DRIVEABILITY EVALUATION FOR ENGINE MANAGEMENT CALIBRATION

by

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DECLARATION

I, the undersigned, declare that the work contained in this thesis is my own original work and has not previously, in its entirety or in part, been submitted at any university for a degree.

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Date

ABSTRACT

Vehicles are expected to deliver adequate power for the engine size and vehicle class. They must also deliver good response to the driver's desired action as well as deliver the lowest possible fuel consumption in all possible conditions and comply with emissions regulations. The combination of these factors is termed good driveability.

Evaluating driveability is time and cost intensive and is most commonly evaluated from a subjective driver prospective. Advanced control systems allow for more accurate control of the vehicles response to the drivers demands.

The objective of this document was to develop a quantitative driveability evaluation model for engine management calibration. The important aspects of engine management control for driveability, as well as how they are manipulated to deliver acceptable driveability were identified. Test procedures were developed to measure and quantify all these important factors. The test procedures can be evaluated for their different sections or for a complete driveability evaluation method.

An optimised driveability evaluation method was developed to reduce the driveability evaluation time. Verification of the driveability evaluation model did provide different results for a different engine management calibration.

SAMEVATTING

Voertuie moet bestuurbaar wees oor ‘n wye spektrum van operasionele kondisies terwyl dit hoë werkverigting, lae brandstof verbuik en lae hoeveelhede van omgewings onvriendelike uitlaatgasse produseer. Hierdie verwagte werkverigting word voertuig bestuurbaarheid genoem.

Voertuig bestuurbaarheid ontleding is baie tyd en koste intensief en word meestal uit ‘n subjektiewe bestuurdersoogpunt ontleed. Gevorderde beheerstelsels verskaf beter beheer van die voertuig se reaksies tot die bestuurder se behoeftes.

Die doel van hierdie dokument is om ‘n meetbare voertuig bestuurbaarheid evalueringsmodel te ontwikkel vir binnebrand motor beheerstelsels. Die belangrikste aspekte vir binnebrand motor beheerstelsels op voertuig bestuurbaarheid word bespreek asook hoe om dit te manipuleer om goeie voertuig bestuurbaarheid te lewer. Toets prosedures was ontwikkel om al die belangrike aspekte te meet en te kwantifiseer. Die toets prosedures van die aspekte kan op hulle eie ontleed word of dit kan gekombineer word om ‘n volledige voertuig bestuurbaarheids ontleding te veskaf.

‘n Geoptimeerde voertuigbestuurbaarheids evaluerings model was ontwikkeld om die voertuig ontledingstydperk te verlaag. Die evaluerings model het verskillende resultate gelewer vir verskillende kalibrasies van ‘n binnebrand motor beheerstelsel.

ACKNOWLEDGEMENTS

First of all I would like to thank my creator for allowing me to share His wonderful creations and inventions. Secondly I would like to thank my family, especially my mother and father for all their love and support. Special thank you to all my friends, without you I would have been finished in a much shorter time. I would also like to thank the University of Stellenbosch for providing the opportunity to improve my knowledge and for the many sleepless nights. Last but not the least I would like to thank Volkswagen of South Africa for their time and technical support.

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GLOSSARY

Nomenclature

$\%N_{change}$ - Max Percentage Change of Engine Speed [%RPM]

%OS – Percent overshoot [%OS]

$\%OS_m$ – Measured percent overshoot [$\%OS_m$]

$\%OS_{TCO}$ – Percent overshoot correction factor [$\%OS_{TCO}$]

ABS – Anti-lock Brake System

AE – Acceleration Enrichment

AF – Air Fuel Ratio (Lambda)

CAN – Controller Area Network

CIS - Continuous Injection System

CO – Carbon Monoxide

DAI – Driveability Acceleration Index

DAI_{AE} – Driveability Acceleration Index for Acceleration Enrichment

DAI_{AF} – Driveability Acceleration Index for Air Fuel Ratio

DAI_{FL} – Driveability Acceleration Index for Full Load

DAI_{FL_C} – Driveability Acceleration Index per Full Load Condition

DAI_{G_PV} – Driveability Acceleration Index for Acceleration to Pedal Input Ratio

DAI_{Jerk} – Driveability Acceleration Index for Jerk

DAI_{PL} – Driveability Acceleration Index for Part Load

DAI_{PL_C} – Driveability Acceleration Index per Part Load Condition

$DAI_{TI/MAF}$ – Driveability Acceleration Index for Fuel Air Factor

DAI_{TIP_IN} – Driveability Acceleration Index for Tip In

$DAI_{TIP\_IN\_C}$ – Driveability Acceleration Index per Tip In Condition

DAI_{TIP_OUT} – Driveability Acceleration Index for Tip Out

DBI – Driveability Brake Index

DCI – Driveability Cruise Index

DI – Driveability Index

DII – Driveability Idle Response Index

DII_{BAI} – Driveability Idle Response Index for Brake Response After Braking

DII_{BDI} – Driveability Idle Response Index for Brake Response During Braking

DII_{Brake} – Driveability Idle Response Index for Brake Response

$DII_{dN/dPV}$ – Driveability Idle Response Index for Pedal Response

DII_{LC} – Driveability Idle Response Index for Load Change

DII_{Nsp} – Driveability Idle Response Index for Idle Speed Set Point

DII_{STD} – Driveability Idle Response Index for Standard Deviation

DMU – DRIVE Main Unit

dN/dPV – Pedal Blip Factor [dRPM/dPV]

dN/dPV_{TCO} – Pedal Blip Correction Factor [dN/dPV_{TCO}]

dN/dt – Rate of Change of Engine Speed [dRPM/dt]

dPV/dt – Rate of Change of Pedal Input [dPV/dt]

DSI – Driveability Start Index

$DSI_{\%OS}$ – Driveability start RPM overshoot index

DSI_{st} – Driveability Start Time Index

DTC - Diagnostic Trouble Codes

EBA – Emergency Brake Assist

EBD – Electronic Brake Force Distribution

ECU – Electronic Control Unit

EFI – Electronic Fuel Injection

EGR – Exhaust Gas Recirculation

EMS – Engine Management System

EOBD – European On Board Diagnostics

EPA - Environmental Protection Agency

ESC - Electronic Stability Control

ESP - Electronic Stability Program

EVAP – Evaporative Fuel Control System

FL – Full Load

G_PV – Acceleration to Pedal Input Ratio [$(m/s^2)/PV$]

HC – Hydro Carbons

IC – Internal Combustion

ISC – Idle Speed Control

LC – Load Change Factor

LC_{TCO} – Load Change Temperature Correction Factor

MAP – Manifold Absolute Pressure

MBT – Most Beneficial Timing

MIL – Malfunction Indicator Lamp

N_{idle} – Corrected Idle Speed [RPM]

N_m – Measured Idle Speed [RPM]

N_{TCO} – Temperature Correction Factor for Idle Speed Set Point [RPM]

OBD – On Board Diagnostics

PA – Pull Away

PC – Personal Computer

PL – Part Load

RPM – Revolutions per Minute

RVP - Reid Vapour Pressure

SI – Spark Ignition

STD – Standard Deviation

TCO – Engine Coolant Temperature

TDC – Top Dead Centre

t_i – Total Injection Time [ms]

TI/MAF – Fuel Air Factor [ms/(kg/hr)]

t_m – Correction and Adaptation Injection Time [ms]

t_{Nc} - Time to reach the Max Percentage Change of Engine Speed [s]

t_p – Base Injection Time [ms]

t_{RVP} – Read Vapour Pressure correction factor [ms]

t_s – Start time [s]

t_s – Voltage Correction Injection Time [ms]

t_{sm} – Measured start time [s]

t_{TCO} – Start time temperature correction factor [ms]

WOT – Wide Open Throttle

Symbols

Φ – Fuel-air equivalence ratio

λ - Lambda

1

INTRODUCTION

Cars are expected to be driveable over a wide range of operating conditions while still delivering high performance, low fuel consumption and limited harmful emissions. This expected performance is termed vehicle driveability.

Adequate power is governed by the thermodynamic cycle efficiency. The higher the thermodynamic cycle efficiency, the better the driveability. The vehicle must respond to the driver's demands. If the driver is stuck in traffic and only desires small load changes, the vehicle must respond to small accelerator pedal changes without any jerks. The vehicle must also respond accordingly when the driver wants to accelerate more aggressively, without obvious delays and jerks.

A substantial amount of time is spent in traffic and the engine management must eliminate excess fuel consumption under these conditions. During normal driving and acceleration conditions the engine must also deliver the most power with the lowest possible fuel consumption.

Emission regulations govern the pollutants that are emitted at the exhaust tail pipe. These pollutant concentrations vary among different countries. The vehicle must comply with the emission regulations for the country it is developed for, without sacrificing power and response behaviour.

In short, driveability is a combination of the following factors delivered by a vehicle:

- Adequate power for the engine size and vehicle class
- Good response to the driver's desired action for the vehicle
- The lowest possible fuel consumption under all desired conditions
- Compliance with emission regulations.

Only subjective evaluation of driveability is currently assessed. Experienced drivers evaluate the response of vehicles and combine their results to present areas that require engine management calibration attention. This leads to extended calibration periods where the same drivers have to re-evaluate a vehicle until they are satisfied with the response. This often leads to an undetected reduction in driveability in another area that was not evaluated for improvement because of the interaction between engine management aspects.

A quantitative driveability evaluation system will eliminate the unforeseen reduction in other driveability fields as well as shorten the calibration period. It will also provide the application engineer with objective values on which to improve, and not vague subjective values that can vary between different evaluations.

In order to determine and define the terminology and techniques used to describe driveability a detailed literature review on driveability was conducted. The literature review discusses the current evaluation criteria and methods that are available. A complete literature review of engine management is presented to explain the fundamentals as well as their effects on driveability.

Current production vehicles were evaluated in order to investigate and evaluate their engine management strategy with regards to driveability. All the important factors that contribute to driveability were extracted from the data as well as from the literature. These factors were divided into subsections and evaluated both individually, and in terms of their effects on the overall driveability.

Methods and models were developed from the measured data to accurately evaluate the different aspects of the engine management function on driveability. This allows for more accurate, quantitative, repetitive and comparative calibration.

The methods and models were then improved to optimise the test procedures to the shortest possible testing time. The optimised methods and models were combined to provide a complete driveability evaluation method. This driveability method was evaluated for sample cases, in which factors were changed to evaluate the accuracy of the model.

2 LITERATURE REVIEW

2.1 Introduction

Insufficient information is available on what is meant by driveability and how it is evaluated. The first section in this chapter (2.2) provides an overview of driveability as well as current evaluation systems available for evaluating driveability. The second section (2.3) describes engine management strategies and their effects on driveability. The chapter provides the background for understanding driveability and the theory of the engine management system for driveability calibration.

2.2 Vehicle Driveability

Driveability is the combination of ride quality and performance response of a vehicle. Vehicles are expected to deliver adequate power for the engine size and vehicle class. They must also deliver a good response to the driver's desired action as well as deliver the lowest possible fuel consumption under all possible conditions and comply with emission regulations. The combination of these factors is termed good driveability.

Driveability is a key factor in buying a vehicle, since a customer usually test- drives a few vehicles before buying one. A customer will not be interested in buying a vehicle if the driveability is poor; therefore driveability is a keystone for product quality. The type of vehicle, its primary function, the power train fitted to the vehicle, the technology features/driving aids, and the vehicle's styling and class all influence a customer's expectation of driveability (Dorey, R E and Holmes C B, 1999). The expectations of the customer are further characterised by the desire for individuality, quality of mobility, and practicality (Schöggl et al., 2001b).

Vehicle manufacturers currently evaluate driveability by having experienced test drivers fill out an evaluation form, with subjectively formulated questions. This procedure is subjective, unrepeatable, and time and cost intensive (Dorey, R E and Holmes C B, 1999).

There exists a need for an objective method for evaluating a vehicle's driveability. Objective evaluation of driveability would enable an evaluator to objectively compare vehicles. An objective measurement of driveability can also be used as a development tool for powertrain development and calibration of control systems for vehicles, as well as analysis and quality or tolerance checks.

Engine and powertrain control systems are becoming more complex because of the demands on emissions, fuel consumption, performance and driving comfort. This complexity of the control systems introduces a significant increase in variables in the management systems. The increase in variables leads to an increase in calibration time, which leads to an increase in the powertrain development period.

The focus of this section is to formulate an extensive definition of driveability. This is achieved by listing all the criteria that are important to a vehicle's driveability.

2.2.1 Background

Driveability is a term that evolved after the 1970's energy crisis. There was concern over the availability of fuel and the emissions from vehicles. Today driveability is further governed by emissions standards (List H. and Schöggl P, 1998). Vehicles must be more environmentally friendly, while maintaining their driver responsiveness.

Driveability can also be described as ride quality. The driver (and passengers) must, at least, not be sceptical about their driving experience. The more they enjoy the ride, the better the perceived driveability of the vehicle will be. The response of the vehicle to the driver's commands can be recognised consciously or subconsciously. Conscious criteria include the response that the driver expects from the vehicle, and is subjective to the vehicle class. Good acceleration response is typical in the case of a sporty vehicle whereas comfort is important in a luxury vehicle. If a vehicle misses conscious criteria then the driveability will immediately be perceived as bad. Subconscious criteria are only noticed when they are below standard. Start behaviour and idle quality are examples of subconscious criteria.

Driving style and classification of a vehicle are also important with regards to driveability. A driver will typically buy a vehicle that suits his/her driving style. If a driver races between traffic lights, then such a driver's perception of good driveability will be a vehicle with fast acceleration, without delay, and good road holding capabilities. However, hard suspension and fast acceleration might be uncomfortable for a person who is interested in a smooth and relaxed ride. To obtain more accurate results, different vehicle classes are defined. By combining all the data from literature, the following vehicle classes that populate the non commercial vehicle market were extracted:

- Small/Light passenger vehicles
- Luxury/Executive vehicles
- Multi-purpose vehicles (MPV)
- Sport utility vehicles (SUV)
- Sport vehicles
- Light delivery vehicles (LDV)/Pickups.

Sport vehicles must have minimal delayed reaction for positive or negative change of power demand, good pedal/drive torque correlation, revability, exceptional power for the engine size, torque gradient for part-load acceleration and load change, shape of pedal mapping, etc. (Schöggl et al., 2000). These criteria are given a higher weighting in the evaluation and can assure good assessment.

Most drivers are inexperienced drivers; they have never driven on a racetrack, nor had some sort of advanced driver training. Therefore they will not know what to look for in a vehicle that will suit their driving style. They are only concerned with travelling from one place to another. Two types of drivers can therefore be classified i.e. experienced drivers and inexperienced drivers

Driveability of pre-production vehicles is improved during the calibration of the engine management system and during vehicle and engine testing. A vehicle's driveability is usually poor at the start of development. This implies that calibration engineers have to adjust the engine management strategy for better driveability, for example, to improve the vehicle's cold-starting time and the engine's throttle response, etc. It is important to evaluate each section of driveability (e.g. start behaviour, acceleration behaviour) separately as well as the overall driveability. Improving the driveability in one aspect might lead to a reduction in other aspects, and therefore might lead to a lower driveability score. The driveability score is a value allocated to a vehicle's response to driveability. This allows one vehicle to be compared to another vehicle, as well as reflect an improvement after recalibration of the engine management system. How this driveability score is formulated is explained in Section 2.2.2.

Technology also aids in improved driveability. Modern control systems facilitate better vehicle stability and improved handling. These additional driving aids make a vehicle safer and add to its marketing potential.

The driveability of a vehicle can also deteriorate over time. This deterioration is caused by components that corrode, foul, perish and wear. If a vehicle is not properly maintained then this deterioration might even be catastrophic. In such an extreme condition the vehicle will not be operational.

To understand how the driver interacts with the vehicle, and how this interaction can be measured, certain driveability conditions are now presented and explained.

2.2.2 Driveability classification

A need exists to allow for driveability evaluation under repetitive testing conditions. Subjective factors have to be eliminated to improve the repeatability. Implementing a system with calibrated sensors will result in an objective driveability test procedure.

Driveability evaluation is simplified by a rating or score system. This limits the evaluator to pre-determined ratings and allows for a score to be allocated to the test results. Schöggl et al. (2001a) developed a driveability score index, presented in Table 2.1.

Table 2.1: Driveability index (Schöggl et al., 2001a)

Driveability score	Subjective rating	Description
10	Excellent	Not noticeable even by experienced drivers
9	Very good	Disturbing for experienced test drivers
8	Good	Disturbing for critical customers
7	Satisfactory	Disturbing for several customers
6	Just satisfactory	Disturbing for all customers
5	Adequate	Very disturbing for all customers
4	Poor	Felt to be deficient by all customers
3	Insufficient	Complained as deficient by all customers
2	Bad	Limited vehicle operation only
1	Very bad	Vehicle not operating

An important aspect to take into consideration is the level of expertise of the driver. A calibration expert or test driver will pick up on more driveability criteria than an inexperienced driver (List H. and Schöggl P, 1998). Figure 2.1 shows the differences between driveability evaluators. List H. and Schöggl P, (1998) reported that interviews conducted during driving lead to a higher number of driveability relevant criteria, compared to interviews after driving.

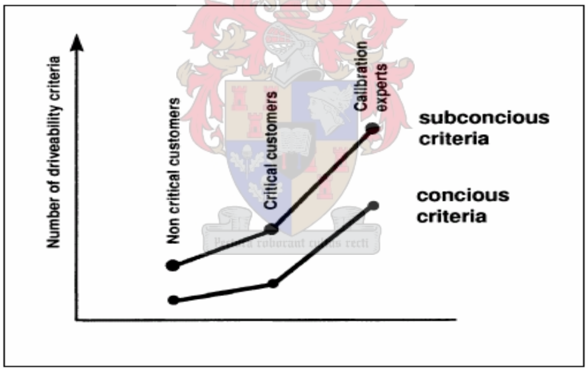
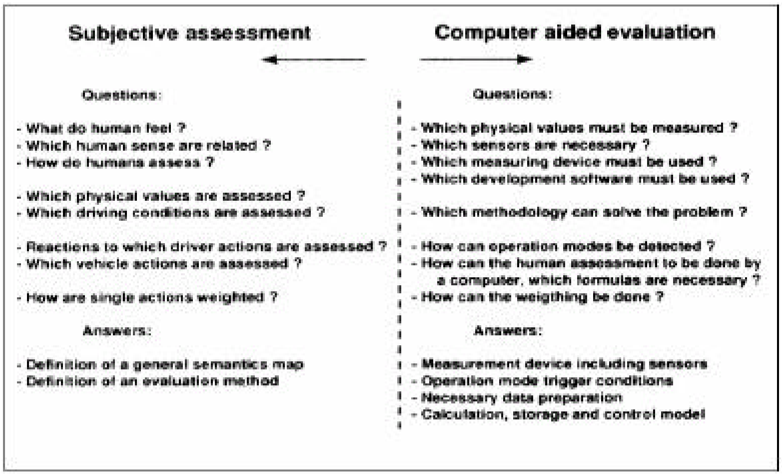


Figure 2.1: Number of named driveability criteria, displaying an increase in driveability criteria with an increase in expertise of the driveability evaluators (List H. and Schöggl P, 1998)

List H. and Schöggl P. (1998) also made a comparison between how the subjective evaluation can be translated to quantitative measurements. This is accomplished by evaluating the human senses and methodology and converting them into a computer aided evaluation. Figure 2.2 shows this correlation.

Exactly what the motor vehicle manufacturers measure for driveability is unknown, since it is proprietary information kept in-house by the industry. Vehicle manufacturers are thought to rely upon the subjective assessment of driveability by experienced drivers (Dorey, R E and Holmes C B, 1999).



Subjective assessment ←

Questions:

- What do human feel ?
- Which human sense are related ?
- How do humans assess ?

- Which physical values are assessed ?
- Which driving conditions are assessed ?

- Reactions to which driver actions are assessed ?
- Which vehicle actions are assessed ?

- How are single actions weighted ?

Answers:

- Definition of a general semantics map
- Definition of an evaluation method

→ **Computer aided evaluation**

Questions:

- Which physical values must be measured ?
- Which sensors are necessary ?
- Which measuring device must be used ?
- Which development software must be used ?

- Which methodology can solve the problem ?

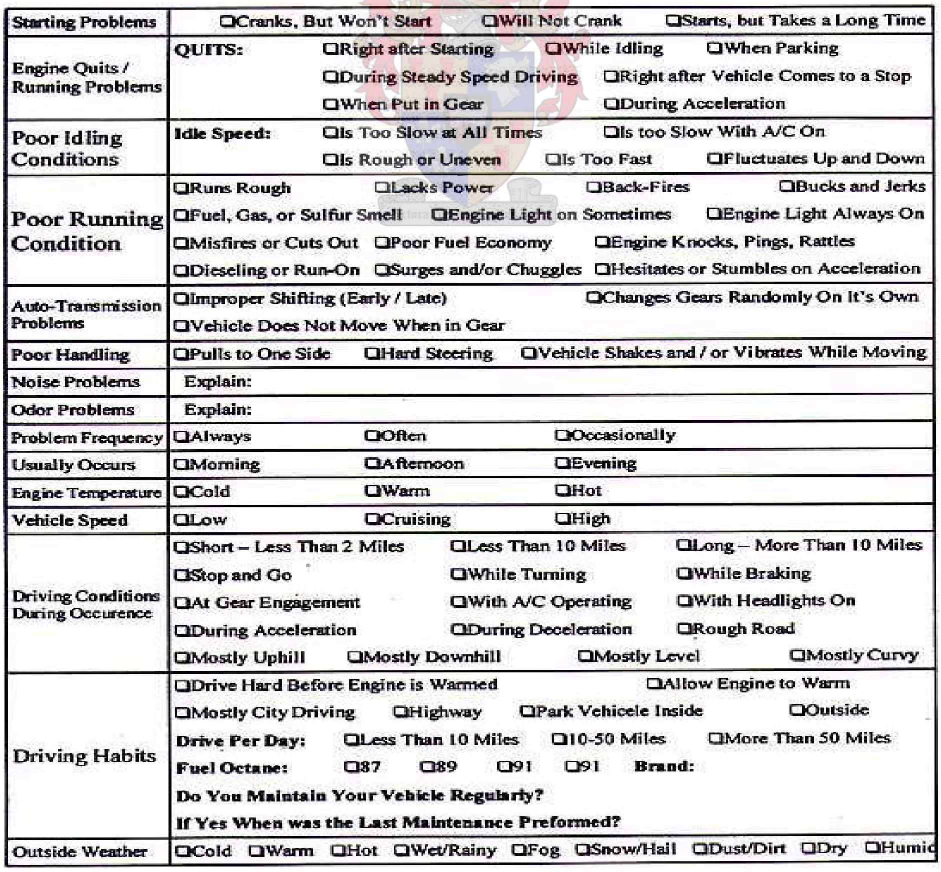
- How can operation modes be detected ?
- How can the human assessment to be done by a computer, which formulas are necessary ?
- How can the weigthing be done ?

Answers:

- Measurement device including sensors
- Operation mode trigger conditions
- Necessary data preparation
- Calculation, storage and control model

Figure 2.2: General semantics versus objective evaluation (List H. and Schöggl P, 1998)

In order to determine driveability, experienced drivers carry out specific tests to rate the vehicle's response. Drivers monitor performance behaviour associated with the responsiveness and smoothness of the vehicle under transient and steady-state conditions, and the performance associated with start and idle. Figure 2.3 is an example of a driveability questionnaire that is filled out by the test drivers/calibration engineers.

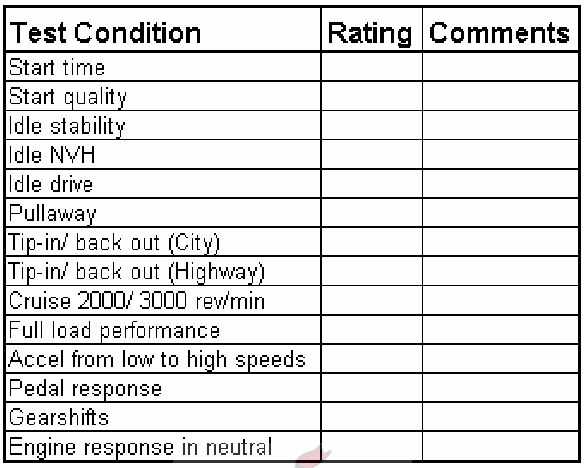


Starting Problems	☐Cranks, But Won't Start ☐Will Not Crank ☐Starts, but Takes a Long Time
Engine Quits / Running Problems	**QUITS:** ☐Right after Starting ☐While Idling ☐When Parking ☐During Steady Speed Driving ☐Right after Vehicle Comes to a Stop ☐When Put in Gear ☐During Acceleration
Poor Idling Conditions	**Idle Speed:** ☐Is Too Slow at All Times ☐Is too Slow With A/C On ☐Is Rough or Uneven ☐Is Too Fast ☐Fluctuates Up and Down
Poor Running Condition	☐Runs Rough ☐Lacks Power ☐Back-Fires ☐Bucks and Jerks ☐Fuel, Gas, or Sulfur Smell ☐Engine Light on Sometimes ☐Engine Light Always On ☐Misfires or Cuts Out ☐Poor Fuel Economy ☐Engine Knocks, Pings, Rattles ☐Dieseling or Run-On ☐Surges and/or Chuggles ☐Hesitates or Stumbles on Acceleration
Auto-Transmission Problems	☐Improper Shifting (Early / Late) ☐Changes Gears Randomly On It's Own ☐Vehicle Does Not Move When in Gear
Poor Handling	☐Pulls to One Side ☐Hard Steering ☐Vehicle Shakes and / or Vibrates While Moving
Noise Problems	Explain:
Odor Problems	Explain:
Problem Frequency	☐Always ☐Often ☐Occasionally
Usually Occurs	☐Morning ☐Afternoon ☐Evening
Engine Temperature	☐Cold ☐Warm ☐Hot
Vehicle Speed	☐Low ☐Cruising ☐High
Driving Conditions During Occurence	☐Short – Less Than 2 Miles ☐Less Than 10 Miles ☐Long – More Than 10 Miles ☐Stop and Go ☐While Turning ☐While Braking ☐At Gear Engagement ☐With A/C Operating ☐With Headlights On ☐During Acceleration ☐During Deceleration ☐Rough Road ☐Mostly Uphill ☐Mostly Downhill ☐Mostly Level ☐Mostly Curvy
Driving Habits	☐Drive Hard Before Engine is Warmed ☐Allow Engine to Warm ☐Mostly City Driving ☐Highway ☐Park Vehicele Inside ☐Outside **Drive Per Day:** ☐Less Than 10 Miles ☐10-50 Miles ☐More Than 50 Miles **Fuel Octane:** ☐87 ☐89 ☐91 ☐91 **Brand:** **Do You Maintain Your Vehicle Regularly?** **If Yes When was the Last Maintenance Preformed?**
Outside Weather	☐Cold ☐Warm ☐Hot ☐Wet/Rainy ☐Fog ☐Snow/Hail ☐Dust/Dirt ☐Dry ☐Humid

Figure 2.3: Driveability questionnaire (Anonymous, 1999)

Ricardo Inc. has developed a vehicle drive appraisal system to evaluate a vehicle's driveability (Dorey, R E and Holmes C B, 1999). Ricardo Inc. pay particular consideration to identifying delay in the responses, stumbles, oscillation, overshoot, hunting and roughness. Table 2.2 lists the vehicle assessment tests developed by Ricardo Inc.

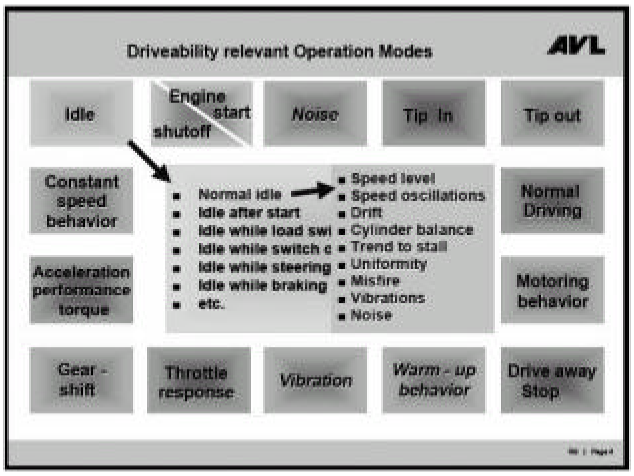
Table 2.2: Vehicle drive appraisal developed by Ricardo Inc. (Dorey, R E and Holmes C B, 1999)



Test Condition	Rating	Comments
Start time		
Start quality		
Idle stability		
Idle NVH		
Idle drive		
Pullaway		
Tip-in/ back out (City)		
Tip-in/ back out (Highway)		
Cruise 2000/ 3000 rev/min		
Full load performance		
Accel from low to high speeds		
Pedal response		
Gearshifts		
Engine response in neutral		

AVL List GmbH, together with Dr. Schöggl, has produced an intelligent measurement system for driveability measurement, known as AVL DRIVE (List H. and Schöggl P, 1998). AVL DRIVE reproduces the test driver's driveability perception and establishes the complex correlation between measured physical values and the driveability rating (Steiner, 2004).

DRIVE starts the analysis by identifying the current main- and sub-operating modes of the vehicle, as laid out in Figure 2.4. After the driving mode has been identified, the relevant criteria are calculated from the measured physical values, and the rating for the current mode is calculated.



Driveability relevant Operation Modes

AVL

Idle

Engine start shutoff

Noise

Tip In

Tip out

Constant speed behavior

- Normal idle
- Idle after start
- Idle while load swi
- Idle while switch c
- Idle while steering
- Idle while braking
- etc.

- Speed level
- Speed oscillations
- Drift
- Cylinder balance
- Trend to stall
- Uniformity
- Misfire
- Vibrations
- Noise

Normal Driving

Acceleration performance torque

Motoring behavior

Gear - shift

Throttle response

Vibration

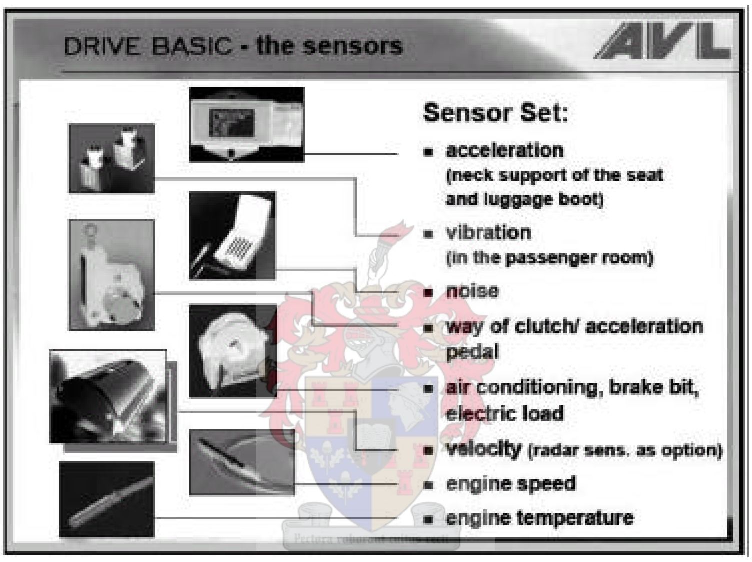
Warm - up behavior

Drive away Stop

Figure 2.4: AVL's operation modes (Steiner, 2004)

DRIVE uses 13 main and 38 sub-operating modes, which describe a wide range of vehicle performance characteristics. After identifying the sub-operating mode, DRIVE calculates the criteria that are relevant for this mode. The combination of these criteria is the basis for the driveability rating for each event (List H. and Schöggl P, 1998).

DRIVE uses a combination of sensors, shown in Figure 2.5, and signals from the vehicle's Controller Area Network (CAN) bus to measure all relevant quantities for the driveability evaluation. AVL List GmbH claims that the installation and calibration of the system typically takes about 4 to 8 hours. DRIVE also consists of a DMU (DRIVE Main Unit) and a laptop PC with evaluation software. Figure 2.6 shows the locations of the various sensors in a typical vehicle installation with a CAN interface.

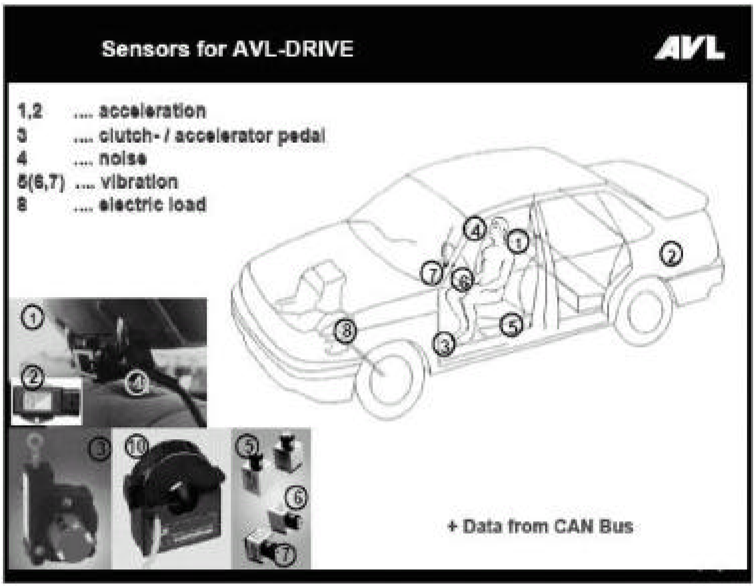


DRIVE BASIC - the sensors

Sensor Set:

- **acceleration** (neck support of the seat and luggage boot)
- **vibration** (in the passenger room)
- **noise**
- **way of clutch/ acceleration pedal**
- **air conditioning, brake bit, electric load**
- **velocity** (radar sens. as option)
- **engine speed**
- **engine temperature**

Figure 2.5: DRIVE sensors (Steiner, 2004)



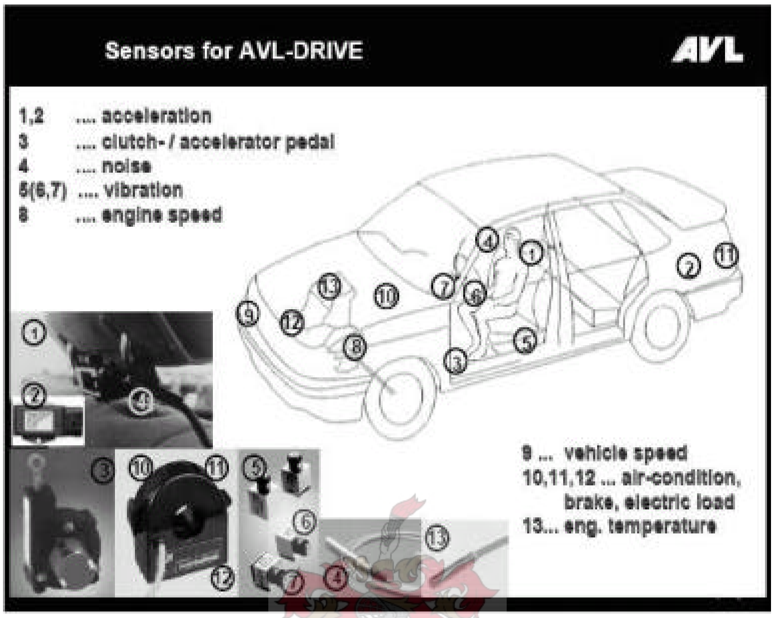
Sensors for AVL-DRIVE

1,2 .... acceleration
3 .... clutch- / accelerator pedal
4 .... noise
5(6,7) .... vibration
8 .... electric load

+ Data from CAN Bus

Figure 2.6: DRIVE sensor installation with CAN interface (Steiner, 2004)

Some vehicles are not equipped with a CAN bus and obtaining information from such an engine is only possible with a calibration Engine Control Unit (ECU). Extra sensors have to be installed to measure relevant data for the calculation of the driveability rating. Figure 2.7 shows the installation in a vehicle without a CAN interface.



Sensors for AVL-DRIVE

AVL

1,2 .... acceleration
3 .... clutch- / accelerator pedal
4 .... noise
5(6,7) .... vibration
8 .... engine speed

9 ... vehicle speed
10,11,12 ... air-condition, brake, electric load
13... eng. temperature

Figure 2.7: DRIVE sensor installation in vehicle without CAN interface (Steiner, 2004)

DRIVE also provides a graphical user interface with a wide range of data and result display possibilities. If the user requires a more detailed analysis then the driveability ratings are available on vehicle level, main operating mode level, sub operating level, criteria level and raw data level. Export functions to AVL CONCERTO post processing software and to ASCII files for further analysis possibilities are also available. AVL CONCERTO is a tool used to combine and evaluate a whole range of data collected during engine development.

Figure 2.8 shows vehicle jerk after a sudden throttle increase, which is defined as tip-in. This map was generated with engine data such as that displayed in Figure 2.9. The AVL List GmbH driveability index, on the z-axis, shows low scores for high engine speeds. The three-dimensional representation allows detailed information on problem areas. If the indices are compared with the contents of Table 2.1 then, for this example, the rating for driveability is poor at high engine speeds.

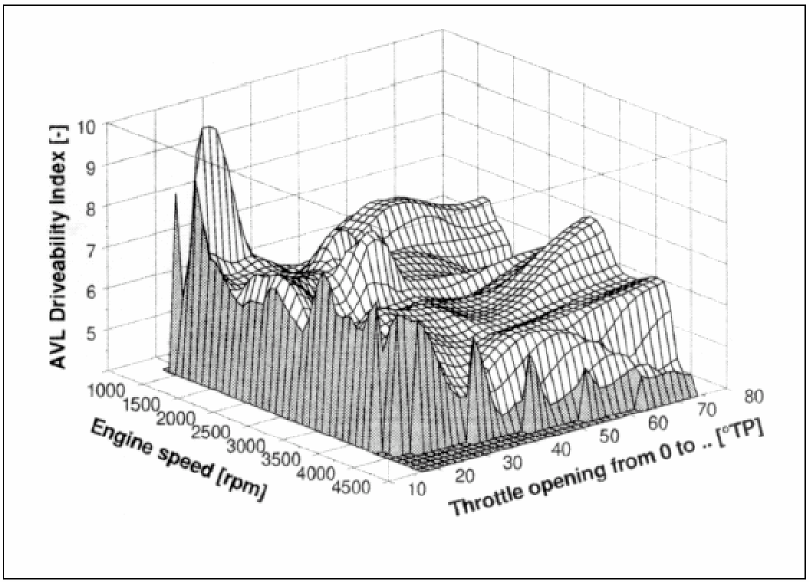


Figure 2.8: Vehicle jerk after tip-in (List H. and Schöggl P, 1998)

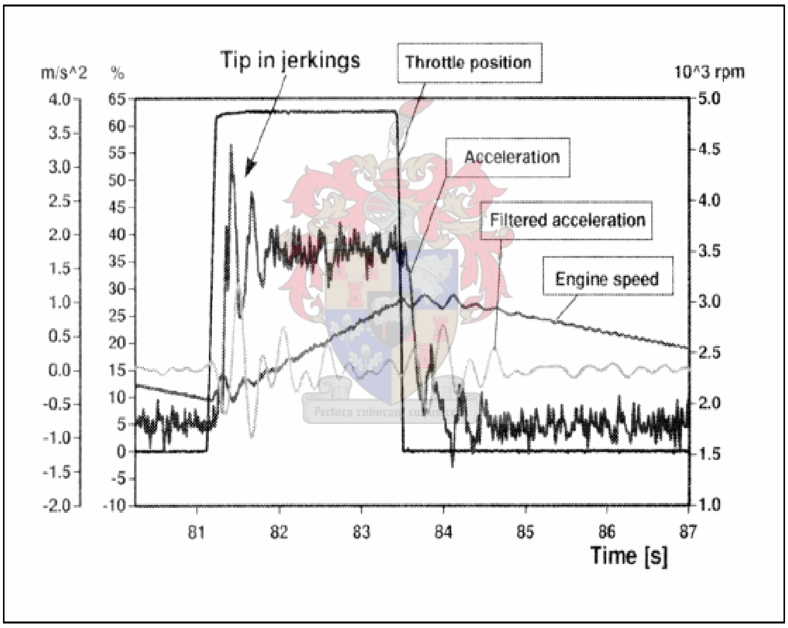


Figure 2.9: Vehicle and engine data during tip-in and tip-out (List H. and Schöggl P, 1998)

Figure 2.10 shows a driveability improvement of a medium class vehicle achieved with the aid of AVL DRIVE. These improvements were achieved by adjusting certain calibration values.

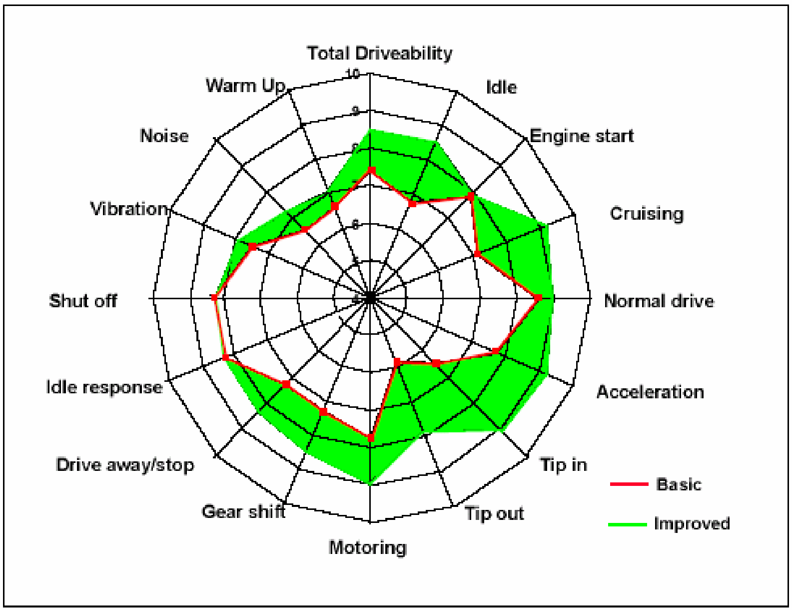


Figure 2.10: Driveability improvement (Schöggl et al., 2000)

It is important to note that improving the expectations of a certain customer group does not always improve the total driveability index. This is illustrated in Figure 2.11. Variant 1 has a total driveability index of 9.21, whereas variant 2 has a total driveability index of 8.46. Variant 1 has a much lower sporty and comfort index than variant 2, but it has a higher total driveability index.

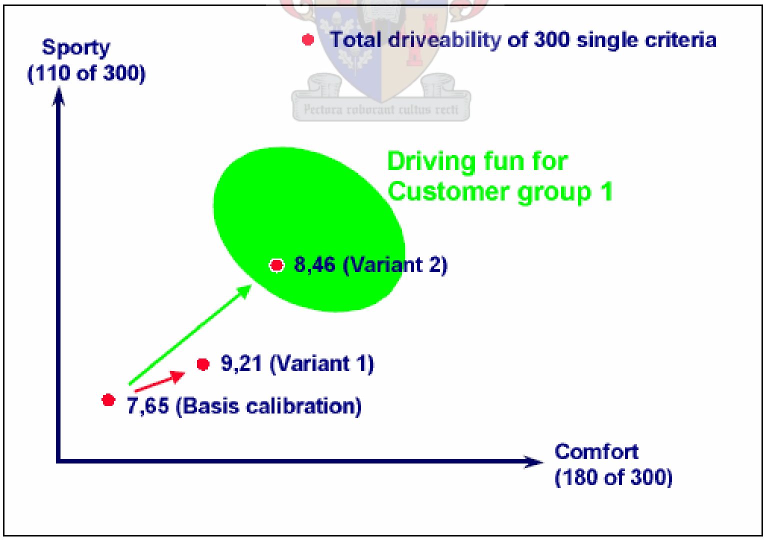


Figure 2.11: Design for a customer-specific driveability response (Schöggl et al., 2000a)

AVL List GmbH has also developed a package to optimise the ECU maps, called AVL CAMEO. The maps are calibration values used by the control system. Another system called AVL PUMA/ISAC is used for dynamic engine testing and vehicle simulation. The combination of AVL DRIVE, AVL CAMEO and AVL PUMA/ISAC allows for a closed-loop driveability calibration of the ECU (Schöggl et al., 2002). Figure 2.12 displays the setup of such a system.

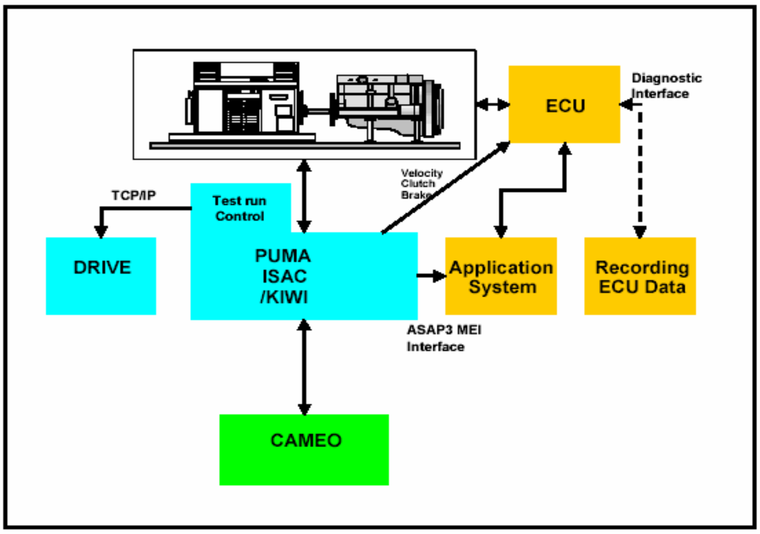


Figure 2.12: Closed-loop driveability calibration setup (Schöggl et al., 2002)

The human body has a certain range of frequencies where it experience great discomfort. This discomfort may lead to motion sickness. Motion sickness is usually associated with sweating, nausea or vomiting. The three Cartesian axes, x, y and z, are used as the primary directions of motions. There is a forward-back motion or longitudinal motion (x-axis), there is a left-right motion or lateral motion (y-axis), and there is an up-down motion or vertical motion (z-axis). If the vertical motion has a frequency of below 0.5 Hz then it may lead to motion sickness (Griffin, 1996).

