EVALUATION OF THE EFFECT OF DETERIORATING RIDING QUALITY ON BUS-PAVEMENT INTERACTION

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DISSERTATION SUMMARY

EVALUATION OF THE EFFECT OF DETERIORATING RIDING QUALITY ON BUS-PAVEMENT INTERACTION

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Department:	Civil Engineering
University:	University of Pretoria
Degree:	M.Eng (Transportation Engineering)

ABSTRACT

Title: Evaluation of the effect of deteriorating riding quality on bus-pavement interaction

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In Mpumalanga, only about 25 per cent of households have car access, which makes Mpumalanga one of the provinces with the highest use of public transport by means of bus or taxi in South Africa. Even though the road network in Mpumalanga is extensive, the maintenance and upgrade of this network is a concern, especially for municipal and provincial roads. Deteriorating roads have a direct (such as vehicle operating costs, VOCs) and indirect impact (such as high bus fares) on the road user.

This study focuses on the interaction between one bus from Buscor and the pavement surface of one specific bus route, including the associated VOCs generated. The ride comfortability of the bus route was evaluated by interpreting International Roughness Index (IRI), Power Spectral Density (PSD), and vertical accelerations (a_{wz}) data, after which the associated vehicle operating costs (VOCs) for the bus were projected. The judgement of ride comfortability in a vehicle is an area of controversy, and studies on this topic dates back from the 1920sThe threshold values from ISO (1997), Cantisani, and Loprencipe (2010) were used for the purposes of this study.

The vertical accelerations generated from the surface of the bus route, for a bi-articulated bus were measured with accelerometers. The accelerometers were placed on the bus where the vertical accelerations were expected to be the highest. The identified bus route included different roads with different responsible authorities and roughness levels. A profiler conducted a survey on the route and five different sections were identified. The collected data were analysed with various programs. From the data collected from the accelerometers the PSD, a_{wz}, and the speed that the bus travelled on each section could be determined.

The IRI data for each section was categorised in three categories, very good to good, fair to mediocre and poor. Anomalies in each section were identified, and the cause of these anomalies determined. The anomalies were analysed with the data, as these values formed part of the route.

The impact of road roughness on fuel consumption, tyre wear and repair and maintenance costs were analysed. The calibrated Highway Development and Management System (HDM 4) model was used to predict the fuel consumption, tyre wear and repair and maintenance cost per km of each section of the bus route under consideration.

In this analysis, the impact of the vehicle speed proved to be significant, as it affected the PSD values, the a_{wz} values and the VOC. The scenario was analysed to improve the riding quality of the two worst sections of the bus route, and by improving the road surface of these two sections, travel time could be reduced and costs could be saved. The scenario of an increase in road roughness was also analysed, to indicate the percentage of increase in costs, if these roads kept deteriorating. The analysis showed a significant increase in repair and maintenance cost, fuel consumption, and tyre wear.

The limitations of this study included some correlation issues with the profiler data and the accelerometer data, unidentified bus stops on gravel shoulders, and the suspension system and interior of the bus that were deemed constants and not variables within the scope of this study.

Despite these limitations, there are still a number of possibilities with the data collected. Apart for the analyses conducted for the study, recommendations for further refinement include the impact of bus mass on the data (full bus versus empty bus), the suspension type and condition, the interior of the bus, trip duration and congestion, evaluation of driver fatigue, tyre pressure and dynamic wheel loads, and safety. Furthermore, the construction cost of upgrading the two worst sections of the route versus the increase in VOCs because of the deteriorating state of the route could be investigated.

In conclusion, the speed played a determining role in the generation of vertical accelerations, therefore user comfort or discomfort, and VOCs. An increase in IRI indicates deteriorating riding quality that affects the comfortability of a ride and the VOCs negatively. IRI can be used to determine the state of the road and q_{wz} gives an indication of the comfortability of a ride.

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LIST OF SYMBOLS AND ABBREVIATIONS

A	Amplitude	
AADT	Annual Average Daily Traffic	
a_w	Weighted Root Mean Square acceleration	m/s^2
a_{wz}	Vertical Acceleration	m/s^2
BW	Band Width	
f	Frequency	cycle/s
FFT	Fast Fourier Transform	
GPS	Global Positioning System	
HDM	Highway Development Management System	
IRI	International Roughness Index	m/km
n	number	
NCHRP	National Cooperative Highway Research Program	
PSD	Power Spectral Density	g^2/Hz
RMS G_i	Root Mean Square Acceleration	m/s^2
RTRRMS	Response-type Road Roughness Measurement Systems	
SANRAL	South African National Road Agency Limited	
TRAC	Trans African Concessions	
v	Speed	km/h
W_k	Frequency band Weighing factor	
λ	Wavelength	m
ν	Wave number	1/length
DWT	Discrete Wavelet Transform	
CWT	Continuous Wavelet Transform	

1. INTRODUCTION

1.1 Background

Public transport depends on infrastructure, however investments in infrastructure are high and regular maintenance should get more attention. Infrastructure is one of the contributing factors in the evaluation of a country's success. The state of the road network has a direct impact on the road user (private as well as public) and in the end on the economy. In South Africa, regular maintenance of the provincial and municipal road network is a concern.

Road roughness is a primary indicator of the condition of the riding quality of a road transportation system. An increase in road roughness affects Vehicle Operating Costs (VOCs) directly, since the tyres and suspension system transfer the unevenness of the road surface as vertical accelerations to the vehicle. These vertical accelerations can lead to damage of vehicle components as well as an increase in fuel consumption. Further damage can be caused to the cargo transported, depending on the suspension and speed of the vehicle (Steyn et al., 2011a). By determining the road roughness of a pavement, engineers can estimate what maintenance, if any, is required in order to restore the pavement to acceptable riding quality levels (Steyn et al., 2011a).

The travel experience of a route is also affected by the riding quality of a road surface (Steyn, 2011). As the surface of the road translates through the components of the vehicle to the occupants. Various studies have been conducted about the effect that different road conditions have on responses and vibrations in vehicles (Steyn, 2011).

1.2 Objectives of the study

The main objective of this study is to determine the effect of a lack of adequate maintenance resulting in low riding quality, and high bus operating costs, as well as a low level of user comfort. Bus routes, covering roads of different responsible authorities (National, Provincial and Municipal) were evaluated by measuring the riding quality on the roads.

The judgement of ride comfortability in a vehicle is an area of controversy, and studies on this topic dates back from the 1920s (Gillespie, 1992), it is also very difficult to evaluate comfort objectively. However, there are certain threshold values and tests that can be conducted to evaluate user comfort. The generated riding quality (in terms of International Roughness Index(IRI), Power Spectral Density (PSD), and vertical accelerations (a_{wz}) from a moving vehicle on a rough road, related to speed, are some of the parameters that give an indication of the road state and the user comfortability. These parameters also give an indication of the road user costs and the impact a higher or lower IRI could have.

The following detailed objectives were specified for a bus traveling on the same bus route twice a day:

- Determine whether an increase in IRI indicates deteriorating riding quality;
- Determine whether an increase in vertical acceleration indicates an uncomfortable ride;
- Determine the role speed plays in user comfortability and VOCs;
- Determine whether the deterioration of the bus route riding quality will increase VOCs, and
- Determine if improvements of the bus route riding quality will decrease VOCs.

Therefore, if the route could be maintained regularly, VOCs and travel time could decrease. The road user will have a more comfortable ride and Buscor could make a higher profit or the subsidies provided by the state could decrease.

1.3 Scope of the study

The scope of this study was to evaluate the riding quality of a bus route, including the associated vertical accelerations and VOCs generated by this route on the bus. The projected VOCs give an indication on the percentage costs that could be saved if the routes are maintained or upgraded to an adequate IRI level. The costs include road user cost, bus operating cost and subsidies.

A profiler surveyed the bus route to determine the IRI of this route. A bi-articulated bus from Buscor was instrumented to measure the accelerations imparted on the bus and passengers during travel over these roads. The resultant damage caused to the bus due to higher than average accelerations caused by uneven riding surfaces, as well as the discomfort caused to passengers were analysed. The economic effect in terms of higher bus operating costs were evaluated in comparison with the additional costs of improving the quality control required during the initial construction to attain good riding quality on the roads.

1.4 Methodology

The vertical accelerations generated from the surface of a specific bus route, of a bi-articulated bus were measured with accelerometers. The accelerometers were placed on the bus where the vertical accelerations were expected to be the highest. The bus route was identified so that different roads with different roughness levels and responsible authorities could be utilised. Five sections were identified from the profiler survey.

The impact of road roughness on fuel consumption, tyre wear and, repair and maintenance costs were analysed. The calibrated HDM 4 model was used to predict the fuel consumption, tyre wear and, repair and maintenance cost per km of each section of the bus route under consideration.

This research should provide an objective indication of the level of increased costs down the line due to the perceived savings by not maintaining a road regularly. It is envisaged that the results of the study can be used to motivate for more emphasis on regular maintenance, and resultant lower VOCs on the South African road network (specifically on provincial and municipal level).

The methodology followed in the study focused on:

- Measuring the riding quality;
- Calculating the VOCs;
- Determining the impact of an increase in roughness;
- Determining the impact of a decrease in roughness;
- Measuring the vertical accelerations generated by the bus;
- Linking deteriorating riding quality to cost impact of the user/passenger/Buscor etc. and
- Evaluating different scenarios by evaluating the IRI of each section of the bus route and determining the projected costs if only certain sections of the bus route could be upgraded.

1.5 Organisation of the report

The report consists of the following chapters:

- Chapter 1: Introduction;
- Chapter 2: Literature Review;
- Chapter 3: Methodology;
- Chapter 4: Data Collection;
- Chapter 5: Data Analysis;
- Chapter 6: Data Application;
- Chapter 7: Conclusions and Recommendations;
- Chapter 8: References, and
- Chapter 9: Appendixes

2. LITERATURE REVIEW

2.1 Introduction

The literature review highlights the current available knowledge, studies, and research on the topic covered in this dissertation. The information presented is an overview discussion and forms part of the broader literature review covered during the study.

After the Second World War, road transport in Sub-Saharan Africa has grown rapidly, and is now the dominant form of transport. In order to cope with this rapid increase of traffic, road networks were expanded considerably during the 1960s and 1970s (Heggie, 2005). The South African road network comprises of 747 000 km (SAICE, 2011) and the responsibility for these roads is shared amongst the South African National Roads Agency Limited (SANRAL), Provincial and Municipal government.

Steyn (2011) indicated that in order to maintain the condition of a road to ensure a safe, reliable and smooth trip for the road users, as well as protecting the underlying materials, routine road maintenance is required. If the road is not maintained regularly, the structural integrity of the pavement reduces over time. Road roughness is used as the primary indicator of the condition of the road (riding quality). By determining the road roughness of a pavement, engineers can estimate what maintenance, if any, is required in order to restore the pavement to acceptable riding quality levels (Steyn et al., 2011a).

Various studies and methods have been conducted concerning the effect that different road conditions have on responses and vertical accelerations in vehicles. The International Organisation for Standardisation (ISO) (1997), Gillespie (1992), Sayers and Karamihas (1998), and Cantisani and Loprencipe (2010) indicated research and standards on this topic. The highest vertical accelerations are measured at the rear of a truck, Chonhenchob et al. (2009) and Jarimopas et al. (2005), which stated that the vertical accelerations are even higher at the rear of a trailer.

The road user judgement largely depends on the ride experienced by the vehicle of the road user (Sayers and Karamihas, 1998). In addition, according to Gillespie (1992), vertical acceleration measurement is the most common and meaningful measure of ride vibration. It is very difficult to evaluate the comfort objectively of a road user. Furthermore, there is no standard to determine human discomfort or comfort expressed in physical terms such as acceleration or amplitudes at a given frequency. Gillespie (1992) however, concluded from various investigations that there is enough correlation among the test data that a zone may be outlined above which vibration is certainly intolerable and below which it is irrelevant.

A number of factors determine the efficient operations of a country's economy such as an efficient economical system, efficient logistics system, and an efficient transport system. Recently, the focus on logistics cost (goods transportation) in a country has become more visible, as these costs have a direct effect on the broader economy. An increase in goods transportation costs lead to an increase of end-product cost to the consumer and that, in turn, lead to a decrease in the global competitiveness of a country as products become more and more expensive. Various studies have proven that deteriorating road quality result in significant increases in repair and vehicle maintenance costs, and fuel and tyre consumption, which in turn, leads to an increase in company logistic costs.

2.2 South African Road Network

The South African road network comprised of 747 000 km in 2011 of which 140 000 km of roads were unproclaimed (SAICE, 2011). The responsibility for these roads is shared amongst the South African National Roads Agency Limited (SANRAL), Provincial and Municipal government.

The SAICE Infrastructure Report Card stated in 2011 that only 37 per cent of the condition data of the classified road network were available, and 75 per cent of the network were unpaved. About 16 200 km (at the date of publication) of the classified paved roads were national roads and SANRAL managed these roads. The provincial road network consisted of approximately 185 000 km with 66 000 km under metropolitan management and the rest managed by municipalities (SAICE, 2011). The availability of information, as well as the condition of roads varies greatly, between both geographical areas and spheres of government (SAICE, 2011).

2.2.1 National Roads

The national road network of South Africa comprised of 16 200 km in 2011 of roads that connects cities, rural areas and towns. The 16 200 km of roads grew to about 20 000 km under SANRAL's management in 2013 (SANRAL, 2013).

The non-toll portion of the national road network account for 84.2 per cent, and the expansion, upgrade and continuing maintenance of these roads are financed by tax-based revenues and government allocations. The funds required for maintenance and upgrade for the tolled roads, which account for the remaining 15.8 per cent, are obtained from the road users by means of tollgates along the toll routes (SANRAL, 2013).

In order to support the non-toll portion of the national road network, the funding allocation from the national budget has increased steadily since 2004. The reason for the increased funding was due to escalating costs of labour, fuel, plant, and civil engineering materials, especially bitumen (SANRAL, 2011).

Some of the major toll road projects underway by SANRAL during 2012/13 are the N1-N2 Winelands toll highway project and Gauteng Open Road Tolling. SANRAL have concessioned about 1 288 km of the tolled sections to private companies to fund, develop, maintain and operate the routes. The three concessioned routes are Bakwena Platinum Corridor Concessionaire, N3 Toll Concession (N3TC) and the Trans African Concessions (TRAC), (SANRAL, 2013).

TRAC operates the N4 East, which links Gauteng with Maputo in Mozambique, this route is known as the Maputo Development Corridor. This route has experienced a steady annual growth in traffic over the last decade, and 10 per cent annual growth of freight vehicle traffic (SANRAL, 2011).

2.2.1.1 Pavement Management System

In order to manage the road network and to plan for required rehabilitation and maintenance, SANRAL operates pavement and bridge management systems as well as data collections to predict traffic volume growth and road usage. A routine maintenance contract covers the entire national road network and it is a continuing process that covers pavement repair, accommodation of traffic, construction of drainage and cleaning (as well as repair, if necessary) of existing drainage, crack sealing and patching. Including the renewal and repair of fences, road signs, burning of firebreaks, road studs and guardrails, maintenance of trees and shrubs in order to protect the environment, litter, weed control and emergency assistance (SANRAL, 2011).

The pavement management system, operated by SANRAL, is used to improve funding and maintenance strategies to ensure that the national road network remains at an adequate level with the given available financial support. An automated road survey vehicle, equipped with video, computer-based technologies and laser measure, collect data at highway speeds in order to obtain detail road data. The data collected are partially used to determine funding allocation by SANRAL in order to ensure that the national road network functions efficient and safe (SANRAL, 2011).

2.2.2 Provincial and Municipal Roads

There is an estimated 5 349 km of paved roads in the Mpumalanga province. The estimated gravel roads in Mpumalanga are 8 492 km (MDPWRT, 2013). The provincial roads of the Mpumalanga Province fall under the responsibility of the Mpumalanga Department Public Works, Roads and Transport (MDPWRT). The maintenance and establishment of the local municipal roads and streets infrastructure is the responsibility of the district and local municipalities. MDPWRT has developed, as part of the Bridge Management System (BMS), a Road Asset Management System (RAMS). RAMS is a database of information relating to a road network, which includes a network inventory, traffic data, condition data, roughness data as well as pavement structure and surface history, (RAMS, 2013). An outline of the national roads and provincial roads in the Mpumalanga Province, as currently indicated on the RAMS system, is presented in Figure 2-1 and Figure 2-2 respectively.

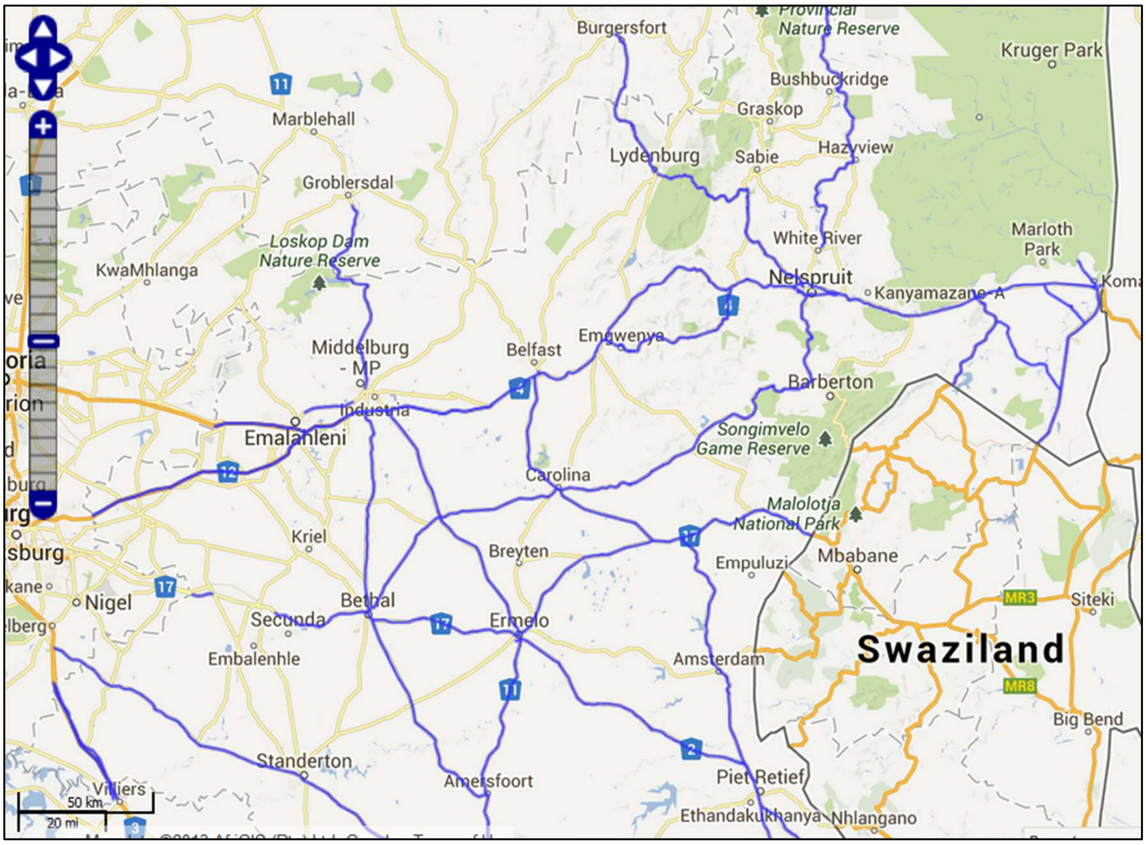

Figure 2-1: National roads in the Mpumalanga Province (RAMS, 2013).

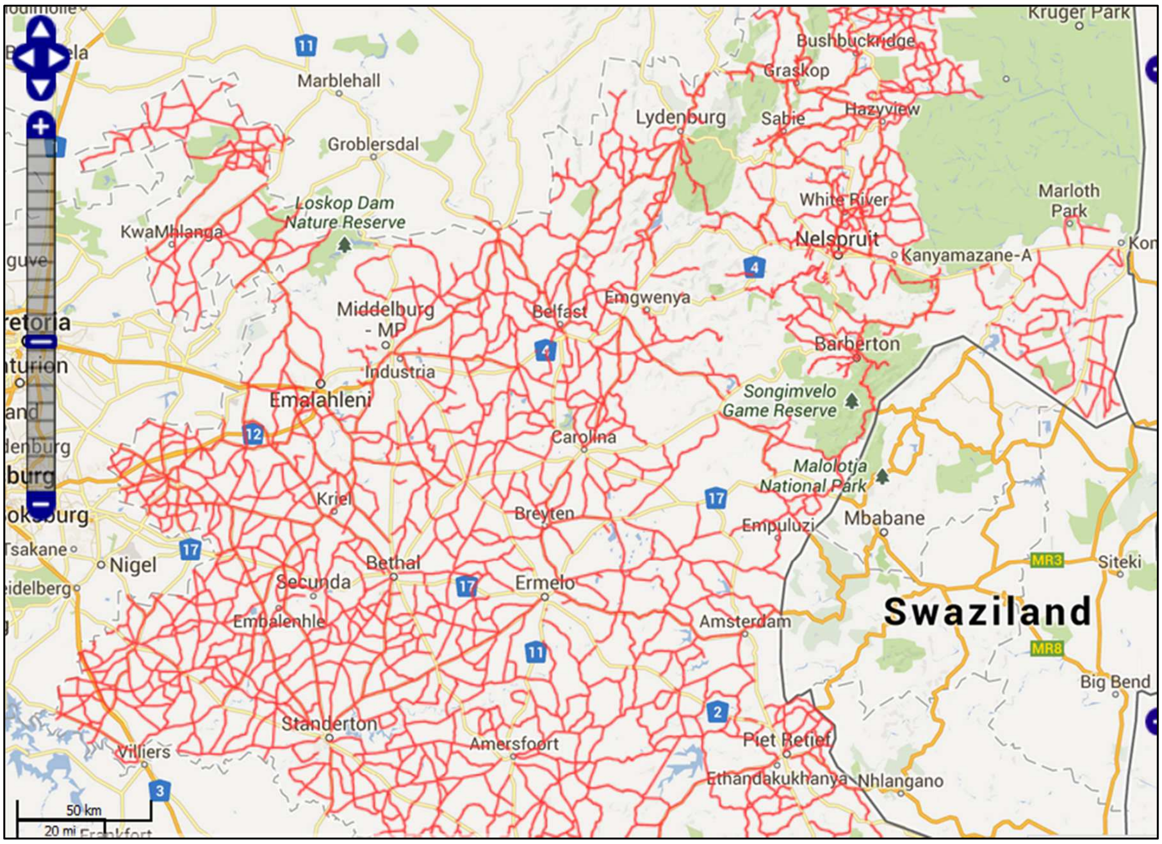

Figure 2-2: Provincial roads in the Mpumalanga Province (RAMS, 2013).

2.2.3 Pavement condition

Figure 2-3 indicates the conditions of the national roads in 2010 (SANRAL 2010). World Bank guidelines state that not more than 10 per cent of the roads under management fall in the poor to very poor category at any time, and SANRAL's management practices are in line with that. Figure 2-3 indicates that most of the national roads in the Mpumalanga Province are in a fair to good condition.

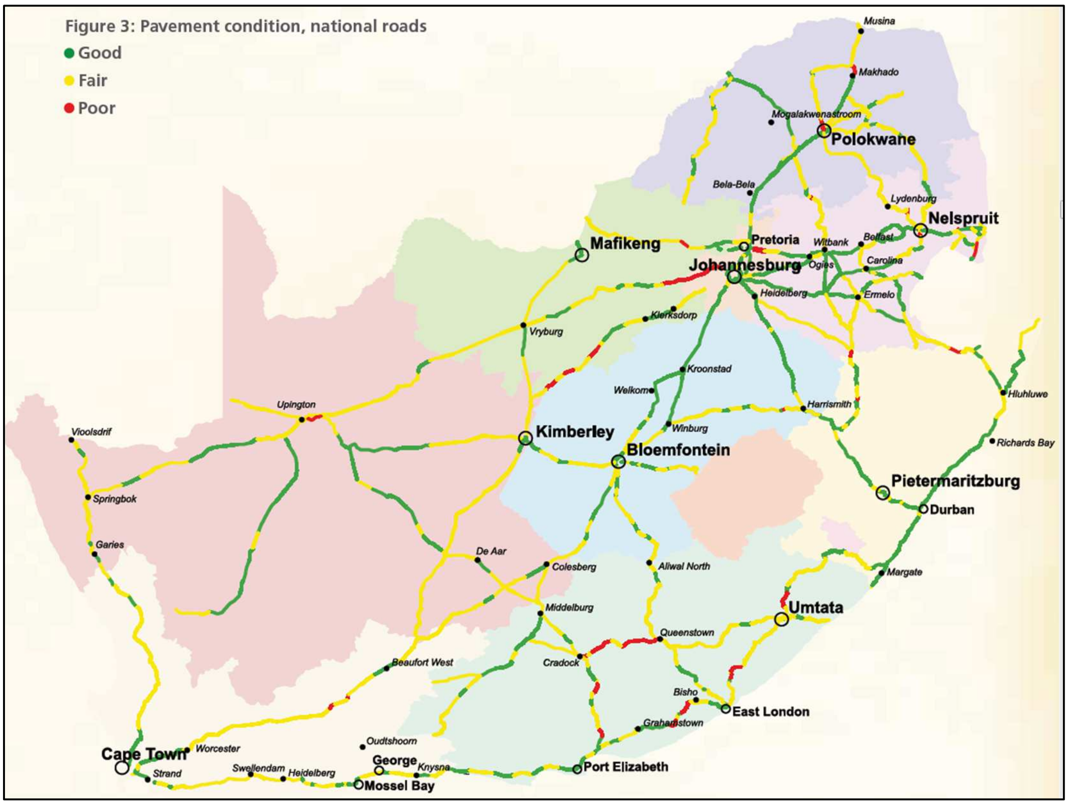

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Figure 2-3: Conditions of the national road network (SANRAL 2010).

Only 82 per cent of road condition data for provincial roads are available, and more than half of these roads have exceeded their design life, therefore making some sections vulnerable to costly and rapid deterioration. The information provided from the visual condition index, of the overall provincial road network, indicated that the network is deteriorating (SAICE 2011).

Municipal roads are not managed well, as there is only 4 per cent of road condition data available of these roads and there is confusion regarding the coordination and responsibility of the municipalities. With this little information available, it appeared that the paved roads were overall in a fairly good condition, but the gravel roads, however, were in a poor to very poor condition (SAICE 2011).

Adding to the information provided by the SAICE Infrastructure Report Card, Hannah (2010) indicated that SANRAL is proactive in the rehabilitation and maintenance of the national road network. Municipal and provincial roads, however, is in a dire situation as the roads are in a poor state.

In May 2010 the then Minister of Transport, Minister Sibusiso Ndebele, said at the Construction and Maintenance Summit that “The total paved and gravelled network at provincial level is 184 816 km and 40 per cent of this network has reached crisis point. We know that about 80 per cent of our road network is now older than the 20-year design life, based on information supplied from surveys undertaken on 64 per cent of the roads, primarily national, provincial and in some cities. The total paved and gravel network at municipal level is 339 849 km" (Hannah, 2010).

2.2.4 Impact of inadequate road maintenance

Steyn (2011) indicated that in order to maintain the condition of a road to ensure a safe, reliable and smooth trip for the road users, as well as protecting the underlying materials, routine road maintenance is required. Typical practise is to design a pavement to be able to sustain a minimum number of Equivalent Standard 80 kN axles (E80s), before any maintenance is required to restore the condition of the pavement. Therefore, good road management practise is essential in order to monitor the roads and ensure that the condition of the pavement is kept to a specific minimum requirement. If this process is well managed and planned, potholes and other defects will develop more slowly and therefore could be fixed immediately.

Current emergency procedures of fixing potholes are inadequate, as it excludes the pavement profile and concentrates on the pothole by filling it with a selection of various types of pothole fillers. This form of maintenance may protect the underlying materials, but the outcome is mostly an uneven road surface, which affect the riding quality and the surface profile. The reduction in riding quality has a negative impact on the accelerations generated in the vehicle and transported freight (Steyn, 2011).

Unfortunately, the lack of data provided by municipalities, suggests severe management problems, including the possible inability of many municipalities to extend and even maintain their road networks, the main reason being extreme skills shortages and lack of capacity in most municipalities. In 2007, a Department of Transport (DoT) survey indicated that many of the municipalities simply lacked the capacity to answer the survey questionnaire, which in turn, implies that the municipality is incapable regarding management and road maintenance. Furthermore, according to the survey, only 36 per cent of the municipalities that did reply indicated some form of a road management system (SAICE, 2011).

If road maintenance is delayed for more than five years, the construction cost to repair the pavement increases from six to eighteen times, excluding other indirect and direct costs. Indirect costs include costs subjected to the non-driver, for example increases in food prices as fuel and time is wasted on deteriorating or congested roads. Direct costs include VOC as well as fuel and time wasted on deteriorating or congested roads (SAICE, 2011).

Heggie (1995) calculated that it would cost Africa nearly US$ 43 billion to restore all the roads that requires immediate reconstruction or rehabilitation, classified as poor in 1995. Of the US$ 150 billion used to expand the African road network, a third of the investment was lost through lack of maintenance during the period 1975 to 1995. Annual expenditures of at least US$ 1.5 billion were required over the period 1995 to 2005, in order to restore the roads that were economically justified and to avoid further deterioration.

The costs saved on road maintenance are borne by road users, thus, each rand saved on maintenance increases the road users' vehicle operating costs. No money is saved by cutting back on road maintenance, as it raises the cost of road transport and that, in turn, increases the net cost to the economy (Heggie, 1995).

2.3 Vehicle-Pavement Interaction

Vehicle–Pavement Interaction (V-PI) refers to the way the vehicle components and pavement components interact with each other. The dynamics of a moving vehicle is influenced by the road roughness. The pavement responds to the dynamic tyre loads and it causes pavement distress. The profile changes under repeated loading of overloaded and heavy vehicles, and this leads to more changes in dynamic tyre loads. Therefore, the structural strength of the pavement reduces over time (Steyn et al., 2011b).

The major components in V-PI analyses are the vehicle operational conditions, the vehicle configuration and the road profile. The condition and life of a road are affected by changes in any of these components and therefore it is essential to understand how these mechanisms work together in order to determine the effect of the ultimate tyre loads applied to the road surface (Steyn, 2001).

Steyn (2001) indicated that tyre loads generally vary in two ways. The two ways are the varying loads applied by a vehicle along the pavement, and the variation of loads between vehicles travelling on a pavement. Road roughness mainly causes the first type of variation whereas, the second type of variation is accommodated in pavement analysis through equivalent load concepts.

Regression relationships were developed for the two variations (Steyn, 2001), which define the Load Coefficient of Variation (CoV) and the Average Load a road is subjected to. The Load CoV is a function of the Gross Vehicle Mass (GVM), number of tyres on the vehicle, road roughness, speed, and the load of the vehicle as a percentage of the legal full load. The Average Load is a function of the gross vehicle mass and of the number of tyres on the vehicle. Steyn (2001) analysed these relationships, and it could be concluded that the Average Load is dependent on the load of the vehicle, whereas the Load CoV depends on the vehicle speed as well as the profile of the road (road roughness).

Motor vehicles travel at high speed, and therefore experience a wide range of vibrations. These vibrations are transmitted to the passengers by visual, tactile or aural paths. According to Gillespie (1992), aural vibrations are typically categorised as ‘noise’, and tactile and visual vibrations are referred to as ‘ride’. Vehicle vibrations can be generated by various sources, Gillespie (1992) regarded these sources as on-board sources and road roughness. On-board sources include the tyre/wheel assemblies, the engine and driveline as it arise from rotating components. Road roughness includes everything from potholes to random deviations within the road surface. Therefore, roughness excites ride vibrations by acting as vertical displacement input to the wheels of a vehicle. Furthermore, according to Gillespie (1992), vertical accelerations measurement is the most common and meaningful measure of ride vibration.

In order to determine the vertical accelerations of a vehicle and the consequences of these accelerations the V-PI should be investigated. As a result, the road roughness and riding quality can be determined from the accelerations measured.

Vertical acceleration magnitudes depend on various factors, such as where the vertical acceleration was measured, the vehicle geometry, vehicle components (including suspension and tyres) and the vehicle occupants’ posture and characteristics. Studies have shown (Jarimopas et al., 2005; Cantisani and Loprencipe, 2010) that the type of road surface (and condition) as well as the speed of the travelling vehicle mostly influence the vertical accelerations of the vehicle. The specific vertical acceleration of the passengers is best measured by attaching an accelerometer to the head of the passenger (Rinehart and Mooney, 2012). Although vertical accelerations are not only caused by road roughness, the focus for this study was on vertical accelerations caused by the road surface.

2.3.1 Road Roughness and Riding quality

Road roughness is the unevenness of a pavement surface defined over an interval between two specified points (Sayers and Karamihas, 1998). A road transportation system can be negatively affected by a decrease in road roughness because (Cantisani and Loprencipe, 2010):

- The road roughness cause stress in the vehicle structure;
- It reduces the riding quality (thus the comfort experienced by the passengers, road users etc.);

- It increases dynamic loads, which, in turn, accelerate fatigue damage of the pavement structure;
- It increases user discomfort as well as user fatigue, which leads to accident risk exposure, and
- It increases VOCs (Steyn et al., 2011a).

Engineers use road roughness as the primary indicator of the condition of the road (riding quality). By determining the road roughness of a pavement, engineers can estimate what maintenance, if any, is required in order to restore the pavement to acceptable riding quality levels (Steyn et al., 2011a).

Riding quality affects VOCs directly, since the tyres and suspension system transfer the unevenness of the road surface as vertical accelerations to the vehicle. These vertical accelerations can lead to damage of vehicle components as well as an increase in fuel consumption. Further damage can be caused to the cargo transported, depending on the suspension and speed of the vehicle (Steyn et al., 2011a). The American Association of State Highway Officials (AASHO) road test indicated in 1960, that more or less 95 per cent of road service performance was because of deteriorating riding quality (Wang et al., 2010). The road roughness of a pavement was officially considered as an inspection and designing indicator in 2003 in the American Association of State Highway and Transportation Officials (AASHTO) design guide (AASHTO, 2003).

The International Roughness Index (IRI) is the most widely used statistic to indicate the riding quality of a pavement. It can be converted between various instruments, as it has time stability, which makes it possible to objectively represent the physical condition of the pavement surface and the dynamic response of the Quarter Car (QC) indicated in Figure 2-4 (Cantisani and Loprencipe, 2010).

The Quarter Car model is characterised by these five constants (Cantisani and Loprencipe, 2010):

- C_s: Suspension damping rate;
- M_s: Sprung mass;
- K_s: Suspension spring rate;
- K_t: tyre spring rate, and
- M_u: unsprung mass.

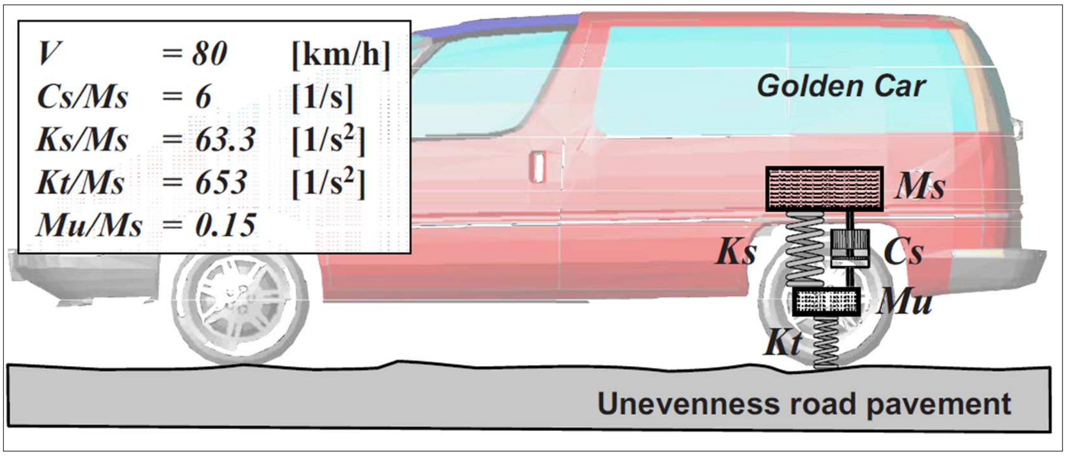

Figure 2-4: Quarter Car adopted for IRI calculation (Cantisani and Loprencipe, 2010)

The Quarter Car model is conventional as it measures in the vertical direction, and its dynamic characteristics cannot be correlated to an actual vehicle as they are settled by the standard (Cantisani and Loprencipe, 2010). The IRI is expressed in units of slope, such as meters per kilometre. It is important to note that, in order to calculate an IRI, the profile must be measured with either ASTM E1364 (static level method) or ASTM E950 (inertial reference for longitudinal profile). The calculation of the IRI can be done with the help of ASTM E1926-98, with a simplified algorithm. This algorithm (in time domain) solves the differential equation of the quarter-car system dynamics (focused on accelerations), riding on an uneven surface at 80 km/h as standard speed (Cantisani and Loprencipe, 2010).

The IRI Quarter Car model is based on World Bank research conducted in 1982. It is based on a motorcar with similar behaviour to most highway cars and developed to correlate responses of light passenger cars. However, according to Sayers and Karamihas (1998), light and heavy trucks showed good correlation with the model. Therefore, for the purposes of this study it was assumed to have little to no impact.

According to Sayers et al. (1986), IRI is not only measurable with profilometric methods, but the particular characteristic that defines the IRI can be measured with response type devices (Response-type Road Roughness Measurement Systems, RTRRMS). Indicated in Figure 2-5 is the IRI roughness scale on different types of roads from Sayers et al. (1986).

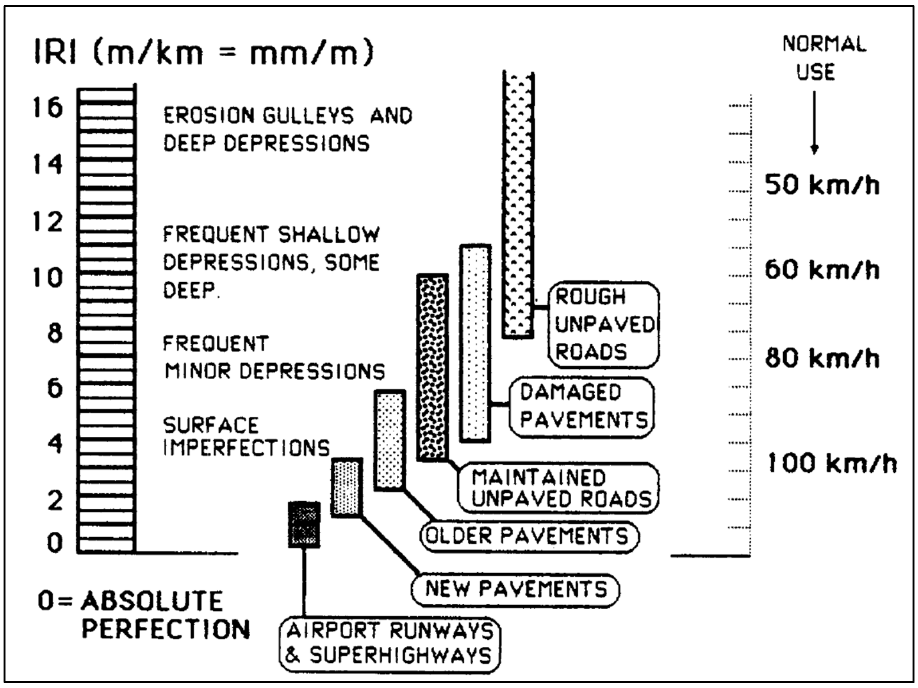

Figure 2-5: IRI Roughness Scale (Sayers et al., 1986)

2.3.2 Factors that affect vertical accelerations

The riding quality of a road surface influences the travel experience significantly. The uneven road surface translates the vibrations through the suspensions and tyres to the vehicle body and from there to the occupants, driver, and cargo. Various studies have been conducted about the effect that different road conditions have on responses and vertical accelerations in vehicles (Steyn, 2011).

The acceleration spectrum tend to have an amplitude that is relatively constant at low frequencies, but from 1 Hz, it rapidly increases up to a magnitude greater than 10 Hz. By analysing the effect of the road roughness as a vertical acceleration, the road roughness presents its largest inputs to the vehicle at high frequencies. This, in turn, has the potential to excite high frequency ride vibrations, depending on the dynamic properties of the vehicle (Gillespie, 1992).

According to the study conducted by Singh et al. (2006), the results indicated that the origin of the dynamic shock and vibration levels came from two sources:

- External sources: Irregular road surface, horizontal acceleration and deceleration, and driver control, and
- Internal sources from the vehicle itself: engine vibration, wheel balancing, and drive mechanisms.

Jarimopas et al. (2005) conducted a study to measure the vibration levels of truck transport and damage of tangerines during transit in Thailand. The study included measuring the accelerations with accelerometers of three different types of trucks on three different road surfaces at three different speeds. The truck transport data were analysed in order to determine the Power Density levels as a function of frequency. The data were analysed in three major power density frequency ranges, to do a comparison between the ride qualities of the different trucks as a function of speed and road quality (Jarimopas et al., 2005):

- 0.1 to 5 Hz. This range represents the response of the truck suspension;
- 5 to 20 Hz. This range represents the response of the axle type, and
- > 20 Hz. This range represents the response from the road roughness, structure, and drive train.

Jarimopas et al. (2005) concluded that the vibration level increased with vehicle speed, as well as that the unpaved road surface produced the highest vertical accelerations, followed by the concrete surface and the asphalt surface with the lowest vertical accelerations. Therefore, the highest damage occurred to the fruit travelled on the unpaved road, whereas the least damage occurred on the asphalt road.

Chonhenchob et al. (2009) conducted a similar study, and the conclusions from the study by observing the damage of fresh produce during transport in Thailand, were similar to Jarimopas et al. (2005). Vibration levels were measured on different trucks transporting four different types of fresh produce (cabbage, plums, pear, and lettuce) on the major distribution routes in Thailand. The damage levels on the produce were measured and the highway vibration levels from the Collecting Centres to the Packing House in Chaing Mai, from the Packing House to the Distribution Centre in Bangkok and lastly from the Distribution Centre to the Retailers were compared. The conclusions made by Jarimopas et al. (2005) supports the findings of the study conducted by Chonhenchob et al. (2009). The vibration levels for the highway transit were in the low frequency range, and highest level of damage to the produce, occurred in the smaller vehicles from the field to the packinghouse due to poor road conditions.

Steyn et al., (2011a), conducted a similar analysis on a database of a fleet of 577 trucks traveling different routes across South Africa over a period of 9 months. Table 2-1 indicates a summary of the database. The database included similar trucks for the various routes, with the actual routes, and the riding quality as the main factor of difference in the analysis. The summary indicates various road conditions, operating costs, Average Daily Truck Traffic (ADTT) of 2008, and damage data determined from the study. Section 3, 7, and 11 are provincial and municipal roads, the remaining sections are National roads. The IRI in Table 2-1 indicates that the national roads have a lower IRI than the provincial and municipal roads, and the repair and maintenance costs and ADTT are higher.

Table 2-1: Summary of road sections, VOCs and Road roughness (Steyn et al., 2011a).

Section	Location Origin and Destination and Route number	Road length (km)	ADTT	IRI (m/Km)	Average Repair and Maintenance Cost (ZAR/Km)	Percentage Vehicles with Broken Suspension/Trailer Components (%)
1	Gauteng to Durban (N3)	630	3000	2.7	0.9	5
2	Gauteng to Nelspruit (N4)	355	1400	2.9	0.82	0
3	Gauteng Network	varies		3.2	0.84	3
4	Gauteng to Witbank (N12)	140	2000	3.4	1.27	2
5	Gauteng to Rustenburg (N4)	140	500	3.3	1.04	4
6	Gauteng to Richards Bay (N17 and N2)	600	900	3.6	1.31	4
7	Johannesburg to Vereeniging (R82)	70	900	3.6	1.57	6
8	Gauteng to Cape Town (N12 and N1)	1400	2000	3.6	1.29	2
9	Gauteng to Botswana (N4)	280	500	3.9	1.35	10
10	Newcastle to Gauteng (N11 and N17)	290	700	4.2	2.09	59
11	Gauteng to construction sites	varies		4.3	2.013	5
Median		N/A	N/A	3.6	1.29	N/A
Standard deviation		N/A	N/A	0.48	0.45	N/A

Apart from the pavement roughness, the speed that a vehicle travels is also an important parameter that affects the riding quality. In Table 2-2 threshold values (Yu et al., 2006) are provided that were used in order to adapt the IRI threshold values of US highways (speed 120 km/h) to other roads with lower operational speeds. These values indicated that by reducing the speed a higher level of roughness could be tolerated. Gillespie (1992) indicated that the amplitude of the acceleration input increases with the square of the speed, and therefore, by measuring the road roughness as an acceleration, the effect of the travel speed can be clearly observed.

Table 2-2: IRI Threshold values at different speeds for riding quality (Yu et al., 2006).

Ride Quality	IRI Threshold for various speeds in km/h				
	120	100	80	70	60
Very Good	<0.95	<1.14	<1.43	<1.63	<1.9
Good	0.95-1.49	1.14-1.79	1.43-2.24	1.63-2.57	1.9-2.99
Fair	1.5-1.89	1.8-2.27	2.25-2.84	2.58-3.25	3.00-3.79
Mediocre	1.9-2.7	2.28-3.24	2.85-4.05	3.26-4.63	3.8-5.4
Poor	>2.7	>3.24	>4.05	>4.63	>5.4

Another factor that influence the vertical accelerations transposed to the driver, cargo or passengers is the type of suspension of the vehicle. Spring stiffness, damping and mass are the main factors taken into account with determining vehicle suspension response. The relative masses of the sprung-body (chassis, load tray and suspension elements), load, stiffness and damping, strongly affects the dynamic response of the vehicle-load combination. Therefore, a heavily loaded truck will react very different from a lightly loaded truck. Holt and Schoorl (1985).

In a study conducted by Singh et al. (2006), one of the objectives was to compare the vibration levels in air ride suspension to the leaf spring suspension trailers of truck shipments of glass product and packaging. The conclusions made by Singh et al. (2006) are similar to various studies made on the same topic. Singh et al. (2006) concluded that the air ride vibration levels are at least 50 per cent less than the leaf spring vibration levels. Pierce et al. (1992) made a similar conclusion that air ride suspension result in a smoother ride than a leaf-spring suspension, however, it comes at a higher cost and it should be maintained regularly.

The suspension characteristics are evaluated by analysing the bounce (vertical) natural frequency and the pitch and roll natural frequencies. The front and rear spring stiffness determines the (vertical) natural frequency of a vehicle in bounce (Edgar, 2013). The natural frequency in roll is determined by the spring stiffness on one side of the vehicle, including the spring effects of the anti-roll bars. The natural frequency in pitch is determined by the front and rear spring stiffness. Another factor that influence the natural frequency is the distribution of mass within the vehicle.

According to Gillespie (1992), for most vehicles, resonance in roll occurs at a lower frequency, than resonance in bounce, and therefore, bounce is the more dominant response. However, at high a high frequency where the roll and bounce inputs are similar in magnitude, the vehicle is less likely to roll. For example, consider a vehicle with a roll natural frequency of 1 Hz, travelling at 100 km/h (27.78 m/s). Thus, roll motions will be generated at the 27.78 m wavelength (0.011 cycle/m) by the roll excitation in the road. However, according to Gillespie (1992), the vehicle passengers will experience discomfort because of the bounce vibrations, rather than the roll as the roll amplitude at this wavenumber is only a fraction of the vertical input.

At low speed, such as 10 km/h (2.8 m/s), a roll resonant frequency of 1 Hz would be excited by low wavenumbers at which the roll and vertical inputs are basically equal in magnitude. Therefore, the roll and bounce motions will be equal at a low speed. A common explanation is during an off-road expedition, with four by four vehicles, where the exaggerated ride accelerations are composed of bounce as well as roll motions (Gillespie, 1992).

The impact of different suspension types, and load capacity were not taken into account into this study, however, it was noted that it influence the measurements made by the RTRRMS devices.

2.4 Measurement devices and methods

The road surface generates accelerations, which are transmitted to the driver, cargo, or passengers through the truck suspension system and chassis (Schoorl and Holt, 1982). Various methods are available to determine the condition of the road surface and the impact the profile has on the vehicle in terms of accelerations generated. The methods discussed in this section under field conditions mainly focus on determining the roughness profile of the road surface. The laboratory tests, however, determine the magnitudes of vertical accelerations the vehicle/cargo/passengers can withstand before any damage occur or before it become too uncomfortable. The following discuss rod and level, dipstick and inertial profiling as examples of field-testing (accelerometers are used both for field-testing and laboratory testing).

