or otherwise simply relatable, so instead ordinary least squares regression was utilised to create empirical correlations. This required the determination of constants in such empirical correlations.

Reference values of each recorded parameter; velocity, acceleration, throttle position and fuel consumption (v_0, a_0, p_0, and c_0) were determined beforehand and these were then used for relating to the overall relationship. This allowed the creation of empirical correlations that could be used independently in a number of situations no matter what units were used to express these parameters. It needs to be kept in mind that the created empirical correlation would require the insertion of reference values in the same units as the units in which the answer is desirable. The following reference values were used in this study: v_0 = 112 km/h, a_0 = 35.316 km/h/s (= 9.81 m/s^2), p_0 = 100%, and c_0 = 0.46 g/s (the average consumption of the studied engine during the NEDC).

4.1.4. Constant speed

The primal method under consideration, that can be adapted for other parameters, is for constant speed results. Similar to above, the relationship between fuel consumption and vehicle speed is assumed to be of a quadratic nature. In this case, the independent variable is settled as the vehicle's speed while the dependent variable is settled as the vehicle's fuel consumption. Again, any set of units can be utilised as long as the reference parameter assumptions were using the same set of units. Reference values for constant vehicle speed and fuel consumption have been used to derive the mathematical regression relationship below. The reference values were not considered in the previous section for the sake of simplicity but to make the empirical correlation between variables more realistic, these reference values are being considered in this case. The case of a constant speed vehicle has been assumed since this provides the simplification of not considering any acceleration terms in the final equation (Yu, et al, 2010).

When a passenger car moves with a constant speed, the acceleration is zero, and the throttle position is constant, although this constant depends on the vehicle speed. The fuel consumption in this case is a quadratic function of the vehicle speed. Thus, it can be assumed in the following form:

$$\frac{c}{c_0} = k_{10} + k_{11}\frac{v}{v_0} + k_{12}\left(\frac{v}{v_0}\right)^2 \tag{4.7}$$

Figure 4.4 shows measured data in constant speed phases together with the quadratic curve that is fitted on those data. Using the relationship provided above along with the reference values, the corresponding constants can be determined as follows:

- k_{10} = 0.3063;
- k_{11} = 0.6532;
- k_{12} = 2.3913.

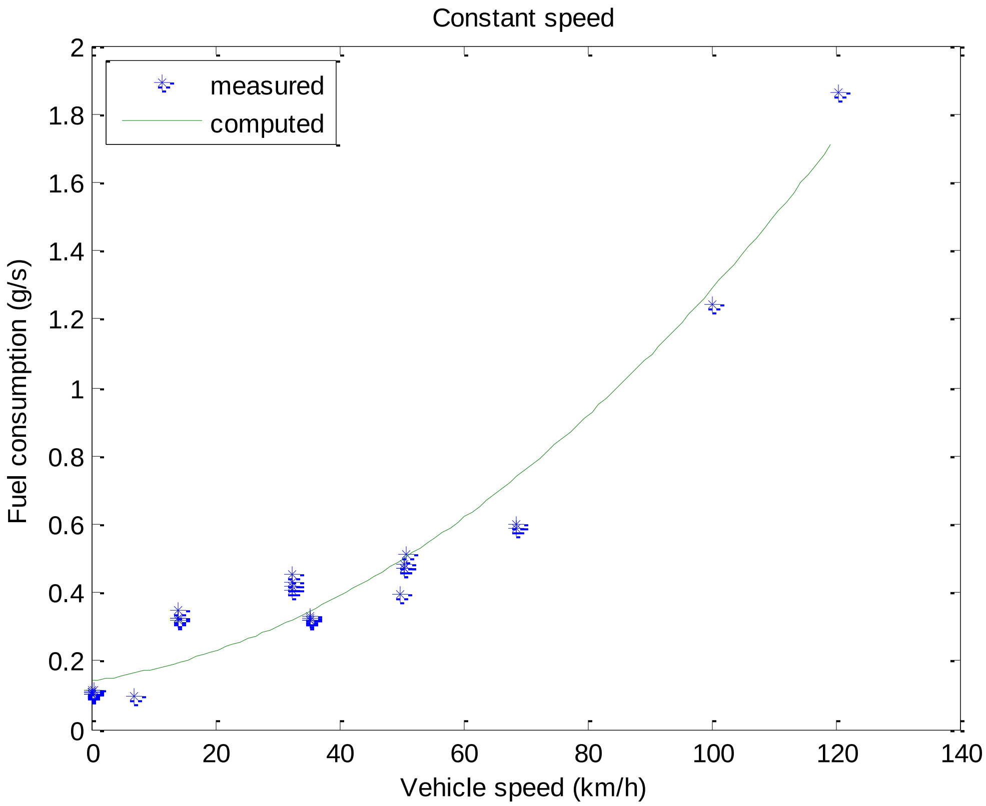


Figure 4.2 - Fuel consumption in "constant speed" phases in the New European Drive Cycle

As shown in the figure presented above, the plot of fuel consumption against vehicle speed can be approximated as a quadratic relationship. It is noticeable that there are data points in the slower speed regions (below 60 kilometres per hour) that are offset from the derived curve. The application of ordinary least squares allows the tabulation of a quadratic curve that is as close as possible to these data points without compromising either the data points or the final curve. The relationship discovered in this fashion can be expressed as:

$$\frac{c}{c_0} = 0.3063 + 0.6532\frac{v}{v_0} + 2.3913\left(\frac{v}{v_0}\right)^2 \qquad (4.8)$$

4.1.5. Acceleration

The case of vehicle acceleration is far differentiated from constant vehicle speed. At constant vehicle speed, the acceleration is zero but in the case of considering acceleration, the vehicle speed itself becomes a transient under consideration

(Green, 2002). In the case of acceleration, the fuel consumption behaves proportional to the parameter $1/(av^2)$.Unlike before, a power-law relationship between variables is assumed with two constants. Thus, the fuel consumption of the vehicle can be assumed to behave in the following form:

$$\frac{c}{c_0} = k_{21}\left(\frac{a_0 v_0^2}{a v^2}\right)^{k_{22}} \tag{4.9}$$

Figure 4.5 shows measured data in acceleration phases together with the curve that is fitted on those data. Again a number of plots are seen to arise on the diagram that can be approximated using the power-law relationship listed above. An investigation of the relationship along with the use of appropriate reference parameters reveals that the corresponding constants are as follows:

- k_{21} = 10.1739;
- k_{22} = –0.3295.

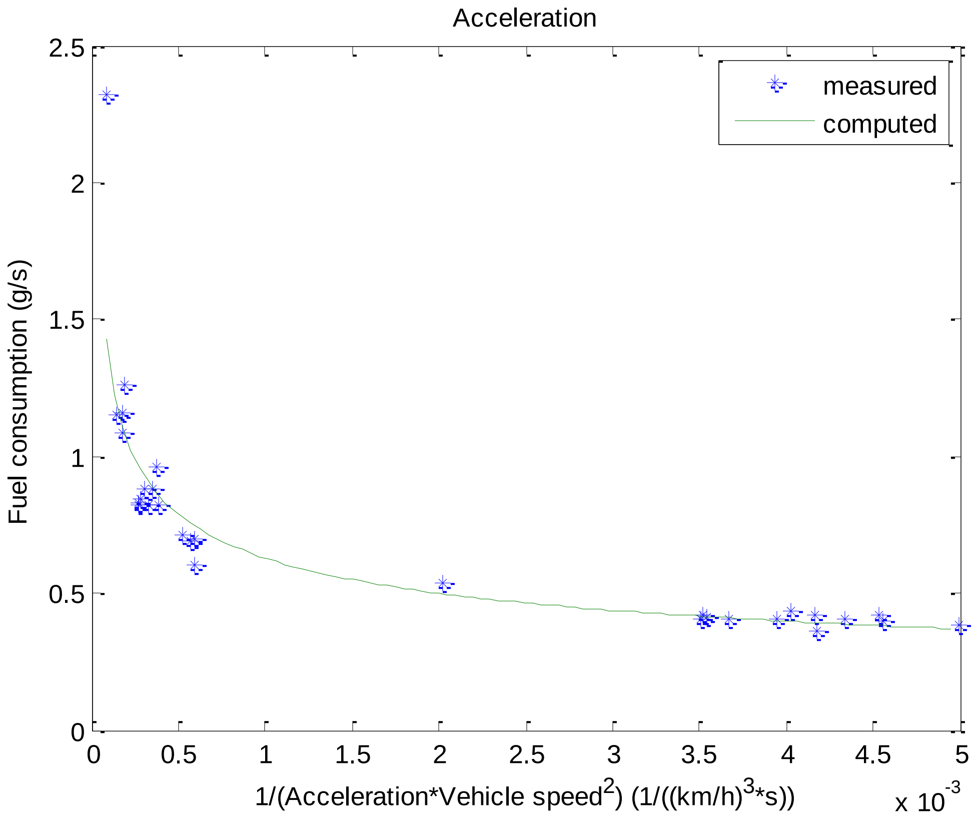


Figure 4.3 - Fuel consumption in "acceleration" phases in the New European Drive Cycle

The plot presented above makes it clear that the relationship between fuel consumption and the derived parameter of acceleration and velocity $1/(av^2)$emulates power-law like behaviour. It could be argued that plotting fuel consumption against acceleration would produce simpler data scatters. However, the presence of vehicle speed in acceleration (since acceleration is the rate of change of vehicle speed) tends to complicate matters further since it produces transients. A polynomial relationship between fuel consumption and acceleration alone could be produced but it would tend to be cumbersome and prone to errors so the parameter $1/(av^2)$has been chosen instead after careful consideration. The relationship between fuel consumption and the parameter $1/(av^2)$can be expressed mathematically with computed constants as follows:

$$\frac{c}{c_0} = 10.1739\left(\frac{a_0 v_0^2}{a v^2}\right)^{-0.3295} \qquad (4.10)$$

4.1.6. Deceleration

The case of acceleration and deceleration may seem connected and simply antipodal to each other at first. However, the case of deceleration is far removed from acceleration on closer observation. Acceleration only occurs in vehicles when the driver depresses the pedal and causes an increase in the throttle position. In contrast, deceleration of the passenger car may happen under two very different circumstances. First, the vehicle may slow down due to a surface gradient even if the driver depresses the throttle pedal by some amount. The decrease in throttle opening reduces the air input to the engine and hence the engine power drops prompting a reduction in the vehicle speed. In the second scenario, the driver may choose to apply the vehicle's brakes. The application of brakes would tend to decrease power output to the vehicle's tyres and lead to deceleration.

In the case of decreased throttle opening, the fuel consumption is proportional to the product of throttle position and vehicle speed *vp*. This indicates that the relationship would be linear in nature and can be expressed in the form of a simple linear equation. Thus, the relationship between throttle opening and fuel consumption for deceleration can be assumed to be of the following form:

$$\frac{c}{c_0} = k_{30} + k_{31}\frac{vp}{v_0 p_0} \qquad (4.11)$$

Fig. 4.6 shows measured data in deceleration due to gradient with throttle phases together with the curve that is fitted on those data. The corresponding constants are computed as follows:

- k_{30} = 0.4675;
- k_{31} = 14.3461.

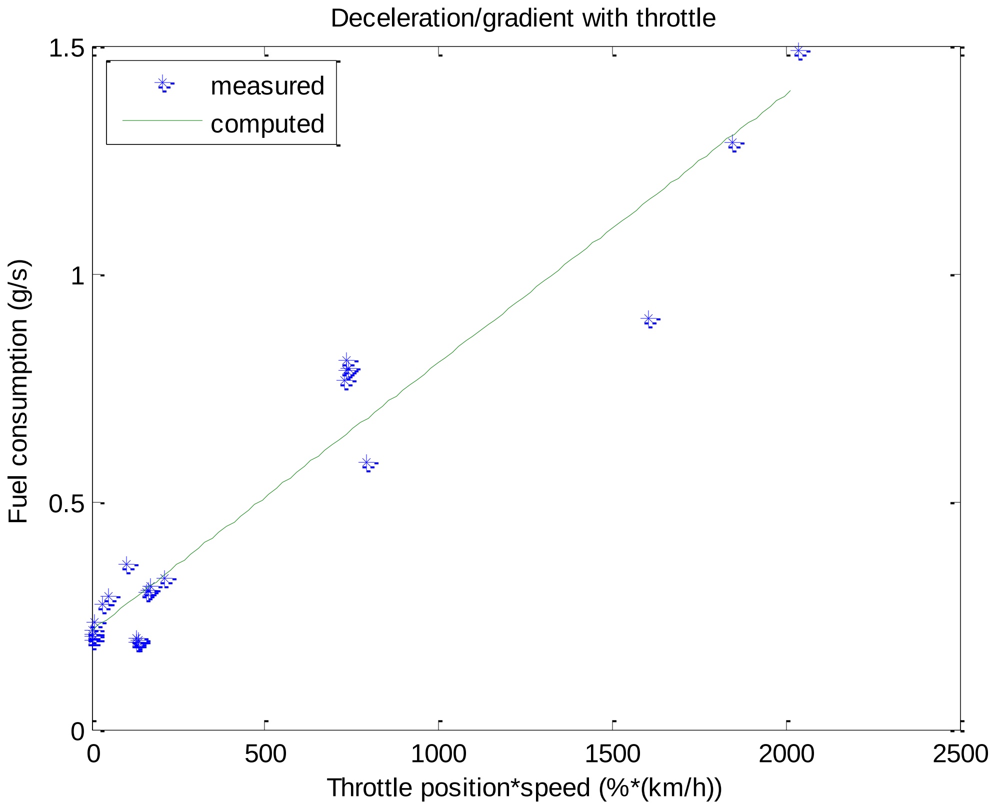


Figure 4.4 - Fuel consumption in "deceleration due to gradient with throttle" phases in the New European Drive Cycle

Given the constraints presented above, the relationship between fuel consumption and throttle position can be expressed as a linear equation of the form:

$$\frac{c}{c_0} = 0.4675 + 14.3461\frac{vp}{v_0 p_0} \qquad (4.12)$$

Then, the vehicle may slow down while it is still in gear, but the driver released the throttle pedal. In this case, the fuel is not injected, thus, the fuel consumption drops to zero. Finally, the vehicle may slow down while the gear is in neutral. In this case, the fuel consumption is approximately the same as during idling, which is a special case of the constant speed phase, i.e. when the speed is zero.

4.1.7. Gear change

The last phase that is discussed here is the gear change. During gear change, the consumption may vary considerably, but this variation occurs during quite short time intervals (1-3 s). Therefore, during this phase the consumption is approximated by a constant that is proportional to the vehicle speed. This relationship was assumed to be linear, although a significant scatter of data can be observed in this phase (see Fig. 4.7). The fuel consumption can be assumed in the following form:

$$\frac{c}{c_0} = k_{40} + k_{41}\frac{v}{v_0} \quad (4.13)$$

Figure 4.7 shows measured data in gear change phases together with the curve that is fitted on those data. The corresponding constants are as follows:

- k_{40} = 0.4503;
- k_{41} = 1.4494.

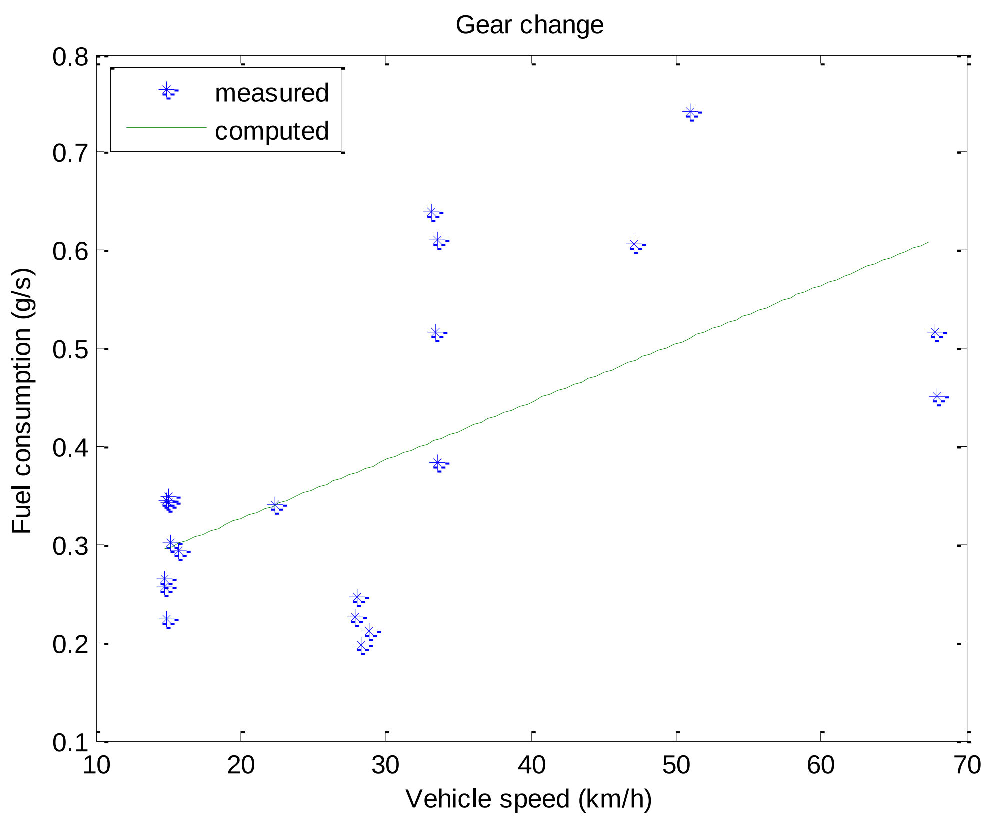


Figure 4.5 - Fuel consumption in “gear change” phases in the New European Drive Cycle

The final linear equation can be expressed mathematically with computed constants as below:

$$\frac{c}{c_0} = 0.4503 + 1.4494\frac{v}{v_0} \tag{4.14}$$

4.2. Functional Representation of the complete Drive Cycle

The functional relationships proposed in Section 4.2 can be applied for an arbitrary drive cycle. The drive cycle is divided into short phases, lasting 3-5 s each, and the consumption in each of those short phases is determined by the corresponding formula. Then, the total consumption during the whole cycle can be calculated. The application of the obtained relationships to the New European Drive Cycle provides a fuel consumption of 0.460 g/s. The fuel density is 860 g/l; thus, this consumption corresponds to6.47 l / 100 km.The consumption during the same cycle was measured 0.461 g/s(6.49 l / 100 km) in laboratory. Thus, the error in the prediction using the proposed formula is 0.3% (DEFRA, 2013).

4.2.1. Algorithm to Divide Drive Cycles into Short Phases

The NEDC drive cycle emulated under laboratory conditions for testing discussed above was sorted into an algorithm for generic processing of similar fuel consumption computations. The algorithm can be expressed as a series of different steps designed to simplify fuel consumption calculations for a number of different vehicles and situations. Software devised for these purposes depends on a number of different inputs. The program requires an input file including 6 columns:

- 1st column: time
- 2nd column: vehicle speed
- 3rd column: acceleration
- 4th column: gradient
- 5th column: throttle position

- 6^{th} column: gear

In simple terms, the algorithm derived for fuel consumption calculations based on several constraints and differing situations can be expressed as below:

- The program first examines if the gear changes from the first till last sample in a given short phase, and if so, then Eq. (4.14) is used to determine consumption in that phase.
- If the gear does not change (or it is changed from neutral), then velocity variation is investigated. If it is smaller than a prescribed limit (± 2 km/h), then Eq. (4.8) is applied to determine consumption.
- If the velocity variation is greater than the prescribed limit, then it is examined whether the acceleration is positive or negative. If it is positive, then Eq. (4.10) is used to determine consumption.
- If the acceleration is negative and the gear is in neutral, then Eq. (4.8) used to determine consumption.
- If the acceleration is negative, the gear is not in neutral, and throttle is not applied (or, throttle position is lower than a prescribed limit), then the consumption is zero.
- If the acceleration is negative, the gear is not in neutral, but throttle is applied (or, throttle position is greater than the prescribed limit), then the consumption is determined by Eq. (4.12).