It is clear that there is a great shortcoming for specialised driveability evaluation. The current systems only evaluate the overall driveability and do not provide specific parameter identification for improving the driveability score. Utilising the engine management in order to improve driveability is crucial in modern vehicles. The following section (2.3) describes how engine management can be used to facilitate improved driveability.

2.3 Engine Management

Internal combustion (IC) engines develop mechanical energy for propulsion from the chemical energy stored in the fuel. The ratio of air to fuel is important in optimising power and efficiency while reducing emissions. The ignition timing is also essential to ensure that the combustion process is initiated to produce the required energy. The main task of the Engine Management System (EMS) is to control the ignition and fuelling of the combustion process. This section describes the basic operation of the engine management system and its effect on driveability.

2.3.1 Sensor and signals

Engine management systems work with different sensors, signals and strategies for the control system. Older vehicles used mechanical control to adjust the fuelling and timing but modern vehicles use more advanced electronics to control the fuelling and timing, since it allows more flexibility under different operating conditions. Basic engine management systems use sensors to measure a condition and to generate an output voltage. These signals are sent to the Electronic Control Unit (ECU) where they are manipulated and combined with other inputs to generate an output signal to control various devices and actuators. This device might be an injector, and the output signal will determine how long it should stay open for the correct fuelling strategy. Figure 2.13 illustrates the different sensors and actuators used by engine management systems. The working of the most common sensors is explained in Appendix A.

All engine management systems operate on the same basic principle but they will have different sensor configurations and/or different control strategies. More modern systems only use the driver's input as a guideline. The direct link between the accelerator pedal and the throttle has been removed and the engine management system decides what it 'thinks' will be the best fuelling and timing strategy for the operating conditions. These modern systems also use a model to calculate an output value from the sensor's input instead of reading it from a pre-calibrated map. It will have different models for different systems, e.g. a torque model, a fuelling model, an air path model, an exhaust temperature model, etc. (Corsetti et al., 2002). This will allow for the engine to adapt to certain conditions, e.g. if the fuel quality is really low and the engine knocks frequently, then it will adapt the fuelling model to limit the engine's ignition advance.

Most systems do not have a temperature sensor in the exhaust system, thus the engine management system has to calculate the estimated temperature (from engine speed, inlet air temperature, ignition advance, lambda value, etc.) to prevent the catalytic converter from being exposed to damaging temperatures (Eriksson, 2002). Some engine management systems 'learn' the driver's style and adapt to the driving style as a trade off between performance and fuel efficiency (Meyer, S and Greff, A, 2002).

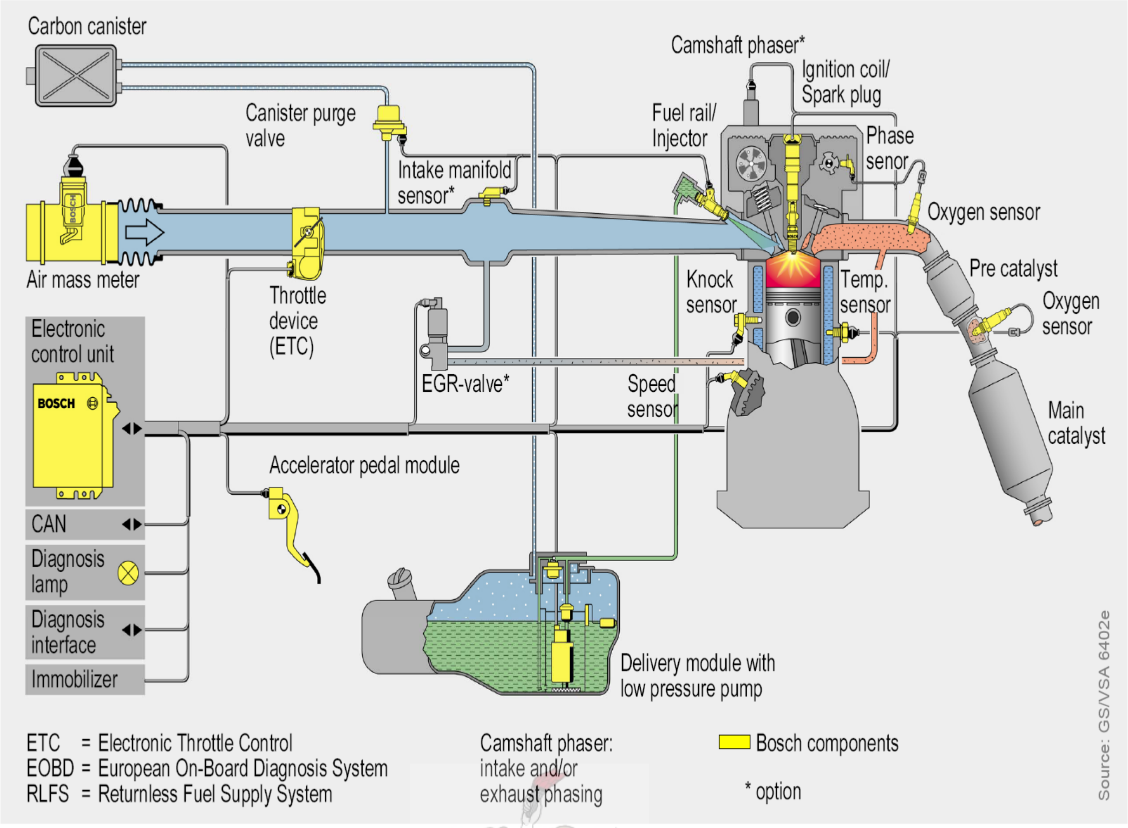


Figure 2.13: Bosch Motronic engine management system (Bosch, 2005)

Engine management systems use data maps to calculate or look up the output signals. These data maps are calibrated during the engine development process on dynamometers and vehicle testing for different operating conditions. The operating conditions vary for each speed and load point as well as other variables under different temperature conditions.

Driveability is directly related to the strategy of the control system. An inadequate fuelling or timing model, for example, will lead to driveability problems. It is important to understand the working principle of the sensors in order to understand how the control system manipulates the input signals to achieve acceptable driveability.

2.3.2 Air-fuel ratio

The ratio of air to fuel is important with a Spark Ignition (SI) engine because of its influence on emission, power and fuel efficiency. Figure 2.14 shows the relationship between power, fuel economy and air-fuel ratio. The stoichiometric ratio is the mass ratio 14.7 kg of air required to 1 kg gasoline for complete combustion (Bosch, 1999). The air ratio, lambda (λ), indicates the deviation of the actual air-fuel ratio from the stoichiometric ratio:

$$\lambda = \frac{actual\ inducted\ air\ mass}{air\ requirement\ \ for\ stoichiometric\ combustion} \tag{2.1}$$

A lambda value of less than one indicates a rich fuel mixture and a value greater than one indicates a lean mixture. This ratio also plays a significant role in engine emissions. Another term that is used is called the fuel-air equivalence ratio (Φ); it is the inverse of lambda.

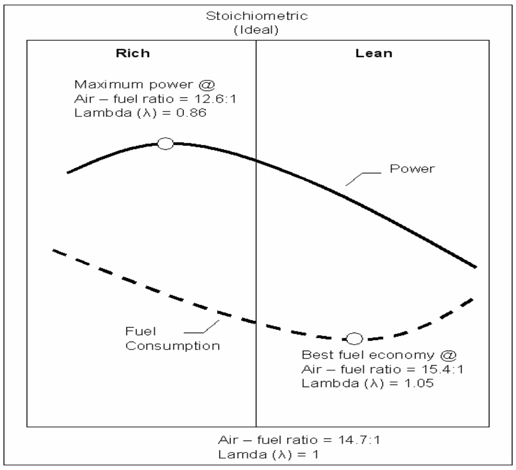


Figure 2.14: Air-fuel ratio effect on power and economy (Probst, 1991)

2.3.2.1 Air-flow system

The throttle controls the amount of air that a spark ignition engine takes in, at a given speed. The pressure in the intake manifold is related to the throttle opening. If the throttle is fully opened then the cylinders induce air at ambient pressure, minus the pressure losses of the air filter and across the throttle plate, etc. If the throttle is closed then there is no air being sucked into the combustion chamber (except the auxiliary air or idle air control) and a low pressure is formed in the inlet manifold.

The higher the altitude above sea level, the less dense the air becomes. This implies that for a given volume of air there is less oxygen available for combustion. Engines that inject fuel by measuring air volume, such as carburettors and air vanes, will inject the same amount of fuel at sea level and above sea level. This will lead to rich mixture conditions at high altitude. Air-mass flow sensors and other pressure sensing sensors compensate for air density to allow for more accurate calculation of the required mixture.

Some engines have an auxiliary air valve fitted at the throttle body. This helps the engine to overcome additional mechanical drag at cold temperatures. The valve closes as the engine warms up. It provides better driveability at cold start, cold idle, post-start and warm-up. With an electronically controlled throttle this valve is replaced by the ECU's ability to open and close the throttle, as required.

The Idle Speed Control (ISC) regulates the engine's idle speed by varying the volume of air induced at engine idle. More advanced systems adjust the timing as well, because of the faster response that can be achieved. Different operating conditions require different idle control. Under cold operating conditions the engine needs to idle a little faster to overcome engine friction and to allow for better throttle response (Bosch, 1999). A change in load requires the amount of air to be adjusted. A typical load change is when the air conditioner is switched on and the compressor requires additional power to operate. The idle control also needs to allow for an automatic transmission load change (e.g. changing from park to drive). All of the above will lead to poor driveability if the engine stalls or over-revs with a change of load at idle.

Exhaust Gas Recirculation (EGR) is a technique used to increase fuel efficiency and reduce oxides of nitrogen (NO_x). The exhaust gas is re-routed back into the intake manifold, resulting in less airflow past the airflow sensor, allowing less fuel to be injected. If the engine is equipped with a MAP sensor then the valve opening of the EGR and the amount of fuel injected must be accurately calibrated. The combustion temperature is reduced when the air-fuel mixture is diluted with inert exhaust gas (Bosch, 1999).

High EGR flow is required during mid-range acceleration and cruising to reduce the combustion temperature. Low EGR flow is required during light load and low engine speed conditions, and no EGR flow is required during critical operating conditions (start, idle, full load, etc.) where driveability will be affected. Incorrect engine management calibration for driveability will lead to high NO_x and knock if the EGR flow is inadequate, and will lead to stumble, hesitation, surge and/or flat spots if the flow is too high (Probst, 1991).

2.3.2.2 Fuel systems

Small variations in air-fuel ratio have a large influence on power output, fuel consumption and exhaust emissions. The optimum control is therefore critical for acceptable driveability. Two basic fuel delivery systems are found in modern vehicles: carburettors and fuel injection.

Carburettors have poor control of the air-fuel ratio. They work on a venturi based principle and the amount of fuel injected is proportional to the airflow rate (Bosch, 2004). The carburettor is restricted with limited adjustment of fuel metering, causing unsatisfactory management in extreme operating conditions and harmful emissions. Carburettors are mainly used on entry-level vehicles, in countries where there are no firm emissions regulations, but they will soon become obsolete in vehicles.

Fuel injection systems can vary the amount of fuel injected more accurately than carburettors. This allows better driveability, e.g. by allowing more fuel with cold start and cold operation. Electronic Fuel Injection (EFI) systems use constant pressure across the fuel rail and manifold and vary the amount of fuel by varying the time the electronically controlled injector stays open (Probst, 1991).

Conventional SI engines use a multi-point (or port) injection configuration. The fuel injector is located near the intake valves, in the inlet manifold. This improves driveability (compared to when a carburettor is used) by eliminating the throttle change lag, which occurs while the air-fuel mixture travels from the throttle body to the intake ports. It also provides more power since it eliminates the venturi losses of a typical carburettor and it provides increased fuel efficiency by reducing the wall wetting area of the whole inlet manifold (Probst, 1991).

Warm-up requires less enrichment as the engine gets warmer. Figure 2.15 shows the typical enrichment periods of the various operating conditions. Engine shut-off problems are eliminated by cutting the fuel when the ignition is switched off, to avoid run-on (dieseling). Maximum power output is achieved with a slightly richer air-fuel mixture, as illustrated in Figure 2.14. A richer mixture also reduces the tendency to knock (Probst, 1991).

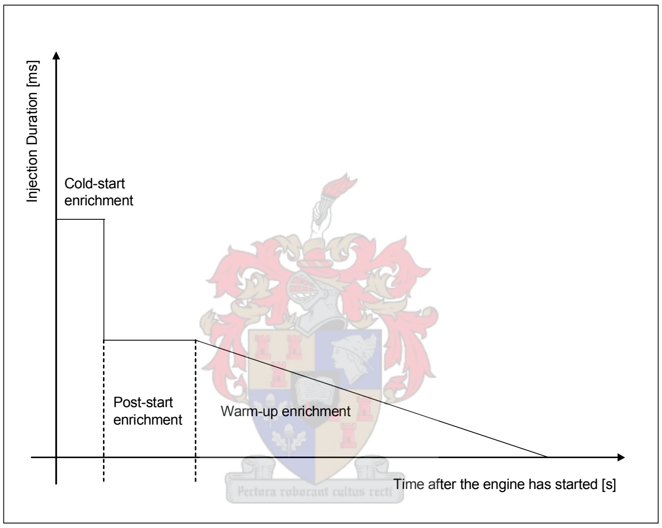


Figure 2.15: Fuel enrichment duration (Probst, 1991)

It is vital to analyse and understand the effect of fuel combustion properties on engine management design and calibration for driveability. The fuel quality and emissions have to be considered by the management system for it to be able to adapt, while not losing too much performance (Stone, 1999). Appendix B describes the effect of fuel characteristics on driveability.

Acceleration enrichment is achieved in various ways. The simplest method is to measure the rate of change of pedal and if the rate of change in voltage is above a certain threshold then additional fuel is added. During Wide Open Throttle (WOT) the throttle position sensor flags the ECU that it is fully open and the ECU changes over from closed-loop control to a pre-calibrated mixture of open-loop control (Probst, 1991). Closed-loop control is when the engine management system tries to keep the engine at a lambda value equal to one. Torque based engine management systems define this condition as Full Load (FL) since the throttle is not necessarily fully open when the accelerator pedal is fully engaged (Bosch, 1999).

Additional fuel will increase the available energy to increase the engine speed. Pull-away enrichment also reduces the probability of engine stall. Excessive fuel resulting from rich air-fuel mixtures will dilute the engine's lubricating oil if excessive wall wetting occurs. Slow cranking and a closed throttle do not allow enough air for cold starting and the engine will require additional fuel (Probst, 1991).

When a vehicle is coasting, or when the vehicle is in over-run, the engine does not require any fuel. The fuel efficiency and emissions can therefore be improved by fuel shut-off. Fuel shut-off can only be implemented above specific engine speeds and temperatures, and must be managed in such a manner so as not to detract from the driver's perception of driveability (Probst, 1991).

The maximum engine speed is limited to keep the engine within acceptable limits. Fuel shut-off is implemented when the engine speed exceeds the limit. Normal injection operation is resumed once the engine speed drops below the limit (Probst, 1991).

Lean mixtures will have a higher combustion temperature than rich mixtures. A slightly lean mixture can improve the fuel economy, as illustrated in Figure 2.14. Backfires and pre-ignition can be symptoms of a lean mixture. This condition can lead to severe engine damage and should be avoided (Bosch, 2004).

Rich mixtures increase emissions of hydrocarbons (HC) and carbon monoxide (CO) because of incompletely burned gasoline. Rich mixtures also increase carbon deposits. Lean mixtures lead to oxides of nitrogen (NO_x) because the fuel will burn at a higher combustion temperature (Bosch, 2004). A more in-depth emissions analysis is presented in Appendix B.

Evaporative fuel control (EVAP) is a method of eliminating evaporative emissions. Fuel vapours created in the fuel system may not be released into the atmosphere and need to be captured and disposed of appropriately. The main source of these vapours is the fuel tank. The fuel evaporates at high temperatures and is passed through a carbon canister. The carbon absorbs the fuel contained in the vapours that pass through it. The ECU then regulates the release of these vapours into the inlet system when the operating conditions can tolerate additional enrichment (Bosch, 1999).

2.3.3 Ignition timing

The formal definition of ignition timing is the exact point at which the spark plug arcs to ignite the air-fuel mixture. The point in time when the combustible mixture is ignited plays a significant role in power, emissions, heat transfer, pressure and engine durability. The point of ignition must change to compensate for the induction period (Bosch, 2004).

A variety of ignition timing control systems is available, ranging from simple mechanical systems to microcomputer control for individual ignition timing for each spark plug. In a mechanical system the timing is advanced by centrifugal weights as engine speed increases, and with a vacuum diaphragm as load decreases. More advanced timing control is required to ensure precise and rapid timing to deliver acceptable driveability (Probst, 1991).

Ignition timing is dependent on engine speed, load, temperature and pressure. If the engine speed increases then the timing needs to be advanced since the fuel burn angle remains relatively constant but there is less time available for combustion to occur. If the load increases then the timing has to be retarded since the burn rate is faster (Bosch, 2004). Figure 2.16 shows the basic ignition advance and retard for different operating conditions.

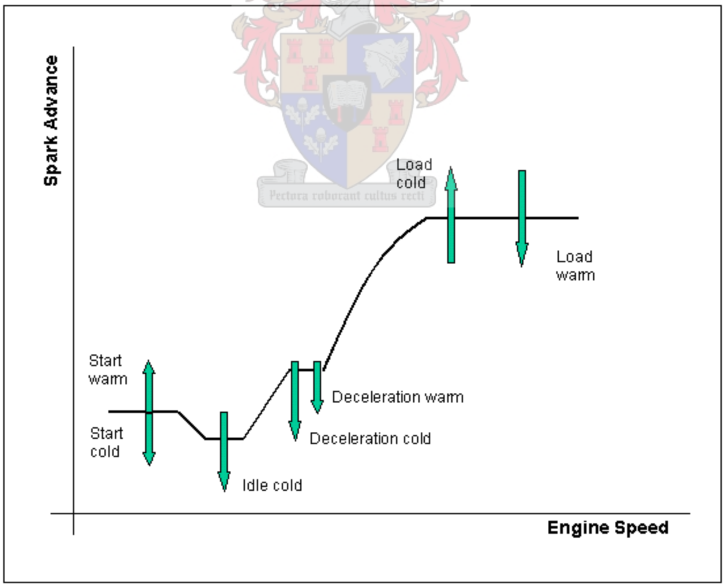


Figure 2.16: Ignition advance for different operating conditions (Probst, 1991)

Advancing the timing during warm-up will aid driveability. The timing is also advanced when the intake air is extremely cold. The timing is retarded back to base timing as the engine warms up to operating temperature. Base timing is defined as the engine provides the optimum efficiency. During part load this point is usually where maximum torque is located, determined with an ignition timing sweep at constant load and engine speed, and during high load and full load this point is usually governed by the knock limit. Retarding timing during warm-up, under closed throttle deceleration, will reduce hydrocarbon emissions, which risk being excessive anyway because of warm-up enrichment (Probst, 1991).

Advancing the timing will increase the engine speed or the available torque since the cycle efficiency is increased. This phenomenon is useful during idle stability control (Royo et al., 2001). The ignition timing is also advanced for EGR according to air-intake volume and engine speed, to compensate for slower burn duration and therefore to increase driveability. Ignition advance is also applied during acceleration, without approaching knock (Probst, 1991).

The timing can also be implemented for shunt and shuffle control, especially during gear shifting. Shunt is the initial jerk experienced in the vehicle after a sudden load change and shuffle is the subsequent oscillation of lateral acceleration. The ignition is retarded to reduce the torque when the ignition detects a gear shift. The strain on the clutch and gears is reduced, resulting in a smoother shift. The same principle applies during tip-in and tip-out (Johansson, 2004).

The ignition timing is retarded at high intake temperatures and when the coolant temperature is very hot, to reduce the risk of the engine running into knocking conditions. The ignition timing is retarded when the ECU detects knock. If severe retard is applied then the driver will experience a loss of torque and it will be perceived as unfavourable driveability (Probst, 1991).

Fast engine response is achieved by adjusting the ignition timing since the response time is an order of magnitude faster than adjusting the air-fuel ratio. With acceleration the ignition is advanced for quick response and then slowly retarded as the effect of the enrichment comes into play. Utilising ignition timing instead of injecting fuel also improves the fuel efficiency of the engine (Royo et al., 2001).

2.3.4 On-board diagnostics

On-Board Diagnostics (OBD) is used to indicate and diagnose engine problems that can lead to the malfunction of the exhaust gas after treatment systems (Catalytic converter etc.) that will lead to poor driveability. The main function of an OBD system is to light a Malfunction Indicator Lamp (MIL). The OBD provides Diagnostic Trouble Codes (DTC) and fault isolation logic charts in the repair manual to assist technicians in repairing the malfunction (Bosch, 2004).

OBD II or European On-Board Diagnosis (EOBD) measure various sensor signals and evaluates them to determine if they are still functioning properly, especially in the case of components that will increase emissions. As an example, OBD II vehicles require two oxygen sensors, one before and one after the catalytic converter. The one before the catalytic converter is to adjust the air-fuel ratio and the one after the catalytic converter is used by the ECU to determine the catalytic converter efficiency. Emission limits for harmful exhaust gasses are defined for OBD II legislation. Different limits of harmful exhaust gasses are regulated for different countries. Appendix B describes the proposed emissions regulations for South Africa from 2006. EOBD legislation also requires electrical monitoring for short-circuit and line interruptions (Bosch, 2004).

A driveability evaluation for engine management calibration will now be developed by combining the basic structures of the current driveability evaluation models and the functionality of basic engine management strategies. The main sections of driveability will be identified and described. The corresponding engine management sections will be identified to improve the different sections of driveability. The effect of fuel quality on engine management control and driveability will also be investigated and discussed. The development of this driveability evaluation model is described in Chapter 3.

3

DRIVEABILITY EVALUATION

3.1 Introduction

The overall objective of this study was to create a repetitive and quantitative method for driveability evaluation for engine management calibration. Such a method should be applicable to any vehicle that needs to be evaluated. The most important factors that have an impact on driveability must be identified with regards to engine management calibration. This chapter lists all the important factors, describes the theory behind them, explains the experimental procedure to evaluate driveability and present results from the experimental tests.

Different engine designs will yield different driveability results. The test data presented in this chapter are for experiments conducted on a 1.6-liter engine, with two valves per cylinder, an electronic throttle body and a switched inlet manifold.

The process of evaluation was initiated by listing all the important factors that contribute to the driveability response. These factors are a combination from AVL's operation modes (Steiner, 2004) together with engine management theory and other operational modes identified during testing. These factors were then broken up into subsections. All these subsections are described and evaluated in this chapter, focussing on their relevance to driveability calibration and evaluation.

The results of the evaluation of the subsections were assigned to quantitative values. These values were then weighted and combined to provide a score for each driveability section. Finally these driveability sections were combined and weighted to provide a single value for the complete driveability response of the vehicle. The scores assigned were created by assumptions based on measured values in order to achieve an objective evaluation method. For example: Starting time can be measured exactly in milliseconds, and the model is based on the assumption that all drivers would consider a shorter starting time to be better and a longer starting time to be worse. The validation of assumptions on human response to the quantitative measured values was not included in the scope of this project. These assumptions will be discussed and motivated in each section.

Creating the sections and subsections allows the calibration engineer and evaluator to focus on specific relevant areas. The complete driveability evaluation must be completed after they have improved the scores of the specific relevant subsections in order to evaluate the change in overall driveability. The scores of all the other sections are also made available after the evaluation. This ensures that the calibration engineer is immediately aware of any positive or negative effects on any other section. All the tables, models and equations that are described here were developed by the author himself since, to the best of his knowledge, no information exists for the evaluation of engine management with regards to driveability. The most important aspect in creating a quantitative driveability evaluation model is to classify the quantitative response. The following section (3.2) describes how quantitative results can be presented.

The number of tests was limited for the very cold and very hot evaluations because of the special conditions under which the vehicles needed to be evaluated. Only four different temperature conditions were evaluated because of the short testing periods as well as availability of the testing vehicles. A large amount of vehicle testing was performed prior to deciding on what sections the driveability evaluation was going to be divided into, as well as what criteria and measurements were important. These results are not discussed individually, but are mentioned in the relevant sections.

The vehicle's response must be measured to allow for quantitative driveability evaluation. The variables that have an effect on fundamental engine management calibration for each section must be identified and measured, and then evaluated for the driveability response. Various methods are available to measure these signals. The preferred method is to use the engine management's own sensors and signals. Some ECUs allow for measurement through the diagnostics port, but the sampling rate is extremely slow and the address protocol of the CAN bus must be known to access the correct labels.

Application ECUs were used for this project in order to measure all the signals. An application ECU allows the calibration engineer to access all the signals of the ECU at very high sampling rates. It also allows the variables to be changed and saved for further evaluation. A notebook computer was connected to the application ECU. The engine parameters were recorded using INCA (Integrated Calibration and Acquisition System) software, especially developed by ETAS GmbH for communicating with the ECU. The ECU and notebook computer communicate with each other by means of a CAN protocol. Lambda is measured with a continuous lambda sensor and lambda scanner. The lambda scanner sends a measured value to INCA by means of the serial port on the notebook computer. Acceleration is measured using an accelerometer and the value is saved using the accelerometer's own software. The two signals are then aligned using the measured time. The post processing and evaluation are completed using a Matlab program that was written by the author.

3.2 Driveability Classification

It is important to correlate a quantitative value to a classification. A value on its own does not mean much unless it can be connected to a description. The author decided to create a base index that any motorist can relate to and understand. A Yes/No evaluation method is not misleading, and gives a precise description. This allows for a narrow range for evaluation. A third base classification is needed since it is important to create a model to evaluate changes in the positive range. The following base classification was decided upon:

- **Unacceptable:** Vehicle is barely driveable. A customer will perceive the vehicle's response to be in need of attention and will typically take the vehicle to a workshop to be repaired or, in the worst case, have the vehicle permanently removed from the road.
- **Acceptable:** If the driveability falls in this range then a customer is oblivious to the response. The vehicle responds to all the driver's demands.
- **Favourable:** The driver notices and enjoys the response from the vehicle.

The base classification is then divided into a driveability range. A value between 1 and 10 is assigned to each classification in the driveability range, where 1 is catastrophic and 10 is excellent. Schöggl et al. (2001a) developed a driveability score index, presented in Table 3.1. Table 3.2 presents the revised driveability index developed by the author for this thesis.

Table 3.1: Driveability index (Schöggl et al., 2001a)

Driveability Score	Subjective Rating	Description
10	Excellent	Not noticeable even by experienced drivers
9	Very good	Disturbing for experienced test drivers
8	Good	Disturbing for critical customers
7	Satisfactory	Disturbing for several customers
6	Just satisfactory	Disturbing for all customers
5	Adequate	Very disturbing for all customers
4	Poor	Felt to be deficient by all customers
3	Insufficient	Complained as deficient by all customers
2	Bad	Limited vehicle operation only
1	Very bad	Vehicle not operating

Table 3.2: Revised driveability index

Base Classification	Driveability Score	Subjective Rating	Subjective Description
Favourable	10	Excellent	Precise response for experienced test drivers
	9	Very good	Good response for experienced test drivers
	8	Good	Acceptable for experienced test drivers
Acceptable	7	Acceptable	Acceptable for most customers
	6	Neutral	Indifferent to most customers
	5	Tolerable	Disappointing to most customers
Unacceptable	4	Poor	Disturbing for most customers
	3	Bad	Unacceptable for all customers
	2	Very bad	Limited vehicle operation only
	1	Catastrophic	Vehicle not operating

Driveability is divided into sections and subsections. Table 3.3 displays all the sections and subsections identified during the development of the driveability evaluation model. These sections and subsections have the greatest influence on the driveability behaviour of a vehicle.

Table 3.3: Driveability sections and subsections

Start Behaviour	Idle Behaviour	Acceleration Behaviour	Cruise Behaviour	Brake Response
Start Time RPM Overshoot	Idle Speed Set Point Idle Speed Response Load Change Pedal Blip Response Idle During Braking Idle After Braking	Pull Away Part Load Acceleration Full Load Acceleration Tip In Tip Out Coasting	Pedal Response	Acceleration

Each of these subsections was evaluated by a test procedure. The results of the tests were combined to present a value of between 1 and 10. This value is the driveability score for that subsection. Table 3.2 is then used, together with this value, to obtain a classification for the evaluation. The subsections are weighted according to importance with response and then added to provide a score for each section. Each subsection will have its own driveability score. All the subsections are then weighted and combined to provide a single score for the overall driveability response of the vehicle. The method of how these values are evaluated and combined, is described in this chapter.

Some criteria can only have a neutral or negative influence on the driveability. Start time, i.e. the delay from first rotation of the starter to the actual starting of the engine, is in principle not responsible for the perception of good driveability. If the starting time exceeds a certain period then the driver or evaluator notice the poor response and the perceived driveability will decrease, therefore decreasing the whole driveability index (Schöggl et al., 2000).

The effect of small changes in pedal position on vehicle acceleration is another example of neutral to negative criteria. The driver does not want to feel any jerks with small changes in pedal value. However, with large pedal changes, the driver expects a surge of acceleration. The above are two examples of how the evaluation model was developed.

3.3 Engine Start Behaviour and Evaluation

The first process in evaluating driveability is to evaluate the starting behaviour of the engine. Failure to start, or anything that draws attention to starting difficulty, will fail to impress the driver and subsequently lead to a negative perception of the driveability of the vehicle. A failed start is classified as unacceptable, even if the vehicle starts with the restart.

This section will describe the theory behind engine management strategies, discuss some start results and describe the testing method developed during this project for different start conditions. The driveability start index is also defined and explained.

3.3.1 Factors influencing engine start behaviour

Engine management strategies play a vital role in a vehicle's start behaviour. Fuelling, airflow and ignition timing are the three most important factors to manage to ensure good start behaviour. A pre-condition for successful ignition is that the air-fuel ratio in the plug gap must be near stoichiometric. Figure 3.1 displays an example of the engine management strategy during a starting condition. The influences of the most important factors of the engine management will be discussed in this section.

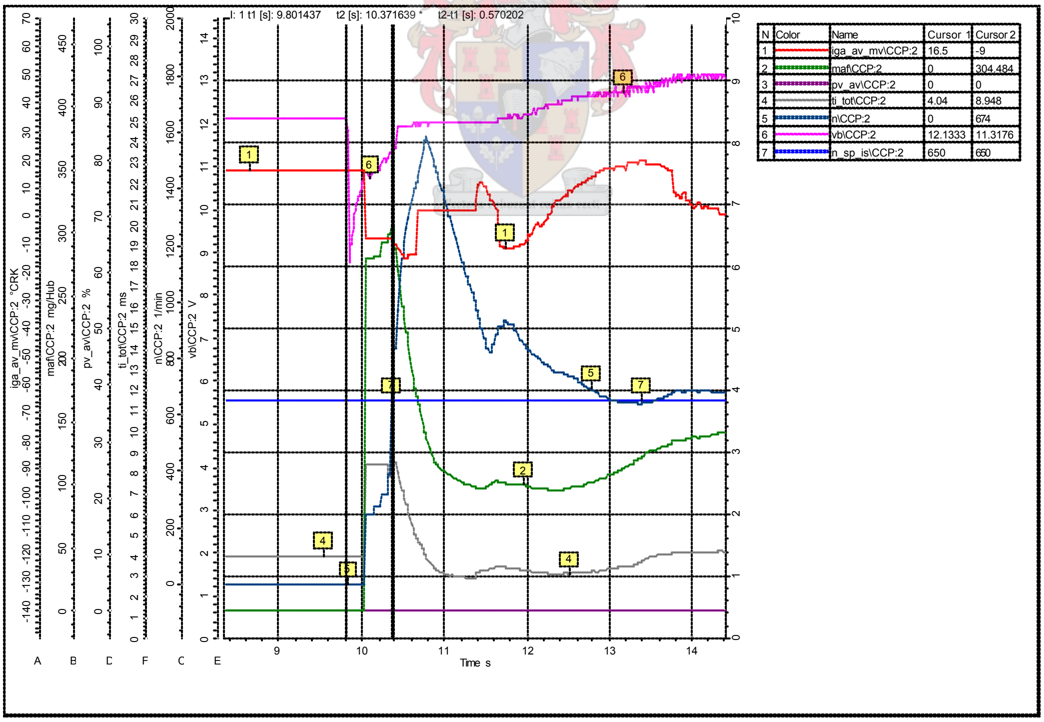


Figure 3.1: Start measurement example, showing ignition angle (IGA_AV_MV), mass air flow (MAF), accelerator pedal position (PV_AV), injection duration (TI_TOT), engine speed (N), battery voltage (VB) and idle speed set point (N_SP_IS)

Gasoline engines require excess fuel to start since some of the fuel is unlikely to vaporise and some fuel is likely to condense on the cylinder walls, pistons, intake port and inlet valve. The warmer the engine, the less excess fuel is required during start. Figure 3.2 shows the average of the recorded injection duration against engine coolant temperature. The cold conditions require extremely high injection duration. Starting at these temperatures is critical since spark plug fouling will occur if the engine takes too long to start. The engine management strategy also needs to compensate for a low Reid vapour pressure (low volatility) fuel as well as the conditions mentioned above. The average injection duration during normal idle (no external load) at operating temperature (90 to 95 ^{o}C) is roughly 3.5 ms. This shows that even at hot starts (> 100 ^{o}C) the excess fuel injected during start is, on average, more than 185%.

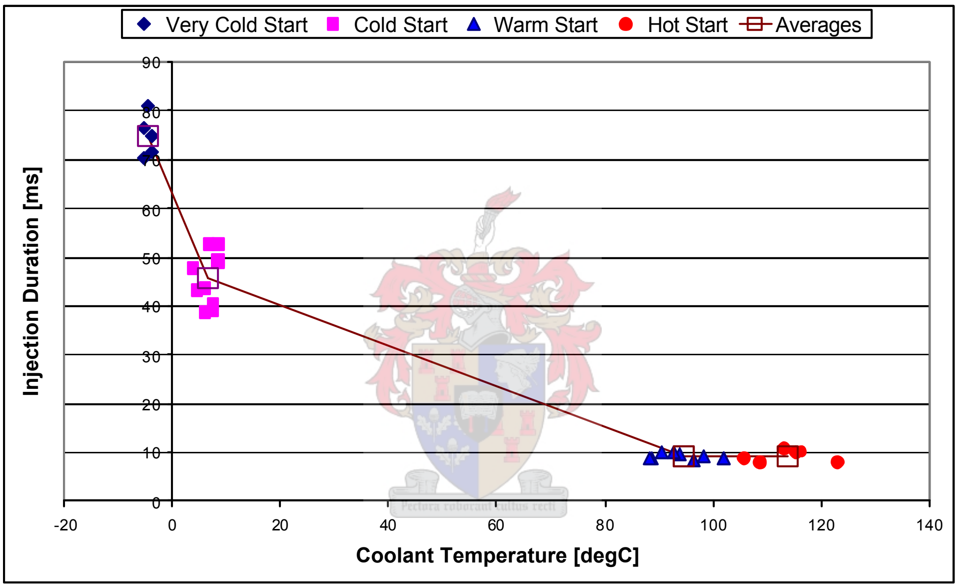


Figure 3.2: Measured injection duration at different operating temperatures

The injection duration values are calibrated as a reference value in the ECU for various conditions. The ECU will look at what the coolant temperature, ambient air temperature, battery voltage and various other factors are and will then calculate what the injection duration should be by adding the various calibrated values for different external conditions. Different engine air-path designs and engine sizes will have different values.

Fuel enrichment increases hydrocarbons and carbon monoxide emissions because of incomplete combustion of the fuel. This cold-start enrichment has a severe effect on emissions. Introducing secondary air into the exhaust manifold will reduce hydrocarbons and carbon monoxide and improve the catalyst's heating cycle. Appendix B describes the effect of emissions and catalytic converters in more detail.

The test results related to start evaluation are presented in Appendices C1 and C2. Test data for six instances at very cold conditions (-5 °C) were used to calculate the average. Test data for ten instances of cold (5 °C), twenty one instances of warm/operating temperature (90 °C) and six instances for hot (110 °C) evaluations, for their respective temperature ranges, were used to calculate the averages. Special conditioning chambers had to be used to bring the vehicle's temperature to below zero (as displayed in Figure 3.3). The vehicles also need to remain in the chamber for a long enough period of time to allow the temperature to be evenly distributed throughout the engine, prior to the evaluation of the vehicle's start response.

The driveability start index was developed from all the measured data obtained during the tests and experiments performed for the purpose of this research project, as well as some subjective inputs from various calibration engineers. The assumption is also made that a shorter starting time will be perceived more favourably by customers. A better and more accurate index can be developed with a larger population of data and subjective inputs, which also applies to all the other driveability indexes. Many of the results were measured and taken as reference behaviour.

Significant long starts were experienced during preliminary evaluations and these starts were used to formulate a value corresponding to very bad start behaviour. Nothing was measured between very bad and neutral start behaviour, and the starting times presented in Table 3.4 were interpolated between very bad and neutral start conditions. The interpolation distribution is a subjective value, either obtained from calibration engineers or by the author. The same method of interpolation was used for all the other driveability tables where no values were measured. The results are still quantitative and directly comparable between different vehicles and engine management calibrations.

Figure 3.3: Cold-conditioning chamber used to carry out cold-start experiments

Table 3.4: Driveability start time index

Driveability standard	Objective Driveability Index	Subjective rating	Start Time [s]
Favourable	10	Excellent	< 0.3
	9	Very good	0.3 to 0.4
	8	Good	0.4 to 0.5
Acceptable	7	Acceptable	0.5 to 0.6
	6	Neutral	0.6 to 0.8
	5	Tolerable	0.8 to 1.5
Unacceptable	4	Poor	1.5 to 1.75
	3	Bad	1.75 to 2.5
	2	Very bad	> 2.5
	1	Catastrophic	Failed start

Sections 3.3.3 to 3.3.6 describe the testing procedure in more detail. The cold-start evaluation (5 °C) was also carried out in the same cold chamber. The warm evaluation criteria (90 °C) were evaluated on a moderate summer's day. The hot evaluations were tested on hot summer days with the temperatures above 30 °C. Special heat-soak tents were used so as not to allow the engine to be cooled by forced convection.

The average starting time with regards to operating temperature was also recorded, and is presented in Figure 3.4. Starting time is defined as the time from when the battery voltage drops by 3 V until the engine speed crosses the idle speed set point. It is clear that the engine has the shortest starting time at operating temperature. Between low and operating temperatures the starting time followed the same behaviour as the injection duration; it decreased with an increase in coolant temperature. Only at very high coolant temperatures did the engine starting time diverge from the injection duration behaviour. Extremely hot engine bay temperatures cause the initial inlet air to become extremely hot and no additional fuel had to be added to increase the starting time.

The driveability score (e.g. 7/10 for start behaviour) must be independent of engine coolant temperature (TCO). Equation 3.1 was developed to allow for a vehicle to be evaluated at any coolant temperature, by adjusting the start time to a reference temperature. The reference temperature is taken as 96.5 °C, with a starting time of 0.519 s. Equation 3.1 is used to calculate a t_{TCO} correction factor by substituting the coolant temperature of the evaluation into the equation. This value must then be subtracted from the actual measured start time. The resulting start time will then correspond to a 96.5 °C start and will be evaluated accordingly. The same method was used to formulate all the correction factor equations in this section.

The 0.519 s starting time is the base time from which the driveability score will be given. In other words, if a vehicle's start time is equal to 0.519 s, the correction factor will be equal to zero. The behaviour will be classified as good, with a score of 7/10, as shown in Table 3.4. If the start time is shorter then it will be between very good and excellent, and if it is less it will be between acceptable and catastrophic. Equation 3.1 was developed from a piecewise regression equation as described by Shao, (2004). The regression equations are plotted on Figure 3.4.

$$x_1 = TCO \qquad x_2 = \begin{Bmatrix} 0 & if & x_1 < 96.5 \\ 1 & if & x_1 \geq 96.5 \end{Bmatrix}$$

$$t_{TCO} = b_0 + b_1 x_1 + b_2 (x_1 - 96.5) x_2$$

$$where \quad b_1 = m_1 \quad and \quad b_0 = c \quad from \quad y = mx + c \quad and \quad b_2 = m_2 - m_1$$

$$t_{TCO} = [1.1268 - 0.0063 * TCO + 0.0144(TCO - 96.5)x_2] - 0.519 \qquad (3.1)$$

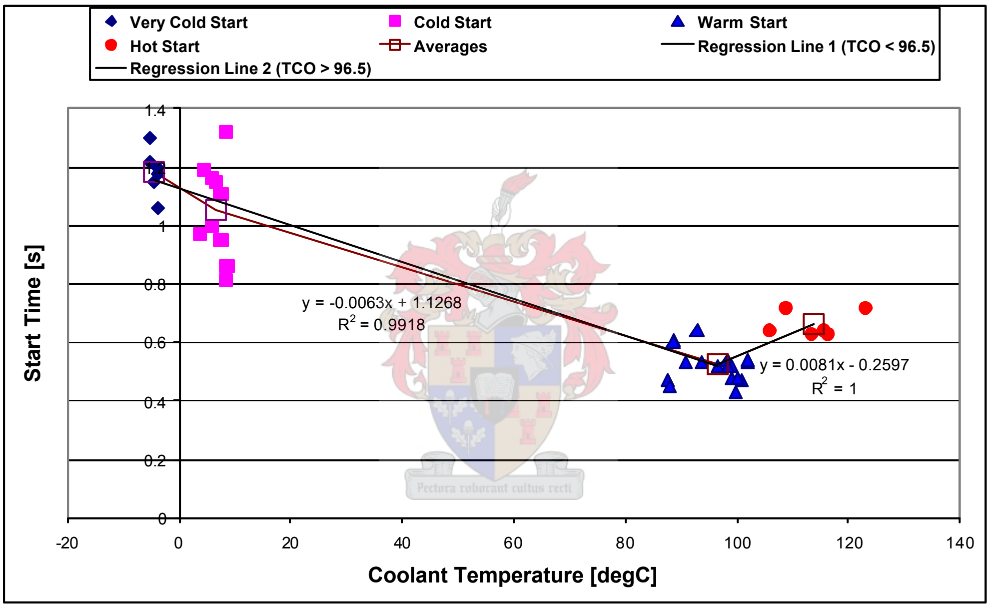


Figure 3.4: Average starting time at different operating temperatures

The use of the driveability starting index and the related quantitative system is illustrated by the following example: The engine is started at –5°C and it has a starting time of roughly 1.2 s. The corresponding correction factor for the temperature is –0.6393 s, as calculated with Equation 3.1. Adding the correction factor to the starting time of 1.2 s gives an adjusted start time of 0.5607 s, which is slightly worse than 0.519 s (the reference starting time at 96.5 °C). The difference is however not large enough for the start to fall under a different classification. A score of 7/10, from Table 3.4, is allocated to the start.

An additional characteristic that is of interest is the response of engine speed (or revolutions per minute (RPM), with regards to injection duration. Overshoot (OS) is defined as the maximum percent RPM overshoot above the idle speed after starting. Figure 3.5 shows this behaviour for three different measurements for three different injection durations. The more fuel injected, the higher is the RPM overshoot. It is important to realise this with regards to calibration for start time. The more fuel injected, the higher is the initial slope of the engine speed with initial combustion, resulting in a faster start time. However, it was assumed that excessive RPM overshoot is not perceived as favourable since it is audible.