2.4.1 Profiling (Field testing)

There are various approaches to determine the degree of discomfort to the road user (COTO, 2007). The most direct method is to measure the profile of the road surface. According to Sayers and Karamihas (1998), the definition of a profile is a two-dimensional view taken along an imaginary line, parallel to the centreline of the road surface. Figure 2-6 shows a graphical presentation of a road profile. A profile taken perpendicular to the centreline (a cross section), measures the crown of the road design, superelevation, rutting and other defects. Longitudinal profiling, however, shows the texture, roughness, and design grade, therefore, for this project longitudinal profiling will be used. Many profiles along the road each in a different line can be measured, the width of the line measured is not standard. A profile works by combining these three important factors (Sayers and Karamihas, 1998):

- Longitudinal distance;
- Reference elevation, and
- Height relative to the reference.

There are various devices available to measuring a profile, the following discuss three devices, the rod and level, dipstick and the inertial profiler (which was used for the measurements of this study).

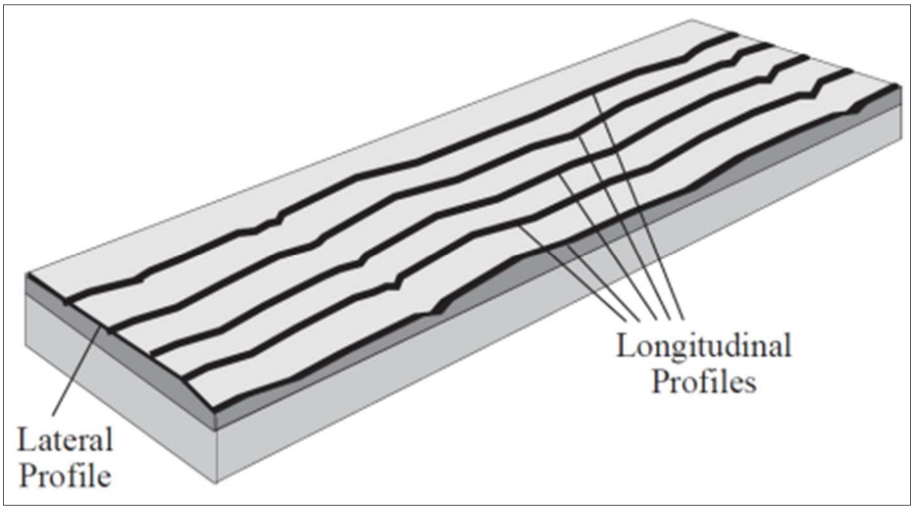

Figure 2-6: Profile of road (Sayers and Karamihas, 1998).

a) Rod and level

The rod and level (Figure 2-7) method is classified as a static method, as the instrument stays static during measurements. Although the rod and level method is simple and familiar to most, the requirements to determine roughness from the measurements differs than for laying out a road. Measurements of the elevation must be in close intervals of 0.3 m or less and the height measurements must be accurate to 0.5 mm or less. For normal surveying, these requirements are not necessary and the absolute height of the profile is not needed to determine roughness (Sayers and Karamihas, 1998). Therefore, it can be concluded that this is not a device that will give accurate road roughness values.

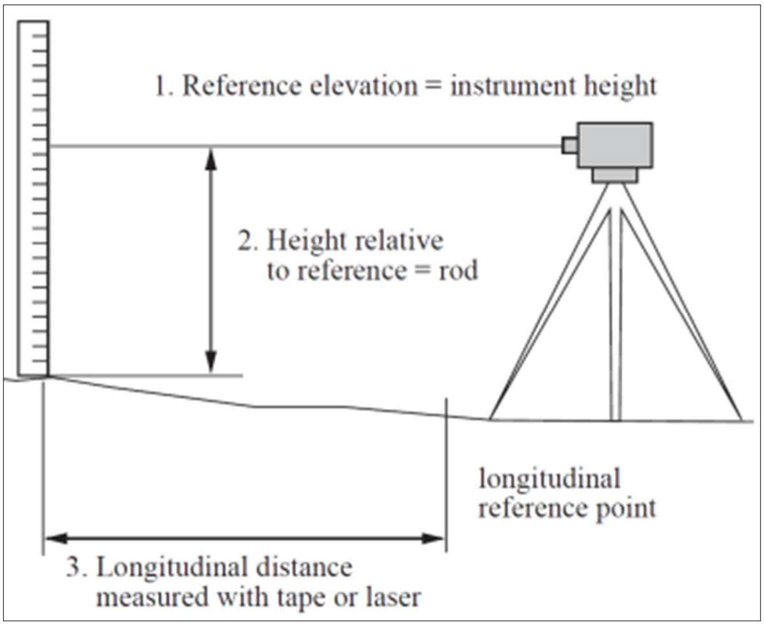

Figure 2-7: Rod and Level (Sayers and Karamihas, 1998).

b) Dipstick

The Dipstick (Figure 2-8) is faster than the rod and level for measuring road profiles to determine road roughness. The data and the arithmetic required to produce a profile are recorded automatically (Sayers and Karamihas 1998).

The device is used by holding it and walking along the line that is being profiled. The difference in height is measured between two supports (spaced 304 mm) with a precision inclinometer. A computer monitors the sensor continuously, and it automatically records the change in elevation when the instrument has stabilised. Therefore, the reference height is the value recorded for the previous point, and by multiplying the known spaces with the number of measures, the longitudinal distance can be determined. The exact instructions of how to operate with this device are provided in the manual (Sayers and Karamihas, 1998).

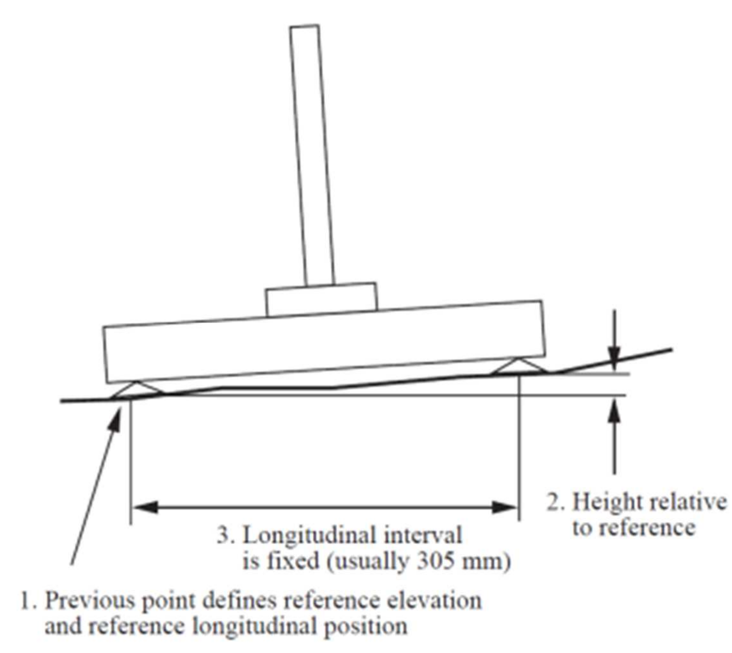

Figure 2-8: Dipstick (Sayers and Karamihas, 1998).

c) Inertial Profiler

The inertial profiler makes it possible to monitor large road networks at high speed (Sayers and Karamihas, 1998). The method use an accelerometer established inertial reference on a profile-measuring vehicle which records and measures a profile of vehicular travelled surfaces. The change in elevation of the surface is detected by measuring the distance between the travelled surface and an inertial plane of reference along with the acceleration of the inertial platform (see Figure 2-9) (ASTM, 1999).

The accelerometer measures the acceleration. The vertical acceleration measurements are converted to an inertial reference with data processing algorithms. A non-contacting sensor, such as a laser transducer, measures the height of the ground relative to the reference (which is the distance between the ground directly under the accelerometer, and the accelerometer in the vehicle). The vehicle speedometer picks up the longitudinal distance of the instruments (Sayers and Karamihas, 1998).

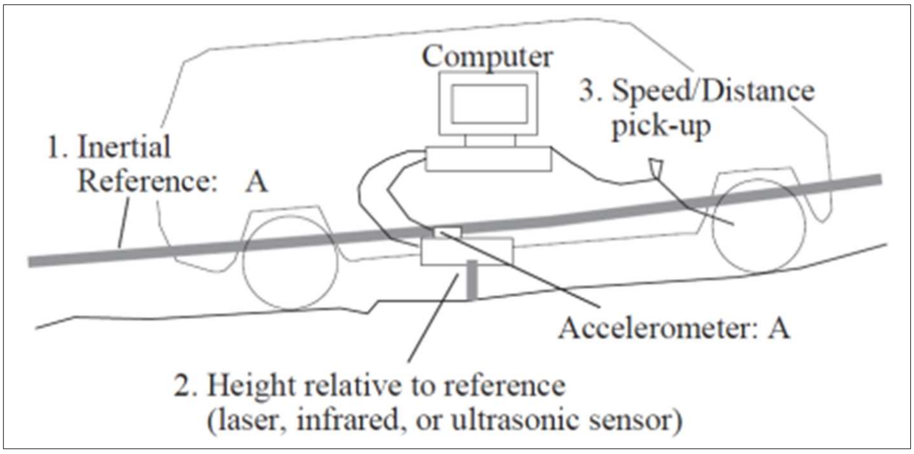

Figure 2-9: Inertial Profiler (Sayers and Karamihas, 1998)

An experienced driver is required to operate this device as it is difficult to obtain the correct speed and to locate the accelerometer and sensor in the proper imaginary line. The measurements obtained from inertial profilers are more accurate than obtained statically. Reason being the inertial profiler is automated and human error is reduced drastically (Sayers and Karamihas, 1998).

Figure 2-10: Dynatest Road Surface Profiler (SRT, 2012).

The model indicated in Figure 2-10 is a Dynatest Road Surface Profiler 5051 Mark 11 (RSP), available from Specialised Road Technologies (SRT). It is a Volkswagen Transporter fitted with a transducer beam (Rut Bar) carrying two accelerometers, 17 lasers, an Inertial Motion Sensor (IMS) and a processing unit. This Road Surface Profiler measures the longitudinal profile (IRI, transverse profile, ride number, rut depth, geometrics, and macro texture) in real-time continuous freeway speed. Digital photographs are taken every 10 m, to both the front and rear. These measurements can be easily integrated with Geographic Integrated systems (GIS), and the measurements can be referenced to Differential Geographic Positioning System (DGPS) and linear chainage.

2.4.2 Accelerometers

The accelerometer can be used for various applications such as to monitor human motor activity, exercise intensity, and sleeping disorders (actigraphy). Other applications of the model includes the monitoring of continuous time stamped shock and motion of critical freight, automotive performance, and for educational purposes.

In a study done by Rinehart and Mooney (2012) the accelerometer was placed on a passenger's head perpendicular to the travel direction of the vehicle. The data were used to determine lateral passenger vibration due to the vehicle travelling on longitudinally grooved pavements. The reason for that specific position of the accelerometer was that the human body has a tendency to attenuate high frequencies and amplify low frequencies. Ostrem and Godshall (1979) described that for determining shock conditions for a load, acceleration measurements are without a doubt very useful, especially if the load is considered as a single mass transported by the vehicle.

2.4.3 Laboratory-based simulation

Wang et al. (2010) conducted a simulation test, which used the designed test scene and Driving Simulation Module (DSM) (Figure 2-11). Accelerometers were fixed on the passenger seat and the passenger wore an Electrocardiograph (ECG) belt. As the DSM was driven at different speeds, the corresponding ECG and acceleration data were recorded. A field study was also conducted on a road with a multi-function laser road condition detection vehicle (Figure 2-11). Accelerometers were fixed on the passenger seat and the passenger wore an ECG belt, as with the laboratory test. The study showed that the conclusions of the field test results were consistent when compared with the simulation test results, both concluded that the larger the IRI, the larger the vibration acceleration caused by IRI, at a constant speed (Wang et al., 2010).

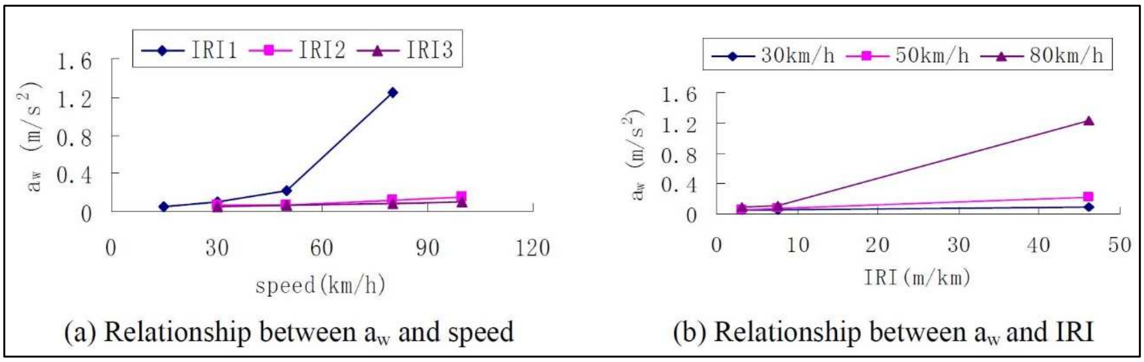

Figure 2-11: Relationship between a_w, speed and IRI (Wang et al., 2010)

O' Brien and Guillou (1969) used a specially designed vibrating table to simulate the accelerations generated in bins and boxes of fruit as cargo on a truck. It concluded that by measuring the acceleration over 10 minutes on the vibrating table, the intensity and amount of bruising of cling peaches corresponded to a 100 mile haul of the cling peaches on a transit truck.

However, Schoorl and Holt (1982) drew a different conclusion and indicated that laboratory simulations of vehicle response are generally applicable to either the forces on the road or vehicle handling characteristics, and therefore not suitable for the prediction of damage to loads of fruit and vegetables. The main limitation is that the load is considered as a single mass, not interacting with the vehicle body, but moving with it. However, for most multi-layered loads, there is a strong interaction with vehicle body movement (Schoorl and Holt, 1982).

Vursavuş and Özgüven (2004) made a similar observation in the study to determine the effects of vibration parameters and packaging methods on Golden Delicious apples. Vertical accelerations were measured on a truck bed and vibration simulator table in order to determine the vertical acceleration frequency magnitudes. In conclusion, the study indicated that the maximum frequencies under road conditions generated by a truck bed are 5-10 Hz and 10-15 Hz. From packaging transmissibility studies, the maximum frequency is 9 Hz, and the truck bed results correspond with that. The vibrator table, however, indicated that for apples sensitive to a frequency of 8.2 Hz, an acceleration of 0.63 g would cause more damage.

2.5 Data analysis

Recording the data is half of the work, the other half is to determine the IRI levels and to evaluate the data to ensure adequate comparison (Sayers and Karamihas, 1998). The deliverables from a profiling company include the IRI, the texture of the profile measured and the DGPS coordinates. The data stored in the accelerometer are accelerations in the X, Y, and

Z direction and in order to interpret this, an analysis is required. Gulf Data Concepts (2012) recommend the data analysis with a commercial or open source mathematical program such as Microsoft Excel.

A typical road profile does not represent a pure sinusoid it, however, involves a spectrum of sinusoidal wavelengths (Sayers and Karamihas, 1998). PSD is defined as "a statistical representation of the importance of various wave numbers". The purpose of the PSD Function is to indicate how variance is distributed over wave number (Sayers and Karamihas, 1998).

Sayers and Karamihas (1998) demonstrate the relationship between profile elevation and vertical acceleration in detail. From an example of three sinusoids the amplitude of the derivative of a sinusoid is indicated in Equation 2-1, A is the Amplitude and λ is the wavelength.

$$Slope\ amplitude = \frac{2\pi A}{\lambda}$$

Equation 2-1: Slope amplitude

In order to get a spatial acceleration sinusoid, the derivative can be repeated a second time. The frequency of the sinusoid is affected by the traveling speed of the vehicle, (Equation 2-2), frequency, f (cycle/sec), speed, V (distance/time), wavelength, λ (length) and wave number, ν (1/length).

$$f = \frac{V}{\lambda} = V\nu$$

Equation 2-2: Frequency

Chonhenchob et al. (2009) analysed acceleration amplitudes recorded during transportation of fresh produce in Thailand as a function of frequency to determine the Power Density (PD) (Equation 2-3). Jarimopas et al. (2005) also used PD to analyse the data recorded to determine damage and vibration levels to packaged tangerines during transit. The data were measured in three major ranges of frequencies, indicated in section 2.3.2. PD represents the Power Density, RMS G_i is the root mean square acceleration (measured in g) within a bandwidth (BW) of frequencies, n is the number of instants sampled. In order to make a relevant conclusion, Chonhenchob et al. (2009) plotted the PSD against the frequency of the bandwidth and compared the results with composite vibration spectrums for vertical vibration recommended by the American Society of Testing and Materials International (ASTM, 1999).

$$PD = \frac{1}{BW}\sum_{i=1}^{n}\frac{(RMS\ G_i^2)}{n}$$

Equation 2-3: Average Power Density

In Figure 2-12 an example from Sayers and Karamihas (1998) indicate the road as an elevation PSD (left), by differentiating once the velocity PSD (middle), and by differentiating twice, the acceleration PSD (right). It can be noted that acceleration input is the largest at high frequencies, as it correspond to short wavelengths in the road.

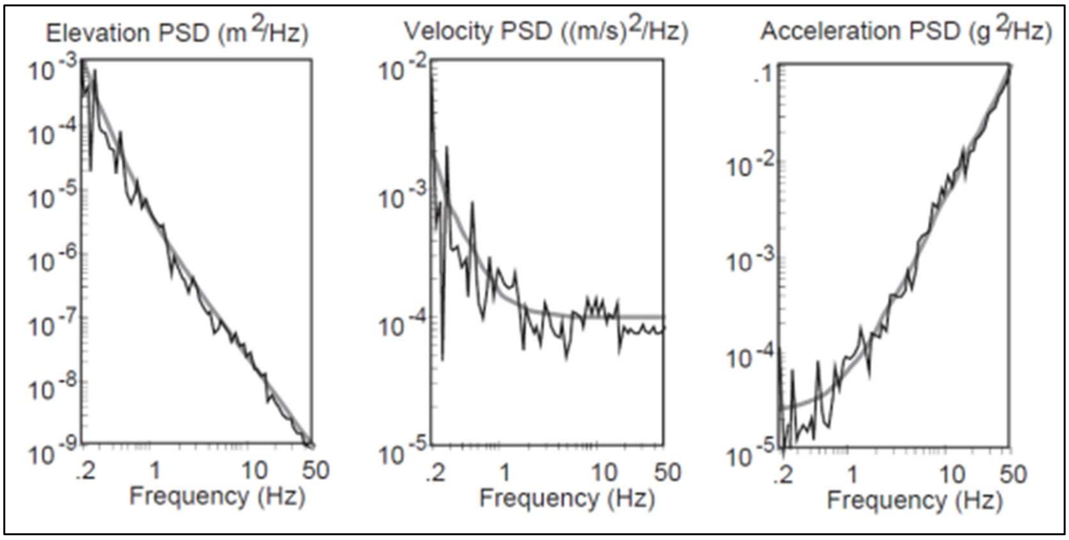

Figure 2-12: Elevation, velocity, and acceleration PSD examples, Sayers and Karamihas (1998)

Cantisani and Loprencipe (2010) calculated human body vertical vibration acceleration from Part 1 of ISO 2631 (1997). The frequency-weighted Root Mean Square (RMS) accelerations are required by standard in order to calculate a synthetic index (a_{wz}, vertical RMS acceleration). The calculation start with vertical accelerations in the time domain, certain operations are required as follows (Cantisani and Loprencipe, 2010) (Equation 2-4):

- RMS acceleration values on the user's body (a_{iz}^{RMS}) have to be with the PSD, which corresponds to each i^th octave thirds band;
- the a_{iz}^{RMS} values have to be multiplied by the corresponding frequency bands weighing factor values W_k, and
- The *vertical RMS acceleration*, a_{wz}, can be calculated by extracting the square root of the sum of squares ($W_{k,i}$, a_{iz}^{RMS})^2 computed in the point before:

$$a_{wz} = \sqrt{\sum_{i=1}^{23} \left(W_{k,i} \cdot a_{iz}^{RMS}\right)^2}$$

Equation 2-4: Vertical RMS acceleration (Cantisani and Loprencipe, 2010)

Cantisani and Loprencipe (2010) used a representative group of 124 the left and right hand side wheel path road profiles, carefully chosen from the road profiles collected in the Strategic Highway Research Program (SHRP). Cantisani and Loprencipe (2010) analysed the relationship between ride quality and surface geometry. IRI values were determined by modifying the surveys and ISO 2631 was used to determine the a_{wz} index, as stated above. The correlation between a_{wz} and IRI is indicated in Figure 2-13, and it shows that there is a wide variation range of a_{wz} for a fixed IRI value, especially for an IRI larger than one, where pavements are severely damaged or very rough. For example, in Figure 2-13 three pavements were isolated, each with about the same IRI value of three, as indicated, their whole body accelerations, on the other hand, differs significantly ranging from 0.47 to 0.94 m/s^2.

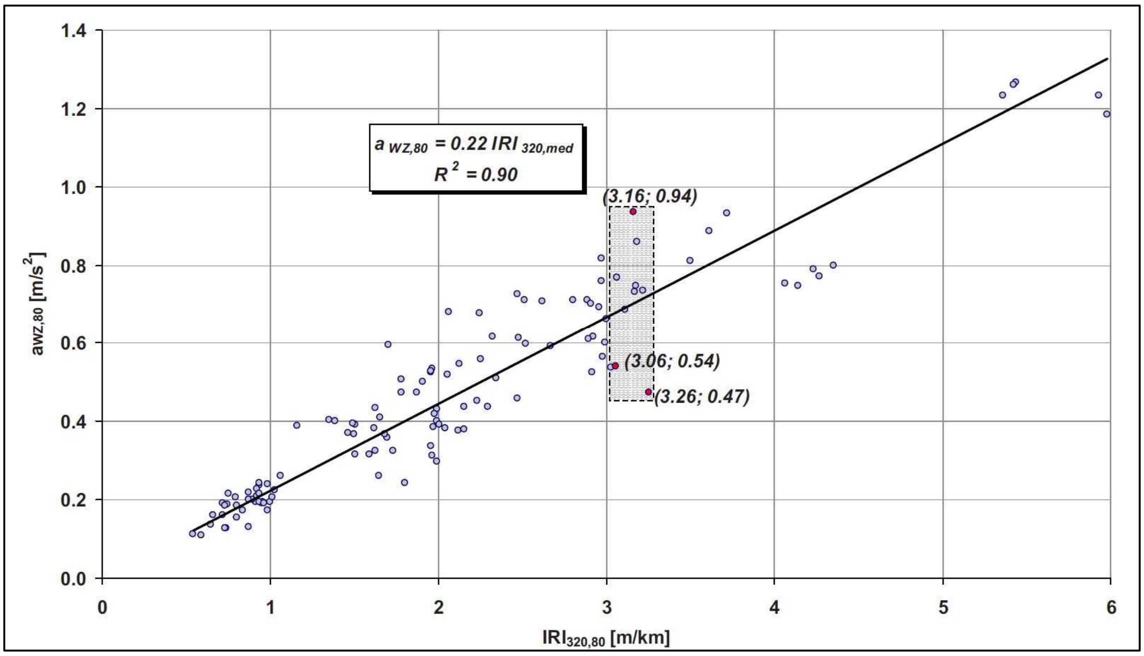

Figure 2-13: Correlation between a_{wz} and IRI, at 80 km/h (Cantisani and Loprencipe, 2010)

The conclusions from the study conducted by Wang et al. (2010), in Figure 2-11, indicate the relationship between a_w and the speed as the driving simulation model was driven in IRI1, IRI2, and IRI3. The data indicate that as the road roughness increase, the speed affects a_w more. Figure 2-11(b) indicates the relationship between a_w and IRI at the same speed, and as the speed increase, the effect of the roughness on a_w increase.

Wang et al. (2010) also conducted a correlation between IRI and a_w at different speeds (50 km/h and 70 km/h) from the field-tests (Figure 2-14). The solid line represents the regression line between IRI and a_w at a speed of 70 km/h and the dotted line represents that of the speed at 50 km/h. Therefore, for an IRI of about 1.5 m/km, a_w varies significantly for each speed, which was similar to the observation made by Cantisani and Loprencipe (2010).

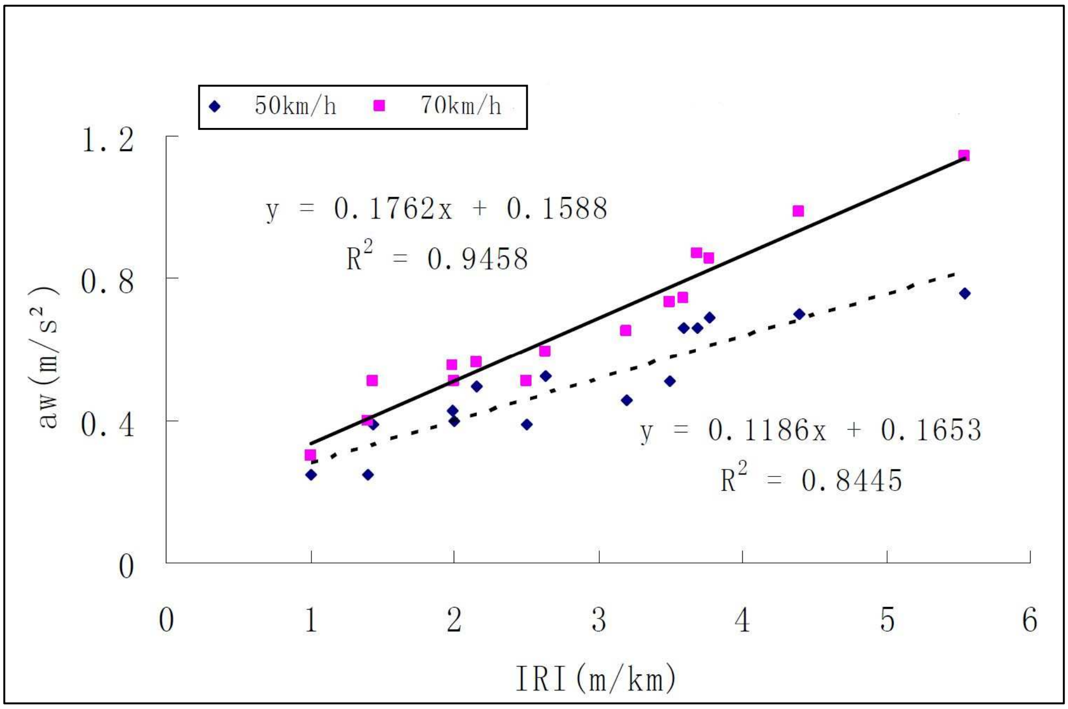

Figure 2-14: Correlation between a_w, speed and IRI (Wang et al., 2010)

According to Cantisani and Loprencipe (2010), it can be concluded that IRI cannot completely indicate the real conditions of pavements concerning user comfort in some situations. Therefore, these conditions and their effects on the users, in terms of vertical accelerations and consequent decrease in comfort, can also be presented by other indexes. In addition to this, Wei et al. (2004) noted that the summary indices (IRI, a_{wz} and Slope Variance) give an average condition for a relatively long section of pavement and, therefore, do not retain the actual contents of pavement roughness, as an average cannot tell where or what exactly the problems are.

However, a high-speed profilometer records sampled road profiles with accuracy. Another dimension to the description of roughness is provided by the roughness profile which indicates with maximum detail how the roughness is distributed over the length of the road. Detailed roughness content information may be necessary especially for diagnosis of surface roughness as a defect, maintenance operations and pavement performance and deterioration trends.

Wei et al. (2004) conducted a study and determined a wavelet-transform analysis procedure to add to information provided for commonly used road indices. The information required for pavement maintenance operations and network pavement management can be derived from the proposed wavelet analysis. This analysis can be very useful, especially for highway engineers, as a supplement to roughness indices (such as IRI), in order to provide more information and insight into the performance and behaviour of highway pavements.

According to Wei et al. (2004) the PSD calculated in the ISO standards, tend to eliminate all the spatial information from the data. Therefore, it is very difficult to locate the exact position of local defects from the PSD distribution.

Wavelet Analysis Theory or Wavelet Transform Theory was developed to overcome the shortcomings of the Fourier Transform (Wei et al., 2004). It is used to split a signal into different frequency components and then each component is presented with a resolution matched to its scale, and in return, resulting in a collection of frequency representations of the signal in various resolutions and time. Wavelets analysis has the ability to perform a local analysis (analyse a localised area of larger signal), which is of major advantage. Therefore, wavelet analysis reveal aspects of data that other signal analysis techniques miss, such as breakdown points, trends, self-similarity and discontinuities in higher derivatives (Wei et al., 2004).

Road roughness profiles can be distributed into different frequency sub-bands by applying the Discrete Wavelet Transform (DWT). Both DWT and Continuous Wavelet Transform (CWT) can detect the presence of local irregularities in the roughness profile. This wavelet analysis procedure can be effectively applied to detect surface distresses such as depressions, potholes, ravelling, settlement or surface heaving in asphalt pavement surface, including the detection of joint faulting in cement concrete pavement surfaces. Lastly, the roughness deterioration of pavement sections can be monitored with both CWT and wavelet based PSD. Wavelet based PSD, however, is smoother compared to the Fourier based PSD which makes it easier and more accurate to use in characterising road roughness features (Wei et al., 2004). The Wavelet Analysis Theory was deemed outside the scope of this study

Another approach of establishing speed related roughness is by using the calibrated full car model developed by Cantisani and Loprencipe (2010). The full car model was developed to simulate the real dynamic phenomena better and to determine other vibratory actions on a vehicle (such as pitching and rolling). In order to do that the complexity of the dynamic system needs to be increased, therefore, the degrees of freedom was increased from the quarter car model (two degrees of freedom) to eight degrees of freedom (full car model). This gives the possibility to perform a number of analytical evaluations with regards to riding quality and user comfort.

2.6 Transportation

2.6.1 Public transport in Mpumalanga

The Department of Transport and the Government of South Africa is focussed on the development of an effective public transportation system in South Africa. The rapid increase of industrial, public, and private road users has the road infrastructure under pressure due to the competition for road space (DOT, 2003).

According to the Key Results of the National Household Travel Survey (DOT, 2003) there are 10 million commuters in South Africa, 3.9 million uses the public transport system, 63 per cent is taxi commuters, 22 per cent bus commuters and the remaining 15 per cent travel by train. The access to public transport services are as such that train services are the least accessible (76 per cent indicated that they have no access to train services), 38 per cent indicated that they do not have access to bus services or stops and 9 per cent indicated that they have no access to taxi service.

The highest levels of car use were indicated in the most urbanised provinces, Gauteng and the Western Cape. In Mpumalanga, only 23.5 per cent of the households have car access. The survey also indicated that Mpumalanga is one of the provinces with the highest use of bus services by household members with 8 per cent.

The Department of Transport pays subsidies to rail, bus, and mini-bus commuter services in order to assist with the rapid increasing costs of public transport. The bus services in each of the major urban centres are the responsibility of municipal sub-divisions or private companies (with government subsidies). In Mpumalanga the operating bus service is Buscor, Figure 2-15 indicates a 144-seater articulated bus used by Buscor (Buscor, 2012).

Figure 2-15: 114-Seater Articulated Bus (Buscor, 2012).

2.6.2 Accelerations generated at different positions

According to Steyn and Bean (2010), the position of the load / passengers in the truck affects the vertical accelerations transposed to different areas in the truck. Investigations done locally and internationally indicated that the highest levels of vibration and damage to cargo occurs at the uppermost location to the rear of the trailer.

In a study conducted by Steyn (2012), it was concluded that the highest vertical accelerations were measured at the rear of the truck, consistent with the findings made by Chonhenchob et al. (2009) and Jarimopas et al. (2005), which stated that the vertical accelerations are even higher at the rear of the trailer.

2.6.3 Riding perception

The comfortability of a ride is a subjective perception and depends on a few factors other than the road surface. According to Gillespie (1992), the factors most associated with ride are the vibrations that transmit through the seat, hands and feet to the passengers' body. However, it is somewhat difficult to evaluate the influence of noise (acoustic vibrations) in the measurement of riding quality, since noise levels tend to be high, correlated with other vibrations in the vehicle. To name a few other factors that could influence the perception of ride could be the seat design, ventilation, interior space, and temperature. The vibrations generated by the road surface is possible to measure objectively, however the factors indicated above, such as seat comfort, are dependent on the perception of the user and a subjective measurement (Gillespie, 1992).

The judgement of ride comfortability in a vehicle is an area of controversy, and studies on this topic dates back from the 1920s (Gillespie, 1992). The International Organisation for Standardisation (1997), Gillespie (1992), Sayers and Karamihas (1998), and Cantisani and Loprencipe (2010) indicated research and standards on this topic.

According to Sayers and Karamihas (1998) acceleration on the seat of vehicles are measured by automotive engineers to determine suspension performance and the relationship between front and rear suspension damping and stiffness. Figure 2-16 indicates the sensitivity to vertical and horizontal accelerations obtained from research of the human body in a sitting position.

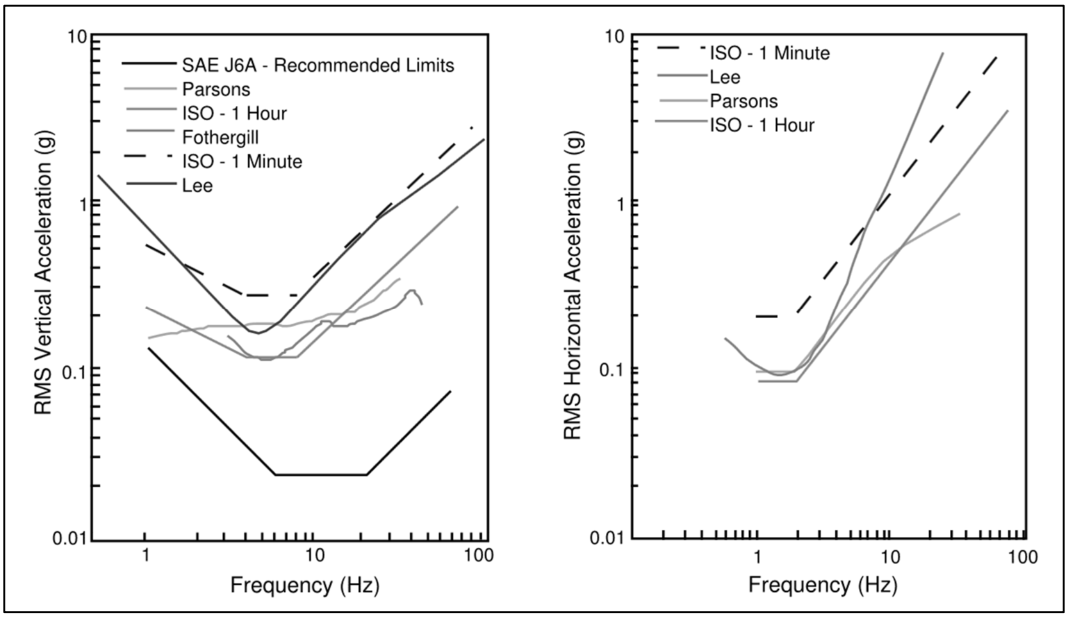

Figure 2-16: Sensitivity to vertical and horizontal vibration (Sayers and Karamihas, 1998)

Sayers and Karamihas (1998) indicated that the human body could tolerate vertical accelerations up to a level of about 5 Hz. Therefore, vehicles are designed to minimise the accelerations on the road user by placing the pitch, and body bounce frequencies at 1 to 2 Hz and a resonance for wheel hop at 10 to 15 Hz. These findings are consistent with Gillespie (1992) which indicated that the minimum tolerance to vertical vibration for a passenger is in the frequency range of 4 to 8 Hz.

The tolerance for horizontal accelerations are in the order of 1 Hz, the effect of these accelerations are mostly observed on the occupants in high vehicles such as buses, trucks, utility vans etc. (Sayers and Karamihas, 1998).

The International Organization for Standardization (ISO) indicates in ISO 2361 threshold values related to a_{wz} proposed for public transport (Table 2-3). However, the validity of these limits are still to be demonstrated, especially the application to human response or resistance to vertical accelerations, and thus it is difficult to compare and learn from it (Cantisani and Loprencipe, 2010; Wang et al., 2010).

Table 2-3: Comfort Levels related to a_{wz} Threshold values (ISO, 1997)

a_{wz} values (m^2/s)	Comfort level
<0.315	Not uncomfortable
0.315-0.63	a little uncomfortable
0.5-1.0	Fairly uncomfortable
0.8-1.6	Uncomfortable
1.25-2.5	Very uncomfortable
>2.0	Extremely uncomfortable

Cantisani and Loprencipe (2010) developed a different approach to determine speed-related roughness thresholds with the calibrated full car model. Therefore, for each representative right- and left hand side profile, the whole-body vibration was quantified by determining the values of a_{wz}. Correlations between IRI and a_{wz} were determined from the same sample of 1124 couples of vertical profiles indicated previously. The results are in Figure 2-17, linear regressions were calculated separately for seven different speeds (30 to 90 km/h), and the threshold values of a_{wz} are presented according to the ISO 2631 standard. Figure 2-17 also indicates a good correspondence between threshold values of a_{wz} indicated in Table 2-2, Section 2.3.2.

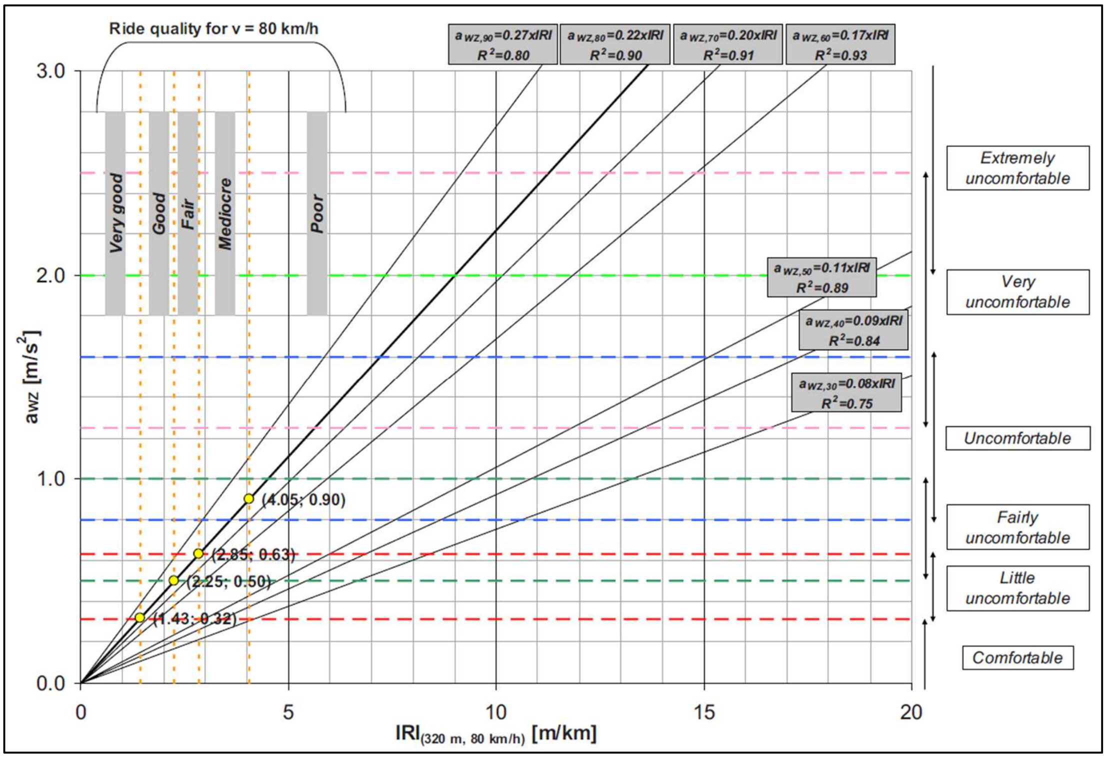

Figure 2-17: IRI versus a_{wz} correlations (Cantisani and Loprencipe, 2010)

A relationship between levels of comfort (proposed by ISO 2631) and ride quality judgements can be determined, (Table 2-4). Figure 2-18 is a proposal by Cantisani and Loprencipe (2010) for speed-related road roughness thresholds derived from the standardised a_{wz} limits. This graph makes it possible to establish IRI thresholds, relative to user comfort, which can be used when the operational conditions (especially the speed) differs. In Table 2-5, the results are compared of the evaluations conducted, highlighted previously in Figure 2-13.

Table 2-4: Proposed IRI and a_{wz} thresholds compared (Cantisani and Loprencipe, 2010)

Ride Quality based on IRI		Very Good m/s²	Good/Fair m/s²	Mediocre m/s²	Poor m/s²
IRI thresholds (80km/h) Yu et al. (2006)		<1.43	1.43-2.84	2.85-4.05	>4.05
IRI thresholds (linear correlations with IRI/a_{wz} full car model)	90 km/h	<1.15	1.15-2.31	2.31-3.30	>3.30
	80 km/h	<1.42	1.42-2.84	2.84-4.06	>4.06
	70 km/h	<1.6	1.60-3.20	3.20-4.58	>4.58
	60 km/h	<1.87	1.87-3.73	3.73-5.33	>5.33
	50 km/h	<2.98	2.98-5.95	5.95-8.51	>8.51
	40km/h	<3.41	3.41-6.83	6.83-9.75	>9.75
	30 km/h	<4.17	4.17-8.34	8.34-11.92	>11.92
Proposed a_{wz} thresholds ISO 2631		<0.315	0.315-0.63	0.63-0.90	<0.90
		comfortable	Little comfortable	fairly uncomfortable	Uncomfortable

Table 2-5: Roughness evaluation of three pavements (Cantisani and Loprencipe, 2010)

Pavement	IRI m/km	Ride Quality 120 km/h	a_{wz},80 m/s²	ISO 2631 Comfort level 80 km/h	a_{wz},50 m/s²	ISO 2631 Comfort level 50 km/h
1	3.06	Poor	0.54	Little/fairly uncomfortable	0.22	Comfortable
2	3.16	Poor	0.94	Uncomfortable	0.34	Little uncomfortable
3	3.26	Poor	0.47	Little uncomfortable	0.28	Comfortable

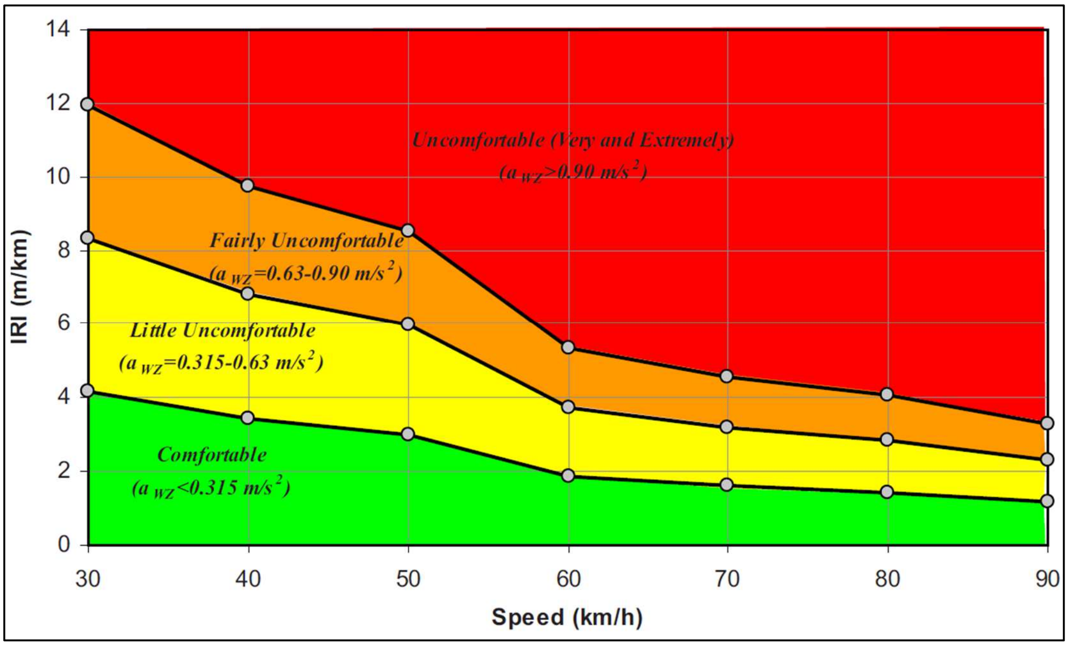

Figure 2-18: Proposal for new speed-related IRI thresholds (Cantisani and Loprencipe, 2010)

2.7 Logistics costs

A number of factors determine the efficient operations of a country’s economy such as an efficient economical system, efficient logistics system, and an efficient transport system. Recently, the focus on logistics cost (goods transportation) in a country has become more visible, as these costs have a direct effect on the broader economy. An increase in goods transportation costs lead to an increase of end-product cost to the consumer and that, in turn, lead to a decrease in the global competitiveness of a country as products become more and more expensive. Transport costs, storage and port costs, inventory-carrying costs and management costs, administration costs and profit are typically incorporated into the costs of logistics. By controlling and managing these costs effectively, the costs of logistics in a country stays in balance with the cost of general goods (Steyn et al., 2011a). Various studies have proven that deteriorating road quality result in significant increases in repair costs and vehicle maintenance costs, and fuel and tyre consumption, which in turn, leads to an increase in company logistic costs.

Indicated in Figure 2-19 is the ‘circle-of-interaction vehicle/roadway/driver’ developed by Von Becker (1992). In Figure 2-20, Steyn et al. (2011) illustrates the circle of interaction with a similar diagram, which indicates some of the potential effects that a decrease in road quality can have on logistics costs. The uneven pavement surface result in an increase in vertical accelerations and that may lead to more damage to the transported cargo and increased vehicle damage. In order to reduce damage to cargo the packaging and vehicle design can be improved, but this solution is not economically feasible as the packaging and design costs will multiply only to reduce the damage caused by poor road conditions (Steyn et al., 2011a). The increased vertical accelerations lead to an increase in environmental and road damage and increased fuel consumption (Steyn et al., 2010). This higher roughness also causes frequent failures of trailer and truck components. Therefore, by improving the road network performance, not only reduces VOCs, it also reduces the contribution of 18 per cent of total CO_2 emissions and 14 per cent of Green House Gasses (Steyn et al., 2011b).

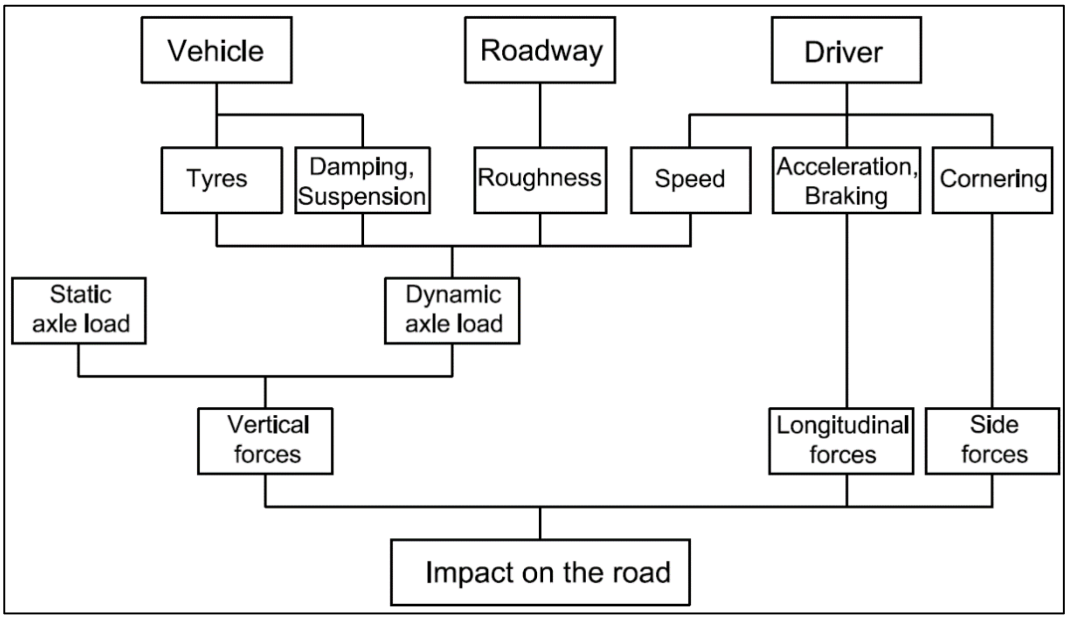

Figure 2-19: Circle-of-interaction vehicle/roadway/driver (Von Becker 1992).

