Identifying pavement deterioration by enhancing the definition of road roughness

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Abbreviations and acronyms

ASTM	American Society for Testing Materials
ARRB	Australian Road Research Board
FHWA	Federal Highway Administration
DWT	discrete wavelet transform
GPS	general pavement studies
HDM	World Bank Highway Design and Maintenance Model, (HDM-3 and HDM4)
IRI	International Roughness Index
ISO	International Standards Organisation
LTPP	long-term pavement performance
NAASRA	National Association of Australian State Road Authorities
NZTA	New Zealand Transport Agency
OECD	Organisation for Economic Co-operation and Development
PCC	Portland Cement concrete
PI	profile index/profilograph index
PIARC	Permanent International Association of Road Congresses, known as World RoadAssociation
PSD	power spectral density
RAMM	road asset and maintenance management (database)
RMSVA	root mean square vertical acceleration
RN	ride number
RTRRMS	response type road roughness measuring system
SHRP	Strategic Highway Research Program
SPS	specific pavement studies
TRRL	Transport and Road Research Laboratory

Contents

Executive summary

Current road roughness deterioration modelling and analysis tends to focus on the prediction of roughness progression in terms of change in the International Roughness Index (IRI) over time. Since IRI is a summary index of actual roughness, which simulates the response of a specific type of vehicle (quarter-car) to certain damping or suspension characteristics, it is difficult to identify the factors that contribute to the deterioration of roads. Understanding the factors that lead to the deterioration of roads and identifying the actual mode of road roughness deterioration will help road controlling authorities refine their road roughness specifications for road design, construction and maintenance.

This research project looked at an alternative method to define the roughness deterioration modes of different pavement sections of the New Zealand road network by analysing the characteristics of the longitudinal profile of the road surface using wavelet analysis.

The analysis took the longitudinal profile data collected in the New Zealand long-term pavement performance (LTPP) programme over the past eight years, processed it using wavelet decomposition to split the longitudinal profiles into a number of wavebands, and then calculated the relative energy within each waveband.

Some promising results were obtained which demonstrated more information was available within the longitudinal profile data and that this information could be extracted using the wavelet analysis process. The analysis showed a good representation of observed changes on the road and the change in energy spectra expected to influence or result from these changes. As the IRI is influenced most by short and medium wavelength roughness, any long wavelength deterioration is not reflected as a change in the IRI. This research showed that long wavelength energy did change over time and was more obvious on heavily trafficked roads. However, there was no obvious visible distress that could be attributed to the changes in long wavelength energy spectra or evidence at the calibration sites that could identify this occurrence.

A significant portion of sites showed little or no visible change in all wavebands, and maintenance undertaken on the sites was often reflected as an increase in the medium wavelength spectra energy and an increase in the IRI.

The extensive statistical and data mining analysis suggested that the wavelength sub-band energy level was an effective measure to describe roughness changes over time. The process showed the behaviour between local authority and state highway sections was significantly different, something that was not obvious using the IRI as a performance indicator. Local authority sections had similar changes for the medium wavelength sub-bands (2m–8m). State highway section changes increased with more frequent wavelengths from the short to the long sub-bands. The longer wavelengths (greater than 8m) accounted for the majority of the changes.

The rate of change in the energy spectra for both LTPP programmes was also significantly different. The local authority sections had a high proportion of mid-range change, while the state highway sections had a more uniform change across the categories examined. This indicated that using the IRI to define pavement condition masked some of the actual profile change occurring over time.

The methodology adopted in this research project showed that the wavelet analysis process could provide valuable information not currently available, and would assist engineers to better understand the deterioration process. We recommend more research be undertaken to understand more fully how this alternative method for pavement performance analysis can be utilised. Some possible avenues include:

- testing the findings on network data

- linking the findings with current pavement strength research and confirming the failure mode patterns
- quantifying the implications of the changes in long wavelength energy
- advancing the development of the roughness deterioration model using the information gained from the wavelet analysis process.

Abstract

Current road roughness deterioration modelling and analysis tends to focus on the prediction of roughness progression in terms of change in the IRI over time. Since the IRI is simply a summary index of the actual roughness, which simulates the response of a specific type of vehicle (quarter-car), it is difficult to identify the factors that contribute to the deterioration of road roughness. Understanding the factors that lead to the deterioration of roads and identifying the actual mode of road roughness deterioration will help road controlling authorities refine their specifications on road roughness requirements for road design, construction and maintenance to reduce their adverse influence on roughness.

This research project looked at an alternative method to analyse and define the roughness deterioration modes of different pavement sections of the New Zealand road network by analysing the characteristics of the longitudinal profile of the road surface using wavelet analysis.

This characterisation process was used to analyse the effects of pavement type, traffic loading, environment and maintenance regime on the deterioration of road roughness and ultimately should lead to the development of a strategy for maintaining road roughness of different pavement types commonly found in New Zealand road networks.

1 Introduction

1.1 Background

In 2001, a long-term pavement performance (LTPP) programme was established to collect pavement condition data for 64 selected state highway sites throughout New Zealand, and was extended in 2003 to include 84 local authority sites.

The data collected included:

- longitudinal profile using the Australian Road Research Board (ARRB) walking profiler
- transverse profile using a purpose-built transverse profile beam
- texture recorded at selected sites using the NZ Transport Agency (NZTA) stationary laser profiler
- a visual assessment of the degree and extent of various pavement distress features
- site notes detailing visible changes in site condition, the observed distress, and its likely effect on the pavement roughness and rutting
- site-specific photos to record the various distress patterns as they occurred.

Prior to this research, LTPP projects had already supplied data for most of the pavement deterioration model development; however, roughness was one of the models yet to be fully developed mainly because sufficient pavement condition data was not available to commence the type of analysis required. Consequently a comprehensive understanding of the factors that influence roughness and pavement deterioration was yet to be fully defined.

A better understanding of the roughness measurement and data processing outcomes was needed before a roughness deterioration model could be developed. To advance this understanding, the NZTA approved funding in August 2008 for a research project to enhance the application of roughness measurement and deterioration. This project attempted to clarify some of those issues through a detailed analysis of the pavement profile spectra energy, and the change in spectral energy with time. The longitudinal profile data collected on 146 state highway and local authority calibration sites formed the basis of the research and analysis for the project.

Road roughness affects road users on a daily basis because it is one of the road characteristics that influence our perception of the condition of the road. Roughness is also the most important performance indicator for roading engineers and asset managers, and has wide-ranging applications in network management. It is used:

- in economic analysis as a key factor in determining road user costs
- as one of the few direct measures that can define pavement condition on both an engineering or technical level, and therefore can be used in public consultation and reporting through measures such as smooth travel exposure
- as a maintenance decision driver – modelled in road management systems such as dTIMS.

The interesting feature of the longitudinal profile is that the wavelength of the profile may identify a number of different problems at different locations along the road. As a general rule of thumb, longer wavelengths indicate problems deeper in the pavement, while shorter wavelengths indicate problems near the surface or in the wearing course. It is important to realise we can get a wealth of information from pavement profile measurements – this has been poorly explored and only partially used in network level analysis.

Despite its usefulness, roughness is one of the most complex performance measures, both in terms of its measurement and deterioration over time.

1.2 Problem statement

It is well known that the International Roughness Index (IRI) was primarily developed to account for 'what the driver feels' when driving on a particular pavement. Although this approach makes perfect sense there are two limitations to the current IRI measure:

1. IRI development was based on vehicle technology of the mid-1980s (Sayers 1986), which is vastly different from the suspension characteristics of today's vehicles.
2. Because the development focused on vehicle response it excluded many of the components of the roughness profile of pavements. Therefore, although it may give an indication of how the perceived roughness deteriorates, it is not an effective measure of how the road profile changes over time.

In order to address these problems, this research considered the following questions:

1. Does an alternative approach demonstrate that it is more capable of explaining changes in pavement condition over time?
2. Can the outputs from this alternative approach be correlated with the factors that influence the change?
3. Is it a practical measure that could calculate a repeatable and accurate process?

1.3 Objectives of the research

This research aimed to better understand roughness, the way it is reported, and its effect on pavement performance and deterioration. This was to be achieved by identifying factors which masked or diluted the effectiveness of roughness analysis in determining pavement deterioration.

The research aimed to:

- develop a method to characterise the roughness deterioration modes of different pavement sections of the New Zealand road network by analysing the characteristics of the pavement longitudinal profile, ie to identify why the road failed by analysing the longitudinal profile of the pavement
- apply the proposed method to analyse the effects of pavement type, traffic loading, environment and maintenance regime on the deterioration of road roughness, ie to get a quantitative indication of how much roughness would be due to, for example, the environment vs traffic loading
- take the first steps in developing a model that would predict road deterioration over time – by gaining a more comprehensive understanding of the technology and deterioration mechanisms.

The intended outcomes from the research are listed in table 1.1.

Table 1.1 Outcome targets for roughness research

Research step	Intended outcome
Literature review	Set the context for the research and provide a brief summary of available technology.
LTPP site categorisation	Identify an appropriate categorisation method that could be used in this research. The aim was to be able to compare pavements in different failure modes with corresponding roughness characteristics. For example, would this be based on pavement condition or profiles?
Wavelength analysis	Understand the IRI's value in describing roughness trends over time. Establish alternative reporting techniques that better quantified roughness decay over time. Understand more fully condition-based roughness and environmental-induced roughness.
Factorial analysis	Investigate different factor analysis techniques to ultimately demonstrate: • whether the roughness measure could identify factors influencing roughness change over time • the respective results for the different analysis techniques.

1.4 Scope of report

Because different types of roughness are associated with different wavelengths, the subdivision of the roughness profile into individual sub-bands can assist with the interpretation of roughness deterioration. Wavelet analysis, which is not yet widely used, provides a means of splitting out the different wavelength components found within the pavement profile and facilitates the analysis of each part of the composite separately.

This research project developed a procedure to analyse pavement profiles using wavelet analysis of the longitudinal profile data collected on 146 New Zealand calibration sites. Each pavement profile was analysed and the energy content was split into six different wave bands (0.5–1m, 1–2m, 2–4m, 4–8m, 8–16m and 16–32m). The relative energy within each wave band was calculated for each year of data and trends in the change in energy from year to year and site to site were recorded. The results obtained were statistically analysed to highlight trends and identify failure modes.

A separate review of the physical deterioration – the observed deterioration characteristics noted over the past six to eight years – was also undertaken and these observations were analysed in tandem with and compared to the results obtained from the wavelet analysis.

The research was expected to provide an additional analysis process which would lead to identifying the source of the problems affecting pavement roughness.

The research project was divided into the following four separate phases:

1 Review: A literature review was undertaken to ensure the research did not replicate work already completed, and also to give it focus.

2 Data processing: Collation and processing of the individual calibration site longitudinal profile data. Analysis and classification of the wavelet time domain transform. This included a pilot programme to ensure the adopted process could provide the anticipated results.

3 Analysis: Statistical analysis of the results obtained from the wavelet process, and a review of the observable deterioration occurring on the calibration sites.

4 Summary: A summary of the findings and how they might influence future roughness deterioration analysis and pavement maintenance.

2 Literature review

2.1 Introduction

Road roughness measurement, characterisation and analysis have been intensively studied since the 1960s, therefore, it is prudent to include a literature review to understand current thinking and research relevant to this research project.

The results of the literature review are detailed below and include reviews of roughness testing and measurement, roughness characterisation and analysis, roughness deterioration monitoring and analysis, and wavelet analysis and waveband filtering.

2.2 Road roughness measurement

Road users judge the quality of a road primarily on its ride quality. From a user's point of view, rough roads mean discomfort, decreased speed, potential vehicle damage and increased vehicle operating cost. The American Society of Testing and Materials standard E867 (ASTM 1999) defines roughness as the deviations of a pavement surface from a true planer surface with characteristic dimensions that affect vehicle dynamics, ride quality, dynamic loads and drainage. Road roughness can also be defined as the distortion of the road surface which imparts undesirable vertical accelerations in the vehicle that contribute to an undesirable or uncomfortable ride.

2.2.1 Equipment

A variety of equipment has evolved over the years to measure pavement roughness; this equipment varies among the highway agencies and has a range of design characteristics which are dependent on intended use. Perera and Kohn (2002) found that devices could be divided into the following five categories:

- response-type road roughness measuring systems
- high-speed inertial profilers/profilometers
- profilographs
- light-weight profilers
- manual devices.

Until the mid-1980s, most highway agencies used the response-type road roughness measuring system (RTRRMS) to measure road roughness. These devices measure the response of the vehicle to the road profile, using transducers to accumulate the vertical movement of the axle of the survey vehicle with respect to the vehicle body. The measurement directly reflects the user's feeling of ride quality. A variety of RTRRMSs have been developed over the years, but all are disadvantaged by the fact that the results are influenced by the suspension characteristics of the vehicle and the measuring speed, and do not provide pavement longitudinal profile for spectral analysis. With the advent of inertial profilers, the use of the RTRRMS has diminished for roughness measurements and most types of pavements.

Inertial road profiling is a technology that began in the 1960s at the General Motors Research Laboratory (Spangler and Kelley 1964). The number of countries that have adopted high-speed inertial profilers to collect roughness data on their highway networks has shown a dramatic increase in the last two decades. High-speed profilers collect pavement condition data at highway speeds and record sufficient data to monitor pavement profile. The principal components of a high-speed profiler are laser-based height sensors, accelerometers and an accurate distance measuring system. The height sensors record the distance to the pavement surface from the vehicle. The accelerometers, located on top of the height sensors, record the vertical acceleration of the sensor. Double integration of the vertical acceleration gives the vertical displacement of the vehicle. The longitudinal profile is then derived from these two height measurements. The distance measuring system ties the measurements to a reference starting point. The non-contact height sensors currently used in profilers are either laser or ultrasonic waves. Figure 2.1 below is a typical high-speed profiler with 13 laser sensors.

Figure 2.1 Laser profiler

Unlike the high-speed laser profiler, a profilograph consists of a rigid beam or frame with a system of support wheels at either end and a central wheel. This wheel is linked to a strip chart recorder or a computer that records the movement of the wheel from the established datum of the support wheels.

The major difference between the high-speed profiler and the profilograph is that they use different reference planes and different filtering to record the surface profile. The profiler is a network survey device while the profilographs are widely used to evaluate the as-constructed smoothness of new pavements and overlays.

Figure 2.2 shows a photograph of the 12-wheel California profilograph.

Figure 2.2 Truss-type California profilograph

Light-weight profilers (figure 2.3) are increasingly used to evaluate new construction. The term light-weight profiler refers to devices in which a profiling system has been installed on a light vehicle, such as a golf cart or an all-terrain vehicle. The profiling system in the light-weight profilers is similar to ones used in high-speed profilers. The profile data is commonly used to simulate a profilograph over the pavement section, generate a profile index (PI) and identify bump locations. The profile data can also be used to compute other roughness indices, such as the IRI or ride number (RN).

Figure 2.3 Lightweight profiler and non-contact sensor

Manual devices such as the dipstick, ARRB walking profiler (figure 2.4) and rod and level are generally used to collect profile data to verify or validate the data collected by high-speed road profilers. The rod and level is perhaps the most accurate method of obtaining the true elevations along a pavement surface and its standard reference procedure is described in the ASTM E-1364. The dipstick and walking profilers usually use an inclinometer between two support feet or multiple wheels to compute the surface profile. The general procedure to verify the output from road profilers is to collect profile data at test sections using a manual reference device, then compute a roughness index such as the IRI from that data and compare the result with the output from the road profiler.