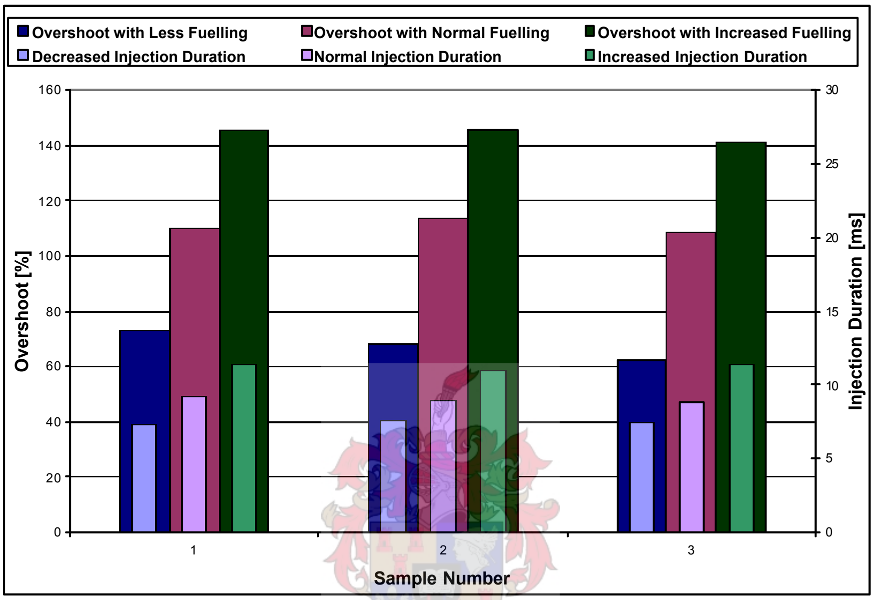


Figure 3.5: RPM overshoot vs. injection duration

Figure 3.6 shows the effect of engine coolant temperature on the measured RPM overshoot. The best start result will be a short start time with a low RPM overshoot. The graph represents all the different starting conditions and corresponds to Figure 3.5 for the increased and decreased injection durations.

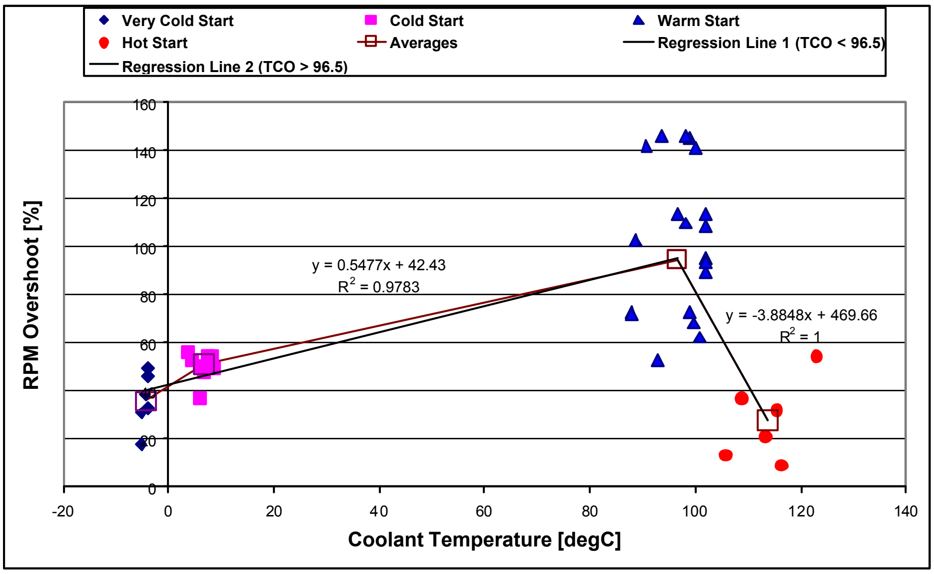


Figure 3.6: RPM overshoot vs. coolant temperatures

Different coolant temperatures lead to different RPM overshoots. Equation 3.2 was formulated, with a piecewise linear regression equation and from the data collected in Appendixes C1 and C2, to adjust the percent overshoot to a reference coolant temperature to be evaluated for a driveability score. The calculated factor, $\%OS_{TCO}$, needs to be added to the measured overshoot, as explained, with the start time evaluation. The result will provide a single value, independent of coolant temperature, to be evaluated for a score.

$$x_1 = TCO \qquad x_2 = \begin{Bmatrix} 0 & if & x_1 < 96.5 \\ 1 & if & x_1 \geq 96.5 \end{Bmatrix}$$

$$t_{OS} = b_0 + b_1 x_1 + b_2 (x_1 - 96.5) x_2$$

$$where \quad b_1 = m_1 \quad and \quad b_0 = c \quad from \quad y = mx + c \quad and \quad b_2 = m_2 - m_1$$

$$t_{OS} = -[42.43 - 0.5477 * TCO - 4.4325(TCO - 96.5)x_2] - 94.8 \tag{3.2}$$

Equation 3.2 does not represent the theoretical overshoot response with regards to coolant temperature. It was developed with limited measurement points. It still needs to be refined with a larger population of data. Table 3.5 presents the driveability overshoot index. The measured percent overshoot corresponds to a score. The higher the overshoot the more unfavourable the perception of the vehicle, since RPM overshoot is audible. The RPM overshoot must be as low as possible while still providing good after-start behaviour. Decreasing the starting time will increase the RPM overshoot. A good relationship can be found with the correct fuelling and timing. The index shown in Table 3.5 was developed from the responses from different measurements and subjective inputs from calibration engineers. Again, this table can be further refined with a larger spread of data.

Table 3.5: Driveability start RPM overshoot index

Driveability standard	Objective Driveability Index	Subjective rating	Overshoot [%]
Favourable	10	Excellent	< 80
	9	Very good	80 to 90
	8	Good	90 to 100
Acceptable	7	Acceptable	100 to 110
	6	Neutral	110 to 130
	5	Tolerable	130 to 180
Unacceptable	4	Poor	180 to 200
	3	Bad	200 to 220
	2	Very bad	> 220
	1	Catastrophic	Failed start

Retarding the timing also assists the start of the engine. The electric starter turns the engine at ± 250 rpm. Most engines idle between 650 and 1000 rpm. When the engine starts, it goes through its natural frequency between cranking and idle. This leads to jerks that are experienced by the driver. If the engine is properly damped then the driver will only experience small jerks (Probst, 1991). Jerk is the derivative of acceleration, or can be explained as the change of acceleration with time. The human body is susceptible to jerk. Jerk is explained in more detail in Section 3.5 (Acceleration behaviour).

The battery voltage must be high enough during start so as not to allow the engine management to compensate with injection duration. Some engine management systems have a learnt adaptation value to compensate for starting conditions with regards to previous starting results. If the start response is below the bottom limit then the ECU will inject more fuel during the next start and if the start behaviour is above the top limit then the ECU will inject less fuel. The test operator must be familiar with all the adaptations and the functionality of the system. For base evaluations these adaptations have to be cleared to ensure repeatability.

Friction is also high during start conditions since little to no oil is present on the cylinder walls. The oil's viscosity decreases with an increase in temperature and increases with pressure. This implies that the oil's temperature needs to increase to ensure better lubrication (Ferguson, C and Kirkpatrick, A, 2001) and better oil distribution.

Higher fuel volatility will increase the fuel economy since less enrichment is necessary to ensure good start behaviour. Volatility assists the starting of an engine under different engine temperature conditions. The design of the fuel delivery system is critical to prevent unnecessary vapour formation, but still deliver good cold-start results. The vapour pressure of a fuel is subjected to the fuel delivered by the oil refineries. The refineries are allowed to distribute fuel with a vapour pressure between an upper and lower limit, regulated by law. It is important to know the Reid Vapour Pressure (RVP) of the fuel used for testing.

When different fuel volatilities are tested with regards to starting behaviour then care must be taken to ensure all the previous fuel is drained. Specialised equipment is required to achieve a clean and safe fuel swap. Figure 3.7 shows the relationship between RVP and start time, recorded at 7 °C. A vehicle with normal fuelling and a similar vehicle with increased fuelling were evaluated. Increasing the fuelling at this engine temperature, and with a high RVP fuel, does not result in significant changes. The high RVP fuel evaporates more easily and additional fuelling is not required. Start adaptation functions allow the engine management system to compensate for different RVPs and allow vehicles to have the same start time. The adaptations get cleared before each start and therefore a compensation factor should be included in the evaluation.

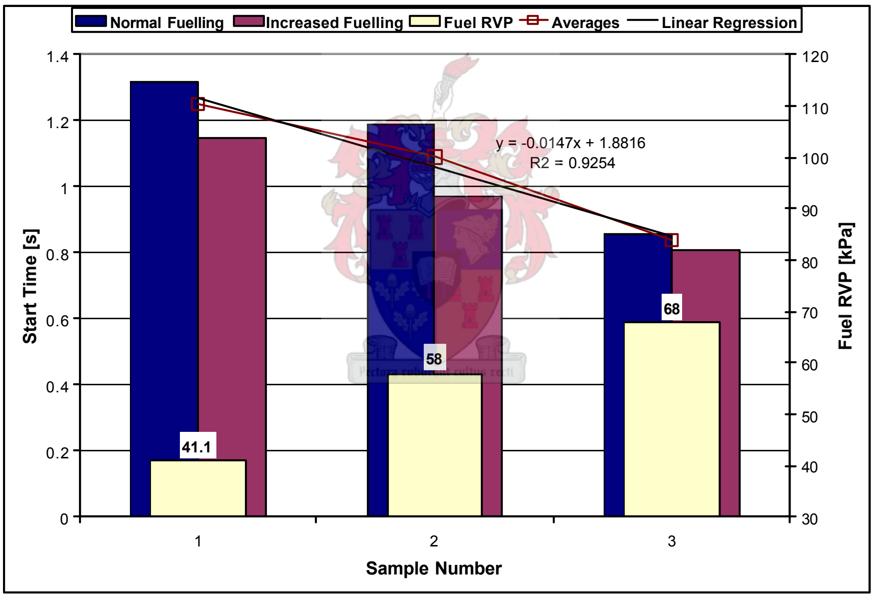


Figure 3.7: Injection duration vs. starting time with three different RVP fuels

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The driveability score includes a factor to compensate for RVP. The factor was developed from a linear regression equation. The factor must be added to the start time. The factor indicates that the start time is roughly 0.4 s shorter between a fuel with a RVP of 68 kPa and a fuel with a RVP of 41.1k Pa. The factor is calculated with the following formula:

$$t_{RVP} = [-0.0147 * RVP + 1.8816] - 1.09 \qquad (3.3)$$

Equation 3.3 is a representation of how the model will calculate compensation for RVP. Again this equation needs to be refined with a larger population of data.

3.3.2 Driveability start index

The measured start time (t_{sm}), coolant temperature (TCO), fuel RVP and measured percent RPM overshoot ($\%OS_m$) are used to calculate the driveability start score. First the start time needs to be calculated with Equation 3.4

$$t_s = t_{sm} + t_{TCO} + t_{OS} + t_{RVP} \tag{3.4}$$

Then the %OS must be determined with Equation 3.5.

$$\%OS = \%OS_m + \%OS_{TCO} \tag{3.5}$$

From Equations 3.4 and 3.5, a driveability score is obtained for each of the two starting evaluations. By combining these two scores a total driveability start index can be determined. Starting time is much more important than RPM overshoot and must therefore be given a higher weighting. If the vehicle has a bad start then it should immediately have a low driveability score. The RPM overshoot is a function of starting time and will not have a direct effect on the driving response of the vehicle. It should however be evaluated on its own since it will be noticeable if the response is poor. The weighting factors are subjective values obtained from calibration engineers and the author as well as assumptions made from literature and test results. Equation 3.6 provides the final driveability score for start behaviour (DSI).

$$DSI = 0.8 * DSI_{st} + 0.2 * DSI_{\%OS} \tag{3.6}$$

The driveability start index allows the engine management to be evaluated for its starting response. The engine is started at a certain coolant temperature, where the starting time and overshoot are measured. The latter are then corrected with equations to be independent of engine temperature. This method allows different starting temperatures to be compared and evaluated.

The next section describes the different start conditions, the test procedures and results for measuring an engine's start behaviour.

3.3.3 General start test procedure

The vehicle's start response must be measured to allow for quantitative driveability evaluation. Table 3.6 is a list of all the important variables that have an effect on fundamental engine management calibration, as well as the general different starting conditions. The list was formulated from a combination of literature and investigations.

The general start test procedure is as follows:

- Cool the vehicle and engine to the desired temperature.
- Check to ensure that the heating/ cooling fan is switched off, as well as the lights, radio and rear demister.
- Ensure that the measuring equipment is switched on and running.
- Crank the engine until the engine starts without engaging the accelerator pedal.

The idea of this test is to see how long the engine will take to have initial combustion and to measure the engine response directly thereafter.

Table 3.6: Start conditions with measured variables

	Measure	Evaluate for
Cold Start	**Coolant temperature range**	**–30degC to 45degC and engine not started for 12 hours prior to test**
	Engine speed	Time the engine speed takes to reach operating point
	Battery voltage	Significant change when the selfstarter engage
	Idle speed setpoint	Reference for the behaviour of the engine speed
	Engine coolant temperature	To ensure the test is conducted under the right conditions and to ensure repeatability
	Ambient temperature	To ensure the test is conducted under the right conditions and to ensure repeatability
	Inlet temperature	To ensure the test is conducted under the right conditions and to ensure repeatability
	Pedal position	To ensure the test is conducted under the right conditions and to ensure repeatability
	Throttle position	Airflow strategy
	Manifold Absolute Pressure	Airflow strategy
	Air-fuel ratio (Lambda)	Fuel strategy
	Injection time	Amount of fuel added
	Ignition angle	Ignition strategy
	Acceleration	Jerks
Warm Start	**Coolant temperature range**	**45degC to 95degC (Operating condition)**
	Engine speed	Time the engine speed takes to reach operating point
	Battery voltage	Significant change when the selfstarter engage
	Idle speed setpoint	Reference for the behaviour of the engine speed
	Engine coolant temperature	To ensure the test is conducted under the right conditions and to ensure repeatability
	Ambient temperature	To ensure the test is conducted under the right conditions and to ensure repeatability
	Inlet temperature	To ensure the test is conducted under the right conditions and to ensure repeatability
	Pedal position	To ensure the test is conducted under the right conditions and to ensure repeatability
	Throttle position	Airflow strategy
	Manifold Absolute Pressure	Airflow strategy
	Air-fuel ratio (Lambda)	Fuel strategy
	Injection time	Amount of fuel added
	Ignition angle	Ignition strategy
	Acceleration	Jerks
Hot Start	**Coolant temperature range**	**Temperatures above operating condition**
	Engine speed	Time the engine speed takes to reach operating point
	Battery voltage	Significant change when the selfstarter engage
	Idle speed setpoint	Reference for the behaviour of the engine speed
	Engine coolant temperature	To ensure the test is conducted under the right conditions and to ensure repeatability
	Ambient temperature	To ensure the test is conducted under the right conditions and to ensure repeatability
	Inlet temperature	To ensure the test is conducted under the right conditions and to ensure repeatability
	Pedal position	To ensure the test is conducted under the right conditions and to ensure repeatability
	Throttle position	Airflow strategy
	Manifold Absolute Pressure	Airflow strategy
	Air-fuel ratio (Lambda)	Fuel strategy
	Injection time	Amount of fuel added
	Ignition angle	Ignition strategy
	Acceleration	Jerks

3.3.4 Cold start

Cold start ranges from –30 °C, called cold-cold, to 45 °C, called warm-cold. Prior to cold-start testing the vehicle has to be cold soaked in a climatic chamber (the engine coolant temperature and oil temperature are in equilibrium with the room temperature) at the desired temperature for more than 8 hours before it is started again (Probst, 1991). In common terms, the temperature needle on the dashboard will be at its rest position at the low end of the gauge. For Environmental Protection Agency (EPA) testing, their cold start is defined at 20 °C room temperature, and the engine must have been cold soaked for approximately 12 hours before the test (Office of Transportation and Air Quality, 2006).

Gasoline engines require excess fuel to start in cold conditions since some of the fuel is unlikely to vaporise and is likely to condense on the walls of the cold intake manifold, intake port and inlet valve, and on the cylinder and cylinder walls (more commonly known as wall wetting). Cold-start enrichment quickly becomes a problem if the engine does not start right away since the enrichment will lead to the spark plugs being fuel-fouled. This implies that either the spark plug is so soaked in fuel that the current uses the fuel as a conductor (less resistance than air), causing a misfire, or small carbon deposits are formed between the two electrodes, caused by localised burning, since there is not enough energy to initialise the desired thermodynamic reaction. The carbon deposits will reduce the spark plug gap, reducing the heat transfer to the air gap. After a failed start the spark plugs need to be replaced or cleaned to ensure repeatability.

Higher fuel volatility assists the starting of an engine under cold conditions. Rich fuel mixtures are applied during cold operating conditions to ensure that there is enough fuel for the engine to start. Cold starting time is reduced with a higher volatility fuel.

Retarding the ignition timing can help the start of a cold engine. For an engine that turns slowly because of viscous, cold oil in the crankcase, high friction or reduced battery voltage at cold temperatures, the best ignition timing is near top dead centre (TDC).

3.3.4.1 Cold-start test procedure

The cold-start test procedure is evaluated at temperatures below 45 °C. The vehicle must be able to start just as well at low temperatures as at warm temperatures for the driveability to be acceptable. The cold-start testing procedure and results are described and presented here.

The vehicle and engine must cool down to the desired ambient temperature. The vehicle must remain at that temperature for approximately 12 hours prior to the test. The vehicle must be started as described in the general testing procedure (Section 3.3.3).

For extreme cold conditions it is important not to engage the handbrake before the vehicle is conditioned since the brake pads might freeze onto the disk. Another important aspect to remember is not to spray water on the windscreen since the water will freeze. After a cold start the oil temperature has to warm up to above 80 °C for the water of condensation, formed as a by-product from combustion, and from the fuel, due to over fuelling, to evaporate from the oil. It is therefore important to run the engine hot after a cold start, especially if the engine needs to be restarted for another cold start.

Figure 3.8 shows the relationship between very cold (approximately –5 °C) starting times with regards to injection duration. Two similar vehicles were compared during each evaluation, using fuel with the same RVP. The one vehicle had a 10% increase in base injection duration. The slight variance of 10%, from the measured results, is from other calculated factors such as compensation for battery voltage, ambient air, etc. Figure 3.8 illustrates the repeatability of the results. It is clear that the increased injection duration leads to a shorter starting time. It is important to note that if too much fuel is injected then the spark plugs may foul. It is also important to compensate for the extreme rich mixture when some of the excess fuel starts to evaporate during the after-start period, since the over fuelling might lead to the engine smoking and hunting. This will be discussed in more detail for after-start evaluation. The start times displayed below have not been corrected with Equation 3.1.

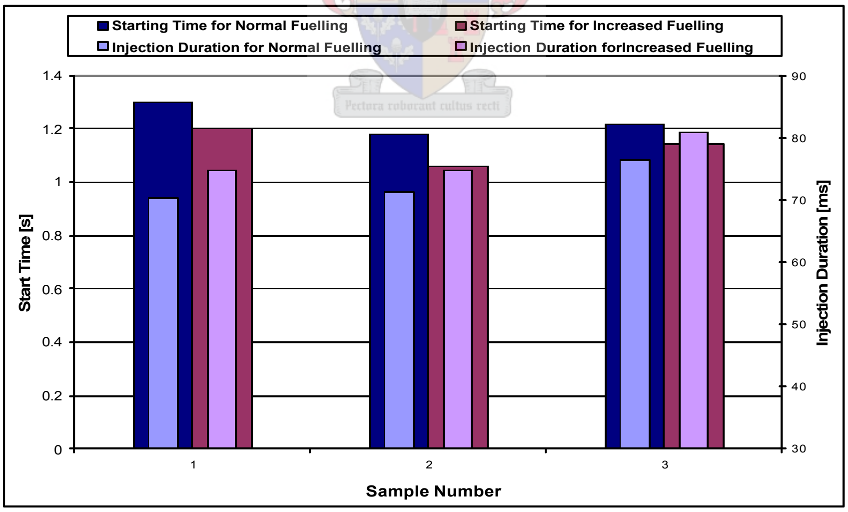


Figure 3.8: Very cold (-5 °C) start times vs. injection duration of three test cases with two fuelling strategies to illustrate repeatability

Figure 3.9 shows the relationship between cold (approximately 7 °C) start time and injection duration. Again an increased injection time leads to a shorter starting time. The starting time is not only dependent on injection duration, but also on other factors such as ignition timing, mass airflow and temperature. Therefore Figure 3.9 shows that injection durations for the richer mixture in sample one and the leaner mixture in sample two are almost the same, but their starting times are different. The reason for this is that the coolant temperature was slightly colder in the case of sample two. Table 3.7 displays typical results for an example of cold start, followed by a short sample calculation for the driveability start index.

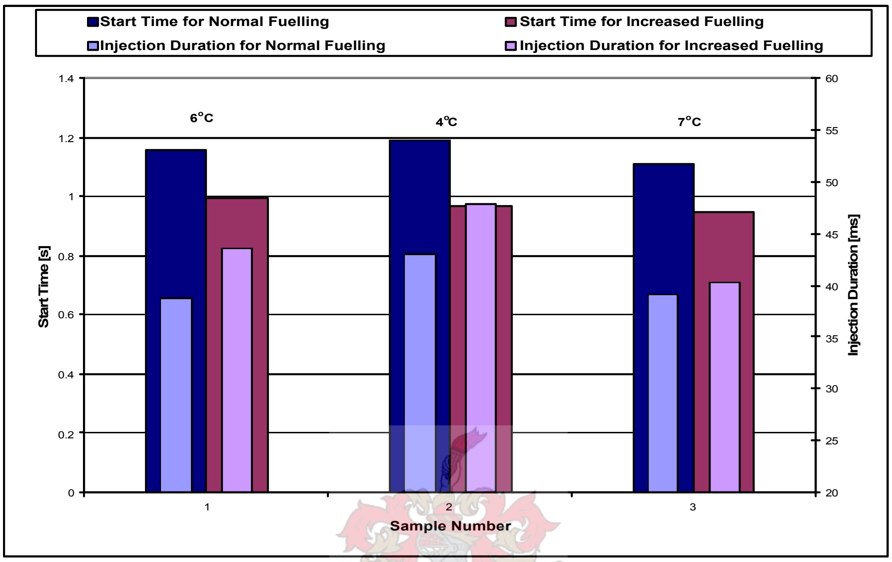


Figure 3.9: Cold-start (7°C) times vs. injection duration of three test cases with two fuelling strategies to illustrate the effect of small temperature variations on repeatability

Table 3.7: Measured example of cold start

Measured Variable	Units	Measured Value	Adjusted Values for Engine Coolant Temperature [Eq. 3.1 and Eq. 3.2]	Adjusted Values for RVP [Eq. 3.3]	Driveability Score [Table 3.4 and 3.5]	Driveability Classification
Fuel RVP	kPa	60				
TCO	[DegC]	-3.8				
Start Time	[s]	1.2	0.57	0.48	8	Good
Idle Speed Setpoint	[RPM]	977				
Max RPM Over shoot	[RPM]	1297				
RPM Overshoot	[%]	32.75	83.48		9	Very Good

$$DSI = 0.8*8+0.2*9$$

$$DSI = 8.2$$

The results obtained from the above calculation classify the evaluation as a very good response. An example of a complete driveability evaluation is presented in section 4.4. The following subsections of start response are calculated in the same manner as this example.

3.3.5 Warm start

Warm starting is defined as starting the engine from hot-cold, at a coolant temperature of about 45 ^{o}C, to operating temperature, at about 90 ^{o}C (Probst, 1991). In this case the engine has most likely been switched off for a short period of time and has not yet had time to cool down to ambient temperature. The warm engine promotes fuel vaporisation and less fuel will condense on the warm walls of the intake manifold, intake port and inlet valve, cylinder and cylinder walls. A slight enrichment will improve warm starting.

3.3.5.1 Warm-start test procedure

Warm start is a common condition for starting a vehicle. It is therefore important to have acceptable start behaviour during this start condition. The following procedure describes the general testing procedure, described in Section 3.3.3, in more detail.

The engine must be warmed up until it reaches an operating temperature of ± 90 ^{o}C before the ignition is switched off. The engine must cool down to the desired testing temperature. If the ambient conditions and engine bay are very hot then the engine temperature might rise before it starts to cool down, because of heat soak. Heat soak is when there is not significant cooling in the engine bay and the temperature inside the engine bay increases because of the high heat flux from the engine and exhaust. Start the engine as described in the general testing procedure (Section 3.3.3).

Warm-start results are presented in Figure 3.10. Again the increased fuelling led to shorter starting times. Excessive injection durations will lead to longer starting times. The optimum injection time for the shortest starting time is dependent on the combustion chamber design with regards to air flow, compression ratio, etc.

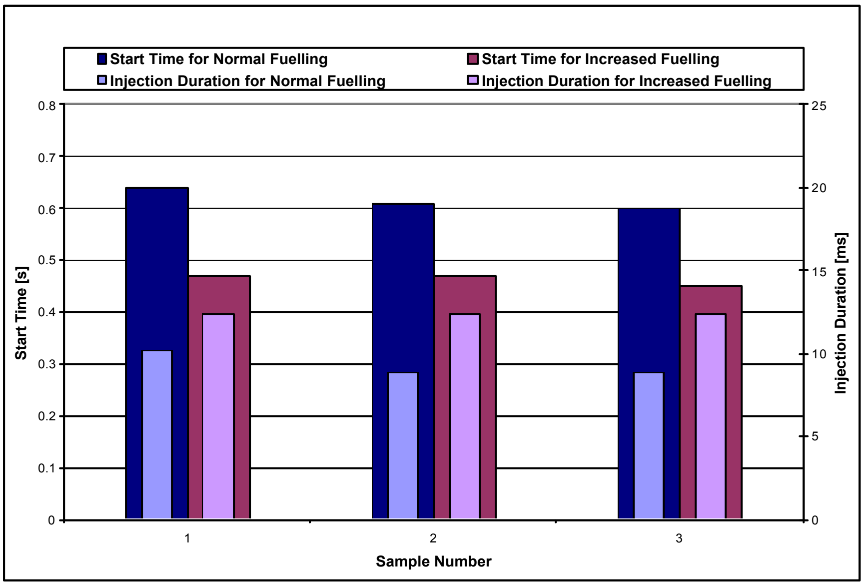


Figure 3.10: Warm-start (88 °C) times vs. injection duration for three test cases with two fuelling strategies to illustrate repeatability

3.3.6 Hot start

Under hot-start conditions the engine coolant is very hot (above 100 °C). The temperature in the engine bay may exceed 120 °C. Switching the engine off for a short period of time after the vehicle has been driven for some time on a hot day and not letting it cool down significantly before shut down may lead to heat soak. These warm conditions may lead to the vaporisation of fuel in the fuel lines and this might cause 'vapour lock'. The fuel lines and injectors must maintain pressure and receive enough fuel flow to ensure a quick hot start.

3.3.6.1 Hot-start test procedure

Hot start is a common phenomenon with warm ambient temperatures and hot engine bay conditions. This is the upper limit for ensuring the vehicle can start under all the required temperatures. The relevant test procedure is now described in more detail and the results obtained from a series of tests are discussed.

This test must be performed under controlled climatic conditions. Such conditions prevent the engine cooling down by means of forced convection (wind, etc.). Special heat-soak tents are used when the vehicle is parked in the sun. Ambient temperatures must range between 30 °C and 40 °C. The engine must be warmed up to its operating temperature and the engine bay temperature must exceed the coolant temperature. The cooling fan can be disconnected to achieve the desired temperatures. Start the engine as described in the general testing procedure (Section 3.3.3).

Figure 3.11 shows the results from hot-start tests. Again an increase in injection time did improve the starting time. It is difficult to obtain both the same engine bay temperatures as well as coolant temperatures for two similar vehicles simultaneously.

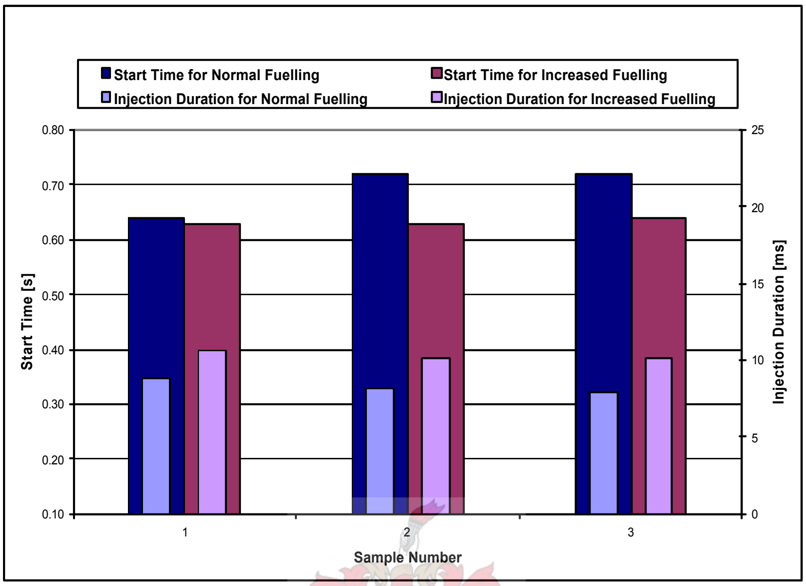


Figure 3.11: Hot-start times vs. injection duration of three test cases with two fuelling strategies to illustrate the effect of temperature variations on repeatability

In the case of sample number 1 in Figure 3.11 the starting times are similar. These results were because of a variance in engine bay temperatures and coolant temperatures between the tests. It is important to note that some results with increased injection duration did not always lead to shorter starting times. This is because the temperature and temperature distribution in the engine bay were not exactly the same each time, influencing the fuel temperature, inlet air temperature, coolant temperature, oil temperature and other factors. The difference was usually less than 0.1 s, which is considered insignificant. Figure 3.12 illustrates the variation in temperatures between hot-start measurements. It is clear that the soak duration as well as the warm-up procedure must be very precise in order to achieve the same heat release in the engine bay.

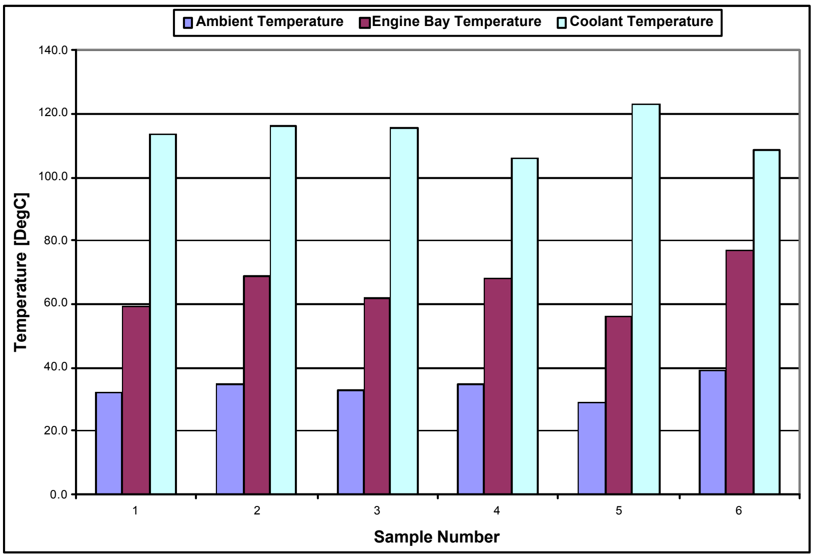


Figure 3.12: Variation in ambient, engine bay and coolant temperatures during hot-start conditions

All the data in this section describe the effects of various parameters such as fuel, temperature and injection duration on starting time, and what effects they will have on driveability evaluation. The driveability start evaluation model is also presented. The model described in this section, on how to evaluate start response, can be used together with the complete driveability model or on its own - just to evaluate starting behaviour. It is important to note that changing the engine management calibration with regards to start will either have a positive, negative or unchanged result. It is therefore not always necessary to compare it with the complete driveability start evaluation index, but just with a few previous tests on the same vehicle or engine. A higher driveability score compared to that of a previous test will show that an improvement was made on the calibration, and this will be a result on its own. Thus the procedure developed for the quantification of starting is also a useful tool for the optimisation of the engine management calibration.

3.4 Engine Idle Behaviour and Evaluation

The second criterion to be evaluated to determine driveability response was the idle and after-start behaviour of a vehicle. During urban driving much time is spend at idle. Waiting at a stop street or traffic light, or before any pull-away condition, or after a stop, are all situations where the engine is usually at idle. It is therefore important to have good idle behaviour and especially a good off-idle response.

3.4.1 Important factors influencing engine idle

Engine idle can be defined as the engine operating at the lowest possible speed that provides smooth operation and good response to throttle input during load change. Idle must provide acceptable engine noise and fuel consumption.

Figure 3.13 displays the idle evaluation measurement. The accelerator pedal is blipped after the engine speed reached steady state from the start period. This is followed by a short idle period. The auxiliary load (air conditioner, etc) is switched on after the engine speed has reached steady state again. The different sections and their evaluation methods are discussed in more detail in this section.

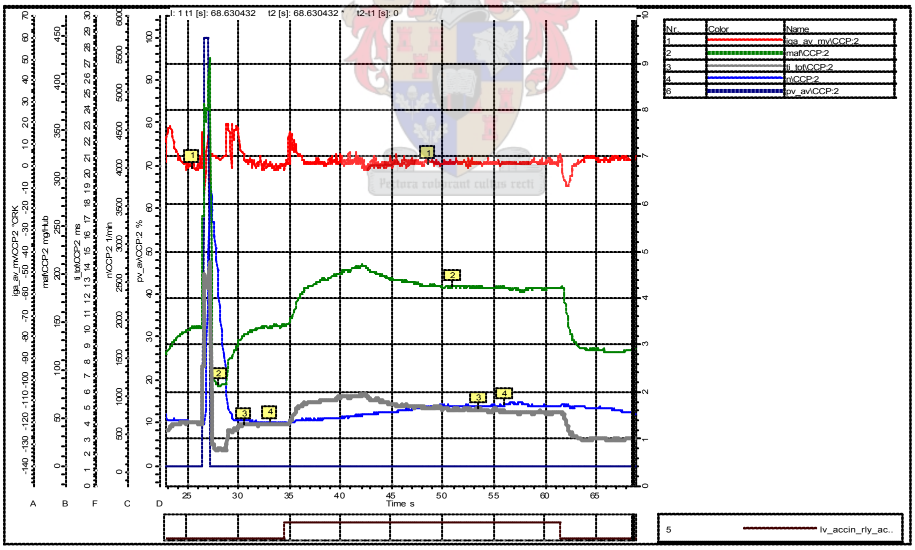


Figure 3.13: Idle evaluation measurement showing ignition angle (IGA_AV_MV), mass air flow (MAF), injection duration (TI_TOT), engine speed (N), accelerator pedal position (PV_AV), air conditioner switching (LV_ACCIN_RLY_AC)

Post-start operation usually only takes a few seconds, but it may last up to 20 seconds if the temperature is extremely cold. To ensure that the lambda sensor and catalytic converter operate at optimum conditions and as soon as possible, the ignition timing can be retarded to increase exhaust gas enthalpy. This operation leads to higher heat rejection to the exhaust system that causes the lambda sensor and catalytic converter to heat up to their operating temperatures more quickly. This is a trade-off against driveability since cycle efficiency is reduced, but it is necessary to pass emissions regulations. After-start fuelling is also important since the lambda sensor(s) are still warming up and the air-fuel ratio is open loop. The idle speed setpoint are also increased to assist the catalyst heating phase.

Different engine temperatures require different idle and post-start management. Cold temperatures require a richer mixture and higher engine speeds for smooth idle and good off-idle throttle response. Figure 3.14 shows the average idle speeds, at different operating temperatures, resulting from the test conducted for this evaluation.

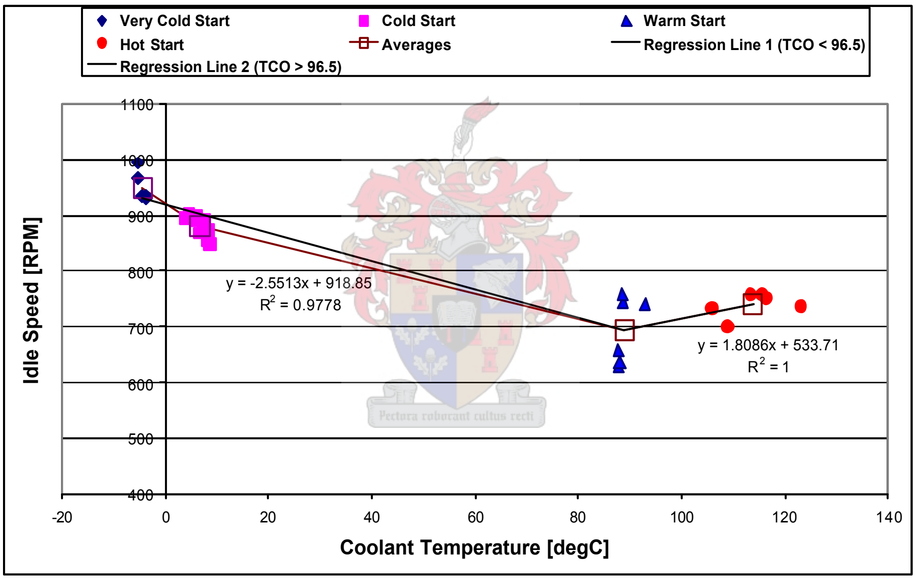


Figure 3.14: Measured idle speed at different operating temperatures

The idle speed set point values are calibrated as a reference value in the ECU for different operating conditions. The ECU will look at what the coolant temperature, load requirements, gear selection (if the vehicle is fitted with an automatic gearbox), and various other factors are, and then calculate what the idle speed should be.

All the test results related to idle evaluation are tabulated in Appendix C3. The same temperature conditions as those used and described in the previous section (Section 3.3) were evaluated. Idle and off-idle performances were determined by several measurements at the following temperatures: six measurements at very cold (-5 °C), ten at cold (5 °C), six at warm (90 °C) and six at hot (110 °C) conditions.

Equation 3.7, which represents the trend in Figure 3.14, allows the idle speed evaluation to be evaluated independent of coolant temperature. An idle speed correction is obtained by substituting the measured coolant temperature into Equation 3.7. Equation 3.7 is a piecewise regression trend line fitted to the measured data, and corrected to the reference temperature. The calculated result from Equation 3.7 is then added to the measured engine idle speed after an evaluation. If the result is above the 650 rpm then the measured idle speed is below average, and if it is below 650 rpm then it is above average. The same method was used to formulate all the correction factor equations described in this section.

$$x_1 = TCO \qquad\qquad x_2 = \begin{Bmatrix} 0 & if & x_1 < 96.5 \\ 1 & if & x_1 \geq 96.5 \end{Bmatrix}$$

$$N_{TCO} = \mathbf{b}_0 + \mathbf{b}_1 x_1 + \mathbf{b}_2 (x_1 - 96.5) x_2$$

$$where \quad \mathbf{b}_1 = m_1 \quad and \quad \mathbf{b}_0 = c \quad from \quad y = mx + c \quad and \quad \mathbf{b}_2 = m_2 - m_1$$

$$N_{TCO} = [918.85 - 2.5513 * TCO - 4.36(TCO - 96.5)x_2] - 694.5 \tag{3.7}$$

The measured engine response was used to develop Equation 3.7 since no data in any literature allows for idle speeds to be compared independent of engine coolant. Again a single value needed to be used since it will simplify the driveability evaluation. The data analysis will become too complex and time consuming if the measured speed has to be compared to a reference speed at different temperatures, stored in some database. Equation 3.7 is not a theoretical representation of idle speed with regards to coolant temperature. It is at this stage still a guideline and needs to be refined with a larger population of data. The optimum idle speed at 40°C might be lower than what the model predicts as very good and will result in a high score when the score should have been lower.

A corresponding idle speed driveability score is allocated to the results, as presented in Table 3.8. Note that a too low idle speed increases the chances of a poor off-idle response, which may lead to engine stall, etc. The table was developed in the same manner as the start index tables (with regards to interpolation of data and assumptions on how drivers will experience the response). A high engine idle speed is audible and therefore noticeable, and undesirable, even if a higher idle speed is required for catalyst heating. If a vehicle idles at 600 rpm in comparison to 1200 rpm, it turns half the amount of revolutions, and therefore uses significantly less fuel. If the engine stalls during pull away then it will receive an unacceptable score in that section, therefore the engine stall condition was not included in Table 3.8.

Table 3.8: Driveability index for idle speed

Driveability Standard	Objective Driveability Index	Subjective Rating	Idle Speed [RPM]
Favourable	10	Excellent	< 600
	9	Very good	600 to 625
	8	Good	625 to 675
Acceptable	7	Acceptable	675 to 725
	6	Neutral	725 to 850
	5	Tolerable	850 to 950
Unacceptable	4	Poor	950 to 1100
	3	Bad	1100 to 1300
	2	Very bad	1300 to 1500
	1	Catastrophic	>1500

Much time in a vehicle is spent at idle and it is therefore beneficial to have the shortest possible injection duration to maintain good engine response in order to achieve low fuel consumption. The total injection duration decreases as the coolant temperature increases. It is therefore very difficult to obtain a reference injection duration with which to evaluate after-start fuelling. The average injection duration between steady-state idle (after the start overshoot) and where the pedal input is received can be used for comparison. Unfortunately the period between after-start idling and pedal blip did vary during the evaluations that were carried out. Accurate comparisons will require a system to control the pedal input to keep the period between after-start idling and pedal blip constant.

Engine speed must remain as steady as possible at all times during idle. Idle-speed hunting is the phenomenon when the engine speed fluctuates around an average speed. This is irritating, especially if it is audible. Idle speed set-point changes when the engine warms up and must be unnoticeable by the driver; it must therefore be gradual. Figure 3.15 shows good steady-state idle behaviour after cold start. The mean is calculated as 883 rpm and the slope is -1.5 rpm/s. The slope is the gradient at which the rpm is reduced due to the engine warming up. It was calculated by fitting a straight line (y = mx+c) through the response. During warm after-start conditions the slope can change much faster since the coolant temperature is close to operating temperature. The standard deviation (STD) for this figure is calculated to be 8.36 rpm. The standard deviation is an indication of how closely the signal follows the mean.

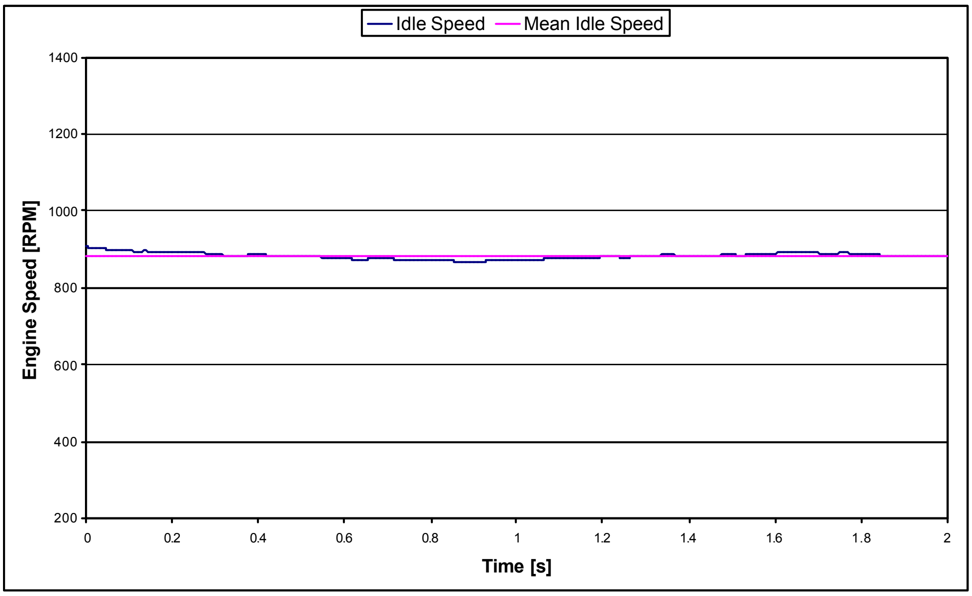


Figure 3.15: Favourable steady-state idle speed response

Figure 3.16 shows an example of where the engine speed has hunted around a mean of 873 rpm. The slope was calculated as 2.73 rpm/s and the standard deviation as 158 rpm. This hunting phenomenon occurred when the after-start fuelling was too rich and the response of the idle speed controller was too abrupt. Such behaviour is unacceptable.

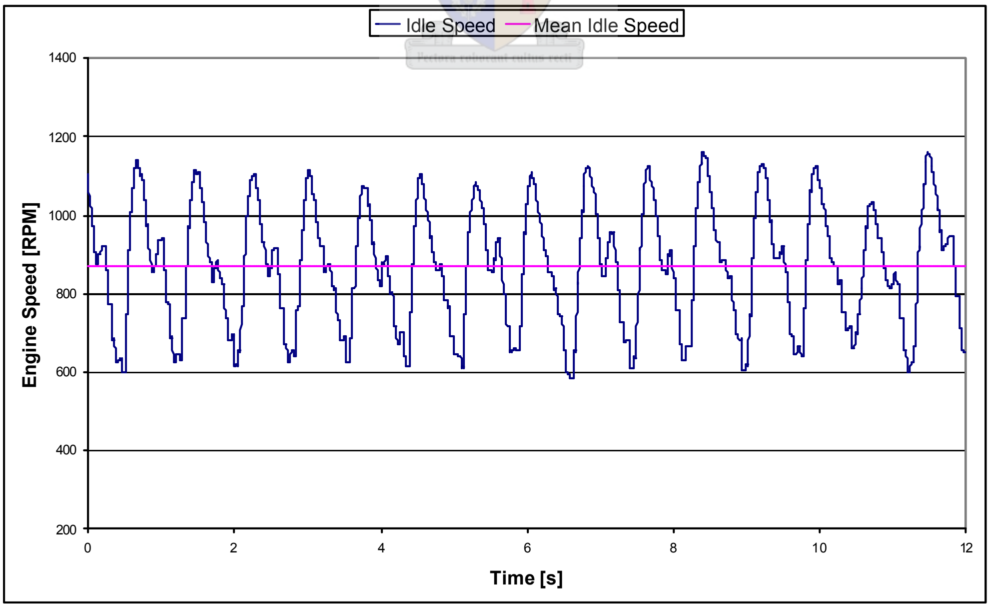


Figure 3.16: Unacceptable hunting during idle speed response

The standard deviation must be as small as possible. A large slope will have a large value for standard deviation during steady-state idle. Hunting will also significantly increase the standard deviation. The period during which standard deviation is calculated must be the same between measurements since the idle speed decreases as the engine warms up.