4.3. Summary

In this chapter different component relating to the empirical correlation for prediction of fuel consumption during drive cycles is discussed. It makes a detailed discussion of the different phases in European drive cycle, its empirical correlationling, and functional representation of the complete drive cycle. The empirical correlation was developed using various drive cycle parameters and a generic scheme for the derivation of an empirical correlation was developed as an algorithm.

CHAPTER-5: ANALYSIS OF THE EMPIRICAL CORRELATION

5. Introduction

Anempirical correlation was presented in the previous chapter that was designed to tabulate the fuel consumption by providing various driving input parameters. Testing and validation was carried out in the laboratory and under real life driving conditions in order to decipher how driving input parameters and fuel consumption were connected. The robustness of the empirical correlation presented before needs to be verified theoretically to ascertain the validity and reliability under various performance regimes. This chapter will look critically at the empirical correlation presented before using sensitivity analysis methods that will target the various inputs to the empirical correlation. The contention behind the sensitivity analysis is to vary inputs to the empirical correlation as a means of measuring the change in the overall output. This would provide for the amount of variation that could occur in the output of the empirical correlation in case that erroneous inputs are received.

Firstly, a sensitivity analysis is carried out where noise is added to the input data (i.e. velocity, acceleration, and throttle position), and fuel consumption is calculated during a drive cycle using the noise generated data. Following this,artificial drive cycles are created, and fuel consumption is measured and calculated during the same drive cycle. When studying the artificial drive cycles, high and low velocities and accelerations are involved in order to study the limits for the empirical correlation between fuel consumption and drive cycle parameters.

5.1. Sensitivity Analysis

Sensitivity analysis is carried out in order to determine how any form of uncertainty in the output of a provided empirical correlation could be traced back to the various inputs that are being provided. The apportionment of output uncertainty to input uncertainties in their respective contribution levels allows improvements on the empirical correlation for bringing about greater reliability and validity (Saltelli, et al., 2008). A sensitivity analysis may be performed for a number of reasons. Primarily, sensitivity analysis allows the determination of model robustness when faced with uncertainty in the inputs (Becker, Rowson, Oakley, Yoxall, Manson, & Worden, 2011).

In addition, sensitivity analysis allows gaining a deeper understanding of how various inputs are tied to the final output. As a whole, sensitivity analysis allows for a reduction of uncertainty since the model's inputs that provide for sizable uncertainty introduction could be focused on. It must be taken to note that sensitivity analysis provides for errors available in empirical correlations but this is not its primary purpose.

In a similar manner, sensitivity analysis allows simplification of the model. The inputs that have little or no impact on the overall empirical correlation, but are still present, and are eliminated in the light of sensitivity analysis results. Comparably, redundancies in the empirical correlation can also be eliminated through a comprehensive sensitivity analysis. Another primal function of sensitivity analysis is to allow optimisation of the empirical correlation by concentrating on inputs that provide the greatest change in the required direction. In the case of the current research, the sensitivity analysis presented below could be used to perform optimisation if required.

5.1.1. Noise

Noise is provided to the empirical correlation in order to produce deviations from the expected outcomes of the proposed empirical correlation. In order to deal with the sensitivity analysis for the noise, the inputs to the empirical correlation (velocity, acceleration and throttle position) are manipulated by providing faulty inputs. In order to deal with the faulty inputs, random numbers are generated and fed to the empirical correlation. The noise based sensitivity analysis in this manner occurs when simulations are taking place for gauging fuel consumption against other driving parameters.

The choice of noise inputs to the empirical correlation holds particular significance. If the noise inputs to the empirical correlation are too high or alternatively too low, it would result in significant deviations from the expected output of the empirical correlation. The noise on the input should correspond to the uncertainty in the measurement. If the empirical correlation provides satisfactory outputs even with such noise in the input, then the robustness of the model is acceptable. The faulty noise inputs to the empirical correlation were kept between -2% and +2% of the regular input range. The random numbers generated to serve as the faulty input were kept within the 2% range listed above. This made it possible to verify that if faulty inputs corresponding to the measurement error were provided to the empirical correlation then the output was still within an acceptable range.

The empirical correlation was supplied with faulty inputs within the range of operation shown below as a list:

- Velocity was varied between ±2% but this limit was not allowed to exceed 2 km/hr;

- Acceleration was varied between ±2%;
- Throttle position was varied between ±2%.

The error limits presented above are the maximum and minimum data measurement errors even though both velocity and acceleration are typically measured even more accurately. The absolute throttle position error was discovered to be no greater than ±1.4% which indicates the efficacy of the overall system. Based on these error tabulations, the discrepancy between actual fuel consumption and that predicted by the empirical correlation remained low and within recognised limits. These issues are discussed in greater detail under Section 5.1.3 and 5.1.4.

Table 5.1 - Parameters and their operating ranges

Parameter	Operating Range (%)
Noise Inputs	±2
Velocity	±2
Acceleration	±2
Throttle Position	±2

5.1.2. Simulation Results

The New European Drive Cycle (NEDC) was utilised as the basic framework for the purposes of this research. The laboratory testing as well as the real life driving tests conducted relied on NEDC and its various components such as urban driving and extra urban driving. In order for the simulation of the NEDC and validation of the empirical correlation, only one sub cycle of the NEDC was simulated. The large amounts of data generated from various sub cycles runs of the NEDC meant that a lot of computing power and time was required for validation and reliability checks of the empirical correlation. In order to deal with this problem, various sub cycles of the NEDC were simulated and their validity and reliability against the empirical correlation was checked in phases. Moreover, various simulated sub cycles of the NEDC were checked for validity and reliability of the empirical correlation using various parameters such as fuel consumption, velocity, acceleration, throttle position etc. For the purposes of this simulation, the first sub cycle of the NEDC was tested for validation and reliability of the empirical correlation.

5.1.3. New European Drive Cycle, 1st sub-cycle

In order for testing to take place, the requirements of the NEDC such as the idling time, cruising time, acceleration and deceleration were observed as close as possible to the provided guidelines. The results of the NEDC were computed for fuel consumption measurement rather than other parameters for the purposes of this simulation. The measured total consumption of the NEDC first sub cycle testing revealed that fuel consumption stood at 0.3404 g/s. On the other hand, computations of fuel consumption for the first sub cycle of the NEDC using the empirical correlation provided a computed fuel consumption of 0.3222 g/s. In order to make the testing more realistic, noise was also added using noise based inputs within the 2% range of inputs specified above. The computed total fuel consumption through the empirical correlation with noise revealed a computed fuel consumption of 0.3224 g/s.

For evaluation of the empirical correlation’s reliability and validity two measures were employed. The first measure relied on the error between the measured total consumption and the computed total consumption of the empirical correlation. The second measure relied on the error between the total consumption obtained using the empirical correlation and the total consumption obtained by the empirical correlation with noise. Results revealed that the error between measured total consumption and computed total consumption was -5.3% while the error between the computed total consumptions without and with noise was +0.1%. The results are summarised in the table shown below.

Table 5.2 – Fuel consumption measurement parameters comparison

Parameter	Fuel Consumption (g/s)
Measured total consumption	0.3404
Computed total consumption	0.3222
Computed total consumption with noise	0.3224

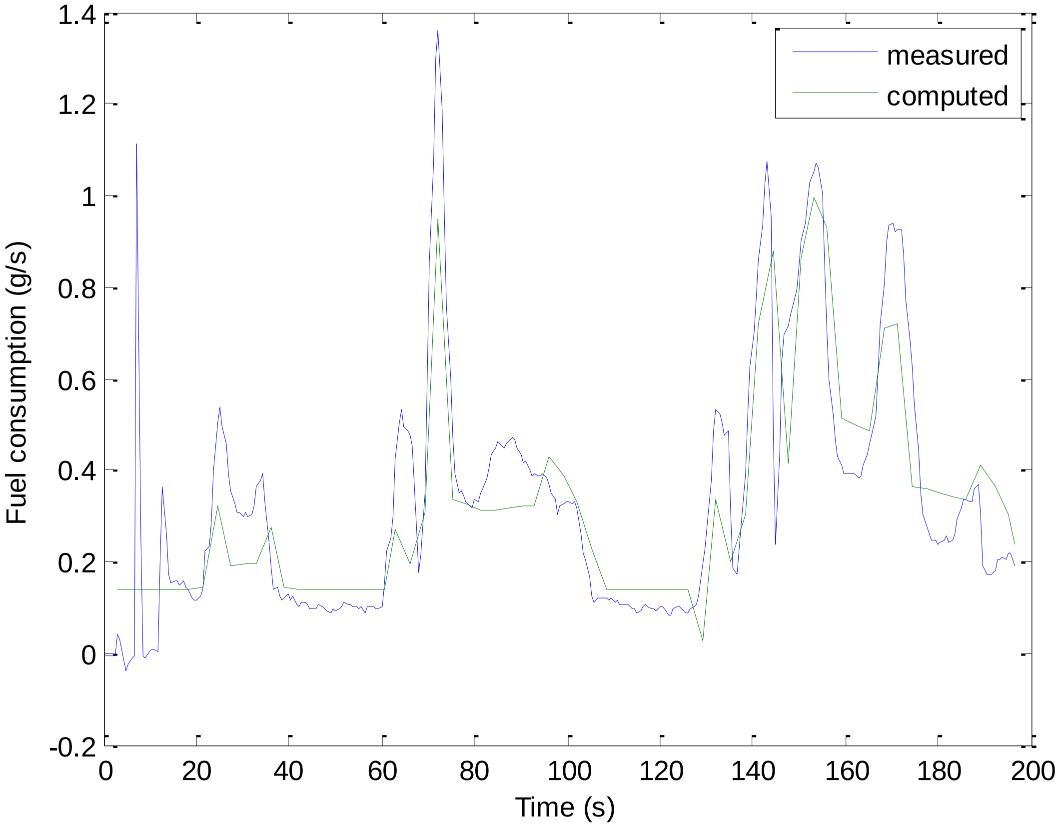


Figure 5.1 - Measured and computed fuel consumptions during first sub-cycle of NEDC without noise in input for computation

(a)

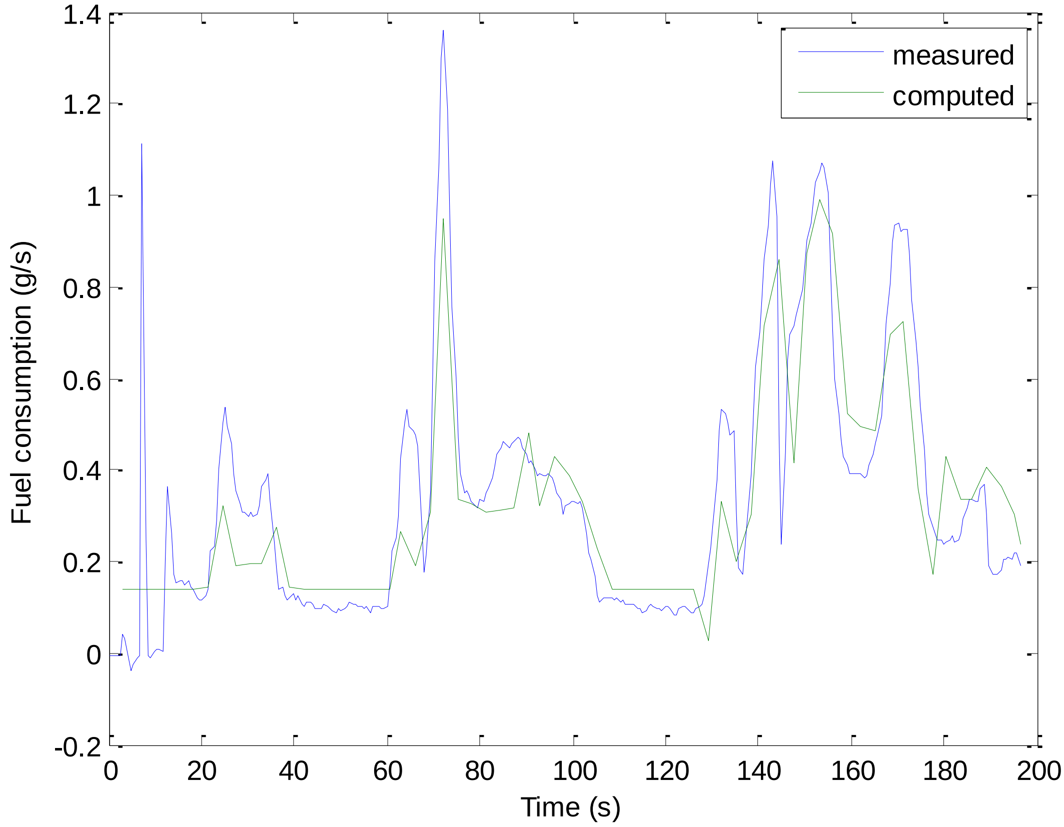


Figure 5.2 - Measured and computed fuel consumptions during first sub-cycle of NEDC, (a) without noise (b) without noise in input for computation

(b)

The graphs shown above show two different simulation runs for the NEDC first sub cycle that compare measured fuel consumption and computed fuel consumption with and without noise. The plots above make it abundantly clear that the difference between measured fuel consumption and computed fuel consumption is hardly noticeable. This stands to indicate that the validity and reliability of the proposed empirical correlation is robust.

5.1.4. New European Drive Cycle, 5th sub-cycle

The fifth sub cycle of the NEDC was also simulated in order to verify the results produced by the empirical correlation. The NEDC cycle was simulated under laboratory conditions as well as under real life driving conditions in order to test the reliability and validity of the empirical correlation. The fifth sub cycle was simulated and discussed in this section. The measured total fuel consumption of the fifth sub cycle was tabulated as 0.6905 g/s. On the other hand, the computed total consumption from the empirical correlation without noise was tabulated as 0.6761 g/s. In contrast, the computed total consumption from the empirical correlation with noise was tabulated as 0.6652 g/s.

The errors between various simulations of measurement and computation were tabulated in order to gauge the reliability and validity of the empirical correlation. The error between the measured total consumption and the computed total consumption of the empirical correlation was -2.1%. In contrast, the error between the computed total consumption of the empirical correlation without noise and with noise was tabulated as -1.6%. It must be noticed that the errors between various measured and computed simulation results has gone up from before indicating that the empirical correlation is robust although the error has increased. The results are summarised in the table shown below.

Table 5.3 - Fuel consumption parameters with noise comparison

Parameter	Fuel Consumption (g/s)
Measured total consumption	0.6905
Computed total consumption	0.6761
Computed total consumption with noise	0.6652

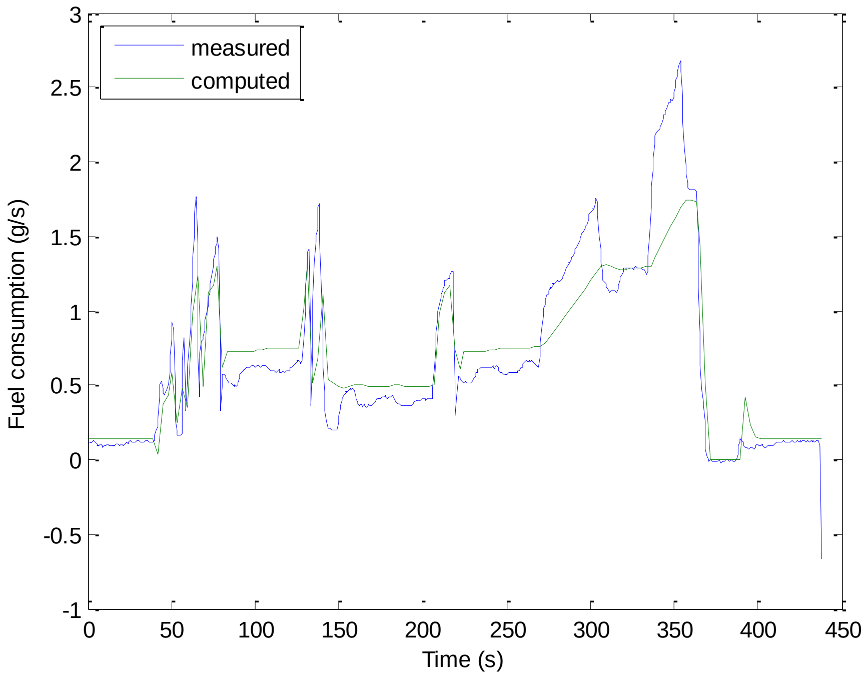


Figure 5.3 - Measured and computed fuel consumptions during fifth sub-cycle of NEDC without noise in input for computation

(a)

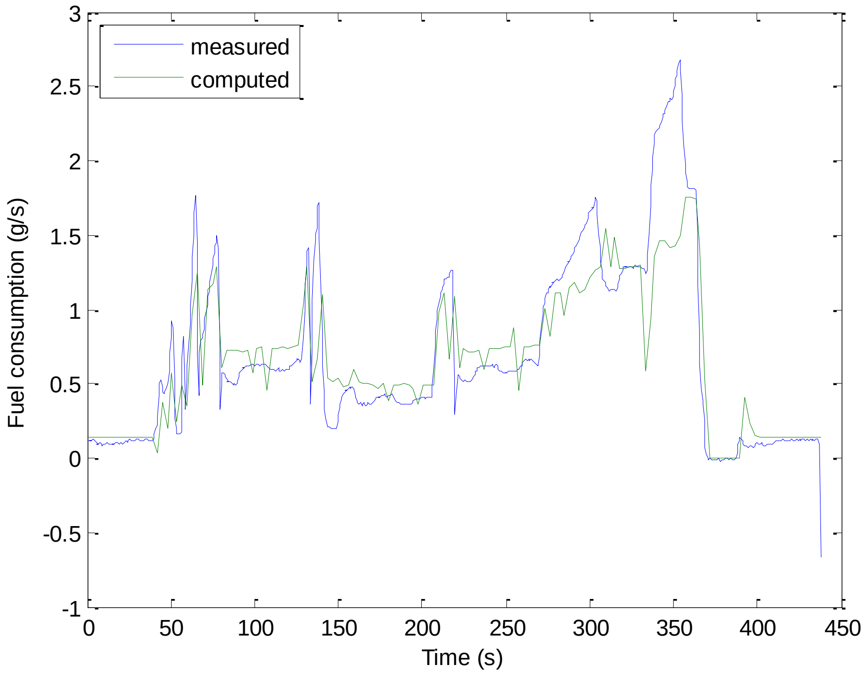


Figure 5.4 - Measured and computed fuel consumptions during fifth sub-cycle of NEDC,(a) without noise,(b) with noise in input for computation