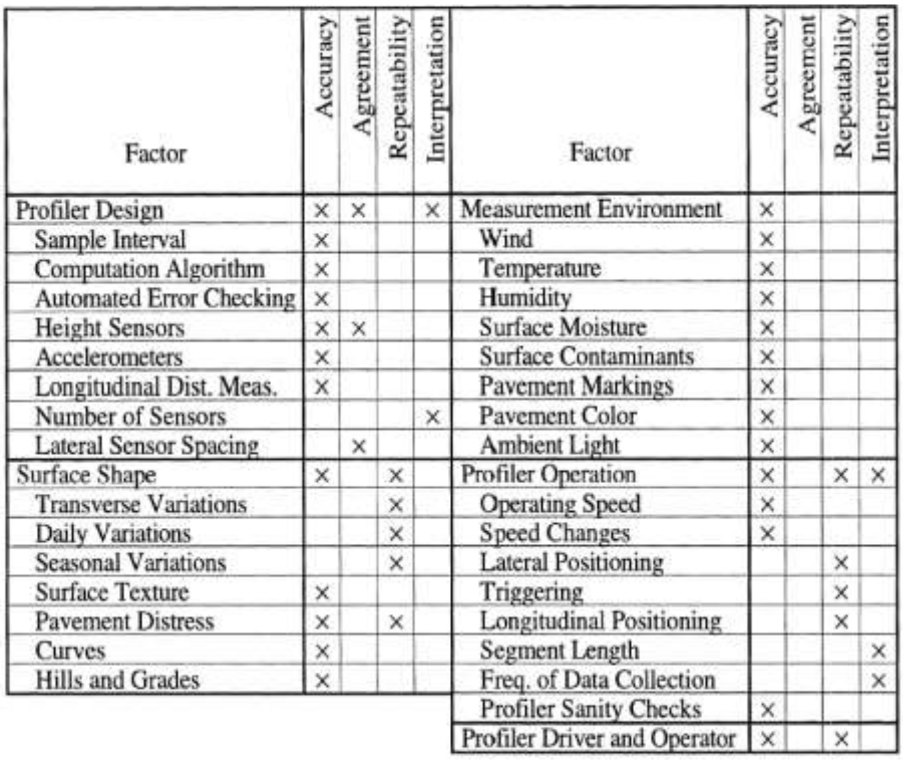
Figure 2.4 Walking profiler

2.2.2 Factors influencing road roughness measurement

Although technology has been available for measuring road roughness for decades, it has still not fully matured. A prevailing sense exists in the road community that if every agency measured the same road with their device, they would obtain a variety of different results. Errors in profile and discrepancies between measurements arise from variations in equipment, inappropriate operating procedures, and aspects of the pavement surface and the surrounding environment. In many cases, these factors interact to reduce their repeatability and accuracy. Table 2.1 shows 34 individual factors that affect longitudinal profile measurement studied in a National Cooperative Highway Research Program research project (Karamihas et al 1999). These factors fall into five broad categories:

- profiler design
- surface shape
- measurement environment
- profiler operation
- driver and operator proficiency.

Table 2.1 Factors influencing roughness measurement (Karamihas et al 1999)



Factor	Accuracy	Agreement	Repeatability	Interpretation	Factor	Accuracy	Agreement	Repeatability	Interpretation
Profiler Design	×	×		×	Measurement Environment	×			
Sample Interval	×				Wind	×			
Computation Algorithm	×				Temperature	×			
Automated Error Checking	×				Humidity	×			
Height Sensors	×	×			Surface Moisture	×			
Accelerometers	×				Surface Contaminants	×			
Longitudinal Dist. Meas.	×				Pavement Markings	×			
Number of Sensors				×	Pavement Color	×			
Lateral Sensor Spacing		×			Ambient Light	×			
Surface Shape	×		×		Profiler Operation	×		×	×
Transverse Variations			×		Operating Speed	×			
Daily Variations			×		Speed Changes	×			
Seasonal Variations			×		Lateral Positioning			×	
Surface Texture	×				Triggering			×	
Pavement Distress	×		×		Longitudinal Positioning			×	
Curves	×				Segment Length				×
Hills and Grades	×				Freq. of Data Collection				×
					Profiler Sanity Checks	×			
					Profiler Driver and Operator	×		×	

In New Zealand, Agrawal and Henning (2005) carried out research for RIMS Group and some participating councils to analyse the roughness data measured by an inertial profilometer on urban networks and to provide guidelines to improve the quality of roughness data. The key findings of this study were as follows:

- Steep gradient and tight curves had an impact on roughness readings. High roughness was observed on sections with a gradient greater than 10% and curves with a radius of less than 100m.
- Some sections had high roughness, particularly the start and end 40m, compared with the remaining length.
- The roughness at roundabouts was at 'unacceptable' levels. The readings before and after the roundabouts also showed elevated roughness.
- High roughness was noticed for the data collected at low speed. The average roughness was up to 9 on the IRI at speeds less than 30km/h.
- Event codes were extremely underutilised during data collection. A variation in roughness of up to 36% was observed between successive surveys on a sample network.

2.3 Road roughness characterisation

2.3.1 Road roughness data processing

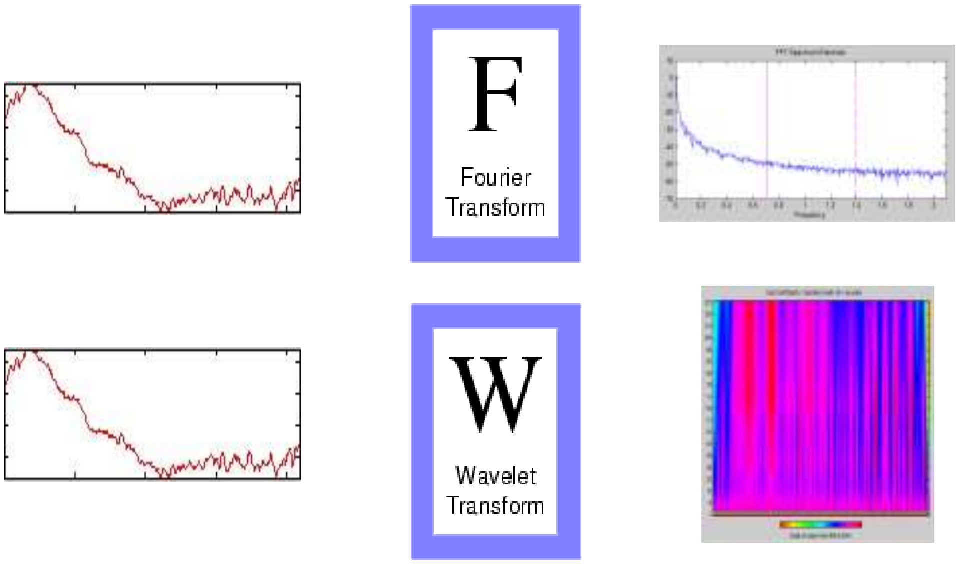
A roughness profile measurement is a series of data representing pavement elevation relative to a reference plane. There could be thousands of data points per kilometre of measured profile. Therefore, road roughness is normally characterised by a summary index obtained by applying a mathematical analysis to reduce the profile data to a single value reported at the desired interval, nominally 100m. Although many profile indices have been proposed and studied over that past 20 years, they are all based on mathematical algorithms that were proposed for characterising profile measurements in the 1970s. The algorithms that are still in use essentially involve a two-step process: 1) transform the original profile and 2) summarise the transformed profile by averaging to give roughness. A transformed profile only takes into account the most prominent wavelengths to describe the overall profile. Before such summary roughness index is derived, it is normal to filter the profile data to improve the quality of measurement by eliminating unwanted 'noise' and then extract information of interest from the profile data. Typically a transformation removes the very long and very short wavelength data and enhances the significance of some of the wavelengths in the profile. Most commonly used transforms are:

- quarter-car or half-car simulation (eg the IRI)
- other vehicle simulations (eg truck dynamic loading)
- finite difference (approximate slope calculation), mid-chord deviation (typified by the root mean square vertical acceleration (RMSVA)
- moving average smoothing (low-pass filter)
- moving average removing (high-pass filter).

A road profile can also be characterised by its wavelength content. Techniques for such analysis include Fourier transform, digital filtering (low-pass filtering to remove noise or high-pass filtering to remove trend) and wavelet transform. A Fourier transform changes a profile from a function of distance to a function of wave number (or wavelength). This type of transformation is often called spectral analysis. One output of a Fourier transform is the power spectral density (PSD) function. The PSD is a function rather than a summary index. The wavelet transform or wavelet analysis (Daubechies 1988 and 1992) is an analytical tool developed relatively recently to overcome the shortcomings of the Fourier transform. Figure 2.5 shows a comparison of Fourier transform and wavelet transform.

Wavelets are functions that satisfy certain mathematical requirements and are used in representing data or other functions. The wavelet transform can be used to decompose a signal into different frequency components and then present each component with a resolution matched to its scale. In the end the result will be a collection of time and frequency representations of the signal in different resolutions. The main difference between these two techniques is that Fourier analysis uses a regular base wave form of regular sine and cosine. Wavelength transform uses irregular base wave form, called wavelet.

Figure 2.5 Difference between the Fourier transform and wavelet transform



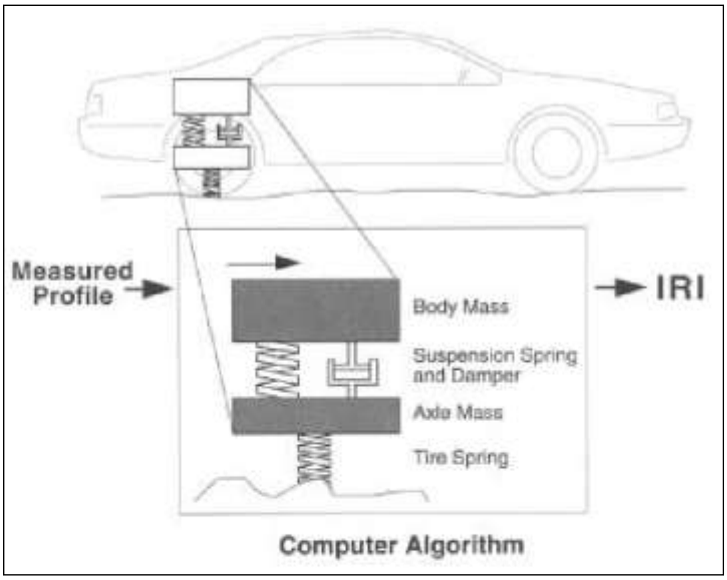
One major advantage afforded by wavelet analysis is the ability to perform local analysis, that is, to analyse a localised area of a larger signal. Therefore, wavelet analysis is capable of revealing aspects of data that other signal analysis techniques miss: aspects like trends, breakdown points, discontinuities in higher derivatives, and self-similarity. When used to analyse pavement roughness, it is able to reveal localised surface irregularities such as surface depressions, potholes, surface heaving and bumps (Liu et al 2005).

2.3.2 Summary index for characterising road roughness

Commonly used roughness indices include the IRI, PI, RN, RMSVA, National Association of Australian State Road Authorities (NAASRA) count and profile variance (PV).

The IRI is a widely accepted measure of roughness developed by the World Bank in the 1980s and adopted by the World Road Association (PIARC). The IRI is a numerical representation of a road profile, designed to replicate the traditional roughness measures obtained from response-type road roughness measuring systems. The computation of the IRI is based on a mathematical model called the quarter-car model. This mathematical model calculates the suspension deflection of a simulated mechanical system with a response similar to a passenger car. The simulated suspension motion is accumulated and then divided by the distance travelled to give an index with units of slope (m/km). The mathematical simulation carried out by the computer program is shown schematically in figure 2.6. The IRI has been found to be highly portable, that is, different roughness or profile measuring devices are capable of producing outputs expressed in the IRI.

Figure 2.6 Graphical presentation of algorithm used to compute IRI (Sayers and Karamihas 1997)



Profilers have been widely used to measure the smoothness of new pavements. The profilers provide a trace of the pavement profile, which is reduced to obtain the PI. This in turn is used to judge the roughness of the pavement. The first step in trace reduction is outlining the trace. This averages out spikes and minor deviations caused by rocks, texture, dirt or transverse grooving. The next process in trace reduction is to place the blanking band on the profile trace. A blanking band is typically 0.2 inches wide but some agencies have used 0.1 inch wide bands, while some use zero blanking bands. Excursions which extend in height more than 0.03 inches above the blanking band for at least 0.08 inches in horizontal distance (ie 2ft on the pavement) will be recorded on the profile and rounded to the nearest 0.05 inches. The sum of the recorded heights within a given segment will be the PI for that segment. This is expressed in terms of inches per mile (Perera and Kohn 2002).

The RN is an index intended to indicate ride quality on a scale similar to the PI. The RN uses a scale from 0 to 5. This scale was selected, as it is familiar to the highway community. The RN is a nonlinear transform of the PI that is computed from profile data. The PI ranges from 0 (a perfectly smooth profile) to a positive value proportional to roughness. The PI is transformed to a scale that goes from 5 (perfectly smooth) to 0 (the maximum possible roughness).

RMSVA is a statistic that measures the root-mean-square of the rate of change of the grade of a pavement longitudinal profile. The method was named RMSVA for two reasons. First, the computation is equivalent to the second derivative of the height with respect to the time of the object in contact with the profile moving at a constant horizontal speed. Such computation yields a vertical acceleration of the object. Second, a series of acceleration values result from the discrete elevation points; therefore, a root mean square of these values is computed to arrive at a single value (Hudson et al 1983). The RMSVA can be computed for any base length. The capacity provides the technique with a strong ability to distinguish between the various components of the roughness that exists in a pavement longitudinal profile.

Since the early 1970s, road pavement roughness has been measured in Australia and New Zealand using the NAASRA roughness meter. This is a standard mechanical device for measuring road roughness by recording the upward vertical movement of the rear axle of a standard station sedan relative to the vehicle's body as the vehicle travels at a standard speed along the road being tested. The NAASRA meter is classified as a response-type road roughness measuring system (RTRRMS). NAASRA roughness counts per kilometre is the cumulative total relative upward displacement between axle and body of a standard vehicle, registered in units of counts per kilometre of distance travelled at either of two principal standard speeds, 80km/h or 50km/h. One NAASRA roughness count corresponds to a measured axle-to-body separation of 15.2mm. Although NAASRA roughness meters have been successfully used for many years, there are particular concerns about maintaining their calibration, and about repeatability and reproducibility of the results. Outputs are very dependent on vehicle suspension characteristics (eg, shock absorbers, springs, tyres) and the speed of travel (Austroads 2000).

In the United Kingdom, ride quality is assessed by profile variance (UK Roads Board 2003), obtained by calculating the differences between the profile and its moving average over selected moving average lengths. Three moving average base lengths (3m, 10m and 30m) are commonly used and accordingly, the road profile data is processed to compare the actual profile and the moving average of the profile over these three lengths. The results are presented in terms of the square of the difference between the moving average of the profile and the measured profile. Profile variance is also used by some Commonwealth countries, for instance Singapore and New Zealand. In a research report recently published by the NZTA, Jamieson (2008) developed a methodology based on road profile variance to identify and prioritise treatment of road sections that promote poor ride quality for heavy commercial vehicles. In the study, he found that high values of profile variance, particularly in the 10m and 30m wavelength data, generally corresponded to locations exhibiting poor truck ride quality in the measured on-road data. However, there were many sections with high-profile variance that did not show poor truck ride. If profile variance is to be used successfully to select and prioritise road section for remedial work the profile variance must first be modified or filtered according to geometry factors and/or vehicle speed.