The classifications from Table 3.9 were determined from the measured data. No data for the standard deviation during idle speed is available in the literature. The results from the measured data were sorted and subjectively classified. An example of this sorting process is discussed with Figure 3.16. It is clear that the results are unacceptable and it was assumed that any driver will experience this as unfavourable. The data is therefore sorted appropriately with other measurements (from unacceptable to acceptable). If no data were available then the values were interpolated. The accuracy of this classification can be improved by increasing the population of data. The current classification was however accurate enough for this research project.

Table 3.9: Driveability idle speed standard deviation index

Driveability Standard	Objective Driveability Index	Subjective Rating	Standard Deviation [RPM]
Favourable	10	Excellent	0 to 2
	9	Very good	2 to 4
	8	Good	4 to 6
Acceptable	7	Acceptable	6 to 10
	6	Neutral	10 to 20
	5	Tolerable	20 to 40
Unacceptable	4	Poor	40 to 60
	3	Bad	60 to 80
	2	Very bad	> 80
	1	Catastrophic	Engine stall after start

Idle speed must also remain as steady as possible when the load is changed. Typical examples of load changes during idle include switching on the air conditioner, radio, headlights, rear demister, etc. Engine management compensation for a load change must ideally be unnoticeable to the driver. During cold conditions the idle set speed is much higher than under warmer conditions. The engine speed should therefore be high enough so as not to change its idle set speed when a load is engaged. Under warmer conditions the engine set speed is too low to drive the extra load of the alternator and still provide good off-idle response. The engine speed cannot immediately be increased since it might lead to the vehicle responding unfavourably (e.g. jerking forward during pull away condition). It will also become audibly noticeable to the driver if the engine speed suddenly increases. Figure 3.17 displays the load request response on engine speed.

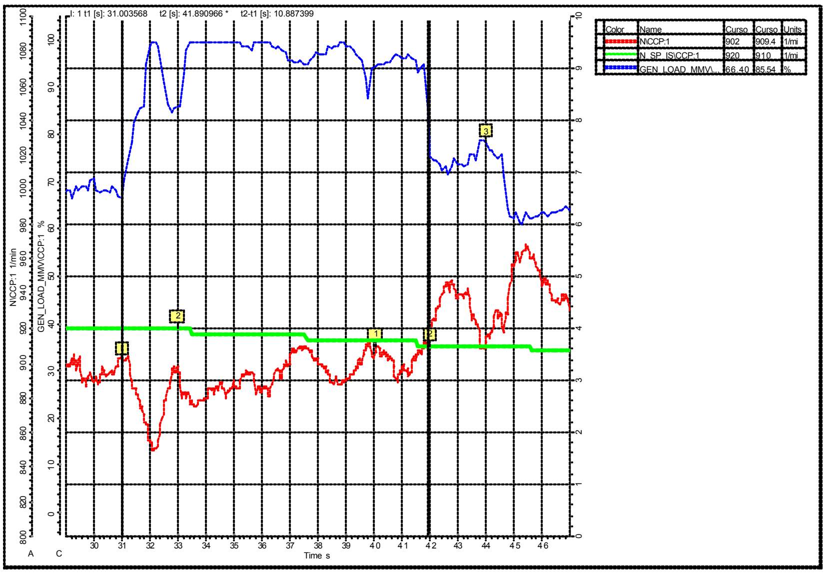


Figure 3.17 Idle load response measurement showing engine speed (N), idle speed set point (N_SP_IS), general load request (GEN_LOAD_MMV)

Equation 3.8 is used to calculate the correction factor for load change with regards to engine coolant temperature. The maximum percentage change in engine speed must be calculated during the load change period. It is then divided by the period it takes to reach the maximum speed change from the initial load request. That result is added to the result of Equation 3.8 to provide a result that is independent of engine coolant temperature.

$$LC_{TCO} = [-0.0538 * TCO + 7.1732] - 2.3 \qquad (3.8)$$

Figure 3.18 displays the measured data. No load factor change variable was measured during the hot evaluation. The equation was developed from a linear regression trend line.

Table 3.10 is used to allocate a driveability score for load change behaviour with regards to engine speed. A small percentage change will result in a smaller value, which is more favourable. If the percentage change is large, but it is over a long period of time then it is not noticeable either and will result in a small score as well.

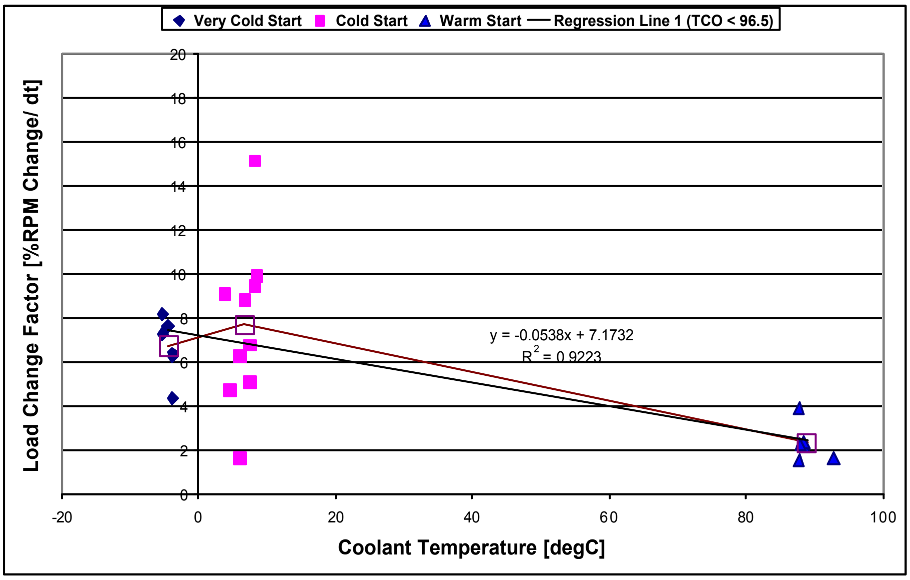


Figure 3.18: Measured load change factors at different operating temperatures

Equation 3.8 and Table 3.10 were produced after combining all the measured data and evaluating the response. It was assumed that drivers will experience a quick increase in engine speed as unfavourable. There is no engine speed change response to load demand data available in the literature. The model had to be developed to determine its effect on driveability. The theory behind the model is applicable to all vehicles, but unfortunately the model was only developed with one vehicle.

The different measurements were sorted, using the results from Equation 3.8. The classifications and scores were then subjectively allocated to the results. Where no results were available an interpolation was used to obtain values. Table 3.10 can be refined with a larger population of data, but for this project it provided good quantitative and comparable results.

Table 3.10: Driveability idle speed index for change in load

Driveability Standard	Objective Driveability Index	Subjective Rating	Rate of Change of Idle Speed during Load Change [%RPM Change/dt]
Favourable	10	Excellent	0 to 1
	9	Very good	1 to 1.5
	8	Good	1.5 to 2
Acceptable	7	Acceptable	2 to 5
	6	Neutral	5 to 10
	5	Tolerable	10 to 20
Unacceptable	4	Poor	20 to 30
	3	Bad	30 to 40
	2	Very bad	> 40
	1	Catastrophic	Engine stall after load engage

Pedal response is another important factor during warm up and off-idle response. The engine needs to respond as quickly as possible to the driver's demands, while also delivering good behaviour. The rate of change of pedal input has a significant effect on the rate of change of engine speed. During this evaluation the pedal input was provided by the driver and was therefore not the same for each pedal blip/tip-in. It is impossible to have a repeatable rate of change for pedal input for each evaluation since humans cannot repeatedly provide the same amount of force at a fixed rate. Better comparative results would have been obtained if the rate of change of pedal input could be better controlled, for example by an external system. For future evaluation it is proposed that a device be constructed to provide the same rate of change.

The rate of change of pedal input is defined as the maximum pedal input divided by the time the pedal takes to reach this value. Rate of change of engine speed is defined as the maximum measured RPM divided by the time the engine speed takes to reach this value. It is therefore obvious that a higher value will indicate a better response. In order to be able to compare all these values the ratio of rate of change of engine speed to rate of change of pedal input was calculated. Equation 3.9 must be used to calculate the pedal response. The measured pedal response is roughly the same for all coolant temperatures.

$$dN/dPV = \left(\frac{dN}{dt} \Big/ \frac{dPV}{dt} \right) \qquad (3.9)$$

Equation 3.9 was developed from the measured data. There is currently no engine speed response to pedal input with reference to coolant temperature data available in the literature and a comparative model had to be developed for this project. The theory behind the development is straightforward and can be applied to any engine. Unfortunately only one vehicle's response could be used to develop this model. If more data were available a better representative reference model could be developed. The evaluation model is however not limited since any vehicle's response can be directly compared to a quantitative value, only the accuracy can be improved. A better pedal controlled pedal input will allow for more accurate measurements.

Table 3.11 provides the driveability score for rate of change of engine speed to pedal blip rate. The values in the table were developed from results from measured data as well as from subjective judgments. It was assumed that if a driver has a very quick engine speed request (with the rate of pedal change as input) then he will expect the engine to react accordingly.

Table 3.11: Driveability idle speed index for rate of change of engine speed to pedal blip

Driveability standard	Objective Driveability Index	Subjective Rating	Ratio between Rate of Change of Engine Speed to Pedal Input [dN / dPV]
Favourable	10	Excellent	> 30
	9	Very good	25 to 30
	8	Good	20 to 25
Acceptable	7	Acceptable	15 to 20
	6	Neutral	10 to 15
	5	Tolerable	5 to 10
Unacceptable	4	Poor	2 to 5
	3	Bad	>0 to 2
	2	Very bad	< 0
	1	Catastrophic	Engine stall after blip

Figure 3.19 shows the variation for the rate of change of pedal input measured during cold idle to illustrate the requirement for a system where a better control of pedal input is required. The average time of rate of change of pedal was calculated at 0.33s, and for maximum pedal of 100% this implies that the average rate of pedal change is 300. It is however impossible for a human to provide this value with every test. The delay of the air path does not allow for the engine speed to change instantaneous and a larger change in engine speed will increase the period of change.

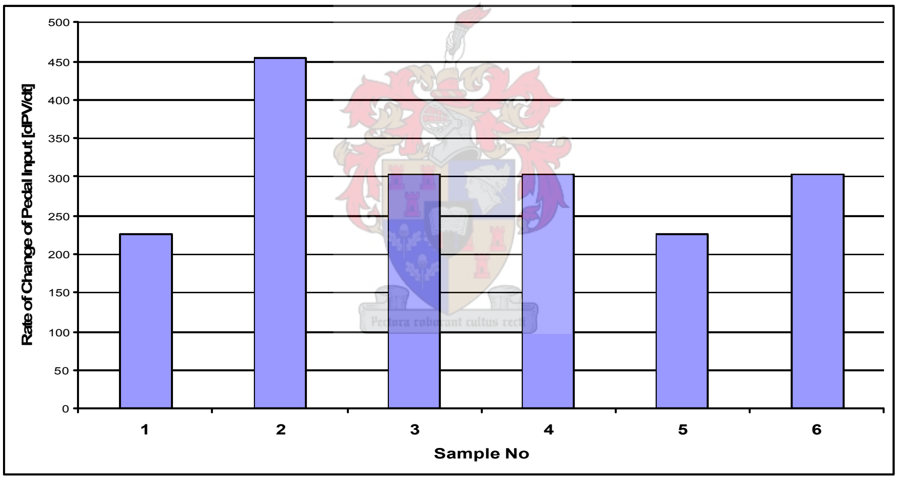


Figure 3.19: Variance of rate of pedal change

The idle response after braking is also of importance with respect to driveability evaluation. The same evaluation method was used as in the case of the steady-state idle response. The idle response was evaluated with regards to standard deviation. Table 3.8 was used to quantify the idle response after braking.

3.4.2 Driveability index for idle

The driveability score for idle operation is calculated by combining the idle speed, the idle speed response during steady state, the idle speed response during load change and the pedal blip response. The idle speed set point is calculated by adding the temperature correction factor for idle speed (N_{TCO}) to the measured idle speed, as in Equation 3.10. An example of an evaluation is presented in section 4.4.

$$N_{idle} = N_{TCO} + N_m \tag{3.10}$$

The effect of load change is calculated by determining the maximum percentage change in engine speed ($\%N_{change}$) during load change divided by the time it took to reach the change (t_{Nc}). The result is added to the temperature correction factor (LC_{TCO}), as displayed in Equation 3.11.

$$LC = {}^{\%N_{change}}\!\!\diagup_{t_{Nc}} + LC_{TCO} \tag{3.11}$$

Equation 3.9 shows that the pedal blip factor (dN/dPV) is calculated as the rate of change of engine speed (dN/dt) divided by the rate of change of pedal input (dPV/dt).

$$dN\!\diagup_{dPV} = \left(\frac{dN}{dt} \Big/ \frac{dPV}{dt} \right) \tag{3.9}$$

A driveability score is obtained from Equations 3.10 to 3.12 as well as for the standard deviation of the idle speed after start and braking. Adding these scores yields a driveability score for idle response (DII) as formulated in Equation 3.12.

$$DII = 0.2 * DII_{Nsp} + 0.3 * DII_{STD} + 0.2 * DII_{LC} + 0.2 * DII_{\frac{dN}{dPV}} + 0.1 * DII_{Brake} \tag{3.12}$$

The standard deviation factor is weighted the highest since having a vehicle that hunts is more unacceptable than a vehicle with a slow pedal response. No data are available to quantify the relationship between the various factors of idle response. The weighting factors are subjective values and were determined from analysing the test data. More accurate relationships can be determined if more test data were available.

The driveability brake response index is a combination of the idle response during braking (DII_{BDI}) and after braking (DII_{BAI}), as in Equation 3.13. The driver is more focused on the brake behaviour of the vehicle during braking than on the idle response. After the vehicle has stopped then the response of idle speed is more significant. Table 3.9 used to obtain the standard deviation score of the idle response.

$$DII_{Brake} = 0.6 * DII_{BAI} + 0.4 * DII_{BDI} \tag{3.13}$$

The driveability index for idle allows the engine management to be evaluated for its idle behaviour. Idle is evaluated at different coolant temperatures with different responses to driver inputs. The measured values are manipulated by a factor to allow for one value, independent of coolant temperature, to be compared with a reference value and or with other measurements. Section 3.4.3 describes the different idle subsections, the test procedures and results for measuring the engine's idle behaviour.

3.4.3 General idle and after-start test procedure

The vehicle's idle response must be measured to allow for quantitative driveability evaluation. Table 3.12 lists all the important variables that have an effect on fundamental engine management calibration, as well as the general different idle and off-idle conditions. The list was formulated from data in the literature and the results of the author's own investigations.

Table 3.12: Idle conditions with measured variables

	Measure	**Evaluate for**
Cold Idle	**Coolant temperature**	**Up to 45degC**
	Engine speed	Speed point, oscillations, drift
	Idle speed setpoint	Reference for the behaviour of the engine speed
	Engine coolant temperature	To ensure the test is conducted under the right conditions and to ensure repeatability
	Ambient temperature	To ensure the test is conducted under the right conditions and to ensure repeatability
	Inlet temperature	To ensure the test is conducted under the right conditions and to ensure repeatability
	Pedal position	To ensure the test is conducted under the right conditions and to ensure repeatability
	Throttle position	Airflow strategy
	Manifold Absolute Pressure	Airflow strategy
	Air-fuel ratio (Lambda)	Fuel strategy
	Injection time	Amount of fuel added
	Ignition angle	Ignition strategy
	Acceleration	Jerks
Post Start	**Performed after each start condition, together with the corresponding idle condition**	
	Engine speed	Oscillations, overshoot, settling time, load change effect
	Idle speed setpoint	Reference for the behaviour of the engine speed
	Engine coolant temperature	To ensure the test is conducted under the right conditions and to ensure repeatability
	Ambient temperature	To ensure the test is conducted under the right conditions and to ensure repeatability
	Inlet temperature	To ensure the test is conducted under the right conditions and to ensure repeatability
	Pedal position	To ensure the test is conducted under the right conditions and to ensure repeatability
	Throttle position	Airflow strategy
	Manifold Absolute Pressure	Airflow strategy
	Air-fuel ratio (Lambda)	Fuel strategy
	Injection time	Amount of fuel added
	Ignition angle	Ignition strategy
	Acceleration	Jerks
Warm-up Idle	**Coolant temperature**	**Between 45degC and 90degC**
	Engine speed	Speed point, oscillations, drift
	Idle speed setpoint	Reference for the behaviour of the engine speed
	Engine coolant temperature	To ensure the test is conducted under the right conditions and to ensure repeatability
	Ambient temperature	To ensure the test is conducted under the right conditions and to ensure repeatability
	Inlet temperature	To ensure the test is conducted under the right conditions and to ensure repeatability
	Pedal position	To ensure the test is conducted under the right conditions and to ensure repeatability
	Manifold Absolute Pressure	Airflow strategy
	Throttle position	Airflow strategy
	Air-fuel ratio (Lambda)	Fuel strategy
	Injection time	Amount of fuel added
	Ignition angle	Ignition strategy
	Acceleration	Jerks
Warm/ Normal Idle	**Coolant temperature**	**Operating condition (90degC)**
	Engine speed	Speed point, oscillations, drift
	Idle speed setpoint	Reference for the behaviour of the engine speed
	Engine coolant temperature	To ensure the test is conducted under the right conditions and to ensure repeatability
	Ambient temperature	To ensure the test is conducted under the right conditions and to ensure repeatability
	Inlet temperature	To ensure the test is conducted under the right conditions and to ensure repeatability
	Pedal position	To ensure the test is conducted under the right conditions and to ensure repeatability
	Throttle position	Airflow strategy
	Manifold Absolute Pressure	Airflow strategy
	Air-fuel ratio (Lambda)	Fuel strategy
	Injection time	Amount of fuel added
	Ignition angle	Ignition strategy
	Acceleration	Jerks

Hot Idle	**Coolant temperature**	**Operating condition (> 100degC)**
	Engine speed	Speed point, oscillations, drift
	Idle speed setpoint	Reference for the behaviour of the engine speed
	Engine coolant temperature	To ensure the test is conducted under the right conditions and to ensure repeatability
	Ambient temperature	To ensure the test is conducted under the right conditions and to ensure repeatability
	Inlet temperature	To ensure the test is conducted under the right conditions and to ensure repeatability
	Pedal position	To ensure the test is conducted under the right conditions and to ensure repeatability
	Throttle position	Airflow strategy
	Manifold Absolute Pressure	Airflow strategy
	Air-fuel ratio (Lambda)	Fuel strategy
	Injection time	Amount of fuel added
	Ignition angle	Ignition strategy
	Acceleration	Jerks
Pedal Blip/ Tip In	**Perform under all Idle temperature conditions**	
	Engine speed	Speed point, oscillations, drift
	Idle speed setpoint	Reference for the behaviour of the engine speed
	Engine coolant temperature	To ensure the test is conducted under the right conditions and to ensure repeatability
	Ambient temperature	To ensure the test is conducted under the right conditions and to ensure repeatability
	Inlet temperature	To ensure the test is conducted under the right conditions and to ensure repeatability
	Pedal position	To ensure the test is conducted under the right conditions and to ensure repeatability
	Throttle position	Airflow strategy
	Manifold Absolute Pressure	Airflow strategy
	Air-fuel ratio (Lambda)	Fuel strategy
	Injection time	Amount of fuel added
	Ignition angle	Ignition strategy
	Acceleration	Jerks
Idle Response during Load Engagement	**Perform under all Idle temperature conditions**	
	Engine speed	Speed point, oscillations, drift
	Idle speed setpoint	Reference for the behaviour of the engine speed
	Engine coolant temperature	To ensure the test is conducted under the right conditions and to ensure repeatability
	Ambient temperature	To ensure the test is conducted under the right conditions and to ensure repeatability
	Inlet temperature	To ensure the test is conducted under the right conditions and to ensure repeatability
	Pedal position	To ensure the test is conducted under the right conditions and to ensure repeatability
	Throttle position	Airflow strategy
	Manifold Absolute Pressure	Airflow strategy
	Air-fuel ratio (Lambda)	Fuel strategy
	Injection time	Amount of fuel added
	Ignition angle	Ignition strategy
	Acceleration	Jerks
Idle while Braking	**Perform under all Idle temperature conditions**	
	Engine speed	Speed point, oscillations, drift
	Idle speed setpoint	Reference for the behaviour of the engine speed
	Engine coolant temperature	To ensure the test is conducted under the right conditions and to ensure repeatability
	Ambient temperature	To ensure the test is conducted under the right conditions and to ensure repeatability
	Inlet temperature	To ensure the test is conducted under the right conditions and to ensure repeatability
	Pedal position	To ensure the test is conducted under the right conditions and to ensure repeatability
	Throttle position	Airflow strategy
	Manifold Absolute Pressure	Airflow strategy
	Air-fuel ratio (Lambda)	Fuel strategy
	Injection time	Amount of fuel added
	Ignition angle	Ignition strategy
	Velocity	To ensure the test is conducted under the right conditions and to ensure repeatability
	Acceleration	Rate of change of velocity
Idle after Braking	**Perform under all Idle temperature conditions**	
	Engine speed	Speed point, oscillations, drift
	Idle speed setpoint	Reference for the behaviour of the engine speed
	Engine coolant temperature	To ensure the test is conducted under the right conditions and to ensure repeatability
	Ambient temperature	To ensure the test is conducted under the right conditions and to ensure repeatability
	Inlet temperature	To ensure the test is conducted under the right conditions and to ensure repeatability
	Pedal position	To ensure the test is conducted under the right conditions and to ensure repeatability
	Throttle position	Airflow strategy
	Manifold Absolute Pressure	Airflow strategy
	Air-fuel ratio (Lambda)	Fuel strategy
	Injection time	Amount of fuel added
	Ignition angle	Ignition strategy
	Acceleration	Jerks

The idle and after-start measurements will typically follow a start evaluation. The general idle test procedure is as follows:

- The vehicle must be cooled to the desired temperature at which the start will be executed.
- The vehicle is started without any pedal input.
- The vehicle is left to idle for 10 seconds after the engine has started.
- The pedal is fully engaged as fast as possible. Release the pedal again after a brief period, long enough for the engine to speed up to 3500 rpm.
- The engine must idle for another 10 seconds.
- The rear demister must be switched on after the 10-second idle period, together with the heating/cooling fan and the headlights. Switch the heating/cooling fan to its middle operating condition (if the maximum number of settings is 4 then switch it to 2), with the air conditioner (if equipped) switched on.
- The engine must idle for another 20 seconds.
- The lights, heating/cooling fan and rear demister must be switched off after the 20-second idle period. Let the vehicle idle for another 10 seconds.

The typical load values are 200 W for the rear demister, 120 W for the headlights, 120 W for the blower motor for AC/heater fan (Bosch, 2004) and 3 kW at moderate engine speeds (Edward , 2001). The reason for setting to heating/cooling to the middle operating position is just to ensure repeatability between tests.

3.4.4 Cold idle and post cold start

The engine temperature must be below 45 °C (Probst, 1991). Post cold start is the period immediately after the engine starts from a cold start, also known as cold after-start. Post-start enrichment is still essential because of wall wetting, which will lead to poor pedal response and performance. This enrichment might lead to unwanted emissions and must be limited.

Cold idle is defined as the idle condition during and after cold post start. The engine will need more air and more fuel at idle, to overcome the higher running friction of a cold engine. The idle speed can slightly increase to prevent the vehicle from stalling and to ensure good off-idle throttle response.

3.4.4.1 Cold idle and post cold-start test procedure

This section describes the cold-idle test procedure. The idea of this test is to inspect the engine management strategy. This test is performed after the cold-start test. The engine is kept idling after the cold-start test. Use the same equipment as with the cold-start test. Measure the cold idle response as described in the beginning of this section. Table 3.13 displays a sample calculation for cold-idle response.

Table 3.13: Measured example for cold idle

Measured Variable	Units	Measured Value	Adjusted Values for Engine Coolant Temperature	Driveability Score	Driveability Classification
TCO	[DegC]	-3.8			
Idle Speed Setpoint	[RPM]	977.0			
Mean at SS Idle [Eq. 3.7 & Table 3.8]	[RPM]	931.0	696.96	7	Acceptable
Standard Deviation [Table 3.9]	[RPM]	6.3		7	Acceptable
Slope of SS Idle	[RPM/s]	2.9			
Min RPM after load was switched on	[RPM]	889.0			
Time to Min RPM after load was switched on	[s]	1.8			
Percentage change	[%RPM]	-7.9			
Rate of change of load change [Eq. 3.8 & Table 3.10]	[%RPM Change/dt]	6.0	0.93	10	Excellent
Max RPM at blip	[RPM]	3123.0			
Rate of change of engine speed	[dRPM/dt]	3547.2			
Max pedal input	[%PV]	99.9			
Rate of change of pedal blip input	[dPV]	227.0			
Ratio of rate of change of engine speed to pedal input [Eq. 3.9 & Table 3.11]	[dPV/dt]	15.6		7	Acceptable

$$DII = 0.2*7 + 0.3*7 + 0.2*10 + 0.2*7 + 0.1*8$$
$$DII = 7.7$$

The results from the calculation above classify the evaluation as acceptable response. The driveability brake response index was not measure for this example and a value of 8 was used. Section 4.4 provides an example evaluation for a complete driveability evaluation. The following subsections of idle response are calculated in the same manner as this example.

3.4.5 Warm-up idle

Engine coolant temperature must be between 45 ^{o}C and 90 ^{o}C (Probst, 1991). Fuel injection systems measure both temperature and engine speed. As the engine starts warming up, the engine control unit will decrease fuel enrichment as well as idle speed set point.

3.4.5.1 Warm-up idle and post cold idle test procedure

This section describes the warm-up idle test procedure. The idea of this test is to inspect the engine management strategy. This test is performed right after the cold-idle test. The engine is kept idling after the cold-idle test. The same equipment was used as for the cold-idle test.

Measure the warm-up idle response as described in the beginning of section 3.4.3. The driveability index for warm-up idle response is calculated with equation 3.7 to equation 3.13.

The effect of different fuelling strategies did not have a significant effect on warm-up idle. The slope of the change in engine speed set point and the idle speed response with an increase in temperature is significant during this period and the pedal blip response.

3.4.6 Warm idle and post warm start

Engine coolant must be at an operating temperature of approximately 90 °C (Probst, 1991). Post warm start is the period immediately after the engine starts from a warm start. Post-start enrichment is still essential, but not as significant as with cold post start. The same basic theory, as described with cold post start, still applies, only with less enrichment.

3.4.6.1 Warm idle and post warm-start test procedure

This is the benchmark engine management response for idle since the vehicle will most likely spend most of its idle time at this condition. The idea of this test is to inspect the engine management strategy.

The test is performed right after the warm start test, the engine is kept idling after the warm-start evaluation. Use the same equipment as for the warm-start test. Measure the warm idle response as described in the beginning of this section.

3.4.7 Hot idle and post hot start

Engine coolant temperatures must be above 100 °C (Probst, 1991). The engine has to have good idle behaviour with good pedal response after a hot start. The coolant temperature has to cool down to normal operating conditions after the engine was started during the hot-start evaluation. Ignition advance will reduce the amount of energy transferred to the coolant. Fuel enrichment will lead to better off-idle response and the unburnt fuel will absorb some of the energy, resulting in lower pressures and temperatures in the combustion chamber (Anderson et al., 1998). Post-start enrichment is hardly necessary since all the manifold walls, intake valves, intake port and combustion chamber are extremely hot and will promote fuel evaporation. The same basic theory, as described with cold post start, still applies, only with reduced enrichment.

3.4.7.1 Hot idle and post hot-start test procedure

This section describes the warm-up idle test procedure. The idea of this test is to evaluate the engine management strategy.

This test is performed right after the hot-start evaluation. The same equipment is used as with the hot-start test. Measure the hot idle response as described in the beginning of this section.

3.5 Acceleration Response and Evaluation

Acceleration is another important consideration of a vehicle’s driveability. Pull away, increasing vehicle speed, tip-in and tip-out are all conditions where the vehicle’s response to a drivers demand for acceleration is measured. The engine management strategy, together with the driveline design can be manipulated to change the behaviour of the vehicle. This section describes the effect of the engine management strategy on acceleration and how it can be evaluated to provide a driveability score.

3.5.1 Important factors influencing acceleration behaviour

In order for a vehicle to change its velocity the available energy needs to be increased. From a thermodynamic perspective this means that the amount of cycle work needs to increase. To increase the cycle work more air and fuel needs to be combusted. This is achieved by allowing more air to flow into the combustion chamber by opening the throttle. The engine management system will use some form of metering system to measure the amount of airflow into the engine and inject extra fuel.

There is a slight delay in requesting an increase in work from the engine by increasing the throttle. To overcome this delay the engine management system should increase the ignition timing and retard the timing as the airflow increases. If the fuelling is increased during acceleration enrichment then the hydro carbons and carbon monoxide concentrations will also increase. Care must be taken to ensure that the increase still fall in the operating range of the catalytic converter. Appendix B discusses the effect of increased fuelling on emissions.

Figure 3.20 shows how the injection duration decreases with an increase in engine coolant temperature during the pull-away condition. The solid line shows the average result of the maximum injection duration measured at four different temperatures. Appendix C4 displays all the measurements for pull-away evaluations. Again the pull away was evaluated at the four different temperature conditions as with start and idle (Section 3.3 & 3.4). Six measurements for very cold, four for cold, and three measurements for warm and hot, were used for the evaluation.

Figure 3.21 show the average results of the mass airflow, associated with the injection duration, through the engine at different coolant temperatures. The mass airflow followed the same trend as in the case of the injection duration at 7 ^{o}C. The solid line shows the result with the two outliers and the dashed line without. It is interesting to note that the mass airflow increases slightly at operating temperature, as the injection duration decreases.

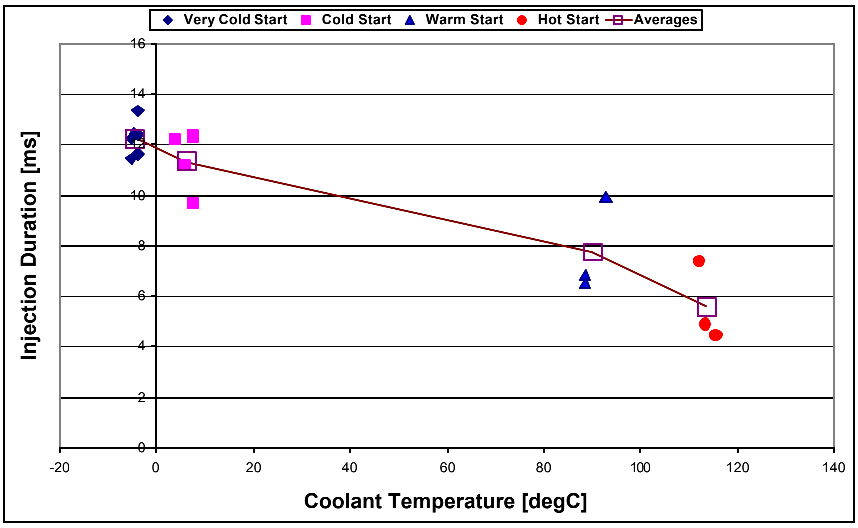


Figure 3.20: Measured injection duration at different operating temperatures during pull away

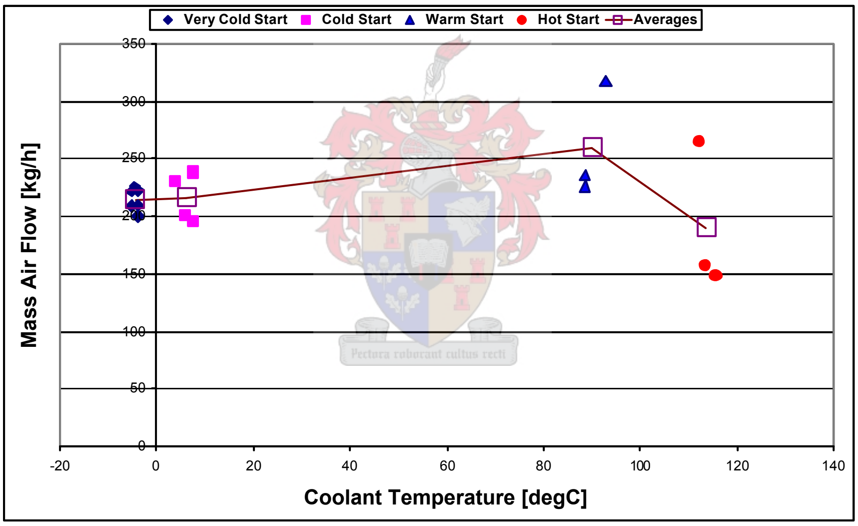


Figure 3.21: Average mass airflow at different operating temperatures during pull away

The maximum injection duration and the maximum mass airflow are combined to give a 'fuel-air' ratio. Figure 3.22 shows that the ratio decreases as the coolant temperature increases. This ratio will give more comparative results and provide a better evaluation of the engine management strategy. The outliers from 7 °C are eliminated since both the injection timing as well as the mass airflow increased at the outliers and the fuel air ratio brings them into the same range as the other values at the same temperature.

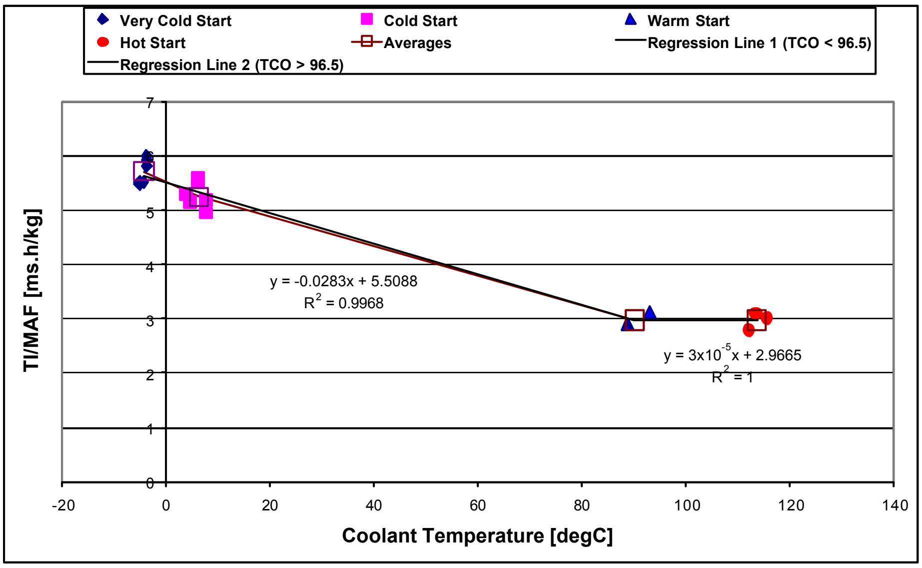


Figure 3.22: Average injection duration per mass airflow at different operating temperatures during pull away

Equation 3.14 gives the formula to calculate the correction factor for the fuel-air ratio. The data from Figure 3.22 were used to formulate this equation. This equation was developed to allow for measured values, at different temperatures, to be adjusted to an independent temperature value in order to be directly comparable for different evaluations. This simplifies the evaluations since no database with discrete values is needed for different coolant temperatures. The reference value was chosen to be the fuel-air ratio at operating temperature. Therefore all results from evaluations are adjusted to represent a response at operating temperature. This was achieved by fitting a piecewise linear regression equation through the measured data. The same method was used to formulate all the acceleration response equations in this section.

$$x_1 = TCO \qquad x_2 = \begin{Bmatrix} 0 & if & x_1 < 96.5 \\ 1 & if & x_1 \geq 96.5 \end{Bmatrix}$$

$$TI\!\!\diagup\!\! MAF_{TCO} = b_0 + b_1 x_1 + b_2 (x_1 - 96.5) x_2$$

$$where \quad b_1 = m_1 \quad and \quad b_0 = c \quad from \quad y = mx + c \quad and \quad b_2 = m_2 - m_1$$

$$TI\!\!\diagup\!\! MAF_{TCO} = [5.5088 - 0.0283 * TCO - 0.0283 (TCO - 96.5) x_2] - 3 \tag{3.14}$$

The engine coolant temperature of a new evaluation must be substituted into Equation 3.14. The result from the equation is then added to the actual measured fuel-air ratio value from the evaluation. The result is then used together with a lookup table to determine what the driveability score and classification is for that evaluation. Table 3.14 provides the driveability score for the fuel-air ratio for pull away and part load conditions. Table 3.15 represents full-load acceleration conditions. The tables were developed from all the measured data and the response thereof. The values were interpolated where no values were available. The acceptable and unacceptable classifications have two sets of scores allocated to them. The reason is that a too rich fuel-air ratio will also lead to a poor response as well as a too lean ratio.

The effect of coolant temperature was only evaluated for pull away conditions since the time the vehicle takes to reach operating temperature was extremely short and no complete acceleration runs could be performed during the testing conditions.

Table 3.14: Driveability part-load TI/MAF index

Driveability Standard	Objective Driveability Index	Subjective Rating	TI/MAF [ms/(kg/h)
Favourable	10	Excellent	3.5 to 4
	9	Very good	3 to 3.5
	8	Good	2.5 to 3
Acceptable	7	Acceptable	2 to 2.5 & 4 to 4.5
	6	Neutral	1.5 to 2 & 4.5 to 5
	5	Tolerable	1 to 1.5 & 5 to 5.5
Unacceptable	4	Poor	0.5 to 1 & 5.5 to 6
	3	Bad	0.25 to 0.5 & 6 to 6.5
	2	Very bad	< 0.25 & > 6.5
	1	Catastrophic	Engine stall during pull away

Table 3.15: Driveability full-load TI/MAF index

Driveability Standard	Objective Driveability Index	Subjective Rating	TI/MAF [ms/(kg/h)
Favourable	10	Excellent	4 to 5
	9	Very good	3.5 to 4
	8	Good	3 to 3.5
Acceptable	7	Acceptable	2.5 to 3 & 5 to 5.5
	6	Neutral	2 to 2.5 & 5.5 to 6
	5	Tolerable	1.5 to 2 & 6 to 6. 5
Unacceptable	4	Poor	1 to 1.5 & 6.5 to 7
	3	Bad	0.25 to 1 & 7 to 7.5
	2	Very bad	< 0.25 & > 7.5
	1	Catastrophic	Engine stall during pull away

Tables 3.14 and 3.15 were developed from all the measured data and for different conditions. Fuelling was decreased and increased to determine the corresponding results. Having a richer fuel-air mixture allows a better pull-away response. The results were then subjectively evaluated and a score assigned. There are no data available in the literature to quantify fuel-air ratios and their effect on pull-away response. The tables provide an acceptable evaluation for the pull-away response on the driveability evaluation for the vehicles tested.

Figure 3.23 shows the effect that increased fuelling had on the fuel-air ratio. These results have not been adjusted with Equation 3.14 to compensate for different temperatures. It is therefore obvious that an increase in fuelling will lead to an increased fuel-air ratio.

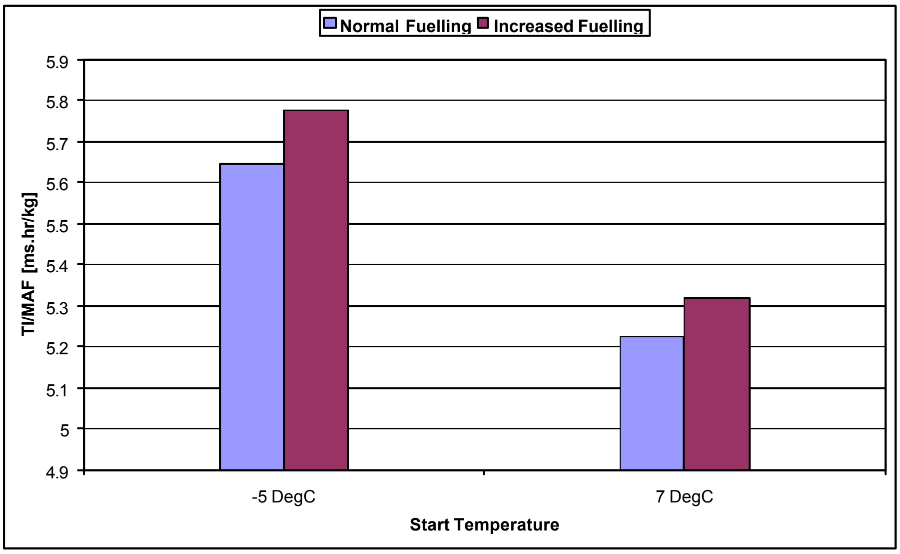


Figure 3. 23: The effect of increased fuelling on fuel-air ratio

In order to evaluate the driver's demand for acceleration, the response needs to be evaluated as a function of vehicle speed change to pedal input. Nothing in the literature provides an appropriate quantitative evaluation method. Therefore the following method was developed for this project. The change in vehicle speed during the acceleration period is measured and divided by the time it takes to reach that speed (average acceleration). That value is divided by the average pedal input (excluding the gear change periods). The value is then multiplied by a hundred to allow for a larger range of values to be quantified. The value implies that if there are two pedal input values, one high and one low, with the same acceleration, then the calculated value from the lower pedal input will yield a higher score. This result will show if there is a "dead spot" in the pedal response and will aid calibration of the pedal map in the ECU. The value also implies that different vehicles' acceleration response can be compared with the same pedal input. In an ideal situation the pedal input must reflect on the increase of the percentage work of the engine. If the driver increase the pedal input by 20% then the engine must provide 20% more work.

Table 3.16 provides a driveability score for evaluating the acceleration to pedal input response for the vehicle that was tested. The values were obtained from the measured data, and where no data was available the data was interpolated.

Table 3.16: Driveability acceleration per pedal input index

Driveability Standard	Objective Driveability Index	Subjective Rating	G_PV [$(m/s^2)/PV$]
Favourable	10	Excellent	> 3
	9	Very good	2.5 to 3
	8	Good	2 to 2.5
Acceptable	7	Acceptable	1.5 to 2
	6	Neutral	0.8 to 1.5
	5	Tolerable	0.5 to 0.8
Unacceptable	4	Poor	0.4 to 0.5
	3	Bad	0.2 to 0.4
	2	Very bad	< 0.2
	1	Catastrophic	Engine stall during pull

Different vehicle classes will have different tables. A sports vehicle will have higher acceleration than an all-purpose vehicle and these vehicles have to be evaluated accordingly. One aspect that is unfavourable in all vehicles is jerk. Jerk is the derivative of acceleration with respect to time (or the third derivative of displacement). This initial change in acceleration of a vehicle occurs in a short window of about a half to one second (Wicke, 2001). Jerk can also trigger motion sickness if it is experienced in periodic cycles (Challen, 2002). Table 3.17 provides a driveability score for jerk. The jerk values were calculated from the measured acceleration data from Appendices C5 to C8 and where no data were available the values were interpolated. It was assumed that some amount of jerk is acceptable by the driver, especially with a large pedal input but too large values will cause discomfort and will be perceived as unfavourable.

Table 3.17: Driveability jerk index

Driveability Standard	Objective Driveability Index	Subjective Rating	Jerk [m/s^3]
Favourable	10	Excellent	10 to 15
	9	Very good	8 to10
	8	Good	6 to 8
Acceptable	7	Acceptable	2 to 6 & 15 to16
	6	Neutral	0.5 to 2 & 16 to 17
	5	Tolerable	0.01 to 0.5 & 17 to 19
Unacceptable	4	Poor	19 to 20
	3	Bad	20 to 22
	2	Very bad	< 22
	1	Catastrophic	Engine stall during

The acceleration enrichment is evaluated with injection duration overshoot. An example of injection duration overshoot is displayed in Figure 3.24. The percentage overshoot is calculated from the maximum value over the average steady-state value. Table 3.18 lists the acceleration enrichment scores and classifications. The table was developed after analysing all the measured data and interpolating where no results were available. The table provides accurate results for comparison. Again the accuracy of the table can be improved with a bigger population of data.

There are two ranges provided for each classification. If too much fuel is injected then the response will decrease and can even lead to engine stall. The fuel-air ratio is not used since the maximum mass airflow does not always correspond to the maximum injection duration. The evaluation was based on the assumption that the driver will perceive the experience as unfavourable if the engine experiences a surge or large delay due to over fuelling or under fuelling.