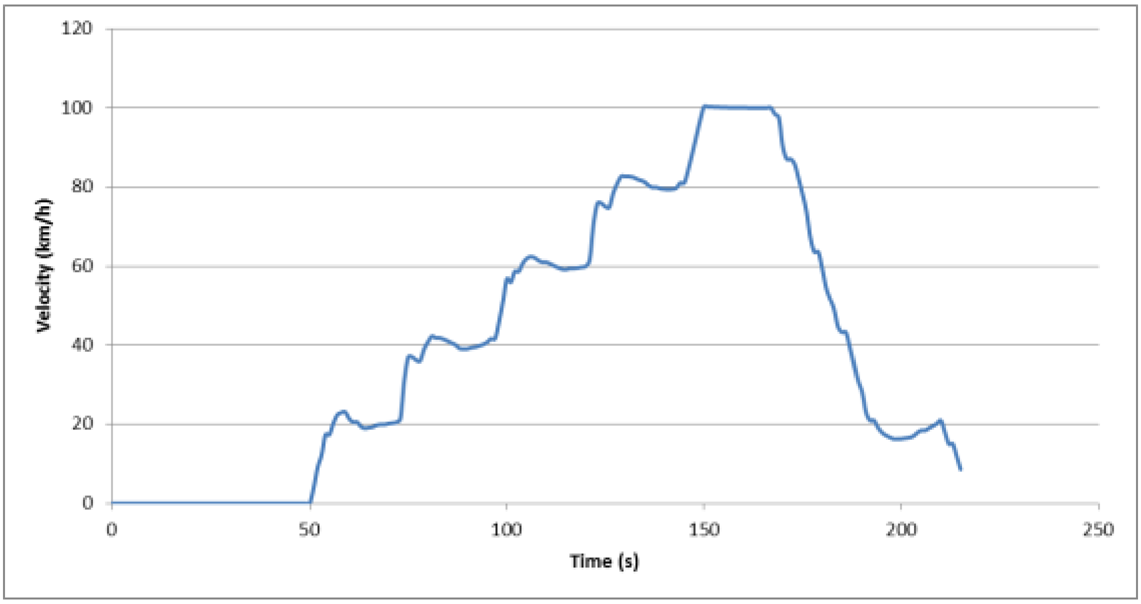
(b)

5.1.5. Prediction of Fuel Consumption in Artificial Driving Phases

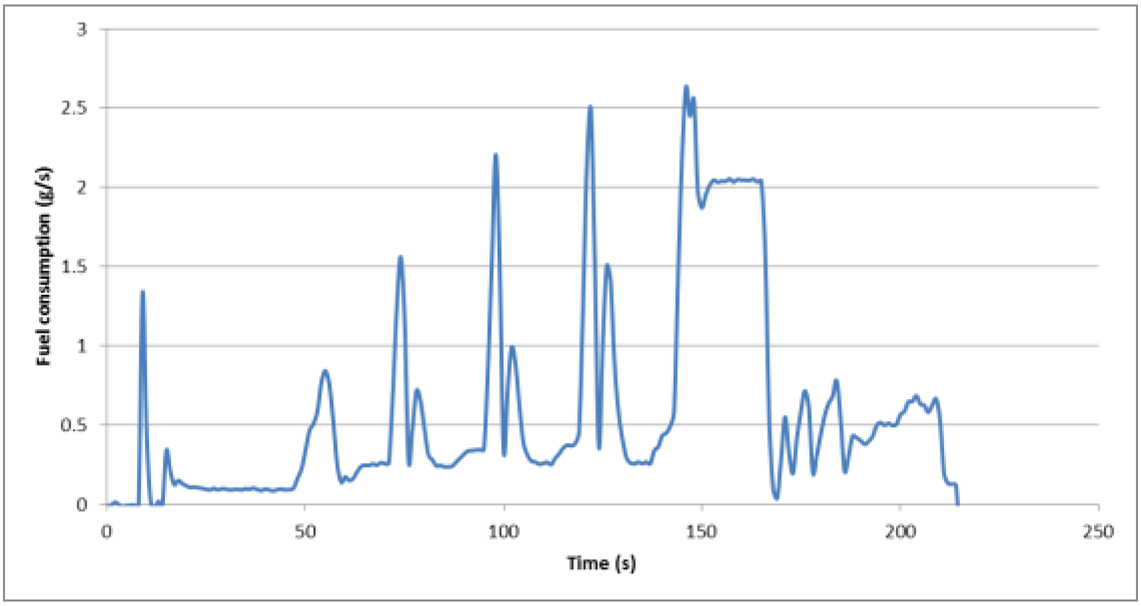
As discussed before, the empirical correlation was created based on the NEDC framework. The sensitivity tests conducted before relied on the NEDC cycle too and it could be expected that their results would provide little aberration from the empirical correlation. In order to touch upon the claims made in Chapter 4 before that the proposed empirical correlation could be applied to any other drive cycles, a number of different tests were conducted on artificially designed drive cycles. Two different drive cycles were utilised in order to test the reliability and validity of the proposed empirical correlation.

The drive cycles created for testing consisted of both constant speed as well as gear change phases. Furthermore, the first artificial drive cycle created for testing purposes consisted of high acceleration phases (with acceleration varying between 4 km/h/s and 5 km/h/s) and medium deceleration phases (with deceleration varying between -2 km/h/s and -3 km/h/s). On the other hand, the second artificial drive cycle created for testing purposes consisted of low acceleration phases (below 1 km/h/s) and high deceleration (varying around -5 km/h/s).The combination of acceleration and deceleration in both tests was meant to cover all available possibilities i.e. low to high acceleration as well as low to high deceleration. The drive cycle testing results are shown in the plots below as Figure 5.3 for the first artificial drive cycle and Figure 5.4 for the second artificial drive cycle (Alghadhi, et al, 2014).

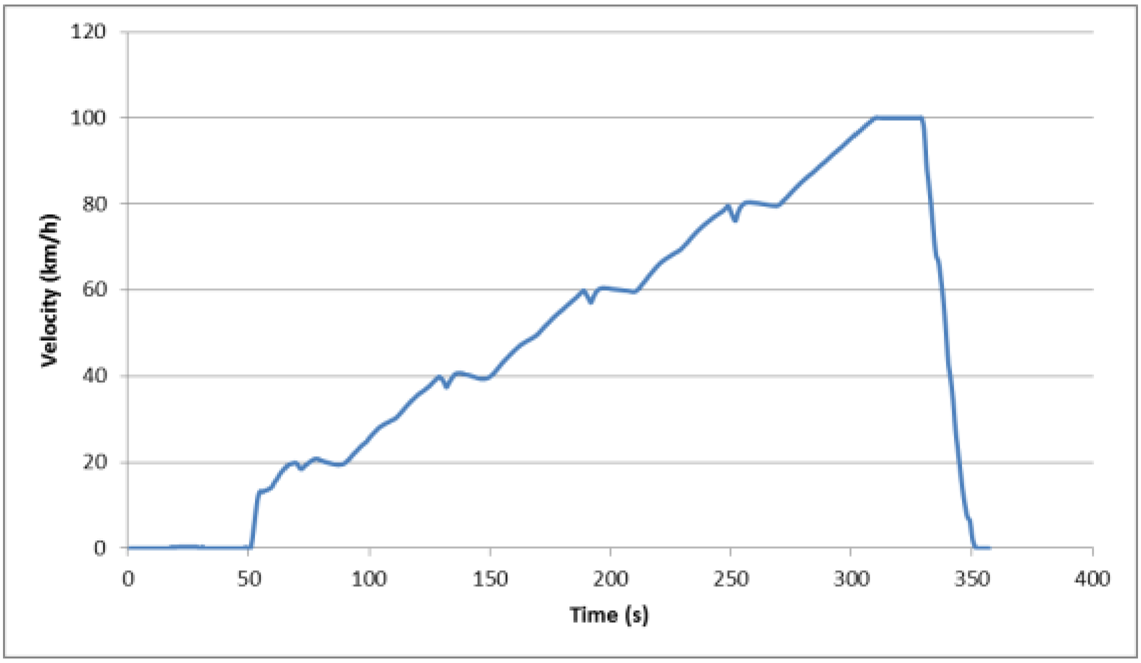
The velocity as well as the resulting fuel consumption for both driving cycles was plotted as shown in Figs. 5.3 and 5.4. The plot characteristics are discussed below for explanation purposes (Berry, 2007).



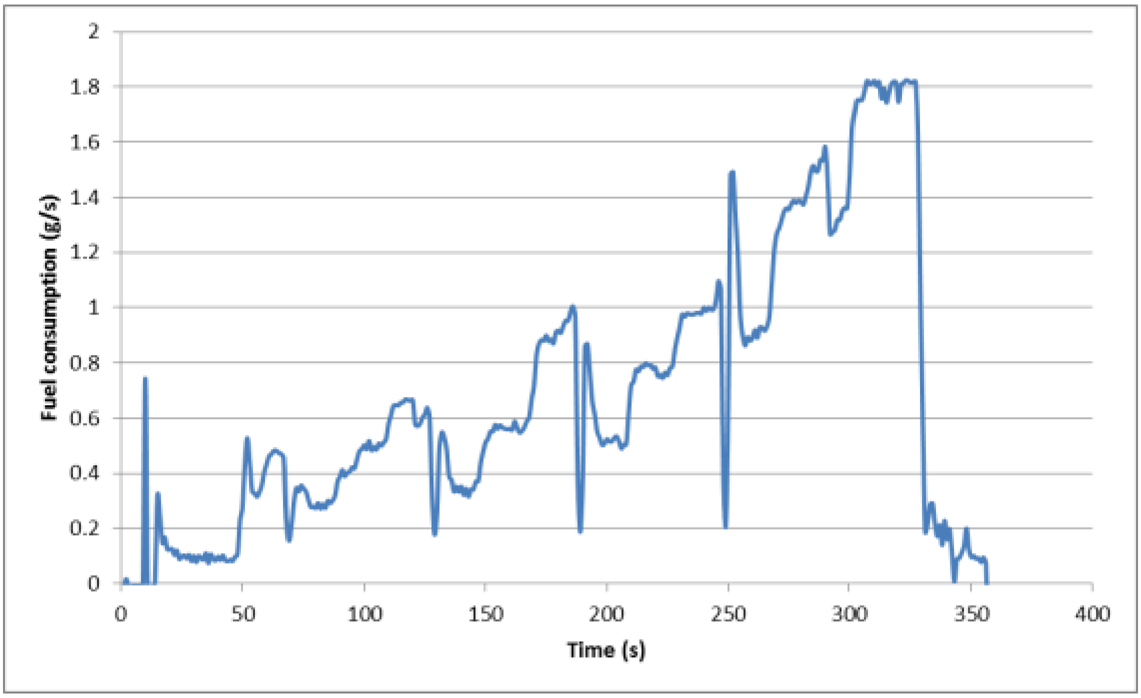
(a)
Figure 5.5 - Drive cycle simulated in Test 1,(a) for velocity



(b)
Figure 5.6 - Drive cycle simulated in Test 1,(b) for fuel consumption



(a)
Figure 5.7 - Drive cycle simulated in Test 2,(a) for velocity



(b)
Figure 5.8 - Drive cycle simulated in Test 2,(b) for fuel consumption

As shown in Figure 5.3, the velocity was varied in phases for testing purposes. The velocity was allowed to increase followed by constant velocity phases for time periods of 25 seconds. This signifies that the acceleration was varied in constant increments between the start of testing (t = 0 seconds) and the end of testing (t = 225 seconds). The jumps in velocity also signify the presence of gear changes of 25 seconds each from the start of the testing to 150 seconds after which a phase of deceleration and decreasing velocity is witnessed.

In the second artificial driving cycle, the velocity was allowed to increase throughout the acceleration phases with constant acceleration. Velocity was allowed to increase between 50 seconds and 325 seconds after which constant deceleration and velocity decrease is available. If the fuel consumption for both phases is compared, it becomes clear that for the first artificial driving cycle the fuel consumption tends to show sharp increases with every gear change. On the other hand, the fuel consumption for the second artificial driving cycle tends to show a constant increase without such high local maxima as in the first cycle. On the other hand, the deceleration phases in both artificial drive cycles tend to display constant decreases. It could also be inferred that fuel consumption in the first artificial drive cycle would be higher due to the presence of local maxima, when compared to the second artificial drive cycle.

5.1.6. Constant Speed

First, the constant speed regimes are evaluated to validate the efficacy of the empirical correlation. The data points from the two artificial driving tests were plotted against the fuel consumption in order to validate the relationship between fuel consumption and constant speed. Regression was performed in order to discern the relationship between fuel consumption and constant speed. Based on the previously proposed empirical correlation from Chapter 4, the equation for constant speed could be expressed as shown in the equation below:

$$\frac{c}{c_0} = 0.3063 + 0.6532\frac{v}{v_0} + 2.3913\left(\frac{v}{v_0}\right)^2 \qquad (4.8)$$

An observation of the plot below (Figure 5.5) clearly shows that the plot has a quadratic nature. The examination of equation 4.8 above also affirms this observation given the presence of quadratic elements.

The derived relationship provides a satisfactory prediction (errors below 20% for most cases), except for the highest velocity where the consumption is significantly underestimated. This is delineated in Figure 5.5 by the outlier points (last two points of the artificial driving test cycles) that are not covered by the regression relationship. In the first test, there is a considerable discrepancy between measured and calculated consumption; however, this may be due to the unexpected behaviour of measured data. Consumption hardly increases with velocity up to 80 km/h, and then it jumps up to a very high value (2.02 g/s). This would indicate that the acceleration and deceleration parameters enunciated before for the first artificial driving cycle are not as valid and reliable as those for the second artificial driving cycle.

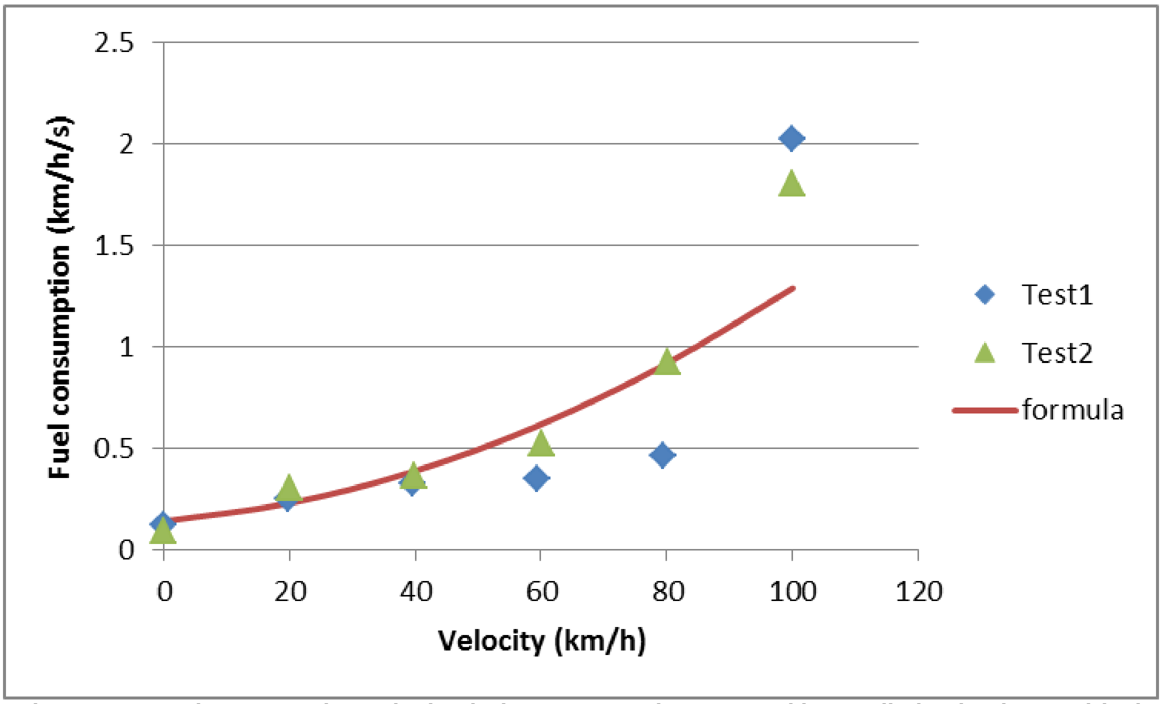


Figure 5.9 - Fuel consumption velocity during Test 1 and Test 2, and its prediction by the empirical correlation

5.1.7. Acceleration

The acceleration regimes are also evaluated to validate the efficacy of the empirical correlation. The data points from the two artificial driving tests were plotted against the fuel consumption in order to validate the relationship between fuel consumption and acceleration. Regression was performed in order to discern the relationship between fuel consumption and acceleration. Based on the previously proposed empirical correlation from Chapter 4, the equation for acceleration could be expressed as shown below:

$$\frac{c}{c_0} = 10.1739\left(\frac{a_0 v_0^2}{a v^2}\right)^{-0.3295} \quad (4.10)$$

An observation of the plot below (Figure 5.6) clearly shows that the plot has an exponential nature. The examination of equation 4.10 above also affirms this observation given the presence of exponential elements.

The derived relationship provides a satisfactory prediction (errors below 20% in most cases). This indicates that for most data points the empirical correlation enunciated before tends to hold true. However, for the highest velocities the consumption is underestimated as the error goes up to 30% to 40%. This signals that for both artificial driving cycles the highest velocities tend to provide unsatisfactory results since the error becomes significantly large. There is need to further investigate this part of the empirical correlation to verify if this observation arises out of mistaken data points during testing or if the relationship provided above does not adequately cover this testing regime.

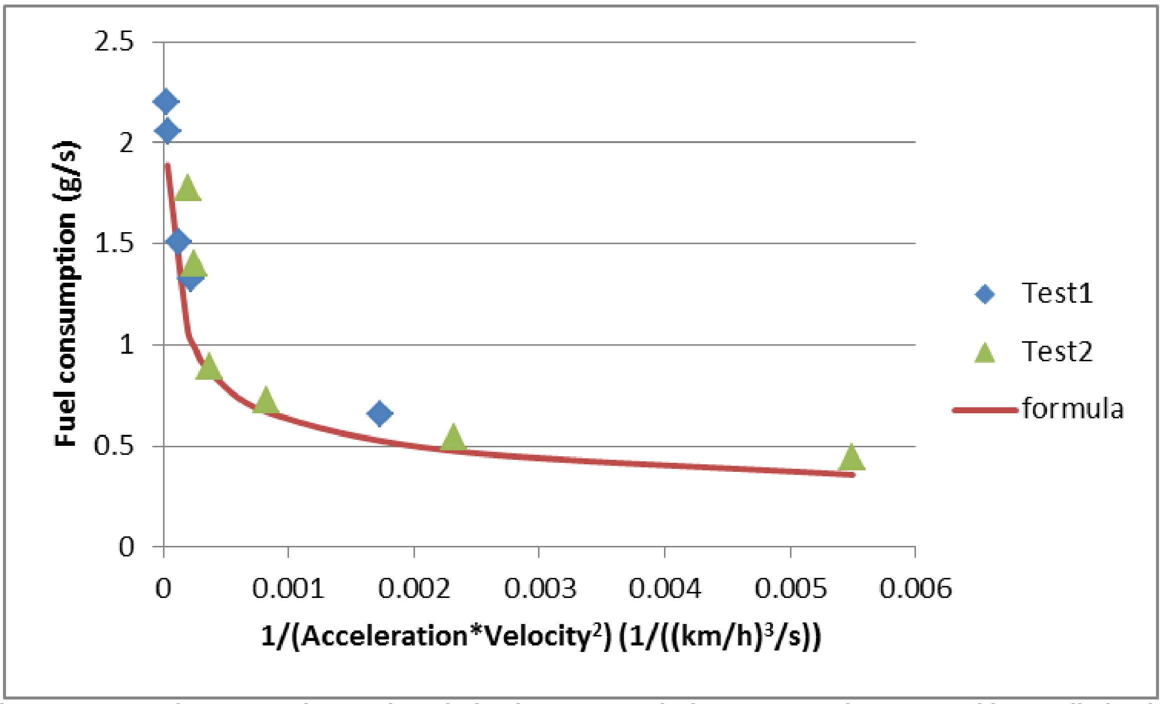


Figure 5.10 - Fuel consumption against derived parameter during Test 1 and Test 2, and its prediction by the empirical correlation

5.1.8. Deceleration with throttle

The deceleration regimes are evaluated in this section. The data points from the two artificial driving tests were plotted against the fuel consumption in order to validate the relationship between fuel consumption and deceleration. Regression was performed in order to discern the relationship between fuel consumption and deceleration. Based on the previously proposed empirical correlation from Chapter 4, the equation for deceleration could be expressed as shown in the equation below:

$$\frac{c}{c_0} = 0.4675 + 14.3461 \frac{vp}{v_0 p_0} \qquad (4.12)$$

An observation of the plot below (Figure 5.7) clearly shows that the plot has a linear nature. The examination of equation 4.12 above also affirms this observation given the presence of linear elements.