Table 2.2 below shows a summary of the roughness indices mentioned above, together with their underlying principles and short descriptions.

Table 2.2 Commonly used roughness summary indices

Index	Principle	Description
IRI	Quarter-car simulation	A statistic that summarises the roughness qualities impacting on vehicle response based on the quarter-car vehicle model at a standard simulation speed of 80km/h.
PI	Profilograph simulation	A smoothness index that is computed from a profilograph trace.
RN	Ride comfort estimation	A calculated roughness index, between 0 and 5, that approximates the mean panel rating for a pavement surface.
RMSVA	Vertical acceleration simulation	A statistic that measures the root mean square of the rate of change of the grade of a pavement longitudinal profile.
NAASRA count	Response accumulation	Cumulative recording of the upward vertical movement of the rear axle of a standard station sedan relative to the vehicle's body as the vehicle travels at a standard speed along the road being tested.
PV	Moving average filtering	A statistic presented in terms of the square of the difference between the moving average of the profile and the measured profile.

In summary, there is a general tendency to use summary indices derived from detailed roughness profile data to describe roughness. These are summary indices which only report a portion of the information available in the profiles.

2.3.3 Characterising road roughness by wavelength contents

The surface deviations in the longitudinal profile of a road pavement are generally random in nature, but they can be characterised by a combination of waveforms of various amplitudes and wavelengths. The full spectrum of roughness amplitudes can be represented by the displacement power spectral density (PSD) as a function of the wave number (the inverse of the wavelength) (Sayers 1986a). Studies have been done that use PSDs to classify the wavelength content of road profiles and represent them mathematically (Dodds and Robson 1973). In some cases, enough road profile data has been available for a range of surface types to identify specific characteristics of each surface type.

Figure 2.7 PSD of a faulted PCC and wavy surface-treated road (Sayers 1986a)

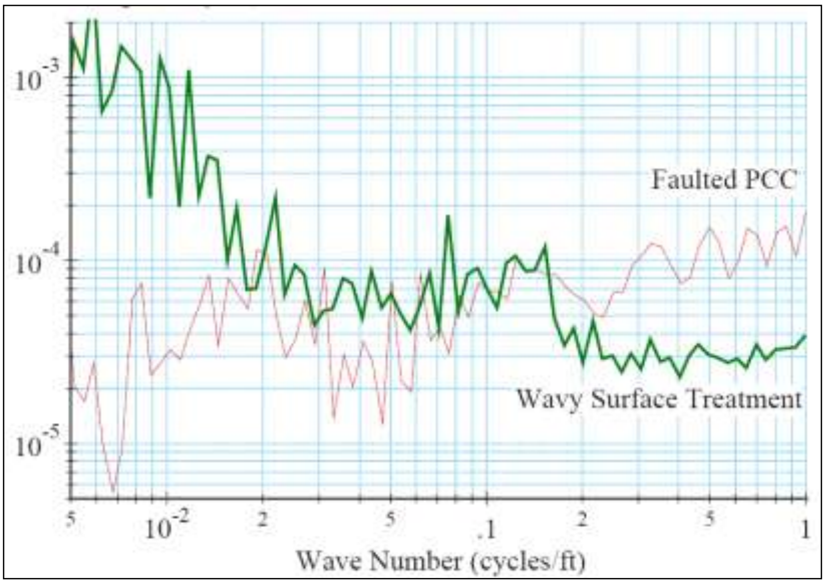
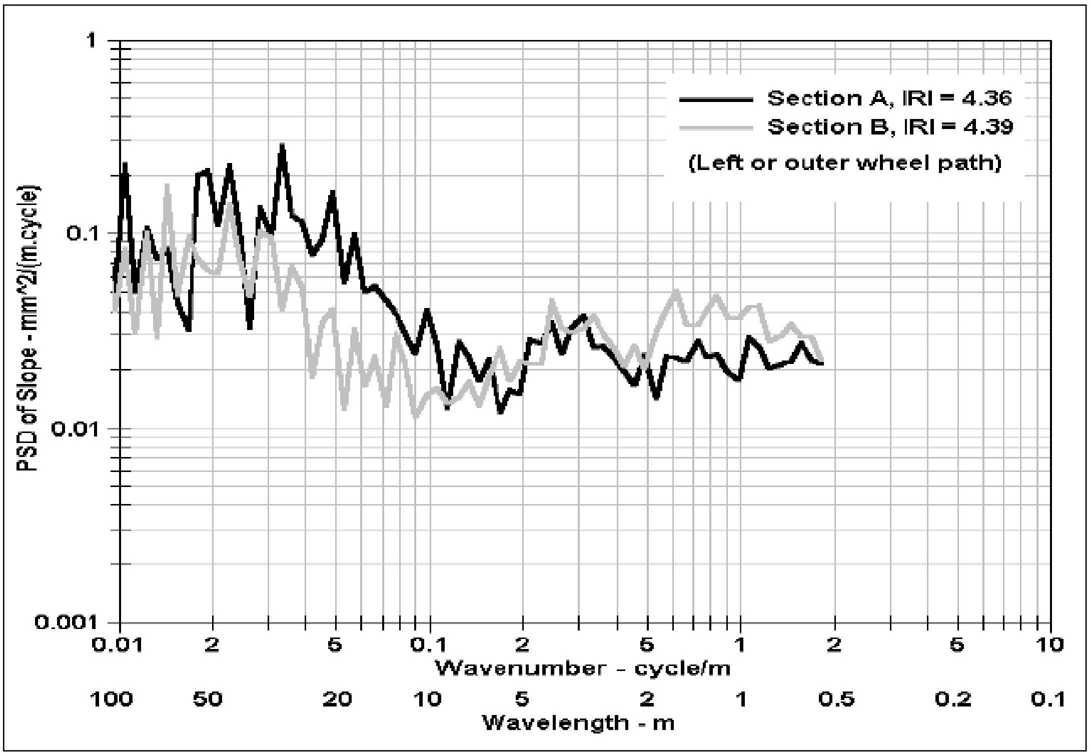


Figure 2.7 above shows PSD functions for a faulted Portland Cement concrete (PCC) and a wavy surface-treated road. The PSD for the surface-treated road is higher on the left-hand side of the plot (low wave numbers = long wavelengths) because the treatment removed all sharp bumps, but left the long wavy roughness. The PSD for the PCC road is high on the right-hand side of the plot (high wave numbers = short wavelengths) because it is faulted. The plot also shows several spikes that correspond to the periodic effect from the uniformly spaced faults.

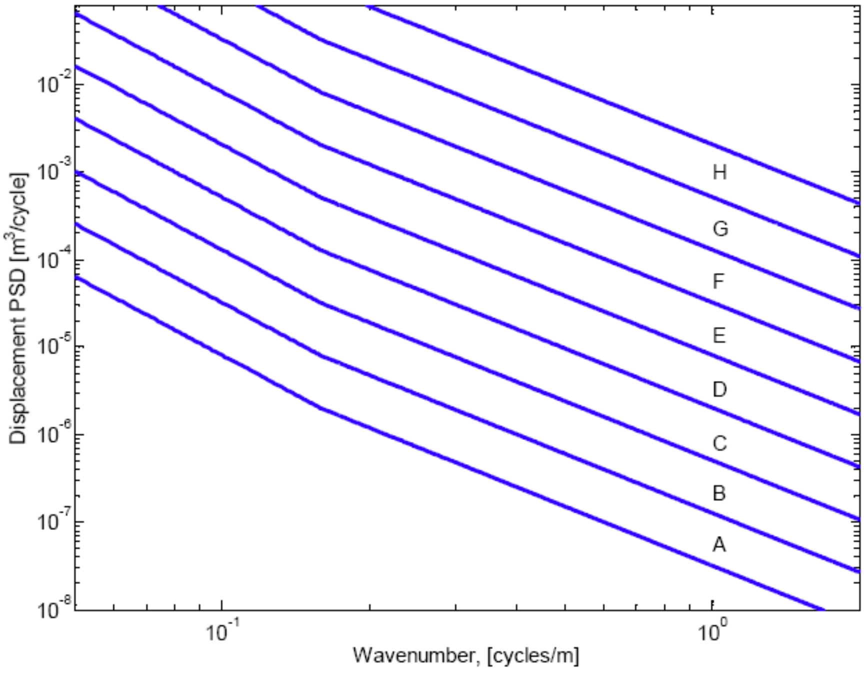
PSD analysis is generally used to determine the ‘type’ of roughness that exists over a road section, and there are claims this can also assist in determining the mode of rehabilitation works most likely to be required (Hassan et al 1998). PSD functions can also help to identify failures in roads that contribute to roughness. Roads where the long wavelengths are dominant have poor foundations. Old dirt roads that were paved without significant grading tend to have high PSD amplitudes at the low wave numbers. Roads where the high wave numbers are dominant tend to have cracks, faulting and other forms of surface distress. Using PSD analysis on two sections of pavement with a similar IRI value, Mann et al (1997) demonstrated a substantial difference in the intensity of the various wavebands. Figure 2.8 shows the different PSD of profile slope plots for two sections of almost identical IRI values.

Figure 2.8 PSD of slope plots of road sections with similar IRI values (Mann 1997)



ISO 8608 standard (ISO 1995) classifies road severity in 8 classes (class A ~ H) using spatial frequency and octave band filtered displacement PSD. It limits the displacement PSD for different classes of roads as functions of the octave bands. Figure 2.9 shows the chart for classification of road roughness by ISO 8608 standard.

Figure 2.9 Road roughness classification according to ISO 8608 1995 (E)



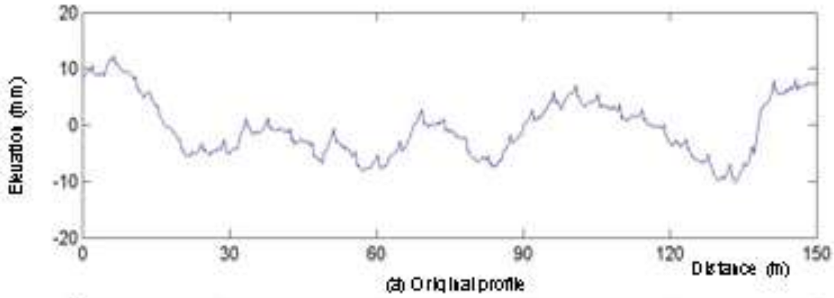
However, to obtain a good estimate of the PSD, it is necessary to have a reasonably long sample. The ISO standard in fact specifies that the sections should be at least 1km long. Thus, the ISO methods are aimed at describing the average condition of the pavement over its entire length. Also, calculating the profile PSD using the ISO standard eliminates all spatial information from the data. Therefore, it is not possible to identify the location of roughness problems from the PSD distribution. Moreover, when the PSD is used as the description of road surfaces, the signal is assumed to have a Gaussian distribution, and statistically uncommon events, such as transients, are lost. Consequently, extreme values (those exceeding three standard deviations) must be analysed separately in order to fully describe the road characteristics.

In mathematical statistics, the outcome of a PSD analysis of a stationary process is treated as an estimate of a true theoretical spectrum. It must also be emphasised, that a spectrum is only defined for stationary processes, where measured profiles often display non-stationary behaviour. Several papers have demonstrated it is possible to describe non-stationary properties using wavelet analysis. The wavelet analysis procedure (Liu et al 2005) has been used to identify the characteristics of a pavement roughness profile in both the frequency and distance domains. Detailed roughness features of interest to pavement engineers not currently available from summary roughness statistics or indices could be obtained using the wavelet analysis procedure. Such detailed roughness information may be useful for maintenance operations, detection of pavement surface distresses, and detailed analysis of the trend of pavement roughness deterioration. Cenek et al (1999) carried out wavelength analysis on longitudinal profiles of various road sections of New Zealand state highways that showed significant roughness deterioration. They recommended that whenever longitudinal elevation profiles were available, either wavelet analysis or sectional power spectral density should be employed in special investigations to aid the interpretation of pavement deterioration. This would lead to more efficient management of the road network through adoption of more appropriate rehabilitation strategies and better formulated pavement deterioration models.

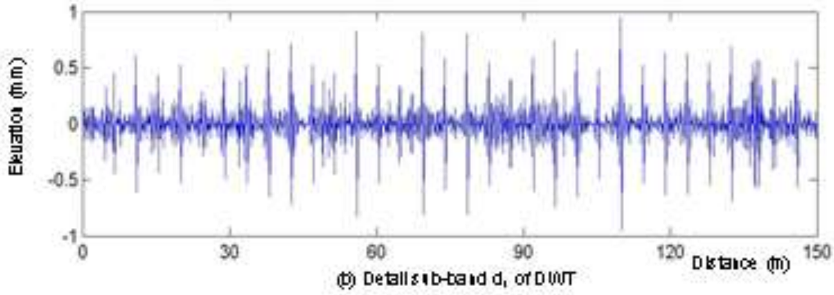
Figure 2.10 shows the results obtained using the wavelet transform to detect pavement defects, and figure 2.11 shows the results of a road roughness deterioration study using the wavelet transform obtained by Liu et al (2005) when they applied analysis. Moreover, the sub-band energy using the wavelet transform of a road profile is found to be a good parameter to correlate different types of roughness index (Liu and Fwa 2005).

In order to characterise the wavelength content of a road roughness profile in the frequency domain, a certain kind of wave-banding is normally applied to the spectrum. The Transport and Road Research Laboratory analysis of road roughness surveys (Jordan and Cooper 1989) has shown that changes in road roughness over time, associated with significant visible pavement distress, are largely reflected by short wavelength features (eg less than 3m). Conversely, the long wavelength features of road roughness surveys may indicate general ground subsidence (Jordan and Cooper 1989).