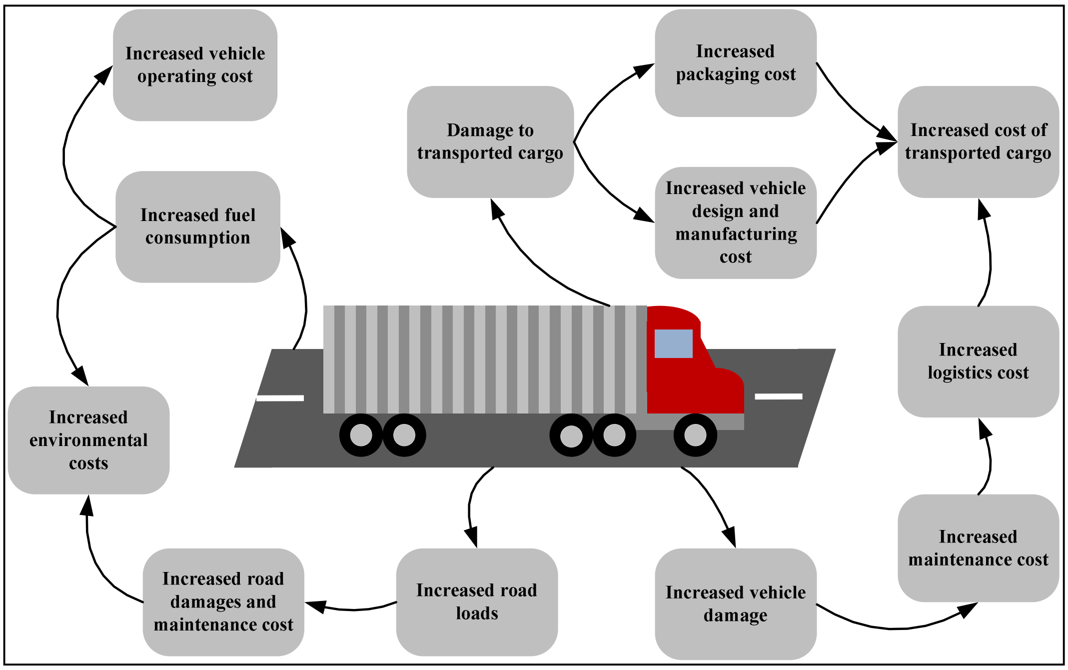

Figure 2-20: Conceptual indication of the effect of riding quality on logistic costs (Steyn, 2011a).

Three main groups represent road transport costs, these are road maintenance cost, road construction cost and, as the biggest proportion, road user cost. Steyn et al. (2011a) conducted a study based on data from a logistics company in Southern Africa. The main purpose of this study was to investigate the effect of road roughness on the three main groups of road transport costs, specifically in South Africa. The data were analysed, and indicated in Table 2-1 as the summary of road conditions, operating costs, damage data, and traffic volumes for the study. Steyn et al. (2011a) concluded three major outputs from the study, there is a relationship between road riding quality and truck maintenance and repair costs, a relationship between road riding quality and vehicle operating costs and a relationship between vehicle operating cost and road maintenance costs.

The data indicated in Table 2-1 show that the total truck and repair maintenance costs consists mainly of the breakdown of trailer and suspension components costs. According to Steyn et al. (2011a) the reason is that, vibration experienced by the tucks traveling on uneven road surfaces cause the problems. The damage is mostly not just on the vehicle or the trailer but the unnecessary vehicle vertical accelerations are transferred to the cargo, which, in turn leads to cargo damage (Steyn et al. 2011a). From the perspective of pavement engineering, this problem can be addressed by improving the riding quality as the breakdowns of trailer and suspension components are dominant. Table 2-1 also indicated that there is a direct relationship between increased truck maintenance and repair costs and increased road roughness. Steyn et al. (2011a) analysed data from a U.S. study and made the same conclusion that truck maintenance and repair costs and road roughness are directly related.

According to Steyn et al. (2011a), the data were analysed in order to determine the relationship between road riding quality and VOCs, with information on oil, tyre and fuel cost. The result indicated an increasing trend. Steyn et al. (2011a) indicated that a decrease in road riding quality causes a direct increase in VOCs, determined by the first part analysis of the database of truck costs (Table 2-1). Obviously, by ensuring that the riding quality is at its best by maintaining the road regularly, the lowest logistic cost component due to road roughness can be ensured. However, this solution to this problem is not that simple, as the cost of maintaining roads to the desired riding quality should be added to the total cost.

Therefore, Steyn et al. (2011a), compared the savings in VOC gained through improved riding quality with the road maintenance cost required to improve road riding quality, a benefit-cost ratio was calculated, (Table 2-6).

Steyn et al. (2011b) indicated that by saving cost with short term highway maintenance only postpone rehabilitation and these savings do not include higher vehicle costs that incurred from pavements with lower riding quality. Highway maintenance costs are 1 to 2 per cent of the total road transport costs, whereas lifetime VOCs could increase to four times the initial construction cost of a highway. VOCs can increase to 15 per cent, caused by the neglect of highway maintenance. The disintegration of a paved road caused by further neglect can increase VOCs to 50 per cent.

Table 2-6: Anticipated traffic volume, VOC savings, and B-C ratios (Steyn et al., 2011a)

Section	Location Origin and Destination and Route number	Average Annual Truck Traffic Volume	Potential VOC Savings R/km	Benefit-Cost Ratio
1	Gauteng to Durban (N3)	204,400	2.7	0.90
2	Gauteng to Nelspruit (N4)	127,750	2.9	0.82
3	Gauteng Network	*	3.2	0.84
4	Gauteng to Witbank (N12)	116,800	3.4	1.27
5	Gauteng to Rustenburg (N4)	109,500	3.3	1.04
6	Gauteng to Richards Bay (N17 and N2)	158,775	3.6	1.31
7	Johannesburg to Vereeniging (R82)	157,680	3.6	1.57
8	Gauteng to Cape Town (N12 and N1)	140,160	3.6	1.29
9	Gauteng to Botswana (N4)	116,070	3.9	1.35
10	Newcastle to Gauteng (N11 and N17)	135,780	4.2	2.09
11	Gauteng to construction sites	*	4.3	2.013

* Not used in analysis, it is difficult to obtain details on this range of road sections

2.8 Vehicle Operating Cost Model

A wide range of information is available on the effects of riding quality on VOCs, including the models used to determine these effects. The NCHRP Project 1-45 developed a VOC model that reflect relevant and up to date vehicle technology. Most models relate VOCs with oil and fuel consumption, tyre wear, maintenance, and repair and depreciation. However, the vehicle class determines most of these costs, and according to Chatti and Zaabar (2012), it should be included in the VOC model.

In a recent study conducted by Steyn and Bean (2013) the VOC model developed by Chatti and Zaabar (2012) was applied to analyse the impact of deteriorating road surface on major freight corridors in South Africa. The model evaluated the relationship between the riding quality and the road user costs (which included the tyre costs, fuel consumption, and maintenance and repair costs) due to an uneven road surface. By applying the model, it was possible to predict what the economic impact (thus cost) would be if the roads were not adequately maintained. It also gave an indication of the potential gain when roads were maintained. This support the notion that the advantage of maintaining a road outweigh the cost of not maintaining a road.

Chatti and Zaabar (2012) listed the relevant major vehicle operating cost models that have been developed in different countries:

- HDM 3 and HDM 4 models from the World Bank (Bennett and Greenwood, 2003a, 2003b);
- Saskatchewan VOC model (Berthelot et al., 1996);
- British COBA VOC module (British Department of Transportation, 1993);

- Australian NIMPAC VOC module (National Association of Australian State Road Authorities, 1978);
- New Zealand NZVOC (Bennet, 1989), and
- South African VOC models (Du Plessis, 1989).

Most of these models were developed from the research conducted to develop the HDM models from the World Bank. Chatti and Zaabar (2012) evaluated the current models, this evaluation considered the appropriateness to model key characteristics for the fuel consumption, tyre wear and repair and maintenance models. Chatti and Zaabar (2012) calibrated the HDM 4 model with field trails. The field trails were conducted with six typical vehicles that currently exist in the United States. These vehicles were a medium car, Sports Utility Vehicle (SUV), van, light truck (diesel and gas) and an articulated truck. Chatti and Zaabar (2012) used the data collected at the field trials and calibrated it for all vehicle classes. The vehicles were classified into five categories, passenger car, light commercial vehicle, four-wheel drive, light truck and heavy truck. The heavy truck category included a medium truck, heavy truck, articulated truck, medium bus, heavy bus and coach.

Chatti and Zaabar (2012) concluded that fuel consumption is the component affected the most by roughness, followed by repair and maintenance and thereafter tyre wear. Surface roughness (indicated as IRI) affects fuel consumption the most, for heavy trucks an increase of 1 m/km in IRI leads to an increase in fuel consumption of about 1 per cent at normal speeds (96 km/h) and 2 per cent at low speeds (56 km/h). Of all the vehicle classes, the fuel consumption of heavy trucks is affected the most by pavement type and surface texture (indicated as Mean Profile Depth (MPD)). An increase of 1 mm in MPD results in an increase in fuel consumption of about 1.5 per cent at a speed of 88 km/h and 2 per cent at a speed of 56 km/h. The effect of roughness on repair and maintenance, however, only becomes significant beyond the range of 3 m/km. The repair and maintenance of trucks increase by 10 per cent with an IRI of up to 4 m/km, and these costs increase up to 50 per cent with an IRI of 5 m/km. The tyre wear increases by 1 per cent at a speed of 88 km/h with an increase of 1 m/km in IRI.

Steyn and Bean (2013) calculated the weighted average of selected freight corridors in South Africa and compared the expected costs of three different scenarios. The cost difference between using the national road network, by comparison of using the provincial network for the same corridors. Indicated in Table 2-7 is the results of the study, this information supports the understanding that in order to avoid additional costs to the road user, good riding quality should be maintained on a road network.

Table 2-7: Impact of VOC on National and Provincial road networks (Steyn and Bean, 2013)

Freight transport total	National Road Network	Provincial Road Network	Difference	% Increase from Actual
Total annual fuel consumption (kℓ)	5,669,502.00	5,698,366.00	28,864.00	0.51%
Total annual fuel cost (R 9.20/ℓ)	R 52,159,000,000.00	R 52,425,000,000.00	R 266,000,000.00	0.51%
Total annual tyre cost	R 2,629,000,000.00	R 2,657,000,000.00	R 28,000,000.00	1.08%
Total annual repair and maintenance cost (damage caused by vibrations only)	R 1,958,000,000.00	R 2,316,000,000.00	R 358,000,000.00	18.34%

2.9 Review summary

There is no standard to determine human discomfort or comfort expressed in physical terms such as acceleration or amplitudes at a given frequency and it is very difficult to evaluate comfort objectively. However, there are certain threshold values and tests that can be conducted to evaluate user comfort. The generated IRI, PSD and vertical accelerations (a_{wz}) form a moving vehicle on a rough road, related to speed, are some of the parameters that give an indication of the road state and the user comfortability. These parameters also give an indication of the road user costs and the impact a higher or lower IRI could have.

In summary, the following aspects of the literature review were highlighted:

- A road transportation system can be negatively affected by a decrease in road roughness;
- The IRI is the most widely used statistic to indicate the riding quality of a pavement;
- The riding quality of a road surface influences the travel experience significantly;
- The speed of the vehicle has a high impact on the user discomfort on a road with a high roughness;
- As road roughness increase, the speed affects vertical accelerations more;
- Riding quality affects VOCs directly;
- The origin of the dynamic shock and vibration levels came from external and internal sources. In this study the external forces are investigated, however, the internal forces impacts the outcomes of the study as the natural frequency of the suspension impacts the vertical vibrations measured by the accelerometers;
- For most vehicles, resonance in roll occurs at a lower frequency, than resonance in bounce, and therefore, bounce is the more dominant response;
- The most direct method to determine the degree of discomfort to the road user is to measure the profile of the road surface;
- Ostrem and Godshall (1979) described that for determining shock conditions for a load, acceleration measurements are without a doubt very useful. The road roughness and riding quality can be determined from the accelerations measured;
- The ISO indicates threshold values related to a_{wz} proposed for public transport;

- Cantisani and Loprencipe (2010) derived a relationship between levels of comfort and ride quality judgements for speed-related road roughness thresholds derived from the standardised a_{wz} limits, and
- The NCHRP Project 1-45 developed a vehicle operating cost model that reflect relevant and up to date vehicle technology. This model relates VOCs with oil and fuel consumption, tyre wear, maintenance and repair and depreciation for each vehicle class.

3. METHODOLOGY

3.1 Introduction

There are two main approaches of measuring road roughness. The one is Response Type Road Roughness Measurement Systems (RTRRMS) and the other is profilometric type measurement. Response type measurement measures the direct response of vehicle on a travelled section of road. The road profile is not actually measured, however the vehicles' response to the profile is measured. Whereas the profilometric type measurement, measures the profile and use the data to determine the road roughness parameter. Each of these measurement approaches has distinct advantages and limitations, and it is discussed in the following paragraphs. The main difference between the two approaches is that a physical filter is applied to the actual road profile with the response type device, whereas a mathematical filter is applied to the measured profile with the profilometric type devices (COTO, 2007).

Both the response type measurement and the profilometric type measurement will be used in this experiment. The response type device is a USB Accelerometer and the profilometric type device is a Profilometer.

The vertical accelerations generated from the surface of a specific bus route, for a bi-articulated bus was measured with accelerometers. The accelerometers were placed in the bus where the vertical accelerations were the highest. The bus route was identified so that different roads with different range of riding qualities and responsible authorities could be utilised. A profiler conducted a survey on the route and from this route five sections were identified. The collected data were analysed with various programs and methods. The VOCs of each road section were calculated using the model developed by Chatti and Zaabar (2012).

3.2 Equipment

3.2.1 Measurement Classes

The wide range of measurement approaches developed over the past 50 years can be grouped into four classes. Sayers et al. (1986) developed four generic classes based on how directly the IRI pertain to the measurements of each device.

Indicated in Table 3-1 is a general classification of roughness measurement devices. Response Type Measurement Devices can be categorised as Class 3 and 4, whereas profilometric type measurement is Class 1 and 2. In order to differentiate more between the classes the vertical measurement resolution is indicated in Table 3-2. The vertical resolution for each class indicates the accuracy required from the device. The device required for this experiment must be Class 1, as high accuracy data is required (Sayers et al., 1986).

Table 3-1: Roughness measurement classes (Sayers et al., 1986)

Device Class	Class Requirement or Characteristics
Class 1: Precision Profiles	High Accuracy High precision IRI Repeatability of about 0.3 m/km on paved roads IRI Repeatability of about 0.5 m/km on other type of roads
Class 2: Non-Precision Profiles	Measurement of road profiles and IRI Profiling devices not capable of Class 1 accuracy
Class 3: IRI Estimates from Correlations	Measurement of the road profile is not required Include all response type devices Calibrate the devices by correlating outputs to known IRI values
Class 4: Subjective Ratings and Uncalibrated Devices	Subjective ratings of roughness Devices that was not calibrated

Table 3-2: Vertical Measurement Resolution (ASTM, 1999)

Device Class	Vertical Resolution (mm)
Class 1	Equal or less than 0.1 mm
Class 2	Between 0.1 mm and 0.2 mm
Class 3	Between 0.2 mm and 0.5 mm
Class 4	Larger than 0.5 mm

3.2.2 Accelerometer

The measurement approach with accelerometers is response type measurement. Therefore, the response of the vehicle on a travelled section of road will be measured. Which means that the suspension of the vehicle will filter out the unimportant wavelengths and in effect quantify the important wavelengths (COTO, 2007).

A typical response type system consists of the following (Sayers et al., 1986):

- Transducer;
- Measurement vehicle;
- Recording system, computer, and data storage;
- Automatic speed control, and
- Accelerometers.

The response type device is calibrated with a procedure known as “correlation by calibration”, In this procedure the output values is correlated with known IRI values from various sections of road, known as calibration sections. A high precision profiling device determines the IRI of these sections. The calibration of the device is valid for the measurement vehicle, as long as the shock absorbers, tyres, loading, suspension etc. remains unchanged (COTO, 2007).

It is important to note the advantages and limitations of the device in order to ensure that the experiment is a success, indicated in Table 3-3.

Table 3-3: Advantages and limitations of Response Type Devices (COTO, 2007)

Advantages	Limitations
Popular, therefore many engineers are acquainted with the output and operation of these devices	Requires frequent maintenance and care or operation
Agree with assessment of roughness and pavement condition	The precision is lower
Inexpensive	The calculation of the IRI value is dependent on the vehicle suspension system.
Simple maintenance and care	
Simple calibration process	Measures only road roughness
More successful on gravel roads than profilers	

There is a wide range of accelerometers available form Gulf Coast Data Concepts, for this study the accelerometer model X16-1C and X6-1A were used (the X16-1C is an upgrade of the X6-1A). Figure 3-1 is a graphical presentation of the USB accelerometer X16-1C.

The USB Accelerometer measures accelerations in the X, Y, and Z-axis, these values are stored in user selectable rates of 12, 25, 50, 100, or 200 Hz. It also uses USB connectivity, precise time stamped data logging, low noise digital accelerometer sensor, MicroSD memory storage (2 GB) and real-time data access. By connecting the accelerometer to a computer, the device acts as a standard mass storage device (flash disc), which contain the user setup files and the data measured (comma delimited data files). The accelerometer operates with a standard 'AA' battery and it provides extended life operation suitable for long-term data acquisition applications (Gulf Coast Data Concepts, 2012).

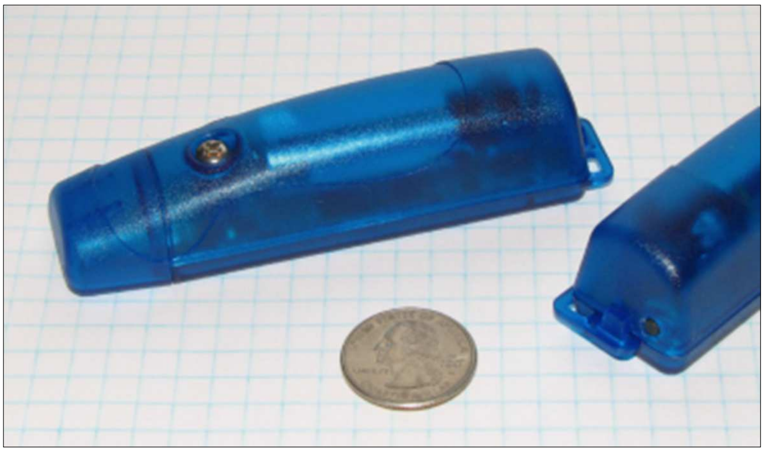

Figure 3-1: USB Accelerometer X16-1C (Gulf Coast Data Concepts, 2012)

The software XLR8R is software provided by Gulf Coast Data Concepts (2012) which enables the user to present the data graphically, to copy, paste or export data segments, and to configure the file and time file utilities easily.

3.2.3 Inertial Profiler

The profilometric approach is more sophisticated and modern than the response type measurement and the data provided are more consistent. The approach, however, requires equipment that is more expensive and with specialised operators (COTO, 2007).

A typical profilometric type system consists of the following (Sayers et al., 1986):

- Transducer (height sensor);
- Measurement vehicle;
- Accelerometers;
- System that measures the longitudinal distance, and
- Recording system, computer and data storage.

The equipment manufacturer calibrates the transducer, accelerometers and distance measuring devices and it should remain calibrated for a relatively long period of time. Therefore, the calibration process does not form part of the measurement process. The device output is rather validated by comparing known IRI values measured from test sections with the output to ensure that all the components work correctly and that the profiler measures the road profile to the required level of precision (COTO, 2007).

It is important to note the advantages and limitations of the device to ensure that the experiment is a success, indicated in Table 3-4.

Table 3-4: Advantages and limitations of High Speed Profiling Devices (COTO, 2007).

Advantages	Limitations
High Precision	Control procedures are required to ensure that the profile is measured correctly
Measured IRI is consistent over time	Expensive, equipment availability.
IRI values can be used to track a network of pavement deterioration because of the stability and precision of IRI values obtained by a validated high-speed profiler.	Gravel roads are not profiled successful with inertial profiling devices that use laser height sensors.
Able to measure the transverse and longitudinal profile simultaneously.	Operation and control procedures are complex

The Dynatest Road Surface Profiler available from Specialised Road Technologies (SRT) is indicated in Figure 2-10. It is a Volkswagen Transporter fitted with a laser bar with two lasers, one for each wheelpath (1 750 mm c/c), carrying two accelerometers mounted above each laser, for each wheelpath, a distance encoder (output pulses at 2 000/revolution to the processor), a GPS (Trimble AG 132 with less than 1 m accuracy) and a processing unit. The

Data Processing Unit captures and processes all the laser signals, GPS, distance pulses etc. for storage and real-time display on two laptops (SRT, 2012). This Road Surface Profiler measures the longitudinal profile (IRI, transverse profile, ride number, rut depth, geometric and macro texture) in real-time continuous freeway speed. Digital photographs were taken every 10 m, to both the front and rear. These measurements can easily be integrated with GIS (Geographic information systems), as the measurements can be referenced to the Differential Geographic Positioning System (DGPS) and linear chainage.

Figure 3-2: Dynatest Road Surface Profiler (SRT, 2012).

3.3 Experimental set-up

Data were collected in three phases. The first phase included the installation of accelerometers at different positions on a bi-articulated bus. The second phase determined the roughness of the roads with a profiler. In addition, the third phase included the analysis of the data by identifying the dominant parameters and comparing it to the parameters indicated in section 2.

3.3.1 Device selection

The vertical accelerations of a bi-articulated bus were measured with accelerometers, and the collected data were analysed with various programs. The accelerometers were placed all around the bus at specific positions, especially where the vertical accelerations were anticipated the highest. The output values required to prove the hypothesis were the IRI, speed, PSD and vertical RMS acceleration. Even though the trip duration of the route is an important factor, it was deemed outside the scope of this study. The output parameters calculated were analysed statistically in order to make a scientific conclusion.

The bus route was profiled with a Dynatest Road Surface Profiler 5051 Mark IV – ASTM E950 Class 1 (Laser Based), as indicated in section 3.2.3. The deliverables received from SRT included the IRI (interval average IRI/10 m) with direction, distance, IRI left, IRI right, IRI middle and the average IRI. The texture was received as a report with the average Mean Profile Depth (MPD) measured in the left wheel path only, in lengths of 10 m. The GPS coordinates received were differentially corrected and in units of latitude, longitude and elevation, stored every 10 m.

3.3.2 Equipment specifications

It is important to know the equipment specification, as the user must be certain that the instrument is compatible with the survey objective and type. If a level of precision is specified for a certain instrument, but it cannot be achieved with the available equipment it has no meaning or purpose (COTO, 2007).

3.3.3 Equipment Validation or Calibration

Calibration consists of the process of measuring an instruments response to the application of known displacements, temperatures, or pressures (Dunnicliff, 1988). Component calibration is the calibration of the individual components of the system. Moreover, system validation or calibration is the check to ensure the accuracy of the system as a whole (COTO, 2007).

The calibration of the individual accelerometers was conducted in the centrifuge at the University of Pretoria. In order to ensure that the accelerometers and the data acquisition system work properly, system calibration for the accelerometers were performed. The system calibration also correlates the device output to known values over a range of roughness values (COTO, 2007).

In order to determine whether all the components in the profiler system work correctly and that the calibration of each was correct, profiler validation was required. SRT (2012) regularly calibrate the components of the Dynatest Road Surface Profiler.

3.3.4 Measurement Control

Several parameters related to the environment and the pavement condition can influence the measurements taken for both response type devices and profilers. Therefore, it is essential to ensure the familiarity with key effects and that the data files are flagged if conditions are observed that may have a negative impact on the precision or accuracy of the device. The following key parameters were identified as pavement related influences (NCHRP, 1999):

- Crocodile Cracking;
- Transverse Cracking;
- Coarse Texture;
- Potholes and Patching;
- Daily Profile Variations, and
- Seasonal Variations.

The following parameters were identified as environmental related influences (NCHRP, 1999):

- Wind;
- High Temperature and Humidity;
- Surface Moisture, and
- Contaminants.

3.4 Survey Location

The route earmarked for the research fell in Zone 3 B0418 of Buscor (Pty) Ltd. bus routes. This route was selected as it utilise different roads with different responsible authorities. The accelerometers were mounted on the bus at the Nelspruit bus terminal, where the commuters board the bus to travel to Nkomeni. The layout of the Nelspruit bus terminal is indicated in Figure 3-3. The bus route information was supplied to SRT to survey the same route with the profiler.

Figure 3-3: Layout of Nelspruit bus terminal (Google Earth, 2013)

3.5 Accelerometer Measurement

3.5.1 Locations of accelerometers

The locations of the accelerometers were estimated to be where the vibrations would be the highest. The suspension system in the Buscor busses is a leaf spring suspension. It was estimated that the accelerometers be placed above each axle (Figure 3-4), with accelerometer A, B, C and E on the left hand side of the bus above each axle and accelerometer G, H, J and L on the left hand side of the bus. The location of accelerometer D, F, K and M were identified as locations where the vertical accelerations might be high. The research conducted in the Literature Review indicated that high accelerations were measured in the front and rear of a trailer (Steyn, 2010, Chonhenchob et al., 2009; and Jarimopas et al., 2005). A GPS was installed in the bus to record the exact bus route, and the speed of the bus can be calculated from the coordinates recorded by the GPS.

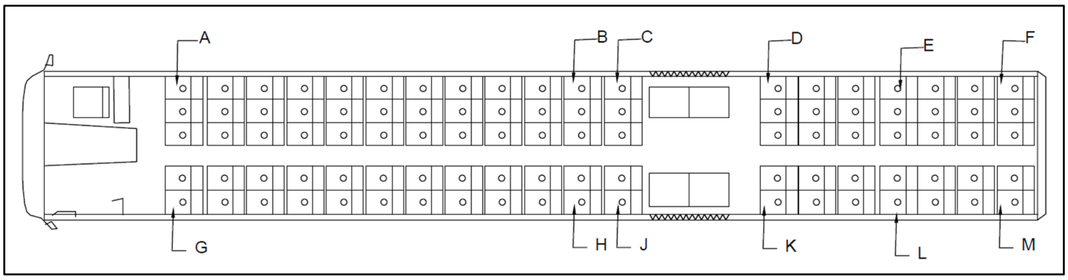

Figure 3-4: Layout of the proposed acceleration configuration

3.5.2 Analysis

a) Vertical Acceleration (a_{wz})

The equations were based on ISO 2631 (1997). Equation 3-1 was used to determine the running a_w of each section. This method takes the occasional shocks and transient vibrations into account with the use of a short integration time constant. The calculated value, $a_w(t_0)$, is the Maximum Transient Vibration Value (MTVV) and the unit is in metres per second squared (m/s^2). Whereas $a_w(t)$ is the instantaneous frequency-weighted acceleration, τ is the integration time for running averaging, t is the time and t_0 is the start time.

$$a_w(t_0) = \left[\frac{1}{\tau}\int_{t_0-\tau}^{t_0} [a_w(t)]^2 dt\right]^{\frac{1}{2}}$$

Equation 3-1: Vertical running RMS acceleration (ISO, 1997)

b) Power Spectral Density

The data from each accelerometer sensor was analysed with the software XLR8R. The Fast Fourier Transform (FFT) analysis data were copied into Microsoft Excel, and from there the PSD values were determined with the Midpoint rule.

c) Midpoint rule

The data generated by the software program XLR8R (Gulf Coast Data Concepts, 2012), were equal length frequency classes in intervals of 0.25 Hz. The energy absorbed by the system was determined by calculating the area under the PSD plot. The method used to do the calculation was the midpoint rule. The midpoint rule calculates the average of two consecutive PSD values and multiplies the result with the adjacent difference in frequencies. These areas were summed to calculate the total area. The method is graphically indicated in Figure 3-5.

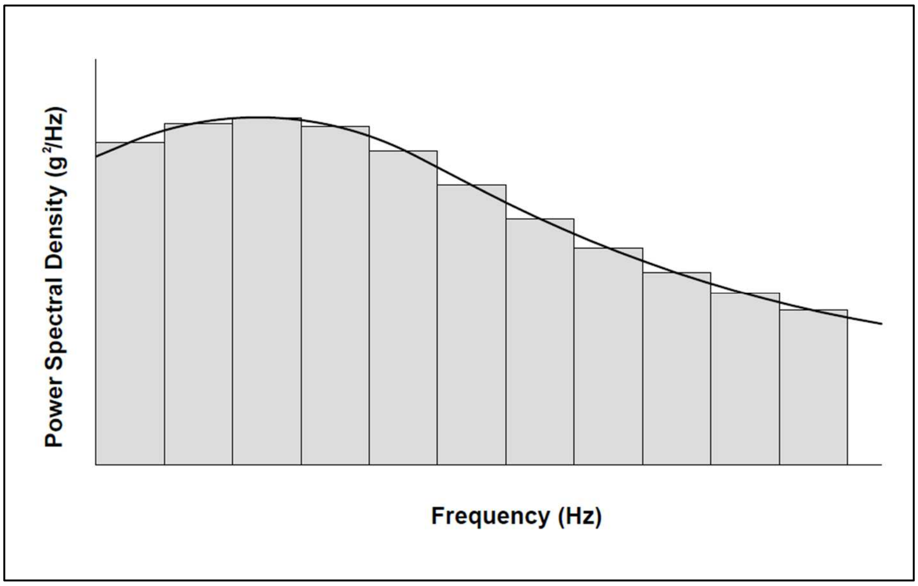

Figure 3-5: Visual presentation of the midpoint rule

3.6 Profiler Measurement

3.6.1 Data Processing

The format of the data received from SRT is indicated Table 3-5.

Table 3-5: Format of data provided by SRT

File	Name of the data set, including the test direction
From Km	kilometre distance from
To Km	kilometre distance to
Speed	Vehicle speed during measurement in km/h
IRI L	IRI in left wheel path (as measured)
IRI M	Average IRI of the profile measured in the left and right wheel path

IRI R	IRI in right wheel path (as measured)
IRI Av	The mathematical average IRI of the right and left wheel path
LAT	GPS Position
LON	GPS Position
ELEV	GPS Height
MPD	Measured texture in mm in left wheel path

3.6.2 Anomaly detection

The definition of an outlier is “an observation that lies an abnormal distance from other values”, (NIST/SEMATECH, 2013). It depends on the analyst to decide what is considered as an abnormal distance.

In this analysis, box-plots with fences were used to determine the outliers of each section. However, outliers are data points that cannot be explained, and these values seemed rather to be anomalies such as speedhumps, potholes, change in surfacing or just an extremely bad road. In relation to the whole section, the anomalies were identified and analysed separately. The box plot includes lower and upper quartiles (25th and 75th percentiles) and the mean.

The ranges were determined as follow:

- Lower inner fence: lower quartile – 1.5 (interquartile range);
- Upper inner fence: upper quartile + 1.5 (interquartile range);
- Lower outer fence: lower quartile – 3 (interquartile range), and
- Upper outer fence: upper quartile + 3 (interquartile range).

3.7 Vehicle Operating Cost Model

The VOCs were based on the model developed by Chatti and Zaabar (2012). Chatti and Zaabar (2012) used the data collected at the field trials and calibrated it for all vehicle classes. The heavy truck category included a medium truck, heavy truck, articulated truck, medium bus, heavy bus and coach. Therefore, the busses used by Buscor fell in the heavy truck category and the vehicle used by Chatti and Zaabar (2012) for the calibration was an articulated truck.

3.7.1 Fuel Consumption

The fuel consumption model is based on the HDM 4 fuel consumption model (Bennett and Greenwood, 2003b). Chatti and Zaabar (2012) calibrated the HDM 4 model and confirmed that the HDM 4 model over predicts the engine speed of the vehicle, and therefore overpredict the engine power, and that in turn leads to an overestimation of the fuel consumption.

In Table 3-6 the effect of roughness on fuel consumption for an articulated truck is indicated. These values makes it possible to adequately predict the fuel consumption under different weather and pavement conditions.

Table 3-6: Fuel consumption parameters (Chatti and Zaabar, 2012).

Speed	Baseline conditions	IRI Factor (m/km)					
km/h	ml/km	1	2	3	4	5	6
56	273.41	1	1.02	1.04	1.07	1.09	1.11
88	447.31	1	1.02	1.03	1.05	1.06	1.08
112	656.11	1	1.01	1.02	1.04	1.05	1.06

3.7.2 Tyre Wear

The tyre wear model developed by Chatti and Zaabar (2012) is also based on a calibrated HDM 4 tyre wear model. Field tests were conducted on four tractor-trailer assemblies that drove around a track, the data were collected and analysed. The calibrated model for an articulated truck is indicated in Table 3-7, this model adequately predict tyre wear.

Table 3-7: Tyre wear parameters (Chatti and Zaabar, 2012)

Speed	Baseline conditions	IRI Factor (m/Km)					
km/h	%/Km	1	2	3	4	5	6
56	0.0006	1	1.01	1.01	1.02	1.02	1.03
88	0.0007	1	1.01	1.02	1.03	1.04	1.05
112	0.0009	1	1.01	1.02	1.03	1.04	1.06

3.7.3 Repair and Maintenance Costs

Chatti and Zaabar (2012) developed the model for repair and maintenance costs from the HDM 4 model and a model identified in the Texas Research and Development Foundation (TRDF) study (Zaniewski et al., 1982). The model is a combination of an updated TRDF study and mechanistic-empirical approach. Indicated in Table 3-8 is the summary of change in repair and maintenance costs per kilometre for an articulated truck. The effect of pavement conditions on repair and maintenance costs for passenger cars and articulated trucks is based on the mechanistic-empirical approach. The results from the TRDF study (Zaniewski et al., 1982) were used to determine the costs for the other vehicle classes.

Table 3-8: Repair and maintenance parameters (Chatti and Zaabar, 2012)

Speed	Baseline conditions	IRI Factor (m/Km)					
Km/h	$/km	1	2	3	4	5	6
56	0.046	1	1	1	1.1	1.5	1.8
88	0.063	1	1	1	1.1	1.5	1.8
112	0.077	1	1	1	1.1	1.5	1.8

3.8 Summary

In conclusion, USB accelerometers and a profiler were used to determine the data required for the analysis to test the hypothesis. A GPS determined the exact bus route and the speed of the bus could be calculated from the coordinates recorded by the GPS every second. The data recorded by the accelerometers, profiler, and GPS were used to determine the PSD and vertical acceleration. Box-plots were used to isolate the outliers. The recorded IRI values were also used to predict the tyre wear, fuel consumption and, repair and maintenance cost of each section.

4. DATA COLLECTION

4.1 Introduction

In this chapter the methods of data collection and processing is explained. Data were collected in two phases. The first phase included the installation of accelerometers at different positions of an articulated bus (front, middle, and back). The second phase was to measure the IRI of the road with a profiler.

The route was divided into five sections with different responsible authorities. A short description and photo of each section is indicated. The data for the calibrated HDM 4 model were analysed and regression equations determined.

4.2 Bus route

4.2.1 Accelerometer Route

The accelerometer testing was conducted in the late afternoon to evening. The bus started full and ended empty. Commuters board the bus at Nelspruit bus terminal (Figure 4-1), and were dropped off at bus stops along this route, the bus returned to the terminal empty.

Figure 4-1: Nelspruit Bus Terminal

The route is graphically presented in Figure 4-2. The bus travelled East on the N4 (National road), turned left on the R538 (Provincial road), turned right and travelled in an Eastward direction toward Tekwane North (Provincial road). The route circled in Daantjie (Municipal road), travelled on the R538, turned right onto D2269, and from there it returned to Nelspruit Bus terminal.

The mass of fuel, passengers and number of passengers in the bus could have an impact on the readings of the accelerometers, however it was deemed outside the scope of this study and is further discussed as recommendations.

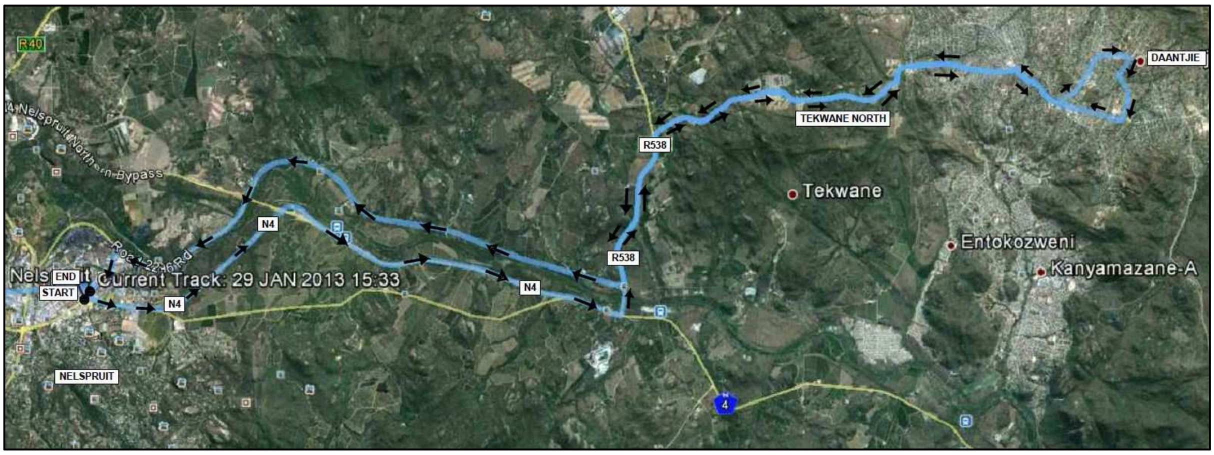

Figure 4-2: Accelerometer Route Description (Google Earth, 2013)

4.2.2 Profiler Route

The route was surveyed by SRT (Specialised Road Technologies) on the 20th of February 2013, there was no rain present, and therefore no weather interferences. The route surveyed was slightly different from the bus route requested, the bus travelled through Tekwane North, whereas the profiler travelled through Emoyeni. However, on the overlapping sections enough data were collected for comparison. The route is graphically indicated in Figure 4-3.

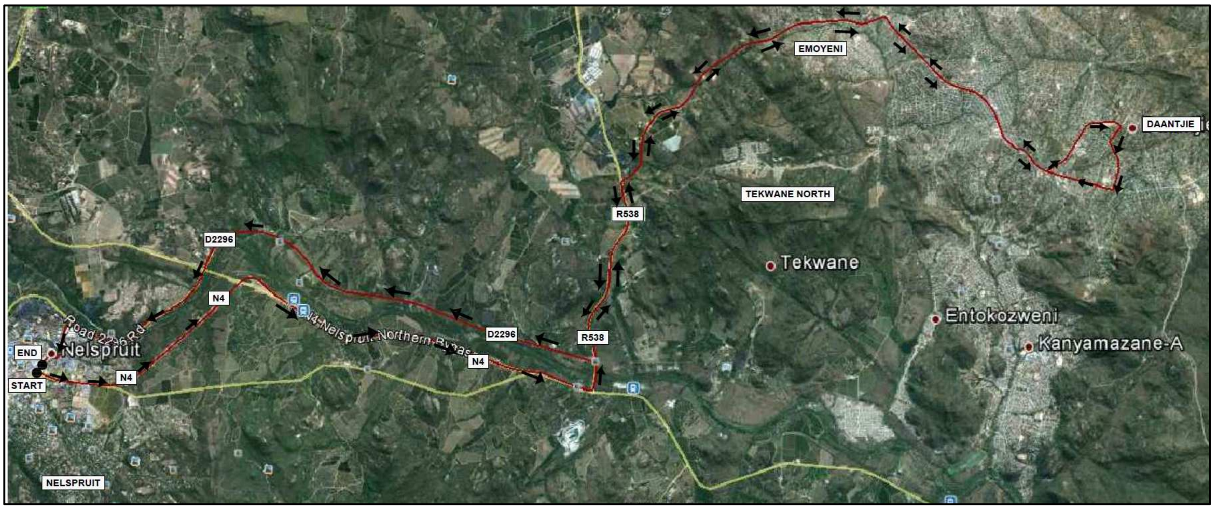

Figure 4-3: Profiler Route Description (Google Earth, 2013)

From this route five sections were identified. In Figure 4-3, a graphical presentation of each section is indicated. In Table 4-1, the name and length of each section is presented followed by a description of each section.

Table 4-1: Summary of Route Section Lengths

Route Name	Responsible Authority	Section length (km)	Distance (km)	
			From	To
N4	National Road SANRAL	12.4	0.60	13.00
R538 (1)	Provincial Road MPWDRT	3.9	13.1	17.00
R538 (2)	Provincial Road MPWDRT	1.13	27.71	28.84
Municipal road	Municipal Road Mbombela Local Municipality	3.33	28.88	32.21
D2296	Provincial Road MPWDRT	12.22	48.79	61.01

a) Section 1 – N4

This section of the route is a National road, and the responsible authority is TRAC (Trans African Concessions). This road accommodates high volumes of traffic especially heavy vehicle traffic with an AADT (annual average daily traffic) of 18 966. A new bypass was recently built in order to accommodate traffic traveling to Mozambique, the section measured is part of the new bypass. The IRI, PSD and vertical vibrations were expected to be very low on this section of the route. SRT supplied photos every 10 m of the surveyed route, (Figure 4-4).

Figure 4-4: Photo of N4 (SRT, 2013)

b) Section 2 – R538 (1)

This section of the route is a provincial road, Mpumalanga Department of Public Works, Roads and Transport is responsible for the maintenance. The traffic volumes on this route is typically associated with a distributor road, with an AADT of 6 033. This road has not been maintained regularly, the IRI, PSD and vertical vibrations of this section of the route were expected to be quite high (Figure 4-5).

Figure 4-5: Photo of R538 (1) (SRT, 2013)

c) Section 3 – R538 (2)

This section of the route is also a provincial road, Mpumalanga Public Works, Department of Roads and Transport is responsible for the maintenance. The AADT on this section is 3 747. This road has also not been maintained regularly, and therefore the IRI, PSD and vertical vibrations of this section of the route were expected to be quite high (Figure 4-6).

Figure 4-6: Photo of R538 (2) (SRT, 2013)

d) Section 4 – Municipal Road in Daantjie

This section of the route is a municipal road, Mbombela Local Municipality is responsible for the maintenance (Figure 4-7). This road accommodates low volumes of traffic with an AADT of 91. The IRI, PSD and vertical vibrations on this section of the route were expected to be high.

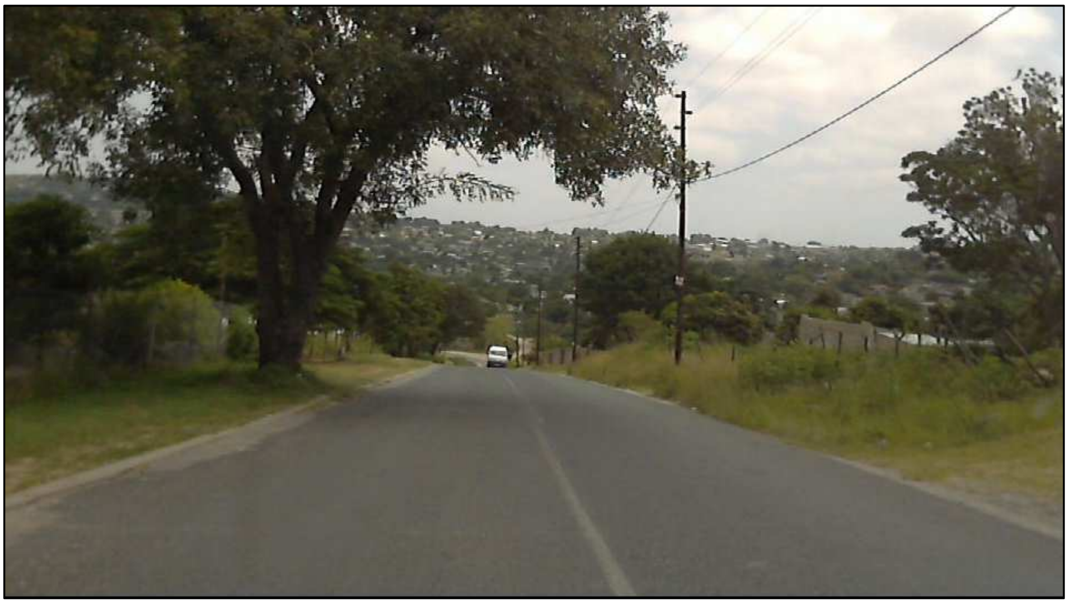

Figure 4-7: Photo of the municipal road in Daantjie (SRT, 2013)

e) Section 5 – D2296

This section of the route is also a provincial road, Mpumalanga Public Works, Department of Roads and Transport is responsible for the maintenance (Figure 4-8). The traffic volumes on this route is typically associated with a distributor road, with an AADT of 7 828. This road has also not been maintained regularly, and therefore, the IRI, PSD and vertical vibrations of this section of the route were expected to be quite high.

Figure 4-8: Photo of road D2296 (SRT, 2013)

4.3 Accelerometer Measurement

4.3.1 Locations of accelerometers

The locations of the accelerometers were estimated to be where the vibrations would be the highest. The locations are indicated in Figure 4-9 and Figure 4-10. Accelerometer no. 4 and 1 measured accelerations above the front axis, accelerometer no. 8 and 13 above the last rear axis, and accelerometer no. 6 and 11 measured accelerations on the main bus next to the connection of the cart. Accelerometer no. 3 and 2 measured accelerations on the cart next to the connection to the main bus, accelerometer no. 5 and 14 above the last rear axis of the cart and the last accelerometers (no. 10 and 12) measured accelerations in the rear of the bus.

Figure 4-9: Acceleration Configuration

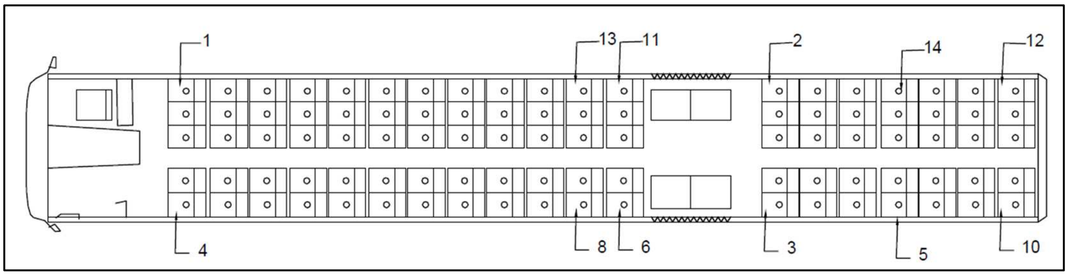

Figure 4-10: Layout of the Acceleration Configuration

The suspension system is a leaf spring suspension. The tyre inflation pressures of each axis are indicated in Table 4-2. The type and condition of the suspension, including the tyre inflation pressure and dynamic wheel loads could have an impact on the accelerations measured by the accelerometers, however, it was deemed outside the scope of this study and further discussed in section 7.

Table 4-2: Tyre inflation pressures

Front Axis tyre pressure		720 kPa
Rear tyre pressure	Axis 1	670/660 kPa
	Axis 2	700 kPa
Cart Axis tyre pressure		770/660 kPa

4.3.2 Data Processing

a) Vertical Acceleration (a_{wz})

The evaluation includes the accelerations of the weighted Root Mean Square (RMS) acceleration according to ISO 2631-1 (1997). The raw accelerometer data were exported from the software program XLR8R, thereafter the data was analysed in Microsoft Excel. The data exported included a time entry and the accelerations in three directions, a_x, a_y and a_z. In order to convert the raw data from digital 'counts' to 'g' each value was divided by 1024. The parameter to be analysed was the vertical acceleration, a_z, with Equation 3-1 the running RMS of each section was determined.

b) Power Spectral Density

The data from each accelerometer sensor were collected and analysed with the software XLR8R. The software program performed a FFT (Fast Fourier Transform) analysis. The FFT analysis data were copied into Microsoft Excel, and from there the PSD values were determined with the Midpoint rule. The PSD results are indicated in Figure 4-11 and Table 4-3, some of the sensors ran out of battery power during the survey of the D2269, and therefore there is limited data available.