Deceleration may happen with or without throttle. In case of deceleration without throttle, the fuel consumption is 0 g/s if a gear in engaged; otherwise, when the gear is in neutral, the consumption is approximately the same as during idling, which is a special case of constant speed. Therefore, the phases of deceleration with throttle are studied in both the first and second artificial driving cycles.

There is a significant scatter in the data; therefore, the prediction provided by the relationship is considerably less accurate, than in the constant speed and acceleration phases. However, it must be taken to note that predicted values follow the same tendency as the measured data.

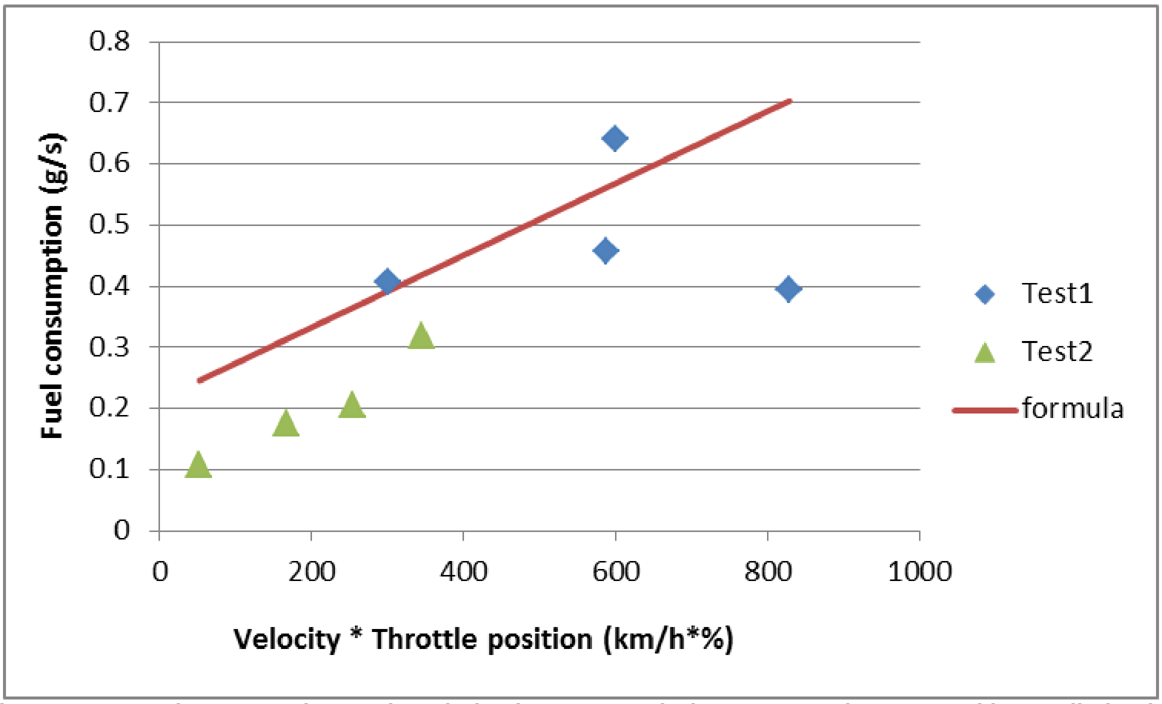


Figure 5.11 - Fuel consumption against derived parameter during Test 1 and Test 2, and its prediction by the empirical correlation

5.1.9. Gear Change

Finally, the gear change regime is evaluated. The data points from the two artificial driving tests were plotted against the fuel consumption in order to validate the relationship between fuel consumption and gear change. Regression was performed in order to discern the relationship between fuel consumption and gear change. Based on the previously proposed empirical correlation from Chapter 4, the equation for gear change could be expressed as shown in the equation below:

$$\frac{c}{c_0} = 0.4503 + 1.4494\frac{v}{v_0} \qquad (4.14)$$

An observation of the plot below (Figure 5.8) clearly shows that the plot has a linear nature. The examination of equation 4.14 above also affirms this observation given the presence of linear elements.

There is a scatter in the data during gear change phases although it seems less significant as during the deceleration phases. The prediction by the relationship is satisfactory in most of the cases during testing for the second artificial driving cycle; however, there is a consistent overestimation during testing for the first artificial driving cycle. Similarly to the deceleration phases, predicted values follow the same tendency as the measured data.

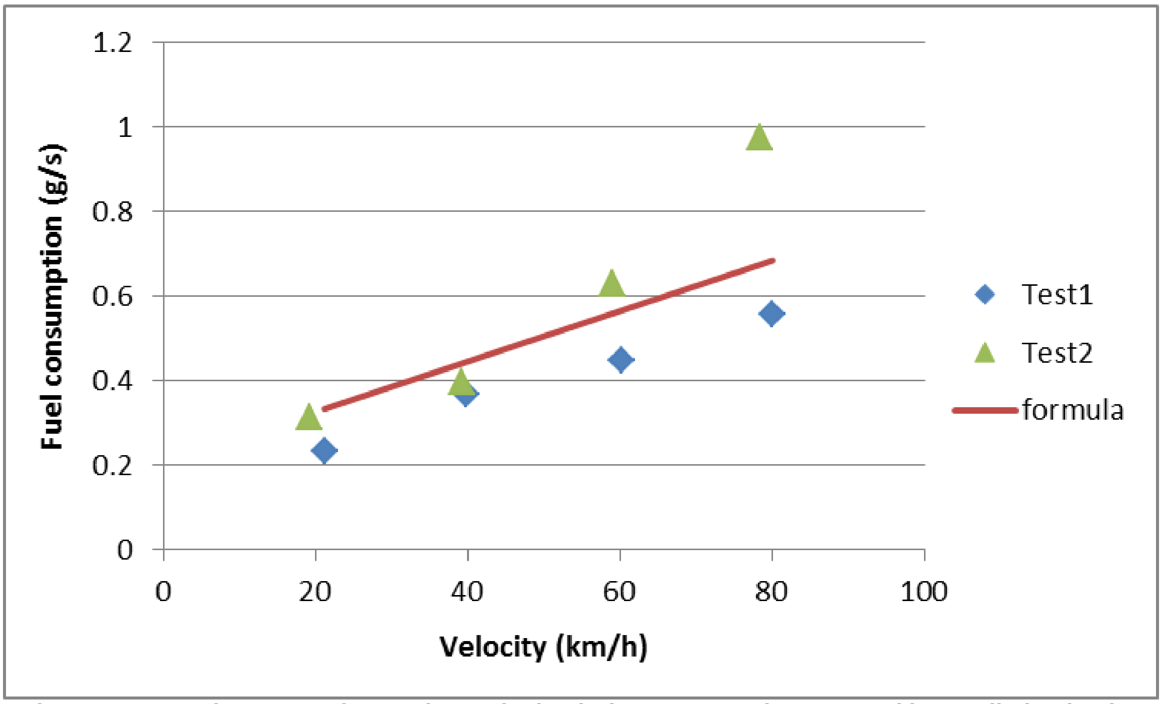


Figure 5.12 - Fuel consumption against velocity during Test 1 and Test 2, and its prediction by the empirical correlation

5.2. Discussion

The empirical correlation is reliable during constant speed and acceleration phases, although there is a significant underestimation of consumption for the highest velocities (above 100 km/h). The relationship is inaccurate in some cases during deceleration and gear change phases; however, it follows the measured tendency even during these phases. This means that the prediction at a given time instance may not be close, but the relationship is applicable to predict the average consumption during a drive cycle.

5.3. Observations

Based on the observations of the tested data and the proposed empirical correlation above, it could be seen that there is further need to investigate certain regimes where the proposed empirical correlation does not hold as true. More importantly more research is required for regimes where the velocity is high. Although the measured data and computed data are far apart but there is a tendency for both data sets to follow each other. This implies that the constants used in the empirical correlations above would require revision. It may also be the case that the empirical correlations listed above would require revision so as to derive differing empirical correlations in differing operating regimes. There is also a need for further research into deceleration and gear change phases of any kinds of driving cycles. This is expected to provide greater reliability and validity to the existing empirical correlation; thus, making it more robust for the purposes of all kinds of driving cycles.

5.4. Summary

In this chapter analysis of the empirical correlation is conducted. While analysing the empirical correlation, its sensitivity is analysed in great detail and its observations and discussed from different relevant perspectives.

CHAPTER6: EXPERIMENTAL RESULTS AND ANALSIS

6. Introduction

The previous chapter validated the proposed empirical correlation and proved that a reliable relationship existed between chosen drive parameters and fuel consumption. This chapter will use real life driving tests and the data derived from them to validate the empirical correlation derived previously. On Board Diagnostics (OBD) II data from the tested vehicles will be analysed so as to classify the various discrete phases in the drive cycle. These will be analysed in detail to see how fuel consumption responds to various chosen parameters.

6.1. An Overview

Real life driving parameter data was obtained through logging on an actual vehicle, a Volkswagen Golf Mk4 1.9 TDi. The data was acquired using the on board OBDII interface and was later processed through MATLAB. A number of different parameter options were available for logging but four major parameters were logged including:

- engine speed (rpm);
- vehicle speed (km/hr);
- engine load (%);
- absolute throttle position (%).

The logged data was utilised in turn to derive other parameters and measurements such as distance, acceleration, fuel consumption etc. The central intention was to compare between the NEDC and real life driving scenarios in order to derive comparables. A fixed sampling rate was employed to make the logged data more comparable. Logged events and parameters were then classified in terms of vehicle behaviour, i.e. cruising, idling, acceleration, deceleration etc., in order to obtain logged runs that could be superimposed onto the NEDC. The gears in use were also tabulated in order to investigate their relationship to parameters. NEDC profiling was also carried out in terms of urban driving and extra urban driving.

6.2. Experimental Results and Data Analysis

6.2.1. Logged and Derived Parameters' Behaviour

Plots were obtained for logged parameters (vehicle speed, acceleration and gradient) as well as for derived parameters (fuel consumption). Parameters were logged and derived as per the NEDC recommendations for the entire test length. The various parameters of interest are plotted in the various plots provided below that have been separated with differentials of 200 seconds starting at 0 seconds and ending at 800 seconds followed by a plot between 800 seconds and 1200 seconds.

It must be reported that the vehicle was allowed to soak so that the engine temperature, engine lubricant temperature and coolant temperature achieved their normal values before testing began. This ensured that no variation would occur in measured parameters values as these temperatures changed over the testing time. The behaviour of the vehicle along with logged parameters and derived fuel consumption are discussed below for greater clarity.

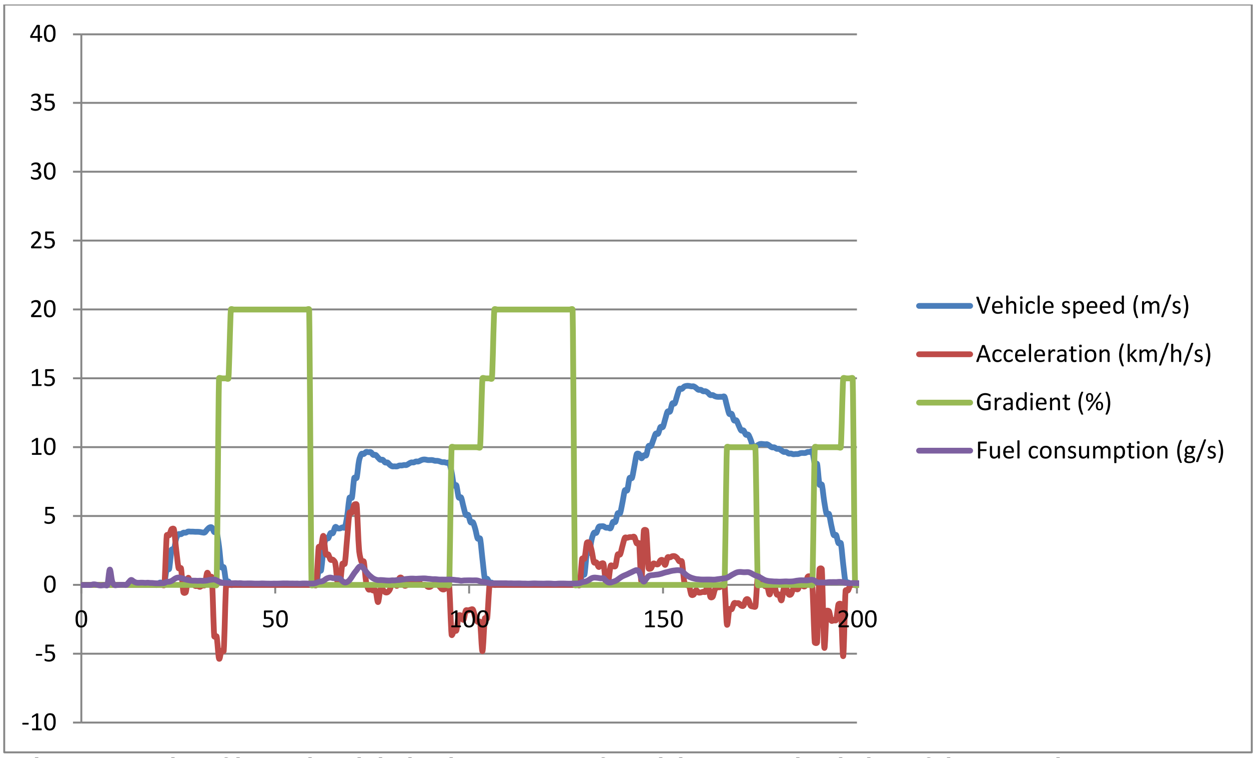


Figure 6.1 - Plot of logged and derived parameters from laboratory simulation of the NEDC between 0s and 200s

As shown in Figure 6.1, the test starts with idling of the engine after which the vehicle is given some speed at around t = 20 seconds. There is a corresponding increase in acceleration and fuel consumption as well. There is a minor spike in fuel consumption during the initial idling regime but this may be considered as an outlier. The vehicle is then braked around t = 40 seconds and allowed to come to a rest. Here, the acceleration enters a negative regime while the fuel consumption decreases, but does not go to zero since the engine is still running. In comparison, NEDC requires an idling time of 40 seconds before moving the vehicle as shown in Figure 6.6.

Subsequently, the engine is loaded to around 15% and then 20% through gear shifts and the vehicle is allowed to move around t = 60 seconds. The increase in vehicle speed is later mitigated around t = 110 seconds. This regime re-enacts the previous observations on acceleration and fuel consumption. However, it must be noticed that, compared to before, there are two distinct acceleration and deceleration regimes present for this section of testing indicating the presence of transients. The vehicle is loaded again around t = 125 seconds and is allowed to accelerate, cruise and then decelerate. The cruising regime for this section of testing could not achieve a stable speed since there are acceleration and deceleration transients that could not be satisfied in such a small amount of time. The deceleration transients just before t = 200 seconds present myriad transients and indicate the difficulty in using deceleration as a reliable measure for fuel consumption.

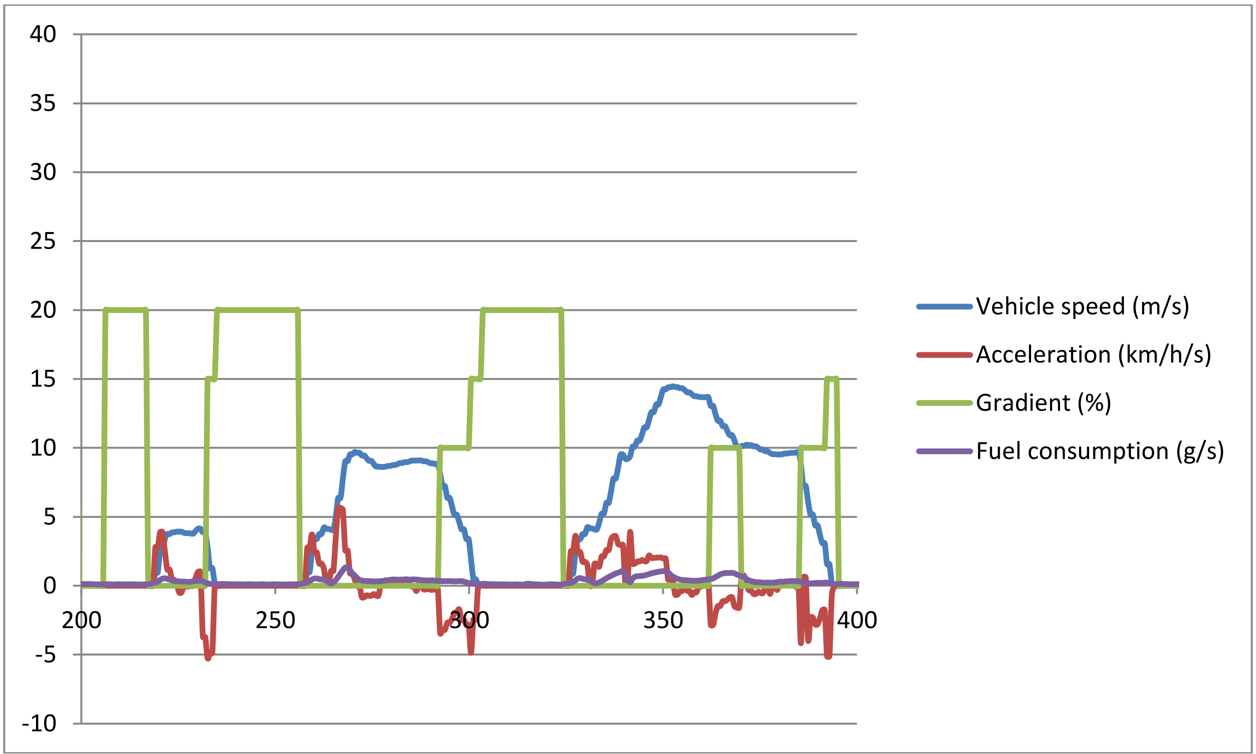


Figure 6.2 - Plot of logged and derived parameters from laboratory simulation of the NEDC between 200s and 400s

The testing in the post-200 seconds' regime is shown in Figure 6.2. It is noticeable that the same testing regime has been initiated with nearly similar idling periods, cruising stints, acceleration and deceleration. Comparably, the acceleration and deceleration transients tend to become more complicated as the overall speed and the cruising speed are increased as shown earlier. Observations regarding all parameters (whether logged or derived) are comparable though not similar. The transients for the last acceleration, cruise and deceleration run are lesser than before and it could be attributed to driver behaviour. As the driver gains more practice with such tests, the number of transients could be expected to decrease as the driver's cognition and expectation of such events improves. This also indicates that the NEDC is not totally realistic since it fails to account for human input into fuel consumption or the tabulation of other logged or derived parameters.