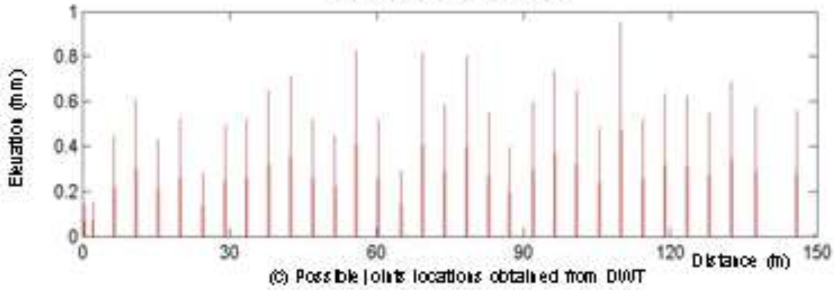
Figure 2.10 Pavement defect detection from roughness profile by wavelet transform



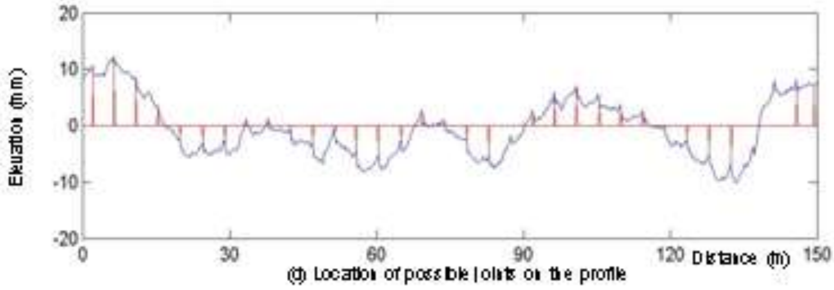
(a) Original profile



(b) Detail sub-band d_1 of DWT

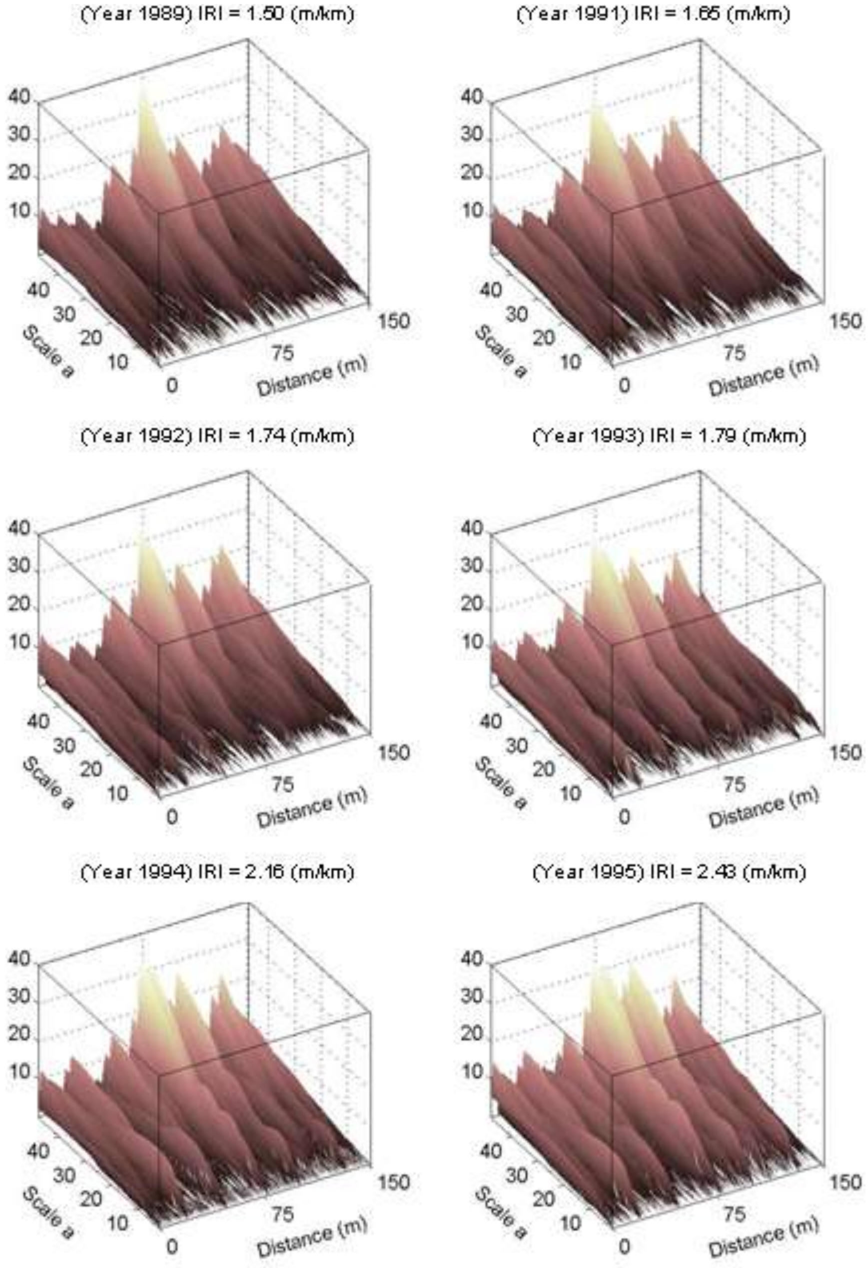


(c) Possible joints locations obtained from DWT



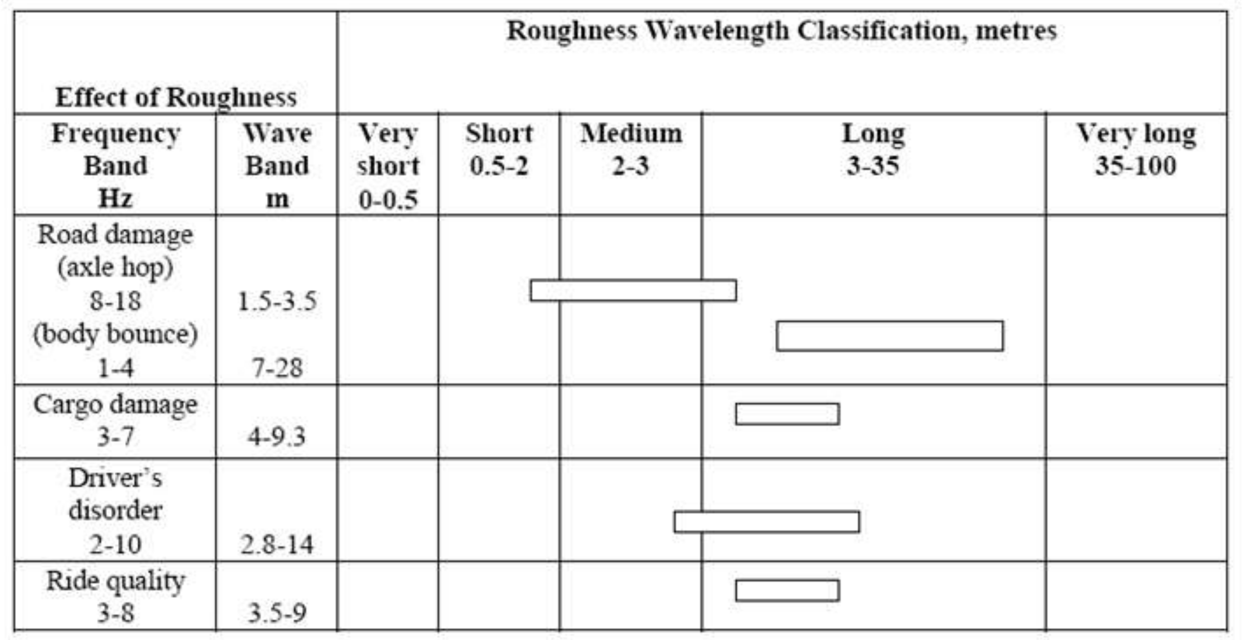
(d) Location of possible joints on the profile

Figure 2.11 Road roughness deterioration study by wavelet transform (Liu et al 2005)



McManus and Hassan (1997) analysed the wavebands affecting road roughness and the user at a vehicle speed of 100km/h. Table 2.3 summarises these roughness frequencies and surface wavelengths.

Table 2.3 Wavebands affecting road roughness and the user at vehicle speeds of 100km/h (McManus and Hassan 1997)



Effect of Roughness		Roughness Wavelength Classification, metres				
Frequency Band Hz	Wave Band m	Very short 0-0.5	Short 0.5-2	Medium 2-3	Long 3-35	Very long 35-100
Road damage (axle hop) 8-18	1.5-3.5		▭	▭	▭	
(body bounce) 1-4	7-28				▭	
Cargo damage 3-7	4-9.3				▭	
Driver's disorder 2-10	2.8-14			▭	▭	
Ride quality 3-8	3.5-9				▭	

2.4 Summary and conclusion

This review researched current literature, papers and reports from previous research carried out on various topics including road roughness measurement, road roughness characterisation and road roughness deterioration monitoring and analysis. Major findings from this review can be summarised as follows:

- Roughness has been used as an important indicator of pavement condition ride comfort and safety for many years.
- The need to measure roughness has facilitated the development of a wide range of instruments, from rather simple devices to quite complicated systems, to aid these measurements. A variety of devices is now available to measure road roughness. The devices range from manually operated walking profilers to high-speed vehicle-based profilers and response-type systems. More and more road agencies have adopted profilers to measure road roughness due to their advantages of accuracy and repeatability.
- Road roughness is usually characterised by a summary index. Commonly used roughness summary index include the IRI, RN, PI, RMSVA and PV. These summary statistics provide an indication of the overall roughness condition of a given length of a pavement section. However, these summary statistics also suffer from a common limitation in that the detailed contents of the surface condition of the pavement section concerned are lost.
- Road roughness profile can also be characterised by its wavelength content. Available techniques for such analysis include Fourier transform, digital filtering and wavelet transform. Fourier transform can be used to generate a power spectrum density function to represent road roughness, which is useful when analysing the wavelength content of the road roughness but requires a large sample to obtain a good estimate of the PSD. Also, calculating the profile PSD eliminates all spatial information from the data. Therefore, it is not possible to identify the location of roughness problems from the PSD distribution. Moreover, when the PSD is used as the description of road surfaces, the signal is

assumed to have a Gaussian distribution, and statistically uncommon events, such as transients, are lost. Consequently, extreme values (those exceeding three standard deviations) must be analysed separately in order to fully describe the road characteristics.

- Roughness deterioration has been found to be the result of a chain of distress mechanisms and it combines the effects of various modes of deterioration. Past studies indicate that roughness progression is complex and there is considerable variability in the rate of roughness progression between similar pavement types. Consequently it is difficult to define parameters that can reliably predict the roughness of a pavement.

This literature review has demonstrated a need to carry out additional research to study the wavelength contents of the roughness profile; to better understand and identify factors that contribute to the deterioration of road roughness; and to find the mode of roughness deterioration for different types of road in order to accurately predict the roughness progress. This understanding will enhance forward work programmes and maintenance actions, so that a safer and smoother road network can be provided to the public.

3 Methodology

3.1 Background

Road roughness is that irregularity of the pavement surface which affects vehicle safety, comfort, speed and operating costs. It is therefore one of the major triggers for pavement maintenance and rehabilitation. While roughness, and more specifically longitudinal profile, can be a valuable diagnostic tool to help indicate when maintenance is required it does not tell the whole story. Pavement deterioration results from the combined effects of heavy vehicles and environment. However, change in roughness is the result of a number of distress mechanisms as evidenced by the various modes of deterioration. An OECD (1984) publication on pavement surface characteristics, reports that short wavelength roughness is generally associated with degradation of the surface or base layer, while long wavelength roughness is often related to deformations or displacements occurring in the sub-grade. It is also well known that road users do not have the same level of sensitivity on surfaces affected by distortions of different wavelengths.

Because different types of roughness are associated with different wavelengths, the subdivision of the roughness profile into individual sub-bands can assist with the interpretation of roughness deterioration.

Wavelet analysis is a mathematical discipline which has generated much interest in both theoretical and applied applications since the 1980s. Wavelet analysis provides the means of splitting out the different wavelength components found within the pavement and analysing each part of the composite separately. The introduction of wavelet analysis of longitudinal profile through this research project may provide the additional analysis process needed to identify the source of problems affecting pavement roughness.

3.2 Profile decomposition and sub-band energy calculation

Longitudinal profiles were measured annually using an ARRB walking profiler on both left and right wheelpaths at the LTPP sites to monitor their roughness condition. The sampling interval of the ARRB walking profiler is approximately 0.25m, therefore the minimum wavelength content of the longitudinal profile data is twice the sampling interval, or 0.5m.

In order to analyse the wavelength content of the longitudinal profiles a mathematical transform was developed. Fourier transform and wavelet transform are the most common methods used to study the characteristics of a complex waveform in the frequency domain. The Fourier transform breaks down a signal into constituent sinusoids of different frequencies. Its popularity is due to the ability to analyse the relative strength of the individual frequency components of the signal in the frequency domain. However, its major limitation is that in transforming the signal to the frequency domain, time information is lost. Researchers have attempted to correct these deficiencies over the years through short-time Fourier transforms (STFT) and Gabor transforms. The former use a window function and translates this in time to split the signal into locally stationary fractions before performing Fourier transforms on each of the parts. The disadvantage is that the window size is fixed. Wavelet transforms provide a way of overcoming this by decomposing a signal into different frequency components and then presenting each component with a resolution matched to its time scale. The result is a collection of time and frequency representations of the signal in different wavebands.

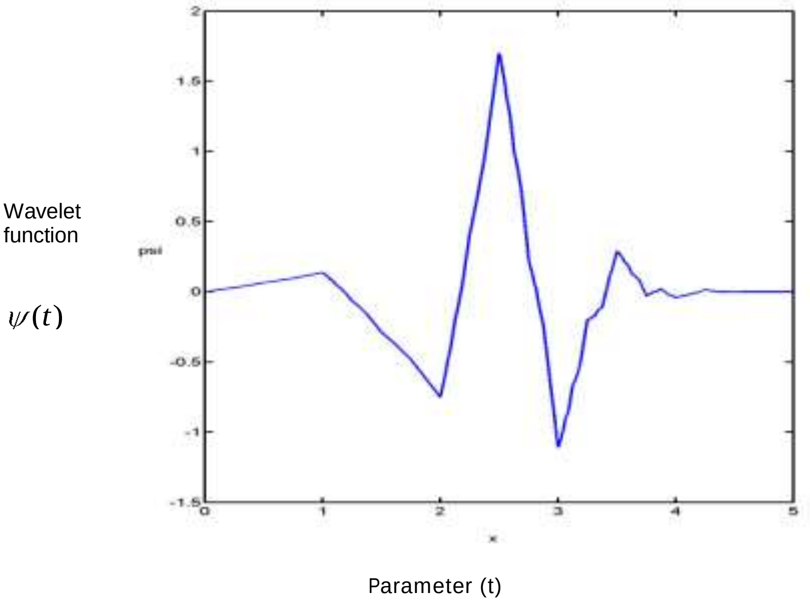
In this study, wavelet transform, more specifically the discrete wavelet transform (DWT) was chosen to decompose the pavement longitudinal profile into several sub-bands with each sub-band representing a range of wavelength features covering the entire wavelength range measured by the ARRB walking profiler.

The wavelet analysis procedure began with the adoption of a wavelet prototype function, called an analysing wavelet or mother wavelet. The mother wavelet processes the properties of square integrability, and is orthornormal in its translations and dilations. There are many kinds of mother wavelets. One can choose from smooth wavelets, wavelets with simple mathematical expressions, wavelets with simple associated filters, compactly supported wavelets, etc (Daubechies 1992). In this study, the wavelet functions $\psi(t)$ developed by Daubechies were considered. The Daubechies family of wavelets DB1 to DB10 was analysed. The index number *N* refers to the number of coefficients. Each wavelet has a number of *zero moments* or *vanishing moments* equal to half the number of coefficients. For example, DB1 (the Haar wavelet) has one vanishing moment, DB2 has two, etc. A vanishing moment limits the wavelet's ability to represent polynomial behaviour or information in a signal. For example, DB1, with one moment, easily encodes polynomials of one coefficient, or constant stepwise signal components. DB2 encodes polynomials with two coefficients, ie constant and linear signal components; DB3 encodes 3-polynomials, ie constant, linear and quadratic signal components; and DB4 encodes 3-polynomials, ie constant, linear, quadratic components and cubic signal components. The wavelet DB3 (see figure 3.5) was selected as the mother wavelet in present analysis as the results based on this can provide adequate resolution in both the frequency and time domains. The mother function can be used to generate a whole family of wavelets

$$\psi a,b(x) = \frac{1}{\sqrt{|a|}}\psi(\frac{x-a}{b}) \qquad \text{(Equation 3.1)}$$

by translating and scaling the mother wavelet (see equation 3.1). Here b is the translation parameter and a is the scaling parameter.

Figure 3.1 Daubechies wavelet function DB3



The DWT on a profile data s(t) can be expressed as:

$$s(t) = \sum_{j=1}^{N} \sum_{k} Cj(k)\psi j,k(k) \qquad \text{(Equation 3.2)}$$

Where *C j (K)* is the wavelet coefficient, $\psi_{j,k}(t)$ is the mother wavelet and N is the level of decomposition.