Table 3.18: Driveability acceleration enrichment index

Driveability Standard	Objective Driveability Index	Subjective Rating	Injection Duration Overshoot [%]
Favourable	10 9 8	Excellent Very good Good	40 to 45 35 to 40 30 to 35
Acceptable	7 6 5	Acceptable Neutral Tolerable	25 to 30 & 45 to 50 20 to 25 & 50 to 55 15 to 20 & 55 to 60
Unacceptable	4 3 2 1	Poor Bad Very bad Catastrophic	10 to 15 & 60 to 65 1 to 10 & 65 to 70 <1 & > 75 Engine stall/ surge during acceleration

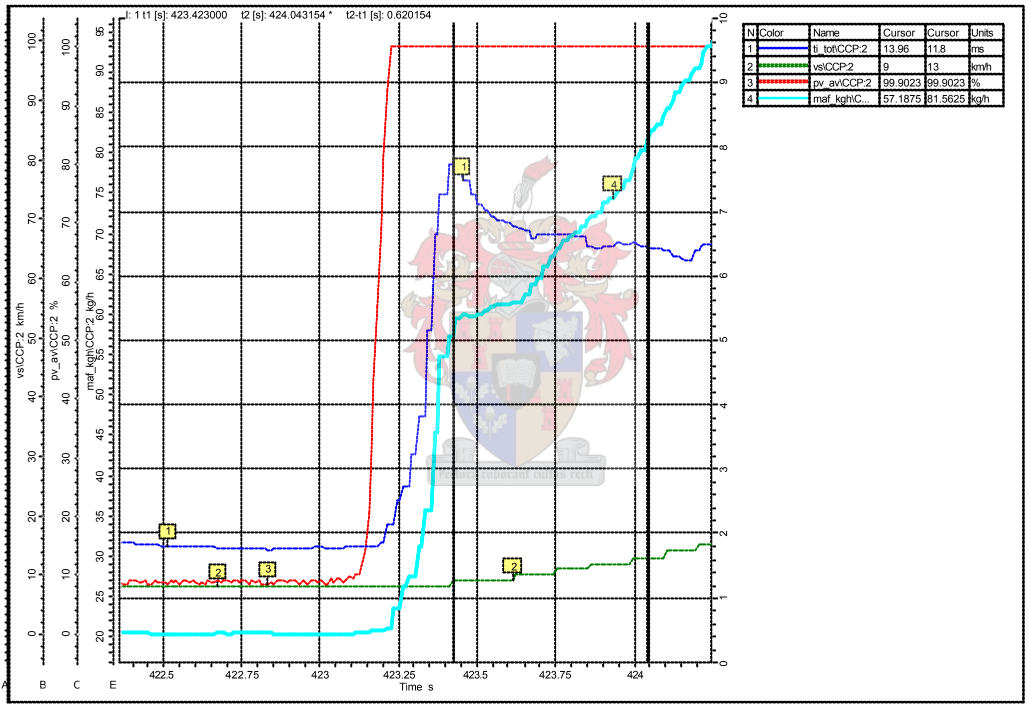


Figure 3.24: Acceleration evaluation measurement showing injection duration (TI_TOT), vehicle speed (VS), accelerator pedal position (PV_AV), mass airflow (MAF)

Fuel shut-off is implemented when the engine is not doing any useful work and it is not in idle condition. Coasting is a good example of when the engine is turning faster than idle, but the driver does not require any torque from the engine. Table 3.19 provides a driveability score for this condition. From all the results presented in Appendix C8, lambda was measured at roughly above 30. The measuring equipment is limited, where 30 corresponds to the top measuring range of the sensor. If lambda is anything less than 30 then it implies that there is a larger amount of fuel injected. If lambda is close to one then it implies that there is no fuel shut-off. The reason why lambda was used and not injection duration was because some engine management systems do not cut fuel to all the cylinders at the same time. The table's accuracy can be improved by evaluating a larger amount of data from different engine management strategies. No direct correlation exists between the driver and the fuel shut-off since he will be unaware of the reaction. Less oxygen is available at higher altitudes and therefore the fuel cut-off periods will be delayed to compensate for the load/ cleaning function of the catalytic converter.

Table 3.19: Driveability fuel shut-off index

Driveability Standard	Objective Driveability Index	Subjective Rating	Lambda
Favourable	10	Excellent	> 30
	9	Very good	28 to 30
	8	Good	26 to 28
Acceptable	7	Acceptable	24 to 26
	6	Neutral	22 to 24
	5	Tolerable	5 to 22
Unacceptable	4	Poor	1 to 5
	3	Bad	0.9 to 1
	2	Very bad	0.7 to 0.9
	1	Catastrophic	Engine stall/ surge at coast

The equations and tables from this section will be used for different types of acceleration evaluations. The test procedure as well the driveability acceleration index for the different types of acceleration evaluations will be discussed in the following section (3.5.2).

3.5.2 General start test procedure

The vehicle's acceleration response must be measured to allow for quantitative driveability evaluation. Table 3.20 tabulates all the important variables that have an effect on fundamental engine management calibration, as well as the general different acceleration conditions. The table was developed from a combination of literature and vehicle response investigations. The different test conditions were developed by evaluating different acceleration conditions and eliminating redundant and overlapping evaluation methods. The chosen test conditions represent the most important acceleration operation modes since the evaluations represent the most common acceleration conditions.

Table 3.20: Acceleration conditions with recording parameters

	Measure	Evaluate for
Pull Away	**Perform Pull Away at the different coolant temperatures (Cold, warm-up, warm and hot)**	
	Engine speed	To ensure the test is conducted under the right conditions and to ensure repeatability
	Engine coolant temperature	To ensure the test is conducted under the right conditions and to ensure repeatability
	Ambient temperature	To ensure the test is conducted under the right conditions and to ensure repeatability
	Inlet temperature	To ensure the test is conducted under the right conditions and to ensure repeatability
	Pedal position	Input from driver for start of test and reference for repeatability
	Throttle position	Airflow strategy
	Manifold Absolute Pressure	Airflow strategy
	Air-fuel ratio (Lambda)	Fuel strategy
	Injection time	Amount of fuel added
	Ignition angle	Ignition strategy
	Velocity	To ensure the test is conducted under the right conditions and to ensure repeatability
	Acceleration	Jerks, hesitation, pedal response, vehicle delay, yank, gearchange jerks

Full Load Acceleration	**Perform Full Load Acceleration at the different coolant temperatures (Cold, warm-up, warm and hot)**	
	Condition 1: 0 - 100km/h (Gear change at 10% above peak torque)	
	Condition 2: 20 - 60km/h (Initial slow vehicle speed overtaking acceleration)	
	Condition 3: 40 - 80km/h (Medium initial vehicle speed overtaking acceleration)	
	Condition 4: 60 - 100km/h (High initial vehicle speed overtaking acceleration)	
	Engine speed	To ensure the test is conducted under the right conditions and to ensure repeatability
	Engine coolant temperature	To ensure the test is conducted under the right conditions and to ensure repeatability
	Ambient temperature	To ensure the test is conducted under the right conditions and to ensure repeatability
	Inlet temperature	To ensure the test is conducted under the right conditions and to ensure repeatability
	Pedal position	Input from driver for start of test and reference for repeatability
	Throttle position	Airflow strategy
	Manifold Absolute Pressure	Airflow strategy
	Air-fuel ratio (Lambda)	Fuel strategy
	Injection time	Amount of fuel added
	Ignition angle	Ignition strategy
	Velocity	To ensure the test is conducted under the right conditions and to ensure repeatability
	Acceleration	Jerks, hesitation, pedal response, vehicle delay, yank, gearchange jerks
Part Load Acceleration	**Perform Part Load Acceleration (70% Pedal Value of Full Load) at operating temperature**	
	Condition 1: 0 - 100km/h (Gear change at 10% above peak torque)	
	Condition 2: 20 - 60km/h (Initial slow vehicle speed overtaking acceleration)	
	Condition 3: 40 - 80km/h (Medium initial vehicle speed overtaking acceleration)	
	Condition 4: 60 - 100km/h (High initial vehicle speed overtaking acceleration)	
	Engine speed	To ensure the test is conducted under the right conditions and to ensure repeatability
	Engine coolant temperature	To ensure the test is conducted under the right conditions and to ensure repeatability
	Ambient temperature	To ensure the test is conducted under the right conditions and to ensure repeatability
	Inlet temperature	To ensure the test is conducted under the right conditions and to ensure repeatability
	Pedal position	Input from driver for start of test and reference for repeatability
	Throttle position	Airflow strategy
	Manifold Absolute Pressure	Airflow strategy
	Air-fuel ratio (Lambda)	Fuel strategy
	Injection time	Amount of fuel added
	Ignition angle	Ignition strategy
	Velocity	To ensure the test is conducted under the right conditions and to ensure repeatability
	Acceleration	Jerks, hesitation, pedal response, vehicle delay, yank, gearchange jerks
Tip-In	**Perform Tip-In and Tip-Out Acceleration at operating temperature**	
	Condition 1: 10km/h - 20km/h in first gear	
	Condition 2: 10km/h - 20km/h in second gear	
	Condition 3: 20km/h - 30km/h in first gear	
	Condition 4: 20km/h - 30km/h in second gear	
	Condition 5: 20km/h - 30km/h in third gear	
	Engine speed	To ensure the test is conducted under the right conditions and to ensure repeatability
	Engine coolant temperature	To ensure the test is conducted under the right conditions and to ensure repeatability
	Ambient temperature	To ensure the test is conducted under the right conditions and to ensure repeatability
	Inlet temperature	To ensure the test is conducted under the right conditions and to ensure repeatability
	Pedal position	Input from driver for start of test and reference for repeatability
	Throttle position	Airflow strategy
	Manifold Absolute Pressure	Airflow strategy
	Air-fuel ratio (Lambda)	Fuel strategy
	Injection time	Amount of fuel added
	Ignition angle	Ignition strategy
	Velocity	To ensure the test is conducted under the right conditions and to ensure repeatability
	Acceleration	Jerks, hesitation, pedal response, vehicle delay, yank, gearchange jerks
Tip-Out	**Condition 1: 20km/h - 10km/h in first gear**	
	Condition 2: 20km/h - 10km/h in second gear	
	Condition 3: 30km/h - 20km/h in first gear	
	Condition 4: 30km/h - 20km/h in second gear	
	Condition 5: 30km/h - 20km/h in third gear	
	Engine speed	To ensure the test is conducted under the right conditions and to ensure repeatability
	Engine coolant temperature	To ensure the test is conducted under the right conditions and to ensure repeatability
	Ambient temperature	To ensure the test is conducted under the right conditions and to ensure repeatability
	Inlet temperature	To ensure the test is conducted under the right conditions and to ensure repeatability
	Pedal position	Input from driver for start of test and reference for repeatability
	Throttle position	Airflow strategy
	Manifold Absolute Pressure	Airflow strategy
	Air-fuel ratio (Lambda)	Fuel strategy
	Injection time	Amount of fuel added
	Ignition angle	Ignition strategy
	Velocity	To ensure the test is conducted under the right conditions and to ensure repeatability
	Acceleration	Jerks, hesitation, pedal response, vehicle delay, yank, gearchange jerks
Coasting	**Evaluate after all part load and full load acceleration conditions with 0% pedal input**	
	Engine speed	To ensure the test is conducted under the right conditions and to ensure repeatability
	Idle speed setpoint	Reference for the behaviour of the engine speed
	Engine coolant temperature	To ensure the test is conducted under the right conditions and to ensure repeatability
	Ambient temperature	To ensure the test is conducted under the right conditions and to ensure repeatability
	Inlet temperature	To ensure the test is conducted under the right conditions and to ensure repeatability
	Pedal position	To ensure the test is conducted under the right conditions and to ensure repeatability
	Throttle position	Airflow strategy
	Manifold Absolute Pressure	Airflow strategy
	Air-fuel ratio (Lambda)	Fuel strategy
	Injection time	Amount of fuel added
	Ignition angle	Ignition strategy
	Velocity	To ensure the test is conducted under the right conditions and to ensure repeatability
	Acceleration	To ensure the test is conducted under the right conditions and to ensure repeatability

Figure 3.25 displays the setup of the accelerometer in the vehicle. The response of the accelerometer is used to quantify the acceleration sensation experience by the driver. The testing surface for acceleration response must be smooth since an uneven road surface will lead to superimposed acceleration values. The test surface must not have a slope since a gradient will influence the results because of the increased or reduced resistance against acceleration. A smooth testing surface will also allow for repeatable testing conditions. Figure 3.26 displays the test track that was used for the development and evaluation of the acceleration model. The wind must also not influence the results. Accelerating against a strong wind will increase the resistance.

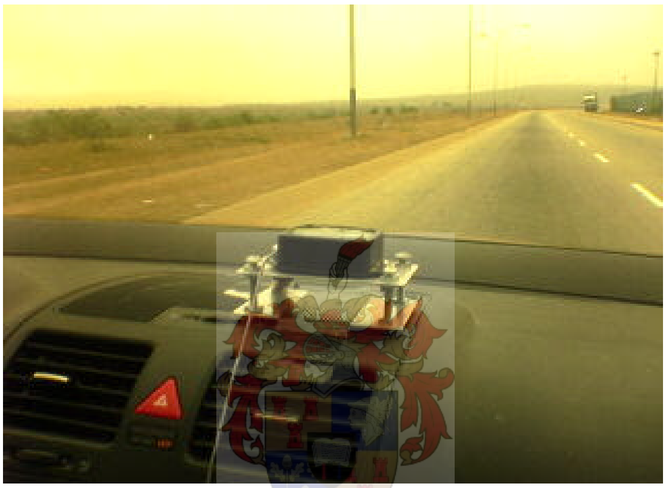


Figure 3.25: Accelerometer setup in vehicle

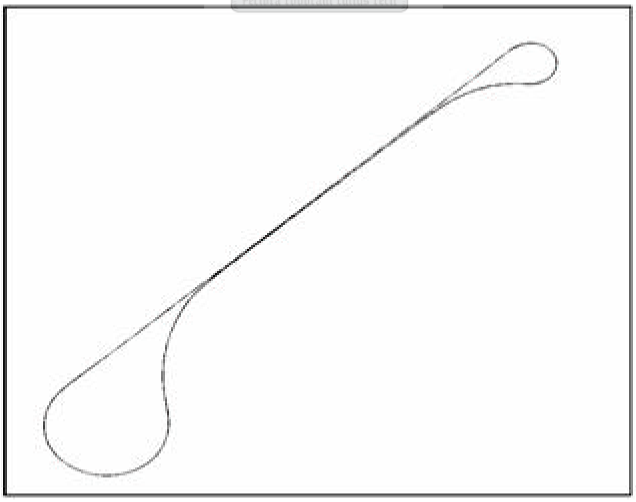


Figure 3.26: Test track layout used for acceleration evaluations

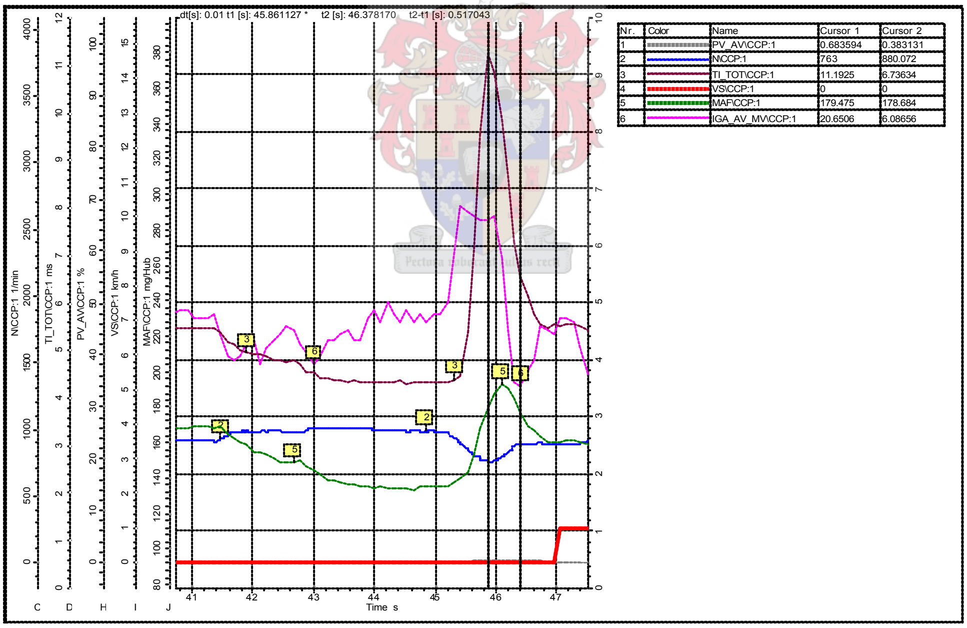
3.5.3 Pull away

During pull away the vehicle is accelerated from a rest position. The engine management receives an input from the pedal and allows more air to flow into the combustion chamber. During cold pull-away conditions the management system needs to add extra fuel to compensate for the fuel that condenses against the inlet path, as well as to overcome the higher friction.

3.5.3.1 Pull-away testing procedure

This section describes the test procedure used for pull-away evaluation and discusses the results of the evaluations.

The injection duration is measured at the time the vehicle starts to pull away. Figure 3.27 show the typical pull-away response. The maximum of all values are recorded except for the ignition timing where the minimum is recorded. Little to no pedal input was used for the initial pull away. The raw data showed that a small amount of pedal input did not make any significant difference to the initial amount of fuel injected because of the electronic throttle. The window of investigation was only until the vehicle reached a maximum of 2 km/h.



Nr.	Color	Name	Cursor 1	Cursor 2
1	▬	PV_AV\CCP:1	0.683594	0.383131
2	▬	N\CCP:1	763	880.072
3	▬	TI_TOT\CCP:1	11.1925	6.73634
4	▬	VS\CCP:1	0	0
5	▬	MAF\CCP:1	179.475	178.684
6	▬	IGA_AV_MV\CCP:1	20.6506	6.08656

Figure 3.27: Pull-away measurement showing accelerator pedal position (PV_AV), engine speed (N), injection duration (TI_TOT), vehicle speed (VS), mass airflow (MAF) and ignition angle (IGA_AV_MV)

The ignition timing varied significantly between measurements and no fixed relationship could be determined from the investigation. Figure 3.27 shows that the ignition timing is first advanced (since the response is faster than fuel and air on combustion) and then retarded as soon as the effect of increased fuelling and air comes into play.

3.5.4 Part load and Full-load acceleration

The response from the vehicle must happen according to the driver’s request to increase the vehicle’s speed. Two categories are identified for increasing vehicle speed. The first condition is part load acceleration. The vehicle must just increase speed, but not as fast as possible. The second condition is full load acceleration. During this condition the vehicle must increase speed as fast as possible. The type and size of the engine, the driveline design, the mass of the vehicle, the vehicle’s wind resistance and the rolling resistance all play an important role in the acceleration response. Only the effect of the engine management strategy is of importance for this report.

3.5.4.1 Part-load and full-load acceleration testing procedure

This section describes the test procedure for full- and part-load acceleration. It also discusses the engine management response and the results. Appendix C5 displays all the measured results.

As for pull away, the airflow and fuelling needs to increase to allow the amount of work done to increase. Figure 3.28 illustrates the basic strategy during part-load acceleration. The ignition timing is also increased to further increase the thermodynamic efficiency and therefore increase the engine output torque. During gear change (at 120 s) the ignition timing is reduced, to decrease the torque to eliminate jerks, as well as the fuelling and mass airflow. The ignition timing is then increased to allow for quicker response and to eliminate any possible surge in torque (because of the delay of fuelling and airflow once the clutch is released again).

The same strategy is implemented during full-load acceleration except that the airflow and fuel air ratio are increased due to full-load enrichment. Figure 3.29 shows differences between part-load acceleration and full-load accelerations with regard to driveability evaluation. The ratio of acceleration to pedal value is roughly the same for the data displayed in Figure 3.29. Table 3.14 is used to assign a driveability score to the fuel air ratio of part-load acceleration and Table 3.15 to full-load acceleration.

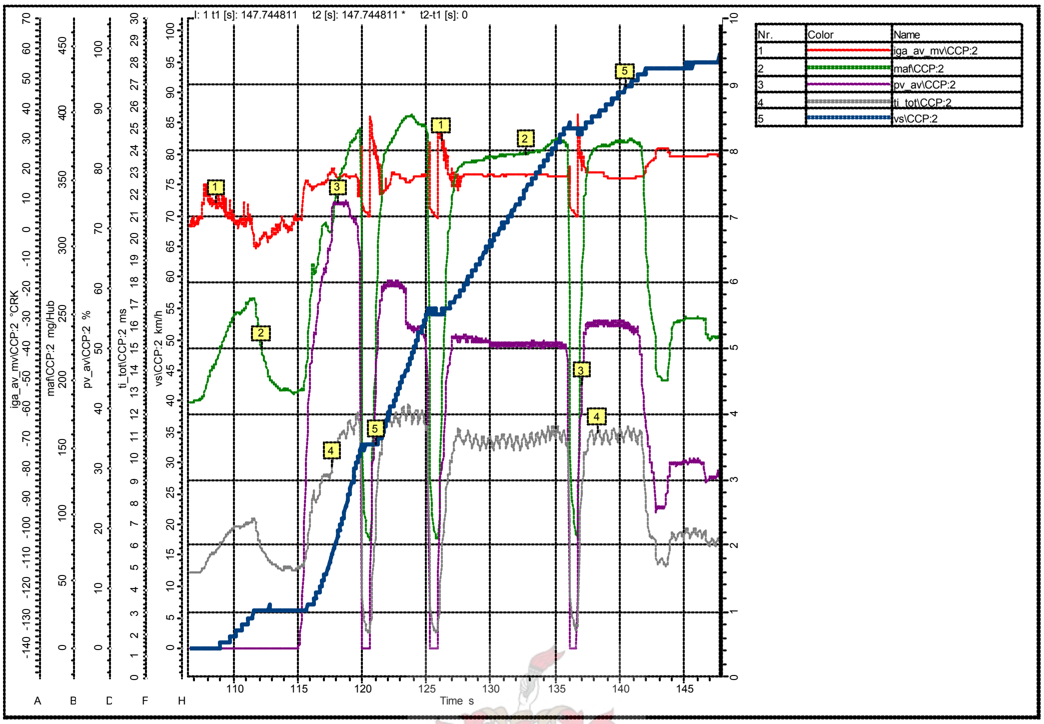


Figure 3.28: Part-load acceleration measurement showing ignition angle (IGA_AV_MV), mass airflow (MAF), accelerator pedal position (PV_AV), injection duration (TI_TOT) and vehicle speed (VS)

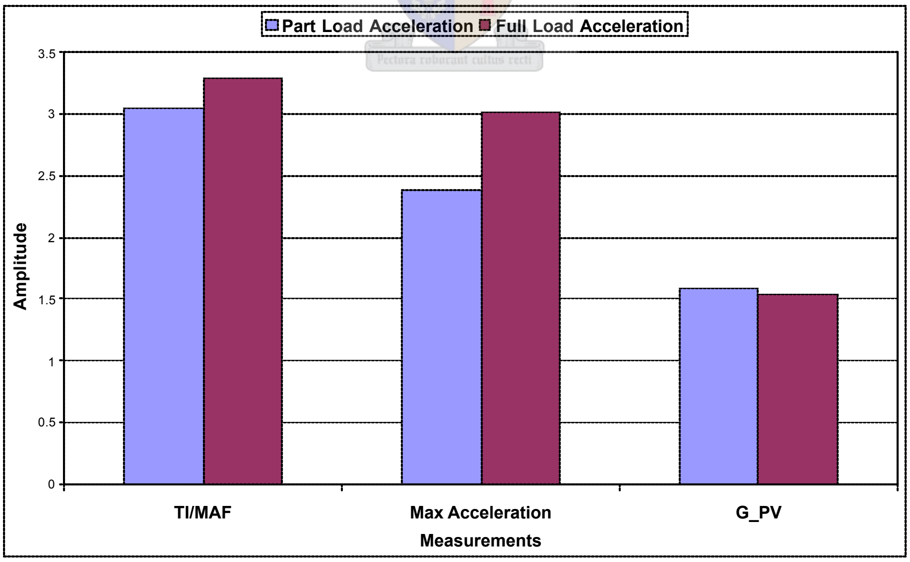


Figure 3.29: Part-load vs. full-load acceleration

Figure 3.30 shows the measured acceleration against vehicle speed for both full-load (FL) and part-load (PL) conditions. As expected, the highest acceleration is during first gear and decreases as the vehicle speed increases and the gear ratios decreases. Full-load acceleration also has a higher measured acceleration value.

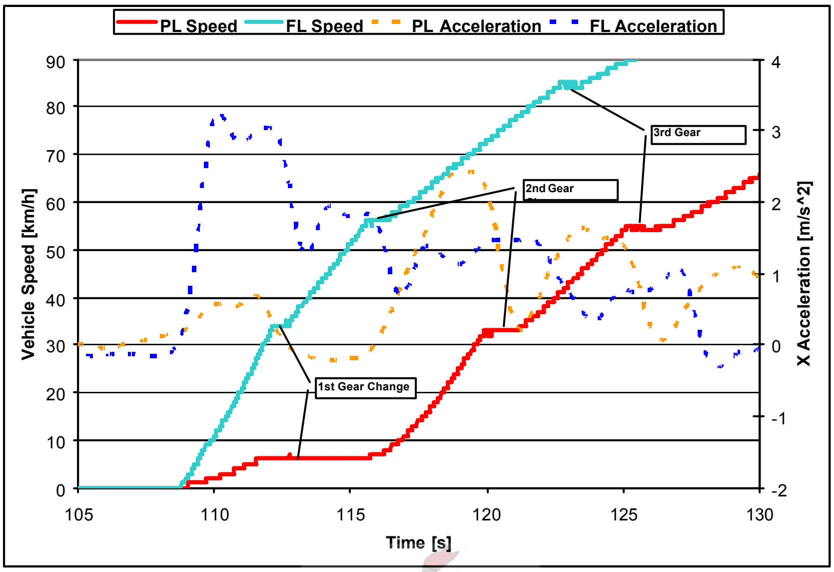


Figure 3.30: Vehicle speed vs. acceleration

Different part-load and full-load acceleration conditions were evaluated. The responses from 0 to 100 km/h, 40 to 80k m/h and 60 to 100km/h were evaluated. Figure 3.31 shows the response for these different conditions. The maximum acceleration as well as the acceleration to pedal values decreases as the acceleration speed start point increases. The motivation behind these tests was to evaluate a vehicle's overtaking response.

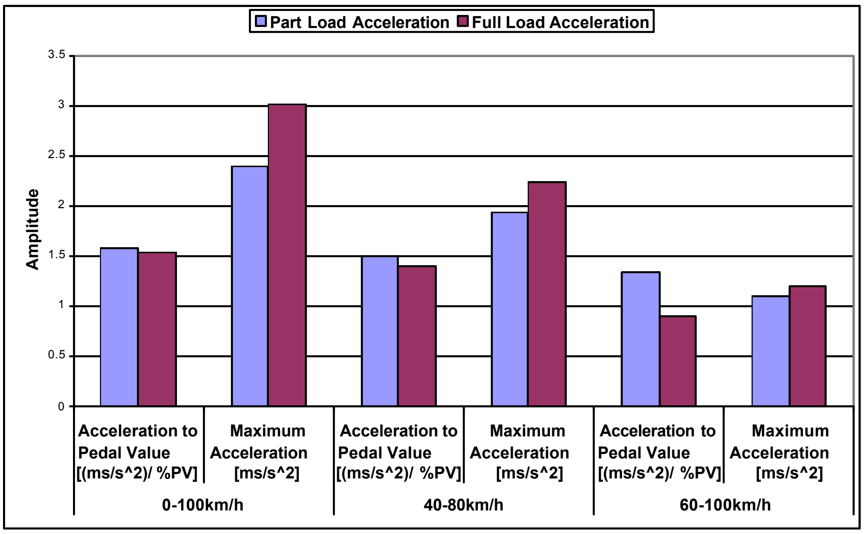


Figure 3.31: Part-load vs. full-load vs. acceleration response

The effect of fuelling was also investigated. Figure 3.32 shows the response to a reduction in the fuelling during part-load acceleration. As expected, the acceleration to pedal response is less for the reduced fuelling as well as the fuel-air ratio. The same response of the variables was obtained for the full-load condition.

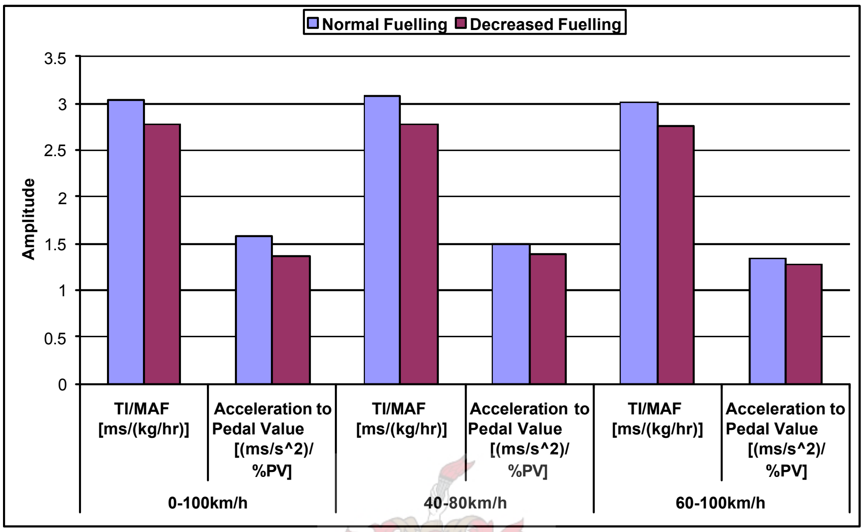


Figure 3.32: Part-load fuelling reduction response

3.5.5 Tip-in/tip-out

Tip-in/tip-out evaluation is one of the most important criteria to evaluate for driveability. Poor response will immediately lower the driver's perception of acceptable driveability. The vehicle's powertrain plays a significant role in the tip-in/tip-out response. The powertrain consists of the engine, clutch, transmission, differential (or final drive), shafts and wheels. Figure 3.33 illustrates the layout of the powertrain for a front-wheel-driven vehicle and Figure 3.34 illustrates the layout of a rear-wheel-driven vehicle. The driveline (also referred to as the drivetrain) is the powertrain, excluding the engine. Since some of these parts are elastic, some mechanical resonance will occur. The engine management can to some extent compensate for this behaviour if it is properly calibrated.

Shunt is defined as the initial jerk that might occur during a rapid change in acceleration. If a sound is produced by this phenomenon, then it is called clonk or clunk. Clonk is a high frequency, metallic noise that occurs after backlash and causes components to lash against each other. Shuffle is defined as the vehicle oscillations that take place after a rapid throttle input or increase in engine load (Johansson, 2004).

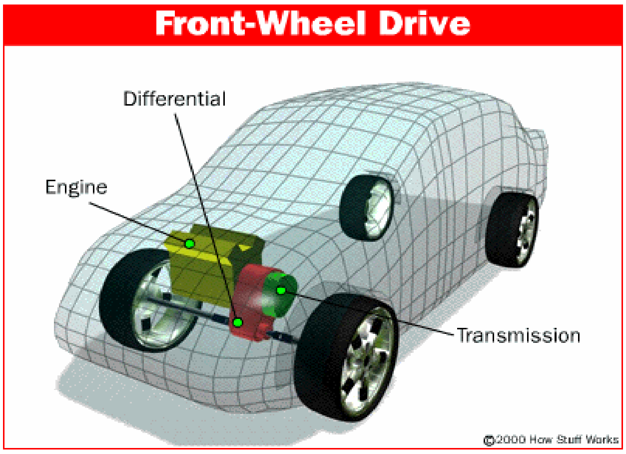


Figure 3.33: Powertrain layout for a front-wheel-driven vehicle (Anonymous, 2005)

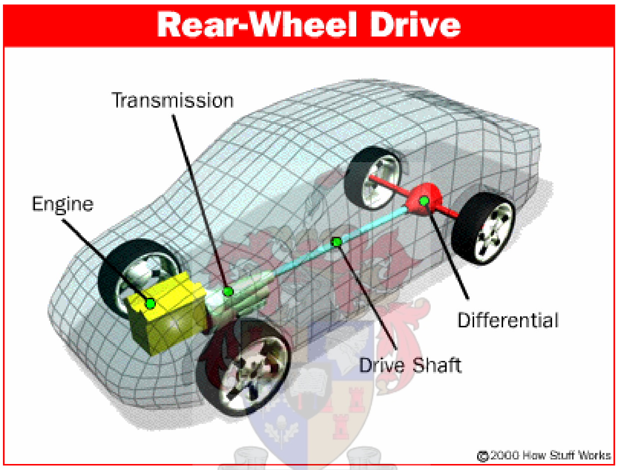


Figure 3.34: Powertrain layout for a rear-wheel-driven vehicle (Anonymous, 2005)

The variation in engine torque demand causes undesirable longitudinal and pitching oscillations (vehicle rocking backwards and forwards), which arise from excitation of the fundamental vehicle driveline resonance. A sudden increase in load, such as an air conditioning compressor switching on, and especially poor throttle control, is the main causes of these oscillations. The oscillations are transmitted to the driver via the chassis (Johansson, 2004). The driver then perceives this undesired behaviour as poor driveability.

3.5.5.1 Tip-in/tip-out testing procedure

Tip-in and tip-out is a method by which to evaluate the shunt and shuffle response of a vehicle. Tip-in and tip-out were evaluated for different conditions. These different conditions were 10 to 20 km/h in first and second gear, and 20 to 40 km/h in first, second and third gear. The measured results for tip-in are presented in Appendix C6 and results for tip-out in Appendix C7.

Figure 3.35 illustrates the response of an engine management system for a tip-in/tip-out evaluation. The ECU's software has an anti-jerk function integrated to allow for specific calibration to compensate for jerk. Figure 3.36 illustrates the acceleration response, with this anti-jerk function active as well as the anti-jerk function disabled. The measurement with the anti-jerk function disabled resulted in a higher acceleration (and jerk) value. Figure 3.37 illustrates the engine management response with the anti-jerk function disabled. By comparing the two engine management strategies it is clear that the jerk is reduced by retarding the ignition timing (thus reducing the torque), for both tip-in and tip-out conditions. The effect of reducing/increasing the fuelling is too slow to compensate for jerk because jerk occurs at a high frequency.

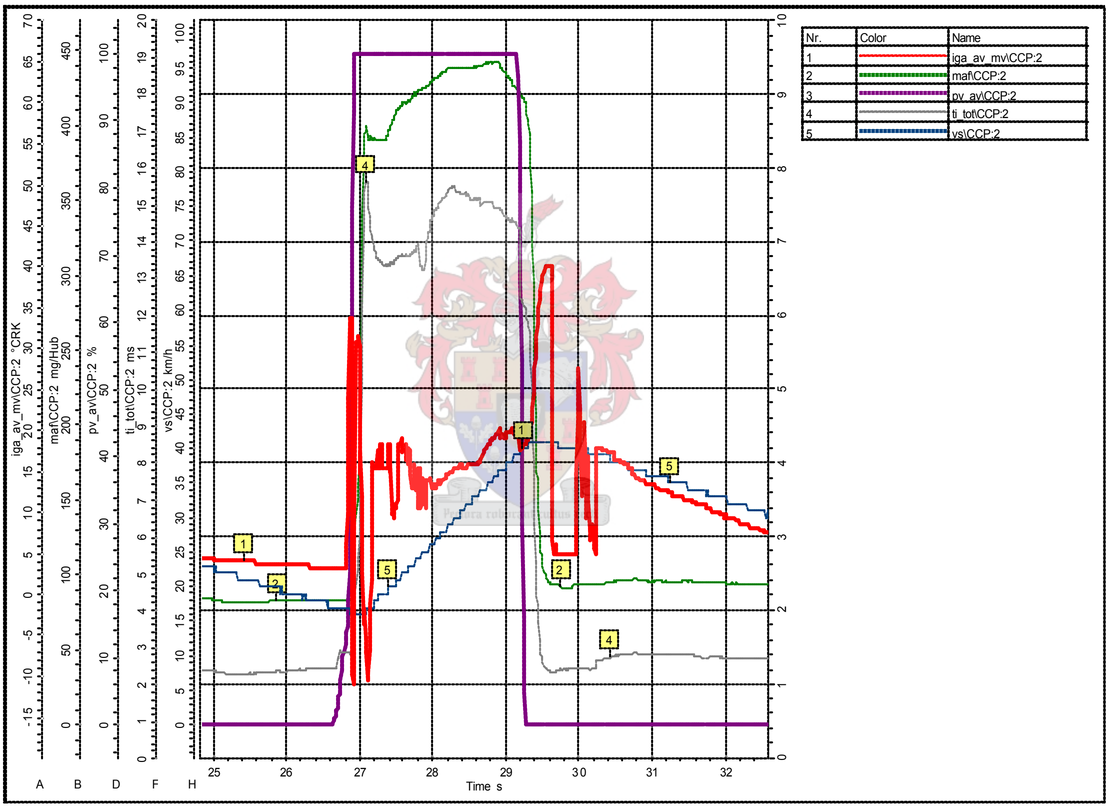


Figure 3.35: Tip-in tip-out engine management measurement, with the anti-jerk function active showing ignition angle (IGA_AV_MV), mass airflow (MAF), accelerator pedal position (PV_AV), injection duration (TI_TOT) and vehicle speed (VS)

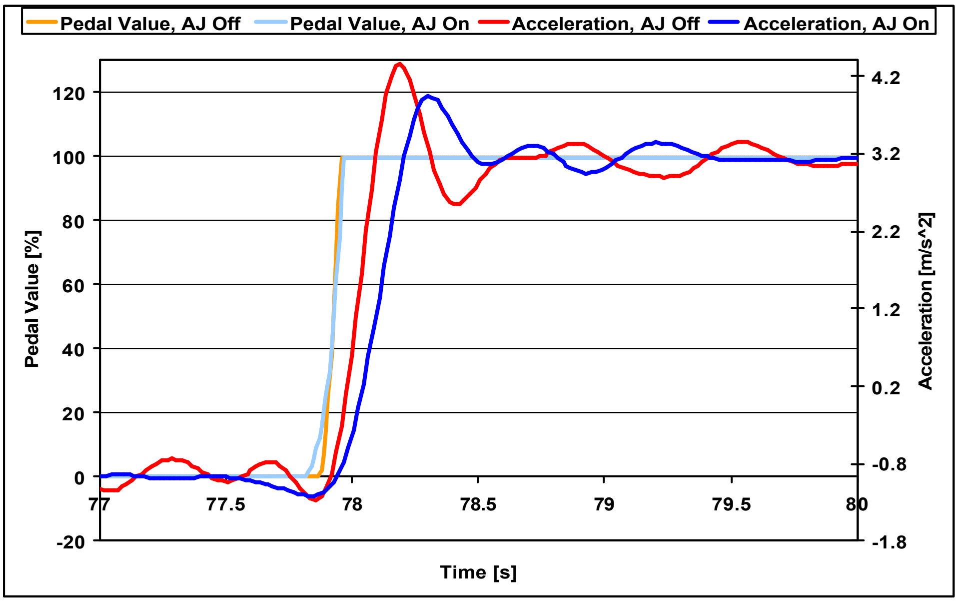
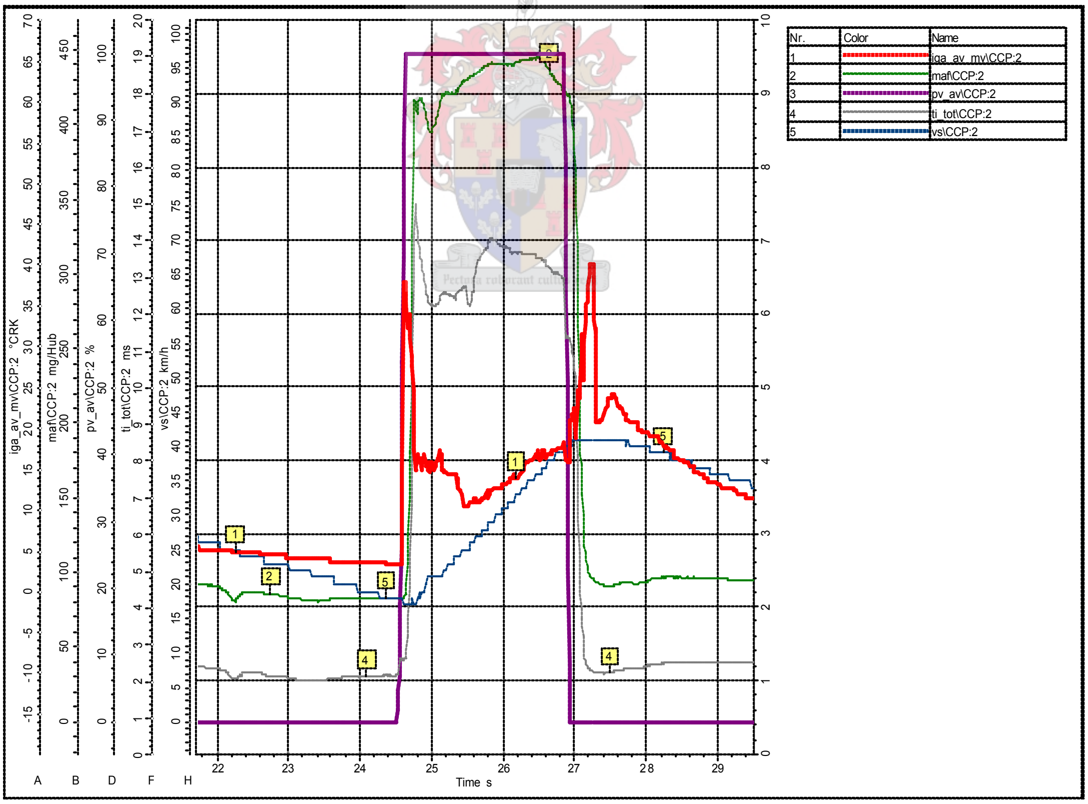


Figure 3.36: Tip-in Acceleration Measurement, with and without the Anti-Jerk (AJ) Function Active



Nr.	Color	Name
1	🟥	iga_av_mv\CCP:2
2	🟩	maf\CCP:2
3	🟪	pv_av\CCP:2
4	▨	ti_tot\CCP:2
5	🟦	vs\CCP:2

Figure 3.37: tip-in/tip-out measurement, without the anti-jerk function active showing ignition angle (IGA_AV_MV), mass airflow (MAF), accelerator pedal position (PV_AV), injection duration (TI_TOT) and vehicle speed (VS)

The jerk, measured during tip-in, with the function active, is 10 m/s^3 and without is 17.03 m/s^3. A driveability score is assigned to tip-in response for jerk with Table 3.17 (presented in section 3.5.1). There is also an injection peak during this period, but this is associated with acceleration enrichment. The period after the jerk, with regards to engine management evaluation, can be evaluated as part-load of full-load acceleration.

3.5.6 Coasting

Coasting is defined as releasing the pedal, from a certain vehicle speed, and not applying any brakes or changing the gear ratio. Under normal conditions releasing the pedal will result in the engine burning fuel without it doing any useful work. Since the engine is still slowing down from a certain speed it still breathes in air and fuel.

Deceleration shut-off, also known as overrun or coasting shut-off, can be implemented to cut the fuel supply under these conditions. Since engine speed is still measured the ECU knows when to introduce more fuel to ensure that the engine does not stall. This technique saves fuel and also reduces emissions. This will typically happen if a car is driving down a hill, in a certain gear, and without a pedal input from the driver. Approaching a stop or red traffic light, or reducing speed because of a speed restriction are other examples of coasting.

3.5.6.1 Coasting testing procedure

Coasting is similar to tip-out except that the gear ratio is lower and the vehicle speed is much higher. Analysis is similar to tip-out, but the air-fuel ratio is the most important aspect that must be analysed during coasting. Figure 3.38 illustrates the strategy of the engine management and Figure 3.39 illustrates the acceleration response. As with tip-out, the ignition timing is initially advanced to reduce the jerk at pedal release, and thereafter retarded. Lambda increases to above 30 (maximum measuring range of equipment). When the engine speed reaches a certain value fuel is re-introduced to prevent the engine from stalling. A driveability score is allocated to jerk, from Table 3.17 and to fuel shut-off from Table 3.19. All the measured data for coasting evaluations are presented in Appendix C8. In Chapter 4 (section 4.4) these data will be used to display four examples of driveability evaluations.