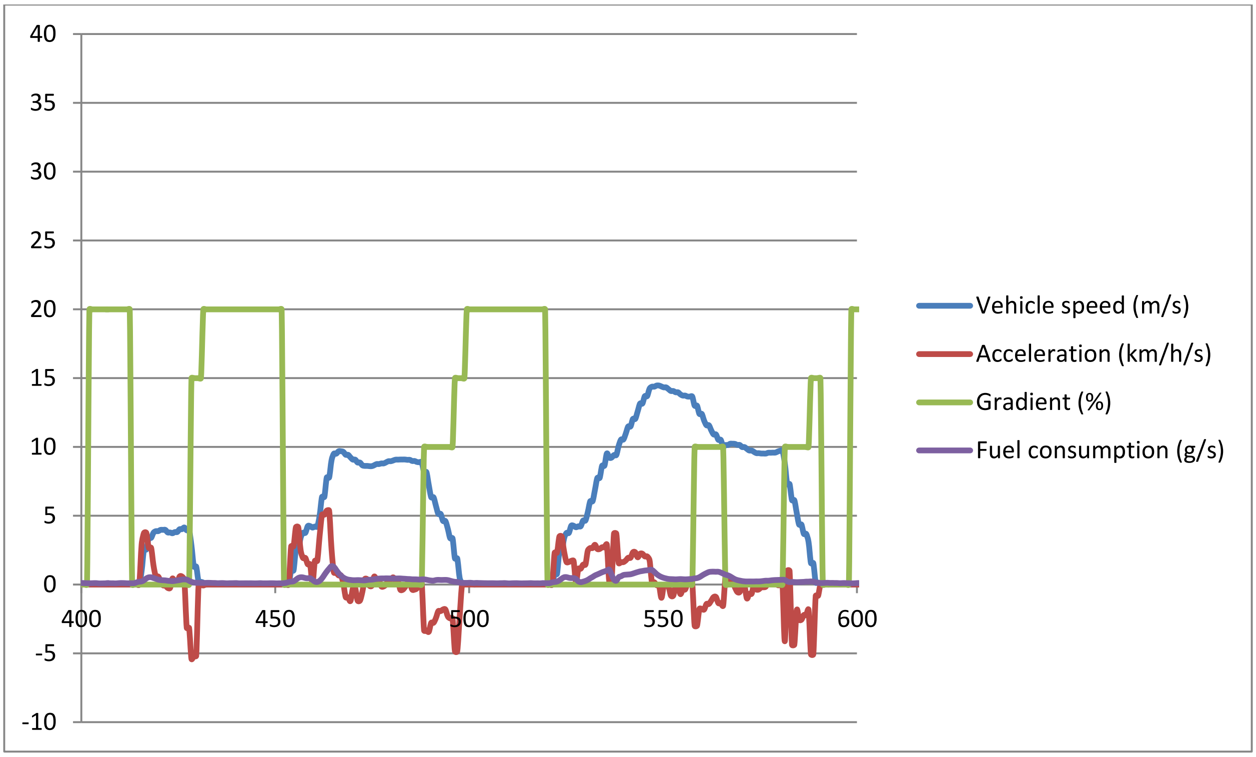


Figure 6.3 - Plot of logged and derived parameters from laboratory simulation of the NEDC between 400s and 600s

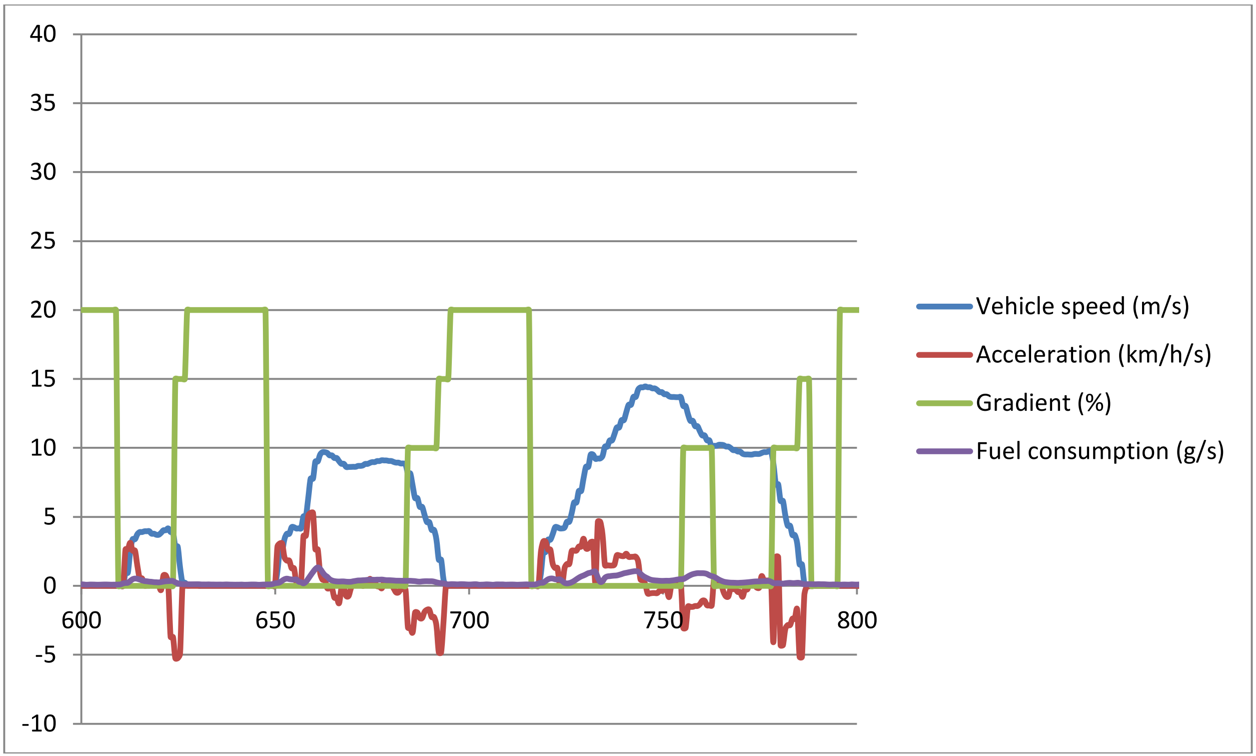


Figure 6.4 - Plot of logged and derived parameters from laboratory simulation of the NEDC between 600s and 800s

Behaviour for various logged and derived parameters for Figures 6.3 and 6.4 is similar and has been discussed before so requires little further elaboration.

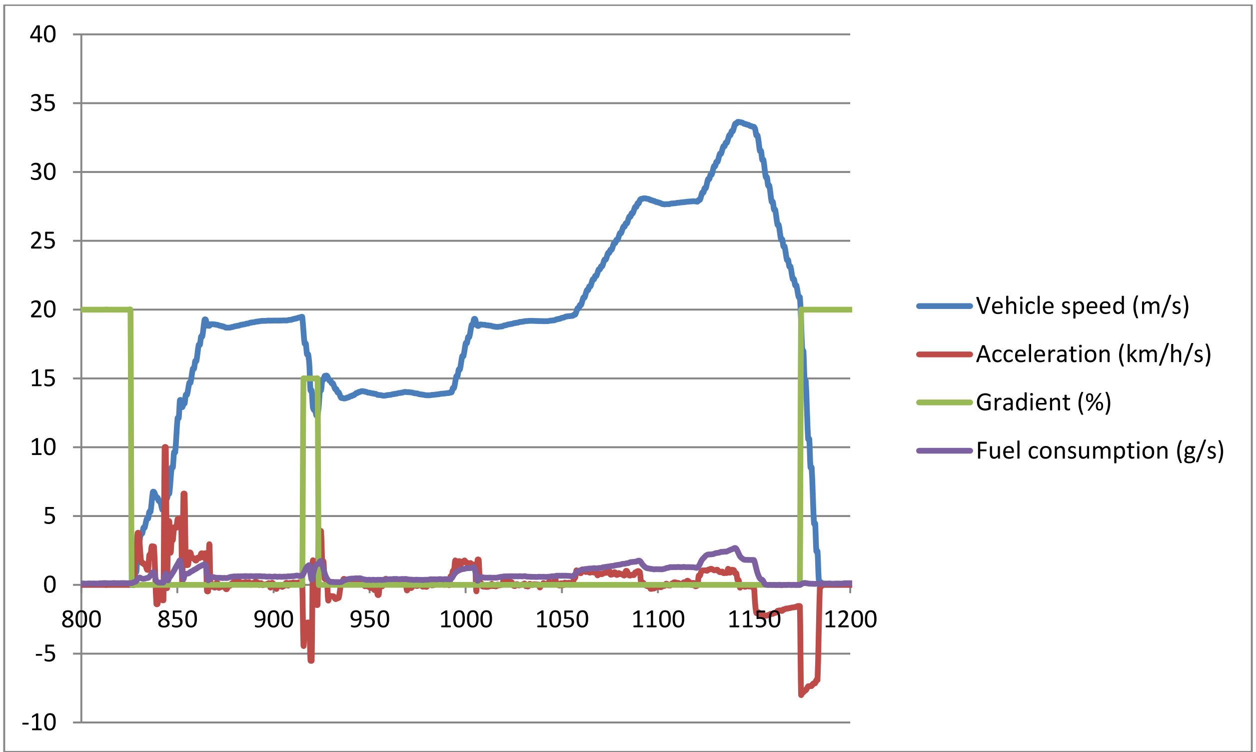


Figure 6.5 - Plot of logged and derived parameters from laboratory simulation of the NEDC between 800s and 1200s

Figure 6.5 depicts the various logged and derived parameters from the laboratory simulation of the NEDC. This plot differs from the other plots shown before since it depicts extra urban driving that is indicated by the consistency of vehicle speed over 300 seconds. After a brief period of idling between 800 seconds and 850 seconds, the vehicle is accelerated, stronger than any acceleration stints tested before. This increases the fuel consumption drastically, which keeps on tailing the acceleration. For a brief period, there is some deceleration that could be attributed to significant increases in engine load over a short period of time. Consequently, acceleration is kept near constant with slight variations over the remaining testing regime. However, there is a significant increase in the fuel consumption as the vehicle speed increases. As discussed in previous sections, the air drag increases proportional to the square of vehicle speed. The increase in fuel consumption with the increase in vehicle speed can be affirmed from the plot shown above.

Finally, it must be noticed that the fuel consumption is related though not directly to the vehicle speed. Instead, it would be more appropriate to surmise that the fuel consumption and acceleration tend to follow each other closely. This is demonstrated with the increases and decreases in acceleration and fuel consumption during periods of vehicle acceleration and deceleration. However, this relationship is not defined similarly during periods of idling or cruising where the fuel consumption is constant or increasing although the acceleration is zero. As noticeable in the plot above, the deceleration between 1150 seconds and 1190 seconds tends to produce the largest deceleration while fuel consumption tends to remain consistent but does not decrease to zero which proves the point listed above.

6.2.2. New European Drive Cycle

The NEDC is depicted below in Figure 6.6 for reference and comparison to the plots shown in Section 6.2.1. It can be seen clearly from Figure 6.6, that the NEDC is essentially an idealised testing regime where the variations in vehicle speed are assumed to be constant for the advised four urban driving cycle runs (Barlow, et al, 2009). The testing runs performed under laboratory conditions and the resultant plots make two things abundantly clear – firstly that four urban driving cycle runs cannot be expected to resemble each other in real life driving conditions and secondly that expecting real life driving conditions to match some defined ideal standard is not possible in the provided regime. The small reaction times mean that slips such as different idling periods in the start of the test could cause significant differences to the tested fuel consumption. This could be addressed in the NEDC by allowing a larger testing period regime where small idling, acceleration, cruising and deceleration runs would not produce large offsets in the final tabulation of the fuel consumption.

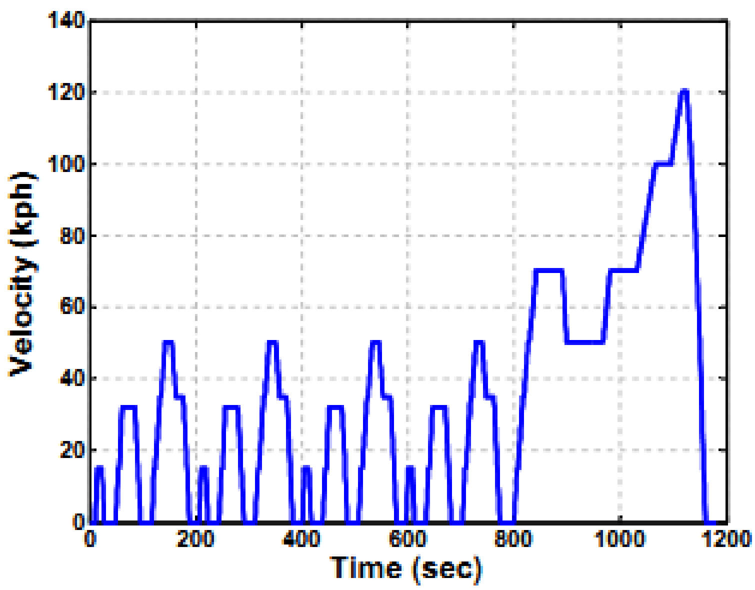


Figure 6.6 - The New European Drive Cycle sourced from (Berry, 2007, p.132)

As iterated above, there are differences between the proposed NEDC testing regime and what can actually be achieved. The differences between the NEDC testing regime and real life driving tests can be justified largely on the basis of human inputs differences. The idealised NEDC does not require any human input, unlike real life driving testing. Hence, the NEDC is not totally realistic since it fails to account for human input into fuel consumption or the tabulation of other logged or derived parameters.

6.3. Real-life Drive Cycles

6.3.1. Analysis of Logged OBDII Data

The post-acquisition analysis of the data logged via OBDII on a Golf Mk4 1.9 TDi (130 PS) was done exclusively in MATLAB.

Four PIDs were monitored: Engine Speed (rpm), Vehicle Speed (km/h), Calculated Engine Load (%) and Absolute Throttle Position (%).

Each PID value logged is time-stamped by the Nexiq on arrival. However, the transmission interval is non-deterministic and dependant on the ECU. In addition each PID arrives independently, so the relationship between PIDs is also non-deterministic. The first stage of analysis was to homogenise the four PID streams acquired so they all have a constant sample rate. Linear interpolation was used to map all the PID data to a fixed sample rate (1 Hz).

From this various parameters are easily calculated. The total distance is the trapezoidal piecewise integral of the vehicle speed. From this average speed can be calculated. Acceleration is calculated by piecewise differentiation of the vehicle speed data.

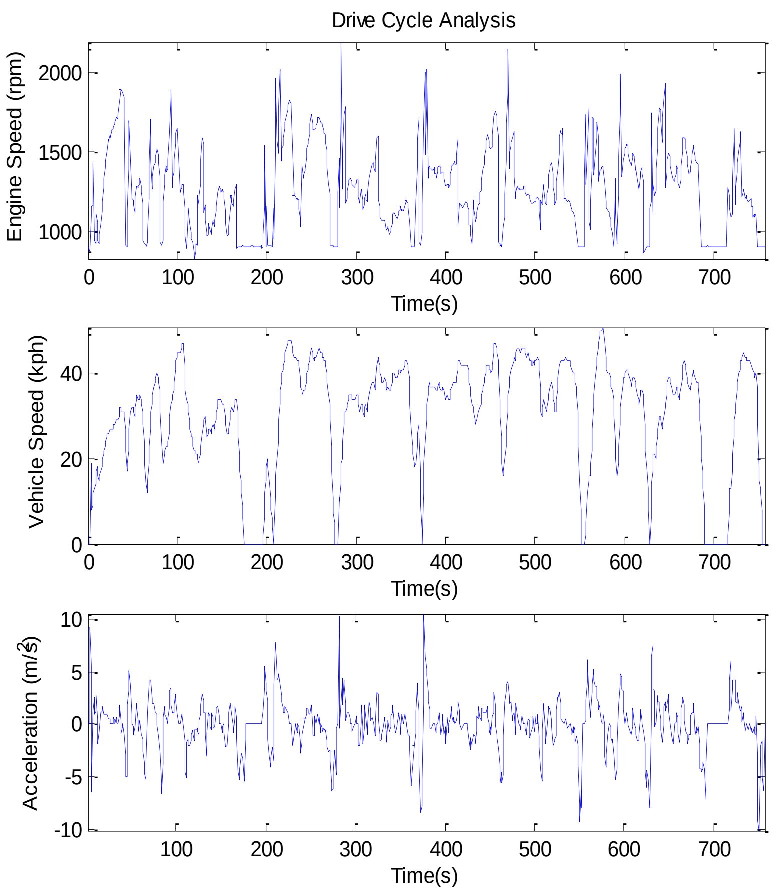


Figure 6.7 - Drive cycle analysis plotted data for the engine speed, vehicle speed and acceleration obtained from Nexiq

6.3.2. Separating Logged Data into Specific Events

The rest of the analysis follows the method of Holmén & Niemeier (1998) whereby the logged data is separated in events. Each event was determined to last for one linearised sample interval (1 second).

Events are separated firstly into cruise, positive acceleration and negative acceleration. A cruise event is defined as occurring when the vehicle is non-stationary and the acceleration is below a set threshold. This was set to 0.5 ms^{-2} which provided a good balance of cruise/acceleration events in the datasets considered.

Cruise events are further classified as high speed cruise (V > 40 mph), mid speed cruise (25 < V ≤ 40 mph) and low speed cruise (≤ 25 mph).

An idle event was defined as occurring when the vehicle was stationary.

In order to provide useful parameters for analysis the events were normalised to the total number of events logged.

6.3.3. Determining Gear Usage via OBDII Data

Information on gear selection is not directly available via OBDII PIDs. It is possible, however, to consider the ratio of vehicle speed to engine speed. There are however three potential unknowns required in addition to derive the gear result. These are gear ratios, differential ratio (for rear wheel drive) and tyre radius. Even with an *a priori* knowledge of a given car gearbox/differential, there is no way of deriving tyre radius as these may be changed as aftermarket items. A more generic solution to determining gear ratio is thus preferential.

It is possible to use a cluster type analysis in order to derive the current gear. An analysis of the distribution of vehicle to engine speed ratio will yield peaks at each valid gear. There will be some noise associated with actions during clutch depression (e.g. revving, coasting) or wheel spinning caused by traction loss.

In order to establish gear positions a normalised distribution of vehicle to engine speed ratio was calculated (200 bin histogram). Calculating the ratio this way avoids the divide by zero that occurs when the vehicle is stationary. A threshold was then used effectively to mask the random noise which is spread fairly across the distribution. Any value below this threshold is zeroed. Experimentally, a threshold value of 0.05 worked well for this purpose. The resulting maxima where then detected by for a sign change in the first order differential of the data.

In this way it is possible to detect the current gear used during the drive cycle, although not the actual gear ratio.

In the following example the four gears were detected and the vehicle-engine speed ratios were calculated as 0.0087, 0.0162, 0.0264 and 0.0359 for first to fourth gear respectively. The relatively small size of the first gear peak indicates little use which corresponds to the presence of a high torque (at low revs) diesel engine. The majority of pull away from stationary is done in second gear.