By using the mother wavelet function, the DWT can be implemented with an efficient and practical filtering algorithm developed by Mallat (1989). In the pyramidal algorithm, the original profile f(t) is first decomposed into a coarse (ie low frequency) component a_1 and a detailed component d_1. This process is repeated to further decompose the coarse component. That is, a coarse component a_j is decomposed into a_{j+1} and d_{j+1}, where a_{j+1} is the lower frequency component of a_j, and d_{j+1} is the higher frequency component of a_j. This decomposition process is mathematically represented as follows,

$$a_j(k) = \sum_{i=1}^{N} h_j(2k-i)s(i) \quad j = 1,2,...N \qquad \text{(Equation 3.3)}$$

and

$$d_j(k) = \sum_{i=1}^{N} g_j(2k-i)s(i) \quad j = 1,2,...N \qquad \text{(Equation 3.4)}$$

where N is the total number of level of decomposition, k=1,2, ..., n, a_j the low frequency component of the level j, d_j the high frequency component of the level j, h_j the low-pass filter of level j, and g_j the high-pass filter of level j. The original signal can thus be represented as the sum of a series of signals as follows:

$$s = a_L(n) + \sum_{j=1}^{L} d_j(n)$$

In the present study, the number of decomposition levels was chosen as 6. After decomposition, the roughness signal s could be expressed as the sum of the following 7 sub-bands

$$s = a_6 + d_6 + d_5 + d_4 + d_3 + d_2 + d_1 \qquad \text{(Equation 3.5)}$$

The corresponding wavelength ranges of these sub-bands are shown in table 3.2. The intervals were developed using the following logic:

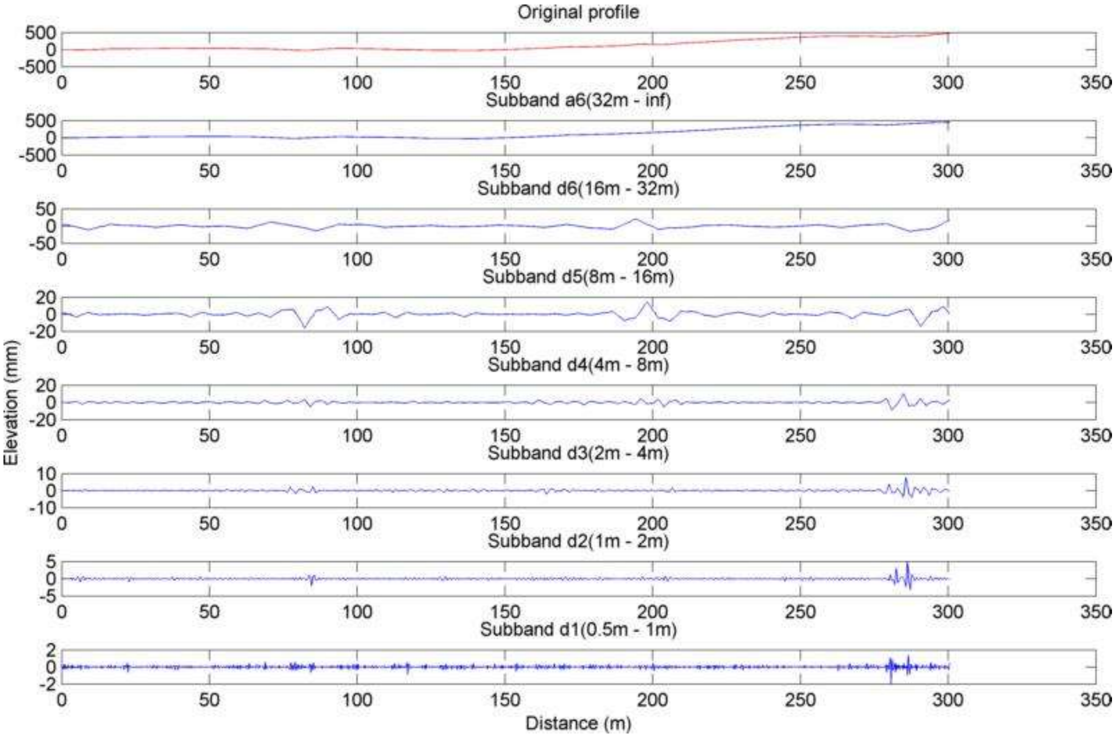
- The sampling interval was 0.25m, the minimum wavelength collected was 0.5 (twice of sample interval).
- At the first level, the wavelet analysis decomposed the profile into one low frequency band (1m – inf) and high frequency band (0.5m–1m). At the next level, it decomposed the low frequency band from first decomposition into a low frequency band (2m – inf) and high frequency band (1m–2m). This process was repeated until level 6 gave the wave band composition in table 3.2.

Table 3.2 Sub-band roughness wavelength used in wavelet analysis

Sub-band	a_6	d_6	d_5	d_4	d_3	d_2	d_1
Wavelength range (m)	32-∞	16–32	8–16	4–8	2–4	1–2	0.5–1

Each sub-band represents a different wavelength of road surface profile. Together, these 7 non-overlapping sub-bands covered the entire wavelength range in the longitudinal profile measured by the ARRB walking profiler. Figure 3.6 gives an example of longitudinal profile decomposition by DWT.

Figure 3.6 Example of profile decomposition by DWT



It can be seen that sub-band a6 represents the general shape of the road section, and sub-bands d6 to d1 contain the detailed information of road roughness ranging from the long wavelength to the short wavelength.

The energy for sub-band d6 to d1, can be expressed as

$$D_j = \sum_k \left| d_j(k) \right|^2$$ (Equation 3.6)

The total energy can be obtained by

$$D_{total} = \sum_{j=1}^{N} \sum_k \left| d_j(k) \right|^2 = \sum_{j=1}^{N} E_j$$ (Equation 3.7)

3.3 Wavelength content analysis and deterioration mode characterisation

The wavelength content is important as each sub-band makes a different contribution to the overall roughness level of the pavement profile. In this study, the energy of each sub-band (d1 to d6) was used to characterise the wavelength content of the pavement longitudinal profiles of LTPP sections. The following steps were carried out for the wavelength content analysis:

1. The energy of each sub-band (d1 to d6) was calculated at 50m intervals for each profile measured in each year for all LTPP sections, using equations 3.2 to 3.6.
2. As there was a minimum of three measured profiles for each wheelpath we found the mean energy of each sub-band for the repeat runs in each wheelpath lane and section measured each year.

3 The rate of energy change of each sub-band was derived for each year as a percentage for each 50m subsection of each LTPP section studied. The average energy change for all survey years was then established.

4 The maximum value of the average energy change rate was found and the corresponding sub-band for each 50m subsection for each LTPP section studied.

5 The roughness deterioration mode of the LTPP section studied was characterised as a sub-band with a maximum value of average energy change rate over the whole LTPP section.

3.4 Computer program and database development

As indicated by the research methodology above, sub-band energies for each profile measured at each LTPP section for eight years on the state highway sections and six years for local authority sections were used in the database. In total, nearly 21,600 profiles were processed and analysed. To enhance the efficiency of data processing and analysis and eliminate any manual errors, a computer program to automate processing of the profile data and organisation of the analysis results into database tables was developed. Key functions of the computer program included:

- opening raw profile data files, loading profile data and profile plot view
- comparison profile plot for selected multiple profiles
- decomposition of profile into sub-bands by DWT
- sub-band energy and IRI calculation
- batch processing all profiles in a selected directory and uploading analysis results into corresponding tables in the database.

More details and some screen shots are presented in appendix B.

4 Site categorisation based on condition

4.1 Objectives

The main purpose in the site categorising process was to define the characteristics of each site, identify the characteristics of any visible deterioration, identify the type of deterioration and the dominant failure mode at each site, and ultimately use this information to aid the factorial and spectral analysis which followed.

If the development of a particular distress pattern or process could be visually identified, then it might be possible to later associate a distress pattern with a change in the energy spectrum and better define roughness deterioration.

4.2 Defining the categorising process

The road asset and maintenance management (RAMM) database contains a wide range of useful site data and this in part was used in the categorising process. The following information was extracted from the RAMM database:

- surface date (the original seal date)
- material (asphalt reseal two coat etc)
- aggregate size
- traffic volume
- maintenance.

Over the previous nine years of the LTPP programme it had become clear that certain distress types were more prevalent, including:

- flushing (texture reduction) – usually in the wheelpaths
- chip loss – usually between the wheelpaths
- surface defects such as potholes – usually a result of wearing coarse failure
- transverse cracking
- structural failures defined as a long depression (anything from 1m–2m to 4m–8m) forming in the wheelpath and often associated with alligator cracking etc
- rutting, longitudinal cracking and shoving
- patching – while this is not specifically a defect the majority of patch repairs invariably resulted in increased roughness and therefore for the purposes of this classification patching was included.

A controlled maintenance regime was stipulated for the LTPP sites whereby sterilised sites had no or minimal maintenance, and all other sites followed normal maintenance practice. All maintenance required approval from the LTPP project manager. However, it became evident that the quality of the maintenance often adversely affected the measured roughness. Therefore maintenance quality was also considered in the site classification process.

These defect types formed the basis of the site categorisation, with each distress associated with a particular wavelength band used in the spectral analysis. The following criteria assumptions were made:

- flushing could be considered to have the most effect on the very short wavelength spectra
- chip loss affected both the very short and the short wavelength spectra
- surface defects affected the short wavelength spectra
- transverse cracking – short to medium wavelength spectra
- structural failures – medium wavelength spectra
- rutting and longitudinal cracking – long wavelength spectra
- patching could affect all wavelength spectra depending on the quality, size and type of patch.

The condition data, photos, site notes and personal knowledge of each site were used to identify the predominant defects or distresses. The sites were then classified and assigned a probable dominant wavelength (very short, short, medium, or long) that was most likely to show the greatest change as a result of the observed dominant deterioration defect.

Where there was no obvious deterioration characteristic the site was designated as ‘G’. This did not mean there was no site deterioration, but that there was no visible deterioration. Subsequent analysis has shown it is possible to have long wavelength deterioration without seeing any physical change.

The sub-band decomposition process (wavelet analysis) analysed each wheelpath separately and produced an energy level for each of the six wavebands for each year analysed. This data was plotted (refer to figure 4.1) and reviewed to identify trends and to see if these matched the categorisation criteria.

This information, the RAMM data, the dominant visible defects and the review of the waveband energy were entered into an Excel spreadsheet along with an expected dominant waveband or wavebands.

Figures 4.1 and 4.2 are included as an example of the individual spectra plots for a specific site used in this process and to demonstrate how they have been interpreted. The plots can be explained as follows:

- Each plot represents a single 300m wheelpath (the length of each calibration site), which is divided into six sub-sections across the page, with eight points representing each of the eight years of data available.
- Each colour (shape) represents a particular waveband: yellow triangles the 0.5–1m or short wavelength, turquoise crosses the 1–2m wavelength, brown dots the 2–4m wavelength, violet crosses the 4–8m wavelength, green pluses the 8–16m wavelength, and the blue dashes the 16–32m or long wavelength.
- Figure 4.2a and b is included to further clarify the information contained in figure 4.1 by amplifying and displaying a single 50m subsection.

Figure 4.1 shows that the energy of the very short (0.5–1m) and short (1–2m) wavelength spectra (yellow triangles and turquoise crosses) reduce from year one to year two, and then increase in year three, followed by a gradual reduction back toward the original energy level after year eight for each of the six subsections. These changes can be attributed to changes in texture as a result of the site reseal and wearing coarse material size change between years two and three, and the gradual smoothing of the surface in the following years to year eight.

The long wavelength 16m–32m spectra (blue dash) show significant increases in sub-sections 4 and 5 from years three to eight; however, there is no visible defect which can be attributed to this energy change.

Figure 4.1 Cal30 increasing lane left wheelpath

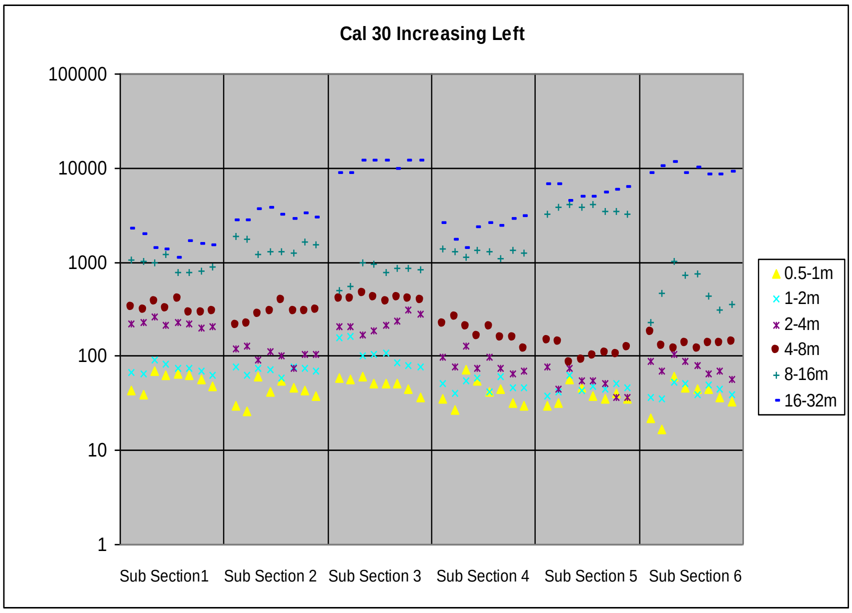
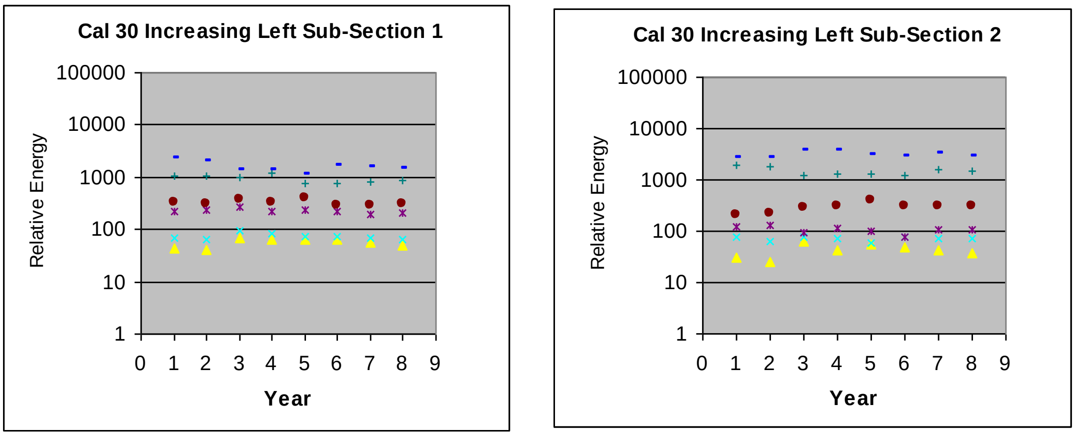