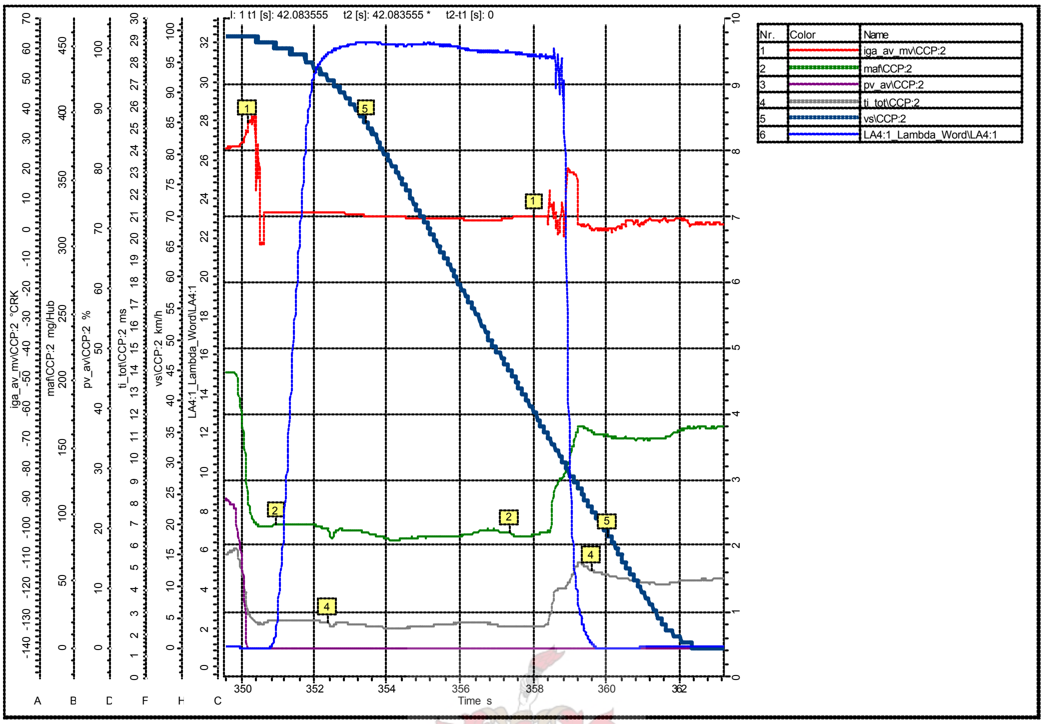


Figure 3.38: Coasting measurement showing ignition angle (IGA_AV_MV), mass airflow (MAF) accelerator pedal position (PV_AV), injection duration (TI_TOT), vehicle speed (VS), and lambda (LA4:1_Lambda_Word)

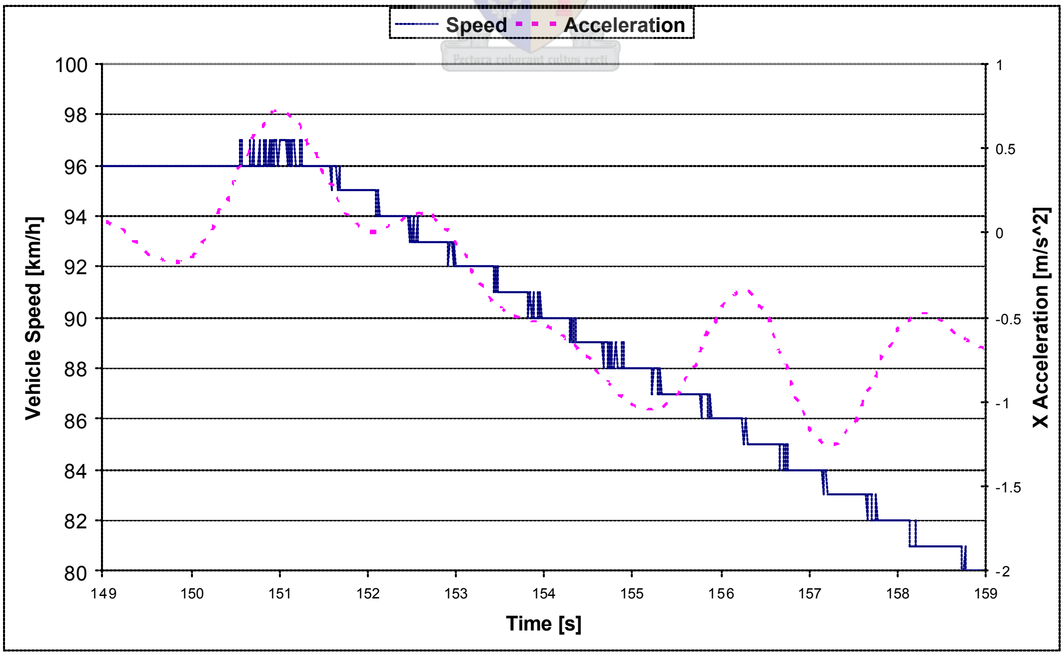


Figure 3.39: Coasting acceleration measurement

3.5.7 Driveability acceleration index

The complete driveability acceleration score is a combination of pull-away response, part-load acceleration, full-load acceleration, tip-in, tip-out and coasting. The pull away score, DAI_{PA}, is determined by the result obtained from Equation 3.15, using Equation 3.14.

$$\left(TI/MAF\right)_{PA} = \left(TI_{\max}/MAF_{\max}\right)_{m} + \left(TI/MAF\right)_{TCO} \tag{3.15}$$

Each part-load acceleration condition is calculated with Equation 3.16 and Tables 3.14, 3.16 and 3.17. Jerk is slightly more important than the fuel-air ratio and the acceleration per pedal input since the driver is the more sensitive to jerk.

$$DAI_{PL\_C} = 0.3*\left(DAI_{TI/MAF}\right)_{PL} + 0.3*\left(DAI_{G\_PV}\right)_{PL} + 0.4*\left(DAI_{Jerk}\right)_{PL} \tag{3.16}$$

Equation 3.17 combines the different part-load acceleration conditions. Accelerating from 0 to 100 km/h is the most important evaluation since this value is often used for marketing purposes. The 40-80 km/h condition is representative of an urban driving overtaking/acceleration response and is therefore weighted slightly higher than the 60-100 km/h condition.

$$DAI_{PL} = 0.5*\left(DAI_{PL}\right)_{0-100km/h} + 0.3*\left(DAI_{PL}\right)_{40-80km/h} + 0.2*\left(DAI_{PL}\right)_{60-100\,km/h} \tag{3.17}$$

Full-load acceleration is calculated with Equation 3.18 and Equation 3.19 in exactly the same manner as part-load acceleration. Tables 3.15, 3.16 and 3.17 are used to obtain the DAI values

$$DAI_{FL\_C} = 0.3*\left(DAI_{TI/MAF}\right)_{FL} + 0.3*\left(DAI_{G\_PV}\right)_{FL} + 0.4*\left(DAI_{Jerk}\right)_{FL} \tag{3.18}$$

$$DAI_{FL} = 0.5*\left(DAI_{FL}\right)_{0-100km/h} + 0.3*\left(DAI_{FL}\right)_{40-80km/h} + 0.2*\left(DAI_{FL}\right)_{60-100\,km/h} \tag{3.19}$$

The driveability acceleration index for tip-in consists of the combination between jerk and acceleration enrichment. A slight enrichment is required for the load increase, but will be penalised if the enrichment is too high (as displayed in Table 3.18). Again jerk is weighted more heavily since it is a representation of what the drivers will experience. Equation 3.20 shows the relationship between jerk and acceleration enrichment. In Equation 3.21 all the tip-in conditions are weighted evenly since no condition has preference to another condition. Tables 3.17 and 3.18 were used to obtain the corresponding DAI values.

$$DAI_{TIP\_IN\_C} = 0.75*\left(DAI_{Jerk}\right)_{TIP\_IN} + 0.25*\left(DAI_{AE}\right)_{TIP\_IN} \tag{3.20}$$

$$\begin{aligned} DAI_{TIP\_IN} &= 0.2*\left(DAI_{TIP\_IN}\right)_{10-20km/h\_1st} + 0.2*\left(DAI_{TIP\_IN}\right)_{10-20km/h\_2nd} + 0.2*\left(DAI_{TIP\_IN}\right)_{20-40km/h\_1st} \\ &\quad + 0.2*\left(DAI_{TIP\_IN}\right)_{20-40km/h\_2nd} + 0.2*\left(DAI_{TIP\_IN}\right)_{20-40km/h\_3rd} \end{aligned} \tag{3.21}$$

Tip-out is only evaluated for jerk. The absolute value is taken and evaluated since the acceleration is negative. All the tip-out conditions are also weighted evenly.

Coasting is evaluated for jerk and air-fuel ratio. Again jerk is weighted more heavily since it is a representation of what the drivers will experience. Equation 3.22 shows how the driveability acceleration score for coasting is evaluated, with the data used from Tables 3.17 and 3.19.

$$DAI_C = 0.75\left(DAI_{Jerk}\right)_C + 0.25\left(DAI_{AF}\right)_C \tag{3.22}$$

Evaluating a vehicle with regards to acceleration is complicated because different types of vehicles focus on different behaviours as well as different customer requirements. The weighting factors applied can therefore be changed for different types of vehicle classes to represent a more accurate indication. If the vehicle is a sports vehicle then full-load acceleration will be weighted more heavily than part-load acceleration, etc. The vehicle tested here was an ordinary light passenger vehicle and it is therefore not expected to score extremely high on full-load acceleration. Part-load acceleration, tip-in and tip-out response were more important since the vehicle will most likely spend most of its life ‘crawling’ through traffic. Equation 3.23 shows the relationship between all the acceleration conditions used to calculate the final driveability acceleration score. It is neccesary to evaluate all the sub equations because of all the interactions between the different measurment. If the acceleration is improved then it might lead to an increase in jerk as well and the calibration engineer must be aware of this. This is achieved by all the sub equations.

$$\begin{aligned} DAI &= 0.2*DAI_{PA} + 0.2*DAI_{PL} + 0.1*DAI_{FL} + 0.2*DAI_{TIP\_IN} + 0.2*DAI_{TIP\_OUT} \\ &\quad + 0.1*DAI_C \end{aligned} \tag{3.23}$$

The use of the driveability acceleration index is illustrated by the following example:

The coolant temperature was measured as 105 ^{o}C during pull away. Equation 3.14 is used to determine the correction factor for the fuel-air ratio at this temperature.

$$x_1 = TCO = 105 \qquad\qquad x_2 = 1$$

$$TI/MAF_{TCO} = [5.5088 - 0.0283 * TCO - 0.0283(TCO - 96.5)x_2] - 3$$

$$TI/MAF_{TCO} = [5.5088 - 0.0283 * 105 - 0.0283(105 - 96.5)] - 3$$

$$TI/MAF_{TCO} = -0.7$$

The maximum injection duration during pull-away was measured to be 7.2 ms and the maximum mass airflow was measured as 261.4 mg/Hub. Equation 3.16 is used to calculate the adjusted fuel-air ratio.

$$\left(TI/MAF\right)_{PA} = \left(TI_{\max}/MAF_{\max} * 100\right)_m + \left(TI/MAF\right)_{TCO}$$

$$\left(TI/MAF\right)_{PA} = \left(7.2/261.4 * 100\right)_m - 0.7$$

$$\left(TI/MAF\right)_{PA} = 2.05$$

The corresponding driveability score, from Table 3.14, is 6/10; this is a neutral classification.

The part-load and full-load conditions that were measured are presented in Table 3.21. Equations 3.16 to 3.19 are used to calculate the part- and full-load conditions for each measurement. Tables 3.14 to 3.17 are used to allocate a score to the measured results.

Table 3.21: Part- and full-load measured results

	PL Acc 0 - 100km/h	PL Acc 40 - 80km/h	PL Acc 60 - 100km/h	FL Acc 0 - 100km/h	FL Acc 40 - 80km/h	FL Acc 60 - 100km/h
TI/MAF	3.001	3.0743	3.0267	3.2845	3.3235	3.326
$DAI_{TI/MAF}$	9	9	9	8	8	8
Acceleration per Pedal Input	1.6954	1.6367	1.3253	1.4927	1.3928	0.99778
DAI_{G_PV}	7	7	6	6	6	6
Max Jerk	0.604	0.368	0.173	0.887	0.64	0.499
DAI_{Jerk}	6	5	5	6	6	6
DAI	7.2	6.8	6.5	6.6	6.6	6.6

$$DAI_{PL\_0-100km/h} = 0.3 * \left(DAI_{TI/MAF}\right)_{PL} + 0.3 * \left(DAI_{G\_PV}\right)_{PL} + 0.4 * \left(DAI_{Jerk}\right)_{PL}$$

$$DAI_{PL\_0-100km/h} = 0.3 * 9 + 0.3 * 7 + 0.4 * 6$$

$$DAI_{PL\_0-100km/h} = 7.2$$

The same equation is used to calculate the other part-load conditions as well as the full -load conditions. The results are displayed in Table 3.21. Equations 3.18 and 3.20 are used to calculate a score for the combination of the conditions for part load and full load.

$$DAI_{PL} = 0.5 * \left(DAI_{PL}\right)_{0-100\,km/h} + 0.3 * \left(DAI_{PL}\right)_{40-80km/h} + 0.2 * \left(DAI_{PL}\right)_{60-100km/h}$$
$$DAI_{PL} = 0.5 * 7.2 + 0.3 * 6.8 + 0.2 * 6.5$$
$$DAI_{PL} = 6.94$$

$$DAI_{FL} = 0.5 * \left(DAI_{FL}\right)_{0-100km/h} + 0.3 * \left(DAI_{FL}\right)_{40-80km/h} + 0.2 * \left(DAI_{FL}\right)_{60-100km/h}$$
$$DAI_{FL} = 6.6$$

The measurements for a tip-in evaluation are displayed in Table 3.22. Equations 3.21 and 3.22 are used to calculate a driveability score for tip-in evaluation. Tables 3.17 and 3.18 are used to allocate a score to the tip-in results.

Table 3.22: Tip-in measured results

	Tip In 10-20 1st	Tip In 10-20 2nd	Tip In 20-40 1st	Tip In 20-40 2nd	Tip In 20-40 3rd
Injection Overshoot (Acceleration Enrichment)	35.457	28.439	20.120	19.228	19.391
DAI_{AE}	9	7	6	5	5
Jerk	1.55	1.683	1.201	0.734	0.4
DAI_{Jerk}	6	6	6	6	5
DAI	6.75	6.25	6	5.75	5

$$DAI_{TIP\_IN\_10-20\_1st} = 0.75 * \left(DAI_{Jerk}\right)_{TIP\_IN} + 0.25 * \left(DAI_{AE}\right)_{TIP\_IN}$$
$$DAI_{TIP\_IN\_10-20\_1st} = 0.75 * 6 + 0.25 * 9$$
$$DAI_{TIP\_IN\_10-20\_1st} = 6.75$$

Table 3.22 displays the results for the other tip-in conditions. Equation 3.21 is used to calculate the total score for all the tip-in conditions.

$$\begin{aligned} DAI_{TIP\_IN} &= 0.2 * \left(DAI_{TIP\_IN}\right)_{10-20km/h\_1st} + 0.2 * \left(DAI_{TIP\_IN}\right)_{10-20km/h\_2nd} + 0.2 * \left(DAI_{TIP\_IN}\right)_{20-40km/h\_1st} \\ &\quad + 0.2 * \left(DAI_{TIP\_IN}\right)_{20-40km/h\_2nd} + 0.2 * \left(DAI_{TIP\_IN}\right)_{20-40km/h\_3rd} \\ DAI_{TIP\_IN} &= 0.2 * 6.75 + 0.2 * 6.25 + 0.2 * 6 + 0.2 * 5.75 + 0.2 * 5 \\ DAI_{TIP\_IN} &= 5.95 \end{aligned}$$

The measurements for a tip-out evaluation are displayed in Table 3.23. Data in Table 3.17 are used to allocate a score to each measurement. The tip-out score was calculated to be 5.6.

Table 3.23: Tip-out measured results

	Tip Out 10-20 1st	Tip Out 10-20 2nd	Tip Out 20-40 1st	Tip Out 20-40 2nd	Tip Out 20-40 3rd
Jerk	-0.62	-0.544	-0.555	-0.292	-0.22
DAI_{Jerk}	6	6	6	5	5

The jerk response was measured as 0.775 m/s^3 and lambda was measured as 31. Data in Tables 3.18 and 3.19 were used to calculate the driveability score.

$$\begin{aligned} DAI_C &= 0.75(DAI_{Jerk})_C + 0.25(DAI_{AF})_C \\ DAI_C &= 0.75*6+0.25*10 \\ DAI_C &= 7 \end{aligned}$$

All the above results must be used together with Equation 3.24 to calculate the driveability score for acceleration response.

$$\begin{aligned} DAI = {} & 0.2*DAI_{PA} + 0.2*DAI_{PL} + 0.1*DAI_{FL} + 0.2*DAI_{TIP\_IN} + 0.2*DAI_{TIP\_OUT} \\ & + 0.1*DAI_C \\ DAI = {} & 0.2*8+0.2*6.94+0.1*6.6+0.2*5.95+0.2*5.6+0.1*7 \\ DAI = {} & 6.66 \end{aligned}$$

The corresponding classification for the acceleration evaluation is acceptable: according to Table 3.2 it is neutral.

3.6 Brake Response and Evaluation

Getting a vehicle to reduce speed or to stop if requested is critical in any vehicle. Anti-lock brake systems (ABS) improve the stopping distance significantly, especially in wet conditions. ABS also provides better handling during braking. Brake response is also a function of the type of braking system fitted (drums or disks), the size of the disk (or drum), the mass of the vehicle, the contact surface, and friction coefficient of the tyre. The speed at which the vehicle is at is also important with regards to stopping distance; the faster the vehicle speed the longer it will take to stop, and the relation between speed and distance is exponential (owing to the fact that kinetic energy is proportional to velocity squared).

3.6.1 Brake response test procedure

The same measuring equipment is used for the brake evaluation as for the acceleration evaluation. This section describes the brake test procedure and discusses the results. The brake evaluation model is also discussed. Appendix C9 displays the results of the brake measurements.

The vehicle is stopped from 80 km/h. The start speed is divided by the time the vehicle takes to come to a stop, and this provides the average negative acceleration. The idle response was looked at during braking as well as after braking. This was evaluated as described in Section 3.4 (Idle Response). The driveability brake index (DBI) is equal to the score obtained from Table 3.24.

Table 3.24: Driveability acceleration during braking index

Driveability Standard	Objective Driveability Index	Subjective Rating	Average Acceleration $[m/s^2]$
Favourable	10	Excellent	< -8.5
	9	Very good	-7.5 to -8.5
	8	Good	-6.5 to -7.5
Acceptable	7	Acceptable	-4.5 to -6.5
	6	Neutral	-2 to -4.5
	5	Tolerable	-2 to -2.5
Unacceptable	4	Poor	-1.5 to -2
	3	Bad	-1 to -1.5
	2	Very bad	>-1
	1	Catastrophic	Brakes fail

Table 3.24 was developed from test data and subjective inputs from various engineers. It was assumed that the driver will perceive higher negative acceleration more favourable because it is a direct indication on how fast the vehicle speed is reduced. During testing the braking was evaluated without the ABS system becoming active. The initial reason for this was to be able to compare vehicles with and without ABS. For future testing the vehicles complete braking system should be evaluated (maximum brake pedal input) since that will be more reflective on the vehicle being evaluated since an ABS will count in favour of the vehicle being evaluated and trying to stop a vehicle without activating the ABS will lead to unrepeatable results. Therefore Table 3.24

can still be improved together with a more in-depth analysis on wheel sizes, surface and tyre friction interactions etc. It does however provide a score for any result obtain through evaluation and can be used as an analysis tool. Again the accuracy can only be improved.

Figure 3.40 displays the strategy of the engine management system during braking, without the ABS assistance. The response is similar to coasting. Figure 3.41 displays the corresponding acceleration measurement.

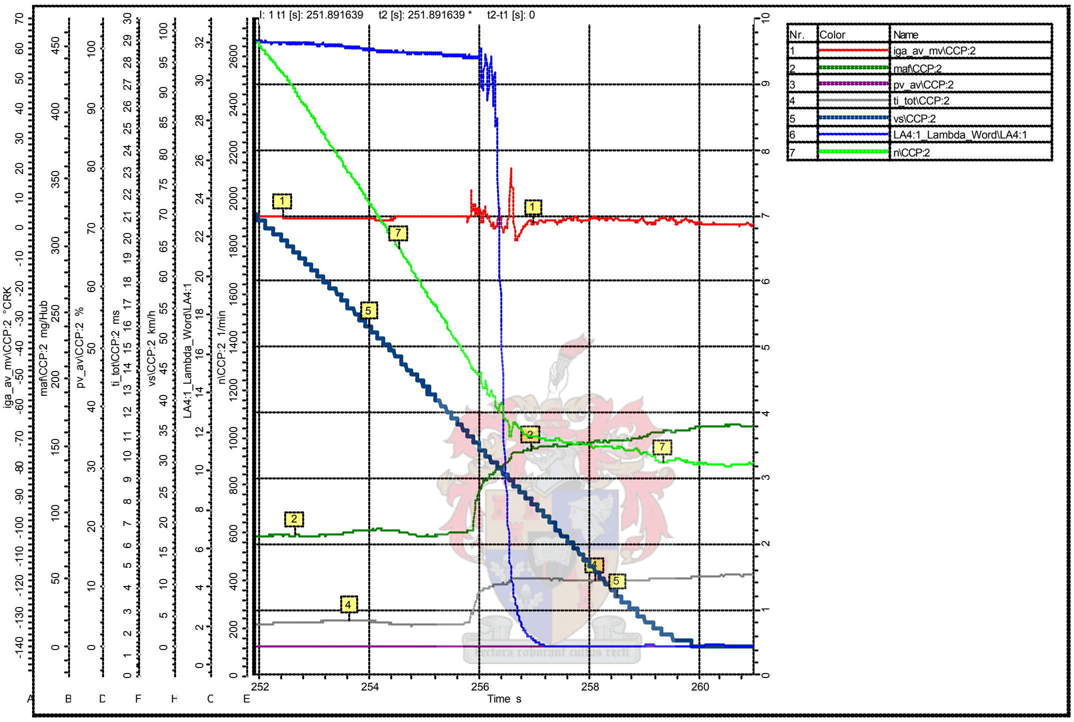


Figure 3.40: Braking measurement showing ignition angle (IGA_AV_MV), mass airflow (MAF), accelerator pedal position (PV_AV), injection duration (TI_TOT), vehicle speed (VS), lambda (LA4:1_Lambda_Word) and engine speed (N)

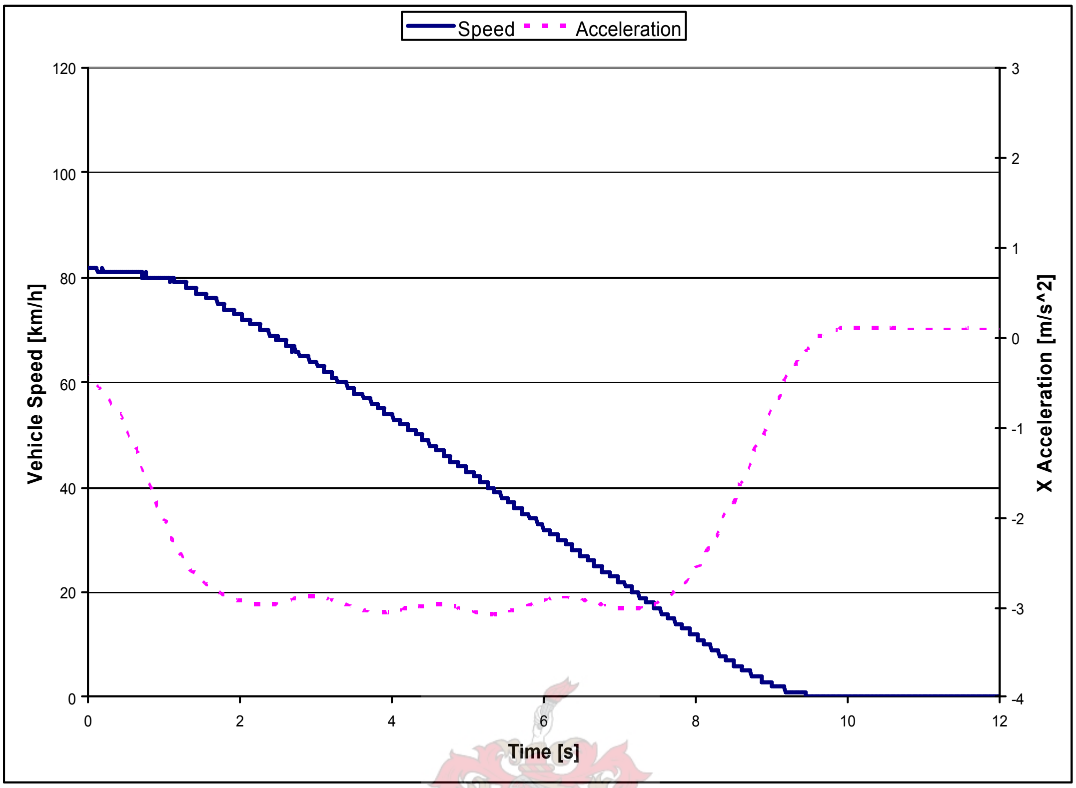


Figure 3.41: Acceleration and vehicle speed measurement for a braking condition

3.7 Cruise

Driving at a constant speed must not be difficult, especially if the driver is driving at a high speed over a long distance. The driver does not want to 'fight' with the pedal to keep the vehicle driving at the desired speed. Some vehicles are equipped with cruise control with which the engine management will keep the vehicle at the desired speed automatically when activated by the driver.

3.7.1 Cruise test procedure

The same measuring equipment is used as for the cruise evaluation as was used with all the other evaluations. The cruise performance of the vehicle was evaluated at 100 km/h and 80 km/h. The vehicle is driven to the desired speed where the speed is maintained. The pedal response evaluates the throttle input required to keep the vehicle speed steady. The test surface must be as flat as possible to eliminate any additional drag and therefore allow for repeatability. Figure 3.42 shows the measurement response of a cruise evaluation. Figure 3.42 displays that halfway trough the evaluation a slight pedal input was provided. This was only due to the fact that the driver's control was not sensitive enough to the analogue display of vehicle speed. A better controlled pedal input is required for more accurate testing. In theory measured throttle should be constant, if the power output is constant.

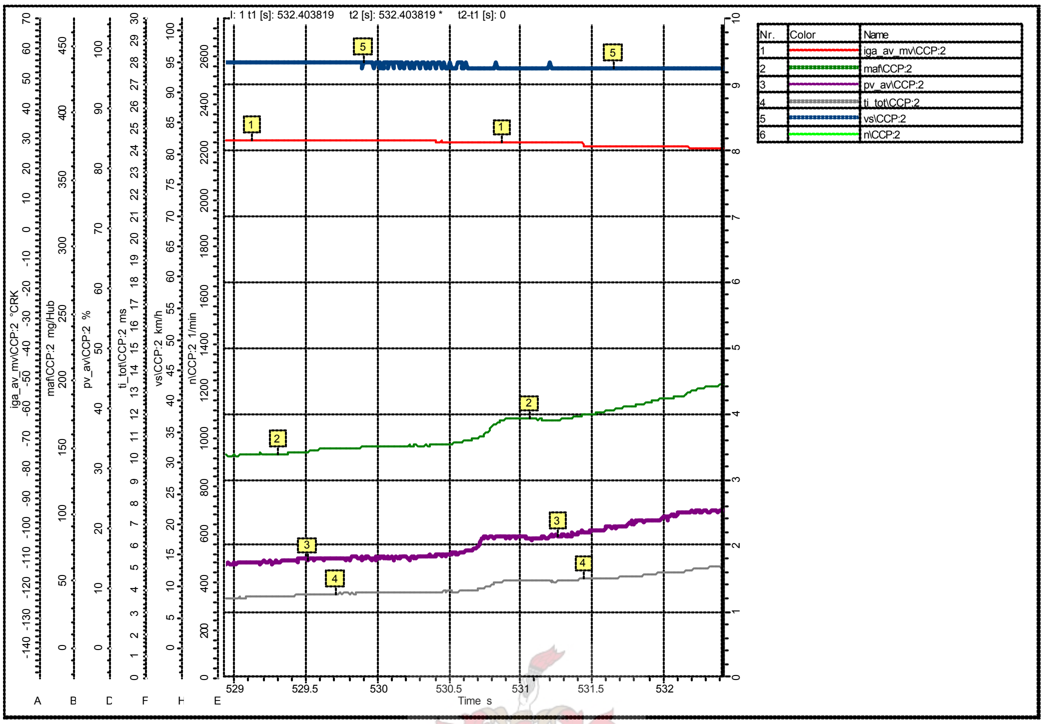


Figure 3.42: Cruise measurement showing ignition angle (IGA_AV_MV), mass airflow (MAF), accelerator pedal position (PV_AV), injection duration (TI_TOT), vehicle speed (VS) and engine speed (N)

A driveability score is allocated with regards to the standard deviation of the throttle position, required to maintain a steady speed. Table 3.25 provides the classification. The driveability cruise index (DCI) is equal to the score obtained from Table 3.25. Table 3.25 was developed from all the measured data as well as subjective input from the author. It was assumed that the driver wants to provide as little as possible change in input during constant vehicle speed cruising. The amount of deviation should be as small as possible and a large amount of deviation will be classified as unfavourable since this will possibly lead to an oscillating speed. The table do provide a meaningful classification, but a larger population of data will increase the accuracy.

Table 3.25: Driveability cruise index

Driveability Standard	Objective Driveability Index	Subjective Rating	Standard Deviation of Throttle Position [%Throttle]
Favourable	10	Excellent	0 to 1
	9	Very good	1 to 2
	8	Good	3 to 4
Acceptable	7	Acceptable	4 to 5
	6	Neutral	5 to 10
	5	Tolerable	10 to 12
Unacceptable	4	Poor	12 to 15
	3	Bad	15 to 20
	2	Very bad	20 to 25
	1	Catastrophic	> 25

The data from this chapter will provide an evaluation method for evaluating the engine management for driveability for each subsection and section of driveability. This chapter has only described how each section and subsection are evaluated on their own, to provide a driveability score for each section. This is useful when the calibration engineer is already aware of the problem area/s where he/she should focus to improve the driveability. To be able to identify problem areas it is most often necessary to evaluate the overall driveability. The breakdown provided from the results of a complete evaluation will highlight these problem areas. Chapter 4 discuss how all the subsections listed in this chapter is combined to formulate a complete driveability score. It also combines all the testing methods into a single, optimised test procedure to allow for a complete driveability evaluation in the shortest possible time.

4 DRIVEABILITY EVALUATION MODEL

4.1 Introduction

The overall objective of this study was to create a model to evaluate driveability with regards to engine management calibration. In order to quantify the driveability, a vehicle must be subjected to a series of tests where after a score is allocated for each test. Driveability is subdivided into sections and subsections. Sections were determined as start behaviour, idle behaviour, acceleration behaviour and cruise behaviour. Each test will have a score to indicate the vehicle's response to each section. The scores indicate where the problem areas are and therefore how the driveability can be improved. All the scores are combined to provide an overall driveability score. Chapter 4 described how the different sections were evaluated.

The model allows the vehicle to be evaluated for its overall driveability behaviour or that of a certain section. If only one of the sections or subsections is important, then it can be evaluated individually and, by changing the relevant section of the calibration, that particular section can be improved - or it can deteriorate.

Measurable parameters have been identified and measured to reflect the response of the vehicle to changes in engine calibration. The model enables these measurements to be manipulated into scores that change in response to changes in ambient conditions or engine calibration. It has been found that these scores responded in a manner that was in line with how a typical driver would perceive the driveability. The objective was thus achieved in that a quantitative system now exists to reflect a quantitative response although this response has not yet been correlated with the perceptions of a representative group of people. Nevertheless, it will enable engineers to a) improve a specific aspect of driveability while b) having a means of detecting the effect on other areas of the driveability.

Owing to the difficulty related to obtaining a vehicle equipped with the necessary equipment, suitable for testing the relevant aspects of driveability, only one vehicle model was used for the development of this model. A Volkswagen Golf 5 was used for the development of this model. Project objectives were however achieved by virtue of being able to adjust the engine calibration and testing at different ambient conditions such as temperature.

Driveability is a human perception. Quantifying driveability requires a correlation between human perception and measured results. One method is to use a large number of people and combining their subjective views to each response. This would have implied a complete separate study on its own on how to correlate human perception with sensed experiences. This was however not in the scope of the thesis since the critical aspect of this thesis was to create a quantitative model to assist a calibration engineer when calibrating for driveability. The option implemented was to use an already market approved vehicle as a reference. This vehicles driveability was decomposed into numerous categories and subcategories. Quantifiable parameters was identified and measured to reflect each aspect of driveability. Logical assumptions were made to correlate the measured results with the human perception.

The Golf 5 is already perceived as a vehicle with accepted driveability since it has been through the whole calibration process by many calibration engineers. The driveability has been accepted by Volkswagen management but more important by the public as well, since it sells at around 1000 units a month (VW, 2006). It has also won several awards in various competitions.

4.2 Driveability Index

The Driveability Index (DI) comprises five sections. These sections are start behaviour, idle behaviour, acceleration behaviour, brake response and cruise behaviour. Some of these sections are divided into subsections. Table 4.1 shows the hierarchy of the driveability index.

Table 4.1: Driveability index hierarchy

Driveability Index				
Start Behaviour, DSI	**Idle Behaviour, DII**	**Acceleration Behaviour, DAI**	**Cruise Behaviour, DCI**	**Brake Response, DBI**
Start Time, DSI_{st} RPM Overshoot, $DSI_{\%OS}$	Idle Speed Set Point, DII_{SP} Idle Speed Response, DII_{STD} Load Change, DII_{LC} Pedal Blip Response, $DII_{dN/dPV}$ Idle During Braking, DII_{BDI} Idle After Braking, DII_{BAI}	Pull Away, DAI_{PA} Part Load Acceleration, DAI_{PL} Full Load Acceleration, DAI_{FL} Tip In, DAI_{TIP_IN} Tip Out, DAI_{TIP_OUT} Coasting, DAI_{C}	Throttle Response	Acceleration

Below is a summary of the equations used to calculate the score of each section (from Chapter 3). The driveability brake index and driveability cruise index are single values and are looked up from their respective evaluation tables.

$$DSI = 0.8 * DSI_{st} + 0.2 * DSI_{\%OS} \tag{3.6}$$

$$DII = 0.2 * DII_{Nsp} + 0.3 * DII_{STD} + 0.2 * DII_{LC} + 0.2 * DII_{\frac{dN}{dPV}} + 0.1 * DII_{Brake} \tag{3.13}$$

$$DAI = 0.2 * DAI_{PA} + 0.2 * DAI_{PL} + 0.1 * DAI_{FL} + 0.2 * DAI_{TIP\_IN} + 0.2 * DAI_{TIP\_OUT} + 0.1 * DAI_{C} \qquad (3.24)$$

The overall driveability score is calculated with Equation 4.1. The weighting factors are an indication of the type of vehicle evaluated. If a different type of vehicle or engine size is evaluated then the weighting factors must be adapted. The start behaviour is the most important factor in evaluation. If a vehicle has a poor start response then the impression created by that vehicle will also be poor. After start behaviour, idle response and brake response are equally important. The light passenger vehicle class evaluated is not designed to be fast but will give a poor impression if the vehicle has poor idle response. Brake response is an important aspect since the vehicle class is most commonly used by the general public. Cruise behaviour is the least important for this vehicle class. There is no literature available to support these weighting factors and they are allocated on a subjective method as describe above. If a larger population of data for this vehicle class are to be evaluated, as well as data from different vehicle classes, then a more accurate and complete model can be developed. The model presented is however accurate enough to quantify and compare a vehicle's driveability.

$$DI = 0.4 * DSI + 2.2 * DII + 1.5 * DAI + 2.2 * DBI + 0.1 * DCI \qquad (4.1)$$

4.3 Optimised Driveability Test Procedure

Calibrating driveability response is carried out over a long period of time and with many different measured files. Analysing the data after testing can become frustrating in terms of remembering what files were recorded at what time. If the period required for recording and analysing driveability can be reduced then it will save a lot of time and money. Having a procedure that enables the operator to be able to compare measurements and visualise improvements will be advantageous.

There is a trade-off between good driveability and emissions limitations. Calibration for a vehicle to pass the emissions regulations is not included in this model. Detailed and quantitative emission test procedures and facilities exist and this will allow the calibration to be subjectively evaluated. All the aspects and influences of engine management strategies on emissions are mentioned in this report. Combining a modal emissions test together with a detailed engine management measurement will allow the calibration engineer to investigate where critical areas are and will allow him to change the calibration to fulfil the requirements for both driveability and emissions.

An optimised procedure was developed to reduce the driveability evaluation and allow measured files to be analysed more easily. Figure 4.1 shows the flow diagram of a warm operating condition test procedure. The cold and hot test procedures used in this study ended at pull away because the period required by the vehicle to reach operating temperature is too short to evaluate acceleration response. The flow diagram can be adapted if the environmental condition changes to extremely hot or extremely cold, since the coolant temperature will remain colder/hotter for longer.

The flow of the test procedure allows all the conditions to be measured in the shortest possible time. It also allows all the conditions to be easily measured simultaneously, without intervals.

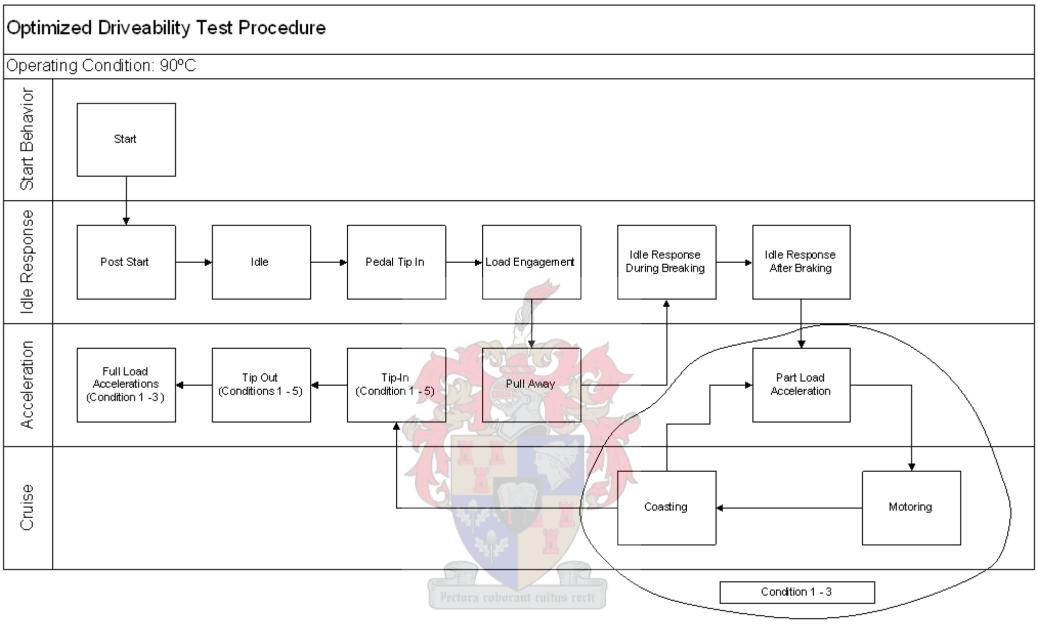


Figure 4.1: Optimised driveability test procedure flow diagram

If only idle response needs to be investigated, then only the idle test flow diagram is used, or any combination of different sections can be evaluated in the shortest possible time.

4.4 Driveability Evaluation Example

The driveability evaluation model needs to be verified to test the accuracy and repeatability for the developed quantitative methodology. The verification of the model is divided into three sections. The first section evaluates the model for repeatability. The second section evaluates the model for a change in calibration and the last section test the accuracy of the model for a vehicle started at a temperature range between the four coolant temperature points used to develop the compensation model.

4.4.1 Verification for repeatability

The vehicle was evaluated for warm operating condition (96°C). The standard production level calibration software was loaded on the application ECU. The expected results should fall in the acceptable to favourable category. The test was repeated three times under the same operating condition. Table 4.2 presents the results.

Table 4.2: Driveability results for warm evaluation to investigate repeatability

Test No.	Measured File	DSI	DII	DAI	DBI	DCI	DI
		Start	Idle	Acceleration	Brake	Cruise	Total
1	Driveability Test 1, Normal Fuelling	6.4	6.56	6.89	6.00	7.00	7.06
2	Driveability Test 2, Normal Fuelling	7.4	6.72	6.89	6.00	6.00	7.39
3	Driveability Test 3, Normal Fuelling	6.6	6.76	6.68	6.00	6.00	7.05

The complete driveability model was evaluated with the results tabulated in Appendix D. Table 4.2 shows the results for each different section as well as the overall driveability score. The results for the first three evaluations received a driveability score of between seven and eight. This classifies them as having acceptable driveability or acceptable for most customers (see Table 3.2). The results show that the driveability model created in this project is repeatable.

4.4.2 Verification for changes in calibration

The next step for verification of the model was to investigate if the model detects a change in calibration. The model must also indicate what influence the change have on the relevant section and if there is a trade off in another section, either positive or negative.

Reducing the fuelling will provide a good reference to investigate the accuracy of the model. Reducing the fuelling should decrease the start time and inhibit the responsiveness of the vehicle. The fuelling system will still try and run the engine in closed loop control and therefore try and hold the air fuel ratio close to stoichiometric. A change in fuelling should therefore only have an impact on open loop control (starting, full load compensation etc.)

The second method used for verifying the model was to switch off the anti-jerk function. The anti-jerk function reduces the amount of jerk experience by the driver when the load is suddenly increased or decreased. The vehicle should therefore have much higher values during tip in and tip out. It should also have an impact on the acceleration behaviour of the vehicle.

Table 4.3 presents the results from the driveability evaluation with reduced fuelling and with the anti-jerk function switched off. The measurement for the anti-jerk function did not include cruising, brake and the acceleration conditions for 40km/h – 80km/h and 60km/h – 100km/h.

Table 4.3: Driveability results for warm evaluation to investigate a change in calibration

Test No.	Measured File	DSI	DII	DAI	DBI	DCI	DI
		Start	Idle	Acceleration	Brake	Cruise	Total
4	Driveability Test 4, 10% Less Fuelling	6	6.42	6.47	6.00	6.00	6.70
5	Driveability Test 5, Anti-Jerk Function Off	7	6.7	7.52	6.00	6.00	7.32

Test case four received a score between six and seven. This classifies it as having neutral driveability, or indifferent by most customers. Table 4.3also shows that the effect of reducing the fuelling was most evident on start, idle and acceleration response, as was expected. This proves that the model does reflect a change in the calibration for a change in a parameter that affects the driveability of a vehicle. The summary of the subsections provides a more detailed analysis of every aspect that was influence by the change in calibration.

Switching off the anti-jerk function actually increased the acceleration score. This was due to the increased response with the acceleration behaviour. Appendix D shows that the evaluation scored high for the tip in and acceleration evaluation and very poor for the tip out behaviour. The vehicle evaluated does have a very aggressive anti-jerk function. It therefore implies that the calibration can be changed to allow for a better tip in response. Tip out response should remain damped since it scored poor during this evaluation and higher with the original calibration. Even though the overall score of the evaluation does not reflect the change in calibration it still provided a more detailed analysis in the subsections. This proves that the model is effective in evaluating a change in calibration, even if it does not change the overall score. It also proves that changing the calibration might have a negative effect in one area and a positive effect in another area.

Driveability evaluation is a combination of different test procedures used to evaluate different aspects of vehicle response, in order to produce a meaningful score that can be compared for similar evaluations. This chapter provides a model that allows a vehicle to be evaluated in terms of overall driveability as well as evaluating specific aspects of a vehicle's driveability. The model also provides the desired response when the calibration of the engine management system is changed in a manner known to detract from good driveability.

This model can be used to electively compare changes in calibrations as well as to rate a vehicle's driveability. The test procedure was also optimised and simplified to evaluate all the desired conditions in one complete test in the shortest time possible.

4.5 Recommendations

The current model only evaluates driveability with regards to engine management calibration. Developing a driveability model to evaluate a vehicle with regards to vibration, driveline design and comfort will enable vehicle manufacturers to optimise driveability when designing and developing a vehicle.

Only one engine size and vehicle class was evaluated. The ideal for this model is for a vehicle manufacturer to have a large database of different vehicle classes, with different engine sizes and configurations. This database will include averages of all the measured data as well as all the outliers. Having a larger spread of data will also improve the accuracy and significance of the driveability index and will reflect closer on subjective perception. The full range between unacceptable and favourable was not always tested and some form of extrapolation or interpolation was used to fit the data. The accuracy will also be improved with a larger population of data as well as more in depth analysis of all the limits. The different behaviours of each vehicle class will be evaluated to provide the correct weighting factors. The driveability scores can also be adapted with a larger population of data to allow for more accurate classifications. The weighting factors can therefore not be finalised without a complete database for different vehicle classes.

The engine coolant compensation equations have to be improved for accuracy by generating a larger population of data at different temperatures. The equations developed for this project are by no means accurate for all engine temperature conditions. The equations developed for this project only provides the methodology on how such equations should be incorporated in the model.

Accurate pedal control will also improve the evaluation results. A proper pedal control device must be constructed to allow for precise rate of pedal change between different tests. All this can be incorporated into an appropriate software package that can be activated by one button and it will provide instructions on the screen which the driver has to follow in order to evaluate the different aspects. When the test program is finished it should automatically produce a file with a summary and breakdown of the test as well as update a database to improve the accuracy of the weighting factors.

The model did provide a quantitative driveability classification for a vehicle. It is clearly reflected in this chapter that changing a parameter (known to have a negative effect on driveability) did result in a lower score for that evaluation. The test procedures were also optimised to lead to a shorter evaluation time, without any compromises to or a reduction in significant data. There is however still areas where this model can be improved to provide more accurate results and provide the driver with an uncomplicated interface to guide him/her through the test.