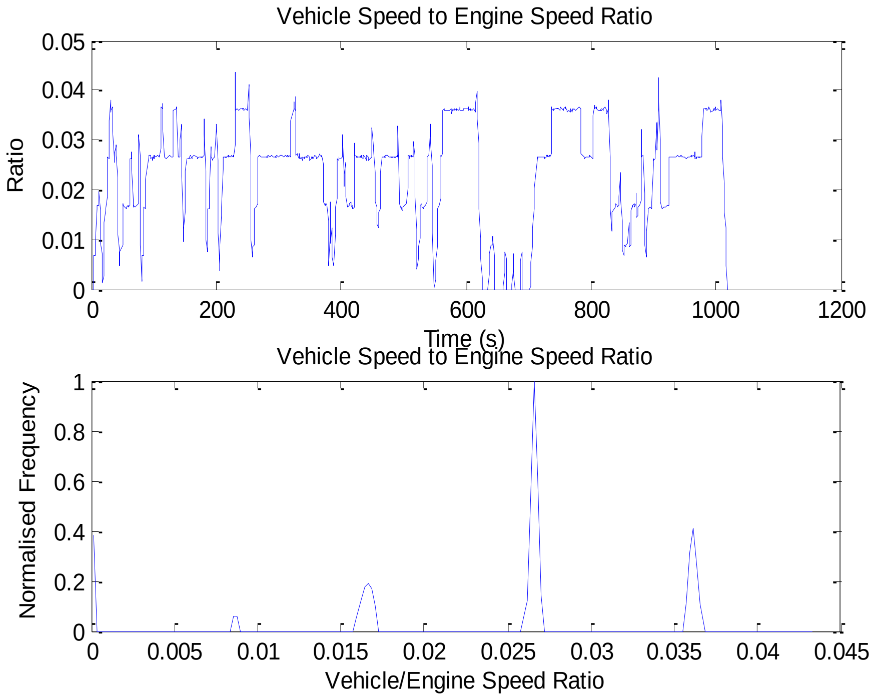


Figure 6.8 - Calculated Vehicle to Engine Speed Ratio Distribution

6.3.4. Calculated Load to Monitor Fuel Consumption

The ability to monitor fuel consumption is something that would be very useful to do via OBDII data. Unfortunately no quantifiable data is generally available for fuel flow in OBDII implementations. It is necessary therefore to try and infer the fuel consumed using other available parameters. Mass air flow can be used to try and determine fuel use in petrol engines, but a stoichiometric air/fuel ratio must be assumed. This is invalid for high load (open loop) conditions. Furthermore, this method is only viable for petrol engines; diesel engines are not throttled thus the airflow is proportional to only engine speed (simple volumetric displacement).

OBDII provides a parameter for ‘Calculate Engine Load’ (Mode 01h, PID 04h) which yields a percentage figure which relates to the current engine load. For petrol engines it is calculated as ratio of airflow to maximum airflow (at any given engine speed). In diesel engines it is calculated as the ratio of fuel flow to peak fuel flow (at any given engine speed).

The diesel method of determining calculated engine load means that it should give a good indication of fuel consumption. The petrol method is still limited by the potential for open loop excursions to result in under-reading. It may be possible to resolve open loop conditions through the monitoring of absolute throttle position (Mode 01, PID 11). A threshold may be set (e.g. > 80%) above which the engine is considered to be in open loop operation. Of course this would still not allow for the fuel flow to be corrected.

The integrating the calculated engine load can provide an indication of overall fuel consumption for any single journey. This is not a relative value and is useful for comparing multiple drive cycles on any single car, but not able to derive an absolute ‘mpg’ value.

6.3.5. Analysing Data logged Events

The project aim is to try and reconstruct parts of the NEDC drive cycle from real logged data. To provide a starting point for analysis the NEDC data captured from the dyno rig was first analysed. To simplify matters at this early stage, only the EDE15 portion was looked at (this corresponds to the urban fuel consumption calculation). The logged engine speed and vehicle speed data is shown below.

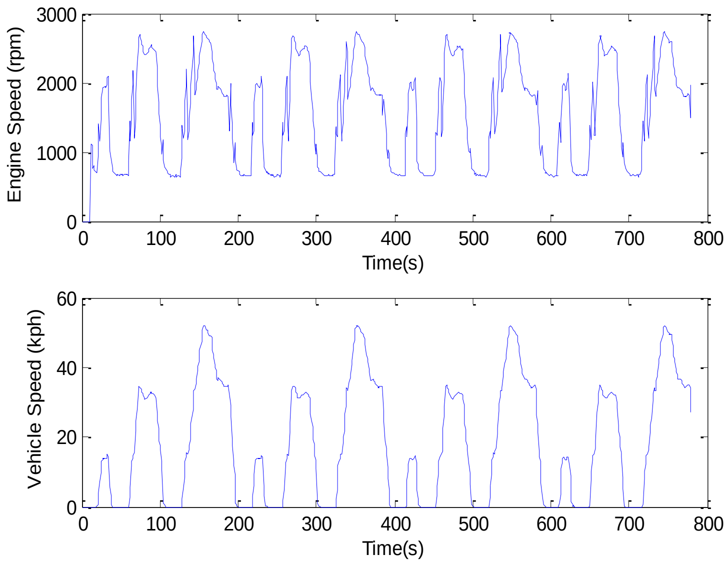


Figure 6.9 - Plots of engine speed and vehicle speed for urban drive cycle

Two real drive cycles were also analysed having a similar duration to the EDE15. Both drive cycles were done from a cold start and the routes were urban in nature. The first was a hilly course, the second more mildly undulating. The analysed results are shown in Appendix 'B'.

A cruise to acceleration ratio was also calculated to try and quantify what is likely to be an important driving style which impacts fuel consumption. The mpg values for the real drive cycles are taken from the on-board trip computer. It is very likely that this calculation will under-read, so some form of calibration will be necessary to confirm this.

The mpg values appear to be higher (especially if under-read is assumed) for both the real drive cycles. This is explained by the fact average speeds are higher and the cruise to acceleration ratio is higher. Clearly the driving was faster and less 'smooth' than in an EDE15 cycle.

6.3.6. Journey Gradient Profiling using OBDII Data

One major impact on fuel consumption is the gradients involved on a journey. Clearly a hilly course is likely to result in a worse mpg value for a given drive time. OBDII does not have access to any accelerometer or inclination data (assuming these sensors even exist on a particular model). A point of weakness in any comparison to the NEDC drive cycle is this lack of information.

One potential method for determining hilliness is by using the engine load and derived cruise data. For any cruise condition (no acceleration) the engine load will be higher for a positive (uphill) gradient. Conversely it might be anticipated that any negative gradients will result in no engine load as the vehicle coasts. The situation is complicated slightly by the fact that engine load goes up slightly (~20% observed) if the engine is idling (clutch in) as the wheels are no longer turning the engine block and as such fuel is being injected to maintain engine operation.

In order to test whether it is possible to gauge any gradient information from engine load and cruise data, two journeys were monitored. One was on a hilly course, the other mildly undulating. Ordnance survey mapping software was used to determine the actual gradient profiles of these two journeys. Both journeys started from the same point and the route/gradient profiles were confirmed as hilly and mildly undulating respectively.

An inclination factor, F was then calculated for all categorised cruise data such that:

$$F = \frac{L}{V^2}$$

Where L is the calculated engine load and V is the vehicle speed. The denominator attempts to account for the approximately square law relationship between power and vehicle speed to consider aerodynamic drag.

The courses utilised for testing are marked in three different colours along with the way points on the map shown in Figure 6.10 below.

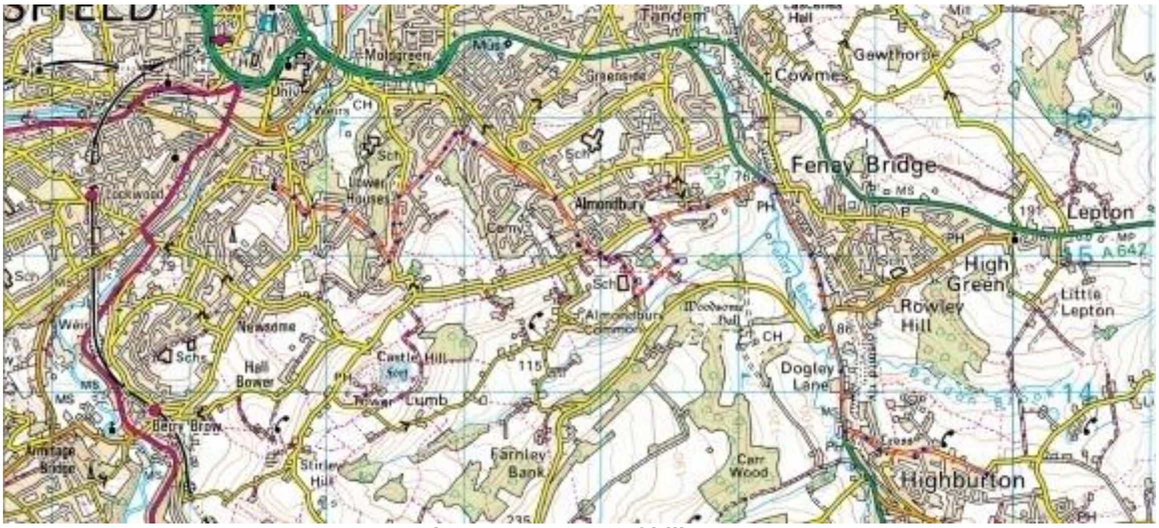


Figure 6.10 - Map of hilly course

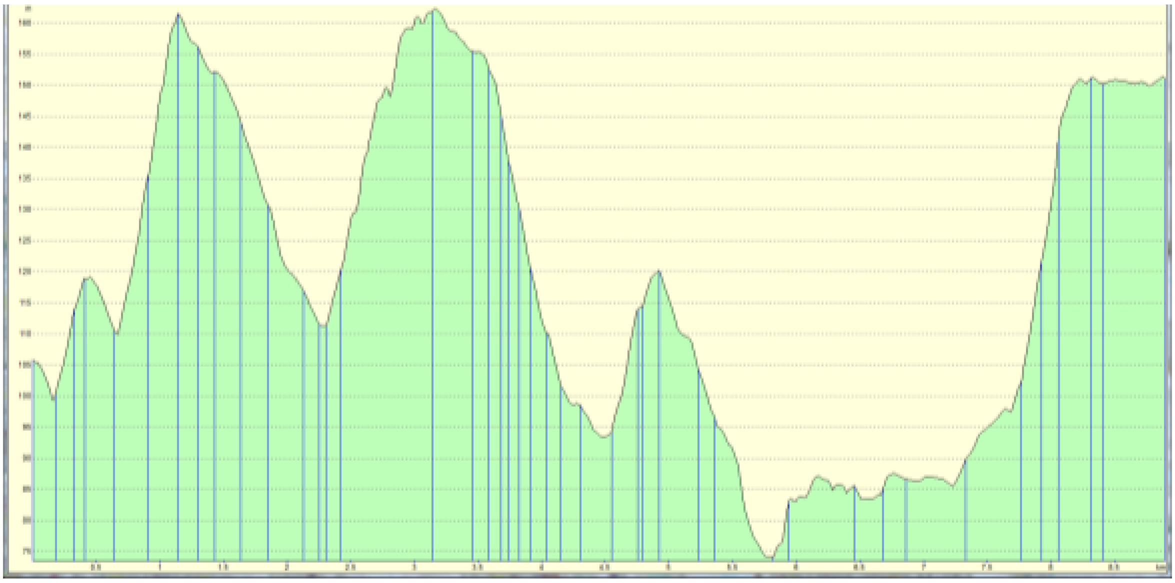


Figure 6.11 – Plot of engine load against cruise data for hilly course

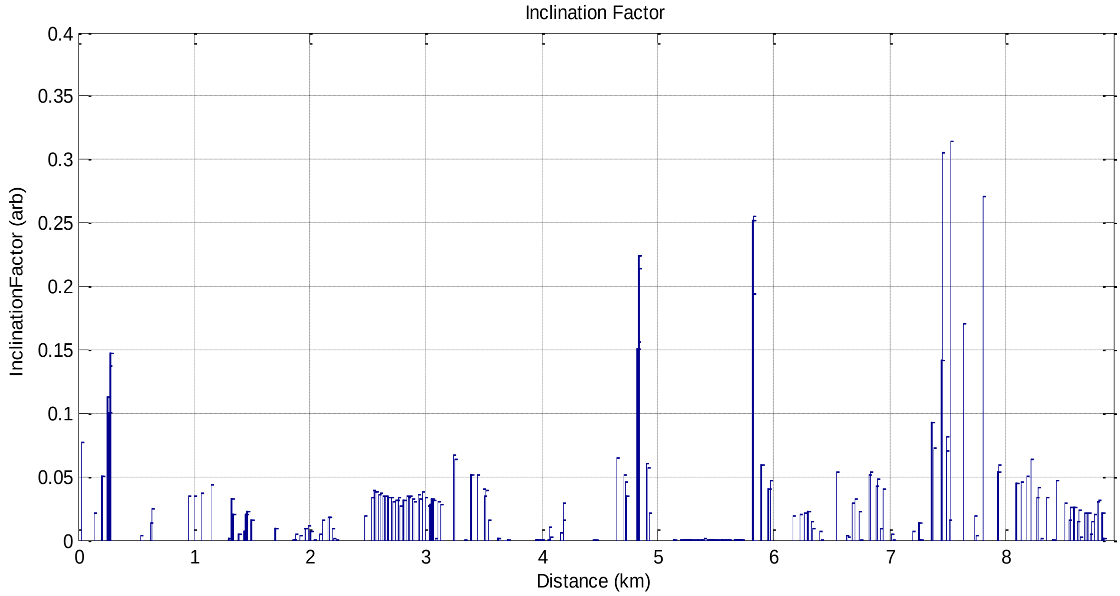


Figure 6.12 - Inclination factor for hilly course

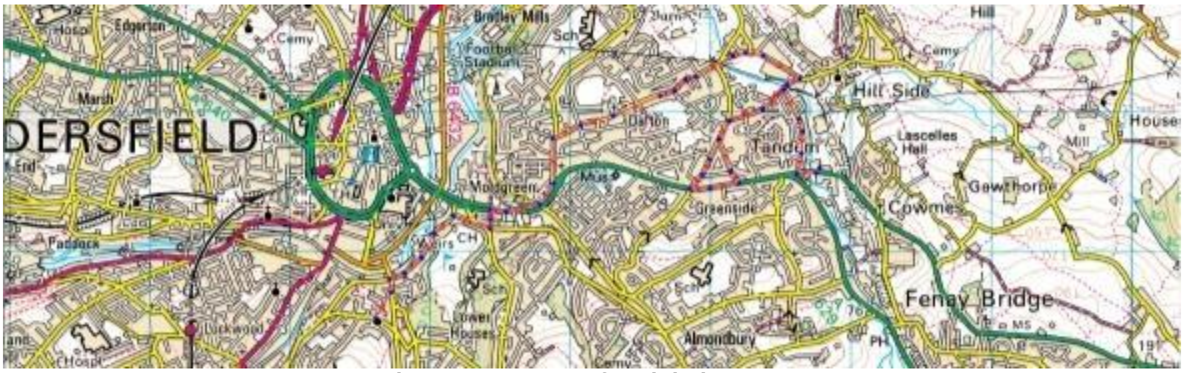


Figure 6.13 - Map of undulating course

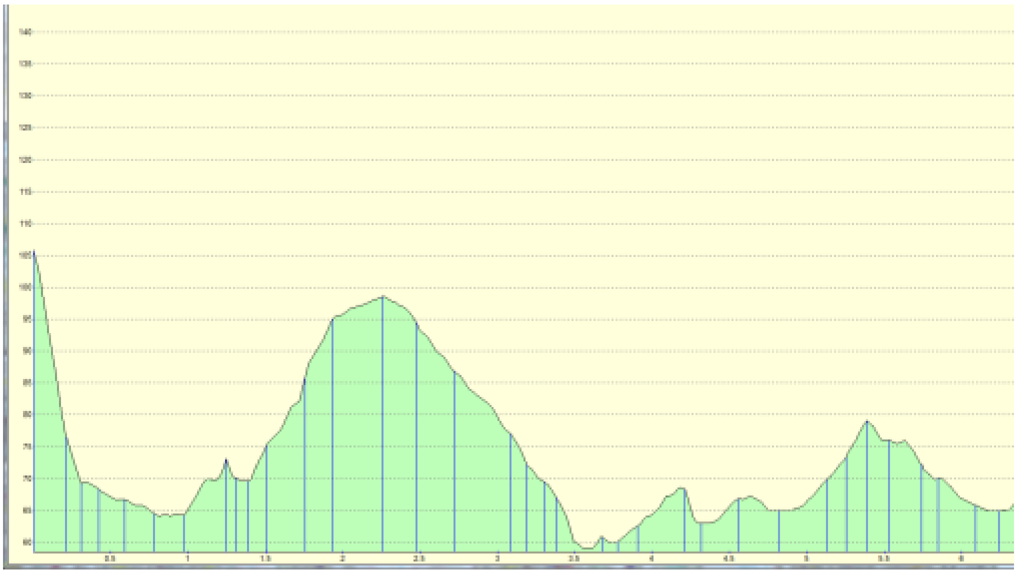


Figure 6.14 - Plot of engine load against cruise data for undulating course

Y

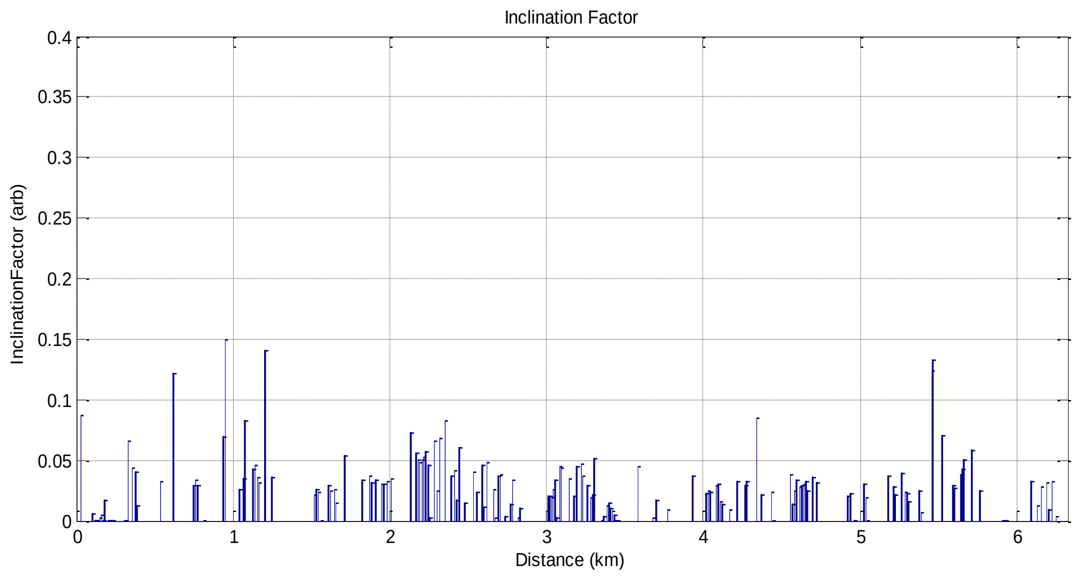


Figure 6.15 - Inclination factor for undulating course

There is without doubt some correlation between the results and the calculated inclination factor for both examples. The peak values do correlate with gradients and the peak excursions are lower for the mildly undulating course. Clearly there is a lot of noise in the data, and a lot of missing data due to acceleration events. There may be scope using more advanced signal processing to derive better data. A more advanced correction factor for the effects of drag with vehicle speed would be a good starting point.