Figure 4.2 Cal30 increasing lane left wheelpath



a) Subsection 1

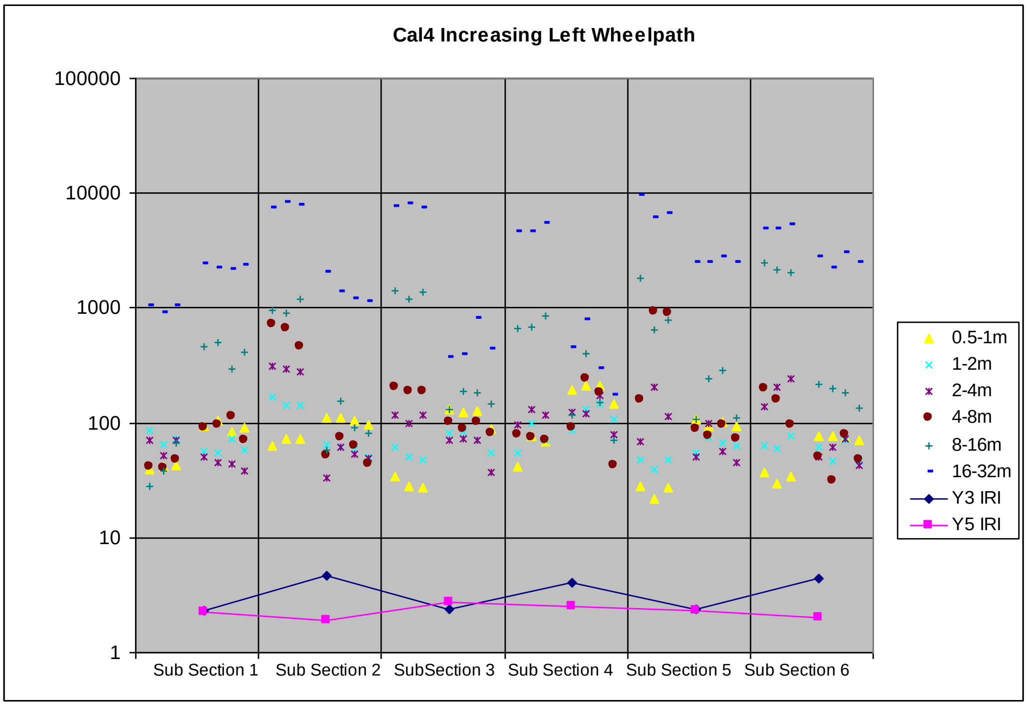
b) Subsection 2

In this example, the dominant effect for the site would be defined as a short-to-medium wavelength change and is a result of the site smoothing and change in wearing coarse grade following the reseal after year two. While there is an increase in long wavelength energy in three subsections there was no visible change to the site to attribute this to and no obvious change in roughness (IRI), so while we can detect a change in long wavelength spectra it cannot be accounted for using current methods.

4.2.1 Observations

This categorisation process has revealed a number of other interesting facts which are demonstrated in the following figures.

Figure 4.3 Cal 4 left wheelpath increasing lane sub-band energy and IRI



Cal4 underwent a full rehabilitation during year four of the LTPP project, which resulted in reduced roughness (IRI) in subsections 2, 4 and 6. Figure 4.3 above shows the sub-band energy levels for years one to three and five to eight for this site, and the year three and year five IRI data. A large reduction in the long wavelength energy resulting from the rehabilitation work can be clearly seen in five of the six subsections. Both the 8m–16m and 16m–32m (green plus and blue dash) have much less energy in year five. At the same time there has been an increase in very short wavelength energy (yellow triangles) as a result of the rehabilitation work. The increase in short wavelength energy may be a result of the change in texture from a smooth surface with little or no texture to one that is quite coarse formed from a two chip locked grade 3/5 surface treatment.

Considering the IRI in isolation there appears to be no change to three of the subsections, where the sub-band analysis process shows significant changes have occurred and provides much more information on the change to the site and the effect of the rehabilitation.

Figure 4.4 Profile changes for Cs13A

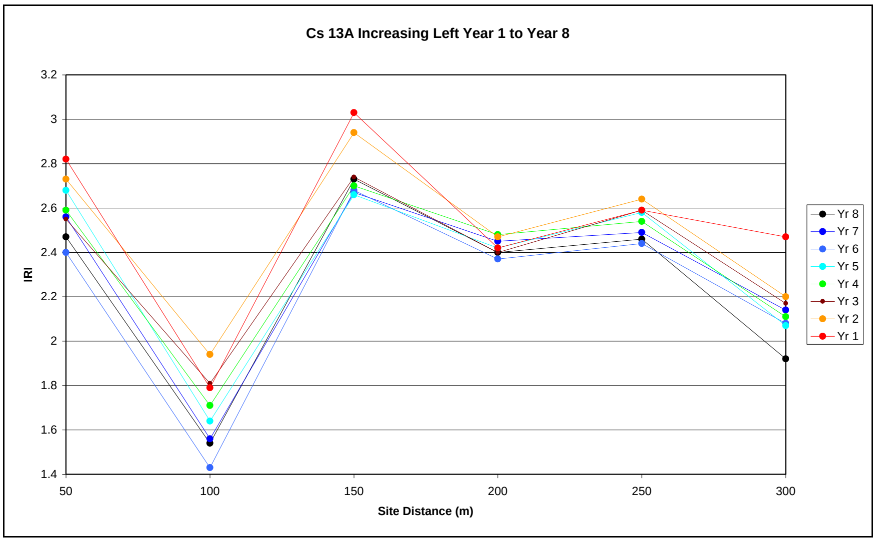
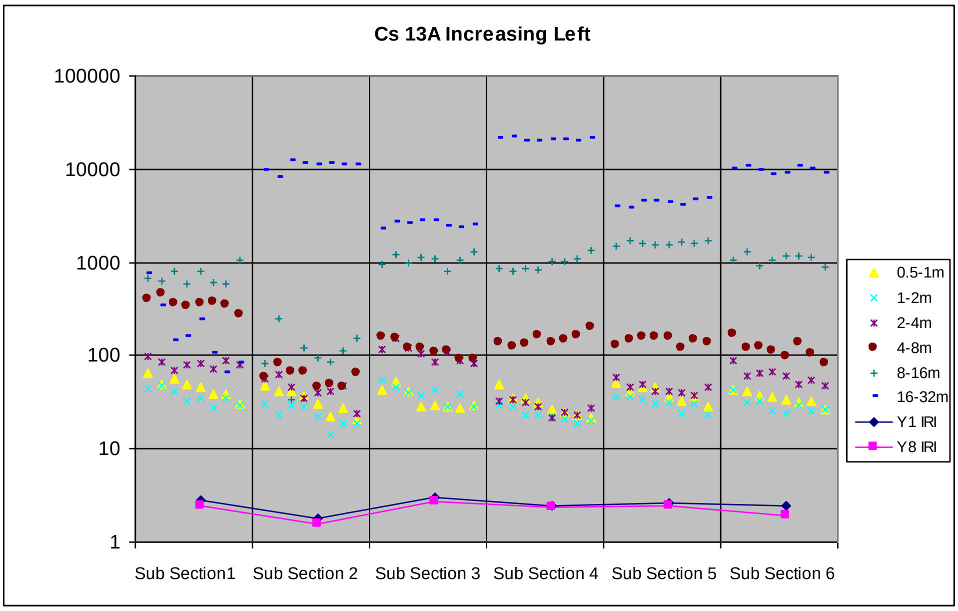


Figure 4.4 shows the change in roughness at site Cs13A over the previous eight years. The roughness had a systematic reduction for five or six years and then a reversal with some increases from year seven to year eight in most subsections. Figure 4.5 shows the corresponding change in sub-band energy over the same period.

Figure 4.5 Sub-band energy for site CS13A



There are significant differences in the magnitude of the long wavelength spectra energy across the six subsections, whereas the roughness did not reflect these changes and in some cases showed the opposite trend.

The reduction in short wavelength (0.5–2m) spectra energy from Y1 to Y6 is consistent with the observed reduction in roughness over the same period.

The site became severely flushed after four years and was scrubbed to remove the excess binder resulting in an increase in surface texture; however, there was no corresponding change in the very short wavelength sub-band energy, indicating that the change in micro texture did not have a significant influence in either the roughness or the sub-band energy.

Figure 4.6 Effect of poor maintenance on the IRI

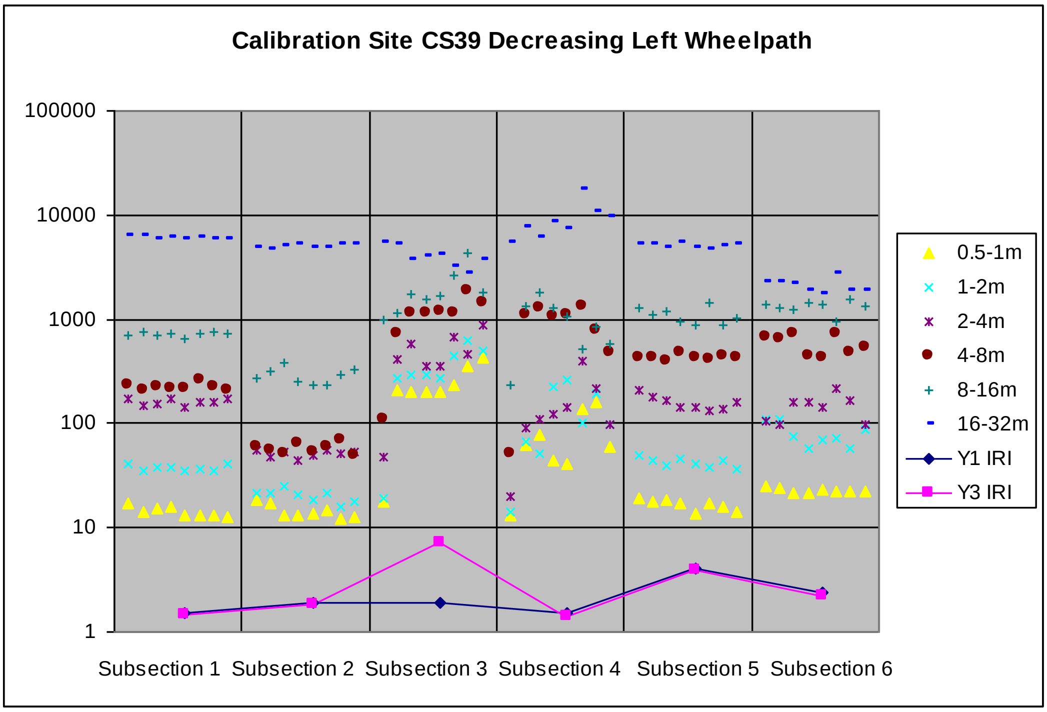


Figure 4.6 demonstrates the effect of poor maintenance on both the IRI and the short wavelength sub-band energy. At this site the left wheelpath of sub-section 3 (100m–150m) was badly cracked in year one and was rehabilitated before the year two measurements. The finished surface had a lot of visible short wavelength roughness features which resulted in a large increase in the 50m IRI from year one to year two at 150m. The sub-band analysis shows an increase in the 0.5m–4m sub-band energy levels as a result of the maintenance.

The relative energy levels for each of the six different wavebands analysed are significantly different; in most cases the long wavelength spectra energy is often 1000–10,000 times that of the short wavelength spectra energy.

Even within the long wavelength spectra there are large variations (up to 100-fold changes) without any obvious change in condition or roughness. Cal4 had a significant reduction in the medium-to-long sub-band energy levels after the year three rehabilitation work but showed no corresponding change in roughness.

4.3 Summary

Clearly there were observable changes in the field and corresponding changes in the energy spectra that we expected to influence these changes.

Short wavelength energy increased following a reseal or site reconstruction and slowly (over several years) reduced back to the original level. This was more obvious on the two grade locked chip-seals and not so significant where a site was badly flushed when the flushing transferred quickly through to the new seal or where the reseal was a fine grade chip-seal. On the open grade asphalt sites (Auckland motorway) the opposite trend was observed.

The IRI was influenced most by the short and medium wavelength roughness; changes in the short and medium wavelength spectra had a corresponding change in the IRI and were the only wavelength energy that could be seen to have a direct correlation with changes in the IRI.

Long wavelength spectra energy (often associated with the underlying geological terrain) does change, and this change was more obvious on state highway and local authority sites with high traffic volumes (Auckland and surrounds). However, there were no obvious visible signs or changes to the calibration sites that could be associated with this change or used to identify this occurrence.

A significant portion of the sites had little or no visible change in condition or in the IRI, while demonstrating a significant change to the long wavelength spectra energy.

Maintenance undertaken on some sites has been poor or carried out at the bare minimum to maintain the site integrity and this was reflected in both the energy spectra level and the IRI as an increase in the short and medium wavelength sub-band energy and an increase in the IRI.

The level of energy within the long wavelength bands can be up to 1000 times that of the energy in the short wavelength bands, and the variation between sites can also be substantial.

Given that changes in the long wavelength sub-bands were observed, there might be grounds for another waveband between 32m and 100m. This would, however, mean the analysis subsection length would need to be increased to quantify trends in the longer wavelengths.

5 Wavelength change over time

5.1 Purpose of analysis

There have always been indications from other research that the IRI does not necessarily quantify the roughness profile of road pavements (Cenek at al 1999). This chapter reviews the sub-band data provided through the wavelet analysis process to see if it would be a more effective performance measure of roughness increase over time, while ensuring all observations drawn from comparisons and apparent differences are statistically quantified.

5.2 Data processing

The LTPP roughness profiles were analysed and divided into energy sub-bands in accordance with the methodology detailed in section 3. Once the wavelength content was established the data was processed according to the following:

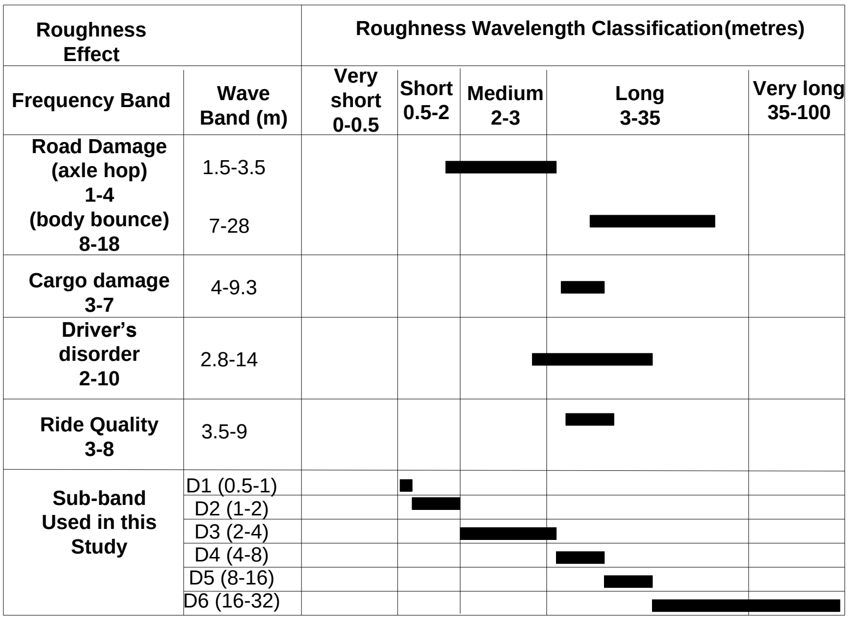
- The energy of each sub-band (d1 to d6) was determined at 50m intervals for each profile measured in each year for all LTPP sections.
- A minimum of three measured profiles for each wheelpath were processed and the mean energy for each sub-band determined in each wheelpath and subsection measured each year.
- The rate of change in energy from one year to the next was determined for each sub-band and expressed as a percentage for each 50m subsection of each LTPP section.
- The dominant sub-band for each section was identified as the sub-band with the maximum overall average annual change rate.