As predicted, the sensors with the highest and second highest PSD values were sensor 11 and 12. Sensor 1 gave an indication of the impact of the road on the driver. With further analysis, driver fatigue could be determined, including the safety of the passengers due to driver fatigue. However, this was deemed outside the scope of this study and sensor 11 and 12 were analysed and discussed further in section 5 and 6.

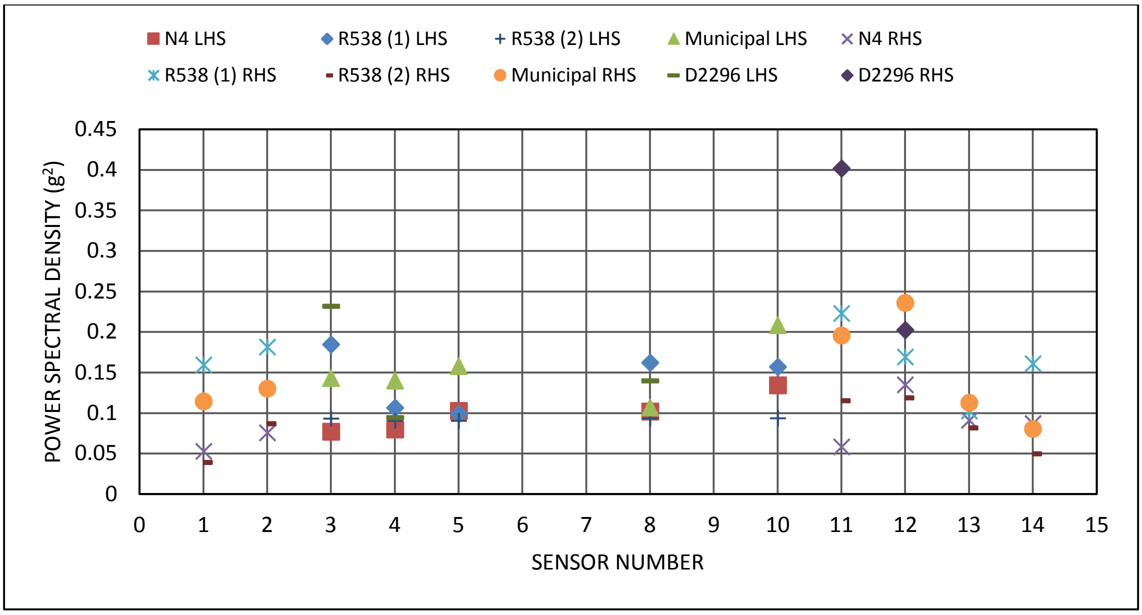

Figure 4-11: Measured PSD over the whole length of the route

Table 4-3: Average PSD values over the whole length of the route

	N4 (g^2)	R538 (1) (g^2)	R538 (2) (g^2)	Municipal Road (g^2)	D2269 (g^2)	Average (g^2)
1	0.053	0.159	0.039	0.114	*	0.091
2	0.076	0.182	0.087	0.130	*	0.118
3	0.077	0.185	0.093	0.143	0.232	0.146
4	0.080	0.107	0.090	0.140	0.094	0.102
5	0.102	0.099	0.090	0.158	*	0.112
8	0.102	0.162	0.093	0.107	0.140	0.121
10	0.134	0.157	0.093	0.209	*	0.148
11	0.058	0.223	0.115	0.196	0.402	0.199
12	0.135	0.169	0.119	0.236	0.203	0.172
13	0.091	0.102	0.082	0.113	*	0.097
14	0.087	0.161	0.050	0.081	*	0.095

* No data available

4.4 Profiler Measurement

With the accelerometer testing a Global Positioning System (GPS) device was used to track the route travelled by the bus. The GPS on the bus measured the location every second, and the accelerometers measured an acceleration reading every second. GPS coordinates every 10m were part of the profiler output. The challenge was to correlate the accelerometer data with the profiler data, and it was graphically done with Google Earth. The identified sections with similar IRI (from the profiler data) were plotted with waypoints on Google Earth. The time the bus passed that point was noted and the time was correlated with the time indicated for each accelerometer reading, which weren't always to the exact second. However, the correlation might deviate with about 10 to 20 m, which is not much if it is kept in mind that for a bus traveling at 60 km/h, 16.67 m is driven every second. Furthermore the IRI values were averaged over the length of each section.

4.5 Vehicle Operating Costs

The model to predict the effect of pavement conditions on fuel consumption, tyre wear and repair and maintenance costs was developed by Chatti and Zaabar (2012). The values used to determine the prediction are indicated in Table 3-6 (fuel consumption model), Table 3-7 (tyre wear model) and Table 3-8 (repair and maintenance cost model).

4.5.1 Fuel Consumption

A regression equation was determined to ease calculation for data analysis as the speed differs for each measured IRI value. Therefore, the main objective was to have two variables, speed and IRI. A linear regression line was fitted for each speed and a regression equation was calculated in the form of Equation 4-1.

$$y = mx + c$$ **Equation 4-1: Linear**

The m values and the c values were plotted, and exponential regression equations were determined for each data set. The regression equations used to determine the predicted fuel consumption for the measured speed and IRI are indicated in Equation 4-2 and Equation 4-3.

$$m = 5.3766e^{0.0026(Speed)}$$ **Equation 4-2: Fuel Consumption slope**

$$c = 110.5e^{0.0157(Speed)}$$ **Equation 4-3: Fuel Consumption constant**

4.5.2 Tyre Wear

The tyre wear model indicated in section 3, Table 3-7, was calculated into an equation to make the calculation process easier. The base factor was incorporated into the adjustment factors and linear regression lines were fitted for each speed.

The corresponding m and c values was plotted and exponential regression equations (Equation 4-4 and Equation 4-5) were determined for each, with speed and IRI as variables.

$$m = -9E - 8(Speed) + 1E - 5$$ **Equation 4-4: Tyre wear slope**

$$c = 0.0013e^{-0.007(Speed)}$$ **Equation 4-5: Tyre wear constant**

4.5.3 Repair and Maintenance Costs

The effect of pavement conditions on repair and maintenance costs is determined with Table 3-8 in section 3. The baseline conditions were converted from \$/km to R/km, with the R/\$ exchange value of 20 September 2013 (Standard Bank, 2013).

The baseline conditions were incorporated into the adjustment factor and exponential regression curves were plotted for each speed. The regression equations are in the form of Equation 4-6, the b value for each regression curve is constant (0.2074).

$$y = ae^{bx}$$ **Equation 4-6: Exponential**

Therefore, the a-values were plotted to determine the regression equation with speed as a variable. The regression equations are indicated in Equation 4-7 and Equation 4-8.

$$a = 0.0028e^{0.076(Speed)}$$ **Equation 4-7: RMC Slope**

$$b = 0.02074$$ **Equation 4-8: RMC constant**

4.6 Summary

In summary, the accelerometers were placed on a bi-articulated bus, the bus started full and ended empty. Sensor 11 and 12 were identified as the sensors with the highest PSD and it was concluded that the highest vertical accelerations were measured with these two sensors. The route that was surveyed with the profiler was slightly different from the bus route, however enough data could be isolated to be analysed.

Regression equations for the fuel consumption, tyre wear, and repair and maintenance cost model were developed, with speed as a variable.

5. DATA ANALYSIS

The data analysis chapter includes the experimental work conducted for the research. It also include the results of the tests conducted and discussions of each road section.

5.1 Introduction

The IRI data for each section were categorised in three categories, very good to good, fair to mediocre and poor. The anomalies for each section were identified, and the cause of these anomalies determined. Some were speed humps, potholes, stop controlled intersections, traffic light controlled intersections or difference in surfacing. These values, however, were not discarded and were analysed with the data as the anomalies are still part of the route. Consecutive sections of each category were isolated, for which the average IRI, area PSD, a_{wz}, average speed and VOCs of each section were calculated.

In Figure 4-11 (section 4), the accelerometer sensors with the highest and second highest average PSD were indicated as sensor 11 and 12. The PSD versus roughness of each isolated section of sensor 11 and 12 were analysed.

Comfort is difficult to evaluate objectively, as user perception of dynamic effects plays a large role. The literature study indicated that to determine the comfortability of a road the evaluation of the RMS acceleration is required. The vertical RMS acceleration (a_{wz}) was calculated for each isolated section. The proposed speed related a_{wz} thresholds by Cantisani and Loprencipe (2010) were adopted for the analysis of the data. The categories were combined, and are indicated in Table 5-10. The IRI versus speed versus vertical acceleration was plotted on three dimensional graphs to indicate the impact of speed on the vertical acceleration data.

The effect of roughness on fuel consumption, the impact of road roughness on tyre wear and, repair and maintenance costs were analysed. The calibrated HDM4 model was used to predict the fuel consumption, tyre wear and, repair and maintenance cost per km of each section of the bus route under consideration.

5.2 Threshold values

The data were categorised according to the different IRI categories (Table 5-1, from the literature study). The values obtained from Sayers et al. (1986) were deduced from Figure 2-5, the categories indicated in the figure were viewed as very good (airport, runways and superhighways), good (new pavements), fair (older pavements), mediocre (maintained unpaved roads and damaged pavements) and poor (rough unpaved roads).

Table 5-1: IRI Categories from literature

	Sayers et al. (1986) (m/km)	Cantisani and Loprencipe (2010) (m/km)
Very Good	<=2.0	<1.42
Good	1.5-3.5	1.42-2.84
Fair	2.5-6.0	
Mediocre	3.8-11.0	2.84-4.06
Poor	>8.0	>4.06

The five categories were combined into three, very good to good as the first, fair to mediocre as the second, and poor as the third category. Table 5-2 indicates the IRI limits adopted during the analysis of the profiler data.

Table 5-2: Combined IRI categories

Category	IRI (m/km)
Very Good to Good	<=2.24
Fair to Mediocre	2.25-4.05
Poor	>4.05

The profiler surveyed the bus route as a whole, and therefore the data on the different roads (N4, R538(1), R538(2), Municipal road and D2296) applicable to this study had to be isolated. With the help of Google Earth, the kilometre distance of each road could be determined and analysed.

The roughness of each road were categorised with the limits from Table 5-2, the results are indicated in Table 5-3. The results of the N4 was as expected, with most of the road in the very good to good category with very little of the road in the poor category. However, a third of the road was in the fair to mediocre category, which was higher than expected. The results of the R538(1) were also as expected, with just over half of the road in a very good to good condition, less than a third in the fair to mediocre condition, and 16.2 percent of the road in the poor and outlier section. According to the data the R538(2) and Municipal road in Daantjie were in the worst condition, with 31.6 per cent of the R538(2) and 41.3 per cent of the municipal road in the poor and anomaly category. The D2296, however, was in a better condition than expected, the data suggested that the tested section of the D2296 was better than the tested section of the N4.

Table 5-3: IRI results.

	N4	R538(1)	R538(2)	Municipal Road	D2296
Very Good to Good	65.4%	55.4%	45.6%	15.0%	77.4%
Fair to Mediocre	30.5%	28.5%	22.8%	43.7%	13.6%
Poor	4.1%	8.7%	27.2%	35.0%	3.8%
Anomaly	none	7.4%	4.4%	6.3%	5.2%

The data were categorised according to the different IRI categories and for each road consecutive sections of more than 10m of each category were isolated. A maximum of 15 sections for each road was identified and the average IRI, area PSD, a_{wz}, average speed and VOCs of each section was calculated. The measured IRI data for each section are graphically indicated in this chapter, and the tabulated data are indicated in Appendix A.

5.3 Anomalies

The IRI anomalies for each section were identified with a box plot. The calculated anomaly for each data set is indicated in Table 5-4. The values below zero were analysed as zero, as the data sets only contained positive values.

Table 5-4: IRI Data - Box plot information for each section

	N4 (m/km)	R538(1) (m/km)	R538(2) (m/km)	Municipal Road (m/km)	D2296 (m/km)
Median	1.9	2.1	2.5	3.6	1.7
Lower quartile	1.4	1.6	1.5	2.6	1.4
Upper quartile	2.5	3.4	5.5	5.3	2.1
Interquartile range	1.1	1.8	4.0	2.7	0.8
Lower inner fence	-0.2	-1.1	-4.4	-1.4	0.2
Upper inner fence	4.2	6.0	11.5	9.3	3.3
Lower outer fence	-1.9	-3.8	-10.4	-5.4	-1.0
Upper outer fence	5.9	8.7	17.5	13.4	4.5

The boxplot was applied to the data of each section. The IRI on the N4 was generally very good, so when the box plot was applied to the data, all the data above the upper inner fence of 4.2 m/km were in the poor category. Therefore, the calculated anomalies of the N4 data were analysed in the poor category.

The measured IRI data of the R538(1) are presented in Figure 5-1. The graph indicates some sections that were in a very poor state (km 13-13.5, km 15.25-15.75, and km 16.5-17). The sections were identified, and these are indicated in Table 9-7. The first two outlier sections were caused by the accelerations generated as the vehicle drove over bridge construction joints, the third and fourth outlier sections were as a result of uneven patching. The last two outlier sections were as a result of uneven patching and surface failures (Figure 5-2).

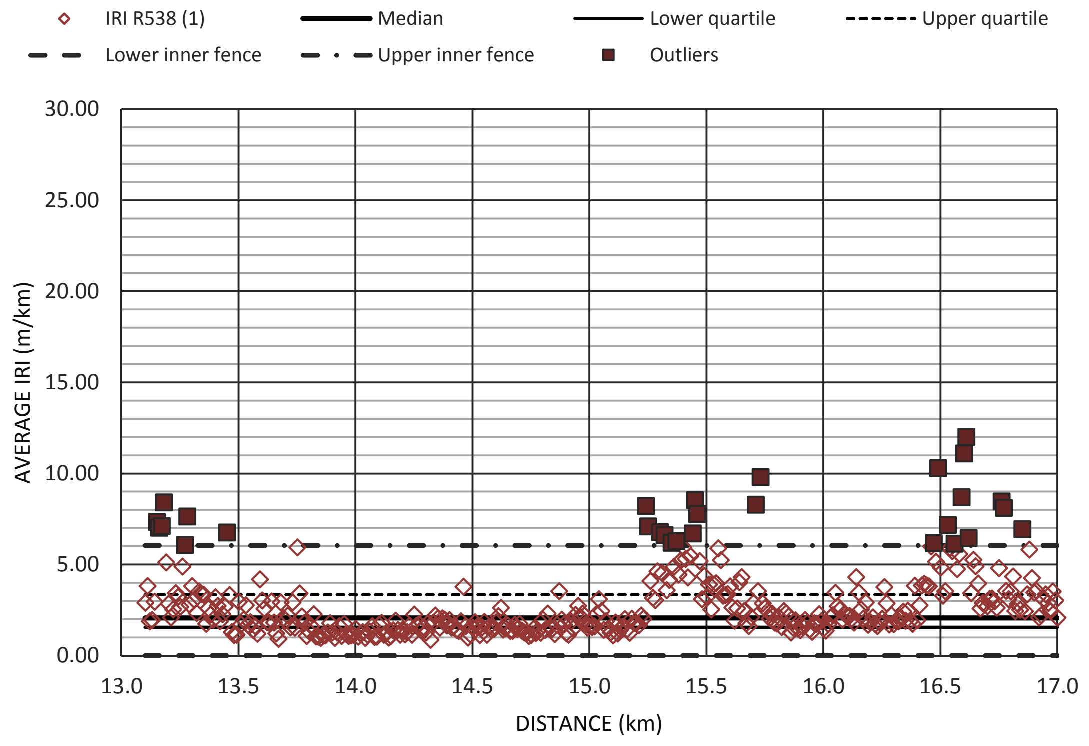

Figure 5-1: IRI outlier data on the R538(1)

Bridge joint at km 13.15

Patch at km 15.44

Patch and Surface failures at km 16.76

Figure 5-2: Outlier sections (R538(1)), SRT (2013)

Figure 5-3 indicates the measured data on the R538(2). This road section was quite short, and one continuous outlier section was identified (Table 9-11). The reason for this outlier was consecutive surface failures (potholes), indicated in Figure 5-4.

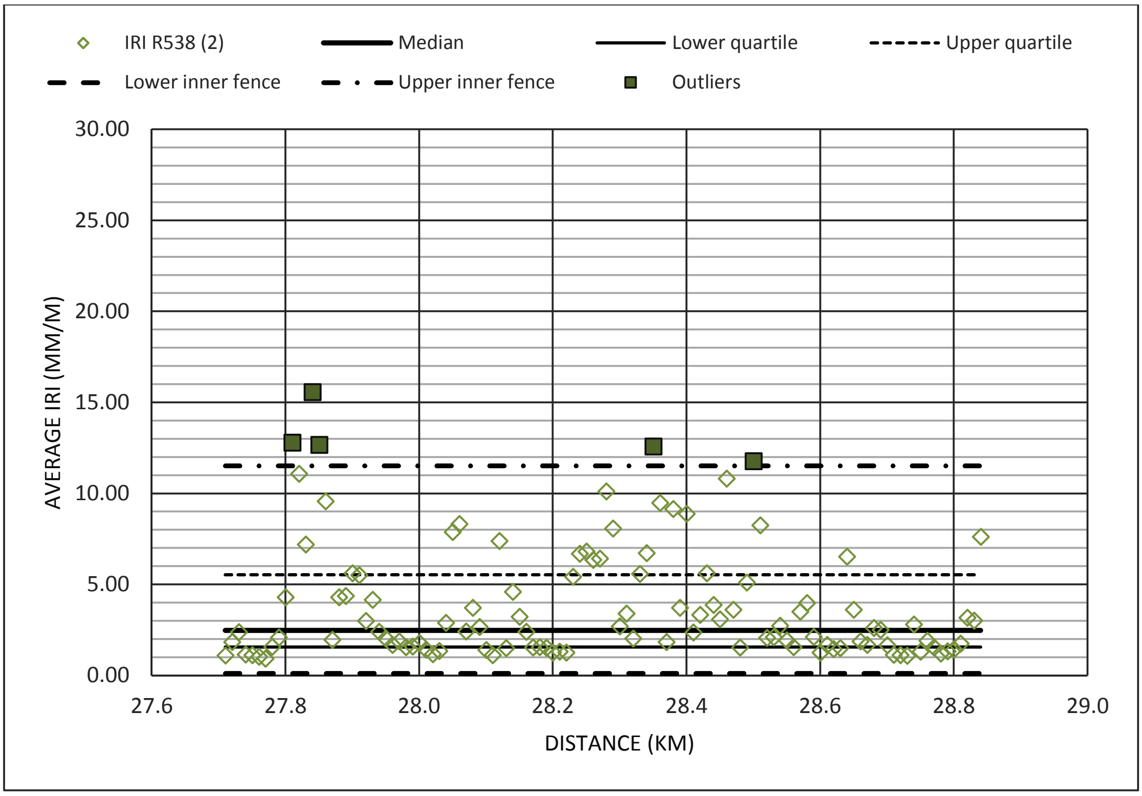

Figure 5-3: IRI outlier data on the R538(2)

Figure 5-4: Surface Failures km 27.84 R538(2), SRT (2013)

In Figure 5-5, the measured data of the Municipal road in Daantjie are presented. This road section was in quite a state, and the highest IRI value was measured on this section. The identified outlier sections are indicated in Table 9-15.

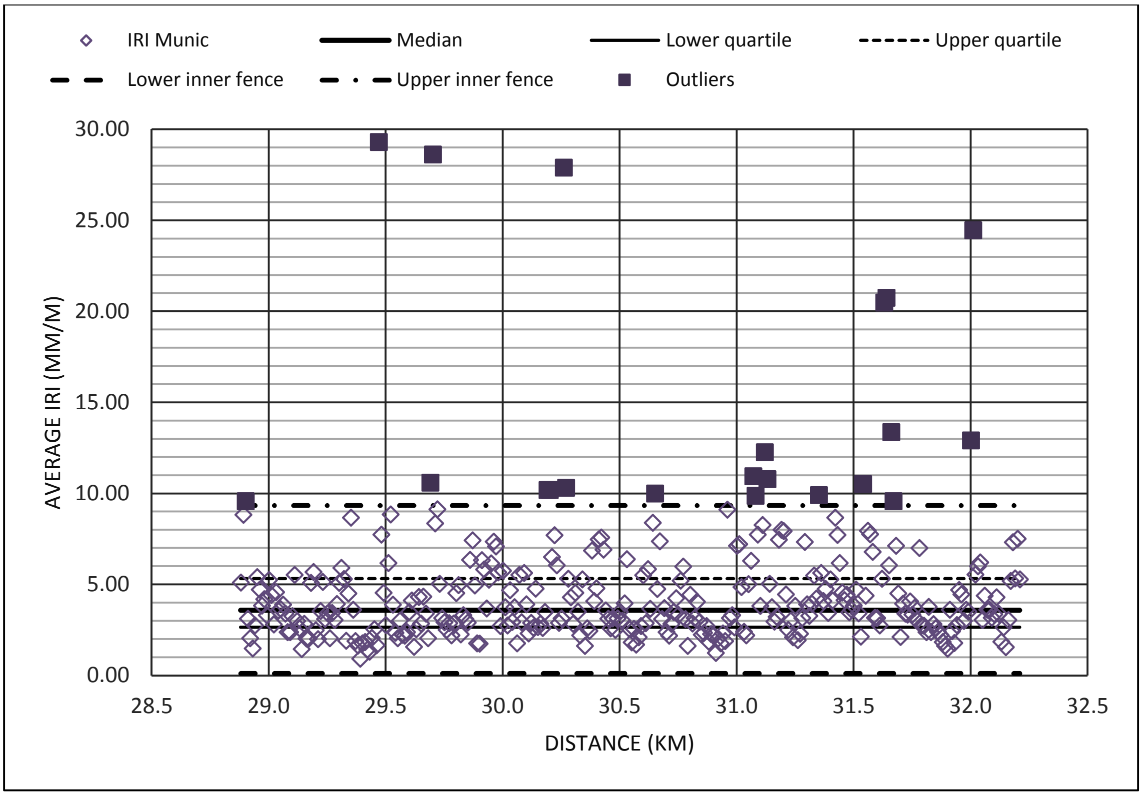

Figure 5-5: IRI outlier data on the Municipal Road

Figure 5-6 indicates the reason for the anomalies. This road had quite a number of speedhumps as the section was in a residential area. The community tried to curb speeding by requesting speedhumps that were higher than standard. The speedhumps have a negative effect on the riding quality, bus suspension, vehicle operating cost and fuel consumption. On this section, the speedhumps were indicated as anomalies, although it was not per definition an outlier, as it was still part of the bus route and did affect the riding quality and VOCs. The speedhumps on this section were at km 29.69, km 30.26, km 31.63, km 31.66 and km 32. The remaining anomalies were uneven patching and surface failures such as potholes.

Speedhump at km 29.69

Speedhump at km 30.26

Uneven patch at km 31.07

Surface Failure at km 31.12

Figure 5-6: Outlier sections (Municipal road), SRT (2013)

The measured data of a section of D2296 are indicated in Table 9-18. This section was in an average state, the identified anomalies were in the fair to mediocre, and in the poor category. The fair to mediocre values will not be analysed as anomalies, but as part of the data, as the values still fell in the category fair to mediocre. The values in the poor category, however were analysed as anomalies.

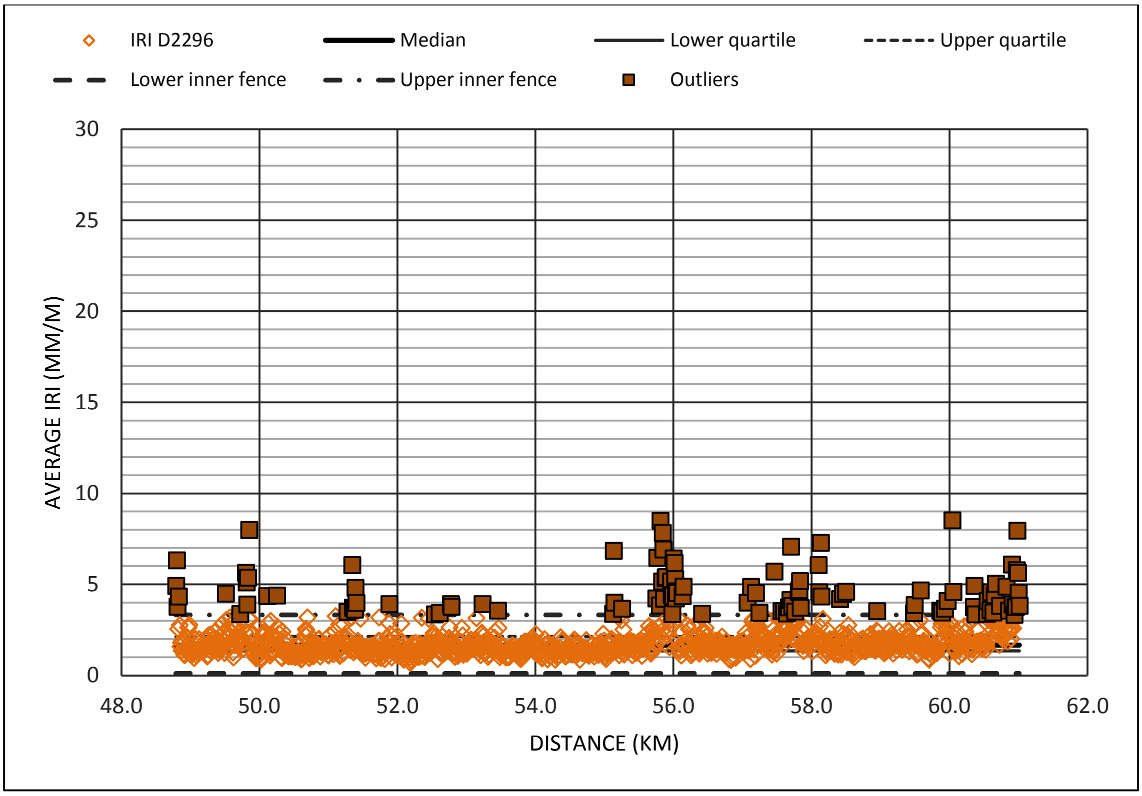

Figure 5-7: IRI outlier data on the D2296

The reason for the anomalies are indicated in Figure 5-8, there were bridge joints at km 49.8, km 58.13 and at km 60.04. There were consecutive potholes at km 55.75 and at km 55.84. The last outlier section was identified as the surfacing changed to concrete paving blocks, which had a higher IRI and it was in a sharp horizontal curve. The only section that was identified as an outlier, but could not determine why is section 4 in Table 9-18 at km 55.99. It could be uneven patching or a vertical dip in the road, this section is indicated in Figure 5-9.

Bridge joint at km 49.8

Surface faliure at km 55.84

Bridge joint at km 58.13

Surfacing changed to paving blocks

Figure 5-8: Outlier sections (D2296), SRT (2013)

Figure 5-9: Outlier at km 56.06, SRT (2013)

5.4 Power Spectral Density versus IRI

In Figure 4-11, in section 4, it was indicated that the accelerometer sensors with the highest and second highest average PSD were sensor 11 and 12. This data correlated with the research conducted and indicated in section 2 that the highest accelerations were located at the rear of a truck and at the rear of a trailer. The weighted averages were calculated by dividing the product of the length of the section and PSD by the sum PSD values. The length of the section weights the weighted average.

5.4.1 N4

Table 5-5 indicates the calculated weighted averages for PSD for sensor 11 and 12. The isolated section data are indicated in Figure 5-10, and the weighted average of sensor 11 and 12 is indicated as a solid and dotted line respectively. The IRI values were (as expected) quite low on this section of road, reason was that this section of road was built recently.

However, it could be noted that for the same IRI there exist a low and high PSD value. Therefore, to compliment the research indicated in the literature review, one cannot only look at the IRI, but should also investigate the area PSD values and vertical acceleration generated by the road.

Table 5-5: PSD weighted averages for N4

	IRI (m/km)	PSD S11 (g^2)	PSD S12 (g^2)
Very good to good	1.39	0.147	0.164
Fair to mediocre	2.88	0.230	0.266
Poor	4.83	0.213	0.287

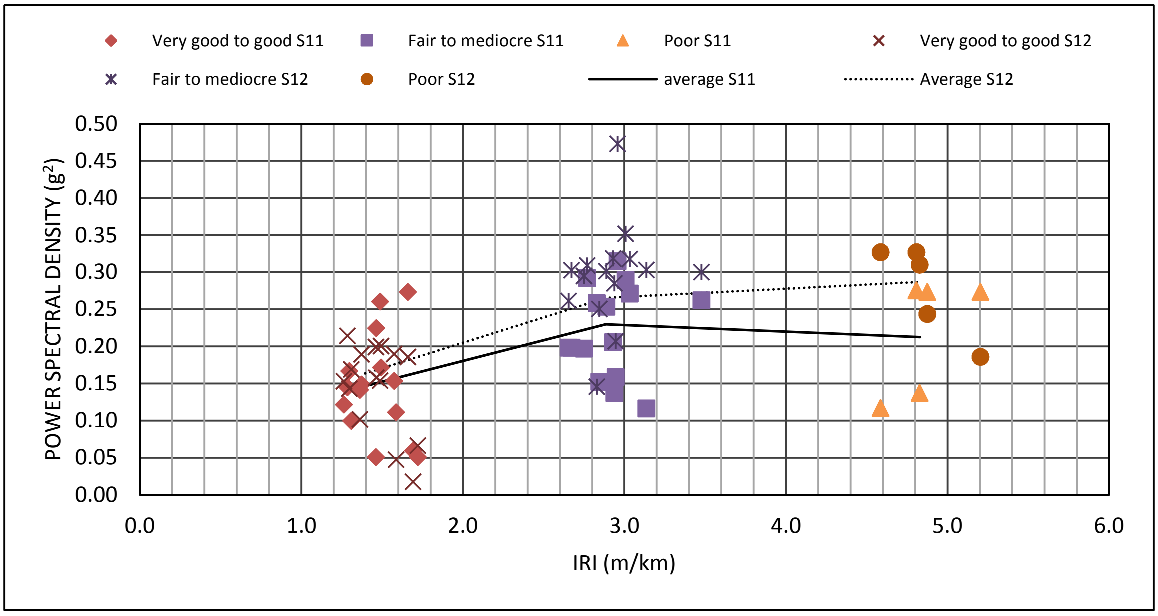

Figure 5-10: PSD versus IRI - N4

5.4.2 R538(1)

This section was expected to have high IRI values, and by comparing the weighted IRI averages (Table 5-6) to the weighted IRI averages of the N4, the values of the R538(1) is higher. The IRI values over the whole section (Table 5-3) indicated that 55.4 per cent of the road was in a good to very good conditions, 28.5 per cent of the road was in a fair to mediocre condition, 8.7 per cent was in a poor condition and 7.4 per cent of the road fell in the outlier category.

The data are graphically indicated in Figure 5-11, the anomalies in the graph were analysed with the data, as it was termed anomalies, but it was part of the road (either surface failures, speedhumps or other defects in the road). Similar with the data observed on the N4, there was more than one PSD value for the same IRI value.

Table 5-6: PSD weighted averages for R538(1)

	IRI (m/km)	PSD S11 (g^2)	PSD S12 (g^2)
Very good to good	1.56	0.155	0.153
Fair to mediocre	3.14	0.107	0.244
Poor	5.53	0.111	0.219
Anomalies	8.04	0.074	0.176

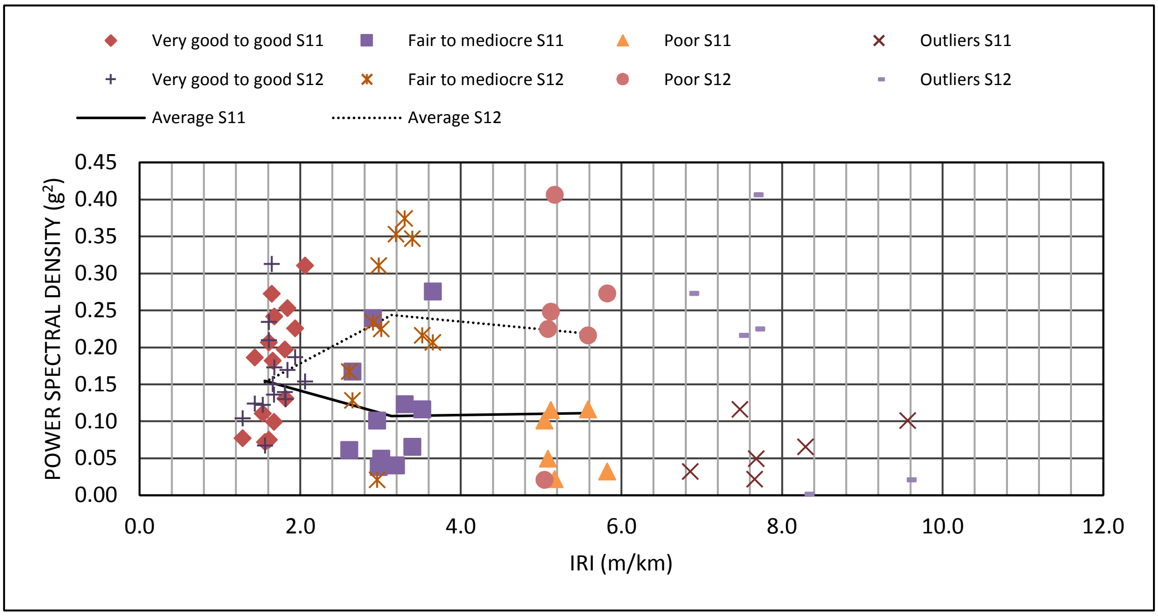

Figure 5-11: PSD versus IRI – R538(1)

5.4.3 R538(2)

The IRI values of this section were also expected to be quite high. The IRI values over the whole section (Table 5-3) indicated that 45.6 per cent of the road was in a good to very good condition, 22.8 per cent of the road was in a fair to mediocre condition, 27.2 per cent was in a poor condition and 4.4 per cent of the road fell in the outlier category.

Table 5-7: PSD weighted averages for R538(2)

	IRI (m/km)	PSD S11 (g^2)	PSD S12 (g^2)
Very good to good	1.47	0.112	0.158
Fair to mediocre	3.06	0.109	0.176
Poor	6.85	0.163	0.276
Anomalies	14.12	0.120	0.150

However, by inspecting the weighted averages of the very good to good and fair to mediocre sections in Table 5-7, the values were lower than the N4 measured values. The poor and outlier sections, however, had very high values, reason could be that there were bus stops on this section where the bus stops next to the road on a badly maintained gravel shoulder. This section of road had more surface failures and defects than the N4, and was therefore expected to have higher weighted average IRI values, than the N4. The measured and analysed data are indicated in Figure 5-12, the calculated weighted average values are indicated for sensor 11 and 12.

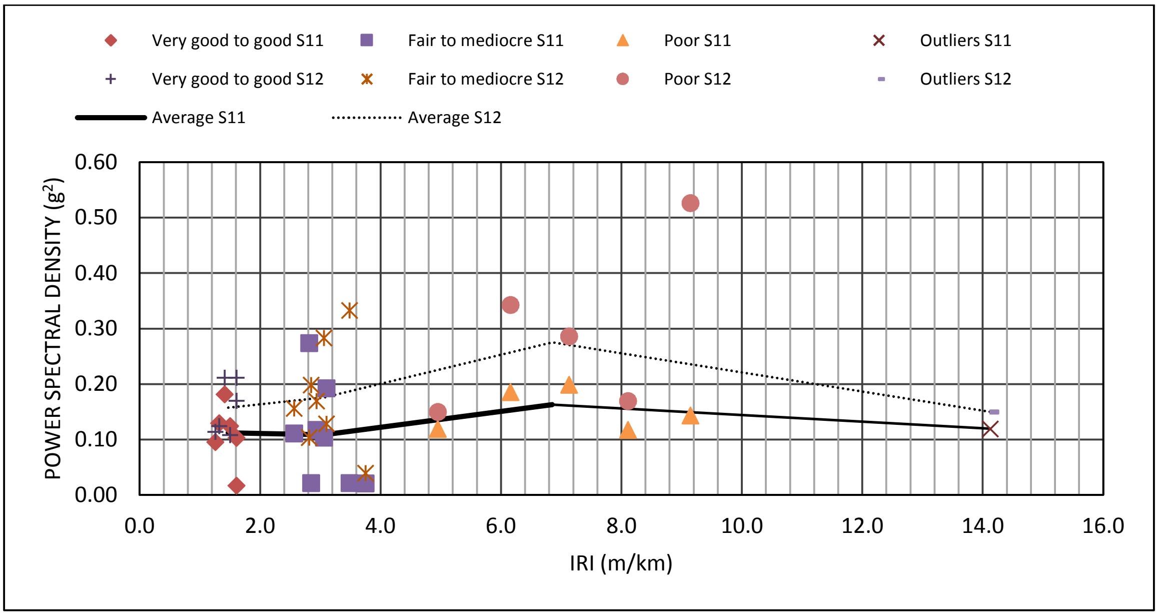

Figure 5-12: PSD versus IRI – R538(2)

5.4.4 Municipal Road

The weighted average values determined from the data measured on the municipal road in Daantjie are indicated in Table 5-8, these values look similar to the weighted averages indicated in Table 5-7 for the provincial road R538(2). This corresponds with the prediction that the IRI values would be higher (Table 5-3), as the road was not regularly maintained. The plotted values for sensor 11 and 12 are indicated in Figure 5-13.

Table 5-8: PSD weighted averages for Municipal Road

	IRI (m/km)	PSD S11 (g^2)	PSD S12 (g^2)
Very good to good	1.76	0.149	0.239
Fair to mediocre	3.09	0.133	0.185
Poor	6.32	0.129	0.188
Anomalies	15.20	0.097	0.266

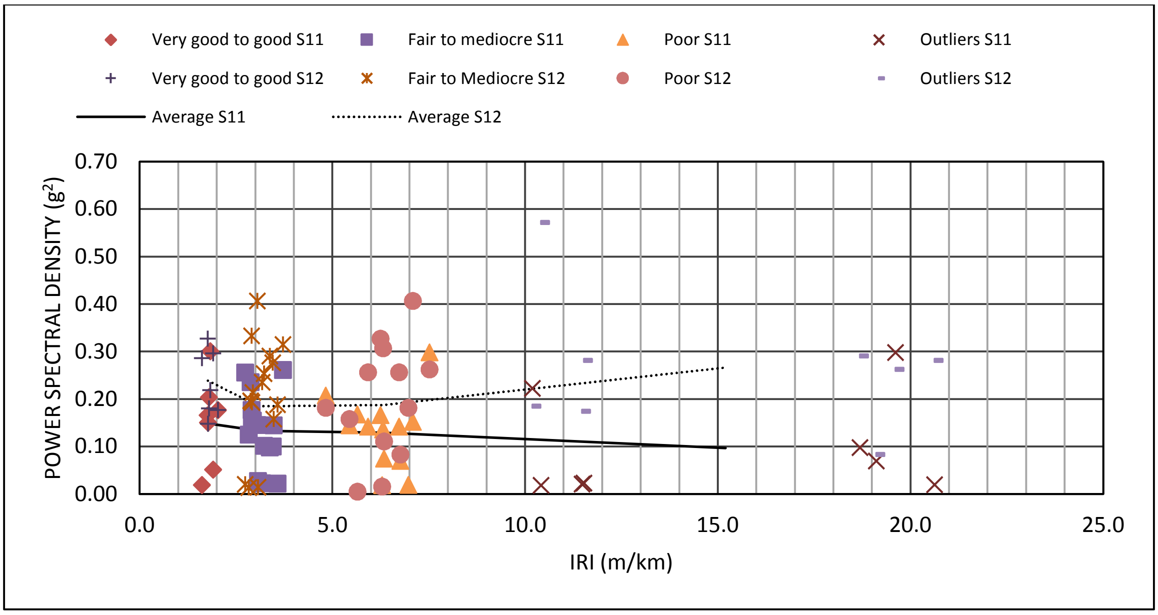

Figure 5-13: PSD versus IRI – Municipal Road

5.4.5 D2296

The values presented in Table 5-3 indicated that this road was in a very good condition, the IRI weighted average values calculated from the data (Table 5-9), relate to Table 5-3. However, the calculated weighted average area PSD values were fairly high, reason could be that these sections were bus stops. The bus stops on this road were on the gravel shoulder, and the profiler did not measure these deviations from the route.

Table 5-9: PSD weighted averages for D2296

	IRI (m/km)	PSD S11 (g^2)	PSD S12 (g^2)
Very good to good	1.45	0.196	0.236
Fair to mediocre	2.66	0.200	0.308
Poor	3.69	0.203	0.301
Anomalies	5.64	0.199	0.462

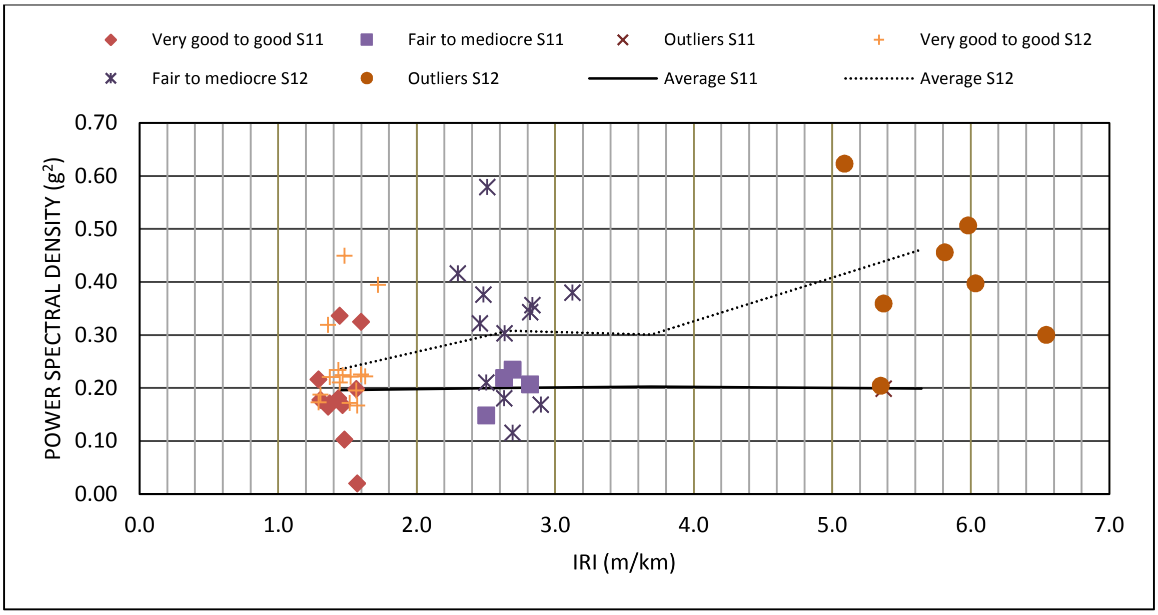

Figure 5-14: PSD versus IRI – D2296

5.5 Vertical Acceleration (a_{wz}) versus IRI versus Speed

Comfort is difficult to evaluate objectively, as user perception of dynamic effects plays a large role. The literature study indicated that to determine the comfortability of a road the evaluation of the root mean square (RMS) acceleration was required. The vertical RMS acceleration (a_{wz}) was calculated for each isolated section.

Indicated in Table 2-3, were the threshold values of a_{wz} from ISO 2631-1:1997, the threshold values were combined into three categories, as with the IRI thresholds, and it is indicated in Table 5-10. Upon further analysis of the data, it became apparent that these values might be too high. The values that fell in the uncomfortable range should be in the extremely uncomfortable range, as the IRI values and the visual condition of the road suggests that this section was in a bad condition. These findings correlate with the findings indicated in the literature study by Cantisani and Loprencipe (2010). Therefore, the proposed speed related a_{wz} thresholds by Cantisani and Loprencipe (2010) were adopted for the analysis of the data. The categories were combined, and are indicated in Table 5-10.

Table 5-10: Combined a_{wz} categories

Category	ISO 2631-01:1997 (m/s²)	Cantisani and Loprencipe (2010) speed related a_{wz} thresholds (m/s²)
Not Uncomfortable	<=0.63	<=0.315
Uncomfortable	0.63-1.6	0.315-0.9
Extremely Uncomfortable	>2	>0.9

5.5.1 N4

Table 5-11 indicates the calculated weighted average IRI and a_{wz} of sensor 11 and 12. Indicated in Figure 5-15 is the values calculated of each section as well as the weighted average a_{wz} values of sensor 11 and 12, indicated as a solid and dotted line respectively.

The threshold values of the IRI and a_{wz} is indicated as green, yellow and red. The values below the green line are in the very good to good IRI category and in the not uncomfortable a_{wz} category. The values between the green and red line (the orange line indicates the centre), is the fair to mediocre IRI category and in the uncomfortable a_{wz} range. The values that exceeds the red threshold line, indicates the poor IRI category and in the extremely uncomfortable a_{wz} range.

Table 5-11: a_{wz} weighted averages for N4

	IRI (m/km)	a_{wz} S11 (m/s^2)	a_{wz} S12 (m/s^2)	Speed (km/h)
Very good to good/ Not Uncomfortable	1.39	0.634	0.615	73.05
Fair to mediocre/ Uncomfortable	2.88	0.820	0.920	76.32
Poor/ Extremely Uncomfortable	4.83	0.692	0.770	67.08

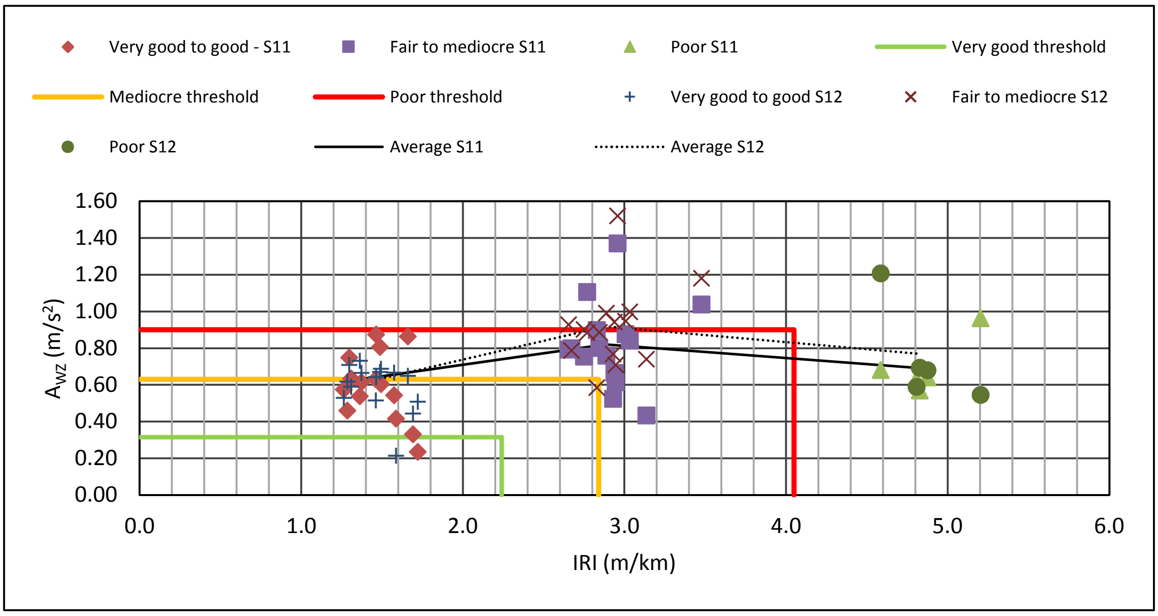

Figure 5-15: a_{wz} versus IRI – N4

The a_{wz} values, as with the IRI values were expected to be quite low on this route. It was also expected that the higher the IRI the higher the vertical accelerations. The weighted averages, however, indicate lower accelerations at higher IRI values. Another parameter that should be included in the discussion is speed. The vertical accelerations were influenced by the IRI and speed of the vehicle. Cantisani and Loprencipe (2010) indicated that a surface failure will register a high IRI value, but depending on the speed the vehicle travel over that surface failure, the accelerations could be high and low. Therefore, Cantisani and Loprencipe (2010) indicated that if the vehicle speed was reduced, a higher level of roughness could be tolerated.