6.3.7. MATLAB Results for Real Life Driving Data

Real life driving data for a number of parameters was tabulated and plotted for interpretation. Among other variables extracted from real life driving, one of the more important parameters was fuel consumption. The current research is largely concerned with tabulation of fuel consumption with various kinds of driving conditions so an examination of fuel consumption was required. The frameworks of investigation developed in preceding chapters were then utilised in order to interpret and understand the trends available in the fuel consumption plots. In order to make things simpler, two different real life driving conditions have been evaluated below.

The first situation depicts largely extra urban driving while the second situation depicts mostly urban driving. The primary means of analysing the fuel consumption against time plot was to decompose the various time bound phases according to the algorithm provided in Chapter Four previously.

The plot provided below depicts the fuel consumption experienced during extra urban driving for a total testing period of approximately 1017 seconds. A look at the plot provided below reveals that the vehicle experienced several gear change regions during the course of the testing. This is reinforced by the presence of multiple peaks and troughs in close proximity on the plot. Based on phase type breakdowns of the NEDC, or any other driving testing cycle, the entire driving cycle can be broken down into phases consisting of:

- Acceleration;
- Deceleration;
- Constant speed;
- Braking.

For the sake of explaining the plot behaviour, it is notable that as the vehicle would have accelerated, it would have required the greatest amount of fuel and hence it would have shown the steepest growth in fuel consumption. In a comparable manner, a decelerating vehicle would tend to exhibit a downtrend in fuel consumption although it would not possess a sharp rate of decline as it did for the acceleration phase.

Y

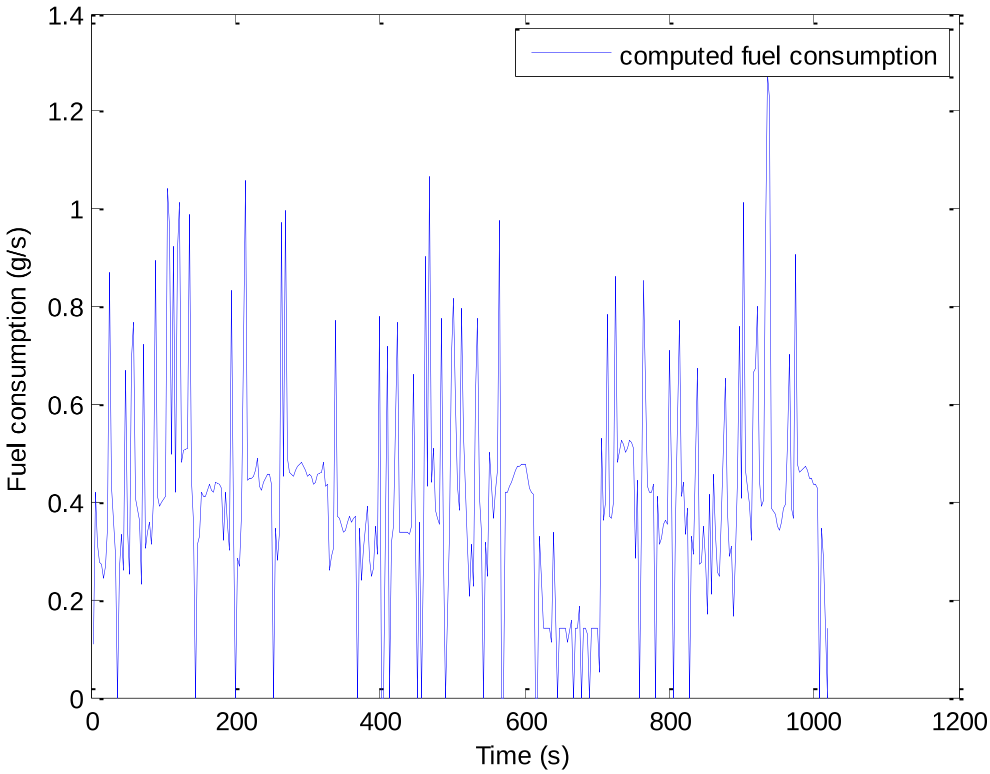


Figure 6.16 - Fuel consumption against time for extra urban driving

An examination of the plot provided above also reveals that there are regions where the vehicle experiences constant speed. These regions are depicted by near straight plot features with some instantaneous increases and decreases in fuel consumption. This would tend to indicate that vehicle fuel consumption is an instantaneous affair since the plot does not offer completely flat lines during the constant speed phases.

Finally, the plot reveals areas where the vehicle was idling. In comparison to other variables tabulated for the purposes of this study, fuel consumption does not approach zero comparable to vehicle velocity or acceleration since fuel consumption remains in place, even during idling.

Table 6.1 - Summary of salient characteristics for extra urban real life driving

Calculated consumption:	0.4051	g/s
Total time:	1017.574	S
Total distance:	8.931605	Km
Total consumption (mass):	412.2192	g
Fuel density:	860	kg/m^3 (g/l)
Total consumption (volume):	0.479325	L
Consumption:	5.366613	l/100 km

Based on the plot provided above and the resulting findings, the average fuel consumption for the extra urban testing regime was 0.4051 g/s that in turn has led to a fuel consumption of approximately 5.34 l/100 km (alternatively 18.63 km/l). Arguably, this fuel consumption figure represents a high value when compared to similar real life driving conditions.

On the other hand, using the plot provided below for urban driving in real life conditions, it becomes clear that fuel consumption can again be divided into the same four phases as above. The urban driving cycle represents sharper peaks in fuel consumption indicating far sharper acceleration regimes, such as after pulling out from a traffic light. In a similar manner, there are a lot of idling patches available, indicated by low fuel consumption that are complemented by some constant speed patches where the fuel consumption shows greater stability than that achieved in the extra urban driving regime.

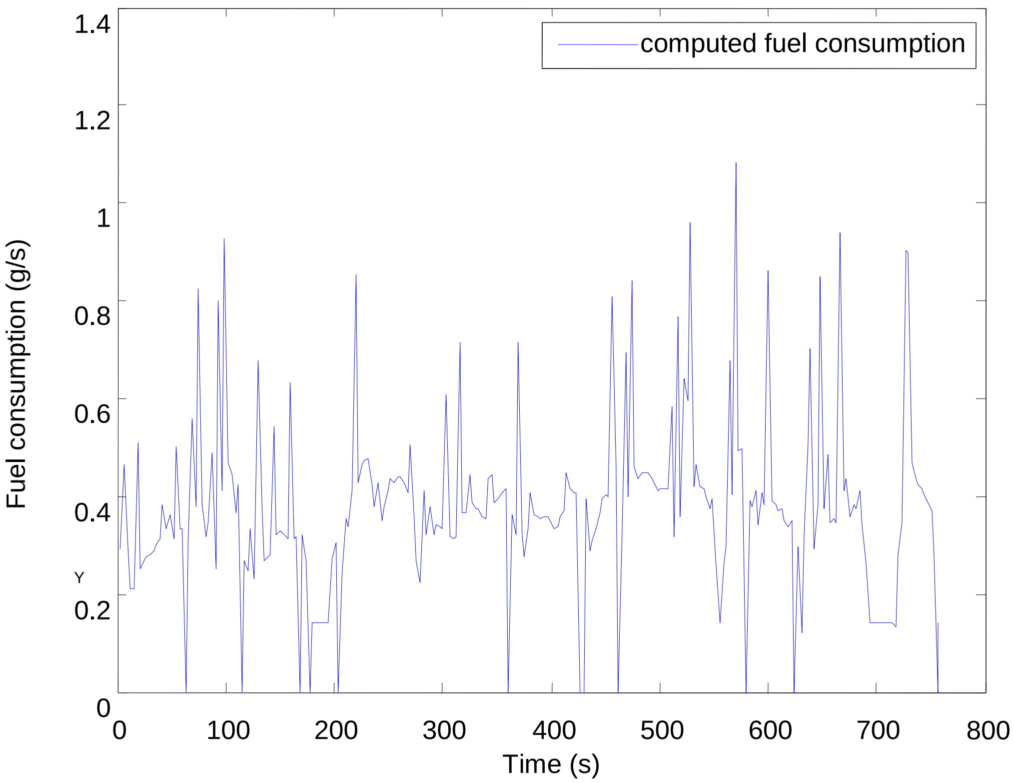


Figure 6.17 – Fuel consumption against time for urban driving

Table 6.2 - Summary of salient characteristics for urban real life driving

Calculated consumption:	0.3775	g/s
Total time:	756.678	S
Total distance:	6.323837	Km
Total consumption (mass):	285.6459	g
Fuel density:	860	kg/m^3 (g/l)
Total consumption (volume):	0.332146	L
Consumption:	5.252293	l/100 km

6.4. Summary

Based on the results and analysis, it was found and believed that the best and ideal option for the standard drive cycle would be the NEDC standard driving cycle providing both urban and extra urban driving features. In terms of the objectives; it was also found that empirical correlation was reliable for all of the four phases of the NEDC standard driving cycle in large part. Sensitivity analysis allowed an examination of how various factors contributed to the final output of the proposed empirical correlation. Overall, the entire NEDC standard driving cycle tests proved to be effective in terms of achieving the proposed objectives of the research.

CHAPTER-7: CONCLUSION AND RECOMENDATIONS

7. Introduction

This chapter will serve as the concluding section ending with recommendations for future research into fuel consumption and various drive-cycle parameters. The work done in the previous chapters will be consolidated in this chapter to provide a conclusion of the current research. The various limitations of the current research will be explored to suggest avenues for further research into this area of interest.

7.1. An Overview

Fuel consumption plays a significant part in environmental degradation and the consumption of non-renewable resources. A number of different driving cycles are available globally. There are no standardised criteria available to work out fuel consumption from the various driving cycles. Differing testing needs and the sizable variety of engines makes standardised testing difficult. The current study examined the fuel consumption of passenger vehicles by both laboratory testing and real life driving in order to arrive at an empirical correlation that could be applied across the board to various driving cycles. Utilising theoretical and experimental methods, a uniform empirical correlation was arrived at that could be applied to small parts of the overall drive cycle to predict fuel consumption without any need for physical testing.

7.2. Summary and Conclusions

7.2.1. Summary

The current research was able to meet its objectives in a large part. Laboratory and real life driving provided significant findings on the fuel consumption of passenger vehicles. An empirical correlation was developed based on the NEDC standard driving cycle that was validated for most testing regimes in the driving cycle. However, the current empirical correlation has certain limitations in the NEDC standard driving cycle and is also limited for other standard driving cycles.

Laboratory testing of engines through a generator type dynamometer revealed that it was not possible to create a valid empirical correlation since air drag and road loads were not being considered. It was concluded that real life driving tests had to be performed under a standard drive cycle to increase the validity of the empirical correlation being proposed. Testing performed on a standard mass-produced passenger vehicle provided data for analysis through the online on board diagnostics system. Mathematical equations were fitted to the data using least squares fitting method. A number of other methods could have been tried but it was concluded that linear modelling was not reliable for all instances and higher order polynomial modelling produced an overly complex empirical correlation.

7.2.2. Conclusion

1. An examination of various standard drive cycle revealed that the best option for a standard drive cycle would be the NEDC standard driving cycle since it provided both urban and extra urban driving features that were simpler to model and produced more reliable data streams. The standard NEDC standard driving cycle was broken up into four distinct phases for analysis that consisted of constant speed, acceleration, deceleration and gear change regimes. The empirical correlation developed in the previous chapters was then applied in presumed situations in order to test its reliability. In order to enhance the credibility of the empirical correlationing, real life testing was carried out that was matched with results from the application of the empirical correlation alone.

2. Results showed that the empirical correlation was reliable for all of the four phases of the NEDC standard driving cycle in large part. Sensitivity analysis allowed an examination of how various factors contributed to the final output of the proposed empirical correlation. The error between real life driving conditions and results obtained from the empirical correlation were in the range of 5% which represents a large measure of reliability and validity on the part of the empirical correlation.

3. The testing, logging and analysis of data from real life driving cycle was based on the NEDC standard driving cycle. Testing results show that it is not possible to achieve the NEDC standard driving cycle in full but it can be replicated in part such that a measure of reliability can be assured. The small measure of time provided for the various sub-cycles of the NEDC standard driving cycle cannot be replicated entirely in real life driving such as repeated acceleration and deceleration sub cycles in urban driving phases. However, it was felt that it was still possible to replicate the NEDC standard driving cycle to a large measure of reliability as long as the testing regime did not deviate significantly from the actually proposed ideal NEDC standard driving cycle.

4. On another note, it was also felt that results of real life driving would tend to vary between various tests due to the fact that human input was not accounted for in the standard NEDC standard driving cycle. The proposed NEDC standard driving cycle relies on sharp features during the acceleration and deceleration phases that would tend to produce varying results between various drivers performing the testing. It might also be possible that future testing may produce large differences between the various sub-cycles of the urban driving phase.

7.3. Suggestions for Future Work

The empirical correlation was tested against real life driving data based on the NEDC standard driving cycle. Data was fitted from real life driving conditions on the empirical correlation. Results from data fitting provided that the empirical correlation was fit for certain regimes of the NEDC standard driving cycle. The use of small differentials for the NEDC standard driving cycle under the empirical correlation provided better data fit results. It can be inferred that using smaller differentials for the driving cycle provided more accurate results. The empirical correlation derived in the current research has not been tested for other driving cycles. Further research is required to validate the current empirical correlation for other standard driving cycles such as the CAFE, JC 08 and other allied driving cycles. The future work proposals are outlined below:

5. On the basis of various observations and tested data that were used to create the proposed empirical correlation, it could be seen that there is further need to investigate certain regimes where the proposed empirical correlation does not hold high validity. The proposed empirical correlation does not hold true for regimes where the vehicle velocity is high, since it produces an exponential increase in the engine load that demands a greater power input. It is recommended that more research is required for regimes where the vehicle velocity is high.

6. For the case of high vehicle velocities, the measured data and computed data are far apart but there is a tendency for both data sets to follow each other. This implies that the constants used in the empirical correlations above would require revision based on more testing and validation through real life driving tests. It

may also be the case that the empirical correlations listed above would require revision so as to derive differing empirical correlations in differing operating regimes.

7. There is also a need for further research into deceleration and gear change phases of any kinds of driving cycles. This is expected to provide greater reliability and validity to the existing empirical correlation; thus, making it more robust for the purposes of all kinds of driving cycles.

8. On another note, the relationship between various operating parameters and fuel consumption for the empirical correlation could be derived by considering an additional drive-cycle parameter, the gradient of the slope. It is felt that certain inconsistencies between real life testing data and results from the empirical correlation may arrive on account of the regression model being used. It is recommended that testing regimes where the empirical correlation does not hold high validity should be researched using regression considering the gradient.

9. The application of the gradient for deriving relationships between the operating parameters and fuel consumption for the empirical correlation are expected to yield better results. Alternatively, it is recommended that regimes where the empirical correlation holds greater validity should be derived using ordinary least squares methods while regimes where the empirical correlation does not hold great validity should be derived using the gradient based methods.

10. In addition to the above, this research highlights the serious shortcomings of a number of standard driving cycles. The NEDC standard driving cycle was seen as the best option in the available driving cycles but the need for an internationally standardised drive cycle remains. Further research is required to

develop standard driving cycles based on the NEDC standard driving cycle and the driving cycle proposed by the United Nations. An internationally standardised drive cycle would ensure that a simpler empirical correlation could be developed and used. Moreover, this would also ensure that a uniform fuel consumption testing system would be available worldwide for testing passenger vehicles.

11. It is recommended that research should be pursued for the development of a standard driving cycle using the empirical correlation for various sub cycles and phases as done in the current research. The current research is limited to passenger vehicles in general and to a specific model of passenger vehicle in particular. It is recommended that future research into fuel consumption and operating parameters should be carried out on a wider scale involving more different kinds of passenger vehicles. Factors such as air drag and road load (depending on tyre contact patch) are shown to have a great effect on the constants derived for the empirical correlation. Based on this observation, it is recommended that more kinds of passenger vehicle testing should be carried out since different vehicles would possess differing frontal areas and tyre contact patches which would lead to limited application of the currently derived empirical correlation.

12. In a similar manner, only passenger vehicle testing was carried out. The current method of investigation could be expanded further to look into the fuel consumption behaviour of commercial vehicles such as buses and trucks to derive empirical correlations for their fuel consumption. The current research has provided beyond doubt that empirical correlationing could be utilised to

investigate fuel consumption and operating parameters so that the same testing methods could be expanded further to test commercial vehicles too.

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Appendix 'A' – Euro V and Euro VI emission limits

Euro 5 emission limits

		Reference mass (RM) (kg)	Limit values													
			Mass of carbon monoxide (CO)		Mass of total hydrocarbons (THC)		Mass of non-methane hydrocarbons (NMHC)		Mass of oxides of nitrogen (NO_x)		Combined mass of total hydrocarbons and oxides of nitrogen ($THC + NO_x$)		Mass of particulate matter (PM)		Number of particles (1) (P)	
			L_1 (mg/km)		L_2 (mg/km)		L_3 (mg/km)		L_4 (mg/km)		$L_2 + L_4$ (mg/km)		L_5 (mg/km)		L_6 (#/km)	
Category	Class		PI	CI	PI	CI	PI	CI	PI	CI	PI	CI	PI (2)	CI	PI	CI
M	—	All	1 000	500	100	—	68	—	60	180	—	230	5,0	5,0		
N_1	I	RM ≤ 1 305	1 000	500	100	—	68	—	60	180	—	230	5,0	5,0		
	II	1 305 < RM ≤ 1 760	1 810	630	130	—	90	—	75	235	—	295	5,0	5,0		
	III	1 760 < RM	2 270	740	160	—	108	—	82	280	—	350	5,0	5,0		
N_2			2 270	740	160	—	108	—	82	280	—	350	5,0	5,0		

Key: PI = Positive ignition, CI = Compression ignition
(1) A number standard is to be defined as soon as possible and at the latest upon entry into force of Euro 6.
(2) Positive ignition particulate mass standards apply only to vehicles with direct injection engines.

Euro 6 emission limits

		Reference mass (RM) (kg)	Limit values													
			Mass of carbon monoxide (CO)		Mass of total hydrocarbons (THC)		Mass of non-methane hydrocarbons (NMHC)		Mass of oxides of nitrogen (NO_x)		Combined mass of total hydrocarbons and oxides of nitrogen ($THC + NO_x$)		Mass of particulate matter (PM)		Number of particles (1) (P)	
			L_1 (mg/km)		L_2 (mg/km)		L_3 (mg/km)		L_4 (mg/km)		$L_2 + L_4$ (mg/km)		L_5 (mg/km)		L_6 (#/km)	
Category	Class		PI	CI	PI	CI	PI	CI	PI	CI	PI	CI	PI (2)	CI	PI	CI
M	—	All	1 000	500	100	—	68	—	60	80	—	170	5,0	5,0		
N_1	I	RM ≤ 1 305	1 000	500	100	—	68	—	60	80	—	170	5,0	5,0		
	II	1 305 < RM ≤ 1 760	1 810	630	130	—	90	—	75	105	—	195	5,0	5,0		
	III	1 760 < RM	2 270	740	160	—	108	—	82	125	—	215	5,0	5,0		
N_2			2 270	740	160	—	108	—	82	125	—	215	5,0	5,0		

Key: PI = Positive ignition, CI = Compression ignition
(1) A number standard is to be defined for this stage.
(2) Positive ignition particulate mass standards apply only to vehicles with direct injection engines.