5 CONCLUSION

Driveability evaluation is an essential requirement for evaluating the response and perceived quality of a vehicle. It is also a development tool with which to evaluate the response of characterising the control system to manage engine behaviour. Only subjective evaluation of driveability is currently assessed. Experienced drivers evaluate the response of vehicles and combine their results to present areas that require engine management calibration attention. This leads to extended calibration periods where the same drivers have to re-evaluate a vehicle until they are satisfied with the response. This often leads to an undetected reduction in driveability in another area that was not evaluated for improvement because of the interaction between engine management aspects.

The purpose of the study described in this thesis was to develop a quantitative driveability evaluation model for engine management calibration. The study also included identifying all the engine management sections that influence the driveability, and then developing a testing method to evaluate these sections. An optimised testing procedure was also required to evaluate all the different sections in the shortest possible time.

First a detailed literature review was carried out. It provided a definition of driveability and how it is currently evaluated. It also referred to other research with regards to the objective evaluation of driveability. The basic fundamentals of engine management theory and its effect on driveability were also discussed in Chapter 2. This provides the reader with a complete background study as well as an overview on the relevant sensors and signals and the interaction between the significant engine management strategies.

Chapter 3 describes how the model for driveability evaluation was developed. Vehicles were evaluated for different responses. The results, in conjunction with current evaluation methods, were used to determine the most important aspects of driveability evaluation with regards to engine management calibration. These aspects were arranged into sections. The sections were subsequently divided into subsections to allow for a more detailed analysis. These sections and subsections list all the important aspects of driveability to allow the calibration engineer to focus on their response and interaction during calibration and evaluation.

A method was developed to allow the results to be adjusted to a reference temperature condition to represent comparative results. This eliminated a large database for each operating condition and simplified the evaluation. A classification for each subsection's results was also developed to allow for the subsections to be evaluated and improved individually. The results of each measured factor were sorted in ascending order. Where no data was available, a subjective interpolation method was used to allow for a full range of responses. The classifications were assigned to the results accordingly. This provides a descriptive classification for each value obtained from the results, where high values result in a good classification and low values in a poor classification. The evaluator is therefore always aware of which classification the results represent. Only one vehicle was evaluated here. A larger population of data should increase the accuracy of the classifications.

Each subsection of driveability was discussed to explain the engine management response, and how the driveability could be improved by changing the calibration of the engine management software. All the subsections' results were combined to provide a classification for each section. The results were combined by means of weighting factors. The weighting factors were allocated according to importance. The importance of each subsection was determined by the measured results and their influence on each other. Where no data was available, a subjective weighting was allocated. The weighting factors allow the results of each subsection to be combined into a single value of the same scale as each of the subsections. The combined value is then classified on the same method and range as the subsection. The more important or significant subsections are also more prominent in the calculations of the response, allowing for a more accurate result. The accuracy of the weighting factors can be improved with a larger population of data.

The driveability sections were combined to provide an overall driveability classification. Weighting factors were allocated according to importance to each section. The importance of each section was again determined by the measured results and their influence on each other, as with the subsections. Where no data was available a subjective weighting was allocated as well. The responses of this model were tested, as described in Chapter 4. Two different calibrations were evaluated to verify the accuracy of the model. The results of the evaluation provided different driveability scores and are therefore accurate enough to detect a change in calibration values.

Chapter 4 describes an optimised driveability testing procedure. The testing procedure is a combination of different test methods to evaluate different aspects of driveability in a vehicle. The test procedure produced a meaningful score that can be compared to similar evaluations. It was developed to allow for the shortest possible evaluation time. It also allows for driveability to be evaluated for different sections.

This driveability evaluation model can be used to effectively compare the effect of changing the calibrations as well as to quantify a vehicle's driveability. The evaluation will provide a value for each section (start behaviour, idle behaviour, acceleration behaviour, cruise behaviour and brake response) to emphasise problem areas that require attention. It will also provide a verification method to compare different calibrations, even if no reference model is available. It will also reduce the amount of testing required to evaluate driveability, and eliminate subjective evaluations.

Although the model provided a quantitative evaluation method, it can still be improved by incorporating a wider range of data i.e. by testing more vehicles of the same engine size and class, as well as vehicles with different engine sizes and classifications.

REFERENCES

Anderson W, Yang J, Brehob D D, Vallance J K and Whiteaker R M, 1998, *Understanding the thermodynamics of direct-injection spark-ignition (DISI) combustion systems: an analytical and experimental investigation*, SAE Paper no. 962018.

Anonymous, 1999, Okeefesauto, http://www.okeeffesauto.ca/handouts/drive_ability.html, [February, 2003]

Anonymous, 2001, Dieselnet, www.dieselnet.com, [24 August, 2005]

Anonymous, 2005, How Stuff Works, www.howstuffworks.com, [26 August, 2005]

Anonymous, 2006, Wikipedia, http://en.wikipedia.org/wiki, [12 July, 2006]

Anonymous, undated, Auto Shop, www.autoshop101.com, [26 June, 2003]

Anonymous, undated, Volvo Club, http://www.volvoclub.org.uk/ tech/fuel_injection/LE-JetronicInjectionSystem.pdf, [16 March, 2005]

Bosch, R, 1999, *Gasoline engine management.* 1st Edition, Robert Bosch GmbH, Stuttgart.

Bosch R, 2004, *Automotive handbook.* 6th Edition, Robert Bosch GmbH, Plochingen.

Bosch, 2005, Bosch, www.bosch-automotive.com, [24 August, 2005]

Challen B J, 2002, *Defining driveability – limits to modelling*, Total Vehicle Technology no 24.

Corsetti, A, O'Connell, G and Watkins, K, 2002, *In-Vehicle engine torque model validation*, SAE Paper no. 2002-01-1143.

Department Of Environmental Affairs and Tourism and the Department Of Minerals and Energy, 2003, *joint implementation strategy for the control of exhaust emissions from road-going vehicles in the republic south africa*.

Department of Industry, Science and Resources, 2001, *Setting national fuel quality standards: discussion paper on operability fuel parameters (petrol and diesel*), Australian Government.

Dorey, R E and Holmes C B, 1999, *Vehicle Driveability – Its characterisation and measurement*, SAE Paper no. 1999-01-0949.

Edward, K N, 2001, *Understanding and modelling NOx emissions from air-conditioned automobiles*, SAE Paper no. 2000-01-0858.

Eriksson, L, 2002, *Mean value models for exhaust system temperatures*, SAE Paper no. 2002-01-0374.

Ferguson, C and Kirkpatrick, A, 2001, *Internal combustion engines: applied thermosciences*, John Wiley Press.

Griffin M J, 1996, *Handbook of Human Vibrations*, Academic Press, USA.

Heywood, J B, 1988, *Internal combustion engine fundamentals*, McGraw-Hill, Singapore.

Johansson S. April 2004, *Shunt and shuffle evaluation for vehicle powertrains.* Masters Thesis, Department of Signals and Systems, Chalmers University of Technology, Göteborg, Sweden.

List H O and Schöggl P, 1998, *Objective evaluation of vehicle driveability,* SAE Paper no. 980204.

Meyer, S and Greff, A, 2002, *New calibration methods and control systems with artificial neural networks*, SAE Paper no. 2002-01-1147.

Office of Transportation and Air Quality, 2006, *Cold Temperature Effects on Vehicle HC Emissions,* United States Enviromental Protection Agency.

Probst C O, 1991, *Bosch fuel injection and engine management,* Robert Bentley, USA.

Royo, R, Corberá, J M, Azara L, Marcheguet, E, Gruchet, P, Terol, R and González, J A, 2001, *The new "torque strategy" for the control of the spark ignition engine. Development of a motorized butterfly valve through experimental techniques and computational modelling*, SAE Paper no. 2001-01-3271.

Schöggl P, Bogner E and Ramschak E, 2001a, *On-board optimization of driveability character depending on driver style by using a new closed loop approach*, SAE Paper no. 2001-01-0556.

Schöggl P, Bogner E and Ramschak E, 2001b, *Adaptive Driveability*, Auto Technology, Vol. 1, 78–80.

Schöggl P, Koegeler, H M, Gschweitl, K, Kokal, H, Williams, P and Hulak, K, 2002, *Automated EMS calibration using objective driveability assessment and computer aided optimisation methods*, SAE Paper no. 2002-01-0849.

Schöggl P and Ramschak E, 2000, '*Adaptive Driveability – Improvement of driving pleasures and individualisation of platform Vehicles'*, AVL Engine and Environment.

Shao, Q, 2004, *Multivariate Statistical Methods, Department of Mathematics*, University of Oregon.

Steiner G, 2004, *AVL DRIVETM: Objective ratings for subjective impressions*, AVL List.

Stone, R, 1999, *Introduction to internal combustion engines*, Society of Automotive Engineers, Warrendale, PA.

Toyota, 2001, *Overview of OBD and regulations*, Toyota Motor Sales, USA.

Volkswagen South Africa, 2006, *Volkswagen News Today*, [28 Desember, 2006]

Wicke, V, 2001, *Driveability and Control Aspects of Vehicles with Continuously Variable Transmissions'*, PhD Thesis, Department of Mechanical Engineering, University of Bath.

A ENGINE MANAGEMENT SENSORS

A.1 Airflow sensors

Engine speed and load determine the amount of air induced into the engine. There are different ways to calculate and measure the amount of airflow into the engine. An air vane sensor measures the airflow into the engine. Figure A.1 shows the working of the air vane sensor. The higher the air flow the higher the resistance leading to a lower voltage output to the ECU, leading to longer injection pulses.

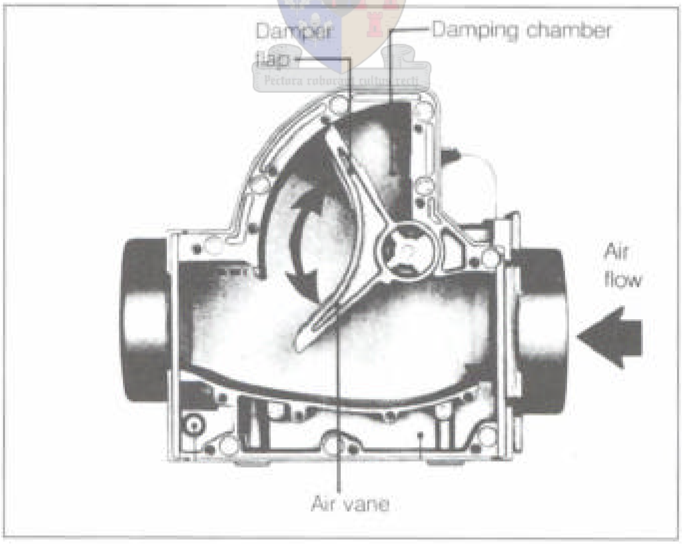


Figure A.1: Air Vane Sensor (Probst, 1991)

An air-mass sensor uses a wire to measure the airflow rate as well as the mass of the air, allowing the ECU to do correction for altitude and temperatures. Figure A.2 shows a detail assembly for the air-mass sensor.

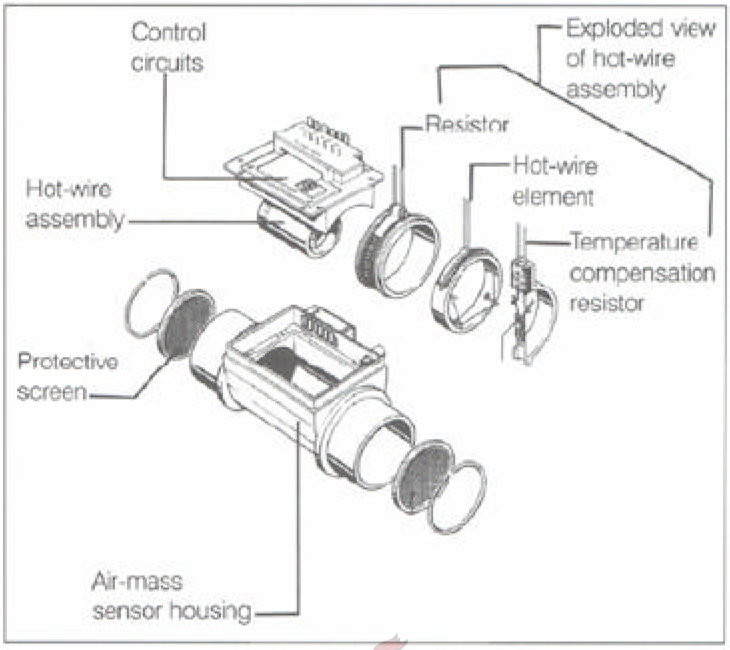


Figure A.2: Air-mass Sensor (Probst, 1991)

A.2 Fuel Pressure Regulator

The amount of fuel that is delivered depends on the size of the injector opening and the pressure by which the fuel is forced through the injector opening. The fuel pump pressurise the fuel delivery system to a constant pressure. The pressure drops when the injectors open. The pressure regulator uses a diaphragm to keep the pressure constant. Figure A.3 shows the construction of a pressure regulator.

The fuel pressure pushes the diaphragm open, allowing fuel to return to the fuel tank. When the injectors open, the pressure drop causes the diaphragm to allow less fuel to return to the fuel tank, maintaining a constant pressure. The pressure regulator is connected to the manifold pressure, to allow the relative pressure (between the fuel rail and manifold) to stay constant with change of the throttle plate. Large fuel rails will reduce the pulsations that is invoked when the injectors open and close.

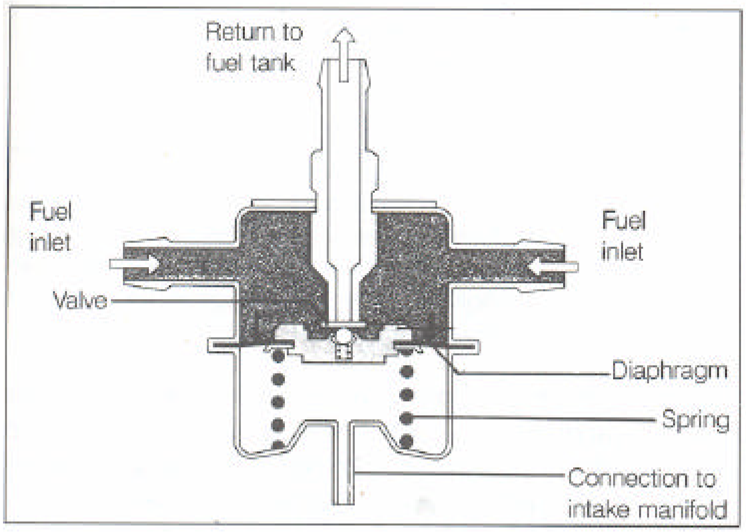


Figure A.3: Fuel Pressure regulator (Probst, 1991)

A.3 Engine Temperature Sensor

Acceptable driveability from engine management is very dependant on this sensor. This sensor determines in what operating condition the engine is operating and adjusts the fuelling and timing accordingly. Most engines use a Negative Temperature Coefficient sensor that reduces its resistance as the engine temperature increases.

A.4 Air Temperature Sensor

This sensor is also important for the correct working of an engine. Air density decreases as the temperature increase. The ECU changes the injector timing with the change in air temperature.

A.5 Lambda Sensor

A lambda sensor, shown in Figure A.4, senses the oxygen content of the exhaust gas. It is situated before the catalytic converter in the exhaust system (and after the catalytic converter on advance OBD systems). The sensor only operates when the ceramic material is hotter than a certain temperature and the ambient air has a higher oxygen concentration than the exhaust (Probst, 1991).

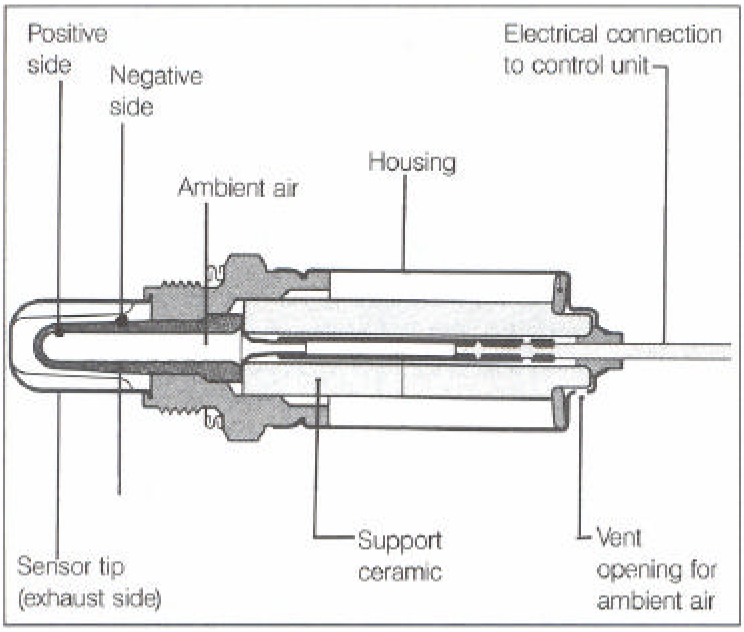


Figure A.4: Lambda Sensor (Probst, 1991)

The core of this probe is a ceramic body coated on both sides with metal electrodes (Nernst cell). One layer is in contact with ambient air and the other is in contact with the exhaust gas. The differential between oxygen concentration in the ambient air and in the exhaust gas causes the electrodes to react to create a voltage. Two types of lambda probes are commonly available; the step type (also know as the narrow range oxygen sensor or simply oxygen sensor) and a broadband lambda probe (also know as the wide range oxygen sensor or air-fuel ratio sensor).

The step type lambda probe's output voltage change as the oxygen concentration change. It can only measure a change from stoichiometric, see Figure A.5. In normal operating conditions the ECU work in closed loop control. The ECU evaluates the voltage and determines if the engine is running rich or lean. If it measures a lean mixture then it will add fuel to enrich the mixture, the lambda sensor switch from lean to rich and the ECU will add less fuel. With this control the air-fuel mixture will cycle between rich and lean the whole time. The operating temperature is around 400^{o}C. The sensor needs to be heated up to this temperature as soon as possible to ensure correct emission regulation. The sensor has a build-in heater to help it achieve operating temperature as quickly as possible.

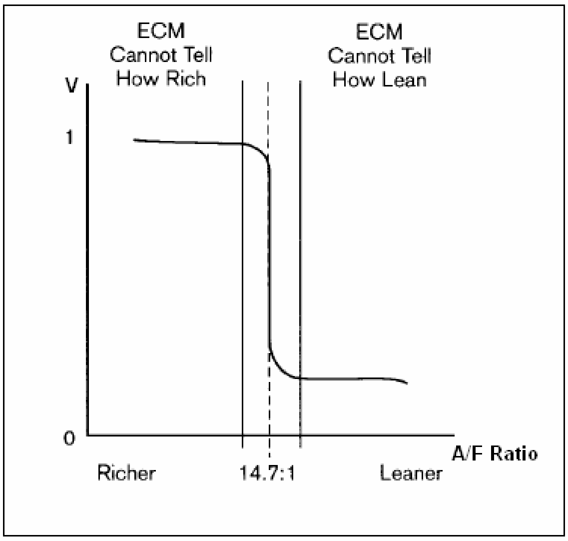


Figure A.5: Step Type Lambda Control (Toyota, 2001)

The broadband lambda probe's current is changed with a change in oxygen concentration. Figure A.6 illustrate that the voltage signal is proportional with the change in air-fuel ratio. The ECU can adjust the amount of fuel to stoichiometric since it knows exactly how far away it is. The operating temperature is around 650oC. Much more accurate control is achieved with this type of lambda probe than with the step type.

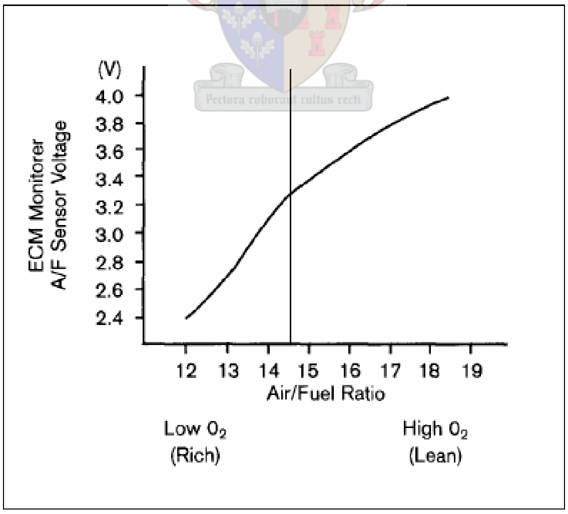


Figure A.6: Broadband Lambda Control (Toyota, 2001)

A.6 Knock sensor

The knock sensor, displayed in Figure A.7, is excited by high pressures in the combustion chamber and any other processes causing the engine block to vibrate. The sensor uses a piezoelectric crystal that generates a voltage when it is excited. The main causes for knock are combustion chamber design, fuel octane, air-fuel ratio and ignition timing.

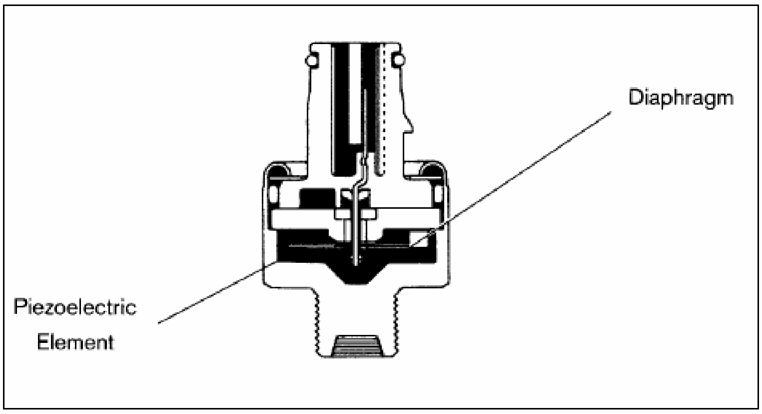


Figure A.7: Knock Sensor (Toyota, 2001)

Closed-loop knock control will maximize the power output without endangering the engine. Ignition timing is advanced to the Most Beneficial Timing (MBT) point, just before the engine experiencing damaging knock. Knock occurs with characteristic frequencies of 5 to 10 KHz together with corresponding harmonics. Some other mechanical vibrations, e.g. valve closure etc., can duplicate these frequencies and cause the ECU to retard the timing during a non-knocking cycle. The ECU has to window its detection period around peak pressure. Figure A.8 shows how the ECU detects a knocking cycle.

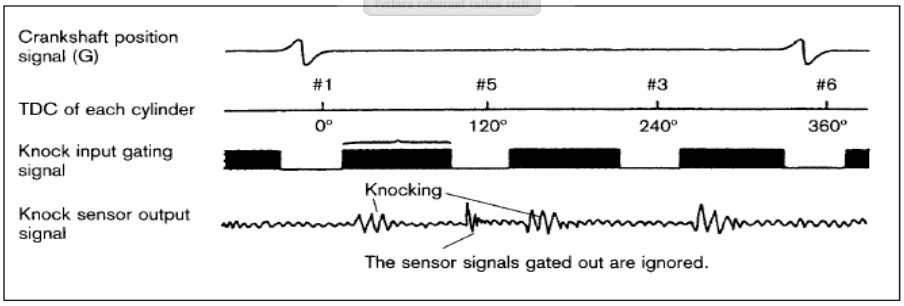


Figure A.8: Knock Signal Identification (Toyota, 2001)

Some ECU's uses only one knock sensor while others uses more than one. Better detection is achieved with more knock sensors. The placement of the knock sensor is also crucial to ensure accurate knock detection. If the knock sensor is to far from a cylinder then it might not detect high overpressures.

A.7 MAP sensor

The Manifold Absolute Pressure (MAP) sensor senses the pressure difference between the manifold and a reference pressure. Figure A.9 shows a configuration with a vacuum chamber. A barometric sensor situated on the ECU compensate for altitude differences. The intake manifold pressure is directly related to engine load. A higher load implicates a higher measured MAP value.

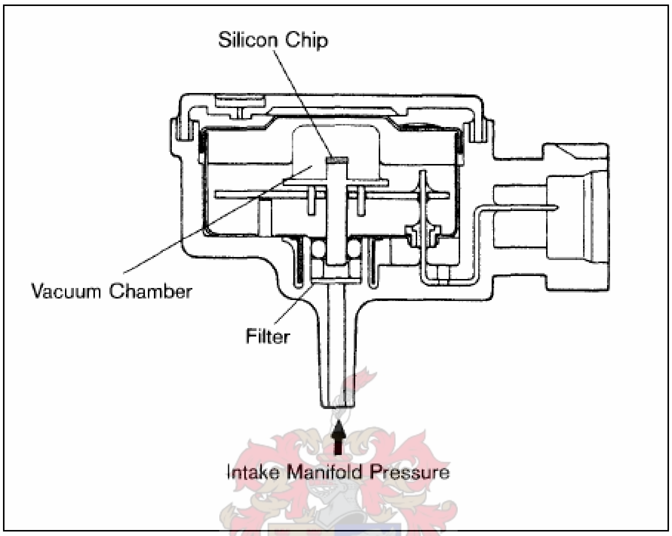


Figure A.9: MAP Sensor (Toyota, 2001)

B

COMBUSTION

B.1 Fuel

Gasoline and air from the atmosphere is blended inside the combustion chamber of an Internal Combustion (IC), Spark Ignition (SI) engine. Chemical energy is released during combustion process that was stored in the fuel. The energy content of typical petrol is 44MJ/kg or 31.8 MJ/liter (Stone, 1999). Only between 20 - 30% of the energy is transferred to the crankshaft, depending on the design of the combustion chamber, engine configuration and engine management. The rest of the energy is wasted to the atmosphere, friction, aerodynamic drag, component operation and heat transferred to the cooling system.

Petrol/ gasoline are a blend of volatile Hydrocarbons (HC), including paraffins, olefins, naphthenes, and aromatics (Ferguson et al, 2001). These hydrocarbons have to mix with oxygen to produce the desired energy release. Oxygen is sourced from the air. Air contains roughly 21% oxygen (O_2), 78% Nitrogen (N_2) and the other 1% is a mixture of other gasses. The practical chemical equilibrium of a general hydrocarbon fuel:

$$\begin{aligned}\varepsilon\phi C_\alpha H_\beta O_\gamma N_\delta + 0.21O_2 + 0.79N_2 \rightarrow\ & \nu_1 CO_2 + \nu_2 H_2O + \nu_3 N_2 + \nu_4 O_2 + \nu_5 CO \\ & + \nu_6 H_2 + \nu_7 H + \nu_8 O + \nu_9 OH + \nu_{10} NO\end{aligned}$$

(Ferguson et al, 2001)

The quality of the fuel has a very significant impact on the driveability of the vehicle. Proper engine management calibration will compensate for low quality fuel, at a loss for performance. The strategy of the engine management system must also reduce emissions, while still delivering acceptable driveability.

Volatility and octane number are the two key factors when relating fuel to driveability, given that the rest of the fuel is of premium quality. A Premium quality fuel don’t have any gum, it must have satisfactory copper corrosion resistance and an acceptable appearance.

B.1.1 Volatility

Volatility is an important characteristic of petrol. Volatility is expressed in terms of the volume percentage that is distilled at, or below fixed temperatures (Stone, 1999). A highly volatile fuel will vaporise at high ambient temperature and it will cause a vapour lock in the fuel lines and fuel rail, charcoal canister overloading and higher emissions. Vapour lock is when vapour “bubbles” form in the fuel line, preventing normal fuel flow to the injectors. This will lead to power loss, rough running, stalling and difficult starting.

Volatility assists the starting of an engine in cold conditions. The design of the fuel delivery system is critical to prevent unnecessary vapour formation and to ensure good cold start results. The volatility also affects the fuel economy of an engine. Rich fuel mixtures are applied during cold operating conditions to ensure that there is enough fuel for the engine to start. Increasing the volatility will increase the fuel economy since less enrichment is necessary to ensure good start behaviour.

Reid Vapour Pressure (RVP) is most commonly used to measure the volatility of a fuel. Another index used to measure the volatility of a fuel is called the Flexible Volatility Index (FVI) and is calculated with Equation B.1.

$$FVI = RVP + 0.7 * E70 \qquad (B.1)$$

Where: RVP = Reid Vapour Pressure

E70 = % evaporated at 70^{o}C

RVP is more relevant to cold engine conditions where FVI is more relevant to hot ambient conditions. Vapour Liquid Protection Temperature (VLPT) is also used to estimate hot weather operability. Europe also use a Vapour Lock Index, this is essentially FVI multiplied by 10. (Department of Industry, Science and Resources, 2001)

Another measure on the volatility on driveability is termed the driveability index (DI). Figure B.1 shows that petrol distil (boil) over a range of temperatures.

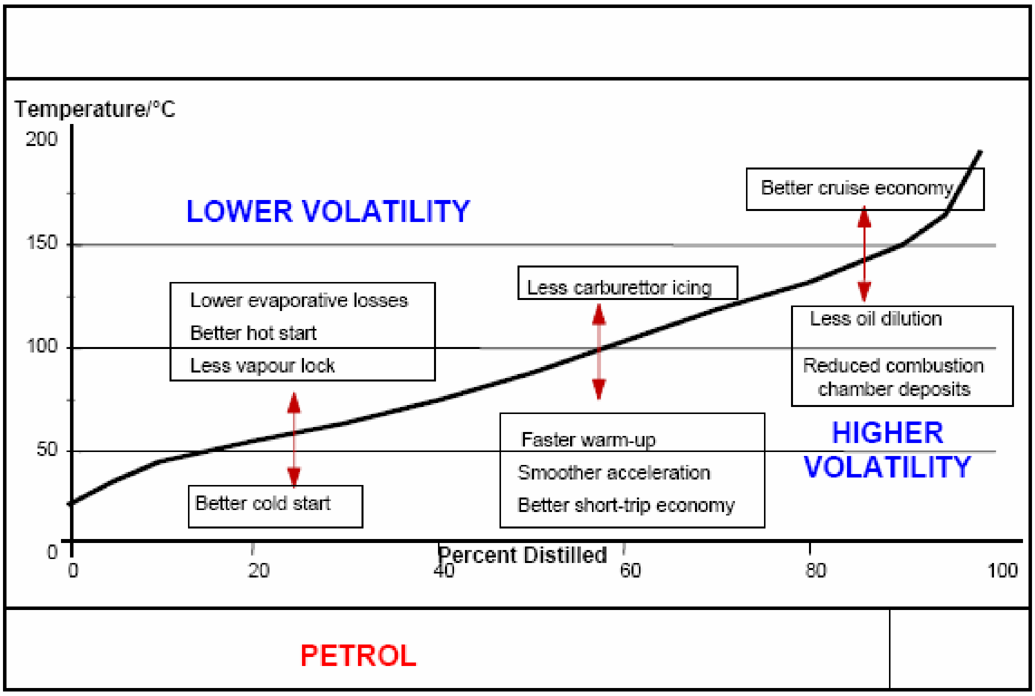


Figure B.1: Typical petrol distillation profile (Department of Industry, Science and Resources, 2001)

The fuel must be able to provide enough energy for the whole operating range, else the vehicle will not drive or run smoothly. DI can therefore be described as the mathematical combination of distillation properties, to describe the influence of fuel volatility on driveability. The World Wide Fuel Charter (WWFC) recommends a maximum level of DI of 570 during summer and 560 during winter. DI is calculated as with Equation B.2.

$$DI = 1.5T_{10} + 3T_{50} + T90 + 11Oxygenates \qquad (B.2)$$

Where T_{10}, T_{50} and T_{90} are the temperatures at which 10%, 50% and 90% of the petrol have evaporated. Oxygenates is the concentration of oxygenates in wt-%. (Note: oxygenate correction does not apply to ethers) (Department of Industry, Science and Resources, 2001)

B.1.2 Octane Number

Petrol's ability to resist abnormal combustion, in particular knock, is measured by its octane number. A higher octane number indicates a higher resistance to knock. The octane number scale is based on two hydrocarbons at each end of the scale, normal heptane (n-C_7H_{16}) at zero and isooctane (C_8H_{18}: 2,2,4 – trimethylpentane) at 100.

Two laboratory test methods are used to obtain a fuel's octane number, the Research Octane Number (RON) and the Motor Octane Number (MON). RON is an indication of a fuel's characteristic at low speed and mild knocking conditions. MON is more an indication of high temperature knocking conditions at full load and high engine speed.

Fuel sensitivity is the numerical difference between these two fuels. The road octane number is a method for rating how a fuel will behave in a vehicle at different speed and loads. Road octane number is calculated with Equation B.3 (Heywood, 1988).

$$RoadON = a(RON) + b(MON) + c \qquad (B.3)$$

Where a, b and c are experimentally derived constants. Recent studies show that a ≈ b ≈ 0.5 gives good agreement. Another method used to characterize antiknock quality is the Antiknock Index (AKI) which is calculated as (RON+MON)/2 (Heywood, 1988).

The Octane Number Requirement (OR) is important to refiners and to engine developers. It is defined as the minimum octane number that will allow safe engine operation. The ignition models use a Knock Limited Spark Advance (KLSA) strategy to improve the engine performance. The ignition advance until it detects knock and retard again to eliminate to high over pressures. (See chapter 3). This implies that if the fuel has a low octane number then the ignition will retard the whole time and deprive the engine of performance and can even lead to engine failure it the knock control strategy is poorly designed. A decrease in engine performance will lead to a decrease in driveability. It is therefore important to design an engine to be robust enough to utilize low octane fuel and be driveable.

B.1.3 Additives and appearance

Most modern gasoline contains chemical additives to improve the fuel quality. Fuel additives are used to raise the octane number, eliminate rust, prevent gum formation, avoid injector fouling, reduce spark plug fouling, minimize deposits in the intake system and prevent valve sticking. It also reduce carburetor icing and removes carburetor deposits.

Corrosion does not have a direct effect on immediate driveability of the vehicle but correspond more to the effect of decreasing driveability due to corrosion of components. Sulfur compounds that remain in the petroleum product after refining cause the corrosion.

Peroxides or gum is formed when petrol slowly oxidize in air. Copper and zinc also promote the oxidation of petrol. The gum is soluble in the fuel but when the fuel evaporates it leaves behind a sticky residue that deposit on carburetors, injectors and intake port valves. This will have an impact on the driveability since the fuel delivery will be inhibited.

Fuel must not be contaminated with water or particles. Water can promote bacterial growth and encourage corrosion. This can lead to filter blockage or injector fouling. This will lead to incorrect fueling and will cause undesired driveability.

B.2 Emissions

The amount of vehicles on the road increase significantly every year. Combustion produces harmful pollutants that must be regulated to protect the environment. The task of the engine management system is to reduce harmful emissions, while not reducing driveability. Unburnt hydrocarbons (HC), carbon monoxide (CO) and oxides of nitrogen (NO_x) are the most harmful pollutants. Carbon monoxide (CO_2) is a necessary by-product but it needs to be reduced in future because of its effect on the “greenhouse” effect.

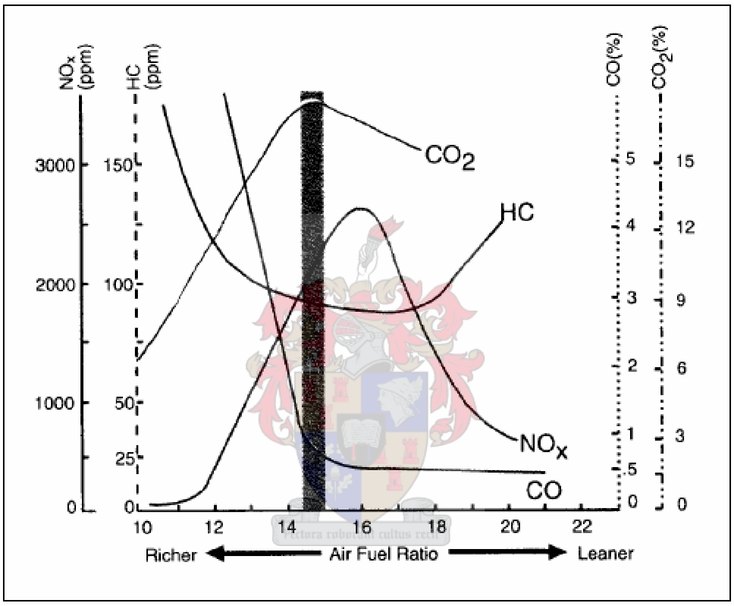


Figure B.2: The Effect of Air-Fuel Ratio on Harmful Emissions (www.autoshop.com)

B.2.1 Hydrocarbons

Gasoline is a chemical compound composed of hydrogen atoms and carbon atoms. During combustion, hydrocarbons will react with oxygen to create water (H_2O) and carbon dioxide (CO_2). HC emissions implicate that all the fuel was not burned. Unburnt fuel indicates an engine misfire. Ignition system malfunctions, very lean air-fuel mixtures, excessive EGR dilution, worn rings/ low compression, release of fuel deposits in the combustion chamber and flame quenching, commonly cause HC emissions.

B.2.2 Carbon Monoxide

Carbon monoxide (CO) is a poisonous gas and is caused by incomplete combustion. There is insufficient oxygen to convert all the carbon to CO_2 with a rich air-fuel ratio. Cold operation, warm-up, acceleration, full load and component protection require fuel enrichment.

Component malfunctions, e.g. leaking injectors, and incorrect engine management calibration, e.g. EVAP control will also lead to fuel enrichment.

B.2.3 Oxides of Nitrogen

Nitrogen dioxide (NO_2) and nitric oxide (NO) is the most significant nitrogen based emissions (NO_x). Nitrogen and oxygen only react with each other when the combustion temperature exceeds approximately 1100^oC. Lean air-fuel mixture and ignition advance raises the combustion temperature and pressure causing NO_x to form. Component malfunctions, e.g. leaking inlet manifold, and incorrect engine management calibration, e.g. incorrect base timing will also increase NO_x formation.

B.3 Catalytic Converter

Catalytic converters convert harmful emissions into less harmful emissions. A three-way catalyst is used to lower all three pollutants. The core of the catalytic converter is coated with three catalysts – platinum/ palladium, rhodium and cerium. The platinum/ palladium are used for oxidizing HC and CO. The rhodium is used to reduce NO_x and the cerium promotes oxygen storage. NO_x is reduced into N_2 and CO_2, HC and CO is oxidized into H_2O and CO_2 as showed in Figure B.3.

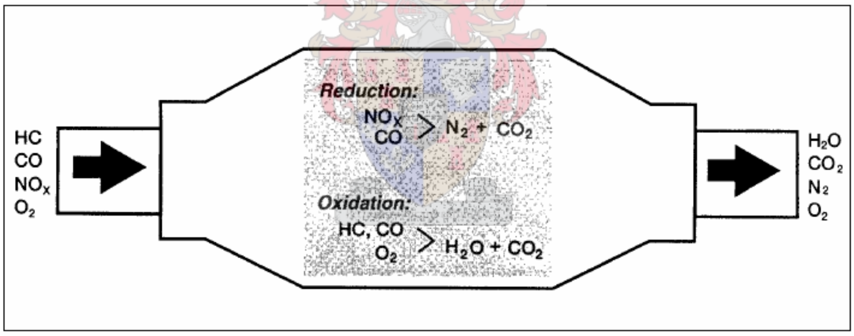


Figure B.3: Three-way Catalytic Converter (Toyota, 2001)

The catalytic converter has to be heated up before it can function properly. Retarding the ignition timing and allowing more heat release into the exhaust will increase the warm-up time. Placing the catalytic converter closer to the exhaust manifold will also increase the warm-up time. The air-fuel ratio is also very critical for conversion efficiency. Figure B.4 shows the effect of the air-fuel ratio.

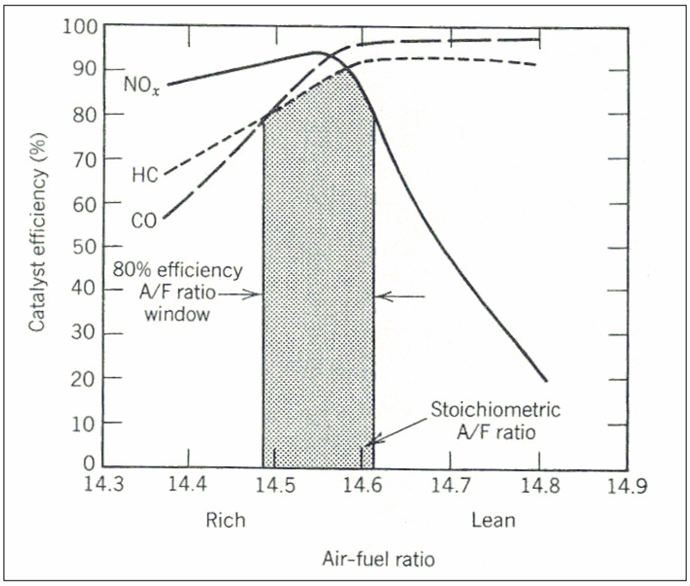
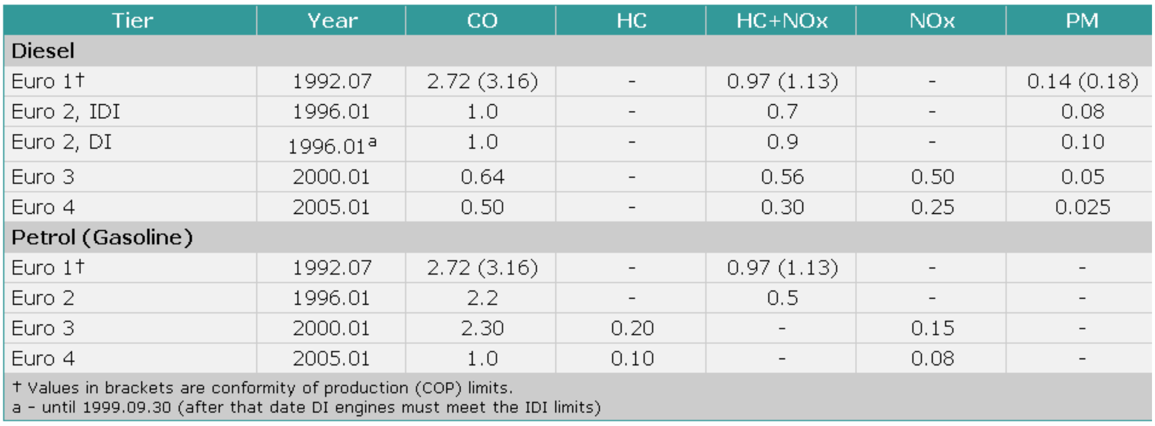


Figure B.4: Conversion Efficiency of a Three-Way Catalytic Converter (Ferguson et al., 2001)

B.4 Emissions Regulations

Emission requirements for light passenger vehicles were introduced to force automotive manufacturers to reduce harmful emissions. Different regulations exist for different regions. America was the first to introduce regulations and the European Union (EU) followed their lead in the early nineties. South Africa is using the European standard for their regulations. Table B.1 shows the EU emission standards for passenger cars.

Table B.1: EU Emission Standards for Passenger Cars, g/km (www.dieselnet.com)



Tier	Year	CO	HC	HC+NOx	NOx	PM
Diesel						
Euro 1†	1992.07	2.72 (3.16)	-	0.97 (1.13)	-	0.14 (0.18)
Euro 2, IDI	1996.01	1.0	-	0.7	-	0.08
Euro 2, DI	1996.01[a]	1.0	-	0.9	-	0.10
Euro 3	2000.01	0.64	-	0.56	0.50	0.05
Euro 4	2005.01	0.50	-	0.30	0.25	0.025
Petrol (Gasoline)						
Euro 1†	1992.07	2.72 (3.16)	-	0.97 (1.13)	-	-
Euro 2	1996.01	2.2	-	0.5	-	-
Euro 3	2000.01	2.30	0.20	-	0.15	-
Euro 4	2005.01	1.0	0.10	-	0.08	-

† Values in brackets are conformity of production (COP) limits.
a - until 1999.09.30 (after that date DI engines must meet the IDI limits)

South Africa will implement regulations in two phases. Phase 1 has EU 1 from 2004 and EU 2 from 2006 (Department of Environmental Affairs and Tourism, 2003). Phase two will see EU 4 in 2010. Emissions are measured with a test cycle that is designed to simulate real driving. The engine management system must pass the test before the vehicle can be sold in the country, or the manufacturers will suffer severe penalties.