It should also be kept in mind that the data indicated in this discussion were real values, these values were deduced from an actual bus travelling on an actual road. Therefore, the speed of the bus changed as required by the road condition. Steyn and Du Plessis (2014) observed a relationship between speed and roughness. The relationship is indicated in Equation 5-1, the units of the speed is in mile per hour and the unit of IRI is inch/mile.

$$Speed = -0.1254IRI + 55.55$$

Equation 5-1: Relationship between Speed and IRI (Steyn and Du Plessis, 2014)

Figure 5-16 indicates a three dimensional plot of the vertical accelerations, IRI and average speed of the bus at the corresponding IRI value, the coefficient of determination (R^2) is 0.38 and the Standard Error (SE) is 0.19. The vertical accelerations were calculated from the accelerometers mounted on the bus, the speed was calculated from the GPS points recorded during the survey, and the IRI was obtained from the profiler data. The profiler travelled at an average speed on 70 km/h. Compared to the speed of the bus, it differs very little and was assumed to have very little impact on the analysis. Google Earth (2013) was used to correlate the GPS points with the isolated sections and IRI. Indicated in Figure 5-16 high acceleration values were recorded at high speeds and at high roughness values.

In Figure 5-17 the speed versus IRI is presented. The thresholds, indicated in green, orange and red, were deduced from the research done by Cantisani and Loprencipe (2010). The values that plot above the mediocre threshold were in the poor IRI and very and extremely uncomfortable a_{wz} range (higher than 0.9 m/s^2). The values that plot between the mediocre and good threshold fell in the mediocre IRI and fairly uncomfortable a_{wz} range (0.63-0.9 m/s^2). The values that plot between the good and very good threshold fell in the mediocre IRI and little uncomfortable a_{wz} range (0.315-0.63 m/s^2). The values that plot below the very good threshold fell in the very good IRI and comfortable a_{wz} range (lower than 0.315 m/s^2).

The plotted values in Figure 5-17 confirmed the research conducted by Cantisani and Loprencipe (2010), the values recorded and sorted in the good to very good, fair to mediocre and poor category each (versus speed) fell in the same category as proposed by Cantisani and Loprencipe (2010).

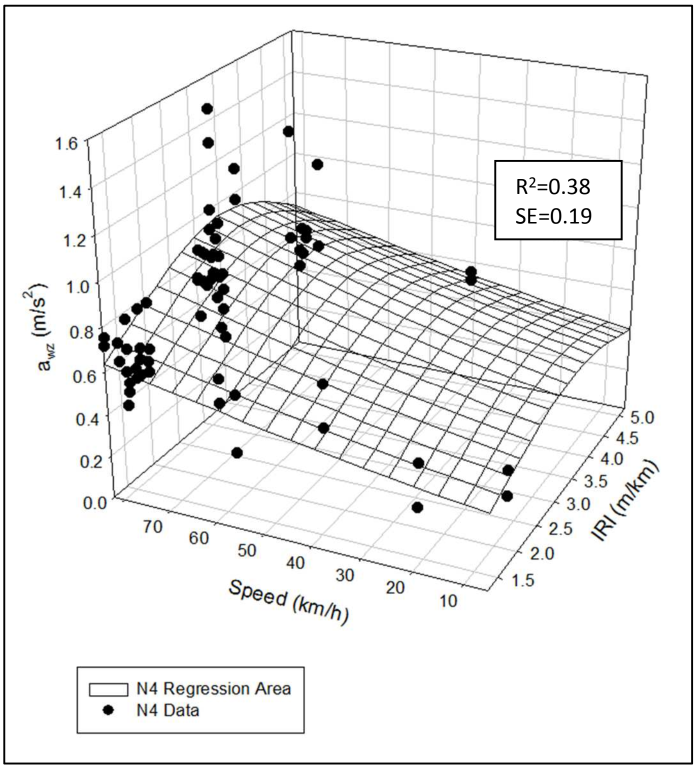

Figure 5-16: 3D Plot a_{wz} versus IRI versus Speed – N4

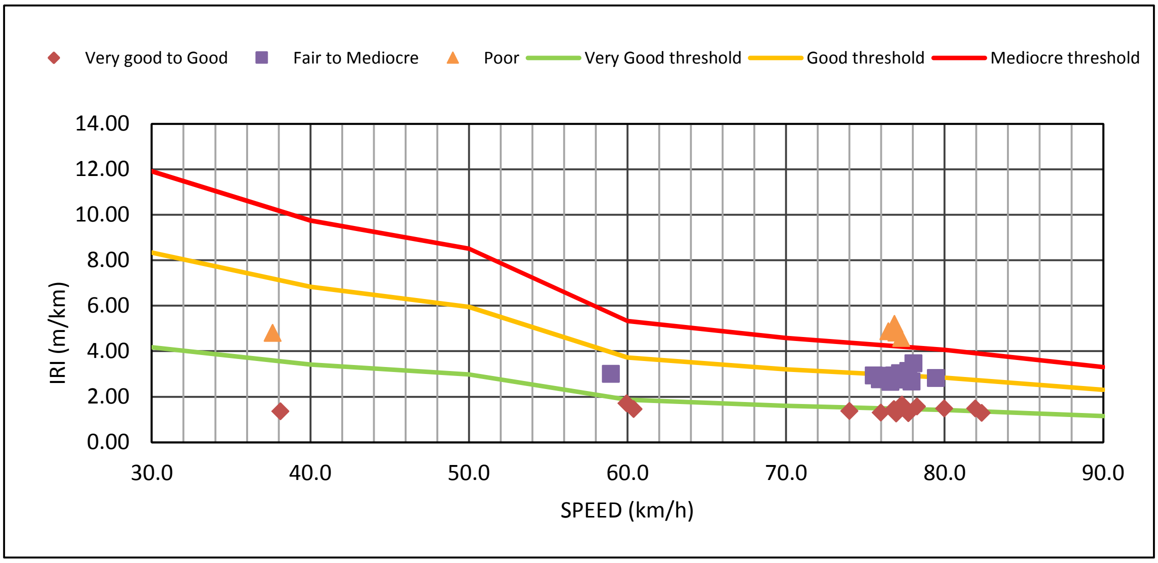

Figure 5-17: Speed versus IRI – N4

5.5.2 R538(1)

The weighted average values for this section of the route are indicated in Table 5-12 and Figure 5-18. The data recorded on sensor 12 followed the expected trend, as the IRI and speed of the bus increase, the accelerations increase. The data recorded from sensor 11, shows a different trend, however, the average values of sensor 12 are still higher than for sensor 11. It was expected that the vibrations would be higher at the rear of the trailer, than at the rear of the bus. The average speed of the profiler for this section was 59, which could have had an impact on the very good to good data range, however, it was assumed as very little.

Table 5-12: a_{wz} weighted averages for R538(1)

	IRI (m/km)	a_{wz} S11 (m/s^2)	a_{wz} S12 (m/s^2)	Speed (km/h)
Very good to good/ Not Uncomfortable	1.56	0.585	0.550	47.202
Fair to mediocre/ Uncomfortable	3.14	0.453	0.712	57.452
Poor/ Extremely Uncomfortable	5.53	0.262	0.837	64.590

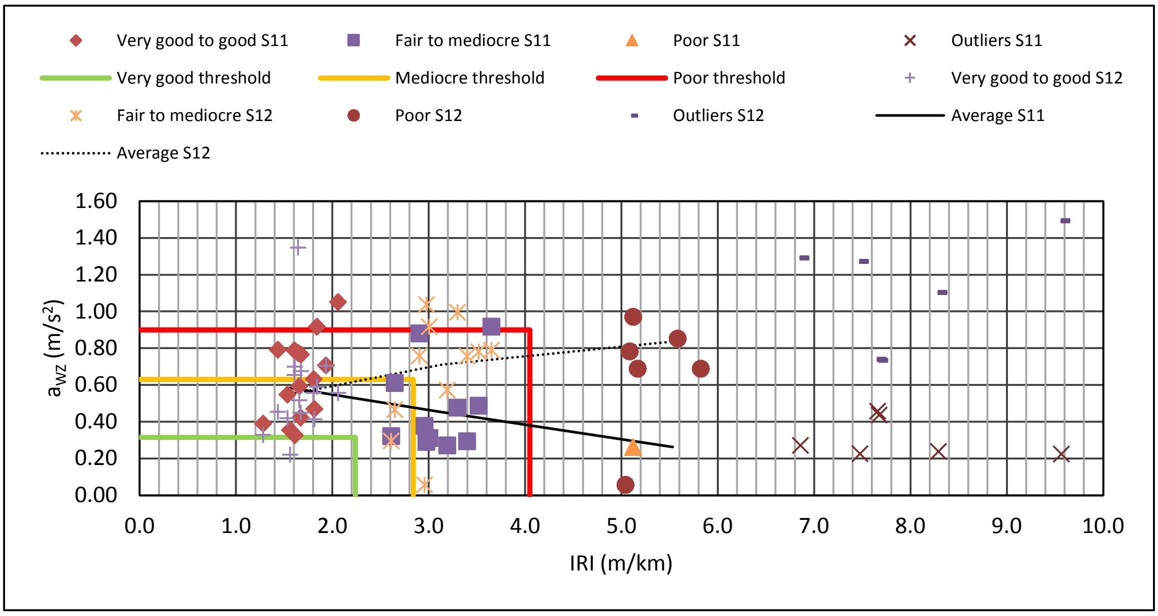

Figure 5-18: a_{wz} versus IRI – R538(1)

The three dimensional plot of IRI versus speed versus a_{wz} is presented in Figure 5-19, R^2 is 0.15 SE is 0.29. It seemed to follow the same trend as indicated with the N4 values, that high acceleration values were recorded at high speeds and at high roughness values.

The recorded values of the isolated sections is presented in Figure 5-20, speed versus IRI. The values fall in the correct category at speeds higher than roughly 50 km/h. Speeds lower than 50 km/h could indicate an anomaly in the data, such as a traffic signal, or stop controlled intersections.

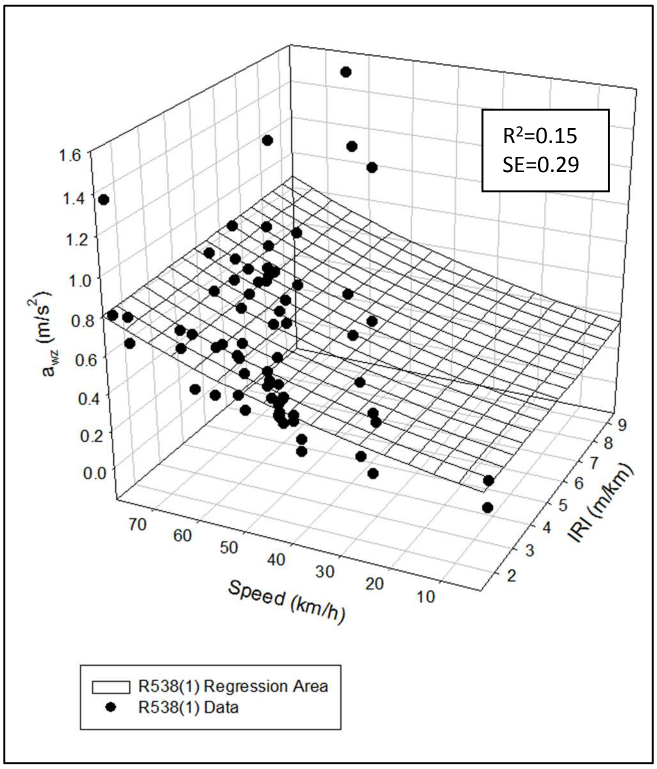

Figure 5-19: 3D Plot a_{wz} versus IRI versus Speed – R538(1)

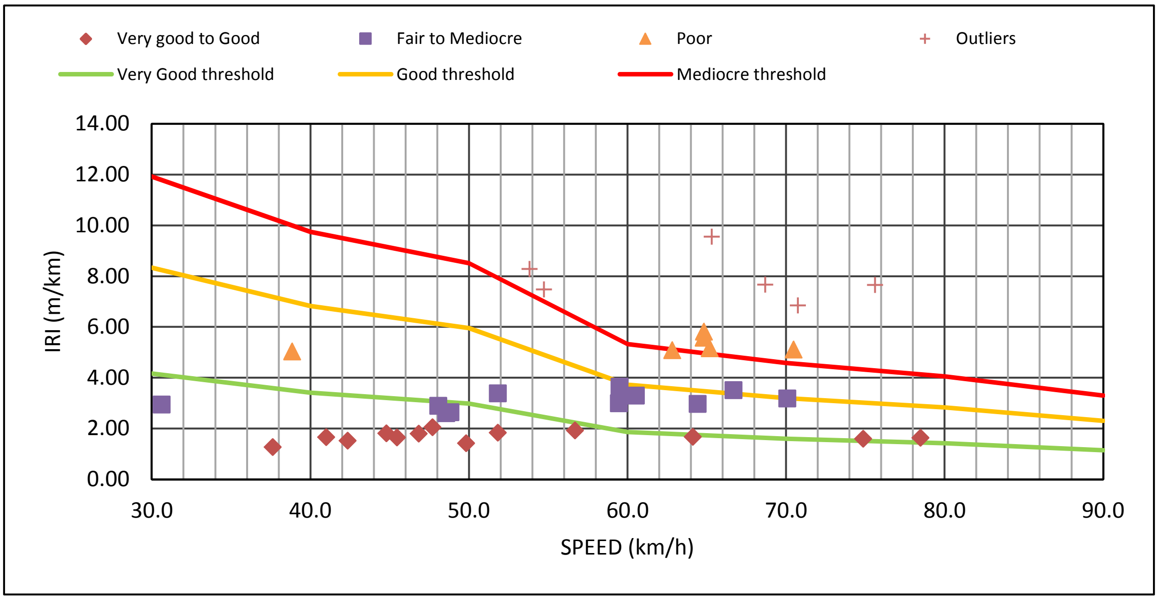

Figure 5-20: Speed versus IRI – R538(1)

5.5.3 R538(2)

Table 5-13 indicates the weighted average values of the isolated data for this section of the route, Figure 5-21 indicates the isolated data and the weighted averages. In relation to the N4 data, the IRI values recorded on this section were higher, which was expected. The accelerations, however, were recorded as lower, even though this section was visibly in a worse condition than the N4. The difference in values could be the variation in speed. On this section, it was not possible to drive 60 km/h as the road was in a deteriorating state, and there were too many potholes and speedhumps. Therefore, in order to prevent further damage to the bus, the driver had to drive slowly. The speeds indicated in Table 5-13 were significantly lower than recorded for the N4, the average speed of the profiler was 39 km/h, which was very low. This is not ideal, as the state of road, congestion, speedhumps, and consecutive bus stops, resulted in longer travel time. The impact of deteriorating riding quality on travel time and congestion were deemed outside the scope of this study.

Table 5-13: a_{wz} weighted averages for R538(2)

	IRI (m/km)	a_{wz} S11 (m/s^2)	a_{wz} S12 (m/s^2)	Speed (km/h)
Very good to good/ Not Uncomfortable	1.47	0.530	0.504	28.961
Fair to mediocre/ Uncomfortable	3.06	0.515	0.721	25.409
Poor/ Extremely Uncomfortable	6.85	0.588	0.984	28.228

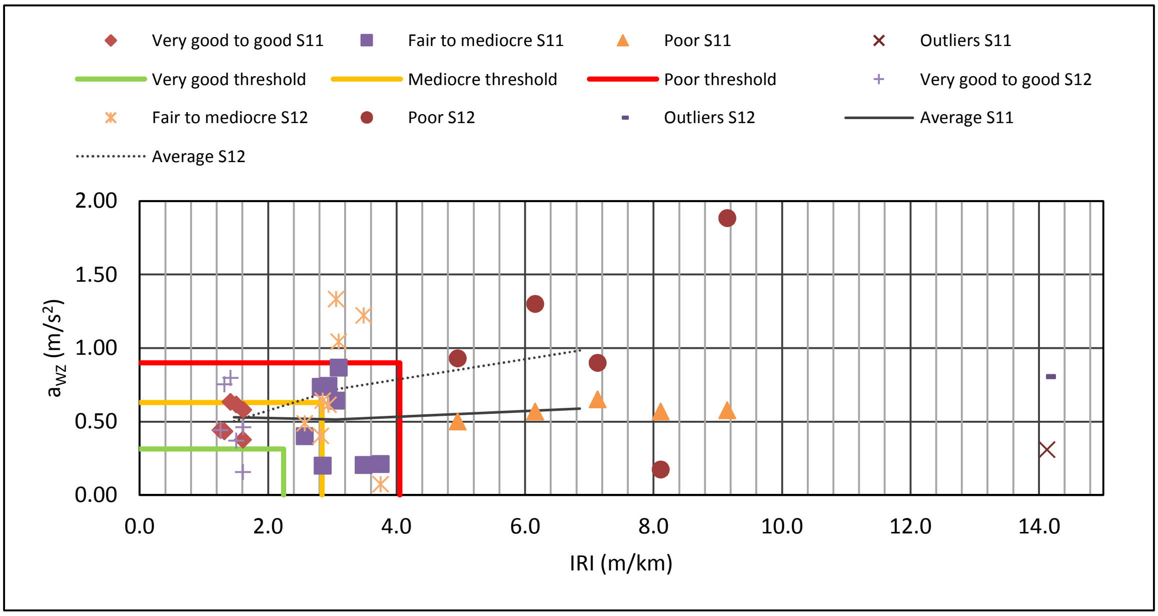

Figure 5-21: a_{wz} versus IRI – R538(2)

Indicated in Figure 5-22 is a three dimensional plot of the accelerations versus speed versus IRI, R^2 is 0.21 SE is 0.34. The recorded speeds on this sections were very low. This section, however, was also very short (approximately 1 km) relative to the other sections. After the data analysis (which includes isolating similar sections), it seemed that it may be too short to make relevant conclusions with this data. The speed versus IRI (Figure 5-23) correlate with the findings that this section might be too short to make relevant conclusions.

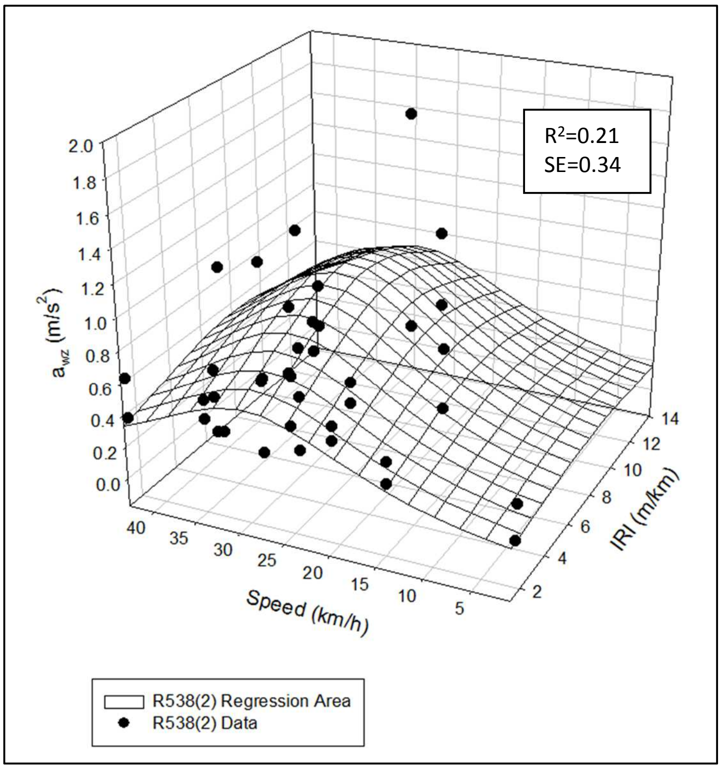

Figure 5-22: 3D Plot a_{wz} versus IRI versus Speed – R538(2)

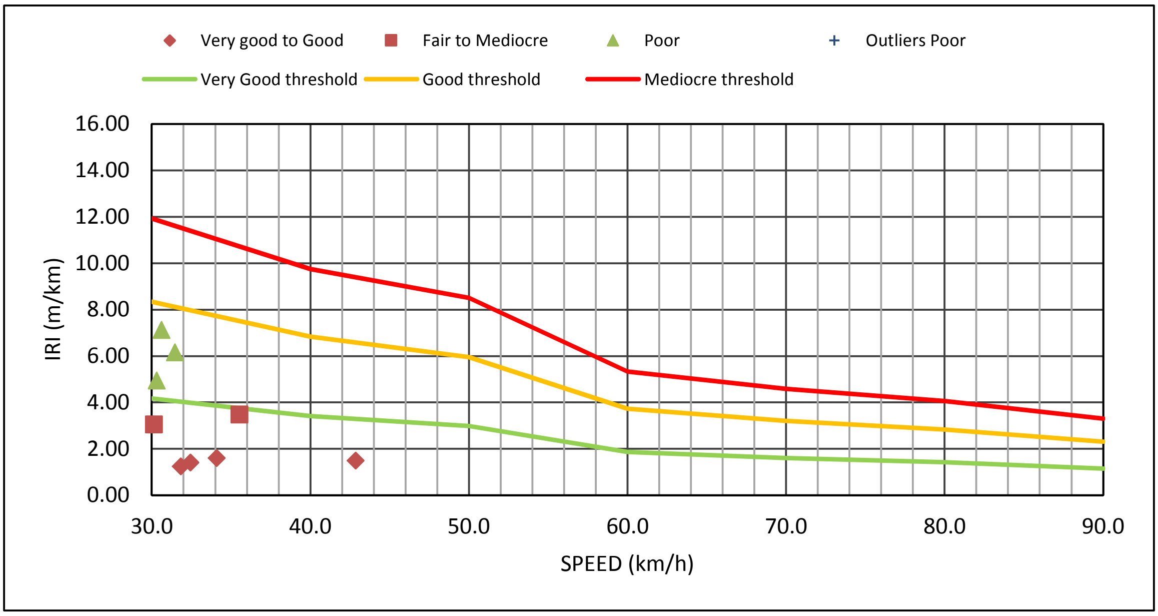

Figure 5-23: Speed versus IRI – R538(2)

5.5.4 Municipal Road

In Table 5-14 is the weighted averages calculated from the isolated section on the municipal road in Daantjie (Mpumalanga) and the values are indicated in Figure 5-24. Similar to the data recorded on the R538(2), the average speeds on this section of the route were very low. The IRI values were also very high on this route, the a_{wz} values, however, for the not uncomfortable and extremely uncomfortable ranges were higher than the values recorded on the N4. The average speed of the profiler on this road was very low, (38 km/h), which correlates with the low bus speed. Furthermore it indicates that the road was in a such as state that it is not possible to drive faster.

Table 5-14: a_{wz} weighted averages for Municipal Road

	IRI (m/km)	a_{wz} S11 (m/s^2)	a_{wz} S12 (m/s^2)	Speed (km/h)
Very good to good/ Not Uncomfortable	1.76	0.441	1.047	37.882
Fair to mediocre/ Uncomfortable	3.09	0.582	0.735	27.892
Poor/ Extremely Uncomfortable	6.32	0.511	1.042	36.624

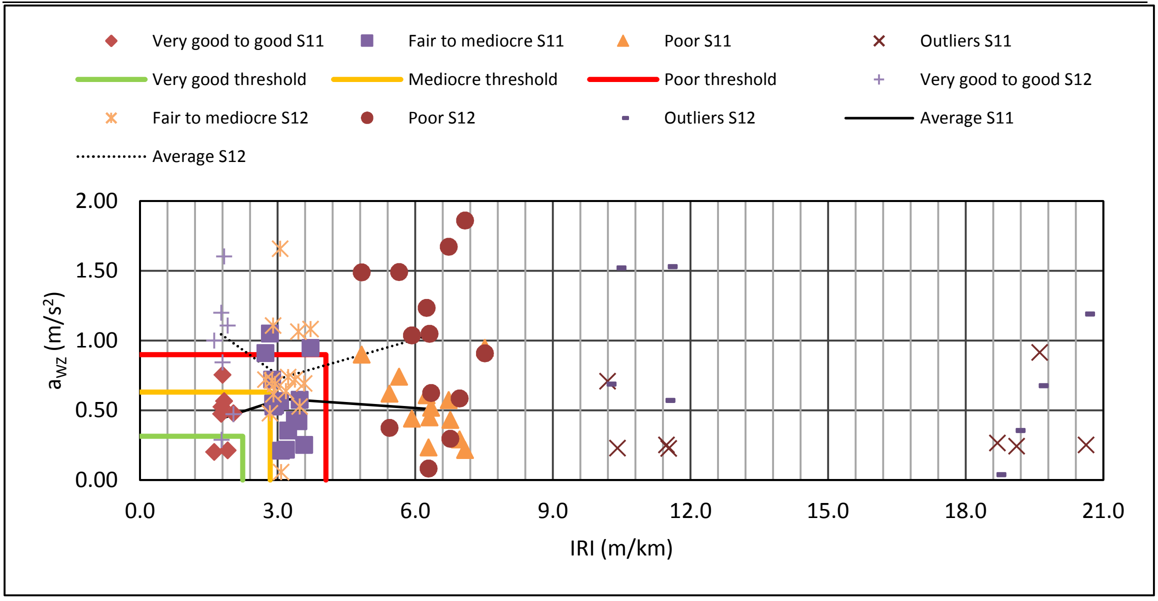

Figure 5-24: a_{wz} versus IRI – Municipal Road

The three dimensional plot in Figure 5-25 indicates high IRI and a_{wz} values with low speeds and high a_{wz} values, and low IRI values at high speeds. This is consistent with the data on the other sections of the route, and the speed plays a large role in the user perception of how the bus travelled on the road. The R^2 of the data is 0.05, which is lower compared to the data collected on the other sections of the route and the SE is 0.41, which is quite high. Reason could be that the data collected, ranged between speeds of 10 km/h and 65 km/h.

Figure 5-26 indicates the data of the municipal road section sorted in the thresholds as proposed by Cantisani and Loprencipe (2010). The very good to good and fair to mediocre values fell in the range as proposed by Cantisani and Loprencipe (2010), the poor values, however, according to this graph is actually still in the good range.

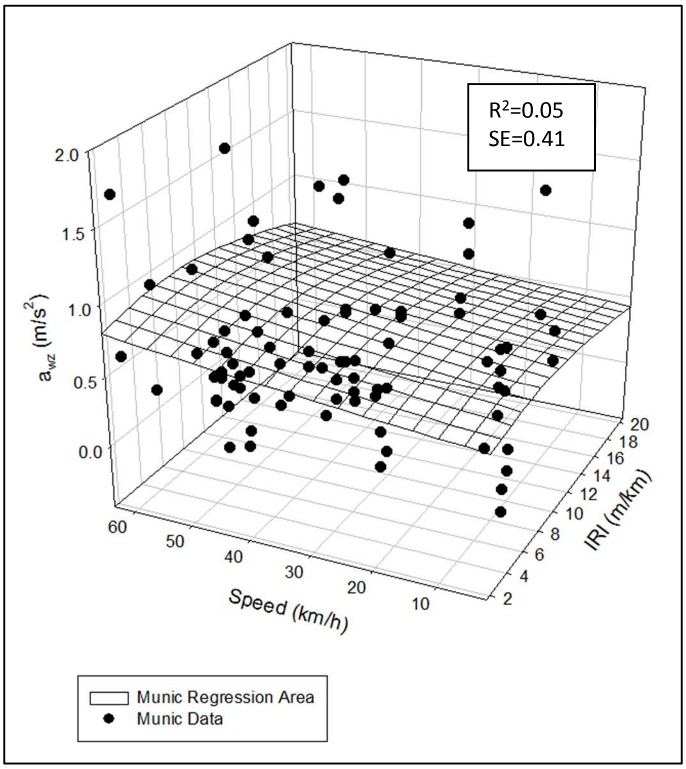

Figure 5-25: 3D Plot a_{wz} versus IRI versus Speed – Municipal Road

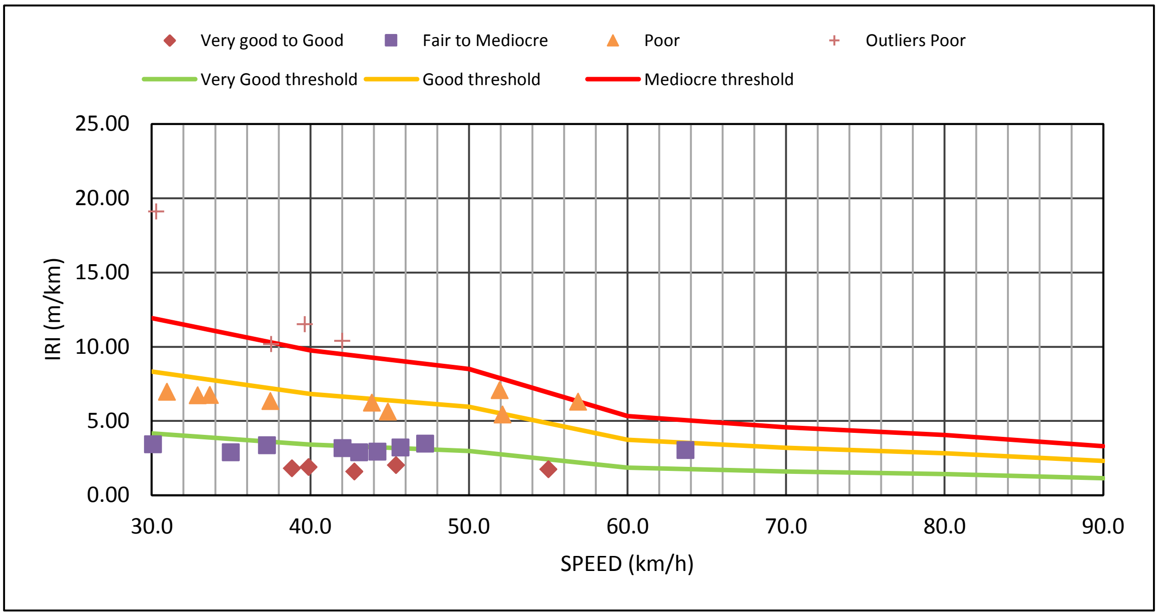

Figure 5-26: Speed versus IRI – Municipal Road

5.5.5 D2296

The weighted average values in Table 5-15 and the isolated data in Figure 5-27 indicate that this section of the route was in a better state than anticipated. The average IRI values for the fair to mediocre and poor range were lower than for the N4. The vertical acceleration values however were higher, but the average speed was lower. This could indicate that there were bus stops and/or congestion on this section of the route. In Figure 5-27 the data fell out of the threshold ranges indicated on the graph, the reason was the differentiating speed of the recorded vertical acceleration values. The recorded average speed of the profiler was 74 km/h for this road, which differs from the poor range, and it could have contributed to the irregularity in the data.

Table 5-15: a_{wz} weighted averages for D2296

	IRI (m/km)	a_{wz} S11 (m/s²)	a_{wz} S12 (m/s²)	Speed (km/h)
Very good to good/ Not Uncomfortable	1.45	0.787	0.867	72.756
Fair to mediocre/ Uncomfortable	2.66	0.692	1.072	69.220
Poor/ Extremely Uncomfortable	3.69	0.927	1.012	43.370

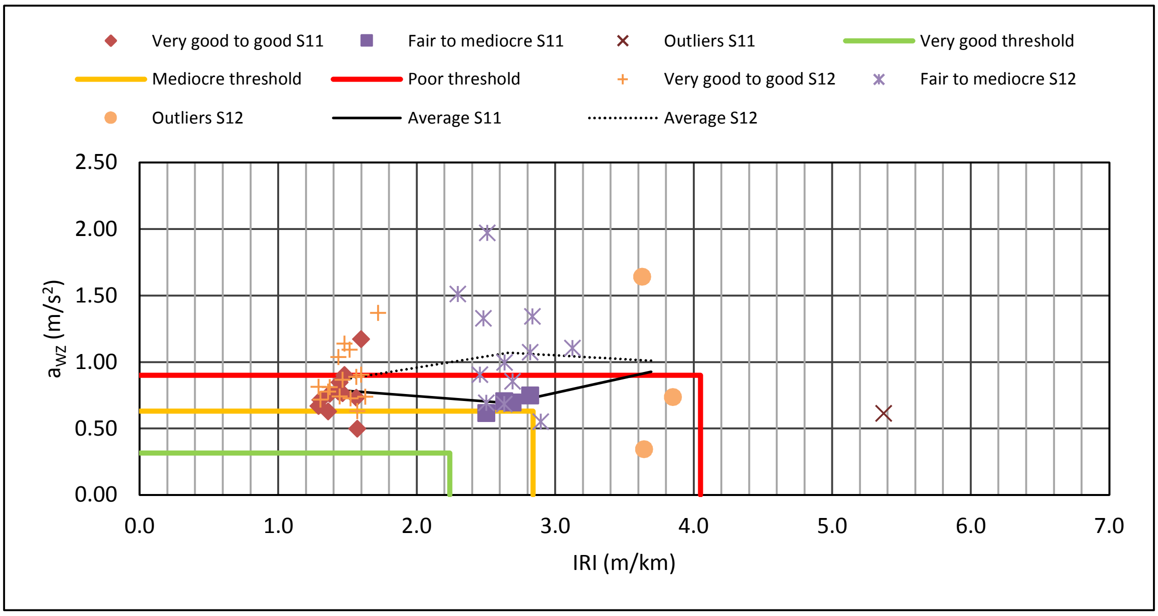

Figure 5-27: a_{wz} versus IRI – D2296

Figure 5-28 indicates the three dimensional plot of the speed versus IRI versus vertical acceleration. This plot indicates high IRI and vertical acceleration values at high speeds with an R^2 of 0.18 and a SE of 0.33.

Indicated in Figure 5-29 is the IRI versus speed categorised according to the threshold values developed by Cantisani and Loprencipe (2010). Some of the anomalies at low speeds tend to fall in a better category than what actually is, however, the recorded values at speeds higher than 60 km/h fall in the anticipated category.

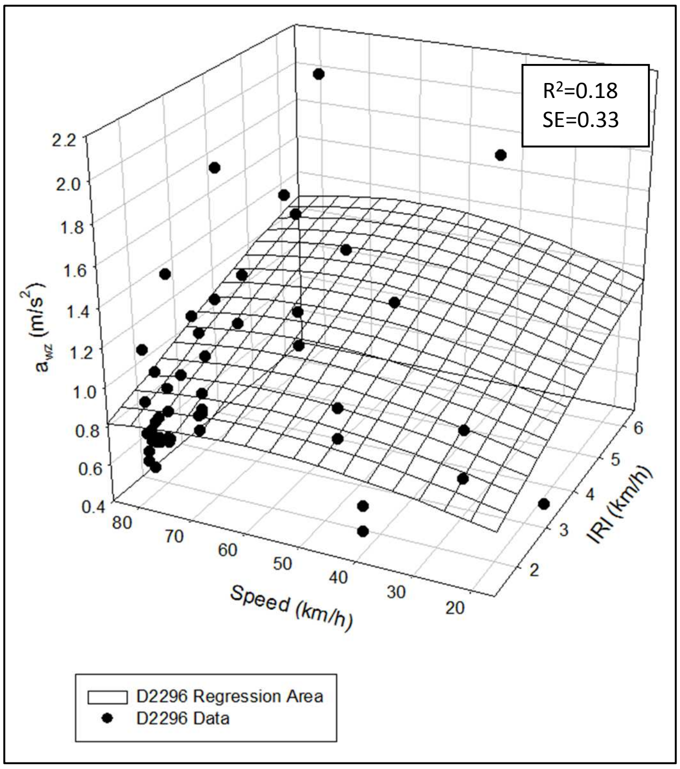

Figure 5-28: 3D Plot a_{wz} versus IRI versus Speed – D2296

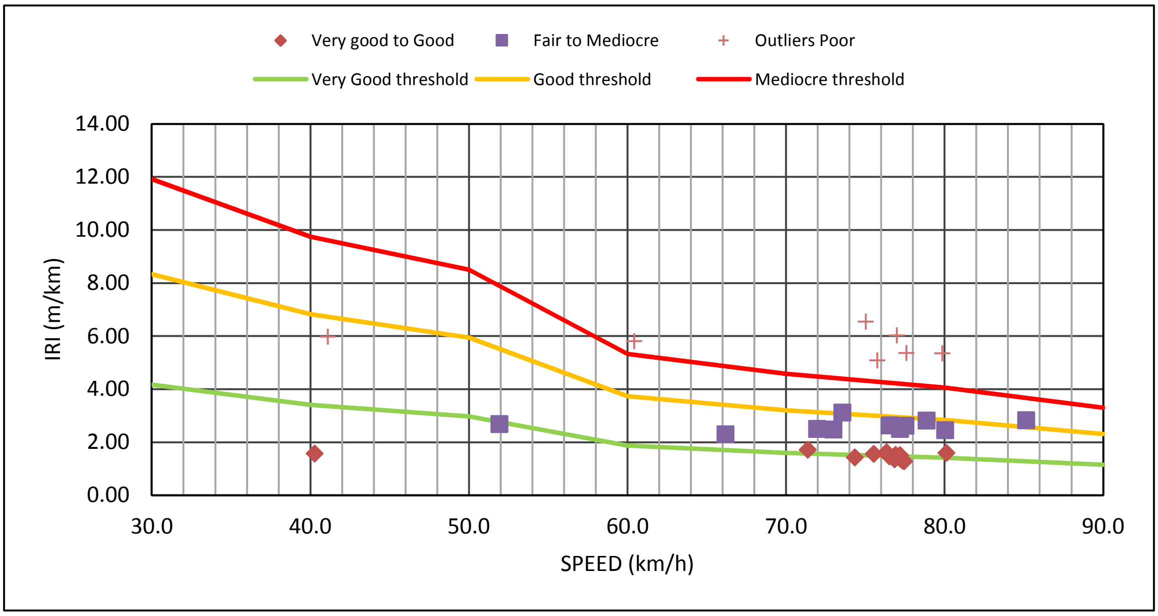

Figure 5-29: Speed versus IRI – D2296

5.6 Costs associated with Public transport

Infrastructure is one of the contributing factors in the evaluation of a country's success. The road network plays a huge part in a country's infrastructure, especially the state of the roads. Even though South Africa is in a fortunate position of having a relatively extensive road network, the maintenance and upgrade of this network is a concern.

Deteriorating roads has a direct and indirect impact on the road user, in the previous sections of this chapter the user perceptibility of riding quality and road roughness were evaluated. In this section, the calibrated HDM 4 model (Chatti and Zaabar, 2012) was used to determine fuel consumption, tyre wear, and repair and maintenance cost per km of each section of the bus route under consideration. The first 100 lines of calculated data of each section is indicated in Appendix C. The calculations were based on the data generated from the profiler on the bus route. The costs indicated are for one bus on each route measured per km.

In order to demonstrate the potential effect of road conditions on fuel, tyre and, repair and maintenance costs, an analysis was done on each road class encountered on this specific bus route. A few scenarios were analysed, the first (indicated in Table 5-16) is the current average projected cost of an articulated truck (bus) traveling on this route.

Table 5-16: Average Current Cost

Route	Average IRI	Average Speed	Fuel Consumption	Tyre Wear	Repair and Maintenance cost
	m/km	km/h	l/km	%/km	R/km
N4	2.10	69.39	0.356	0.00082	1.80
R538(1)	2.76	51.78	0.275	0.00092	1.03
R538(2)	3.85	23.55	0.181	0.00114	0.10
Municipal road	4.61	21.66	0.185	0.00116	0.19
D2296	1.96	67.11	0.344	0.00083	1.50
Average	3.06	46.70	0.268	0.00097	0.92

The average speed of each section is indicated. The bus travelled the slowest on the municipal road in Daantjie and second slowest on the provincial road R538(2). These two road sections also had the highest average IRI values. However, the fuel consumption, tyre wear, and repair and maintenance costs on these sections were the best, because of the low speeds. The reason for the low speeds could be that the road was in such a bad state that it was not possible to drive faster, or it could be congestion, too many consecutive speed humps, bus stops, or a combination of these factors.

According to Chatti and Zaabar (2012), the effect of roughness on tyre wear, and repair and maintenance cost increase as the speed increase. The effect of roughness on fuel consumption, however, is statistically not significant at higher speeds.

Indicated in Table 5-17 is the fuel consumption, tyre wear, repair, and maintenance cost for each section at the indicative speed of 60 km/h. The fuel consumption and tyre wear values of the two worst sections do not differ as much, the repair and maintenance costs, however, differs with an average of R 0.53 per km. The analysis were continued with a constant speed of 60 km/h for each section, to determine the impact of the roughness of the road on the fuel consumption, tyre wear and, repair, and maintenance costs.

Table 5-17: Cost of travelling the route at a constant speed of 60 km/h

Route	Average IRI m/km	Average Speed km/h	Fuel Consumption l/km	Tyre Wear %/km	Repair and Maintenance cost R/km
N4	2.10	60.00	0.297	0.00086	0.581
R538(1)	2.76	60.00	0.301	0.00087	0.759
R538(2)	3.85	60.00	0.308	0.00087	1.057
Municipal road	4.61	60.00	0.312	0.00088	1.256
D2296	1.96	60.00	0.296	0.00086	0.546
Average	3.06	60.00	0.303	0.00087	0.840

The second scenario was to determine the associated costs of a bus route with an average IRI that falls below the good to very good threshold. The IRI values that were worse than an IRI of 2.24 m/km (worse roughness than the good to very good threshold) was improved to 2.24 m/km. The costs associated with an improved IRI for each section is indicated in Table 5-18.

Table 5-18: Improved costs at a constant speed of 60 km/h

Route	Average IRI m/km	Average Speed km/h	Fuel Consumption l/km	Tyre Wear %/km	Repair and Maintenance cost R/km
N4	1.79	60.00	0.295	0.00086	0.500
R538(1)	2.24	60.00	0.298	0.00086	0.619
R538(2)	1.92	60.00	0.296	0.00086	0.535
Municipal road	2.18	60.00	0.297	0.00086	0.604
D2296	1.69	60.00	0.294	0.00086	0.474
Average	1.96	60.00	0.296	0.00086	0.546

The fuel consumption and tyre wear values did not change significantly, but the repair and maintenance costs decreased significantly. The percentage decrease in costs is indicated in Table 5-19. The fuel consumption decreased with an average of about 2 per cent over the whole route. The improved IRI affected the R538(2) and Municipal road the most, with a decrease in fuel consumption of about 4 and 5 per cent respectively. The tyre wear decreased with an average of about 0.6 per cent over the whole route, where the highest impact were shown on the R538(2) and Municipal road. The repair and maintenance costs had the largest decrease of about 30 per cent over the whole length of the bus route, with the Municipal road at a decrease of 50 per cent and the R538(2) at a decrease of about 52 per cent.

Table 5-19: Percentage improvement from current cost

Route	Average IRI %	Average Speed km/h	Fuel Consumption %	Tyre Wear %	Repair and Maintenance cost %
N4	14.67%	60.00	0.63%	0.16%	14.00%
R538(1)	18.94%	60.00	1.07%	0.28%	18.46%
R538(2)	50.01%	60.00	3.91%	1.03%	49.33%
Municipal road	52.75%	60.00	4.81%	1.28%	51.88%
D2296	13.85%	60.00	0.57%	0.14%	13.32%
Average	30.04%	60.00	2.20%	0.58%	29.40%

Therefore, it was further investigated what the impact will be if the R538(2) and the municipal road in Daantjie were repaired and, if necessary, upgraded to an average IRI of 1.92 m/km and 2.18 m/km respectively.

It could be costly to upgrade the whole bus route to an acceptable IRI, below the very good to good threshold of 2.24 m/km, and therefore, the impact of upgrading the two worst sections (R538(2) and the municipal road) were determined. Indicated in Table 5-20 is the potential decrease in costs determined by the model if the IRI of the R538(2) and the municipal road were decreased to an average below 2.24 m/km.

Table 5-20: Decrease in cost by improving two sections of the route

Route	Average IRI %	Average Speed km/h	Fuel Consumption %	Tyre Wear %	Repair and Maintenance cost %
N4	0.00%	60.00	0.00%	0.00%	0.00%
R538(1)	0.00%	60.00	0.00%	0.00%	0.00%
R538(2)	50.01%	60.00	3.91%	1.03%	49.33%
Municipal road	52.75%	60.00	4.81%	1.28%	51.88%
D2296	0.00%	60.00	0.00%	0.00%	0.00%
Average	20.55%	60.00	1.74%	0.46%	20.24%

Therefore, by upgrading the two worst sections of the road a saving of about 2 percent in fuel consumption, 0.5 per cent in tyre wear and about 20 percent on repair and maintenance cost could be possible for the bus travelling on this bus route.

Lack of maintenance on South African roads is a concern, as discussed in section 2. In order to demonstrate the impact of no maintenance, the IRI on the sections was increased with 1 m/km. Indicated in Table 5-21 are the predicted fuel consumption, tyre wear and repair, and maintenance cost if the IRI increased with 1 m/km. The speed indicated is the actual speed the bus travelled during the survey. By comparing Table 5-21 with the current average VOCs on these road sections (Table 5-16), the percentage increase in fuel consumption, tyre wear and repair, and maintenance cost were calculated.

Table 5-21: Increase in cost as IRI increase with 1 m/km

Route	Average IRI m/km	Average Speed km/h	Fuel Consumption l/km	Tyre Wear %/km	Repair and Maintenance cost R/km
N4	3.10	69.43	0.362	0.00082	2.67
R538(1)	3.76	51.78	0.281	0.00093	1.30
R538(2)	4.87	23.55	0.186	0.00115	0.13
Municipal road	5.61	21.66	0.190	0.00117	0.22
D2296	2.96	67.11	0.350	0.00083	2.29
Average	4.06	46.71	0.274	0.00098	1.32

Indicated in Table 5-22 is the percentage increase in fuel consumption, tyre wear and repair, and maintenance cost if the IRI increased with 1 m/km. The speed indicated is the actual speed the bus travelled during the survey. Chatti and Zaabar (2012) concluded that fuel consumption is the component affected the most by roughness, followed by repair and maintenance and thereafter tyre wear. However, according to the results indicated in Table 5-22, repair and maintenance cost was affected the most by an increase in IRI with about 33 per cent.

Table 5-22: Percentage increase in cost as IRI increase with 1 m/km

Route	Average IRI %	Average Speed km/h	Fuel Consumption %	Tyre Wear %	Repair and Maintenance cost %
N4	47.69%	69.43	1.82%	0.46%	48.19%
R538(1)	36.25%	51.78	2.16%	0.58%	26.99%
R538(2)	26.63%	23.55	2.85%	0.70%	21.34%
Municipal road	21.67%	21.66	2.78%	0.69%	18.03%
D2296	50.91%	67.11	1.87%	0.48%	52.48%
Average	36.63%	46.71	2.30%	0.58%	33.41%

5.7 Conclusion

In summary, even though it is very difficult to quantify the level of comfort of a section of road for the road user, it is possible to give an indication. The riding comfort of the bus route depends on more factors than the road surface, the suspension, type of vehicle and interior of a vehicle. However, the road surface does play the largest role, and has the biggest impact on VOCs.

In this analysis, the impact of the vehicle speed proved to be significant, it affected the PSD values, the vertical acceleration values and the VOCs. The two sections with the highest IRI values also had the lowest speeds. This is not ideal, as the state of road, congestion, speedhumps, and consecutive bus stops, resulted in longer travel time.

The three dimensional plots indicated that high IRI and a_{wz} values were recorded at low speeds, and high a_{wz} values, low IRI values at high speeds. Therefore, it can be concluded that an increase in IRI reduces the travelling speed of the driver and it decreases user comfortability.

Therefore, the scenario was analysed to improve the riding quality of the two worst sections of the bus route, and by improving the road surface of these two sections the VOCs reduced significantly.

Lack of maintenance is often the cause of deteriorating roads, the impact thereof was determined by increasing the surveyed IRI values with 1 m/km. The increase in VOCs were significant, and it is recommended that this be researched further. Buscor can determine the cost of maintaining the bus route, versus the current VOCs for the busses.

6. DATA APPLICATION

This chapter includes the data application of the tests conducted. It also indicates conclusion graphs of the tests conducted and serves as an introduction to the conclusions and recommendations chapter that follow.

6.1 Introduction

The data used for proving the hypothesis were actual measured data. There were many external factors influencing the data and the outcomes. The speed, for one, played a very large role in the data application. If the road was in a bad state, (the IRI was high) while the bus drove slower, but the vertical acceleration values and PSD were low. The same can be concluded about the predicted VOCs of a section of road. For a high IRI, the VOCs should be high, however, if the bus drove slow over the area that had a high IRI, the VOCs will lower again. The slower speed may reduce VOCs and decrease the vertical accelerations of the bus, but it did increase the travel time of the bus user. Therefore, the hypothesis of an increase in IRI leads to an increase in user comfortability and VOCs, should include the speed.

6.2 Section Analysis

In section 5, an analysis of each section of the bus route were shown. The graphs and tables indicated the values of consecutive sections with IRI values in the same category. In order to form a relevant conclusion, the data over the whole length of each section were plotted in a three dimensional plot of IRI versus speed versus vertical acceleration. The data recorded by sensor 11 and 12 were used as these sensors recorded the highest PSD values.