Appendix‘B’ – Analysis of two real drive cycles

os cel	Neg Accel	All Cruise	L Cr
2067	0.2028	0.2798	0
3923	0.3333	0.2252	0
3783	0.3175	0.2368	0

Appendix ‘C’ –Fuel Consumption MATLAB Code

```
% Relationship for predicting consumption in different drive-cycle phases

clear;

% Input
% Measured data
load measdata.dat
tint = measdata(:,1);   % Time interval (s)
vel = measdata(:,2);    % Vehicle speed (km/h)
acc = measdata(:,3);    % Acceleration (km/h/s)
gr = measdata(:,4);     % Gradient (%)
thr = measdata(:,5);    % Throttle position (%)
cons = measdata(:,6);   % Consumption (g/s)
st = measdata(:,7);     % Stage (1: const speed, 2: acceleration,
                  % 3: decel/grad with throttle;
                  % 4: decel/grad without throttle in gear;
                  % 5: gear change)
n = size(measdata,1);
n1 = 0;
n2 = 0;
n3 = 0;
n4 = 0;
n5 = 0;
fori = 1:n
```

```
ifst(i) == 1
        n1 = n1+1;
t1(n1) = tint(i);
vel1(n1) = vel(i);
cons1(n1) = cons(i);
end
ifst(i) == 2
        n2 = n2+1;
t2(n2) = tint(i);
vel2(n2) = vel(i);
acc2(n2) = acc(i);
cons2(n2) = cons(i);
end
ifst(i) == 3
        n3 = n3+1;
t3(n3) = tint(i);
vel3(n3) = vel(i);
thr3(n3) = thr(i);
cons3(n3) = cons(i);
end
ifst(i) == 4
        n4 = n4+1;
t4(n4) = tint(i);
end
ifst(i) == 5
```

```
    n5 = n5+1;
t5(n5) = tint(i);
vel5(n5) = vel(i);
cons5(n5) = cons(i);
end
end
% Reference values (in same units as measured data)
v0 = 112;            % Max speed limit
a0 = 9.81*3.6;         % Gravitational acceleration
G0 = 100;             % Max gradient
th0 = 100;            % Max throttle position
c0 = 0.46;            % Average consumption (nominal)
% Minimum value for acceleration/speed^2
%   (in order to avoid infinite consumption for 0 acceleration)
accvelmin = 1e-5;

% Determine elements of coefficient matrix (A), consumption vector (b) and
%   calculate constants in relationship (x)
% 1: constant speed
v1 = 0;
v2 = 0;
v3 = 0;
v4 = 0;
c1 = 0;
v1c1 = 0;
```

```
v2c1 = 0;
for i1 = 1:n1
    v1 = v1 + vel1(i1);
    v2 = v2 + vel1(i1)^2;
    v3 = v3 + vel1(i1)^3;
    v4 = v4 + vel1(i1)^4;
    c1 = c1 + cons1(i1);
    v1c1 = v1c1 + vel1(i1)*cons1(i1);
    v2c1 = v2c1 + vel1(i1)^2*cons1(i1);
end
A1 = [n1 v1/v0 v2/v0^2; ...
v1/v0 v2/v0^2 v3/v0^3; ...
v2/v0^2 v3/v0^3 v4/v0^4];
b1 = [c1/c0; v1c1/(v0*c0); v2c1/(v0^2*c0)];
x1 = A1\b1;
% 2: acceleration
av1 = 0;
av2 = 0;
c1 = 0;
av1c1 = 0;
for i2 = 1:n2
    av1 = av1 + log(a0*v0^2/(acc2(i2)*vel2(i2)^2));
    av2 = av2 + (log(a0*v0^2/(acc2(i2)*vel2(i2)^2)))^2;
    c1 = c1 + log(cons2(i2)/c0);
    av1c1 = av1c1 + log(a0*v0^2/(acc2(i2)*vel2(i2)^2))*log(cons2(i2)/c0);
```

```
end
A2 = [n2 av1; ...
    av1 av2];
b2 = [c1; av1c1];
x2t = A2\b2;
x2 = [exp(x2t(1)); x2t(2)];
% 3: deceleration/gradient with throttle
vth1 = 0;
vth2 = 0;
c1 = 0;
vthc1 = 0;
for i3 = 1:n3
    vth1 = vth1 + vel3(i3)*thr3(i3);
    vth2 = vth2 + (vel3(i3)*thr3(i3))^2;
    c1 = c1 + cons3(i3);
    vthc1 = vthc1 + vel3(i3)*thr3(i3)*cons3(i3);
end
A3 = [n3 vth1/(v0*th0); ...
    vth1/(v0*th0) vth2/(v0*th0)^2];
b3 = [c1/c0; vthc1/(v0*th0*c0)];
x3 = A3\b3;
% 5: gear change
v1 = 0;
v2 = 0;
%v3 = 0;
```

```
%v4 = 0;
c1 = 0;
v1c1 = 0;
%v2c1 = 0;
for i5 = 1:n5
   v1 = v1 + vel5(i5);
   v2 = v2 + vel5(i5)^2;
%    v3 = v3 + vel5(i5)^3;
%    v4 = v4 + vel5(i5)^4;
   c1 = c1 + cons5(i5);
   v1c1 = v1c1 + vel5(i5)*cons5(i5);
%    v2c1 = v2c1 + vel5(i5)^2*cons5(i5);
end
A5 = [n5 v1/v0; ...
v1/v0 v2/v0^2];
b5 = [c1/c0; v1c1/(v0*c0)];
x5 = A5\b5;

% Compare consumption measured and calculated by the obtained formula
% 1: constant speed
for i1 = 1:n1
concal1(i1) = c0*(x1(1) + x1(2)*vel1(i1)/v0 + x1(3)*(vel1(i1)/v0)^2);
err1(i1) = (concal1(i1)-cons1(i1))/cons1(i1);
end
[cons1' concal1' err1'];
```

```
v1min = min(vel1);

v1max = max(vel1);

v1st = (v1max-v1min)/100;

for j1 = 1:100

vcal1(j1) = v1min + (j1-1)*v1st;

ccal1(j1) = c0*(x1(1) + x1(2)*vcal1(j1)/v0 + x1(3)*(vcal1(j1)/v0)^2);

end

figure(1)

plot(vel1,cons1,'*',vcal1,ccal1)

title('Constant speed')

xlabel('Vehicle speed (km/h)')

ylabel('Fuel consumption (g/s)')

legend('Location','NorthWest','measured','computed')

% 2: acceleration

for i2 = 1:n2

accvel2(i2) = 1/(acc2(i2)*vel2(i2)^2);

if accvel2(i2) <accvelmin

accvel2(i2) = accvelmin;

end

concal2(i2) = c0*x2(1)*(a0*v0^2/(acc2(i2)*vel2(i2)^2))^x2(2);

err2(i2) = (concal2(i2)-cons2(i2))/cons2(i2);

end

[cons2' concal2' err2'];

av2min = min(accvel2);

av2max = max(accvel2);
```

```
av2st = (av2max-av2min)/100;
for j2 = 1:100
avcal2(j2) = av2min + (j2-1)*av2st;
if avcal2(j2) <accvelmin
avcal2(j2) = accvelmin;
end
ccal2(j2) = c0*x2(1)*(avcal2(j2)*a0*v0^2)^x2(2);
end
figure(2)
plot(accvel2,cons2,'*',avcal2,ccal2)
title('Acceleration')
xlabel('1/(Acceleration*Vehicle speed^2) (1/((km/h)^3*s))')
ylabel('Fuel consumption (g/s)')
legend('measured','computed')
% 3: deceleration/gradient with throttle
for i3 = 1:n3
velth3(i3) = vel3(i3)*thr3(i3);
concal3(i3) = c0*(x3(1) + x3(2)*vel3(i3)*thr3(i3)/(v0*th0));
err3(i3) = (concal3(i3)-cons3(i3))/cons3(i3);
end
[cons3' concal3' err3'];
vth3min = min(velth3);
vth3max = max(velth3);
vth3st = (vth3max-vth3min)/100;
for j3 = 1:100
```

```
vthcal3(j3) = vth3min + (j3-1)*vth3st;
ccal3(j3) = c0*(x3(1) + x3(2)*vthcal3(j3)/(v0*th0));
end
figure(3)
plot(velth3,cons3,'*',vthcal3,ccal3)
title('Deceleration/gradient with throttle')
xlabel('Throttle position*speed (%*(km/h))')
ylabel('Fuel consumption (g/s)')
legend('Location','NorthWest','measured','computed')
% 5: gear change
for i5 = 1:n5
concal5(i5) = c0*(x5(1) + x5(2)*vel5(i5)/v0);
err5(i5) = (concal5(i5)-cons5(i5))/cons5(i5);
end
[cons5' concal5' err5'];
v5min = min(vel5);
v5max = max(vel5);
v5st = (v5max-v5min)/100;
for j5 = 1:100
vcal5(j5) = v5min + (j5-1)*v5st;
ccal5(j5) = c0*(x5(1) + x5(2)*vcal5(j5)/v0);
end
figure(5)
plot(vel5,cons5,'*',vcal5,ccal5)
title('Gear change')
```

```
xlabel('Vehicle speed (km/h)')
ylabel('Fuel consumption (g/s)')
legend('Location','NorthWest','measured','computed')

% Average consumption through drive cycle
tsum = 0;
const = 0;
for i1 = 1:n1
tsum = tsum + t1(i1);
const = const + concal1(i1)*t1(i1);
end
for i2 = 1:n2
tsum = tsum + t2(i2);
const = const + concal2(i2)*t2(i2);
end
for i3 = 1:n3
tsum = tsum + t3(i3);
const = const + concal3(i3)*t3(i3);
end
for i4 = 1:n4
tsum = tsum + t4(i4);
const = const + 0;
end
for i5 = 1:n5
tsum = tsum + t5(i5);
```

```
const = const + concal5(i5)*t5(i5);

end

consmean = const/tsum
```

Appendix 'D' – Sensitivity Study MATLAB Code

```
% Sensitivity study: create input files with variation of up to a given
%   noise (nmax) as percentage in input data


clear;


% Input
% Max noise assumed in %
nmax = 5;
cvalid = 1;          % If validation will be done (comparison with
                     % measured consumption), then cvalid = 1 (measured
                     % consumption must be provided in input file
                     % 'dcycle.txt' in this case).
% Measured data
load dcycle.txt
tint = dcycle(:,1);   % Time interval (s)
vel = dcycle(:,2);    % Vehicle speed (km/h)
acc = dcycle(:,3);    % Acceleration (km/h/s)
gr = dcycle(:,4);     % Gradient (%)
thr = dcycle(:,5);    % Throttle position (%)
gear = dcycle(:,6);   % Gear
ifcvalid == 1        % Consumption (g/s)
consm = dcycle(:,7);
end
```

```
% Data with noise (no noise on time and gear)
ndata = size(dcycle,1);
nois = (rand(1,4*ndata)*2-1)*nmax/100;
fori = 1:ndata
   % Velocity (max noise is 2 km/h)
ifvel(i) < 40
vel1(i) = vel(i)*(1+nois(i));
else
vel1(i) = vel(i)+40*nois(i);
end
   % Acceleration
acc1(i) = acc(i)*(1+nois(ndata+i));
   % Gradient
gr1(i) = gr(i)*(1+nois(2*ndata+i));
   % Throttle position
thr1(i) = thr(i)*(1+nois(3*ndata+i));
end
ifcvalid == 1
   dcycle1 = [tint vel1' acc1' gr1' thr1' gear consm];
else
   dcycle1 = [tint vel1' acc1' gr1' thr1' gear];
end


% Output file with noisy data
save dcycle1.txt dcycle1 –ascii
```

Appendix 'E' – Prediction of Fuel Consumption in Drive Cycles

% Prediction of consumption in drive cycles (from input file 'dcycle.txt')

v (kph)	v (m/sec)	Throttle	Braking	Gear	Engine Speed (rpm)	Torque (N-m)	n_a	n_g	r_w (m)	m (kg)	θ (°)	R_c	R_r	Drag (N)	TE	a (m/sec^2)	a-braking (m/sec2)	a_{avg} (m/sec
100.00	27.8	20%		5	3100	67.4	4.214	0.821	0.296	1040	5.71	0.0120	121	317.8	787.8	0.29	-1.19	-1.12
85.00	23.6	20%		5	2635	74.1	4.214	0.821	0.296	1040	5.71	0.0120	121	229.6	866.1	0.43	-1.05	
85.00	23.6	0%		5						1040	5.71	0.0120	121	229.6	0.0	-0.29	-1.77	
76.70	21.3			4														
76.70	21.3	20%		4	2980	68.4	4.214	1.029	0.296	1040	5.71	0.0120	121	186.9	1002.0	0.58	-0.90	-0.82
63.00	17.5	20%		4	2448	77.6	4.214	1.029	0.296	1040	5.71	0.0120	121	126.1	1136.8	0.74	-0.74	
63.00	17.5	0%		4						1040	5.71	0.0120	121	126.1	0.0	-0.21	-1.69	
55.11	15.3		10% grad.	3														
55.11	15.3	20%		3	2899	69.5	4.214	1.393	0.296	1040	5.71	0.0120	121	96.5	1378.3	0.97	-0.51	-0.39
43.00	11.9	20%		3	2262	82.2	4.214	1.393	0.296	1040	5.71	0.0120	121	58.8	1630.1	1.21	-0.27	
43.00	11.9	0%		3						1040	5.71	0.0120	121	58.8	0.0	-0.15	-1.63	
35.37	9.8			2														
35.37	9.8	20%		2	2735	72.1	4.214	2.048	0.296	1040	5.71	0.0120	121	39.8	2102.2	1.62	0.14	0.38
23.00	6.4	20%		2	1779	90.9	4.214	2.048	0.296	1040	5.71	0.0120	121	16.8	2650.3	2.10	0.62	
23.00	6.4	0%		2						1040	5.71	0.0120	121	16.8	0.0	-0.12	-1.60	
15.53	4.3			1														

v (kph)	v (m/sec)	Throttle	Braking	Gear	a (m/sec^2)	t (sec)
100 85	27.8 23.6	0%	20% grad.	5 5	-1.61	2.6
85 77.656	23.6 21.6	0%	20% grad.	5 4	-1.70	1.2
77.656 63	21.6 17.5	0%	20% grad.	4 4	-1.61	2.5
63 55.656	17.5 15.5	0%	20% grad.	4 3	-1.70	1.2
55.656 43	15.5 11.9	0%	20% grad.	3 3	-1.61	2.2
43 35.656	11.9 9.9	0%	20% grad.	3 2	-1.70	1.2
35.656 23	9.9 6.4	0%	20% grad.	2 2	-1.61	2.2
23 15.656	6.4 4.3	0%	20% grad.	3 2	-1.70	1.2
15.656 10	4.3 2.8	0%	20% grad.	1 1	-1.61	1.0

v (kph)	v (m/sec)	Throttle	Braking	Gear	a (m/sec^2)	t (sec)
100 85	27.8 23.6	0%	0% grad.	5 5	-0.31	13.7
85 77.656	23.6 21.6	0%	0% grad.	5 4	-1.70	1.2
77.656 63	21.6 17.5	0%	0% grad.	4 4	-0.31	13.3
63 55.656	17.5 15.5	0%	0% grad.	4 3	-1.70	1.2
55.656 43	15.5 11.9	0%	0% grad.	3 3	-0.31	11.5
43 35.656	11.9 9.9	0%	0% grad.	3 2	-1.70	1.2
35.656 23	9.9 6.4	0%	0% grad.	2 2	-0.31	11.5
23 15.656	6.4 4.3	0%	0% grad.	3 2	-1.70	1.2
15.656 10	4.3 2.8	0%	0% grad.	1 1	-0.31	5.2

```
% Prediction of consumption in drive cycles (from input file 'dcycle.txt')

Clear;

% Input

cvalid = 0;      % If validation will be done (comparison with
                 % measured consumption), then cvalid = 1 (measured
                 % consumption must be provided in input file
                 % 'dcycle.txt' in this case).


% Measured data

Load dcycle.txt

Tint = dcycle(:,1);   % Time interval (s)

vel = dcycle(:,2);    % Vehicle speed (km/h)

acc = dcycle(:,3);    % Acceleration (km/h/s)

gr = dcycle(:,4);     % Gradient (%)

thr = dcycle(:,5);    % Throttle position (%)

gear = dcycle(:,6);   % Gear


% Reference values and constants in relationship

v0 = 112;             % Max speed limit

a0 = 9.81*3.6;        % Gravitational acceleration

G0 = 100;             % Max gradient
```

```
th0 = 100;            % Max throttle position

c0 = 0.46;            % Average consumption (nominal)

k10 = 0.3063;

k11 = 0.6532;

k12 = 2.3913;

k21 = 10.1739;

k22 = -0.3295;

k30 = 0.4675;

k31 = 14.3461;

k40 = 0.4503;

k41 = 1.4494;


% Calculation of consumption in different phases

dt = 3;               % Max time (s) in one phase

ndata = size(dcycle,1);

nmax = ceil(tint(ndata)/dt);

dvmax = 2;            % Max variation in speed in constant speed phases

th0max = 2;           % Max throttle position accepted as no throttle

v = zeros(nmax,1);

a = zeros(nmax,1);

G = zeros(nmax,1);
```

```
th = zeros(nmax,1);

ge = zeros(nmax,1);

c = zeros(nmax,1);

jmin = 1;

j = 1;

for i = 1:nmax

if i < nmax

while tint(j) < i*dt

j = j+1;

end

else

 while tint(j) < tint(ndata)

  j = j+1;

end

end

t(i) = tint(j) - tint(jmin);

tcum(i) = tint(j) - tint(1);

for k = jmin:j

v(i) = v(i) + vel(k)/(j-jmin+1);

end

%    [jmin j]
```

```
    % Gear change
    if gear(jmin) ~= gear(j)
 if gear(jmin) ~= 0
if gear(j) ~= 0
c(i) = c0*(k40+k41*v(i)/v0);
jmin = j;
continue
 end
 end
    end
    % Constant speed
    kv = 0;
    for k = jmin:j
if abs(vel(k)-v(i)) > dvmax
kv = kv + 1;
end
    end
    if kv == 0
        c(i) = c0*(k10 + k11*v(i)/v0 + k12*(v(i)/v0)^2);
        jmin = j;
        continue
```

```
    end
    % Acceleration
    for k = jmin:j
        a(i) = a(i) + acc(k)/(j-jmin+1);
        ge(i) = ge(i) + gear(k)/(j-jmin+1);
        th(i) = th(i) + thr(k)/(j-jmin+1);
end
if a(i) > 0
        c(i) = c0*k21*(a0*v0^2/(a(i)*v(i)^2))^k22;
        jmin = j;
 elseif ge(i) == 0
        c(i) = c0*(k10 + k11*v(i)/v0 + k12*(v(i)/v0)^2);
jmin = j;
 elseif th(i) < th0max
        c(i) = 0;
        jmin = j;
 else
        c(i) = c0*(k30 + k31*v(i)*th(i)/(v0*th0));
        jmin=j;
 end
end
```

```
% Total consumption in the whole cycle
ct = 0;
for i=1:nmax
    ct = ct + c(i)*t(i);
end
ctotal = ct/sum(t)

% Plot consumption in time (and compare with measured consumption)
if cvalid == 1
    consm = dcycle(:,7);
    plot(tint-tint(1),consm,tcum,c)
    legend('Location','NorthWest','measured','computed')
else
    plot(tcum,c)
    legend('computed fuel consumption')
end
xlabel('Time (s)')
ylabel('Fuel consumption (g/s)')
```