The following sections summarises the finding from this analysis.

5.3 Changes in wavelength distribution

The main objective of this analysis was to determine how the roughness profile changed over time. The literature review and study objective suggest that the IRI as it is presently reported does not necessarily quantify the change in the full profile spectrum. This analysis investigated whether a pattern could be identified which linked the roughness profile changes to the pavement characteristics. Figure 5.1 assists with the interpretation of these results.

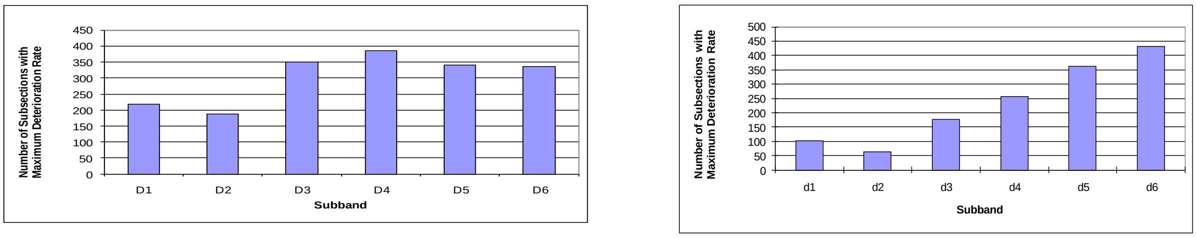
Figure 5.1 Classification of the wavelengths



Roughness Effect		Roughness Wavelength Classification(metres)				
Frequency Band	Wave Band (m)	Very short 0-0.5	Short 0.5-2	Medium 2-3	Long 3-35	Very long 35-100
Road Damage (axle hop) 1-4	1.5-3.5		■	■	■	
(body bounce) 8-18	7-28				■	
Cargo damage 3-7	4-9.3				■	
Driver's disorder 2-10	2.8-14			■	■	
Ride Quality 3-8	3.5-9				■	
Sub-band Used in this Study	D1 (0.5-1)		■			
	D2 (1-2)		■			
	D3 (2-4)			■	■	
	D4 (4-8)				■	
	D5 (8-16)				■	
	D6 (16-32)				■	■

Figure 5.2 depicts the distribution of the change in energy per sub-band for both the local authority and state highway sections. For each LTPP sub-section the energy sub-band with the most significant change from one year to another was recorded, and the total number of sub-sections with the highest energy changes per sub-band energy was displayed.

Figure 5.2 Changes in roughness energy for each wavelength sub-band



Local authority LTPP sections

State highway LTPP sections

The most significant observation was that the behaviour between local authority sections and state highway sections was significantly different. As indicated in the next section, this pattern was mostly driven by urban sections contained in local authority LTPP data. More detailed observation of these graphs revealed that:

- local authority sections had similar changes for sub-bands d3 to d6, with sub-bands d3 and d4 containing the most significant (approximately 40%) change
- state highway section changes increased with increasing wavelength from d2 to d6. The longer wavelengths, d5 and d6, accounted for over 56% of all the maximum changes.

It can be concluded from this section that the deterioration change characteristics from urban and rural road sections were different. Most of the urban sections changes occurred in the d3 and d4 sub-bands, while the state highway section changes occurred in the longer wavelength d5 and d6 sub-bands.

The statistical significance of the difference between the urban and state highway sections was investigated and is presented in table 5.1. The table presents the p-value from the Student's t-test[1], which is an indication of the significance of the difference. It is accepted that for any value less than 0.05 (95%) the difference would be significant. From this table it can be concluded that the two network types did indeed behave differently in the short wavelength energy bands d1 to d4. Statistically, the difference in the longer wavelength d5 and d6 sub-bands was not significant; however, most of the energy change in the state highway sections was within these two sub bands. Urban and state highway sections had similar changes in sub-bands d5 and d6, or wavelengths greater than 8m.

Table 5.1 Statistical significance in differences between local authority and state highway LTPP sections

Sub-band		d1 (05-1.0)	d2 (1-2)	d3 2-4)	d4 (4-8)	d5 (8-16)	d6 (16-32)	ΔIRI (m/km/year)
State highway vs local authority	p value	0.02	0.04	0.01	0.02	0.56	0.16	0.022
	Significant difference	Yes	Yes	Yes	Yes	No	No	Yes

These findings suggest that the deterioration would be similar for the longer wavelengths d5 and d6. However, for the shorter wavelengths, typically the ones that were captured in the IRI simulation, there was a significant difference in performance between urban and rural sections.

Further investigation was undertaken to see if the difference between state highway and local authority sections might be attributed to the urban rural difference. Table 5.2 illustrates the statistical significance in changes within the sub-bands and the IRI by comparing urban and rural sections on the local authority LTPP.

Table 5.2 Statistical significance in differences between urban and rural sections (local authority sections)

Sub-band		d1 (05–1.0)	d2 (1–2)	d3 2–4)	d4 (4–8)	d5 (8–16)	d6 (16–32)	ΔIRI (m/km/year)
Urban vs rural	p value	0.22	0.09	0.08	0.02	0.05	0.08	0.1746
	Significant difference	No	Yes	Yes	Yes	Yes	Yes	No

The table includes the annual change in the IRI to highlight the fact that although there was a significant difference between wavelength changes for urban and rural environs, the IRI did not recognise this change. The IRI is therefore not an effective performance measure to describe the actual road condition deterioration in terms of its profile. This suggests that the wavelength sub-band energy level could be a more effective measure to describe deterioration changes over time.

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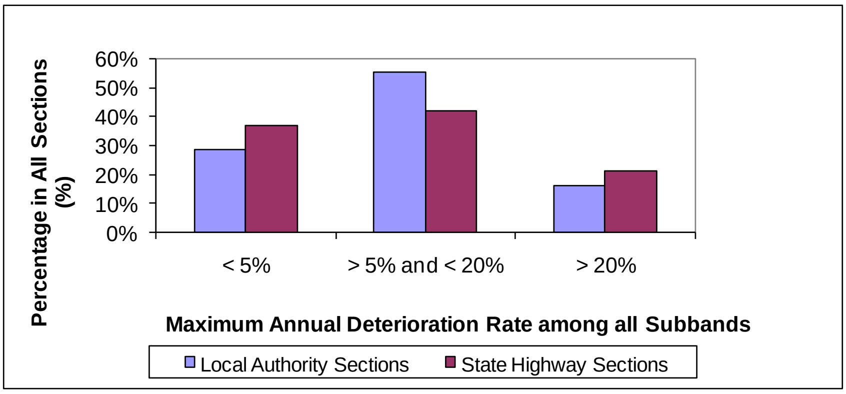
[1] A common statistical method for testing differences between two parameters.

5.4 The rate of change for sub-band energy

The rate of change in the energy spectra for both LTPP programmes is presented in figure 5.3. It shows the changes binned into three categories for both local authority and state highway sections. The local authority sections had a high proportion of mid-range change in the 5% to 20% category, while the state highway sections had a more uniform change across all three categories, and also had the highest proportion within the 5% to 20% category. This compared to an expected annual roughness change of 0.03IRI, typical of the New Zealand network and equated to 1% annual change. Therefore, it is clear that the IRI masked some of the actual profile change occurring over time.

Figure 5.3 The rate of change for LTPP sections



5.5 Comparing roughness change (IRI) and wavelength energy change

This section investigates whether roughness, as expressed in the IRI, changed at the same rate as the changes in the wavelength energy. There have been some instances where the perceived roughness on roads increased, but it was not reflected in the IRI roughness measurement. For this reason, NZTA operations now report the profile variance as an additional measure to quantify roughness change over time (see section 2.3.2).

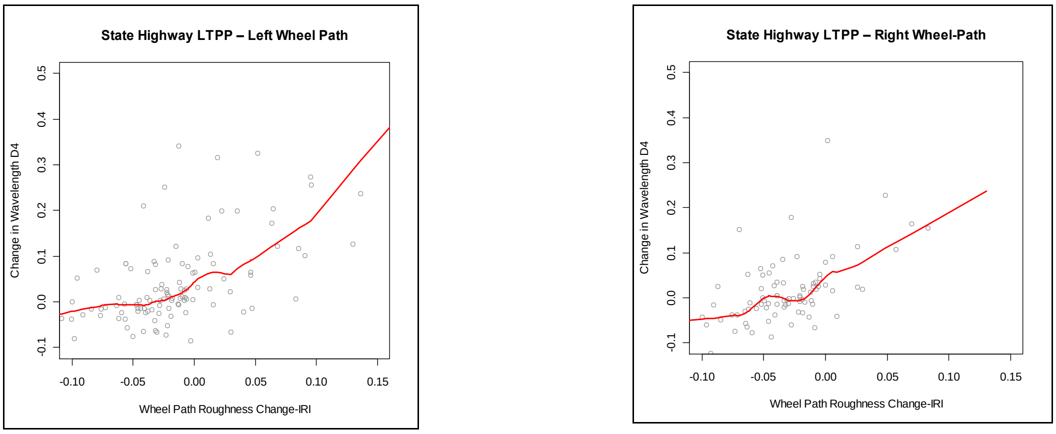
One would expect that across the wavelength spectrum between 0.5m and 32m the typical relationship would be similar for the resulting IRI. If a common filtering and analysis process was used, a certain percentage increase in wavelength energy would result in a given percentage increase in the IRI. However, it was expected and confirmed in our analysis that different roads underwent a different change pattern in each wavelength sub-band. For example, figure 5.3 shows that the state highways had increased sub-band energy in the longer wavelengths, while urban roads had a more even roughness progression across all wavelengths.

A number of comparative graphs between roughness in the IRI and wavelength energy were produced and some typical examples are presented in figures 5.4 and 5.5. These figures illustrate scatter plots between values for sub-sections as a function of roughness change (in the IRI) and energy change within individual sub-bands. The figures also show a smoothing line that uses locally weighted regression. This smoothing line is indicative of potential trends. Therefore one can graphically observe potential linear or exponential relationships.

Some observations from this analysis revealed:

1 The sub-band energy increase for left wheelpaths in the respective wavelengths was steeper for corresponding IRI roughness compared with the right wheelpaths (refer to figure 5.4). This shows the energy for wavelength d4 of both the left and right wheelpaths on state highway LTPP sections. For a 0.15 IRI change in roughness, a wavelength energy change of 0.3 and 0.2 was observed for left and right wheelpaths respectively. Note that these observations were consistent for both state highway and urban local authority sections.

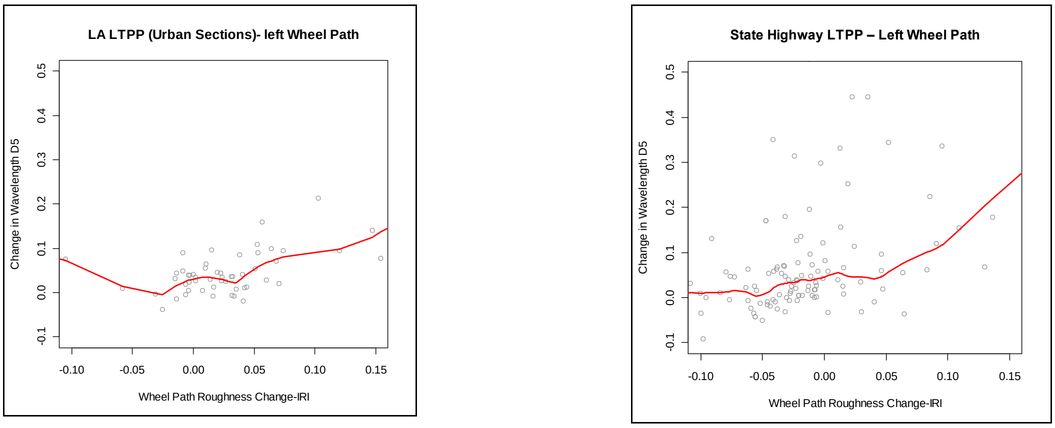
Figure 5.4 Comparing wavelength increase with roughness IRI increase for different wheelpaths



Left wheelpath (outer) Right wheelpath (inner)

2 This result was consistent with previous sections. In particular it was evident that the local authority LTPP sections had a more consistent increase across all wavelength energy compared with the state highway sections where the increases tended to reside in the longer wavelengths. Figure 5.5 illustrates the d5 left wheel path wavelength for both the urban and state highway networks. The d5 wavelength energy increase was approximately 0.1 and 0.25 respectively for the urban and state highway sections.

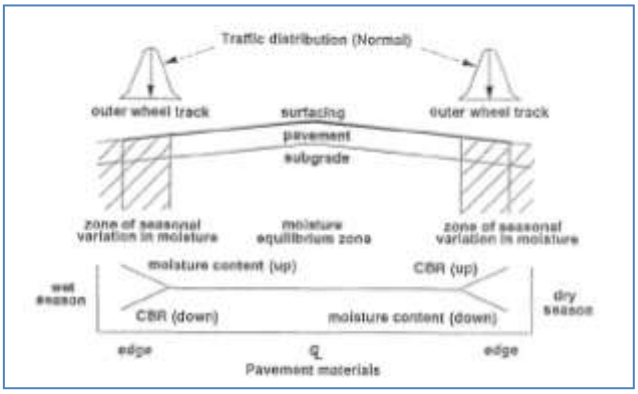
Figure 5.5 Comparing wavelength energy increase between urban and state highway sections



Urban sections (left wheelpath) State highway sections (left wheelpath)

The difference identified in the performance of the two wheelpaths is well known to engineers. In her study, Schlotjes et al (2009) showed that rutting in the outer wheelpaths was expected to be deeper and more variable compared with the inner wheel path. This observation was best explained by the moisture variation expected on the outside wheeltracks of pavements as illustrated in figure 5.6.

Figure 5.6 Zone of moisture variation (Emery 1992)

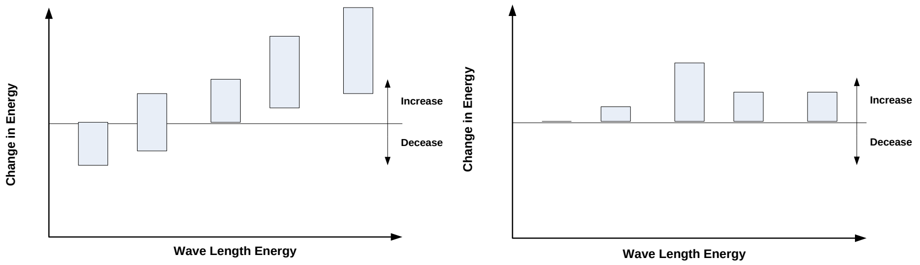


5.6 Discussion of results

This analysis demonstrated that the wavelength energy provided more information than current methods used to determine what caused changes to the pavement, and so might be a more effective measure of roughness or pavement deterioration than the IRI. It has been demonstrated that the data processing used to determine roughness (IRI) can have a strong masking effect for pavements that display significant deterioration over their life. For example, roughness values on a motorway system only change slightly between maintenance intervals. The range of roughness on these pavements is far less compared with low-volume roads in developing countries, where the IRI measure is very effective as a performance measure.

Figure 5.7 illustrates the roughness changes of two networks in the respective wavelength energy levels. In reality the roughness change expressed in terms of the IRI may have been exactly the same. The IRI therefore did not explain the difference in deterioration of the networks, while the wavelet analysis was able to do this.