The regression area of the data collected over the whole length of the bus route on the N4 is indicated in Figure 6-1. From the three dimensional graph it seems that the vertical accelerations reached a peak, and then decrease. Thus, at a certain IRI the vertical vibrations were the highest over the length of the section. However, as the speed increased, the IRI and vertical accelerations also seemed to increase. This observation was consistent with the literature, and according to Gillespie (1992), the amplitude of the acceleration will increase with the square of the speed. Gillespie (1992) also indicated that a vehicle that travelled on a rough road had a roll and bounce natural frequency. Moreover, at high speeds the accelerations caused by bounce vibrations were higher than the accelerations generated by roll vibrations. However, at low speeds, (such as a 4x4 vehicle travelling off road) the exaggerated ride vibrations were composed of bounce as well as roll vibrations.

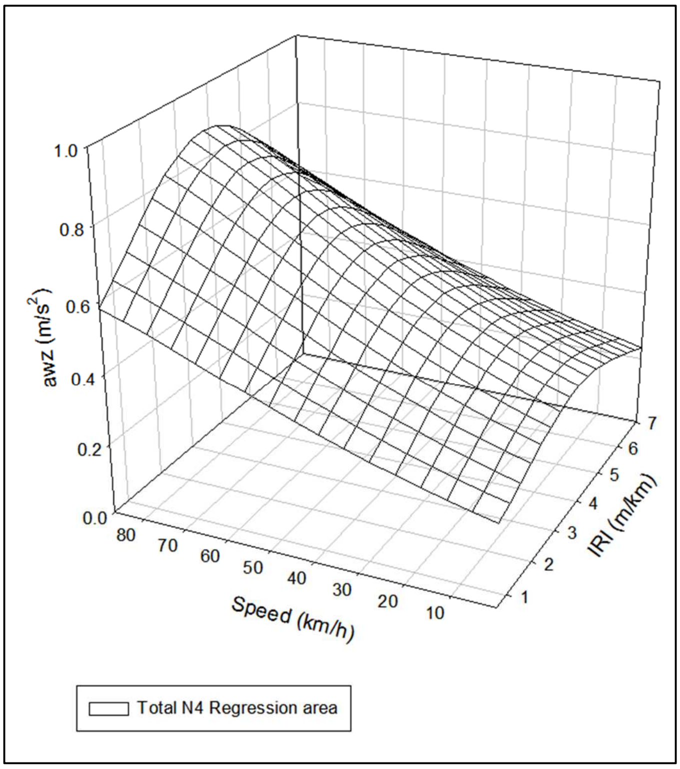

Figure 6-1: 3D regression area of a_{wz} versus IRI versus speed – Total N4

Figure 6-2 indicate the regression area of the data collected over the whole length of the bus route on the first part of the R538. The regression area followed the same trend as the N4 data. The vertical acceleration reached a peak at a certain IRI and as the speed increased, the IRI and vertical accelerations increased.

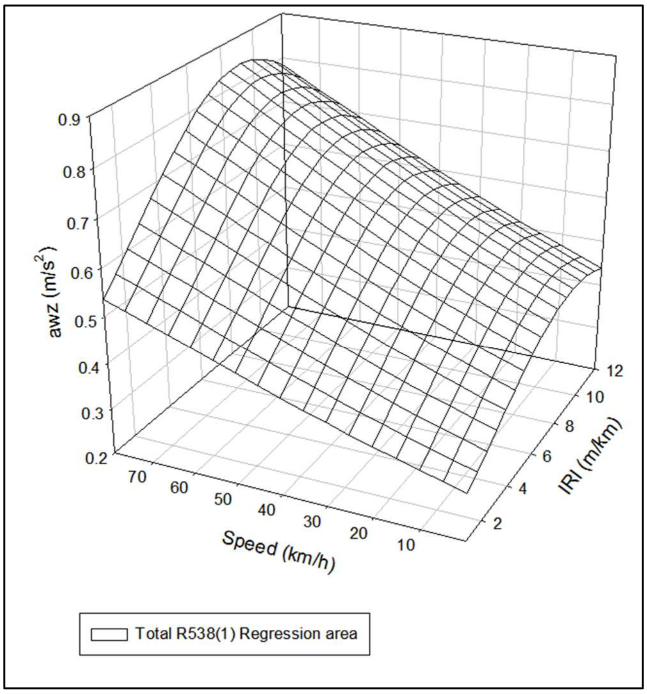

Figure 6-2: 3D regression area of a_{wz} versus IRI versus speed – Total R538(1)

Indicated in Figure 6-3 is the regression area of area of the data collected over the whole length of the bus route on the second part of the R538. This section was very short, with an average speed of 23 km/h. This area, similar to the N4 and R538(1) regression areas, also seemed to peak at a certain vertical acceleration and IRI point. However, the speed also reached a peak at a maximum vertical acceleration value. Compared to Figure 6-1 and Figure 6-2, the a_{wz} and IRI reached a peak at 30 km/h. The reason could be that the measured IRI on the R538(2) is higher compared to the N4 and R538(1) and therefore the IRI and a_{wz} reached a peak at a lower speed.

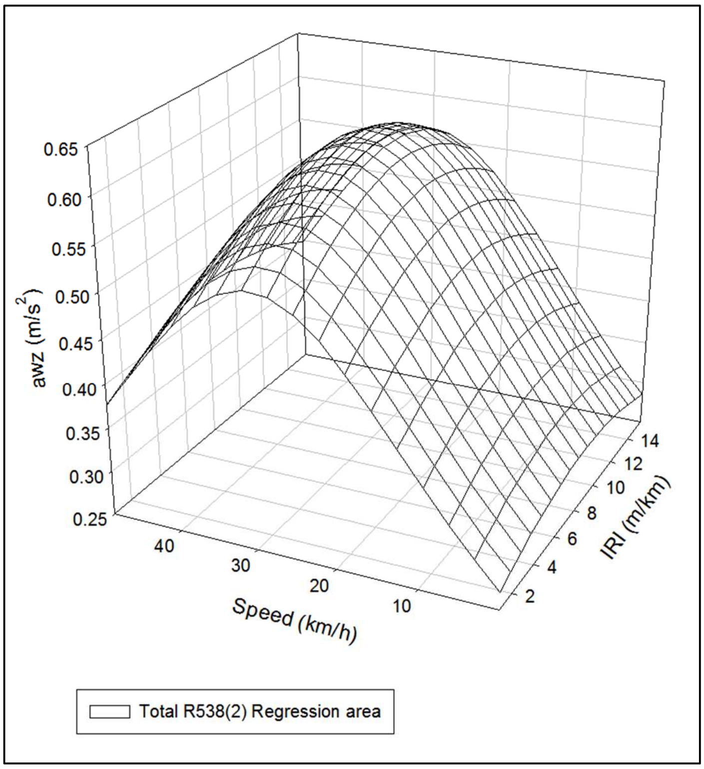

Figure 6-3: 3D regression area of a_{wz} versus IRI versus speed – Total R538(2)

Figure 6-4 represent the regression area of the collected data from the bus route on the municipal road in Daantjie. The average speed of 22 km/h on this section was also very low in comparison to the N4 and R538(2). Similar to the R538(2), the vertical acceleration reached a peak at a certain IRI and speed (values indicated in Table 6-1).

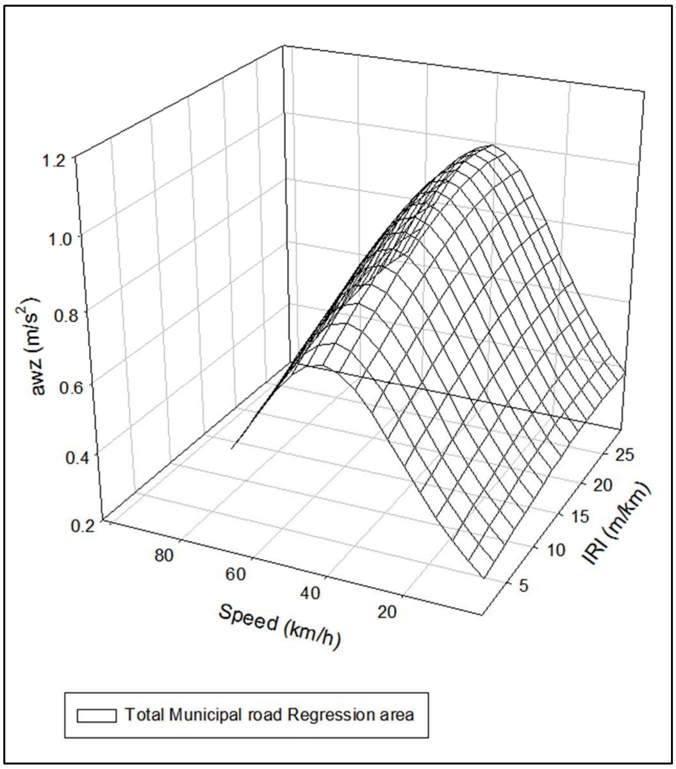

Figure 6-4: 3D regression area of a_{wz} versus IRI versus speed – Total Municipal Road

The regression area calculated from the data collected of the bus route on the D2296 is indicated in Figure 6-5. The maximum vertical acceleration value seemed to be at a very low IRI value. Therefore, according to this graph, in order to experience lower vertical accelerations, one should drive slower or faster than 51.8 km/h.

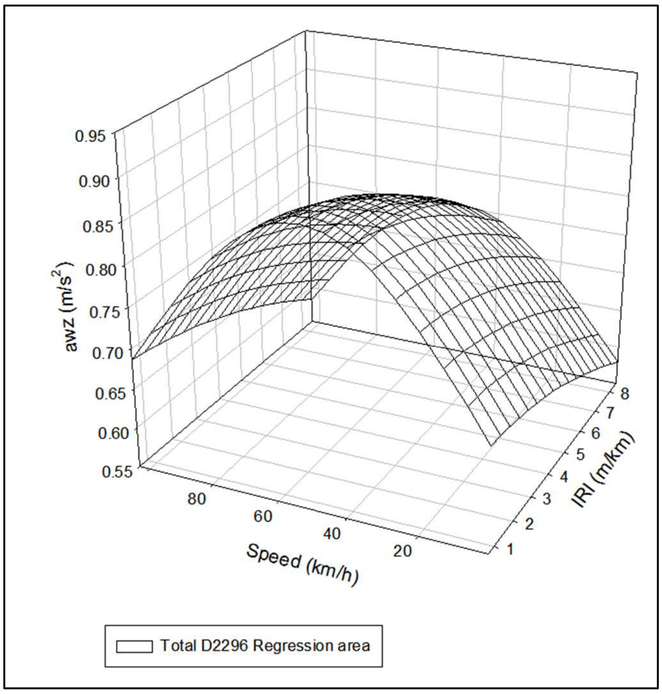

Figure 6-5: 3D regression area of a_{wz} versus IRI versus speed – Total D2296

Therefore, for each of these road sections, it seems that the bus reached an optimum frequency, at a certain vertical acceleration, speed, and IRI. This point indicated that (out of a comfort viewpoint) the speed should either be increased or decreased to reduce the vertical accelerations.

The peak regression values for each road section is indicated in Table 6-1, even though the IRI over the section R538(1) was high, an average speed of 79.3 km/h was recorded, which was close to the speed limit. It seems there is a trend that the optimum speed reduces, as the road authority change from national to provincial to municipal.

Table 6-1: Maximum values of regression areas

Route	IRI m/km	Speed km/h	a_{wz} m/s^2
N4	3.83	87.16	0.88
R538(1)	9.23	79.35	0.84
R538(2)	9.16	30.82	0.61
Municipal road	23.99	40.77	1.01
D2296	0.71	51.82	0.88

6.3 Costs associated with Public transport

The graphs indicated in the section analysis, indicated that for each road section there was an optimum frequency where the vertical acceleration reached a peak and then reduced with increased IRI and speed. However, this came at a price, as the impact (thus repair and maintenance cost, fuel consumption, and tyre wear) of the vehicle was higher as the speed increased. Moreover, the driver may lose control over the vehicle if the bus drove too fast over the road irregularities. Indicated in Table 6-2 is the predicted fuel consumption, tyre wear and repair and maintenance costs on each road section at a speed of 80 km/h.

Table 6-2: VOCs at a constant speed of 80 km/h

Route	Average IRI m/km	Average Speed km/h	Fuel Consumption l/km	Tyre Wear km	Repair and Maintenance cost R/km
N4	2.10	80.00	0.404	0.00075	2.584
R538(1)	2.76	80.00	0.408	0.00075	3.398
R538(2)	3.85	80.00	0.416	0.00075	4.758
Municipal road	4.61	80.00	0.421	0.00076	5.667
D2296	1.96	80.00	0.403	0.00075	2.424
Average	3.06	80.00	0.410	0.00075	3.766

Therefore, to travel on these roads in these conditions at higher speeds results at a greater cost. The two roads with the highest average IRI values had very high repair and maintenance costs. If the R538(2) and the municipal road could upgraded so that the IRI fall in the good to very good category, the repair and maintenance cost will decrease significantly, the fuel consumption will decrease and the tyres will be able to cover longer distances. The current marked speed of these two roads are 60 km/h, so the saving in cost will be as indicated in Table 5-20.

6.4 Summary

The values for the N4 and R538(1) followed the same trend and seemed to indicate that the highest vertical acceleration is out of the data range at a higher speed. The data collected on the R538(2) and the municipal road reached an optimum frequency at a low speed and the accelerations seemed to reduce as the speed increase. The optimum frequency for the D2296 road seemed to be at a low IRI value but at a speed higher than the R538(2) and municipal road.

The VOCs analysis indicated that in order to reduce the vertical accelerations, the speed was increased. However, this had cost implications and it could be unsafe. The safety of a deteriorating road surface should be kept in mind, however, it was deemed outside the scope of this study.

7. CONCLUSIONS AND RECOMMENDATIONS

7.1 Introduction

The objectives of this research was to determine the effect of deteriorating road roughness on a bi-articulated bus by analysing the IRI and vertical accelerations, the effect of speed on user comfortability and VOCs, and the increase in VOCs associated with an increase in roughness. The effect of improvement on the bus route riding quality on VOCs were also evaluated.

A bus route was specified, with different road sections with different responsible authorities. The route was surveyed with a profiler and the bus was fitted with accelerometers while driving on the bus route. The relevant outputs, after analyses, from these two surveys were speed, IRI, PSD, and a_{wz}.

The literature indicated that by analysing the IRI alone, one could not completely determine the real conditions of pavements concerning user comfort in some situations. Therefore, in addition to IRI, vertical accelerations were also used to evaluate the comfort of the road user.

The limitations of this study included some correlation issues with the profiler data and the accelerometer data, unidentified bus stops on gravel shoulders, the suspension system and the interior of the bus were not taken into account. Despite of these limitations, there are still a variety of possibilities with the data collected.

In conclusion, deteriorating riding quality affect the comfortability of a ride and the VOCs negatively, IRI can be used to determine the state of the road and q_{wz} gives an indication of the comfortability of a ride.

7.2 Conclusion

The principal results of this study were that the speed played a determining role in the generation of vertical accelerations, therefore user comfort, and VOCs. The anomalies indicated that high IRI values were generated by driving over a surface failure (such as a pothole), change in surfacing (from asphalt to concrete block paving), uneven patching, speedhumps or bridge construction joints.

The IRI on a road indicates the state of the road surface, the N4 was mostly in a good state with about 60 per cent in the very good to good riding quality category. The state of the R538(1) was also not too concerning with 55 per cent in the very good to good riding quality category. The two sections with the highest IRI values were the R538(2), with 30 per cent in the poor category, and the municipal road in Daantjie, with 40 per cent in the poor category.

These values were as expected, however, the D2296 was in a better state than expected with only 14 per cent in the fair to mediocre category and 9 per cent in the poor category.

The vertical accelerations measured by the accelerometers indicated the comfortability of the ride, however, the speed the bus travelled played the largest role. The R538(2) and the municipal road in Daantjie were the two sections with the highest IRI values, and also had the lowest speeds. This is not ideal, as the state of road, congestion, speedhumps, and consecutive bus stops, resulted in longer travel time. The three dimensional plots in section 5 and section 6 indicated that high IRI and a_{wz} values were recorded at low speeds, high a_{wz} values, low IRI values at high speeds, and that there is an optimum frequency at a certain speed, IRI and a_{wz}, that indicated the vertical accelerations decreased if the bus travelled faster or slower. This in turn, compromised the safety of the route. Therefore, it can be concluded that an increase in IRI reduces the travelling speed of the driver and it decreases user comfortability.

The VOCs of one bus on this specific bus route were projected with the HDM4 model. The calculated current VOCs of travelling on this route at a speed on 60 km/h, were 0.3 l/km fuel consumption, tyre wear of 0.086 %/km and 0.6 R/km for repair and maintenance costs. However, with regular maintenance, the average IRI of the route can be improved with 30 per cent (average IRI fall in the very good to good category). This could reduce fuel consumption with 2.2 per cent, tyre wear with 0.6 per cent and repair and maintenance cost with 30 per cent. The construction cost of improving the whole bus route may be extensive, therefore the impact of upgrading the two worst sections (R538(2) and the municipal road) were analysed. The average IRI improved with 21 per cent, fuel consumption decreased with 1.7 per cent, tyre wear with 0.5 per cent, and repair and maintenance cost with 20 per cent.

In order to illustrate the impact of lack of maintenance on VOCs the IRI was increased with 1 m/km. This overall lead to a 37 per cent increase in IRI, 2.3 per cent increase in fuel consumption, 0.6 per cent increase in tyre wear and 33 per cent increase in repair and maintenance cost.

7.3 Limitations

The route surveyed by the accelerometers and the profiler were not the exact same routes. Some of the bus stops were located on gravel shoulders, which the profiler did not survey. The routes of the accelerometers and profiler were correlated visually on Google Earth (2013) with GPS coordinates. The anomalies were identified with the profiler survey, and not with the accelerometer survey. However, the photos taken every 10 m indicated the cause of the anomalies. The PSD and a_{wz} data did indicate high values at certain points, and it proved difficult to estimate the exact cause of these high values, as the accelerometers measured the vertical accelerations on the bus generated by the road. Another limitation was that sensor 11 ran out of battery power, and data was collected up to half of D2296. However, the data collected from sensor 12, sensor 11 were sufficient, and relevant conclusions were made.

The accelerometers measured the vertical accelerations on the outside of the bus, and these values were used to determine the user comfort. However, the suspension system, interior of the bus, bus mass (full bus versus empty bus), driver fatigue, tyre pressure and dynamic wheel loads were not taken into account, and these could have had a larger impact than anticipated.

7.4 Recommendations

Further research on the following issues are recommended:

- The impact of the bus mass;
- The impact of the suspension system and the bus interior;
- Trip duration and congestion;
- Driver fatigue because of the deteriorating riding quality;
- The safety of the driver and bus user;
- The impact of the tyre pressure and dynamic wheel loads on the VOCs and comfortability of the ride;
- Benefit cost ratio of the construction cost of upgrading the two worst road sections versus the increase in VOCs of the bus travelling on that route;
- Impact of short wavelengths and long wavelengths with differentiation in speed, and
- Effect of the horizontal accelerations as the bus travel over surface failures.

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9. APPENDIXES

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A. Appendix A – Summary Tables

A.1. N4

Table 9-1: Very Good to Good category – N4

No	Start km km	End km km	Length km	Ave IRI m/km	PSD S11 g^2	PSD S12 g^2	a_{wz} 11 m/s^2	a_{wz} 12 m/s^2	Speed km/h
1	0.64	0.66	0.02	1.69	0.060	0.018	0.3325	0.4458	5.46
2	0.81	0.87	0.06	1.59	0.112	0.048	0.4187	0.2152	21.66
3	1.01	1.19	0.18	1.36	0.142	0.102	0.5402	0.7334	38.09
4	1.32	1.41	0.09	1.72	0.051	0.067	0.2362	0.5096	59.91
5	1.9	2.2	0.3	1.46	0.051	0.200	0.6318	0.5175	60.36
6	2.21	2.46	0.25	1.37	0.149	0.190	0.6168	0.6665	73.97
7	2.47	2.74	0.27	1.49	0.172	0.201	0.6055	0.6904	81.91
8	2.85	3.09	0.24	1.57	0.154	0.190	0.5459	0.6682	78.23
9	3.47	3.68	0.21	1.28	0.145	0.215	0.4607	0.6200	77.68
10	4.14	4.84	0.7	1.26	0.122	0.153	0.5766	0.5312	76.93
11	4.85	5.24	0.39	1.31	0.100	0.170	0.6349	0.5923	75.94
12	5.76	6.22	0.46	1.30	0.168	0.143	0.7501	0.7108	82.32
13	6.84	6.98	0.14	1.66	0.274	0.186	0.8648	0.6507	77.28
14	9.16	9.33	0.17	1.49	0.261	0.155	0.8087	0.6715	79.95
15	11.57	11.84	0.27	1.46	0.225	0.158	0.8753	0.6437	76.78
Average				1.47	0.146	0.146	0.5933	0.5911	64.43
WEIGHTED AVERAGE				1.39	0.147	0.164	0.6337	0.6153	73.05

Table 9-2: Fair to Mediocre category – N4

No	Start km km	End km km	Length km	Ave IRI m/km	PSD S11 g^2	PSD S12 g^2	a_{wz} 11 m/s^2	a_{wz} 12 m/s^2	Speed km/h
1	7.520	7.580	0.06	3.03	0.272	0.318	0.8434	0.9996	77.17
2	8.090	8.200	0.11	2.75	0.197	0.295	0.7564	0.9042	76.87
3	8.220	8.290	0.07	2.65	0.199	0.262	0.7946	0.9302	76.56
4	8.320	8.420	0.1	2.94	0.138	0.286	0.6668	0.9442	76.80
5	8.550	8.630	0.08	2.93	0.206	0.319	0.5254	0.7693	76.07
6	8.680	8.730	0.05	2.84	0.153	0.251	0.8032	0.8881	76.31
7	8.820	9.160	0.34	2.83	0.259	0.146	0.8996	0.5871	79.44
8	9.880	9.960	0.08	2.94	0.159	0.207	0.6157	0.7102	75.51
9	10.270	10.330	0.06	2.67	0.199	0.303	0.8013	0.7895	77.88
10	11.220	11.270	0.05	3.13	0.117	0.304	0.4349	0.7423	77.68
11	11.960	12.010	0.05	3.48	0.263	0.301	1.0399	1.1821	78.01
12	12.210	12.320	0.11	2.77	0.292	0.310	1.1078	0.8869	75.89
13	12.470	12.600	0.13	2.89	0.254	0.302	0.7611	0.9920	77.48
14	12.710	12.760	0.05	2.95	0.315	0.474	1.3729	1.5225	77.55
15	12.890	12.980	0.09	3.01	0.290	0.352	0.8785	0.9495	58.93
Average				2.92	0.221	0.295	0.8201	0.9198	75.88
WEIGHTED AVERAGE				2.88	0.230	0.266	0.8278	0.8483	76.32

Table 9-3: Poor category – N4

No	Start km	End km	Length	Ave IRI	PSD S11	PSD S12	a_{wz} 11	a_{wz} 12	Speed
	km	km	km	m/km	g^2	g^2	m/s^2	m/s^2	km/h
1	6.820	6.840	0.02	5.20	0.274	0.186	0.9648	0.5469	76.83
2	8.630	8.650	0.02	4.87	0.274	0.244	0.6428	0.6803	76.45
3	10.840	10.860	0.02	4.82	0.138	0.310	0.5706	0.6945	76.95
4	12.760	12.790	0.03	4.58	0.118	0.327	0.6835	1.2084	77.24
5	12.980	13.010	0.03	4.81	0.276	0.327	0.6315	0.5900	37.60
Average				4.86	0.216	0.279	0.6986	0.7440	69.01
WEIGHTED AVERAGE				4.83	0.213	0.287	0.6918	0.7699	67.08

A.2. R538(1)

Table 9-4: Very Good to Good category – R538(1)

No	Start km	End km	Length	Ave IRI	PSD S11	PSD S12	a_{wz} 11	a_{wz} 12	Speed
	km	km	km	m/km	g^2	g^2	m/s^2	m/s^2	km/h
1	13.54	13.59	0.05	1.56	0.072	0.067	0.3553	0.2208	2.38
2	13.77	13.82	0.05	1.61	0.075	0.234	0.3262	0.6987	27.26
3	13.83	14.25	0.42	1.28	0.077	0.104	0.3890	0.3278	37.60
4	14.26	14.46	0.2	1.67	0.099	0.136	0.4224	0.4492	40.98
5	14.47	14.62	0.15	1.53	0.111	0.122	0.5477	0.4191	42.33
6	14.63	14.82	0.19	1.43	0.186	0.124	0.7925	0.4535	49.80
7	14.88	14.95	0.07	1.67	0.242	0.173	0.7657	0.6748	64.10
8	14.98	15.03	0.05	1.61	0.207	0.210	0.7876	0.6541	74.85
9	15.06	15.24	0.18	1.64	0.273	0.313	0.7738	1.3479	78.46
10	15.79	15.83	0.04	1.81	0.131	0.130	0.4694	0.4133	44.78
11	15.85	15.98	0.13	1.65	0.182	0.151	0.5933	0.5166	45.45
12	15.99	16.05	0.06	1.80	0.197	0.140	0.6321	0.5562	46.80
13	16.1	16.14	0.04	2.05	0.310	0.154	1.0507	0.5561	47.69
14	16.19	16.26	0.07	1.84	0.253	0.170	0.9165	0.5895	51.80
15	16.28	16.34	0.06	1.93	0.226	0.187	0.7068	0.7056	56.66
Average				1.67	0.176	0.161	0.6353	0.5722	47.40
WEIGHTED AVERAGE				1.56	0.155	0.153	0.5849	0.5500	47.20

Table 9-5: Fair to Mediocre category – R538(1)

No	Start km	End km	Length	Ave IRI	PSD S11	PSD S12	a_{wz} 11	a_{wz} 12	Speed
	km	km	km	m/km	g^2	g^2	m/s^2	m/s^2	km/h
1	13.22	13.26	0.04	2.97	0.038	0.311	0.2909	1.0380	64.41
2	13.29	13.36	0.07	3.19	0.041	0.353	0.2708	0.5718	70.05
3	15.50	15.55	0.05	3.52	0.116	0.216	0.4867	0.7806	66.66
4	15.57	15.62	0.05	3.29	0.123	0.374	0.4771	0.9958	60.50
5	15.74	15.77	0.03	2.64	0.167	0.128	0.6099	0.4656	48.82
6	16.05	16.08	0.03	2.90	0.240	0.234	0.8810	0.7594	48.04
7	16.41	16.46	0.05	3.65	0.276	0.207	0.9166	0.7904	59.48
8	16.66	16.75	0.09	3.00	0.050	0.225	0.3114	0.9177	59.43
9	16.78	16.81	0.03	3.39	0.066	0.347	0.2930	0.7566	51.81
10	16.82	16.85	0.03	2.61	0.061	0.167	0.3210	0.2956	48.54
11	16.94	16.98	0.04	2.95	0.101	0.021	0.3775	0.0572	30.59
Average				3.10	0.116	0.235	0.4760	0.6753	55.30
WEIGHTED AVERAGE				3.14	0.107	0.244	0.4527	0.7119	57.45

Table 9-6: Poor category – R538(1)

No	Start km	End km	Length	Ave IRI	PSD S11	PSD S12	a_{wz} 11	a_{wz} 12	Speed
	km	km	km	m/km	g^2	g^2	m/s^2	m/s^2	km/h
1	15.38	15.44	0.06	5.12	0.115	0.248	0.2621	0.9711	70.46
2	15.55	16.47	0.92	5.58	0.116	0.216		0.8526	64.79
3	16.54	16.56	0.02	5.82	0.032	0.273		0.6891	64.81
4	16.57	16.59	0.02	5.16	0.022	0.406		0.6891	65.17
5	16.64	16.66	0.02	5.08	0.050	0.225		0.7833	62.82
6	16.88	16.90	0.02	5.04	0.101	0.021		0.0567	38.84
Average				5.30	0.073	0.232	0.2621	0.6737	61.15
WEIGHTED AVERAGE				5.53	0.111	0.219	0.2621	0.8368	64.59

Table 9-7: Anomaly Data R538(1)

No	Start km	End km	Length	Ave IRI	PSD S11	PSD S12	a_{wz} 11	a_{wz} 12	Speed
	km	km	km	m/km	g^2	g^2	m/s^2	m/s^2	km/h
1	13.15	13.19	0.04	7.47	0.116	0.216	0.2252	1.2719	54.71
2	13.27	13.29	0.02	6.86	0.032	0.273	0.2715	1.2913	70.72
3	15.24	15.26	0.02	7.66	0.022	0.406	0.4573	0.7389	75.58
4	15.44	15.47	0.03	7.67	0.050	0.225	0.4360	0.7342	68.67
5	16.59	16.63	0.04	9.56	0.101	0.021	0.2246	1.4942	65.30
6	16.76	16.78	0.02	8.29	0.066	0.001	0.2376	1.1033	53.81
Average				7.92	0.064	0.190	0.3087	1.1056	64.80
WEIGHTED AVERAGE				8.04	0.074	0.176	0.2965	1.1490	63.90

A.3. R538(2)

Table 9-8: Very Good to Good category – R538(2)

No	Start km	End km	Length	Ave IRI	PSD S11	PSD S12	a_{wz} 11	a_{wz} 12	Speed
	km	km	km	m/km	g^2	g^2	m/s^2	m/s^2	km/h
1	27.74	27.80	0.06	1.31	0.130	0.125	0.4339	0.7545	22.97
2	27.95	28.04	0.09	1.61	0.104	0.170	0.5807	0.4622	34.06
3	28.17	28.23	0.06	1.41	0.182	0.212	0.6345	0.7986	32.41
4	28.59	28.64	0.05	1.60	0.018	0.212	0.3779	0.1572	1.11
5	28.70	28.74	0.04	1.25	0.096	0.114	0.4424	0.4434	31.81
6	28.75	28.82	0.07	1.50	0.125	0.109	0.6179	0.3715	42.84
	Average			1.447	0.109	0.157	0.5145	0.4979	27.54
	WEIGHTED AVERAGE			1.47	0.112	0.158	0.5303	0.5037	28.96

Table 9-9: Fair to Mediocre category – R538(2)

No	Start km	End km	Length	Ave IRI	PSD S11	PSD S12	a_{wz} 11	a_{wz} 12	Speed
	km	km	km	m/km	g^2	g^2	m/s^2	m/s^2	km/h
1	28.07	28.10	0.03	2.93	0.118	0.170	0.7440	0.6149	20.15
2	28.15	28.17	0.02	2.81	0.274	0.104	0.7359	0.4035	26.62
3	28.30	28.32	0.02	3.06	0.104	0.284	0.6424	1.3336	30.11
4	28.41	28.43	0.02	2.84	0.022	0.198	0.2008	0.6430	29.80
5	28.44	28.46	0.02	3.48	0.022	0.333	0.2061	1.2213	35.51
6	28.57	28.59	0.02	3.75	0.021	0.040	0.2119	0.0749	17.68
7	28.68	28.70	0.02	2.56	0.112	0.156	0.4005	0.4882	21.67
8	28.82	28.84	0.02	3.09	0.193	0.129	0.8679	1.0445	24.35
	Average			3.07	0.108	0.177	0.5012	0.7280	25.74
	WEIGHTED AVERAGE			3.06	0.109	0.176	0.5155	0.7213	25.41

Table 9-10: Poor category – R538(2)

No	Start km	End km	Length	Ave IRI	PSD S11	PSD S12	a_{wz} 11	a_{wz} 12	Speed
	km	km	km	m/km	g^2	g^2	m/s^2	m/s^2	km/h
1	27.82	27.84	0.02	9.14	0.144	0.527	0.5769	1.8845	23.06
2	27.88	27.92	0.04	4.95	0.120	0.150	0.5013	0.9294	30.30
3	28.05	28.07	0.02	8.11	0.118	0.170	0.5683	0.1750	17.74
4	28.23	28.3	0.07	7.13	0.199	0.287	0.6509	0.8993	30.60
5	28.33	28.35	0.02	6.15	0.186	0.343	0.5689	1.3013	31.44
	Average			7.10	0.153	0.295	0.5733	1.0379	26.63
	WEIGHTED AVERAGE			6.85	0.163	0.276	0.5876	0.9844	28.23

Table 9-11: Anomaly Data R538(2)

No	Start km	End km	Length	Ave IRI	PSD S11	PSD S12	a_{wz} 11	a_{wz} 12	Speed
	km	km	km	m/km	g^2	g^2	m/s^2	m/s^2	km/h
1	27.84	27.86	0.02	14.12	0.120	0.150	0.3100	0.8058	26.62

A.4. Municipal Road

Table 9-12: Very Good to Good category – Municipal Road

No	Start km	End km	Length	Ave IRI	PSD S11	PSD S12	a_{wz} 11	a_{wz} 12	Speed
	km	km	km	m/km	g^2	g^2	m/s^2	m/s^2	km/h
1	28.92	28.94	0.02	1.77	0.151	0.148	0.5275	0.2925	18.81
2	29.16	29.18	0.02	2.03	0.177	0.177	0.4823	0.4761	45.37
3	29.37	29.45	0.08	1.61	0.019	0.286	0.2035	1.0024	42.74
4	29.89	29.91	0.02	1.76	0.166	0.327	0.4779	1.2023	54.99
5	30.57	30.59	0.02	1.90	0.052	0.296	0.2161	1.1111	39.86
6	30.88	30.94	0.06	1.82	0.301	0.218	0.5681	1.6068	38.81
7	31.87	31.91	0.04	1.79	0.204	0.181	0.7564	0.8474	23.01
	Average			1.81	0.153	0.233	0.4617	0.9341	37.66
	WEIGHTED AVERAGE			1.76	0.149	0.239	0.4412	1.0467	37.88

Table 9-13: Fair to Mediocre category – Municipal Road

No	Start km	End km	Length	Ave IRI	PSD S11	PSD S12	a_{wz} 11	a_{wz} 12	Speed
	km	km	km	m/km	g^2	g^2	m/s^2	m/s^2	km/h
1	29.04	29.11	0.07	3.22	0.102	0.254	0.3576	0.7405	45.66
2	29.27	29.30	0.03	3.47	0.145	0.158	0.5772	0.5291	47.22
3	29.74	29.78	0.04	2.87	0.236	0.196	0.7228	0.7169	20.92
4	29.82	29.86	0.04	2.89	0.177	0.333	0.5502	1.1107	34.96
5	30.10	30.14	0.04	2.93	0.155	0.214	0.5386	0.6919	44.21
6	30.15	30.19	0.04	2.90	0.148	0.193	0.5300	0.6183	43.06
7	30.44	30.53	0.09	3.17	0.023	0.236	0.2202	0.6395	42.00
8	30.68	30.71	0.03	3.07	0.028	0.014	0.2136	0.0595	2.36
9	30.81	30.90	0.09	2.83	0.125	0.014	1.0534	0.4823	4.74
10	30.97	31.00	0.03	3.05	0.145	0.406	0.5689	1.6614	63.63
11	31.30	31.33	0.03	3.71	0.261	0.315	0.9501	1.0858	3.89
12	31.71	31.74	0.03	3.57	0.022	0.189	0.2550	0.6945	20.62
13	31.79	31.87	0.08	2.73	0.256	0.021	0.9132	0.7234	2.80
14	31.97	32.00	0.03	3.37	0.098	0.291	0.4317	0.7234	37.24
15	32.07	32.11	0.04	3.44	0.100	0.277	0.4236	1.0675	30.06
	Average			3.15	0.135	0.207	0.5537	0.7697	29.56
	WEIGHTED AVERAGE			3.09	0.133	0.185	0.5820	0.7345	27.89

Table 9-14: Poor category – Municipal Road

No	Start km	End km	Length	Ave IRI	PSD S11	PSD S12	a_{wz} 11	a_{wz} 12	Speed
	km	km	km	m/km	g^2	g^2	m/s^2	m/s^2	km/h
1	29.30	29.33	0.03	5.44	0.145	0.158	0.6216	0.3755	52.10
2	29.71	29.74	0.03	7.51	0.298	0.263	0.9494	0.9116	24.28
3	29.86	29.89	0.03	6.25	0.166	0.327	0.6096	1.2364	43.86
4	29.94	29.99	0.05	6.31	0.136	0.307	0.4513	1.0517	56.87
5	30.21	30.24	0.03	6.76	0.070	0.083	0.4344	0.2979	33.65
6	30.38	30.44	0.06	6.29	0.018	0.016	0.2362	0.0853	5.51
7	30.96	31.03	0.07	7.08	0.152	0.406	0.2184	1.8631	51.92
8	31.18	31.22	0.04	6.97	0.019	0.182	0.2937	0.5865	30.95
9	31.36	31.39	0.03	4.82	0.207	0.182	0.9028	1.4910	22.10
10	31.40	31.48	0.08	5.64	0.167	0.005	0.7426	1.4930	44.88
11	31.55	31.59	0.04	6.72	0.142	0.257	0.5765	1.6759	32.88
12	32.02	32.05	0.03	5.92	0.142	0.257	0.4438	1.0399	25.98
13	32.17	32.21	0.04	6.34	0.075	0.111	0.5200	0.6275	37.46
Average				6.31	0.134	0.196	0.5385	0.9796	35.57
WEIGHTED AVERAGE				6.32	0.129	0.188	0.5105	1.0424	36.62

Table 9-15: Anomaly Data Municipal Road

No	Start km	End km	Length	Ave IRI	PSD S11	PSD S12	a_{wz} 11	a_{wz} 12	Speed
	km	km	km	m/Km	g^2	g^2	m/s^2	m/s^2	km/h
1	29.69	29.71	0.02	19.61	0.298	0.263	0.9171	0.6799	29.62
2	30.19	30.21	0.02	10.18	0.223	0.185	0.7125	0.6900	37.50
3	30.26	30.28	0.02	19.11	0.070	0.083	0.2445	0.3578	30.25
4	31.07	31.09	0.02	10.40	0.019	0.572	0.2320	1.5235	41.98
5	31.12	31.14	0.02	11.52	0.023	0.281	0.2298	1.5340	39.62
6	31.63	31.65	0.02	20.62	0.020	0.281	0.2538	1.1937	17.69
7	31.66	31.68	0.02	11.47	0.021	0.174	0.2549	0.5735	12.48
8	32.00	32.02	0.02	18.69	0.098	0.291	0.2686	0.0416	12.91
Average				15.20	0.097	0.266	0.3891	0.8243	27.76
WEIGHTED AVERAGE				15.20	0.097	0.266	0.3891	0.8243	27.76

A.5. D2296

Table 9-16: Very Good to Good category – D2296

No	Start km km	End km km	Length km	Ave IRI m/km	PSD S11 g^2	PSD S12 g^2	a_{wz} 11 m/s^2	a_{wz} 12 m/s^2	Speed km/h
1	48.85	48.96	0.11	1.57	0.020	0.167	0.4994	0.6300	40.25
2	48.99	49.29	0.3	1.48	0.103	0.450	0.9034	1.1393	22.78
3	49.73	50.05	0.32	1.46	0.168	0.224	0.7656	0.8669	76.51
4	50.34	50.67	0.33	1.30	0.178	0.187	0.7154	0.7182	77.33
5	50.71	51.09	0.38	1.44	0.337	0.211	0.8482	0.7420	77.00
6	51.47	51.73	0.26	1.36	0.165	0.319	0.6277	0.7777	76.82
7	52.06	52.35	0.29	1.29	0.216	0.173	0.6684	0.8132	77.43
8	52.94	53.14	0.2	1.56	0.198	0.195	0.7327	0.8885	75.50
9	53.47	54.00	0.53	1.43	0.181	0.234	0.7786	1.0385	74.32
10	54.01	54.98	0.97	1.37	0.171	0.220	0.7602	0.8122	77.20
11	55.28	55.60	0.32	1.60	0.325	0.225	1.1716	0.9052	80.08
12	56.47	57.04	0.57	1.52	*	0.221	*	0.7278	76.89
13	58.97	59.12	0.15	1.63	*	0.222	*	0.7384	76.33
14	59.61	59.86	0.25	1.51	*	0.172	*	1.0920	77.17
15	60.40	60.54	0.14	1.72	*	0.395	*	1.3696	71.34
Average				1.48	0.188	0.241	0.7701	0.8840	70.46
WEIGHTED AVERAGE				1.45	0.196	0.236	0.7875	0.8675	72.76

* No data available

Table 9-17: Fair to Mediocre category – D2296

No	Start km km	End km km	Length km	Ave IRI m/km	PSD S11 g^2	PSD S12 g^2	a_{wz} 11 m/s^2	a_{wz} 12 m/s^2	Speed km/h
1	48.96	48.99	0.03	2.69	0.235	0.116	0.6955	0.8552	51.91
2	49.57	49.61	0.04	2.82	0.207	0.343	0.7497	1.0729	78.83
3	49.86	49.90	0.04	2.50	0.149	0.211	0.6169	0.6927	77.17
4	50.67	50.71	0.04	2.63	0.219	0.181	0.7067	0.6839	77.51
5	55.69	55.72	0.03	2.45	*	0.322	*	0.9058	80.01
6	57.20	57.24	0.04	2.89	*	0.169	*	0.5521	16.19
7	57.51	57.56	0.05	2.83	*	0.356	*	1.3437	85.11
8	58.03	58.06	0.03	2.29	*	0.416	*	1.5122	66.16
9	59.94	59.97	0.03	2.63	*	0.304	*	0.9973	76.52
10	60.21	60.24	0.03	2.51	*	0.579	*	1.9717	71.93
11	60.56	60.59	0.03	3.12	*	0.380	*	1.1050	73.53
12	60.68	60.72	0.04	2.48	*	0.376	*	1.3298	72.97
Average				2.65	0.202	0.313	0.6922	1.0852	68.99
WEIGHTED AVERAGE				2.66	0.200	0.308	0.6920	1.0718	69.22

* No data available

Table 9-18: Poor Anomaly Data D2296

No	Start km	End km	Length	Ave IRI	PSD S11	PSD S12	a_{wz} 11	a_{wz} 12	Speed
	km	km	km	m/km	g^2	g^2	m/s^2	m/s^2	km/h
1	49.80	49.82	0.02	5.37	0.199	0.359	0.6147	0.8045	77.56
2	55.75	55.77	0.02	5.35	*	0.205	*	1.4502	79.82
3	55.83	55.87	0.04	6.03	*	0.398	*	2.0201	76.95
4	55.99	56.06	0.07	5.09	*	0.623	*	1.3971	75.73
5	58.13	58.15	0.02	5.81	*	0.456	*	0.8848	60.40
6	60.04	60.06	0.02	6.54	*	0.300	*	1.0081	75.01
7	60.97	61.01	0.04	5.98	*	0.507	*	1.7500	41.07
	Average			5.74	0.199	0.407	0.6147	1.3307	69.51
	WEIGHTED AVERAGE			5.64	0.017	0.462	0.0535	1.4416	69.03

* No data available

B. Appendix B – Vehicle Operating Cost Model

B.1. N4

								Current projection			Constant speed			IRI better at constant speed			
From (Km)	To (Km)	Speed (km/h) (Profiler)	Speed (km/h) (gps)	Constant Speed	IRI	a_{wz} S11	a_{wz} S12	Fuel Consumption	Tyre Wear	Repair and Maintenance Cost	Fuel Consumption	Tyre Wear	Repair and Maintenance Cost	Better IRI	Fuel Consumption	Tyre Wear	Repair and Maintenance Cost
km	km	km/h	km/h	km/h	m/km	m/s²	m/s²	l/km	km	R/km	l/km	km	R/km	m/km	l/km	km	R/km
0.61	0.62	42.50	26.76	60.00	5.21	0.26	0.23	0.20	0.00	0.13	0.32	0.00	1.42	2.24	0.30	0.00	0.62
0.62	0.63	42.20	25.77	60.00	5.28	0.18	0.10	0.19	0.00	0.13	0.32	0.00	1.43	2.24	0.30	0.00	0.62
0.63	0.64	41.50	26.51	60.00	3.16	0.24	0.14	0.18	0.00	0.09	0.30	0.00	0.87	2.24	0.30	0.00	0.62
0.64	0.65	41.10	16.42	60.00	1.63	0.25	0.14	0.15	0.00	0.04	0.29	0.00	0.46	1.63	0.29	0.00	0.46
0.65	0.66	41.00	12.40	60.00	1.75	0.14	0.13	0.14	0.00	0.03	0.29	0.00	0.49	1.75	0.29	0.00	0.49
0.66	0.67	41.40	9.10	60.00	2.97	0.23	0.05	0.14	0.00	0.04	0.30	0.00	0.82	2.24	0.30	0.00	0.62
0.67	0.68	41.90	5.94	60.00	4.69	0.21	0.05	0.14	0.00	0.04	0.31	0.00	1.28	2.24	0.30	0.00	0.62
0.68	0.69	41.80	6.16	60.00	5.78	0.20	0.13	0.15	0.00	0.05	0.32	0.00	1.57	2.24	0.30	0.00	0.62
0.69	0.70	40.80	2.19	60.00	2.80	0.29	0.11	0.13	0.00	0.03	0.30	0.00	0.77	2.24	0.30	0.00	0.62
0.70	0.71	39.60	0.48	60.00	3.40	0.17	0.06	0.13	0.00	0.03	0.30	0.00	0.93	2.24	0.30	0.00	0.62
0.71	0.72	39.00	1.28	60.00	2.62	0.11	0.15	0.12	0.00	0.03	0.30	0.00	0.72	2.24	0.30	0.00	0.62
0.72	0.73	38.30	1.74	60.00	2.31	0.46	0.08	0.12	0.00	0.03	0.30	0.00	0.64	2.24	0.30	0.00	0.62
0.73	0.74	37.90	3.65	60.00	4.76	0.14	0.08	0.14	0.00	0.04	0.31	0.00	1.30	2.24	0.30	0.00	0.62
0.74	0.75	37.80	5.10	60.00	3.67	0.35	0.12	0.14	0.00	0.04	0.31	0.00	1.00	2.24	0.30	0.00	0.62
0.75	0.76	37.70	4.85	60.00	3.05	0.43	0.12	0.13	0.00	0.03	0.30	0.00	0.84	2.24	0.30	0.00	0.62
0.76	0.77	38.40	4.40	60.00	3.11	0.41	0.08	0.13	0.00	0.03	0.30	0.00	0.85	2.24	0.30	0.00	0.62
0.77	0.78	38.30	3.24	60.00	2.98	0.74	0.08	0.13	0.00	0.03	0.30	0.00	0.82	2.24	0.30	0.00	0.62
0.78	0.79	37.50	1.28	60.00	3.28	0.33	0.12	0.13	0.00	0.03	0.30	0.00	0.90	2.24	0.30	0.00	0.62
0.79	0.80	36.70	1.41	60.00	6.24	0.28	0.08	0.14	0.00	0.04	0.32	0.00	1.69	2.24	0.30	0.00	0.62
0.80	0.81	35.80	1.60	60.00	2.36	0.36	0.08	0.12	0.00	0.03	0.30	0.00	0.65	2.24	0.30	0.00	0.62
0.81	0.82	35.70	1.87	60.00	1.55	0.42	0.05	0.12	0.00	0.03	0.29	0.00	0.43	1.55	0.29	0.00	0.43
0.82	0.83	35.20	2.19	60.00	2.48	0.28	0.09	0.13	0.00	0.03	0.30	0.00	0.68	2.24	0.30	0.00	0.62
0.83	0.84	34.30	3.15	60.00	2.33	0.25	0.05	0.13	0.00	0.03	0.30	0.00	0.64	2.24	0.30	0.00	0.62
0.84	0.85	33.70	3.52	60.00	1.93	0.27	0.08	0.13	0.00	0.03	0.30	0.00	0.54	1.93	0.30	0.00	0.54
0.85	0.86	33.80	3.91	60.00	1.39	0.26	0.05	0.12	0.00	0.03	0.29	0.00	0.39	1.39	0.29	0.00	0.39
0.86	0.87	34.40	6.32	60.00	1.48	0.29	0.08	0.13	0.00	0.03	0.29	0.00	0.42	1.48	0.29	0.00	0.42
0.87	0.88	35.20	7.84	60.00	3.13	0.27	0.12	0.14	0.00	0.04	0.30	0.00	0.86	2.24	0.30	0.00	0.62
0.88	0.89	35.70	9.48	60.00	2.74	0.28	0.13	0.14	0.00	0.04	0.30	0.00	0.75	2.24	0.30	0.00	0.62
0.89	0.90	36.30	8.28	60.00	2.72	0.33	0.13	0.14	0.00	0.04	0.30	0.00	0.75	2.24	0.30	0.00	0.62
0.90	0.91	36.20	6.15	60.00	3.72	0.35	0.39	0.14	0.00	0.04	0.31	0.00	1.02	2.24	0.30	0.00	0.62
0.91	0.92	35.80	4.46	60.00	3.19	0.44	0.71	0.13	0.00	0.03	0.30	0.00	0.87	2.24	0.30	0.00	0.62
0.92	0.93	33.70	3.31	60.00	2.24	0.34	0.90	0.13	0.00	0.03	0.30	0.00	0.62	2.24	0.30	0.00	0.62
0.93	0.94	29.90	2.39	60.00	2.06	0.53	0.62	0.12	0.00	0.03	0.30	0.00	0.57	2.06	0.30	0.00	0.57
0.94	0.95	27.70	1.45	60.00	1.71	0.29	0.34	0.12	0.00	0.03	0.29	0.00	0.48	1.71	0.29	0.00	0.48
0.95	0.96	26.80	1.60	60.00	4.28	0.51	0.33	0.13	0.00	0.03	0.31	0.00	1.17	2.24	0.30	0.00	0.62
0.96	0.97	26.80	3.42	60.00	1.56	0.37	0.33	0.12	0.00	0.03	0.29	0.00	0.44	1.56	0.29	0.00	0.44
0.97	0.98	25.30	9.07	60.00	1.03	0.53	0.97	0.13	0.00	0.03	0.29	0.00	0.30	1.03	0.29	0.00	0.30
0.98	0.99	26.80	12.12	60.00	2.06	0.39	1.20	0.14	0.00	0.04	0.30	0.00	0.57	2.06	0.30	0.00	0.57
0.99	1.00	26.60	14.86	60.00	1.26	0.43	0.39	0.15	0.00	0.03	0.29	0.00	0.36	1.26	0.29	0.00	0.36
1.00	1.01	25.40	16.50	60.00	7.04	0.33	0.35	0.18	0.00	0.09	0.33	0.00	1.91	2.24	0.30	0.00	0.62
1.01	1.02	25.20	18.74	60.00	1.58	0.36	0.15	0.16	0.00	0.04	0.29	0.00	0.44	1.58	0.29	0.00	0.44
1.02	1.03	25.90	19.40	60.00	1.33	0.55	0.31	0.16	0.00	0.04	0.29	0.00	0.38	1.33	0.29	0.00	0.38
1.03	1.04	26.80	21.08	60.00	3.27	0.59	0.11	0.17	0.00	0.07	0.30	0.00	0.89	2.24	0.30	0.00	0.62
1.04	1.05	27.30	24.30	60.00	1.87	0.65	0.14	0.17	0.00	0.05	0.30	0.00	0.52	1.87	0.30	0.00	0.52
1.05	1.06	28.60	28.23	60.00	1.63	0.65	0.05	0.18	0.00	0.06	0.29	0.00	0.46	1.63	0.29	0.00	0.46
1.06	1.07	29.40	32.18	60.00	1.66	0.56	0.06	0.19	0.00	0.07	0.29	0.00	0.47	1.66	0.29	0.00	0.47
1.07	1.08	29.50	34.78	60.00	1.44	0.36	0.04	0.20	0.00	0.08	0.29	0.00	0.40	1.44	0.29	0.00	0.40
1.08	1.09	29.70	35.48	60.00	1.25	0.32	0.04	0.20	0.00	0.07	0.29	0.00	0.35	1.25	0.29	0.00	0.35
1.09	1.10	30.00	37.99	60.00	1.16	0.17	0.06	0.21	0.00	0.08	0.29	0.00	0.33	1.16	0.29	0.00	0.33
1.10	1.11	31.70	39.69	60.00	1.19	0.23	0.08	0.21	0.00	0.09	0.29	0.00	0.34	1.19	0.29	0.00	0.34
1.11	1.12	32.60	40.33	60.00	1.29	0.18	0.10	0.22	0.00	0.10	0.29	0.00	0.36	1.29	0.29	0.00	0.36
1.12	1.13	33.60	40.73	60.00	1.03	0.21	0.13	0.22	0.00	0.08	0.29	0.00	0.30	1.03	0.29	0.00	0.30
1.13	1.14	34.60	40.10	60.00	1.37	0.25	0.17	0.21	0.00	0.10	0.29	0.00	0.39	1.37	0.29	0.00	0.39
1.14	1.15	35.70	39.71	60.00	1.61	0.23	0.27	0.22	0.00	0.11	0.29	0.00	0.45	1.61	0.29	0.00	0.45
1.15	1.16	36.90	38.88	60.00	1.45	0.21	0.42	0.21	0.00	0.10	0.29	0.00	0.41	1.45	0.29	0.00	0.41
1.16	1.17	37.30	36.45	60.00	1.03	0.24	0.58	0.20	0.00	0.07	0.29	0.00	0.30	1.03	0.29	0.00	0.30
1.17	1.18	37.20	33.18	60.00	0.94	0.23	0.45	0.19	0.00	0.05	0.29	0.00	0.27	0.94	0.29	0.00	0.27
1.18	1.19	38.40	29.20	60.00	1.32	0.25	0.52	0.18	0.00	0.05	0.29	0.00	0.37	1.32	0.29	0.00	0.37
1.19	1.20	39.60	25.68	60.00	3.22	0.26	0.32	0.18	0.00	0.08	0.30	0.00	0.88	2.24	0.30	0.00	0.62