Appendix C1: Start Results

Date	Start Condition	Fuel RVP	TIA [deg C]	Toil [deg C]	TCO [deg C]	V_Batt	Start Time	Idle Speed Setpoint	Max RPM Overshoot	RPM Overshoot	Time to Steady State Idle	Max TI_TOT	Min Lambda	Soak Duration [hrs]
11/30	Very Cold	60	-3	-3	-3.8	12.24	1.2	977	1297	32.75	5.58	74.74	0.701	14.0
12/01	Very Cold	60	-4.5	-3	-3.8	12.34	1.06	977	1460	49.44	5.377	74.67	0.74	14.0
12/03	Very Cold	60	-5.8125	-4	-4.5	12.133	1.147	977	1350	38.18	5.9	80.884	0.712	14.0
11/30	Very Cold	60	-6	-5	-5.25	11.93	1.3	977	1149	17.60	7.2	70.48	0.7	14.0
12/01	Very Cold	60	-4.5	-3	-3.8	12.03	1.18	977	1427	46.06	5.56	71.37	0.82	14.0
12/03	Very Cold	60	-6.75	-5	-5.25	11.8275	1.218	977	1277	30.71	6.83	76.488	0.7	14.0

Date	Start Condition	Fuel RVP	TIA [deg C]	Toil [deg C]	TCO [deg C]	V_Batt	Start Time	Idle Speed Set Point	RPM Overshoot	RPM Overshoot	Time to Steady State Idle	Max TI_TOT	Min Lambda	Soak Duration [hrs]
05/11/30_1	Cold	58	3	6	6	12.24	0.996	926	1392	50.32	5.76	43.5	0.7	14.0
05/11/30_2	Cold	58	1.5	4	3.8	12.13	0.97	935	1461	56.26	3.911	47.85	0.7	14.0
05/12/01_02	Cold	58	4.5	8	7.5	12.34	0.95	920	1419	54.24	5.48	40.28	0.7	14.0
05/11/30_1	Cold	58	3.75	6	6	12.03	1.16	926	1269	37.04	5.88	38.77	0.87	14.0
05/11/30_2	Cold	58	0.75	4	4.5	12.03	1.19	932	1426	53.00	6.08	43.04	0.841	14.0
05/12/01_2	Cold	58	4.5	8	7.5	12.03	1.11	920	1423	54.67	6.49	39.13	0.824	14.0
05/12/06_01	Cold	41.1	4.5	7	6.75	12.23	1.15	923	1365	47.89	3.45	52.56	0.7	14.0
05/12/06_01	Cold	41.1	4.5	9	8.25	11.93	1.318	917	1418	54.63	5.08	49.32	0.689	14.0
05/12/07_02	Cold	68	3.75	9	8.25	12.337	0.81	917	1388	51.36	2.97	52.664	0.7	14.0
05/12/07_02	Cold	68	5.25	9	8.5714	12.23	0.858	917	1368	49.18	4.84	48.832	0.674	14.0

Date	Start Condition	Fuel RVP	TIA [deg C]	Toil [deg C]	TCO [deg C]	V_Batt	Start Time	Idle Speed Set Point	Max RPM Overshoot	RPM Overshoot	Time to Steady State Idle	Max TI_TOT	Min Lambda	Soak Duration [min]
05/01/28	Hot	95Ron with 70-75kPa	59.0	89.0	113.3	11.9	0.63	750	907	20.93	4.7	10.64	0.729	20.0
05/01/29	Hot	95Ron with 70-75kPa	69.0	88.0	116.3	12.0	0.63	750	817	8.93	3.36	10.18	0.699	20.0
05/01/28	Hot	95Ron with 70-75kPa	62.0	93.0	115.5	12.1	0.64	750	989	31.87	3.56	10.18	0.734	20.0
05/01/28	Hot	95Ron with 70-75kPa	68.0	84.0	105.8	12.2	0.64	750	849	13.20	2.45	8.89	0.707	25.0
05/01/25	Hot	95Ron with 70-75kPa	56.0	104.0	123.0	12.0	0.72	750	1156	54.13	3.58	8.11	0.875	10.0
05/01/31	Hot	95Ron with 70-75kPa	77.0	80.0	108.8	12.4	0.72	700	957	36.71	3.79	7.97	0.718	30.0

Appendix C2: Start Results

Date	Start Condition	Fuel RVP	TIA [deg C]	Toil [deg C]	TCO [deg C]	V_Batt	Start Time	Idle Speed Set Point	RPM Overshoot	RPM Overshoot	Time to Steady State Idle	Max TI_TOT	Min Lambda
2005/02/11	Normal, warm start	95RON ??kPa	49.7	91	90.75		0.53	650	1573	142	-	9.844	0.914
2005/02/11	Less fuel (10%), warm start, AJ switched off	95RON ??kPa	50.25	95.6364	96.6364		0.52	650	1390	113.8461538	-	8.328	1.043
2005/02/11	Normal, warm start	95RON ??kPa	50.76	81.81	93.75		0.53	650	1597	145.6923077	-	9.548	0.89
2005/02/11	Normal, warm start	95RON ??kPa	42.75	89	98.179		0.54	650	1364	109.8461538	4.97	9.18	0.963
2005/02/11	Normal, warm start	95RON ??kPa	45.53	88	102		0.54	650	1388	113.5384615	3.04	8.936	0.935
2005/02/11	Normal, warm start	95RON ??kPa	46.5	87	102		0.53019	650	1356	108.6154	6.31	8.844	0.942
2005/02/11	Less fuel (10%), warm start	95RON ??kPa	48	87	101.9788		0.54017	650	1230	89.2308	-	8.176	1.03
2005/02/11	Less fuel (10%), warm start	95RON ??kPa	48	87	102		0.53017	650	1271	95.5385	-	8.236	1.015
2005/02/11	Less fuel (10%), warm start	95RON ??kPa	48.5906	87	102		0.54016	650	1257	93.3846	-	8.18	1.038
2005/02/11	Less fuel (20%), warm start	95RON ??kPa	49.5	87	99		0.52051	650	1123	72.7692	2.94	7.264	1.144
2005/02/11	Less fuel (20%), warm start	95RON ??kPa	48.75	87	99.8451		0.43084	650	1093	68.1538	2.9	7.556	1.137
2005/02/11	Less fuel (20%), warm start	95RON ??kPa	48.75	87	100.9653		0.47018	650	1055	62.3077	3.2	7.44	1.133
2005/02/11	More fuel (20%), warm start	95RON ??kPa	50.25	87	99		0.4801	650	1596	145.5385	3.74	11.34	0.781
2005/02/11	More fuel (20%), warm start	95RON ??kPa	50.25	87	98.25		0.52016	650	1597	145.6923	3.2	10.964	0.779
2005/02/11	More fuel (20%), warm start	95RON ??kPa	50.25	87	100.1003		0.48012	650	1566	140.9231	3.9	11.368	0.779
2005/09/12	Normal warm start	>95RON 68kPa	47.0744	95	92.8244		0.6402	650	994	52.9231	2.8	10.172	0.734
2005/09/12	Normal warm start	>95RON 68kPa	53.25	89.4545	88.5911		0.61027	650	1315	102.3077	3.1	8.856	0.867
2005/09/12	Normal warm start	>95RON 68kPa	54	89	88.5		0.60017	650	1320	103.0769	3.2	8.832	0.869
2005/09/12	More fuel (50%), warm start	>95RON 68kPa	56.0111	88	87.75		0.47022	650	1122	72.6154	2.9	12.412	0.685
2005/09/12	More fuel (50%), warm start	>95RON 68kPa	56.25	88	87.75		0.47015	650	1120	72.3077	2.7	12.408	0.678
2005/09/12	More fuel (50%), warm start	>95RON 68kPa	57	88	87.9983		0.45015	650	1118	72	3.06	12.384	0.679

Appendix C3: Idle Results

Date	Idle Condition	Fuel RVP	TCO [deg C]	Mean at SS Idle	Standard Deviation	Slope of SS Idle	Min RPM after load was switched on	Time to Min RPM after load was switched on	Percentage undershoot	Rate of change of load change	Max RPM after load was switched on	Time to Max RPM after load was switched on	Percentage overshoot	Min RPM after load was switched off	Time to Min RPM after load was switched off	Percentage undershoot	Max RPM after load was switched off	Time to Max RPM after load was switched off	Percentage overshoot	Rate of change of load change	Max RPM at blip	Rate of change of engine speed	Max pedal input	Rate of change of pedal blip input	Ratio of rate of change of engine speed to pedal input
05/11/30	Very Cold	60	-3.8	931	6.32	2.94	889	1.8302	-7.8756	-4.303136269	973	14.503	0.82902	925	16.932	-2.6316	1055	1.8401	11.053	6.006738764	3123	3547.2	99.902	226.98	15.628
05/12/01	Very Cold	60	-3.8	934	7.47	3.65	898	1.0596	-6.6528	-6.278595696	969	10.358	0.72765	940	0.099728	-1.0526	1006	1.3595	5.8947	4.335932328	2740	3806	99.902	454.17	8.3801
05/12/03	Very Cold	60	-4.5	934	5.95	3.54	861	1.4597	-11.146	-7.635815579	962	8.9497	-0.72239	947	0.10977	-1.5593	1065	1.0997	10.707	9.736291716	2994	3651	99.902	302.71	12.061
05/11/30	Very Cold	60	-5.25	967	13.46	9.72	861	1.4095	-11.511	-8.166725789	980	13.767	0.71942	769	6.6581	-20.311	1045	0.51963	8.2902	15.95404422	3192	3893.2	99.902	302.77	12.859
05/12/01	Very Cold	60	-3.8	930	7.89	3.17	888	1.2498	-7.9793	-6.384461514	999	13.939	3.5233	975	6.0093	1.7745	1047	2.9496	9.2902	3.14964741	3236	3946.2	99.902	227.04	17.381
05/12/03	Very Cold	60	-5.25	994	10.2	11.71	899	1.0498	-7.6053	-7.244522766	977	0.019765	0.4111	967	0.019695	-0.2064	1092	1.2597	12.693	10.07620862	3101	3564	99.902	302.63	11.777

Date	Idle Condition	Fuel RVP	TCO [deg C]	Mean at SS Idle	Standard Deviation	Slope of SS Idle	Min RPM after load was switched on	Time to Min RPM after load was switched on	Percentage undershoot	Rate of change of load change	Max RPM after load was switched on	Time to Max RPM after load was switched on	Percentage overshoot	Min RPM after load was switched off	Time to Min RPM after load was switched off	Percentage undershoot	Max RPM after load was switched off	Time to Max RPM after load was switched off	Percentage overshoot	Rate of change of load change	Max RPM at blip	Rate of change of engine speed	Max pedal input	Rate of change of pedal blip input	Ratio of rate of change of engine speed to pedal input
05/11/30_1	Cold	58	6	892	4.89	3.11	850	4.8387	-7.909	-1.634529936	948	15.516	2.7086	902	4.5985	-0.87912	968	0.54971	6.3736	11.59447709	3094	4071.8	99.902	454.1	8.9668
05/11/30_2	Cold	58	3.8	896	12.19	1.99	837	1.1297	-10.193	-9.022749402	949	11.11	1.824	949	0.019753	2.8169	993	0.7397	7.584	10.25280519	3065	3692.7	99.902	302.72	12.198
05/12/01_02	Cold	58	7.5	883	8.36	1.51	849	1.53	-7.7174	-5.044052288	909	13.101	-1.1957	898	0.079775	-1.3187	1006	1.7899	10.549	5.893625342	2931	3530.6	99.902	302.66	11.665
05/11/30_1	Cold	58	6	898	8.72	5.3	835	1.5294	-9.5341	-6.233882568	986	12.448	6.8256	760	4.0991	-17.121	1012	1.2596	10.36	8.22483328	3447	2802.8	99.902	151.35	18.519
05/11/30_2	Cold	58	4.5	903	5.95	2.058	856	1.6596	-7.8579	-4.734815618	1005	16.898	8.1808	897	4.519	-2.5	1003	1.4995	9.0217	6.016472157	2868	3540.1	99.902	302.75	11.693
05/12/01_2	Cold	58	7.5	893	7.72	6.073	840	1.2899	-8.6957	-6.7413753	923	7.7304	0.32609	890	0.019786	-2.5192	998	0.8198	9.31	11.3564284	3151	3889	99.902	302.69	12.848
05/12/06_01	Cold	41.1	6.75	868	27.91	-10.55	858	0.76985	-6.7391	-8.753783205	912	8.0406	-0.86957	909	0.019786	-0.87241	989	0.75991	7.8517	10.33240779	3307	4131.1	99.902	302.68	13.649
05/12/06_01	Cold	41.1	8.25	875	12.37	3.788	827	1.3698	-9.4195	-9.4195	964	7.8302	5.586	927	1.3998	1.8681	979	1.9298	7.5824	-9.4195	3681	3915.4	99.902	227.02	17.247
05/12/07_02	Cold	68	8.25	854	25.65	-13.36	840	0.52981	-7.9956	-15.09144788	906	7.3308	-0.7667	903	0.029775	-0.76923	985	1.4899	8.2418	5.531780656	3413	4375.3	99.902	302.66	14.456
05/12/07_02	Cold	68	8.5714	848	11.78	-1.39	823	0.16983	-9.8576	-9.8576	987	6.9915	8.1051	947	0.17979	4.0659	1024	1.3601	12.527	9.21035218	3372	4555.7	99.902	453.94	10.036

Date	Condition	Fuel	Coolant Temperature	Mean at Steady State Idle after Start	Standard Deviation	Slope of Steady State Idle after Start	Min RPM after load was switched on	Time to Min RPM after load was switched on	Percentage undershoot	Max RPM after load was switched on	Time to Max RPM after load was switched on	Percentage overshoot	Rate of change of load change	Min RPM after load was switched off	Time to Min RPM after load was switched off	Percentage undershoot	Rate of change of load change	Max RPM after load was switched off	Time to Max RPM after load was switched off	Percentage overshoot	Max RPM at blip	Rate of change of engine speed	Max pedal input	Rate of change of pedal blip input
05/09/12	Warm	>95	92.8244	741	29.51	-17.22	642	2.0106	-6.0429	938	9.833	37.277	3.791009865	599	19.346	-31.854	-1.646541921	899	0.3101	2.2753	3466	4681.7	99.902	332.93
05/09/12	Warm	>95	88.5911	744	28	-17.87	698	1.2604	7.8772	930	16.745	43.733	2.611704987	572	16.165	-34.926	-2.160593876	894	0.040021	1.7065	3270	211.86	99.902	416.17
05/09/12	Warm	>95	88.5	759	17.83	-13.93	713	0.0099901	10.687	938	9.6329	45.616	4.735437926	580	14.384	-34.016	-2.364849833	928	0.10986	5.5745	3155	258.74	99.902	434.24
05/09/12	Warm, 50% > fuel	>95	87.75	659	98.88	2.8	546	0.77023	-11.747	980	8.3426	58.402	7.000455493	678	5.9519	-22.867	-3.841966431	908	0.26008	3.2992	4291	435.94	99.902	356.69
05/09/12	Warm, 50% > fuel	>95	87.75	627	15.3	5.26	535	0.37017	-19.744	1115	8.5527	67.263	7.864534007	634	18.586	-27.873	-1.499677176	993	0.30008	12.969	3472	324.99	99.902	525.66
05/09/12	Warm, 50% > fuel	>95	87.9983	637	25.4	11	532	0.54017	-16.917	1086	8.6727	69.602	8.025413078	668	10.843	-24.091	-2.221802084	961	0.080031	9.2045	3778	465.13	99.902	554.82

Date	Idle Condition	Fuel	TCO [deg C]	Mean at SS Idle	Standard Deviation	Slope of SS Idle
05/01/28	Hot	95Ron with 70-75kPa	113.3	758	22.82	7.96
05/01/29	Hot	95Ron with 70-75kPa	116.3	752	14.62	-0.94
05/01/28	Hot	95Ron with 70-75kPa	115.5	757	29.14	10.6
05/01/28	Hot	95Ron with 70-75kPa	105.8	733	12.86	2.18
05/01/25	Hot	95Ron with 70-75kPa	123.0	737	13.86	4.04
05/01/31	Hot	95Ron with 70-75kPa	108.8	700	16.6	0.91

Appendix C4: Acceleration Results

Date	Condition	TCO [deg C]	Max TI_TOT at pull away 0 - 2 km/h	PV_AV at max TI_TOT	max MAF	TI/MAF	min IGA_AV	Max TQ_AV
2005/11/30	Very Cold	-3.8	11.634	16.123	200.353	5.806751	4.11	41.538
200512/01	Very Cold	-3.8	13.342	11.816	222.245	6.003285	7.875	45.316
2005/12/03	Very Cold	-4.5	12.46	5.95	225.942	5.51469	3.84	36.41
2005/11/30	Very Cold	-5.25	12.25	0	221.47	5.531223	5.68	38.02
2005/12/01	Very Cold	-3.8	12.4	5.66	209.5	5.918854	4.53	32.262
2005/12/03	Very Cold	-5.25	11.46	5.64	208.78	5.489032	-4.32	30.56

Date	Condition	TCO [deg C]	Max TI_TOT at pull away 0 - 2 km/h	PV_AV at max TI_TOT	max MAF	TI/MAF	min IGA_AV	Max TQ_AV
2005/11/30_1	Cold	6	18.086	12.89	329.319	5.49	-10.46	67.6459
2005/11/30_2	Cold	3.8	12.2	8.05	230.822	5.29	1.5	27.422
2005/12/01_02	Cold	7.5	12.34	11.8	238.245	5.18	7.875	45.16
2005/11/30_1	Cold	6	11.19	0.68	200.495	5.58	6.014	25.4
2005/11/30_2	Cold	4.5	19.511	3.91	378.551	5.15	-1.5	71.52
2005/12/01_2	Cold	7.5	9.68	6.37	196	4.94	2.64	25.5

Date	Condition	Coolant Temperature	Max TI_TOT at pull away 0 - 2 km/h	PV_AV at max TI_TOT	max MAF	TI/MAF	min IGA_AV	Max TQ_AV
2005/09/12	Warm	92.8244	9.924	0	317.18	3.128823	-13.87	66.25
2005/09/12	Warm	88.5911	6.824	0	235.304	2.900078	-10.125	46.65
2005/09/12	Warm	88.5	6.516	0	226.318	2.879135	-9.375	42.09

Date	Condition	TCO [deg C]	Max TI_TOT at pull away 0 - 2 km/h	PV_AV at max TI_TOT	max MAF	TI/MAF	min IGA_AV	Max TQ_AV
2005/01/28	Hot	113.3	4.9	0	158	3.101266	-4.125	41.75
2005/01/25	Hot	112.0	7.4	0	265	2.792453	-4.1	86.84
2005/01/28	Hot	115.5	4.48	0	148.512	3.016591	-4.875	42.34

Date	Condition	Coolant Temperature	MaximumTI	Max MAF	TI/MAF
01/11/2005	Warm	105	7.228	261.416	2.76
01/11/2005	Warm	99	7.361	258.36	2.85
02/11/2005	Warm	90.75	7.33	250.012	2.93
02/11/2005	Warm	96.75	6.884	258.78	2.46

Appendix C5: Acceleration Results

Date	Condition	TCO	TI/MAF	PV	Max IGA	Average IGA	Max Speed	Time to Max Speed	Average Acceleration	Acceleration per Pedal Input	Max Acceleration	Max Jerk
01/11/2005	Part Load Acceleration 0 - 100km/h	99	3.001	53.732	33.094	17.774	93	26.528	0.911	1.6954	2.43	0.604
01/11/2005	Part Load Acceleration 0 - 100km/h	95	3.0325	59.609	31.688	16.51	95	26.588	0.92982	1.5599	2.28	0.463
02/11/2005	Part Load Acceleration 0 - 100km/h	95	3.0841	65.676	32.813	15.041	93	26.168	0.98723	1.5032	2.45	0.525
02/11/2005	Part Load Acceleration 0 - 100km/h, <10% TI	95	2.7784	67.697	33.563	14.995	93	27.818	0.92864	1.3718	2.37	0.555

Date	Condition	TCO	TI/MAF	PV	Max IGA	Average IGA	Max Speed	Time to Max Speed	Average Acceleration	Acceleration per Pedal Input	Max Acceleration	Max Jerk
01/11/2005	Part Load Acceleration 40 - 80km/h	95	3.0743	68.021	32.438	17.237	75	8.7327	1.1133	1.6367	2.17	0.368
01/11/2005	Part Load Acceleration 40 - 80km/h	96	3.0915	75.728	24.938	14.032	74	8.4125	1.1227	1.4825	1.9	0.745
02/11/2005	Part Load Acceleration 40 - 80km/h	95	3.0958	75.615	28.688	15.448	75	9.3528	1.0395	1.3747	1.721	0.421
02/11/2005	Part Load Acceleration 40 - 80km/h, <10% TI	95	2.7769	74.491	28.313	16.031	74	9.1228	1.0353	1.3898	1.707	0.783

Date	Condition	TCO	TI/MAF	PV	Max IGA	Average IGA	Max Speed	Time to Max Speed	Average Acceleration	Acceleration per Pedal Input	Max Acceleration	Max Jerk
01/11/2005	Part Load Acceleration 60 - 100km/h	95	3.0267	60.261	29.813	17.913	94	12.174	0.79862	1.3253	1.1668	0.173
01/11/2005	Part Load Acceleration 60 - 100km/h	96	3.0349	59.189	29.063	16.657	95	12.674	0.78903	1.3331	1.071	0.421
02/11/2005	Part Load Acceleration 60 - 100km/h	94	2.9731	48.218	30.188	20.684	94	14.774	0.65805	1.3647	1.056	0.511
02/11/2005	Part Load Acceleration 60 - 100km/h, <10% TI	94	2.7623	56.912	29.25	19.243	94	12.424	0.78255	1.275	1.173	0.398

Date	Condition	TCO	TI/MAF	PV	Max IGA	Average IGA	Max Speed	Time to Max Speed	Average Acceleration	Acceleration per Pedal Input	Max Acceleration	Max Jerk
01/11/2005	Full Load Acceleration 0 - 100km/h	99	3.2878	92.677	32.719	12.34	94	18.466	1.414	1.5258	3.25	1.87
01/11/2005	Full Load Acceleration 0 - 100km/h	95	3.2845	90.936	33.938	11.531	94	19.236	1.3574	1.4927	2.71	0.887
02/11/2005	Full Load Acceleration 0 - 100km/h	95	3.2963	90.793	33.656	12.359	95	18.456	1.4299	1.5749	3.07	0.75
02/11/2005	Full Load Acceleration 0 - 100km/h, <10% TI	95	2.965	91.252	33.938	12.287	95	20.646	1.2781	1.4007	2.77	0.631

Date	Condition	TCO	TI/MAF	PV	Max IGA	Average IGA	Max Speed	Time to Max Speed	Average Acceleration	Acceleration per Pedal Input	Max Acceleration	Max Jerk
01/11/2005	Full Load Acceleration 40 - 80km/h	94	3.3235	98.816	25.875	13.395	74	6.8621	1.3763	1.3928	2.42	0.64
02/11/2005	Full Load Acceleration 40 - 80km/h	95	3.3381	98.64	26.813	13.879	74	6.812	1.3865	1.4056	2.062	0.7065
02/11/2005	Full Load Acceleration 40 - 80km/h, <10% TI	95	2.9994	98.479	27.375	12.658	74	7.5623	1.2489	1.2682	1.96	0.671

Date	Condition	TCO	TI/MAF	PV	Max IGA	Average IGA	Max Speed	Time to Max Speed	Average Acceleration	Acceleration per Pedal Input	Max Acceleration	Max Jerk
01/11/2005	Full Load Acceleration 60 - 100km/h	94	3.326	98.323	28.5	12.946	95	10.193	0.98105	0.99778	1.107	0.499
02/11/2005	Full Load Acceleration 60 - 100km/h	95	3.3435	98.753	28.5	12.205	95	12.574	0.79531	0.80536	1.29	0.52
02/11/2005	Full Load Acceleration 60 - 100km/h, <10% TI	95	3.0179	98.107	27.188	12.196	98	13.394	0.756	0.77	1.13	0.85

Appendix C6: Acceleration Results

Date	Tip In Condition	Start Speed	End Speed	Max PV	dPVdt	Max Injection Duration	Average Injection Duration	Injection Overshoot (Acceleration Enrichment)	Max Mass Air Flow	Average Mass Air Flow	TI/MAF	Min Ignition Angle	Average Ignition Angle	Max Acceleration	Jerk
01/11/2005	10 to 20km/h 1st Gear	8	15	99.902	374.27	14.116	10.421	35.457	393.4	329.25	3.17	-15	4.125	2.43	1.55
01/11/2005	10 to 20km/h 1st Gear	8	27	99.902	374.29	15.032	11.664	28.875	438.27	367.57	3.17	-15	9.5877	3.01	1.47
02/11/2005	10 to 20km/h 1st Gear	8	27	99.902	373.97	14.22	11.638	22.186	432.78	366.42	3.18	-15	10.439	3.077	1.368
02/11/2005	10 to 20km/h 1st Gear	9	26	99.902	399.35	13.08	10.5	24.571	429.98	366.29	2.87	4.875	14.069	2.94	1.51

Date	Tip In Condition	Start Speed	End Speed	Max PV	dPVdt	Max Injection Duration	Average Injection Duration	Injection Overshoot (Acceleration Enrichment)	Max Mass Air Flow	Average Mass Air Flow	TI/MAF	Min Ignition Angle	Average Ignition Angle	Max Acceleration	Jerk
01/11/2005	10 to 20km/h 2nd Gear	10	25	99.902	299.39	14.452	11.252	28.439	428.41	355.38	3.17	-15	9.4133	2.904	1.683
01/11/2005	10 to 20km/h 2nd Gear	11	28	99.902	374.29	12.628	11.207	12.680	380.96	359.5	3.12	-3.375	6.4223	1.996	0.729
02/11/2005	10 to 20km/h 2nd Gear	11	29	99.902	315.17	12.6	11.168	12.822	381.34	357.79	3.12	-1.875	7.0594	1.6881	0.5
02/11/2005	10 to 20km/h 2nd Gear	12	28	99.902	374.27	11.416	10.119	12.817	378.39	355.97	2.84	2.625	8.769	1.702	1.2

Date	Tip In Condition	Start Speed	End Speed	Max PV	dPVdt	Max Injection Duration	Average Injection Duration	Injection Overshoot (Acceleration Enrichment)	Max Mass Air Flow	Average Mass Air Flow	TI/MAF	Min Ignition Angle	Average Ignition Angle	Max Acceleration	Jerk
01/11/2005	20 to 40km/h 1st Gear	18	37	99.902	352.24	15.624	13.007	20.120	447.55	391.8	3.32	-10.875	13.027	2.636	1.201
01/11/2005	20 to 40km/h 1st Gear	19	36	99.902	399.24	16.064	12.987	23.693	445.58	392.44	3.31	-9.375	13.455	2.929	1.586
02/11/2005	20 to 40km/h 1st Gear	18	35	99.902	352.24	15.54	12.79	21.501	442.48	384.54	3.33	-9	13.172	Lost Communication	
02/11/2005	20 to 40km/h 1st Gear	20	37	99.902	365.87	14.824	11.711	26.582	443.37	391.43	2.99	10.5	16.682	3.125	1.53

Date	Tip In Condition	Start Speed	End Speed	Max PV	dPVdt	Max Injection Duration	Average Injection Duration	Injection Overshoot (Acceleration Enrichment)	Max Mass Air Flow	Average Mass Air Flow	TI/MAF	Min Ignition Angle	Average Ignition Angle	Max Acceleration	Jerk
01/11/2005	20 to 40km/h 2nd Gear	17	37	99.902	332.68	13.592	11.4	19.228	408.85	363.27	3.14	-4.875	11.674	1.754	0.734
01/11/2005	20 to 40km/h 2nd Gear	18	38	99.902	399.21	13.724	11.417	20.207	410.54	365.63	3.12	-8.625	11.578	1.884	1.618
02/11/2005	20 to 40km/h 2nd Gear	18	38	99.902	399.24	14.28	11.55	23.636	410.06	365.69	3.16	-5.25	12.655	1.862	0.47
02/11/2005	20 to 40km/h 2nd Gear	18	38	99.902	374.29	12.252	10.414	17.649	410.56	366.93	2.84	6.375	14.085	2.563	1.182

Date	Tip In Condition	Start Speed	End Speed	Max PV	dPVdt	Max Injection Duration	Average Injection Duration	Injection Overshoot (Acceleration Enrichment)	Max Mass Air Flow	Average Mass Air Flow	TI/MAF	Min Ignition Angle	Average Ignition Angle	Max Acceleration	Jerk
01/11/2005	20 to 40km/h 3rd Gear	17	37	99.902	399.11	13.256	11.103	19.391	383.12	365.76	3.04	-2.25	4.9347	0.959	0.4
01/11/2005	20 to 40km/h 3rd Gear	19	37	99.902	399.24	13.464	11.118	21.101	381.29	363.97	3.05	0.75	5.575	0.971	0.6112
02/11/2005	20 to 40km/h 3rd Gear	20	37	99.902	399.21	13.148	11.096	18.493	375.17	362.07	3.06	1.875	6.6685	1.33	0.6719
02/11/2005	20 to 40km/h 3rd Gear	20	36	99.902	374.32	11.7	10.147	15.305	375.89	362.06	2.80	3	7.4154	1.148	0.987

Appendix C7: Acceleration Results

Date	Tip Out Condition	Average PV	dPVdt	Max Injection Duration	Min Injection Duration	Average Injection Duration	Max Mass Air Flow	Min Mass Air Flow	Average Mass Air Flow	Min Ignition Angle	Max Ignition Angle	Average Ignition Angle	Max Acceleration	Jerk
01/11/2005	Tip In - 10 to 20km/h 1st Gear	13.827	-102.53	11.908	2.12	3.3754	379.6	86.644	121.82	2.625	36.75	31.273	-0.91	-0.62
01/11/2005	Tip In - 10 to 20km/h 1st Gear	10.955	-102.54	15.032	2.384	4.8348	439.86	94.147	175.72	-6.375	37.5	15.637	-1.173	-0.531
02/11/2005	Tip In - 10 to 20km/h 1st Gear	8.2728	-128.92	14.532	2.464	3.081	435.47	92.77	110.11	-6.375	37.125	26.366	-1.03	-0.301
02/11/2005	Tip In - 10 to 20km/h 1st Gear	9.8297	-9.3742	13.168	2.396	3.0747	432.48	94.232	117.66	12.75	38.25	26.375	-1.0667	-0.65

Date	Tip Out Condition	Average PV	dPVdt	Max Injection Duration	Min Injection Duration	Average Injection Duration	Max Mass Air Flow	Min Mass Air Flow	Average Mass Air Flow	Min Ignition Angle	Max Ignition Angle	Average Ignition Angle	Max Acceleration	Jerk
01/11/2005	Tip In - 10 to 20km/h 2nd Gear	10.694	-81.033	13.88	2.116	3.1349	432.33	94.253	113.27	10.125	37.875	29.807	-1.16	-0.544
01/11/2005	Tip In - 10 to 20km/h 2nd Gear	7.2374	-16.198	12.056	2.144	3.2346	381.48	81.409	117.23	12.75	33.375	23.718	-1.058	-0.496
02/11/2005	Tip In - 10 to 20km/h 2nd Gear	8.376	-48.523	12.16	2.096	4.4611	381.59	81.769	162.69	9.75	33	20.535	Communication Lost	
02/11/2005	Tip In - 10 to 20km/h 2nd Gear	8.9537	-4.7556	10.684	2.192	2.8079	378.84	87.556	105.81	13.125	33.75	27.859	-0.716	-0.56

Date	Tip Out Condition	Average PV	dPVdt	Max Injection Duration	Min Injection Duration	Average Injection Duration	Max Mass Air Flow	Min Mass Air Flow	Average Mass Air Flow	Min Ignition Angle	Max Ignition Angle	Average Ignition Angle	Max Acceleration	Jerk
01/11/2005	Tip In - 20 to 40km/h 1st Gear	8.9547	-111.01	15.112	2.396	3.4264	446.72	92.812	123.45	4.875	40.125	26.004	-1.0064	-0.555
01/11/2005	Tip In - 20 to 40km/h 1st Gear	8.9417	-102.54	14.996	2.432	3.258	443.59	92.134	117.29	4.875	40.125	31.424	-1.68	-1.056
02/11/2005	Tip In - 20 to 40km/h 1st Gear	11.515	-5.5133	15.076	2.424	3.8119	442.95	92.24	133.47	15.75	40.125	35.72	-1.23	-0.375
02/11/2005	Tip In - 20 to 40km/h 1st Gear	11.473	-6.2435	13.448	2.432	3.3294	442.25	93.554	128.52	15.375	40.125	36.097	-1.32	-1.18

Date	Tip Out Condition	Average PV	dPVdt	Max Injection Duration	Min Injection Duration	Average Injection Duration	Max Mass Air Flow	Min Mass Air Flow	Average Mass Air Flow	Min Ignition Angle	Max Ignition Angle	Average Ignition Angle	Max Acceleration	Jerk
01/11/2005	Tip In - 20 to 40km/h 2nd Gear	7.8813	-173.84	12.82	1.816	2.7868	410.52	77.276	100.92	-0.75	38.625	29.337	-0.685	-0.292
01/11/2005	Tip In - 20 to 40km/h 2nd Gear	7.3604	-81.584	12.292	1.728	4.0016	412.43	78.272	154.79	-0.375	38.625	24.142	-1.155	-0.601
02/11/2005	Tip In - 20 to 40km/h 2nd Gear	9.8861	-266.56	12.772	1.908	3.222	411.2	77.319	116.51	13.5	38.625	32.658	-0.714	-0.3229
02/11/2005	Tip In - 20 to 40km/h 2nd Gear	10.38	-173.79	11.584	1.6	2.8531	412.64	77.573	113.84	15	38.625	33.096	-0.9111	-1.89

Date	Tip Out Condition	Average PV	dPVdt	Max Injection Duration	Min Injection Duration	Average Injection Duration	Max Mass Air Flow	Min Mass Air Flow	Average Mass Air Flow	Min Ignition Angle	Max Ignition Angle	Average Ignition Angle	Max Acceleration	Jerk
01/11/2005	Tip In - 20 to 40km/h 3rd Gear	14.396	-4.8162	11.916	2.944	3.8229	373.75	112.71	140.77	10.875	30.375	28.346	-0.654	-0.22
01/11/2005	Tip In - 20 to 40km/h 3rd Gear	11.967	-57.952	12.004	2.268	4.9029	373.26	87.662	179.08	-9.375	31.125	20.261	-0.736	-0.43
02/11/2005	Tip In - 20 to 40km/h 3rd Gear	14.02	-3.7195	12.092	2.316	3.7675	373.01	92.218	138.07	11.25	30.375	28.066	-0.678	-0.215
02/11/2005	Tip In - 20 to 40km/h 3rd Gear	17.512	-4.8144	10.468	2.456	4.0404	371.95	111.99	160.53	11.25	30.375	28.207	Lost Communication	

Appendix C8: Acceleration Results

Date	Condition	Start Speed	End Speed	Average PV	Average TI	Average MAF	TI/MAF	Max Lambda	Average IGA	Max Acceleration	Max Jerk
01/11/2005	Coast	97	79	0.000849	2.472	87.419	2.8277	31.652	6.0848	0.723	0.775
01/11/2005	Coast	96	58	0.009698	2.4105	85.024	2.8351	31.32	4.8957	0.162	0.11
01/11/2005	Coast	75	57	0.005234	2.4476	86.168	2.8405	31.457	5.2375	0.095	0.646
01/11/2005	Coast	95	68	0	2.3888	84.529	2.826	31.58	5.2713	0.457	0.467
01/11/2005	Coast	95	65	0.004322	2.5521	88.942	2.8694	32.223	5.9015	-0.18	0.192
01/11/2005	Coast	76	57	0.004609	2.4453	86.019	2.8428	31.719	4.8784	0.015	0.357
01/11/2005	Coast	92	76	0	2.408	85.457	2.8178	31.33	6.0495	0.0176	0.171
02/11/2005	Coast	97	70	0	2.4261	86.054	2.8192	32.01	5.6879	0.36	0.558
02/11/2005	Coast	99	38	0	2.4801	86.472	2.868	31.77	4.6616	0.28	0.511
02/11/2005	Coast	79	58	0.003456	2.4949	87.69	2.8451	32.197	4.5398	0.143	0.098
02/11/2005	Coast, <10% TI	95	73	0.001132	2.2034	86.686	2.5419	32.185	5.3851	-0.079	0.33
02/11/2005	Coast, <10% TI	96	77	0.012314	2.2042	86.281	2.5547	32.109	5.4018	0.2608	0.287
02/11/2005	Coast, <10% TI	77	57	0.007276	2.232	86.915	2.568	32.128	5.2606	0.191	0.205
02/11/2005	Coast, <10% TI	76	57	0.004832	2.2306	86.778	2.5704	31.175	5.1753	0.0842	0.167

Appendix C9: Brake Results

Date	Condition	Start Speed	End Speed	Time to Stop	Average Engine Speed During Braking	Engine Speed Standard Deviation During Braking	Average Engine Speed After Braking	Engine Speed Standard Deviation After Braking	Max TI_TOT	Average TI_TOT	Max MAF	Average MAF	TI/MAF	Max IGA	Average IGA	Average Acceleration	Max Acceleration
01/11/2005	Brake	79	0	8.3426	967.85	27.497	878.86	9.05	5.032	4.4192	158.56	152.98	2.8887	19.875	2.3378	-2.630	-3.071
01/11/2005	Brake	68	0	7.1122	973.32	17.461	887.52	12.6	4.964	4.47	157.63	153.54	2.9113	20.25	2.6513	-2.656	-3.42
01/11/2005	Brake	76	0	7.4322	871.63	3.4353	884.76	14.81	4.584	4.5638	165.57	164.94	2.767	19.875	1.3816	-2.840	-3.23
02/11/2005	Brake	70	0	8.0724	895	0	881.45	12.3	4.496	4.48	163.54	163.16	2.7458	19.875	2.25	-2.409	-2.808
02/11/2005	Brake	69	0	7.4427	921.13	2.8852	886.7	12.45	4.488	4.4638	159.41	158.82	2.8105	19.875	0.35156	-2.575	-2.58
02/11/2005	Brake, <10% TI	73	0	8.0124	972.81	28.99	873.74	9.0551	4.248	4.0818	161.99	155.12	2.6315	20.25	2.9354	-2.531	-3.182
02/11/2005	Brake, <10% TI	76	0	8.7727	952.08	34.874	868.57	6.8	4.284	4.1127	168.07	158.53	2.5942	20.25	2.7373	-2.406	-3.098

Appendix C10: Cruise Results

Date	Condition	TCO	Average PV	PV Standard Deviation	Average Cruise Speed	Average Cruise Speed Standard Deviation	Average TI	Average MAF	TI/MAF	Average IGA
01/11/2005	Cruise	96	29.517	3.0581	94.882	0.93967	6.3667	239.03	2.6636	24.206
01/11/2005	Cruise	93.75	25.808	5.6645	94.821	0.98514	5.8242	217.44	2.6785	25.764
01/11/2005	Cruise	96	24.27	4.1864	94.068	0.2952	5.598	207.63	2.6961	25.949
01/11/2005	Cruise	93.75	23.96	3.3358	95.606	0.52575	5.544	205.02	2.7041	26.32
02/11/2005	Cruise	95.25	40.099	6.9934	96.088	0.88117	8.5387	301.99	2.8275	22.396
02/11/2005	Cruise	93	27.543	4.1657	97.188	1.5435	6.2566	226.2	2.766	26.027
02/11/2005	Cruise, <10% TI	95.25	37.561	5.2077	94.641	0.57434	7.6285	288.46	2.6445	22.259
02/11/2005	Cruise, <10% TI	93	26.417	2.5987	95.096	0.85326	5.6303	218.14	2.5811	26.084
01/11/2005	Cruise	93.75	15.769	5.1438	75.296	1.3554	4.2068	155.71	2.7016	29.449
01/11/2005	Cruise	94.5	17.311	6.0989	75.929	0.34546	4.6538	170.27	2.7331	28.597
01/11/2005	Cruise	94.5	18.29	8.2809	92.59	0.89847	4.6232	170.03	2.7191	29.066
02/11/2005	Cruise	93.75	25.132	5.4911	77.658	1.3132	6.0352	216	2.7941	26.932
02/11/2005	Cruise, <10% TI	93.75	25.184	4.8681	75.762	1.2669	5.4829	211.78	2.589	26.594
02/11/2005	Cruise, <10% TI	93	18.057	10.065	75.64	0.67063	4.5898	178.35	2.5734	27.874

Appendix D: Driveability Evaluation

Date	Measured File	DSI_{st}	$DSI_{\%OS}$	DII_{Nsp}	DII_{STD}	DII_{LC}	$DII_{dN/dPV}$	DII_{BDI}	DII_{BAI}	DII_{Brake}
01/11/2005	Driveability Test 1, Normal Fuelling	7.0000	5.0000	8.00	6	7.00	6.00	5.00	6.00	5.6
01/11/2005	Driveability Test 2, Normal Fuelling	8.0000	5.0000	8.00	6	7.00	6.00	9.00	6.00	7.2
02/11/2005	Driveability Test 3, Normal Fuelling	7.0000	5.0000	8.00	6	7.00	6.00	10.00	6.00	7.6
02/11/2005	Driveability Test 4, 10% Less Fuelling	6.0000	6.0000	8.00	6	7.00	5.00	5.00	7.00	6.2
12/09/2005	Driveability Test 4, Anti-Jerk Function Off	7.0000	5.0000	8.00	6	7.00	6.00	Not measured		

Date	Measured File	$DAI_{TI/MAF}$	DAI_{G_PV}	DAI_{Jerk}	DAI_1	$DAI_{TI/MAF}$	DAI_{G_PV}	DAI_{Jerk}	DAI_2	$DAI_{TI/MAF}$	DAI_{G_PV}	DAI_{Jerk}	DAI_3
		PL Acc 0 - 100km/h				PL Acc 40 - 80km/h				PL Acc 60 - 100km/h			
01/11/2005	Driveability Test 1, Normal Fuelling	9	7	6	7.2	9	7	5	6.8	9	6	5	6.5
01/11/2005	Driveability Test 2, Normal Fuelling	9	7	6	7.2	9	6	6	6.9	9	6	5	6.5
02/11/2005	Driveability Test 3, Normal Fuelling	9	7	6	7.2	9	6	5	6.5	8	6	6	6.6
02/11/2005	Driveability Test 4, 10% Less Fuelling	8	6	6	6.6	8	6	6	6.6	8	6	5	6.2
12/09/2005	Driveability Test 4, Anti-Jerk Function Off	9	7	6	7.2	Not measured				Not measured			

Date	Measured File	$DAI_{TI/MAF}$	DAI_{G_PV}	DAI_{Jerk}	DAI_1	$DAI_{TI/MAF}$	DAI_{G_PV}	DAI_{Jerk}	DAI_2	$DAI_{TI/MAF}$	DAI_{G_PV}	DAI_{Jerk}	DAI_3
		FL Acc 0 - 100km/h				FL Acc 40 - 80km/h				FL Acc 60 - 100km/h			
01/11/2005	Driveability Test 1, Normal Fuelling	8	7	6	6.9	Not measured				Not measured			
01/11/2005	Driveability Test 2, Normal Fuelling	8	6	6	6.6	8	6	6	6.6	8	6	6	6.6
02/11/2005	Driveability Test 3, Normal Fuelling	8	7	6	6.9	8	6	6	6.6	8	6	6	6.6
02/11/2005	Driveability Test 4, 10% Less Fuelling	7	6	6	6.3	7	6	6	6.3	8	5	6	6.3
12/09/2005	Driveability Test 4, Anti-Jerk Function Off	8	7	10	8.5	Not measured				Not measured			

Date	Measured File	DAI_{AE}	DAI_{Jerk}	DAI_1	DAI_{AE}	DAI_{Jerk}	DAI_2	DAI_{AE}	DAI_{Jerk}	DAI_3	DAI_{AE}	DAI_{Jerk}	DAI_4	DAI_{AE}	DAI_{Jerk}	DAI_5
		Tip In 10-20 1st			Tip In 10-20 2nd			Tip In 20-40 1st			Tip In 20-40 2nd			Tip In 20-40 3rd		
01/11/2005	Driveability Test 1, Normal Fuelling	9	6	6.75	7	6	6.25	6	6	6	5	6	5.75	5	5	5
01/11/2005	Driveability Test 2, Normal Fuelling	7	6	6.25	5	6	5.75	6	6	6	6	6	6	6	6	6
02/11/2005	Driveability Test 3, Normal Fuelling	7	6	6.25	5	Lost communication	5	6	Lost com	6	6	5	5.25	5	6	5.75
02/11/2005	Driveability Test 4, 10% Less Fuelling	7	6	6.25	5	6	5.75	7	6	6.25	5	6	5.75	5	Lost com	5
12/09/2005	Driveability Test 4, Anti-Jerk Function Off	8	5	5.75	5	8	7.25	6	8	7.5	6	10	9	5	7	6.5

Date	Measured File	DAI_{Jerk}	DAI_{Jerk}	DAI_{Jerk}	DAI_{Jerk}	DAI_{Jerk}
		Tip Out 10-20 1st	Tip Out 10-20 2nd	Tip Out 20-40 1st	Tip Out 20-40 2nd	Tip Out 20-40 3rd
01/11/2005	Driveability Test 1, Normal Fuelling	6	6	6	5	5
01/11/2005	Driveability Test 2, Normal Fuelling	6	6	6	6	5
02/11/2005	Driveability Test 3, Normal Fuelling	5	Lost communication with accelerometer		5	5
02/11/2005	Driveability Test 4, 10% Less Fuelling	6	5	6	5	Lost communication
12/09/2005	Driveability Test 4, Anti-Jerk Function Off	2	4	2	9	8

Date	Measured File	DAI_{PA}	DAI_{AF}	DAI_{Jerk}
		Pull Away	Coast	
01/11/2005	Driveability Test 1, Normal Fuelling	8	10	6
01/11/2005	Driveability Test 2, Normal Fuelling	8	10	5
02/11/2005	Driveability Test 3, Normal Fuelling	8	10	6
02/11/2005	Driveability Test 4, 10% Less Fuelling	7	10	5
12/09/2005	Driveability Test 4, Anti-Jerk Function Off	8	10	7