								Current projection			Constant speed			IRI better at constant speed			
From (Km)	To (Km)	Speed (km/h) (Profiler)	Speed (km/h) (gps)	Constant Speed	IRI	awz S11	awz S12	Fuel Consumption	Tyre Wear	Repair and Maintenance Cost	Fuel Consumption	Tyre Wear	Repair and Maintenance Cost	Better IRI	Fuel Consumption	Tyre Wear	Repair and Maintenance Cost
km	km	km/h	km/h	km/h	m/km	m/s^2	m/s^2	l/km	km	R/km	l/km	km	R/km	m/km	l/km	km	R/km
1.20	1.21	40.10	21.59	60.00	5.72	0.24	0.93	0.18	0.00	0.10	0.32	0.00	1.55	2.24	0.30	0.00	0.62
1.21	1.22	39.70	18.36	60.00	2.44	0.22	1.17	0.16	0.00	0.05	0.30	0.00	0.68	2.24	0.30	0.00	0.62
1.22	1.23	38.80	17.05	60.00	1.21	0.22	0.67	0.15	0.00	0.03	0.29	0.00	0.34	1.21	0.29	0.00	0.34
1.23	1.24	38.40	16.83	60.00	1.80	0.27	0.51	0.15	0.00	0.04	0.29	0.00	0.50	1.80	0.29	0.00	0.50
1.24	1.25	38.60	16.81	60.00	1.46	0.23	0.30	0.15	0.00	0.04	0.29	0.00	0.41	1.46	0.29	0.00	0.41
1.25	1.26	38.90	18.61	60.00	1.44	0.21	0.21	0.15	0.00	0.04	0.29	0.00	0.41	1.44	0.29	0.00	0.41
1.26	1.27	39.40	19.52	60.00	3.57	0.26	0.19	0.17	0.00	0.06	0.31	0.00	0.98	2.24	0.30	0.00	0.62
1.27	1.28	40.20	20.10	60.00	1.70	0.19	0.30	0.16	0.00	0.04	0.29	0.00	0.48	1.70	0.29	0.00	0.48
1.28	1.29	40.70	19.14	60.00	2.18	0.24	0.22	0.16	0.00	0.05	0.30	0.00	0.61	2.18	0.30	0.00	0.61
1.29	1.30	41.10	18.04	60.00	1.18	0.28	0.26	0.15	0.00	0.03	0.29	0.00	0.34	1.18	0.29	0.00	0.34
1.30	1.31	41.50	17.88	60.00	2.47	0.23	0.34	0.16	0.00	0.05	0.30	0.00	0.68	2.24	0.30	0.00	0.62
1.31	1.32	41.60	18.19	60.00	2.69	0.23	0.36	0.16	0.00	0.05	0.30	0.00	0.74	2.24	0.30	0.00	0.62
1.32	1.33	41.50	18.41	60.00	2.14	0.26	0.41	0.16	0.00	0.05	0.30	0.00	0.59	2.14	0.30	0.00	0.59
1.33	1.34	41.40	19.14	60.00	2.00	0.28	0.53	0.16	0.00	0.04	0.30	0.00	0.56	2.00	0.30	0.00	0.56
1.34	1.35	41.40	20.03	60.00	1.40	0.30	0.43	0.16	0.00	0.04	0.29	0.00	0.40	1.40	0.29	0.00	0.40
1.35	1.36	41.60	21.02	60.00	1.74	0.20	0.74	0.16	0.00	0.04	0.29	0.00	0.49	1.74	0.29	0.00	0.49
1.36	1.37	41.90	21.55	60.00	1.70	0.23	0.47	0.16	0.00	0.05	0.29	0.00	0.48	1.70	0.29	0.00	0.48
1.37	1.38	42.20	22.89	60.00	1.65	0.30	0.45	0.17	0.00	0.05	0.29	0.00	0.46	1.65	0.29	0.00	0.46
1.38	1.39	42.40	24.80	60.00	1.64	0.27	0.44	0.17	0.00	0.05	0.29	0.00	0.46	1.64	0.29	0.00	0.46
1.39	1.40	42.50	26.08	60.00	1.61	0.37	0.46	0.17	0.00	0.05	0.29	0.00	0.45	1.61	0.29	0.00	0.45
1.40	1.41	42.70	26.75	60.00	1.59	0.29	0.44	0.18	0.00	0.05	0.29	0.00	0.45	1.59	0.29	0.00	0.45
1.41	1.42	43.00	28.19	60.00	2.30	0.30	0.54	0.18	0.00	0.08	0.30	0.00	0.64	2.24	0.30	0.00	0.62
1.42	1.43	43.20	29.31	60.00	1.93	0.29	0.53	0.19	0.00	0.07	0.30	0.00	0.54	1.93	0.30	0.00	0.54
1.43	1.44	43.60	30.25	60.00	1.29	0.30	0.47	0.18	0.00	0.06	0.29	0.00	0.37	1.29	0.29	0.00	0.37
1.44	1.45	43.80	31.11	60.00	1.16	0.31	0.69	0.19	0.00	0.06	0.29	0.00	0.33	1.16	0.29	0.00	0.33
1.45	1.46	44.00	31.38	60.00	1.54	0.35	0.48	0.19	0.00	0.07	0.29	0.00	0.43	1.54	0.29	0.00	0.43
1.46	1.47	44.20	32.90	60.00	1.18	0.41	0.47	0.19	0.00	0.06	0.29	0.00	0.34	1.18	0.29	0.00	0.34
1.47	1.48	44.30	34.23	60.00	1.68	0.29	0.85	0.20	0.00	0.08	0.29	0.00	0.47	1.68	0.29	0.00	0.47
1.48	1.49	44.50	35.16	60.00	1.64	0.42	0.60	0.20	0.00	0.09	0.29	0.00	0.46	1.64	0.29	0.00	0.46
1.49	1.50	44.90	35.85	60.00	1.54	0.27	0.29	0.20	0.00	0.09	0.29	0.00	0.43	1.54	0.29	0.00	0.43
1.50	1.51	45.10	36.56	60.00	2.84	0.41	0.31	0.21	0.00	0.15	0.30	0.00	0.78	2.24	0.30	0.00	0.62
1.51	1.52	45.10	36.72	60.00	1.13	0.60	0.16	0.20	0.00	0.07	0.29	0.00	0.32	1.13	0.29	0.00	0.32
1.52	1.53	45.10	37.29	60.00	1.58	0.61	0.11	0.21	0.00	0.10	0.29	0.00	0.44	1.58	0.29	0.00	0.44
1.53	1.54	45.10	38.11	60.00	2.13	0.35	0.13	0.21	0.00	0.13	0.30	0.00	0.59	2.13	0.30	0.00	0.59
1.54	1.55	45.20	39.09	60.00	3.64	0.34	0.24	0.22	0.00	0.22	0.31	0.00	0.99	2.24	0.30	0.00	0.62
1.55	1.56	45.10	38.98	60.00	3.96	0.37	0.14	0.23	0.00	0.24	0.31	0.00	1.08	2.24	0.30	0.00	0.62

B.2. R538(1)

								Current projection			Constant speed			IRI better at constant speed			
From (Km)	To (Km)	Speed (km/h) (Profiler)	Speed (km/h) (gps)	Constant Speed	IRI	awz S11	awz S12	Fuel Consumption	Tyre Wear	Repair and Maintenance Cost	Fuel Consumption	Tyre Wear	Repair and Maintenance Cost	Better IRI	Fuel Consumption	Tyre Wear	Repair and Maintenance Cost
km	km	km/h	km/h	km/h	m/km	m/s^2	m/s^2	l/km	km	R/km	l/km	km	R/km	m/km	l/km	km	R/km
13.10	13.11	42.40	76.54	60.00	2.91	0.22	0.61	0.39	0.00	2.76	0.30	0.0009	0.7996	2.2400	0.30	0.0009	0.6202
13.11	13.12	44.20	76.54	60.00	3.83	0.19	0.95	0.39	0.00	3.62	0.31	0.0009	1.0444	2.2400	0.30	0.0009	0.6202
13.12	13.13	45.30	74.16	60.00	1.90	0.20	1.04	0.37	0.00	1.51	0.30	0.0009	0.5292	2.2400	0.30	0.0009	0.6202
13.13	13.14	46.00	74.16	60.00	1.96	0.19	0.83	0.37	0.00	1.56	0.30	0.0009	0.5440	2.2400	0.30	0.0009	0.6202
13.14	13.15	46.90	70.41	60.00	2.97	0.26	1.74	0.35	0.00	1.77	0.30	0.0009	0.8143	2.2400	0.30	0.0009	0.6202
13.15	13.16	47.70	70.41	60.00	7.35	0.26	1.72	0.38	0.00	4.36	0.33	0.0009	1.9865	2.2400	0.30	0.0009	0.6202
13.16	13.17	48.50	66.16	60.00	7.01	0.23	1.00	0.36	0.00	3.02	0.33	0.0009	1.8982	2.2400	0.30	0.0009	0.6202
13.17	13.18	49.30	66.16	60.00	7.12	0.32	0.94	0.36	0.00	3.06	0.33	0.0009	1.9250	2.2400	0.30	0.0009	0.6202
13.18	13.19	49.80	61.94	60.00	8.42	0.32	1.18	0.35	0.00	2.63	0.34	0.0009	2.2729	2.2400	0.30	0.0009	0.6202
13.19	13.20	50.90	61.94	60.00	5.12	0.23	0.95	0.32	0.00	1.61	0.32	0.0009	1.3910	2.2400	0.30	0.0009	0.6202
13.20	13.21	52.20	57.18	60.00	2.87	0.34	1.23	0.29	0.00	0.64	0.30	0.0009	0.7875	2.2400	0.30	0.0009	0.6202

								Current projection			Constant speed			IRI better at constant speed			
From (Km)	To (Km)	Speed (km/h) (Profiler)	Speed (km/h) (gps)	Constant Speed	IRI	awz S11	awz S12	Fuel Consumption	Tyre Wear	Repair and Maintenance Cost	Fuel Consumption	Tyre Wear	Repair and Maintenance Cost	Better IRI	Fuel Consumption	Tyre Wear	Repair and Maintenance Cost
km	km	km/h	km/h	km/h	m/km	m/s²	m/s²	l/km	km	R/km	l/km	km	R/km	m/km	l/km	km	R/km
13.21	13.22	53.30	51.89	60.00	2.11	0.22	0.72	0.26	0.00	0.32	0.30	0.0009	0.5841	2.2400	0.30	0.0009	0.6202
13.22	13.23	54.40	46.02	60.00	2.55	0.39	0.89	0.24	0.00	0.26	0.30	0.0009	0.7032	2.2400	0.30	0.0009	0.6202
13.23	13.24	56.10	40.76	60.00	3.43	0.24	1.33	0.23	0.00	0.23	0.31	0.0009	0.9387	2.2400	0.30	0.0009	0.6202
13.24	13.25	57.50	37.07	60.00	3.23	0.26	0.81	0.22	0.00	0.17	0.30	0.0009	0.8852	2.2400	0.30	0.0009	0.6202
13.25	13.26	58.40	34.96	60.00	2.69	0.27	1.29	0.21	0.00	0.13	0.30	0.0009	0.7393	2.2400	0.30	0.0009	0.6202
13.26	13.27	59.00	33.68	60.00	4.90	0.20	1.35	0.21	0.00	0.20	0.31	0.0009	1.3321	2.2400	0.30	0.0009	0.6202
13.27	13.28	59.50	34.34	60.00	6.07	0.35	1.72	0.22	0.00	0.25	0.32	0.0009	1.6439	2.2400	0.30	0.0009	0.6202
13.28	13.29	59.70	35.88	60.00	7.65	0.27	0.61	0.24	0.00	0.35	0.33	0.0009	2.0668	2.2400	0.30	0.0009	0.6202
13.29	13.30	59.90	37.70	60.00	2.80	0.23	0.35	0.22	0.00	0.16	0.30	0.0009	0.7701	2.2400	0.30	0.0009	0.6202
13.30	13.31	60.20	42.79	60.00	3.83	0.24	0.85	0.24	0.00	0.30	0.31	0.0009	1.0458	2.2400	0.30	0.0009	0.6202
13.31	13.32	60.30	45.89	60.00	3.07	0.31	0.78	0.24	0.00	0.30	0.30	0.0009	0.8437	2.2400	0.30	0.0009	0.6202
13.32	13.33	60.20	47.90	60.00	2.35	0.35	0.84	0.25	0.00	0.27	0.30	0.0009	0.6510	2.2400	0.30	0.0009	0.6202
13.33	13.34	60.30	50.27	60.00	3.53	0.26	0.62	0.26	0.00	0.47	0.31	0.0009	0.9641	2.2400	0.30	0.0009	0.6202
13.34	13.35	60.10	52.87	60.00	3.39	0.23	0.61	0.27	0.00	0.55	0.30	0.0009	0.9267	2.2400	0.30	0.0009	0.6202
13.35	13.36	60.10	54.54	60.00	3.35	0.31	0.45	0.28	0.00	0.61	0.30	0.0009	0.9160	2.2400	0.30	0.0009	0.6202
13.36	13.37	59.90	54.74	60.00	1.75	0.22	0.40	0.27	0.00	0.33	0.29	0.0009	0.4878	2.2400	0.30	0.0009	0.6202
13.37	13.38	59.70	56.71	60.00	2.59	0.28	0.36	0.29	0.00	0.56	0.30	0.0009	0.7139	2.2400	0.30	0.0009	0.6202
13.38	13.39	59.40	58.84	60.00	2.26	0.27	0.25	0.29	0.00	0.57	0.30	0.0009	0.6256	2.2400	0.30	0.0009	0.6202
13.39	13.40	59.30	60.54	60.00	1.99	0.30	0.31	0.30	0.00	0.57	0.30	0.0009	0.5520	2.2400	0.30	0.0009	0.6202
13.40	13.41	59.10	60.54	60.00	3.21	0.29	0.14	0.31	0.00	0.92	0.30	0.0009	0.8798	2.2400	0.30	0.0009	0.6202
13.41	13.42	59.00	62.41	60.00	2.73	0.31	0.09	0.31	0.00	0.90	0.30	0.0009	0.7514	2.2400	0.30	0.0009	0.6202
13.42	13.43	58.70	62.41	60.00	1.89	0.27	0.13	0.31	0.00	0.63	0.30	0.0009	0.5266	2.2400	0.30	0.0009	0.6202
13.43	13.44	58.50	64.84	60.00	2.28	0.29	0.06	0.32	0.00	0.90	0.30	0.0009	0.6296	2.2400	0.30	0.0009	0.6202
13.44	13.45	58.50	64.84	60.00	2.70	0.35	0.05	0.32	0.00	1.06	0.30	0.0009	0.7434	2.2400	0.30	0.0009	0.6202
13.45	13.46	58.70	66.15	60.00	6.76	0.36	0.14	0.36	0.00	2.91	0.33	0.0009	1.8286	2.2400	0.30	0.0009	0.6202
13.46	13.47	59.10	66.15	60.00	3.34	0.47	0.08	0.33	0.00	1.45	0.30	0.0009	0.9133	2.2400	0.30	0.0009	0.6202
13.47	13.48	59.60	68.12	60.00	1.29	0.29	0.04	0.33	0.00	0.66	0.29	0.0009	0.3660	2.2400	0.30	0.0009	0.6202
13.48	13.49	60.00	68.12	60.00	1.14	0.23	0.12	0.33	0.00	0.58	0.29	0.0009	0.3245	2.2400	0.30	0.0009	0.6202
13.49	13.50	60.30	69.28	60.00	1.15	0.39	0.07	0.34	0.00	0.64	0.29	0.0009	0.3285	2.2400	0.30	0.0009	0.6202
13.50	13.51	60.40	69.28	60.00	2.96	0.32	0.05	0.35	0.00	1.63	0.30	0.0009	0.8143	2.2400	0.30	0.0009	0.6202
13.51	13.52	60.10	70.80	60.00	1.72	0.35	0.12	0.35	0.00	1.07	0.29	0.0009	0.4811	2.2400	0.30	0.0009	0.6202
13.52	13.53	58.70	70.80	60.00	1.98	0.61	0.19	0.35	0.00	1.22	0.30	0.0009	0.5493	2.2400	0.30	0.0009	0.6202
13.53	13.54	56.50	72.09	60.00	2.77	0.83	0.25	0.36	0.00	1.88	0.30	0.0009	0.7621	2.2400	0.30	0.0009	0.6202
13.54	13.55	53.80	72.09	60.00	1.69	0.55	0.31	0.35	0.00	1.15	0.29	0.0009	0.4730	2.2400	0.30	0.0009	0.6202
13.55	13.56	50.30	72.64	60.00	1.84	0.46	0.23	0.36	0.00	1.30	0.30	0.0009	0.5118	2.2400	0.30	0.0009	0.6202
13.56	13.57	46.00	72.64	60.00	1.41	0.80	0.18	0.36	0.00	1.01	0.29	0.0009	0.3981	2.2400	0.30	0.0009	0.6202
13.57	13.58	42.40	72.70	60.00	1.64	0.77	0.25	0.36	0.00	1.17	0.29	0.0009	0.4583	2.2400	0.30	0.0009	0.6202
13.58	13.59	41.10	72.70	60.00	1.21	0.48	0.18	0.35	0.00	0.87	0.29	0.0009	0.3446	2.2400	0.30	0.0009	0.6202
13.59	13.60	40.70	72.27	60.00	4.18	0.40	0.36	0.37	0.00	2.87	0.31	0.0009	1.1408	2.2400	0.30	0.0009	0.6202
13.60	13.61	39.20	72.27	60.00	3.04	0.28	0.15	0.36	0.00	2.08	0.30	0.0009	0.8330	2.2400	0.30	0.0009	0.6202
13.61	13.62	39.90	71.75	60.00	2.58	0.33	0.15	0.36	0.00	1.71	0.30	0.0009	0.7112	2.2400	0.30	0.0009	0.6202
13.62	13.63	41.70	71.75	60.00	1.85	0.34	0.12	0.35	0.00	1.23	0.30	0.0009	0.5145	2.2400	0.30	0.0009	0.6202
13.63	13.64	42.80	70.42	60.00	1.80	0.35	0.19	0.35	0.00	1.08	0.29	0.0009	0.5011	2.2400	0.30	0.0009	0.6202
13.64	13.65	43.70	70.42	60.00	2.99	0.33	0.21	0.35	0.00	1.78	0.30	0.0009	0.8196	2.2400	0.30	0.0009	0.6202
13.65	13.66	44.30	68.89	60.00	1.83	0.37	0.13	0.34	0.00	0.98	0.30	0.0009	0.5092	2.2400	0.30	0.0009	0.6202
13.66	13.67	44.60	68.89	60.00	1.23	0.35	0.25	0.33	0.00	0.67	0.29	0.0009	0.3499	2.2400	0.30	0.0009	0.6202
13.67	13.68	44.90	67.24	60.00	0.92	0.37	0.23	0.32	0.00	0.45	0.29	0.0009	0.2670	2.2400	0.30	0.0009	0.6202
13.68	13.69	45.10	67.24	60.00	2.93	0.34	0.14	0.34	0.00	1.38	0.30	0.0009	0.8036	2.2400	0.30	0.0009	0.6202
13.69	13.70	45.40	64.50	60.00	2.06	0.35	0.14	0.32	0.00	0.80	0.30	0.0009	0.5721	2.2400	0.30	0.0009	0.6202
13.70	13.71	45.70	64.50	60.00	1.94	0.33	0.29	0.32	0.00	0.75	0.30	0.0009	0.5399	2.2400	0.30	0.0009	0.6202
13.71	13.72	46.00	60.95	60.00	2.21	0.30	0.19	0.30	0.00	0.65	0.30	0.0009	0.6109	2.2400	0.30	0.0009	0.6202
13.72	13.73	46.20	60.95	60.00	1.56	0.33	0.21	0.30	0.00	0.47	0.29	0.0009	0.4369	2.2400	0.30	0.0009	0.6202
13.73	13.74	46.40	56.12	60.00	2.93	0.37	0.13	0.28	0.00	0.60	0.30	0.0009	0.8049	2.2400	0.30	0.0009	0.6202
13.74	13.75	46.80	51.07	60.00	1.54	0.36	0.18	0.26	0.00	0.23	0.29	0.0009	0.4316	2.2400	0.30	0.0009	0.6202
13.75	13.76	47.00	44.91	60.00	5.95	0.44	0.14	0.26	0.00	0.53	0.32	0.0009	1.6132	2.2400	0.30	0.0009	0.6202
13.76	13.77	47.30	38.90	60.00	3.42	0.36	0.16	0.22	0.00	0.20	0.30	0.0009	0.9347	2.2400	0.30	0.0009	0.6202
13.77	13.78	47.40	34.04	60.00	2.16	0.32	0.26	0.20	0.00	0.10	0.30	0.0009	0.5988	2.2400	0.30	0.0009	0.6202
13.78	13.79	47.60	29.71	60.00	1.80	0.33	0.32	0.19	0.00	0.07	0.30	0.0009	0.5038	2.2400	0.30	0.0009	0.6202
13.79	13.80	47.70	25.31	60.00	1.08	0.37	0.41	0.17	0.00	0.04	0.29	0.0009	0.3084	2.2400	0.30	0.0009	0.6202
13.80	13.81	48.00	20.47	60.00	1.36	0.37	0.32	0.16	0.00	0.04	0.29	0.0009	0.3834	2.2400	0.30	0.0009	0.6202
13.81	13.82	48.50	15.38	60.00	1.64	0.36	0.22	0.15	0.00	0.04	0.29	0.0009	0.4583	2.2400	0.30	0.0009	0.6202
13.82	13.83	49.10	9.85	60.00	2.28	0.35	0.25	0.14	0.00	0.03	0.30	0.0009	0.6296	2.2400	0.30	0.0009	0.6202
13.83	13.84	49.40	2.80	60.00	1.06	0.35	0.29	0.12	0.00	0.02	0.29	0.0009	0.3044	2.2400	0.30	0.0009	0.6202
13.84	13.85	49.70	3.06	60.00	1.05	0.29	0.60	0.12	0.00	0.02	0.29	0.0009	0.3018	2.2400	0.30	0.0009	0.6202

								Current projection			Constant speed			IRI better at constant speed			
From (Km)	To (Km)	Speed (km/h) (Profiler)	Speed (km/h) (gps)	Constant Speed	IRI	awz S11	awz S12	Fuel Consumption	Tyre Wear	Repair and Maintenance Cost	Fuel Consumption	Tyre Wear	Repair and Maintenance Cost	Better IRI	Fuel Consumption	Tyre Wear	Repair and Maintenance Cost
km	km	km/h	km/h	km/h	m/km	m/s^2	m/s^2	l/km	km	R/km	l/km	km	R/km	m/km	l/km	km	R/km
13.85	13.86	50.30	7.45	60.00	0.98	0.35	0.91	0.13	0.00	0.03	0.29	0.0009	0.2844	2.2400	0.30	0.0009	0.6202
13.86	13.87	50.80	0.68	60.00	1.12	0.37	0.83	0.12	0.00	0.02	0.29	0.0009	0.3205	0.6835	0.29	0.0009	0.2037
13.87	13.88	51.40	3.09	60.00	1.12	0.34	0.28	0.12	0.00	0.02	0.29	0.0009	0.3205	2.2400	0.30	0.0009	0.6202
13.88	13.89	51.80	3.35	60.00	1.29	0.37	0.86	0.12	0.00	0.03	0.29	0.0009	0.3646	2.2400	0.30	0.0009	0.6202
13.89	13.90	52.30	7.62	60.00	1.79	0.32	1.04	0.13	0.00	0.03	0.29	0.0009	0.4985	2.2400	0.30	0.0009	0.6202
13.90	13.91	52.60	9.32	60.00	1.28	0.28	0.35	0.13	0.00	0.03	0.29	0.0009	0.3620	2.2400	0.30	0.0009	0.6202
13.91	13.92	52.80	10.34	60.00	0.97	0.30	0.37	0.13	0.00	0.03	0.29	0.0009	0.2817	2.2400	0.30	0.0009	0.6202
13.92	13.93	53.10	11.58	60.00	1.29	0.30	0.23	0.14	0.00	0.03	0.29	0.0009	0.3646	2.2400	0.30	0.0009	0.6202
13.93	13.94	53.40	13.77	60.00	1.64	0.29	0.27	0.14	0.00	0.03	0.29	0.0009	0.4583	2.2400	0.30	0.0009	0.6202
13.94	13.95	53.60	14.45	60.00	1.08	0.33	0.29	0.14	0.00	0.03	0.29	0.0009	0.3084	2.2400	0.30	0.0009	0.6202
13.95	13.96	53.80	14.31	60.00	1.75	0.39	0.19	0.15	0.00	0.04	0.29	0.0009	0.4891	2.2400	0.30	0.0009	0.6202
13.96	13.97	54.00	15.10	60.00	1.19	0.31	0.31	0.15	0.00	0.03	0.29	0.0009	0.3392	2.2400	0.30	0.0009	0.6202
13.97	13.98	54.20	16.18	60.00	1.08	0.29	0.36	0.15	0.00	0.03	0.29	0.0009	0.3098	2.2400	0.30	0.0009	0.6202
13.98	13.99	54.40	18.52	60.00	1.12	0.35	0.45	0.15	0.00	0.03	0.29	0.0009	0.3192	2.2400	0.30	0.0009	0.6202
13.99	14.00	54.90	20.60	60.00	1.15	0.36	0.56	0.16	0.00	0.04	0.29	0.0009	0.3272	2.2400	0.30	0.0009	0.6202
14.00	14.01	55.40	21.26	60.00	1.47	0.34	0.33	0.16	0.00	0.04	0.29	0.0009	0.4128	2.2400	0.30	0.0009	0.6202
14.01	14.02	56.00	20.66	60.00	1.05	0.38	0.23	0.16	0.00	0.03	0.29	0.0009	0.3018	2.2400	0.30	0.0009	0.6202
14.02	14.03	56.30	20.13	60.00	1.21	0.34	0.32	0.16	0.00	0.04	0.29	0.0009	0.3446	2.2400	0.30	0.0009	0.6202
14.03	14.04	55.10	20.95	60.00	1.30	0.29	0.31	0.16	0.00	0.04	0.29	0.0009	0.3673	2.2400	0.30	0.0009	0.6202
14.04	14.05	54.70	22.35	60.00	0.97	0.32	0.32	0.16	0.00	0.04	0.29	0.0009	0.2817	2.2400	0.30	0.0009	0.6202

B.3. R538(2)

								Current projection			Constant speed			IRI better at constant speed			
From (Km)	To (Km)	Speed (km/h) (Profiler)	Speed (km/h) (gps)	Constant Speed	IRI	awz S11	awz S12	Fuel Consumption	Tyre Wear	Repair and Maintenance Cost	Fuel Consumption	Tyre Wear	Repair and Maintenance Cost	Better IRI	Fuel Consumption	Tyre Wear	Repair and Maintenance Cost
km	km	km/h	km/h	km/h	m/km	m/s^2	m/s^2	l/km	km	R/km	l/km	km	R/km	m/km	l/km	km	R/km
27.71	27.72	49.10			1.10	0.89	0.60										
27.72	27.73	49.60	11.02	60.00	1.84	0.92	0.32	0.14	0.00	0.03	0.30	0.0009	0.5132	1.8400	0.30	0.0009	0.5132
27.73	27.74	49.20	14.77	60.00	2.38	0.99	0.30	0.15	0.00	0.04	0.30	0.0009	0.6577	2.2400	0.30	0.0009	0.6202
27.74	27.75	48.80	16.01	60.00	1.15	0.86	0.18	0.15	0.00	0.03	0.29	0.0009	0.3285	1.1500	0.29	0.0009	0.3285
27.75	27.76	48.10	20.60	60.00	1.13	0.62	0.16	0.16	0.00	0.04	0.29	0.0009	0.3218	1.1250	0.29	0.0009	0.3218
27.76	27.77	47.10	21.82	60.00	1.04	0.36	0.17	0.16	0.00	0.04	0.29	0.0009	0.2977	1.0350	0.29	0.0009	0.2977
27.77	27.78	46.20	24.20	60.00	0.92	0.40	0.29	0.17	0.00	0.04	0.29	0.0009	0.2670	0.9200	0.29	0.0009	0.2670
27.78	27.79	46.00	24.74	60.00	1.58	0.37	0.52	0.17	0.00	0.05	0.29	0.0009	0.4423	1.5750	0.29	0.0009	0.4423
27.79	27.80	45.70	23.82	60.00	2.08	0.32	1.30	0.17	0.00	0.06	0.30	0.0009	0.5774	2.0800	0.30	0.0009	0.5774
27.80	27.81	45.20	21.40	60.00	4.30	0.35	1.38	0.18	0.00	0.08	0.31	0.0009	1.1716	2.2400	0.30	0.0009	0.6202
27.81	27.82	44.80	19.62	60.00	12.79	0.36	1.51	0.21	0.00	0.18	0.36	0.0009	3.4438	2.2400	0.30	0.0009	0.6202
27.82	27.83	44.30	21.14	60.00	11.09	0.72	2.09	0.21	0.00	0.18	0.35	0.0009	2.9875	2.2400	0.30	0.0009	0.6202
27.83	27.84	43.90	21.74	60.00	7.20	0.33	1.61	0.19	0.00	0.13	0.33	0.0009	1.9490	2.2400	0.30	0.0009	0.6202
27.84	27.85	43.40	23.72	60.00	15.57	0.31	0.43	0.24	0.00	0.29	0.38	0.0009	4.1878	2.2400	0.30	0.0009	0.6202
27.85	27.86	42.80	24.42	60.00	12.67	0.32	0.78	0.23	0.00	0.25	0.36	0.0009	3.4117	2.2400	0.30	0.0009	0.6202
27.86	27.87	42.70	25.88	60.00	9.57	0.29	1.05	0.22	0.00	0.21	0.34	0.0009	2.5807	2.2400	0.30	0.0009	0.6202
27.87	27.88	42.70	27.35	60.00	1.97	0.30	1.38	0.18	0.00	0.06	0.30	0.0009	0.5466	1.9650	0.30	0.0009	0.5466
27.88	27.89	41.40	28.83	60.00	4.30	0.46	1.01	0.20	0.00	0.13	0.31	0.0009	1.1716	2.2400	0.30	0.0009	0.6202
27.89	27.90	40.00	29.70	60.00	4.37	0.63	0.95	0.20	0.00	0.14	0.31	0.0009	1.1890	2.2400	0.30	0.0009	0.6202
27.90	27.91	39.20	29.56	60.00	5.61	0.49	0.41	0.21	0.00	0.17	0.32	0.0009	1.5222	2.2400	0.30	0.0009	0.6202
27.91	27.92	38.30	30.62	60.00	5.51	0.55	0.31	0.21	0.00	0.18	0.32	0.0009	1.4967	2.2400	0.30	0.0009	0.6202
27.92	27.93	37.70	31.20	60.00	3.01	0.43	0.43	0.20	0.00	0.11	0.30	0.0009	0.8250	2.2400	0.30	0.0009	0.6202
27.93	27.94	37.80	32.77	60.00	4.16	0.34	0.28	0.21	0.00	0.16	0.31	0.0009	1.1341	2.2400	0.30	0.0009	0.6202
27.94	27.95	38.80	33.19	60.00	2.40	0.38	0.22	0.20	0.00	0.10	0.30	0.0009	0.6617	2.2400	0.30	0.0009	0.6202
27.95	27.96	39.50	35.01	60.00	2.03	0.33	0.33	0.20	0.00	0.10	0.30	0.0009	0.5627	2.0250	0.30	0.0009	0.5627
27.96	27.97	39.50	35.60	60.00	1.68	0.31	0.40	0.20	0.00	0.09	0.29	0.0009	0.4704	1.6800	0.29	0.0009	0.4704
27.97	27.98	39.20	36.75	60.00	1.87	0.55	0.97	0.21	0.00	0.11	0.30	0.0009	0.5212	1.8700	0.30	0.0009	0.5212

								Current projection			Constant speed			IRI better at constant speed			
From (Km)	To (Km)	Speed (km/h) (Profiler)	Speed (km/h) (gps)	Constant Speed	IRI	awz S11	awz S12	Fuel Consumption	Tyre Wear	Repair and Maintenance Cost	Fuel Consumption	Tyre Wear	Repair and Maintenance Cost	Better IRI	Fuel Consumption	Tyre Wear	Repair and Maintenance Cost
km	km	km/h	km/h	km/h	m/km	m/s²	m/s²	l/km	km	R/km	l/km	km	R/km	m/km	l/km	km	R/km
27.98	27.99	38.30	38.21	60.00	1.57	0.74	0.47	0.21	0.00	0.10	0.29	0.0009	0.4396	1.5650	0.29	0.0009	0.4396
27.99	28.00	38.00	38.67	60.00	1.59	0.78	0.28	0.21	0.00	0.10	0.29	0.0009	0.4463	1.5900	0.29	0.0009	0.4463
28.00	28.01	38.90	37.64	60.00	1.78	0.72	0.30	0.21	0.00	0.11	0.29	0.0009	0.4971	1.7800	0.29	0.0009	0.4971
28.01	28.02	39.30	33.51	60.00	1.42	0.80	0.17	0.19	0.00	0.07	0.29	0.0009	0.4008	1.4200	0.29	0.0009	0.4008
28.02	28.03	38.90	26.21	60.00	1.17	0.47	0.19	0.17	0.00	0.04	0.29	0.0009	0.3325	1.1650	0.29	0.0009	0.3325
28.03	28.04	38.50	20.22	60.00	1.36	0.40	0.41	0.16	0.00	0.04	0.29	0.0009	0.3834	1.3550	0.29	0.0009	0.3834
28.04	28.05	37.60	16.83	60.00	2.89	0.57	0.83	0.16	0.00	0.05	0.30	0.0009	0.7929	2.2400	0.30	0.0009	0.6202
28.05	28.06	35.80	18.68	60.00	7.89	1.06	0.45	0.19	0.00	0.11	0.33	0.0009	2.1324	2.2400	0.30	0.0009	0.6202
28.06	28.07	33.20	19.82	60.00	8.33	1.14	0.67	0.19	0.00	0.13	0.34	0.0009	2.2488	2.2400	0.30	0.0009	0.6202
28.07	28.08	31.80	21.62	60.00	2.43	0.49	0.29	0.17	0.00	0.06	0.30	0.0009	0.6698	2.2400	0.30	0.0009	0.6202
28.08	28.09	32.40	22.03	60.00	3.71	0.99	0.32	0.17	0.00	0.08	0.31	0.0009	1.0150	2.2400	0.30	0.0009	0.6202
28.09	28.10	33.30	22.28	60.00	2.66	0.78	0.35	0.17	0.00	0.06	0.30	0.0009	0.7326	2.2400	0.30	0.0009	0.6202
28.10	28.11	34.20	22.97	60.00	1.40	0.89	0.37	0.17	0.00	0.04	0.29	0.0009	0.3954	1.4000	0.29	0.0009	0.3954
28.11	28.12	35.40	24.97	60.00	1.12	0.50	0.43	0.17	0.00	0.04	0.29	0.0009	0.3205	1.1200	0.29	0.0009	0.3205
28.12	28.13	35.30	27.13	60.00	7.40	0.58	1.01	0.21	0.00	0.18	0.33	0.0009	1.9999	2.2400	0.30	0.0009	0.6202
28.13	28.14	33.90	27.97	60.00	1.51	0.57	0.80	0.18	0.00	0.06	0.29	0.0009	0.4235	1.5050	0.29	0.0009	0.4235
28.14	28.15	33.10	30.18	60.00	4.59	0.80	0.76	0.20	0.00	0.15	0.31	0.0009	1.2492	2.2400	0.30	0.0009	0.6202
28.15	28.16	33.00	30.70	60.00	3.23	0.46	1.14	0.20	0.00	0.11	0.30	0.0009	0.8852	2.2400	0.30	0.0009	0.6202
28.16	28.17	34.20	32.58	60.00	2.40	0.76	0.77	0.20	0.00	0.10	0.30	0.0009	0.6617	2.2400	0.30	0.0009	0.6202
28.17	28.18	36.00	33.13	60.00	1.54	1.10	0.36	0.19	0.00	0.07	0.29	0.0009	0.4316	1.5350	0.29	0.0009	0.4316
28.18	28.19	37.40	34.48	60.00	1.57	0.39	0.42	0.20	0.00	0.08	0.29	0.0009	0.4396	1.5650	0.29	0.0009	0.4396
28.19	28.20	38.40	33.90	60.00	1.52	0.42	1.04	0.20	0.00	0.08	0.29	0.0009	0.4275	1.5200	0.29	0.0009	0.4275
28.20	28.21	39.30	31.29	60.00	1.26	0.32	1.32	0.19	0.00	0.06	0.29	0.0009	0.3566	1.2550	0.29	0.0009	0.3566
28.21	28.22	39.60	29.68	60.00	1.32	0.54	1.63	0.18	0.00	0.06	0.29	0.0009	0.3740	1.3200	0.29	0.0009	0.3740
28.22	28.23	39.10	28.49	60.00	1.26	0.85	0.49	0.18	0.00	0.05	0.29	0.0009	0.3580	1.2600	0.29	0.0009	0.3580
28.23	28.24	38.10	28.78	60.00	5.43	0.49	1.53	0.20	0.00	0.16	0.32	0.0009	1.4727	2.2400	0.30	0.0009	0.6202
28.24	28.25	37.20	30.72	60.00	6.68	0.47	1.08	0.21	0.00	0.21	0.33	0.0009	1.8085	2.2400	0.30	0.0009	0.6202
28.25	28.26	35.30	31.32	60.00	6.81	0.52	1.09	0.22	0.00	0.23	0.33	0.0009	1.8433	2.2400	0.30	0.0009	0.6202
28.26	28.27	34.30	32.00	60.00	6.36	0.32	0.71	0.22	0.00	0.22	0.32	0.0009	1.7229	2.2400	0.30	0.0009	0.6202
28.27	28.28	33.80	29.65	60.00	6.43	0.19	0.60	0.21	0.00	0.19	0.32	0.0009	1.7403	2.2400	0.30	0.0009	0.6202
28.28	28.29	33.80	26.29	60.00	10.12	0.20	0.71	0.22	0.00	0.23	0.35	0.0009	2.7279	2.2400	0.30	0.0009	0.6202
28.29	28.30	33.60	23.17	60.00	8.08	0.21	0.63	0.20	0.00	0.15	0.33	0.0009	2.1832	2.2400	0.30	0.0009	0.6202
28.30	28.31	33.40	23.64	60.00	2.70	0.20	0.54	0.17	0.00	0.07	0.30	0.0009	0.7434	2.2400	0.30	0.0009	0.6202
28.31	28.32	32.80	24.03	60.00	3.41	0.21	1.38	0.18	0.00	0.08	0.30	0.0009	0.9334	2.2400	0.30	0.0009	0.6202
28.32	28.33	31.60	27.13	60.00	2.03	0.21	0.91	0.18	0.00	0.07	0.30	0.0009	0.5627	2.0250	0.30	0.0009	0.5627
28.33	28.34	31.30	28.45	60.00	5.59	0.20	0.33	0.20	0.00	0.16	0.32	0.0009	1.5168	2.2400	0.30	0.0009	0.6202
28.34	28.35	30.50	32.48	60.00	6.71	0.22	0.29	0.22	0.00	0.24	0.33	0.0009	1.8179	2.2400	0.30	0.0009	0.6202
28.35	28.36	29.30	33.86	60.00	12.57	0.20	0.28	0.26	0.00	0.48	0.36	0.0009	3.3849	2.2400	0.30	0.0009	0.6202
28.36	28.37	29.40	35.61	60.00	9.49	0.22	0.65	0.25	0.00	0.42	0.34	0.0009	2.5606	2.2400	0.30	0.0009	0.6202
28.37	28.38	31.20	35.40	60.00	1.85	0.21	1.23	0.20	0.00	0.10	0.30	0.0009	0.5145	1.8450	0.30	0.0009	0.5145
28.38	28.39	33.20	35.16	60.00	9.14	0.20	0.71	0.24	0.00	0.39	0.34	0.0009	2.4669	2.2400	0.30	0.0009	0.6202
28.39	28.40	34.20	35.57	60.00	3.72	0.21	0.26	0.21	0.00	0.18	0.31	0.0009	1.0150	2.2400	0.30	0.0009	0.6202
28.40	28.41	35.10	36.13	60.00	8.88	0.21	0.24	0.24	0.00	0.41	0.34	0.0009	2.3987	2.2400	0.30	0.0009	0.6202
28.41	28.42	35.70	33.57	60.00	2.36	0.22	0.11	0.20	0.00	0.11	0.30	0.0009	0.6524	2.2400	0.30	0.0009	0.6202
28.42	28.43	36.90	29.27	60.00	3.33	0.22	0.07	0.19	0.00	0.11	0.30	0.0009	0.9106	2.2400	0.30	0.0009	0.6202
28.43	28.44	38.30	25.08	60.00	5.63	0.21	0.07	0.19	0.00	0.13	0.32	0.0009	1.5262	2.2400	0.30	0.0009	0.6202
28.44	28.45	39.00	21.04	60.00	3.87	0.21	0.05	0.17	0.00	0.07	0.31	0.0009	1.0565	2.2400	0.30	0.0009	0.6202
28.45	28.46	39.30	19.25	60.00	3.09	0.21	0.05	0.16	0.00	0.06	0.30	0.0009	0.8477	2.2400	0.30	0.0009	0.6202
28.46	28.47	39.20	16.12	60.00	10.82	0.21	0.05	0.20	0.00	0.12	0.35	0.0009	2.9165	2.2400	0.30	0.0009	0.6202
28.47	28.48	39.20	11.89	60.00	3.60	0.21	0.06	0.15	0.00	0.05	0.31	0.0009	0.9856	2.2400	0.30	0.0009	0.6202
28.48	28.49	39.30	6.24	60.00	1.55	0.24	0.06	0.13	0.00	0.03	0.29	0.0009	0.4342	1.5450	0.29	0.0009	0.4342
28.49	28.50	39.70	2.06	60.00	5.11	0.24	0.06	0.14	0.00	0.04	0.32	0.0009	1.3883	2.2400	0.30	0.0009	0.6202
28.50	28.51	39.20	1.43	60.00	11.77	0.20	0.05	0.17	0.00	0.06	0.36	0.0009	3.1695	2.2400	0.30	0.0009	0.6202
28.51	28.52	37.90	2.02	60.00	8.25	0.23	0.05	0.15	0.00	0.05	0.33	0.0009	2.2287	2.2400	0.30	0.0009	0.6202
28.52	28.53	38.90	1.56	60.00	2.08	0.30	0.05	0.12	0.00	0.03	0.30	0.0009	0.5761	2.0750	0.30	0.0009	0.5761
28.53	28.54	40.70	0.83	60.00	2.11	0.30	0.06	0.12	0.00	0.03	0.30	0.0009	0.5854	2.1100	0.30	0.0009	0.5854
28.54	28.55	41.90	0.76	60.00	2.74	0.34	0.05	0.12	0.00	0.03	0.30	0.0009	0.7527	2.2400	0.30	0.0009	0.6202
28.59	28.60	45.50	0.96	60.00	2.12	0.48	0.05	0.12	0.00	0.03	0.30	0.0009	0.5881	2.1200	0.30	0.0009	0.5881
28.61	28.62	44.80	0.64	60.00	1.68	0.35	0.05	0.12	0.00	0.03	0.29	0.0009	0.4704	1.6800	0.29	0.0009	0.4704
28.62	28.63	44.50	0.34	60.00	1.45	0.44	0.10	0.12	0.00	0.02	0.29	0.0009	0.4088	1.4500	0.29	0.0009	0.4088
28.63	28.64	43.90	0.34	60.00	1.51	0.44	0.10	0.12	0.00	0.03	0.29	0.0009	0.4235	1.5050	0.29	0.0009	0.4235
28.64	28.65	43.70	1.07	60.00	6.53	0.34	0.04	0.14	0.00	0.04	0.32	0.0009	1.7671	2.2400	0.30	0.0009	0.6202
28.65	28.66	44.50	2.66	60.00	3.61	0.34	0.24	0.13	0.00	0.03	0.31	0.0009	0.9856	2.2400	0.30	0.0009	0.6202

B.4. Municipal road

								Current projection			Constant speed			IRI better at constant speed			
From (Km)	To (Km)	Speed (km/h) (Profiler)	Speed (km/h) (gps)	Constant Speed	IRI	awz S11	awz S12	Fuel Consumption	Tyre Wear	Repair and Maintenance Cost	Fuel Consumption	Tyre Wear	Repair and Maintenance Cost	Better IRI	Fuel Consumption	Tyre Wear	Repair and Maintenance Cost
km	km	km/h	km/h	km/h	m/km	m/s²	m/s²	l/km	km	R/km	l/km	km	R/km	m/km	l/km	km	R/km
28.88	28.89	27.00	11.77	60.00	5.12	0.60	0.36	0.16	0.00	0.06	0.32	0.0009	1.3897	2.2400	0.30	0.0009	0.6202
28.89	28.90	30.50	12.60	60.00	8.84	0.43	0.62	0.18	0.00	0.09	0.34	0.0009	2.3866	2.2400	0.30	0.0009	0.6202
28.90	28.91	34.90	14.85	60.00	9.57	0.55	0.46	0.19	0.00	0.10	0.34	0.0009	2.5820	2.2400	0.30	0.0009	0.6202
28.91	28.92	37.30	17.93	60.00	3.13	0.61	0.71	0.16	0.00	0.05	0.30	0.0009	0.8571	2.2400	0.30	0.0009	0.6202
28.92	28.93	38.00	21.21	60.00	2.06	0.51	0.29	0.16	0.00	0.05	0.30	0.0009	0.5707	2.0550	0.30	0.0009	0.5707
28.93	28.94	39.20	24.53	60.00	1.49	0.54	0.35	0.17	0.00	0.05	0.29	0.0009	0.4182	1.4850	0.29	0.0009	0.4182
28.94	28.95	40.60	25.99	60.00	2.75	0.42	0.63	0.18	0.00	0.08	0.30	0.0009	0.7567	2.2400	0.30	0.0009	0.6202
28.95	28.96	41.40	29.43	60.00	5.41	0.58	0.79	0.20	0.00	0.16	0.32	0.0009	1.4686	2.2400	0.30	0.0009	0.6202
28.96	28.97	41.40	30.52	60.00	4.72	0.85	0.90	0.20	0.00	0.16	0.31	0.0009	1.2840	2.2400	0.30	0.0009	0.6202
28.97	28.98	41.50	33.20	60.00	3.84	0.54	0.80	0.21	0.00	0.15	0.31	0.0009	1.0485	2.2400	0.30	0.0009	0.6202
28.98	28.99	41.30	34.17	60.00	4.20	0.56	0.98	0.21	0.00	0.18	0.31	0.0009	1.1435	2.2400	0.30	0.0009	0.6202
28.99	29.00	40.90	36.72	60.00	3.32	0.33	0.92	0.21	0.00	0.17	0.30	0.0009	0.9093	2.2400	0.30	0.0009	0.6202
29.00	29.01	40.40	39.68	60.00	5.25	0.39	0.74	0.24	0.00	0.32	0.32	0.0009	1.4258	2.2400	0.30	0.0009	0.6202
29.01	29.02	40.20	44.36	60.00	4.43	0.33	0.89	0.25	0.00	0.38	0.31	0.0009	1.2064	2.2400	0.30	0.0009	0.6202
29.02	29.03	40.10	46.55	60.00	2.81	0.33	0.38	0.25	0.00	0.29	0.30	0.0009	0.7728	2.2400	0.30	0.0009	0.6202
29.03	29.04	40.00	49.58	60.00	4.58	0.69	0.38	0.27	0.00	0.58	0.31	0.0009	1.2465	2.2400	0.30	0.0009	0.6202
29.04	29.05	39.90	51.27	60.00	3.56	0.97	0.75	0.27	0.00	0.51	0.31	0.0009	0.9735	2.2400	0.30	0.0009	0.6202
29.05	29.06	39.90	52.53	60.00	3.65	0.71	0.49	0.27	0.00	0.57	0.31	0.0009	0.9963	2.2400	0.30	0.0009	0.6202
29.06	29.07	39.80	49.96	60.00	3.90	0.43	0.49	0.27	0.00	0.51	0.31	0.0009	1.0645	2.2400	0.30	0.0009	0.6202
29.07	29.08	39.70	46.34	60.00	3.40	0.57	0.45	0.25	0.00	0.34	0.30	0.0009	0.9294	2.2400	0.30	0.0009	0.6202
29.08	29.09	39.90	42.81	60.00	2.38	0.43	0.73	0.23	0.00	0.19	0.30	0.0009	0.6564	2.2400	0.30	0.0009	0.6202
29.09	29.10	40.10	41.88	60.00	2.39	0.33	0.89	0.23	0.00	0.18	0.30	0.0009	0.6604	2.2400	0.30	0.0009	0.6202
29.10	29.11	40.20	44.04	60.00	3.27	0.37	0.72	0.24	0.00	0.28	0.30	0.0009	0.8959	2.2400	0.30	0.0009	0.6202
29.11	29.12	40.30	46.43	60.00	5.54	0.58	0.55	0.26	0.00	0.55	0.32	0.0009	1.5021	2.2400	0.30	0.0009	0.6202
29.12	29.13	40.40	49.36	60.00	3.00	0.70	0.34	0.26	0.00	0.38	0.30	0.0009	0.8223	2.2400	0.30	0.0009	0.6202
29.13	29.14	40.20	52.24	60.00	2.59	0.67	0.47	0.27	0.00	0.41	0.30	0.0009	0.7139	2.2400	0.30	0.0009	0.6202
29.14	29.15	40.00	55.15	60.00	1.45	0.41	0.30	0.27	0.00	0.29	0.29	0.0009	0.4088	1.4500	0.29	0.0009	0.4088
29.15	29.16	40.00	54.97	60.00	2.85	0.25	0.28	0.28	0.00	0.54	0.30	0.0009	0.7822	2.2400	0.30	0.0009	0.6202
29.16	29.17	39.60	52.74	60.00	2.03	0.21	0.60	0.27	0.00	0.33	0.30	0.0009	0.5627	2.0250	0.30	0.0009	0.5627
29.17	29.18	39.20	48.12	60.00	2.03	0.20	1.64	0.25	0.00	0.24	0.30	0.0009	0.5627	2.0250	0.30	0.0009	0.5627
29.18	29.19	39.40	40.01	60.00	5.09	0.20	0.94	0.24	0.00	0.32	0.32	0.0009	1.3817	2.2400	0.30	0.0009	0.6202
29.19	29.20	39.30	30.11	60.00	5.69	0.21	0.71	0.21	0.00	0.18	0.32	0.0009	1.5449	2.2400	0.30	0.0009	0.6202
29.20	29.21	39.30	26.03	60.00	2.48	0.21	0.41	0.18	0.00	0.07	0.30	0.0009	0.6845	2.2400	0.30	0.0009	0.6202
29.21	29.22	39.20	24.15	60.00	1.99	0.21	0.76	0.17	0.00	0.06	0.30	0.0009	0.5547	1.9950	0.30	0.0009	0.5547
29.22	29.23	39.00	22.45	60.00	3.54	0.22	0.31	0.17	0.00	0.08	0.31	0.0009	0.9668	2.2400	0.30	0.0009	0.6202
29.23	29.24	38.50	21.89	60.00	5.15	0.21	0.32	0.18	0.00	0.10	0.32	0.0009	1.3977	2.2400	0.30	0.0009	0.6202
29.24	29.25	38.20	22.30	60.00	3.10	0.22	0.47	0.17	0.00	0.07	0.30	0.0009	0.8504	2.2400	0.30	0.0009	0.6202
29.25	29.26	38.10	20.12	60.00	3.42	0.21	0.79	0.17	0.00	0.06	0.30	0.0009	0.9360	2.2400	0.30	0.0009	0.6202
29.26	29.27	38.00	18.08	60.00	2.06	0.20	1.21	0.16	0.00	0.04	0.30	0.0009	0.5707	2.0550	0.30	0.0009	0.5707
29.27	29.28	37.90	18.32	60.00	3.44	0.21	0.68	0.16	0.00	0.06	0.31	0.0009	0.9414	2.2400	0.30	0.0009	0.6202
29.28	29.29	37.80	18.25	60.00	3.05	0.21	0.48	0.16	0.00	0.05	0.30	0.0009	0.8370	2.2400	0.30	0.0009	0.6202
29.29	29.30	37.90	15.86	60.00	3.93	0.21	0.11	0.16	0.00	0.06	0.31	0.0009	1.0712	2.2400	0.30	0.0009	0.6202
29.30	29.31	38.20	10.49	60.00	5.09	0.23	0.04	0.15	0.00	0.05	0.32	0.0009	1.3817	2.2400	0.30	0.0009	0.6202
29.31	29.32	38.30	4.07	60.00	5.92	0.22	0.05	0.15	0.00	0.04	0.32	0.0009	1.6038	2.2400	0.30	0.0009	0.6202
29.32	29.33	38.70	4.52	60.00	5.30	0.25	0.07	0.14	0.00	0.04	0.32	0.0009	1.4405	2.2400	0.30	0.0009	0.6202
29.33	29.34	39.00	2.30	60.00	1.91	0.25	0.05	0.12	0.00	0.03	0.30	0.0009	0.5306	1.9050	0.30	0.0009	0.5306
29.34	29.35	39.50	1.99	60.00	4.50	0.30	0.06	0.13	0.00	0.04	0.31	0.0009	1.2264	2.2400	0.30	0.0009	0.6202
29.35	29.36	40.30	1.43	60.00	8.67	0.52	0.06	0.15	0.00	0.05	0.34	0.0009	2.3411	2.2400	0.30	0.0009	0.6202
29.36	29.37	41.30	1.13	60.00	3.62	0.76	0.06	0.13	0.00	0.03	0.31	0.0009	0.9882	2.2400	0.30	0.0009	0.6202
29.37	29.38	42.30	0.58	60.00	1.90	0.82	0.05	0.12	0.00	0.03	0.30	0.0009	0.5292	1.9000	0.30	0.0009	0.5292
29.38	29.39	42.70	0.58	60.00	1.64	0.64	0.05	0.12	0.00	0.03	0.29	0.0009	0.4597	1.6400	0.29	0.0009	0.4597
29.39	29.40	42.50	0.48	60.00	0.93	0.59	0.05	0.12	0.00	0.02	0.29	0.0009	0.2696	0.9300	0.29	0.0009	0.2696
29.40	29.41	41.70	0.54	60.00	1.77	0.54	0.05	0.12	0.00	0.03	0.29	0.0009	0.4945	1.7700	0.29	0.0009	0.4945
29.41	29.42	40.80	0.68	60.00	1.84	0.51	0.05	0.12	0.00	0.03	0.30	0.0009	0.5132	1.8400	0.30	0.0009	0.5132
29.42	29.43	39.70	0.24	60.00	1.43	0.41	0.05	0.12	0.00	0.02	0.29	0.0009	0.4021	1.4250	0.29	0.0009	0.4021
29.43	29.44	38.30	2.59	60.00	1.31	1.02	0.05	0.12	0.00	0.03	0.29	0.0009	0.3700	1.3050	0.29	0.0009	0.3700
29.44	29.45	35.30	4.48	60.00	2.07	0.72	0.18	0.13	0.00	0.03	0.30	0.0009	0.5734	2.0650	0.30	0.0009	0.5734
29.45	29.46	30.10	5.65	60.00	2.54	0.53	0.22	0.13	0.00	0.03	0.30	0.0009	0.6992	2.2400	0.30	0.0009	0.6202
29.46	29.47	24.40	10.35	60.00	1.67	0.77	0.34	0.14	0.00	0.03	0.29	0.0009	0.4664	1.6650	0.29	0.0009	0.4664
29.47	29.48	18.30	14.29	60.00	29.31	0.74	0.61	0.28	0.00	0.26	0.46	0.0010	7.8651	2.2400	0.30	0.0009	0.6202
29.48	29.49	19.80	15.51	60.00	7.75	0.55	0.67	0.18	0.00	0.09	0.33	0.0009	2.0949	2.2400	0.30	0.0009	0.6202
29.49	29.50	23.40	19.14	60.00	4.54	0.66	1.29	0.17	0.00	0.08	0.31	0.0009	1.2358	2.2400	0.30	0.0009	0.6202

								Current projection			Constant speed			IRI better at constant speed			
From (Km)	To (Km)	Speed (km/h) (Profiler)	Speed (km/h) (gps)	Constant Speed	IRI	awz S11	awz S12	Fuel Consumption	Tyre Wear	Repair and Maintenance Cost	Fuel Consumption	Tyre Wear	Repair and Maintenance Cost	Better IRI	Fuel Consumption	Tyre Wear	Repair and Maintenance Cost
km	km	km/h	km/h	km/h	m/km	m/s²	m/s²	l/km	km	R/km	l/km	km	R/km	m/km	l/km	km	R/km
29.50	29.51	25.70	22.92	60.00	2.77	1.10	0.99	0.17	0.00	0.06	0.30	0.0009	0.7621	2.2400	0.30	0.0009	0.6202
29.51	29.52	28.20	24.07	60.00	6.18	0.89	1.09	0.19	0.00	0.13	0.32	0.0009	1.6734	2.2400	0.30	0.0009	0.6202
29.52	29.53	30.70	28.75	60.00	8.85	1.14	0.76	0.22	0.00	0.24	0.34	0.0009	2.3893	2.2400	0.30	0.0009	0.6202
29.53	29.54	32.20	30.78	60.00	3.90	1.10	0.68	0.20	0.00	0.13	0.31	0.0009	1.0645	2.2400	0.30	0.0009	0.6202
29.54	29.55	33.70	29.62	60.00	2.36	1.10	0.66	0.19	0.00	0.08	0.30	0.0009	0.6510	2.2400	0.30	0.0009	0.6202
29.55	29.56	34.80	24.95	60.00	2.05	1.06	0.46	0.17	0.00	0.06	0.30	0.0009	0.5694	2.0500	0.30	0.0009	0.5694
29.56	29.57	35.00	21.90	60.00	3.02	1.37	0.75	0.17	0.00	0.07	0.30	0.0009	0.8277	2.2400	0.30	0.0009	0.6202
29.57	29.58	36.90	20.08	60.00	2.25	1.27	2.15	0.16	0.00	0.05	0.30	0.0009	0.6216	2.2400	0.30	0.0009	0.6202
29.58	29.59	37.90	24.34	60.00	2.18	1.16	0.66	0.17	0.00	0.06	0.30	0.0009	0.6055	2.1850	0.30	0.0009	0.6055
29.59	29.60	38.70	25.99	60.00	2.39	0.87	0.95	0.18	0.00	0.07	0.30	0.0009	0.6604	2.2400	0.30	0.0009	0.6202
29.60	29.61	39.30	30.05	60.00	3.49	0.93	0.82	0.20	0.00	0.12	0.31	0.0009	0.9534	2.2400	0.30	0.0009	0.6202
29.61	29.62	39.80	32.88	60.00	4.13	0.85	0.60	0.21	0.00	0.16	0.31	0.0009	1.1247	2.2400	0.30	0.0009	0.6202
29.62	29.63	40.30	37.05	60.00	1.57	0.72	0.72	0.21	0.00	0.09	0.29	0.0009	0.4409	1.5700	0.29	0.0009	0.4409
29.63	29.64	40.40	38.53	60.00	2.54	0.65	1.41	0.22	0.00	0.15	0.30	0.0009	0.6992	2.2400	0.30	0.0009	0.6202
29.64	29.65	40.00	43.86	60.00	4.31	0.69	0.99	0.24	0.00	0.36	0.31	0.0009	1.1756	2.2400	0.30	0.0009	0.6202
29.65	29.66	39.80	46.07	60.00	2.86	0.55	0.85	0.24	0.00	0.29	0.30	0.0009	0.7862	2.2400	0.30	0.0009	0.6202
29.66	29.67	38.90	54.99	60.00	4.33	0.54	1.40	0.29	0.00	0.81	0.31	0.0009	1.1783	2.2400	0.30	0.0009	0.6202
29.67	29.68	35.50	55.62	60.00	3.40	0.62	1.14	0.29	0.00	0.67	0.30	0.0009	0.9307	2.2400	0.30	0.0009	0.6202
29.68	29.69	30.40	57.00	60.00	2.05	0.49	1.21	0.28	0.00	0.46	0.30	0.0009	0.5694	2.0500	0.30	0.0009	0.5694
29.69	29.70	24.50	56.31	60.00	10.60	0.55	1.49	0.33	0.00	2.16	0.35	0.0009	2.8563	2.2400	0.30	0.0009	0.6202
29.70	29.71	20.20	57.58	60.00	28.62	0.38	1.34	0.45	0.00	6.39	0.46	0.0010	7.6804	2.2400	0.30	0.0009	0.6202
29.71	29.72	25.90	56.45	60.00	8.36	0.33	1.17	0.32	0.00	1.73	0.34	0.0009	2.2582	2.2400	0.30	0.0009	0.6202
29.72	29.73	31.80	53.62	60.00	9.13	0.36	0.95	0.31	0.00	1.53	0.34	0.0009	2.4642	2.2400	0.30	0.0009	0.6202
29.73	29.74	34.60	46.58	60.00	5.05	0.63	1.17	0.26	0.00	0.51	0.31	0.0009	1.3710	2.2400	0.30	0.0009	0.6202
29.74	29.75	35.40	41.84	60.00	3.16	0.60	1.06	0.23	0.00	0.23	0.30	0.0009	0.8665	2.2400	0.30	0.0009	0.6202
29.75	29.76	37.30	41.98	60.00	2.94	0.52	0.79	0.23	0.00	0.22	0.30	0.0009	0.8062	2.2400	0.30	0.0009	0.6202
29.76	29.77	39.50	41.84	60.00	2.52	0.50	0.65	0.23	0.00	0.19	0.30	0.0009	0.6938	2.2400	0.30	0.0009	0.6202
29.77	29.78	41.10	40.57	60.00	2.87	0.58	0.77	0.22	0.00	0.20	0.30	0.0009	0.7888	2.2400	0.30	0.0009	0.6202
29.78	29.79	42.10	38.73	60.00	2.20	0.53	0.56	0.22	0.00	0.14	0.30	0.0009	0.6095	2.2000	0.30	0.0009	0.6095
29.79	29.80	42.60	37.15	60.00	2.86	0.56	0.56	0.21	0.00	0.16	0.30	0.0009	0.7862	2.2400	0.30	0.0009	0.6202
29.80	29.81	42.80	34.20	60.00	4.54	0.46	0.99	0.21	0.00	0.19	0.31	0.0009	1.2345	2.2400	0.30	0.0009	0.6202
29.81	29.82	43.10	32.13	60.00	4.96	0.72	0.74	0.21	0.00	0.18	0.31	0.0009	1.3482	2.2400	0.30	0.0009	0.6202
29.82	29.83	43.30	29.53	60.00	2.26	0.83	0.54	0.19	0.00	0.08	0.30	0.0009	0.6256	2.2400	0.30	0.0009	0.6202

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								Current projection			Constant speed			IRI better at constant speed			
From (Km)	To (Km)	Speed (km/h) (Profiler)	Speed (km/h) (gps)	Constant Speed	IRI	awz S11	awz S12	Fuel Consumption	Tyre Wear	Repair and Maintenance Cost	Fuel Consumption	Tyre Wear	Repair and Maintenance Cost	Better IRI	Fuel Consumption	Tyre Wear	Repair and Maintenance Cost
km	km	km/h	km/h	km/h	m/km	m/s²	m/s²	l/km	km	R/km	l/km	km	R/km	m/km	l/km	km	R/km
48.79	48.80	28.90	1.49	60.00	4.92	1.18	0.69	0.14	0.00	0.0362	0.31	0.0009	1.3375	2.2400	0.30	0.0009	0.6202
48.80	48.81	28.00	1.74	60.00	6.33	0.69	0.93	0.14	0.00	0.0410	0.32	0.0009	1.7135	2.2400	0.30	0.0009	0.6202
48.81	48.82	28.70	4.32	60.00	3.77	0.88	0.49	0.14	0.00	0.0354	0.31	0.0009	1.0297	2.2400	0.30	0.0009	0.6202
48.82	48.83	30.70	8.03	60.00	2.57	1.35	0.60	0.14	0.00	0.0340	0.30	0.0009	0.7072	2.2400	0.30	0.0009	0.6202
48.83	48.84	33.10	12.91	60.00	4.34	1.08	0.68	0.16	0.00	0.0532	0.31	0.0009	1.1823	2.2400	0.30	0.0009	0.6202
48.84	48.85	35.90	18.01	60.00	2.77	0.94	0.81	0.16	0.00	0.0512	0.30	0.0009	0.7621	2.2400	0.30	0.0009	0.6202
48.85	48.86	39.00	24.43	60.00	1.59	0.65	1.77	0.17	0.00	0.0492	0.29	0.0009	0.4449	1.5850	0.29	0.0009	0.4449
48.86	48.87	42.20	29.86	60.00	1.81	0.56	0.58	0.19	0.00	0.0696	0.30	0.0009	0.5038	1.8050	0.30	0.0009	0.5038
48.87	48.88	45.40	29.88	60.00	1.36	0.53	0.53	0.18	0.00	0.0576	0.29	0.0009	0.3847	1.3600	0.29	0.0009	0.3847
48.88	48.89	49.10	32.26	60.00	1.94	0.43	0.58	0.19	0.00	0.0836	0.30	0.0009	0.5386	1.9350	0.30	0.0009	0.5386
48.89	48.90	53.00	34.29	60.00	1.74	0.28	0.72	0.20	0.00	0.0865	0.29	0.0009	0.4851	1.7350	0.29	0.0009	0.4851
48.90	48.91	56.80	44.51	60.00	1.21	0.09	0.65	0.23	0.00	0.1206	0.29	0.0009	0.3446	1.2100	0.29	0.0009	0.3446
48.91	48.92	59.10	47.02	60.00	1.13	0.20	0.68	0.24	0.00	0.1330	0.29	0.0009	0.3218	1.1250	0.29	0.0009	0.3218
48.92	48.93	58.70	48.53	60.00	1.40	0.32	0.63	0.24	0.00	0.1775	0.29	0.0009	0.3954	1.4000	0.29	0.0009	0.3954

								Current projection			Constant speed			IRI better at constant speed			
From (Km)	To (Km)	Speed (km/h) (Profiler)	Speed (km/h) (gps)	Constant Speed	IRI	awz S11	awz S12	Fuel Consumption	Tyre Wear	Repair and Maintenance Cost	Fuel Consumption	Tyre Wear	Repair and Maintenance Cost	Better IRI	Fuel Consumption	Tyre Wear	Repair and Maintenance Cost
km	km	km/h	km/h	km/h	m/km	m/s²	m/s²	l/km	km	R/km	l/km	km	R/km	m/km	l/km	km	R/km
48.93	48.94	57.60	48.24	60.00	1.60	0.18	0.58	0.25	0.00	0.1960	0.29	0.0009	0.4490	1.6000	0.29	0.0009	0.4490
48.94	48.95	56.50	47.39	60.00	1.41	0.26	0.56	0.24	0.00	0.1649	0.29	0.0009	0.3968	1.4050	0.29	0.0009	0.3968
48.95	48.96	56.30	47.75	60.00	2.10	0.23	0.62	0.25	0.00	0.2418	0.30	0.0009	0.5814	2.0950	0.30	0.0009	0.5814
48.96	48.97	56.70	48.82	60.00	2.64	0.25	0.53	0.25	0.00	0.3229	0.30	0.0009	0.7273	2.2400	0.30	0.0009	0.6202
48.97	48.98	57.00	50.45	60.00	2.65	0.20	0.65	0.26	0.00	0.3634	0.30	0.0009	0.7286	2.2400	0.30	0.0009	0.6202
48.98	48.99	57.20	51.92	60.00	2.79	0.24	0.54	0.27	0.00	0.4241	0.30	0.0009	0.7661	2.2400	0.30	0.0009	0.6202
48.99	49.00	57.60	53.36	60.00	1.32	0.24	0.59	0.26	0.00	0.2332	0.29	0.0009	0.3727	1.3150	0.29	0.0009	0.3727
49.00	49.01	58.30	54.86	60.00	1.45	0.22	0.51	0.27	0.00	0.2834	0.29	0.0009	0.4088	1.4500	0.29	0.0009	0.4088
49.01	49.02	59.20	52.28	60.00	1.12	0.22	1.05	0.26	0.00	0.1867	0.29	0.0009	0.3192	1.1150	0.29	0.0009	0.3192
49.02	49.03	60.10	47.49	60.00	1.21	0.24	0.83	0.24	0.00	0.1459	0.29	0.0009	0.3446	1.2100	0.29	0.0009	0.3446
49.03	49.04	60.90	40.24	60.00	1.52	0.24	0.99	0.22	0.00	0.1113	0.29	0.0009	0.4275	1.5200	0.29	0.0009	0.4275
49.04	49.05	61.60	32.86	60.00	1.31	0.24	0.77	0.19	0.00	0.0653	0.29	0.0009	0.3713	1.3100	0.29	0.0009	0.3713
49.05	49.06	62.20	27.60	60.00	0.97	0.24	0.58	0.18	0.00	0.0428	0.29	0.0009	0.2790	0.9650	0.29	0.0009	0.2790
49.06	49.07	62.80	21.95	60.00	1.99	0.22	0.48	0.17	0.00	0.0503	0.30	0.0009	0.5533	1.9900	0.30	0.0009	0.5533
49.07	49.08	63.00	17.82	60.00	1.99	0.26	0.34	0.16	0.00	0.0423	0.30	0.0009	0.5533	1.9900	0.30	0.0009	0.5533
49.08	49.09	63.20	14.69	60.00	1.11	0.23	0.38	0.14	0.00	0.0302	0.29	0.0009	0.3178	1.1100	0.29	0.0009	0.3178
49.09	49.10	63.90	11.33	60.00	1.44	0.25	0.44	0.14	0.00	0.0303	0.29	0.0009	0.4061	1.4400	0.29	0.0009	0.4061
49.10	49.11	64.80	8.34	60.00	1.25	0.21	0.30	0.13	0.00	0.0273	0.29	0.0009	0.3539	1.2450	0.29	0.0009	0.3539
49.11	49.12	65.90	5.80	60.00	1.38	0.22	0.29	0.13	0.00	0.0267	0.29	0.0009	0.3901	1.3800	0.29	0.0009	0.3901
49.12	49.13	67.30	3.58	60.00	2.00	0.22	0.66	0.13	0.00	0.0281	0.30	0.0009	0.5560	2.0000	0.30	0.0009	0.5560
49.13	49.14	68.60	1.37	60.00	1.81	0.25	0.98	0.12	0.00	0.0264	0.30	0.0009	0.5052	1.8100	0.30	0.0009	0.5052
49.14	49.15	69.80	1.08	60.00	1.43	0.24	1.36	0.12	0.00	0.0251	0.29	0.0009	0.4035	1.4300	0.29	0.0009	0.4035
49.15	49.16	71.00	1.74	60.00	1.40	0.23	1.12	0.12	0.00	0.0252	0.29	0.0009	0.3954	1.4000	0.29	0.0009	0.3954
49.16	49.17	72.30	0.76	60.00	1.44	0.24	1.07	0.12	0.00	0.0250	0.29	0.0009	0.4061	1.4400	0.29	0.0009	0.4061
49.17	49.18	73.40	1.99	60.00	1.33	0.24	1.84	0.12	0.00	0.0251	0.29	0.0009	0.3767	1.3300	0.29	0.0009	0.3767
49.18	49.19	74.40	1.53	60.00	1.34	0.27	2.19	0.12	0.00	0.0250	0.29	0.0009	0.3794	1.3400	0.29	0.0009	0.3794
49.19	49.20	75.30	1.74	60.00	1.54	0.25	2.81	0.12	0.00	0.0257	0.29	0.0009	0.4329	1.5400	0.29	0.0009	0.4329
49.20	49.21	76.00	1.41	60.00	1.40	0.26	2.02	0.12	0.00	0.0251	0.29	0.0009	0.3941	1.3950	0.29	0.0009	0.3941
49.21	49.22	76.60	2.11	60.00	1.63	0.24	0.80	0.12	0.00	0.0261	0.29	0.0009	0.4570	1.6300	0.29	0.0009	0.4570
49.22	49.23	77.10	1.64	60.00	1.94	0.27	0.57	0.12	0.00	0.0269	0.30	0.0009	0.5386	1.9350	0.30	0.0009	0.5386
49.23	49.24	77.70	1.87	60.00	1.60	0.24	0.20	0.12	0.00	0.0259	0.29	0.0009	0.4476	1.5950	0.29	0.0009	0.4476
49.24	49.25	78.00	3.90	60.00	1.06	0.24	0.21	0.12	0.00	0.0247	0.29	0.0009	0.3031	1.0550	0.29	0.0009	0.3031
49.25	49.26	78.40	7.19	60.00	1.13	0.20	0.15	0.13	0.00	0.0262	0.29	0.0009	0.3218	1.1250	0.29	0.0009	0.3218
49.26	49.27	78.70	10.86	60.00	2.20	0.19	0.05	0.14	0.00	0.0348	0.30	0.0009	0.6095	2.2000	0.30	0.0009	0.6095
49.27	49.28	79.00	14.07	60.00	1.66	0.33	0.05	0.15	0.00	0.0343	0.29	0.0009	0.4650	1.6600	0.29	0.0009	0.4650
49.28	49.29	79.20	15.20	60.00	1.38	0.53	0.03	0.15	0.00	0.0330	0.29	0.0009	0.3887	1.3750	0.29	0.0009	0.3887
49.29	49.30	79.40	16.76	60.00	2.26	0.21	0.02	0.15	0.00	0.0433	0.30	0.0009	0.6243	2.2400	0.30	0.0009	0.6202
49.30	49.31	79.60	18.78	60.00	1.68	0.25	0.04	0.16	0.00	0.0403	0.29	0.0009	0.4690	1.6750	0.29	0.0009	0.4690
49.31	49.32	79.60	21.84	60.00	1.47	0.70	0.03	0.16	0.00	0.0423	0.29	0.0009	0.4128	1.4650	0.29	0.0009	0.4128
49.32	49.33	79.70	25.25	60.00	1.77	0.42	0.04	0.17	0.00	0.0545	0.29	0.0009	0.4945	1.7700	0.29	0.0009	0.4945
49.33	49.34	79.80	28.78	60.00	1.99	0.34	0.04	0.18	0.00	0.0703	0.30	0.0009	0.5520	1.9850	0.30	0.0009	0.5520
49.34	49.35	80.00	30.63	60.00	2.07	0.54	0.04	0.19	0.00	0.0803	0.30	0.0009	0.5761	2.0750	0.30	0.0009	0.5761
49.35	49.36	80.10	31.87	60.00	1.86	0.65	0.03	0.19	0.00	0.0795	0.30	0.0009	0.5185	1.8600	0.30	0.0009	0.5185
49.36	49.37	80.20	33.60	60.00	2.43	0.53	0.03	0.20	0.00	0.1082	0.30	0.0009	0.6711	2.2400	0.30	0.0009	0.6202
49.37	49.38	80.20	36.27	60.00	1.42	0.41	0.05	0.20	0.00	0.0833	0.29	0.0009	0.4008	1.4200	0.29	0.0009	0.4008
49.38	49.39	80.30	39.17	60.00	1.60	0.65	0.07	0.21	0.00	0.1084	0.29	0.0009	0.4476	1.5950	0.29	0.0009	0.4476
49.39	49.40	80.40	40.56	60.00	1.46	1.18	0.04	0.22	0.00	0.1096	0.29	0.0009	0.4101	1.4550	0.29	0.0009	0.4101
49.40	49.41	80.40	45.49	60.00	1.24	1.29	0.11	0.23	0.00	0.1309	0.29	0.0009	0.3526	1.2400	0.29	0.0009	0.3526
49.41	49.42	80.40	49.65	60.00	1.40	1.34	0.20	0.25	0.00	0.1908	0.29	0.0009	0.3941	1.3950	0.29	0.0009	0.3941
49.42	49.43	80.50	52.84	60.00	1.55	0.84	1.74	0.26	0.00	0.2606	0.29	0.0009	0.4342	1.5450	0.29	0.0009	0.4342
49.43	49.44	80.60	54.62	60.00	1.53	1.19	2.07	0.27	0.00	0.2918	0.29	0.0009	0.4289	1.5250	0.29	0.0009	0.4289
49.44	49.45	80.60	56.37	60.00	1.62	1.04	2.59	0.28	0.00	0.3498	0.29	0.0009	0.4543	1.6200	0.29	0.0009	0.4543
49.45	49.46	80.60	58.24	60.00	1.70	0.96	3.44	0.29	0.00	0.4177	0.29	0.0009	0.4744	1.6950	0.29	0.0009	0.4744
49.46	49.47	80.60	59.03	60.00	2.84	0.84	1.86	0.30	0.00	0.7255	0.30	0.0009	0.7795	2.2400	0.30	0.0009	0.6202
49.47	49.48	80.50	59.67	60.00	1.54	0.65	3.06	0.29	0.00	0.4212	0.29	0.0009	0.4316	1.5350	0.29	0.0009	0.4316
49.48	49.49	80.40	60.90	60.00	1.89	0.47	1.38	0.30	0.00	0.5622	0.30	0.0009	0.5266	1.8900	0.30	0.0009	0.5266
49.49	49.50	80.40	62.62	60.00	1.24	0.38	1.79	0.30	0.00	0.4256	0.29	0.0009	0.3526	1.2400	0.29	0.0009	0.3526
49.50	49.51	80.40	64.54	60.00	2.45	0.69	2.48	0.32	0.00	0.9445	0.30	0.0009	0.6751	2.2400	0.30	0.0009	0.6202
49.51	49.52	80.30	66.10	60.00	4.50	0.74	2.15	0.34	0.00	1.9331	0.31	0.0009	1.2238	2.2400	0.30	0.0009	0.6202
49.52	49.53	80.30	68.21	60.00	3.08	0.52	2.78	0.34	0.00	1.5565	0.30	0.0009	0.8437	2.2400	0.30	0.0009	0.6202
49.53	49.54	80.30	70.58	60.00	2.06	0.44	1.14	0.35	0.00	1.2527	0.30	0.0009	0.5721	2.0600	0.30	0.0009	0.5721
49.54	49.55	80.20	72.89	60.00	1.60	0.39	0.50	0.36	0.00	1.1580	0.29	0.0009	0.4476	1.5950	0.29	0.0009	0.4476
49.55	49.56	80.20	74.90	60.00	2.51	0.43	0.30	0.38	0.00	2.1010	0.30	0.0009	0.6912	2.2400	0.30	0.0009	0.6202
49.56	49.57	80.30	74.90	60.00	2.13	0.36	0.29	0.37	0.00	1.7854	0.30	0.0009	0.5895	2.1250	0.30	0.0009	0.5895

								Current projection			Constant speed			IRI better at constant speed			
From (Km)	To (Km)	Speed (km/h) (Profiler)	Speed (km/h) (gps)	Constant Speed	IRI	awz S11	awz S12	Fuel Consumption	Tyre Wear	Repair and Maintenance Cost	Fuel Consumption	Tyre Wear	Repair and Maintenance Cost	Better IRI	Fuel Consumption	Tyre Wear	Repair and Maintenance Cost
km	km	km/h	km/h	km/h	m/km	m/s^2	m/s^2	l/km	km	R/km	l/km	km	R/km	m/km	l/km	km	R/km
49.57	49.58	80.20	75.70	60.00	3.19	0.30	0.37	0.39	0.00	2.8319	0.30	0.0009	0.8732	2.2400	0.30	0.0009	0.6202
49.58	49.59	80.20	75.70	60.00	2.76	0.38	0.28	0.38	0.00	2.4524	0.30	0.0009	0.7581	2.2400	0.30	0.0009	0.6202
49.59	49.60	80.10	76.91	60.00	2.43	0.36	0.40	0.39	0.00	2.3725	0.30	0.0009	0.6711	2.2400	0.30	0.0009	0.6202
49.60	49.61	80.10	76.91	60.00	2.90	0.44	0.33	0.39	0.00	2.8226	0.30	0.0009	0.7955	2.2400	0.30	0.0009	0.6202
49.61	49.62	80.00	78.26	60.00	1.26	0.40	0.55	0.39	0.00	1.3715	0.29	0.0009	0.3580	1.2600	0.29	0.0009	0.3580
49.62	49.63	80.00	78.26	60.00	1.00	0.34	0.42	0.39	0.00	1.0874	0.29	0.0009	0.2870	0.9950	0.29	0.0009	0.2870
49.63	49.64	80.00	79.01	60.00	2.70	0.40	0.45	0.40	0.00	3.0858	0.30	0.0009	0.7434	2.2400	0.30	0.0009	0.6202
49.64	49.65	79.90	79.01	60.00	1.66	0.35	0.63	0.39	0.00	1.9052	0.29	0.0009	0.4650	1.6600	0.29	0.0009	0.4650
49.65	49.66	79.90	79.23	60.00	1.89	0.39	0.60	0.40	0.00	2.2012	0.30	0.0009	0.5266	1.8900	0.30	0.0009	0.5266
49.66	49.67	79.90	79.23	60.00	2.63	0.35	0.73	0.40	0.00	3.0492	0.30	0.0009	0.7233	2.2400	0.30	0.0009	0.6202
49.67	49.68	79.80	79.83	60.00	2.66	0.40	0.68	0.41	0.00	3.2340	0.30	0.0009	0.7326	2.2400	0.30	0.0009	0.6202
49.68	49.69	79.60	79.83	60.00	1.73	0.29	0.62	0.40	0.00	2.1045	0.29	0.0009	0.4824	1.7250	0.29	0.0009	0.4824
49.69	49.70	79.40	80.49	60.00	2.32	0.47	0.59	0.41	0.00	2.9673	0.30	0.0009	0.6417	2.2400	0.30	0.0009	0.6202
49.70	49.71	79.30	80.49	60.00	2.14	0.48	0.52	0.41	0.00	2.7323	0.30	0.0009	0.5921	2.1350	0.30	0.0009	0.5921
49.71	49.72	79.20	80.43	60.00	1.97	0.48	0.66	0.41	0.00	2.5059	0.30	0.0009	0.5466	1.9650	0.30	0.0009	0.5466
49.72	49.73	79.00	80.43	60.00	3.38	0.42	0.67	0.42	0.00	4.2891	0.30	0.0009	0.9240	2.2400	0.30	0.0009	0.6202
49.73	49.74	78.90	79.84	60.00	2.03	0.34	0.62	0.40	0.00	2.4684	0.30	0.0009	0.5627	2.0250	0.30	0.0009	0.5627

C. Appendix C – Regression area output

C.1. N4

Nonlinear Regression

```
[Variables]
x = col(2)
y = col(1)
z = col(3)
reciprocal_z = 1/abs(z)
reciprocal_zsquare = 1/z^2
[Parameters]
x0 = xatymax(x;z) ''Auto {{previous: 3.82709}}
y0 = xatymax(y;z) ''Auto {{previous: 111.924}}
a = max(z) ''Auto {{previous: 0.951686}}
b = fwhm(x;z)/2 ''Auto {{previous: 4.49321}}
c = fwhm(y;z)/2 ''Auto {{previous: 85.2313}}
[Equation]
f=a/((1+((x-x0)/b)^2)*(1+((y-y0)/c)^2))
fit f to z
''fit f to z with weight reciprocal_z
''fit f to z with weight reciprocal_zsquare
[Constraints]
[Options]
tolerance=0.000100
stepsize=100
iterations=100
```

R = 0.40292532 Rsqr = 0.16234881 Adj Rsqr = 0.16099503

Standard Error of Estimate = 0.2791

	Coefficient	Std. Error	t	P
x0	3.8271	0.1917	19.9619	<0.0001
y0	111.9245	19.039	5.8787	<0.0001
a	0.9517	0.1103	8.6305	<0.0001
b	4.4932	0.3547	12.6669	<0.0001
c	85.2313	11.1378	7.6524	<0.0001

Analysis of Variance:

	DF	SS	MS	F	P
Regression	4	37.3553	9.3388	119.9226	<0.0001
Residual	2475	192.7375	0.0779		
Total	2479	230.0928	0.0928		

PRESS = 193.5069

Durbin-Watson Statistic = 0.6784

Normality Test: K-S Statistic = 0.0753 Significance Level = <0.0001

Constant Variance Test: Failed (P = 0.0048)

Power of performed test with alpha = 0.0500: 1.0000

C.2. R538(1)

Nonlinear Regression

```
[Variables]
x = col(2)
y = col(1)
z = col(3)
reciprocal_z = 1/abs(z)
reciprocal_zsquare = 1/z^2
[Parameters]
x0 = xatymax(x;z) ''Auto {{previous: 9.51308}}
y0 = xatymax(y;z) ''Auto {{previous: 210.173}}
a = max(z) ''Auto {{previous: 1.21199}}
b = fwhm(x;z)/2.2 ''Auto {{previous: 9.00573}}
c = fwhm(y;z)/2.2 ''Auto {{previous: 150.775}}
[Equation]
f=a*exp(-.5*( ((x-x0)/b)^2 + ((y-y0)/c)^2 ))
fit f to z
''fit f to z with weight reciprocal_z
''fit f to z with weight reciprocal_zsquare
[Constraints]
[Options]
tolerance=0.000100
stepsize=1000
iterations=1000
```

R = 0.36298609 Rsqr = 0.13175890 Adj Rsqr = 0.12725441

Standard Error of Estimate = 0.2868

	Coefficient	Std. Error	t	P
x0	9.5131	2.4169	3.936	<0.0001
y0	210.1728	281.998	0.7453	0.4563
a	1.212	1.0478	1.1567	0.2478
b	9.0057	2.3719	3.7969	0.0002
c	150.7753	150.7121	1.0004	0.3174

Analysis of Variance:

	DF	SS	MS	F	P
Regression	4	9.6215	2.4054	29.2505	<0.0001
Residual	771	63.402	0.0822		
Total	775	73.0236	0.0942		

PRESS = 64.8905

Durbin-Watson Statistic = 0.6267

Normality Test: K-S Statistic = 0.1424 Significance Level = <0.0001

Constant Variance Test: Failed (P = <0.0001)

Power of performed test with alpha = 0.0500: 1.0000

C.3. R538(2)

Nonlinear Regression

```
[Variables]
x = col(2)
y = col(1)
z = col(3)
reciprocal_z = 1/abs(z)
reciprocal_zsquare = 1/z^2
[Parameters]
x0 = xatymax(x;z) ''Auto {{previous: 9.18736}}
y0 = xatymax(y;z) ''Auto {{previous: 29.8624}}
a = max(z) ''Auto {{previous: 0.608924}}
b = fwhm(x;z)/2 ''Auto {{previous: 21.6915}}
c = fwhm(y;z)/2 ''Auto {{previous: 29.9966}}
[Equation]
f=a/((1+((x-x0)/b)^2)*(1+((y-y0)/c)^2))
fit f to z
''fit f to z with weight reciprocal_z
''fit f to z with weight reciprocal_zsquare
[Constraints]
[Options]
tolerance=0.000100
stepsize=100
iterations=100
```

R = 0.30138018 Rsqr = 0.09083001 Adj Rsqr = 0.07452203

Standard Error of Estimate = 0.3446

	Coefficient	Std. Error	t	P
x0	9.1874	6.2073	1.4801	0.1403
y0	29.8624	3.4656	8.6169	<0.0001
a	0.6089	0.055	11.0693	<0.0001
b	21.6915	19.9647	1.0865	0.2784
c	29.9966	6.7276	4.4587	<0.0001

Analysis of Variance:

	DF	SS	MS	F	P
Regression	4	2.6463	0.6616	5.5697	0.0003
Residual	223	26.4885	0.1188		
Total	227	29.1348	0.1283		

PRESS = 27.8647

Durbin-Watson Statistic = 0.6687

Normality Test: K-S Statistic = 0.1392 Significance Level = 0.0003

Constant Variance Test: Failed (P = <0.0001)

Power of performed test with alpha = 0.0500: 0.9966

C.4. Municipal road

Nonlinear Regression

```
[Variables]
x = col(2)
y = col(1)
z = col(3)
reciprocal_z = 1/abs(z)
reciprocal_zsquare = 1/z^2
[Parameters]
x0 = xatymax(x;z) ''Auto {{previous: 24.2105}}
y0 = xatymax(y;z) ''Auto {{previous: 40.9251}}
a = max(z) ''Auto {{previous: 1.00865}}
b = fwhm(x;z)/2 ''Auto {{previous: 42.7682}}
c = fwhm(y;z)/2 ''Auto {{previous: 32.0899}}
[Equation]
f=a/((1+((x-x0)/b)^2)*(1+((y-y0)/c)^2))
fit f to z
''fit f to z with weight reciprocal_z
''fit f to z with weight reciprocal_zsquare
[Constraints]
[Options]
tolerance=0.000100
stepsize=100
iterations=100
```

R = 0.47018868 Rsqr = 0.22107740 Adj Rsqr = 0.21636380

Standard Error of Estimate = 0.3971

	Coefficient	Std. Error	t	P
x0	24.2105	16.0158	1.5117	0.1311
y0	40.9251	1.9595	20.8859	<0.0001
a	1.0087	0.1344	7.5062	<0.0001
b	42.7682	27.6595	1.5462	0.1225
c	32.0899	2.8294	11.3417	<0.0001

Analysis of Variance:

	DF	SS	MS	F	P
Regression	4	29.585	7.3962	46.902	<0.0001
Residual	661	104.2368	0.1577		
Total	665	133.8218	0.2012		

PRESS = 106.1003

Durbin-Watson Statistic = 0.6568

Normality Test: K-S Statistic = 0.1310 Significance Level = <0.0001

Constant Variance Test: Failed (P = <0.0001)

Power of performed test with alpha = 0.0500: 1.0000

C.5. D2296

Nonlinear Regression

```
[Variables]
x = col(2)
y = col(1)
z = col(3)
reciprocal_z = 1/abs(z)
reciprocal_zsquare = 1/z^2
[Parameters]
x0 = xatymax(x;z) ''Auto {{previous: -0.232573}}
y0 = xatymax(y;z) ''Auto {{previous: 52.2964}}
a = max(z) ''Auto {{previous: 0.886591}}
b = fwhm(x;z)/2 ''Auto {{previous: 20.843}}
c = fwhm(y;z)/2 ''Auto {{previous: 93.731}}
[Equation]
f=a/((1+((x-x0)/b)^2)*(1+((y-y0)/c)^2))
fit f to z
''fit f to z with weight reciprocal_z
''fit f to z with weight reciprocal_zsquare
[Constraints]
[Options]
tolerance=0.000100
stepsize=100
iterations=100
```

R = 0.08106447 Rsqr = 0.00657145 Adj Rsqr = 0.00494354

Standard Error of Estimate = 0.4063

	Coefficient	Std. Error	t	P
x0	-0.2326	4.087	-0.0569	0.9546
y0	52.2964	2.6741	19.5564	<0.0001
a	0.8866	0.033	26.8896	<0.0001
b	20.843	12.5564	1.66	0.0971
c	93.731	14.0759	6.659	<0.0001

Analysis of Variance:

	DF	SS	MS	F	P
Regression	4	2.6659	0.6665	4.0368	0.0029
Residual	2441	403.0206	0.1651		
Total	2445	405.6865	0.1659		

PRESS = 404.8752

Durbin-Watson Statistic = 0.7273

Normality Test: K-S Statistic = 0.1441 Significance Level = <0.0001

Constant Variance Test: Passed (P = 0.8940)

Power of performed test with alpha = 0.0500: 0.9801