Figure 5.7 Wavelength energy changes for two road networks



Road network type A

Road network type B

6 Results from factor analysis

6.1 Purpose of the analysis

Earlier research into the development of pavement deterioration models suggested it was difficult to find significant factors that influenced rutting and roughness deterioration as quantified by the IRI (Henning et al 2006a). Two potential explanations for this were either the data was not collected to the required accuracy or the IRI did not fully explain the deterioration of the road. The latter theory is supported by the previous section.

This section investigates different factor analysis techniques to demonstrate:

- whether the roughness measure can identify factors influencing roughness change over time
- what the respective results are for the different analysis techniques.

Four different techniques were used to determine which gave the best results for the available data. The techniques included:

- correlation matrices
- manual stratification
- hypothesis testing and the Student t-test
- data mining.

6.2 Results based on correlation matrix

The resulting correlation matrices for both the local authority LTPP and the state highway LTPP are depicted in appendix A. The following observations were made from these tables:

6.2.1 Observations from the local authority LTPP

- There was a strong correlation between the left wheelpath sub-band energy and the annual rut change in the left wheelpath. The strongest correlation (0.75) was between the rut change and the change in the d4 sub-band energy. The relationship between the annual rut change in the left wheelpath and the annual roughness change (in IRI) was weaker (0.66).
- The rut/wavelength energy relation was absent in the right wheelpath.
- The relationship between the right wheelpath IRI and sub-band energy was weaker compared with the corresponding trend for the left wheelpath.
- There was an apparent relationship between the right-hand d2 sub-band energy and alligator cracking.

6.2.2 Observations from the state highway LTPP

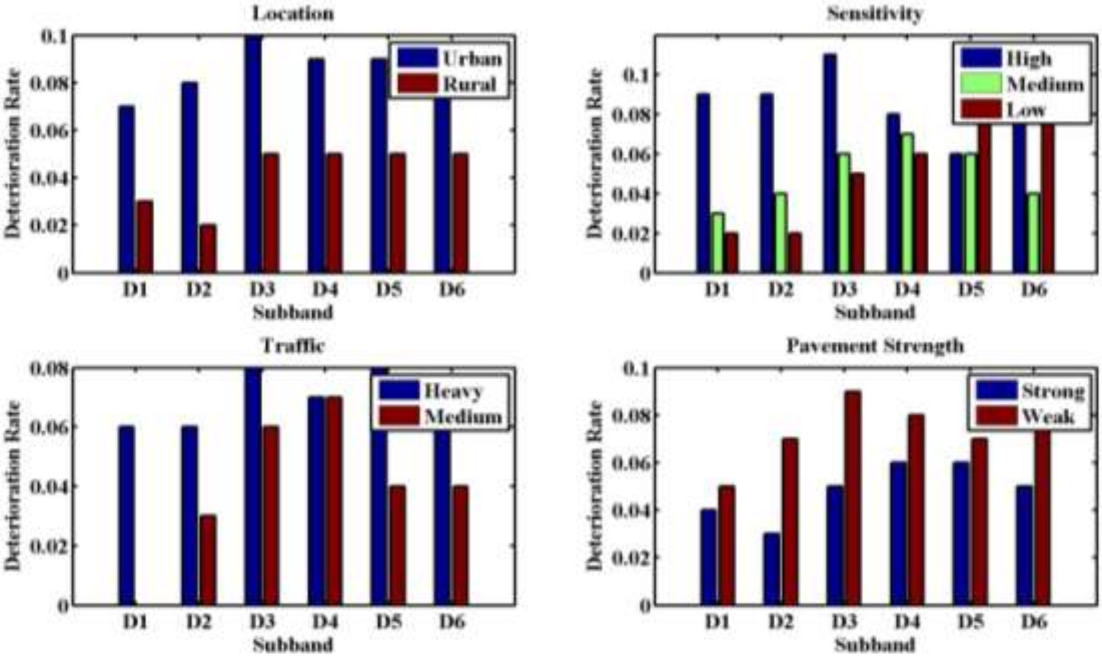
In general, there were only weak correlations between both the left and right wheelpath sub-band energy levels and all the factors contained within the matrix. The only factor that did show some potential relationship was the flushing in the right wheelpath and corresponding wavelength energy levels. Weaker correlation existed between the factors investigated and the annual roughness change expressed in the IRI.

6.3 Results based on the hypothesis testing

6.3.1 Local authority sections

The changes in energy for the respective sub-band energy levels were tested against the various factors to determine the potential relationship. Figure 6.1 illustrates the outcome for four factors used in the design matrix of the experiment including the urban/rural split, climatic sensitivity, traffic classification and pavement strength. Henning et al (2004) discussed the rationale behind the design matrix for both LTPP programmes.

Figure 6.1 Change in sub-band energy for different factors



Observations from figure 6.1included:

- The deterioration of the urban sections was much greater than that of the rural sections.
- Although not conclusive, it seemed the rural sections had the same deterioration pattern as the urban sections.
- The high-risk climatic regions deteriorated faster than the medium and low sensitivity areas. This observation was consistent with findings from other model development work (Henning et al 2006b).
- Heavy trafficked sections deteriorated faster than lower volume roads. The trend was most noticeable in the short (d1, d2) and long wavelength (d5, d6) spectra.
- Weaker pavements also deteriorated faster than stronger pavements.

The data mining technique made it possible to rank factors in terms of their sensitivity, and their ability to influence the outcome of the roughness deterioration within each sub-band energy level. Tables 6.1 and 6.2 show the sensitivity of each factor for both the urban and rural sections.

Table 6.1 Urban sections – sensitivity of factors on the roughness sub-band energy

Subband / Factor	Relative Effect on Subband Energy						
	D1	D2	D3	D4	D5	D6	
Climate	7	8	7	0	0	4	
Traffic	10	9	8	3	6	4	
Pavement	7	8	7	3	4	6	

- 0-2 very low
- 3-4 low
- 5-6 medium
- 7-8 strong
- 9-10 very strong

Table 6.2 Rural sections – sensitivity of factors on the roughness sub-band energy

Subband / Factor	Relative Effect on Subband Energy					
	D1	D2	D3	D4	D5	D6
Climate	10	6	6	6	4	6
Traffic	3	-2	-4	-2	2	2
Pavement	3	0	-2	-1	1	0

- 0-2 very low
- 3-4 low
- 5-6 medium
- 7-8 strong
- 9-10 very strong

Observations from these tables included:

- The most significant factor for the urban sections seemed to be the traffic volume.
- All the factors viewed for both urban and rural sections were more significant in the shorter wavelengths (d1 to d3).
- The most significant factors for rural sections seemed to be the climatic area.

Again, stronger trends were observed in urban sections than in rural sections. This was consistent with the observations from the correlation matrix outcomes.

Table 6.3 displays the significance of the respective factors on the wavelet sub-bands and IRI roughness. Observations from this table included:

- There were a number of factors that had a significant influence on some sub-band energy levels where the difference in IRI roughness was not significant.
- A number of factors had significance in the d1 and d2 sub-bands, while the IRI did not show significant differences for the same factors.
- The factor that was significant in most of the sub-bands was the urban/rural split.
- The pavement strength split did not show any significance at all.

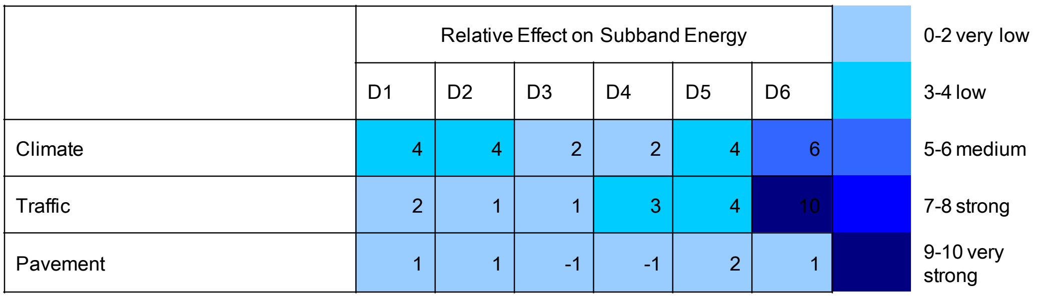
Table 6.3 Significance of trends for local authority LTPP

Sub-band		d1	d2	d3	d4	d5	d6	∆IRI
Urban vs rural	p value	0.22	0.09	0.08	0.02	0.05	0.08	0.1746
	conclusion	No	Yes	Yes	Yes	Yes	Yes	No
Sensitivity high vs medium	p value	0.10	0.29	0.30	0.80	0.93	0.03	0.7508
	conclusion	Yes	No	No	No	No	Yes	No
Sensitivity high vs low	p value	0.05	0.11	0.11	0.40	0.58	0.92	0.6786
	conclusion	Yes	No	No	No	No	No	No
Sensitivity medium vs low	p value	0.56	0.07	0.04	0.42	0.64	0.10	0.0087
	conclusion	No	Yes	Yes	No	No	Yes	Yes
Traffic high vs medium	p value	0.08	0.42	0.71	0.60	0.10	0.09	0.8844
	conclusion	Yes	No	No	No	No	Yes	No
Pavement strong vs weak	p value	0.74	0.27	0.20	0.18	0.56	0.15	0.6182
	conclusion	No	No	No	No	No	No	No

6.3.2 State highway sections

Table 6.4 ranks the factors that influenced roughness change within each respective sub-band. From this table it can be observed that, similar to local authority sections, the most significant factor was the traffic loading. For urban sections most of the change took place within the shorter wavelengths, while on the state highway sections, the changes took place within the longer wavelengths. These observations could possibly be explained by the vehicle dynamic at different speed environments. It was also noted that the climatic area sensitivity was most significant in the longer wavelengths, although this trend was inconclusive, and pavement strength had the least influence on the roughness deterioration.

Table 6.4 State highway sections – sensitivity of factors on the roughness wavelength energy



	Relative Effect on Subband Energy						
							0-2 very low
	D1	D2	D3	D4	D5	D6	3-4 low
Climate	4	4	2	2	4	6	5-6 medium
Traffic	2	1	1	3	4	10	7-8 strong
Pavement	1	1	-1	-1	2	1	9-10 very strong

Table 6.5 shows the significance of the various factors as a function of the respective sub-band wavelengths. Apart from the traffic loading, there was a limited number of factors that showed any significance. Furthermore the agreement between sub-band wavelength energy and the IRI was not consistent either. Little conclusive information could be made from the table, although there was some climatic classification (sensitivity) influence on the shorter wavelengths (d1 to d3).

Table 6.5 Significance of trends for state highway LTPP

Sub-band		d1	d2	d3	d4	d5	d6	Δ**IRI**
Sensitivity high vs medium	p value	0.03	0.01	0.08	0.16	0.35	0.42	0.0139
	conclusion	Yes	Yes	Yes	No	No	No	Yes
Sensitivity high vs low	p value	0.17	0.15	0.38	0.25	0.13	0.10	0.1742
	conclusion	No	No	No	No	No	No	No
Sensitivity medium vs low	p value	0.20	0.27	0.47	0.74	0.50	0.38	0.0845
	conclusion	No	No	No	No	No	No	Yes
Traffic high vs medium	p value	0.07	0.43	0.34	0.02	0.14	0.00	0.98
	conclusion	Yes	No	No	Yes	No	Yes	No
Pavement strong vs weak	p value	0.44	0.48	0.76	0.72	0.33	0.63	0.1347
	conclusion	No	No	No	No	No	No	No

6.4 Results from data mining

6.4.1 Local authority LTPP data

The main factors identified using data mining are presented in table 6.6. The strength of the respected factors was defined by the following measures:

- minimum support level (10%) – how frequently all of the items in a rule appeared in transactions
- minimum confidence level (20%) – how frequently the left-hand side of a rule implied the right-hand side.

Also note that the values indicated in the bracket presents the minimum values used in this research.

Table 6.6 Data mining result for local authority LTPP data

Sub-band		d1	d2	d3	d4	d5	d6
Single factor single	Factor			Heavy traffic	Heavy traffic	Climate low	Rural
	Support			21%	23%	22%	21%
	Confidence			78%	78%	36%	51%
Combined two factor results	Factors			Urban heavy traffic	Urban heavy traffic	Rural heavy traffic	Heavy traffic weak pavements
	Support			22%	22%	22%	20%
	Confidence			41%	41%	37%	41%
Combined three factor results	Factors			Rural climate (low) heavy traffic	Rural climate (low) heavy traffic	Rural heavy traffic weak pavements	Rural heavy traffic weak pavements
	Support			21%	21%	14%	35%
	Confidence			23%	28%	21%	55%

Note: Empty cells contained factors of lower support and confidence levels not reported here.

Observations from this table included:

- Only the longer wavelengths d3 to d6 displayed strong trends with the factors tested.
- Heavy traffic appeared the most as a dominant factor, including where more than one factor was tested.
- Heavy traffic and weak pavements were the combined factors that appeared most; also it seemed this trend was the strongest on the rural network.

6.4.2 State highway LTPP data

Table 6.7 reflects the data mining results for the state highway sections.

Table 6.7 Data mining results for state highway LTPP data

Sub-band		d1	d2	d3	d4	d5	d6
Single factor single	Factor				Climate (medium)	Weak pavements	Heavy traffic
	Support				22%	28%	35%
	Confidence				27%	33%	55%
Combined two factor results	Factors				Climate (medium) medium traffic	Climate (high) weak pavements	Heavy traffic weak pavements
	Support				12%	14%	11%
	Confidence				32%	34%	67%
Combined three factor results	Factors					Climate (low) heavy traffic weak pavements	Climate (low) heavy traffic weak pavements
	Support					12%	10%
	Confidence					29%	67%

Observations from this table included:

- The longer wavelengths showed potential relationship with the factors investigated.
- Climate was the factor repeated the most.
- Climate, heavy traffic and weak pavements were the combined factors that appeared the most.

The results from the data mining yielded expected results that were consistent with the other testing methods.

6.5 Discussion of results

The outcome from the factor analysis was that the wavelength energy was indeed able to highlight factors that influenced the profile changes over time. It was able to highlight the difference in impact from functional factors such as traffic loading and pavement strength, and the environmental impact on roughness changes over time. The methods were inconsistent in defining where the impacting factors had the most significant influence. The hypothesis testing suggested most factors influenced the shorter wavelength sub-bands, whereas the data mining indicated the most significant trends were in the longer wavelengths.

When considering whether one technique is more appropriate than another, one has to realise that each method has its strengths, and depending on the purpose of the analysis each has unique outcomes that could be useful. In general the following points were identified in this chapter:

The correlation matrices gave the poorest result in terms of establishing significant factors that influenced roughness deterioration for different sub-band energy levels. Most of the potential relationships not effectively identified by this technique would be non-linear. However, correlation matrices remained effective in identifying cross-correlation between independent factors.

The hypothesis testing gave useful results and it was especially useful in determining whether an apparent relationship between two factors was statistically significant or not.

Data mining gave the most useful results as it was able to test second and third order combined effects. For example it was encouraging to notice that the combined effect of heavy traffic and weak pavements had a strong combined effect on roughness deterioration. Many combined effects correlated with intuitively expected impact factors.

7 Roughness change for different failure mechanisms

7.1 Purpose of the analysis

Ultimately, one of the primary applications of performance indicators, such as roughness, is to assist in monitoring and reporting on the road condition and using this information as an input to a maintenance decision process. It is in this area, in particular, that the IRI measuring limitations are noticed. The IRI works well in determining road user costs and it is also effective as a condition performance measure on networks in developing countries where a significant IRI variance is observed. However, on most of the New Zealand network IRI variation is relatively minor and therefore the effectiveness of roughness as a condition performance measure is lost.

However, as already shown in this report, the longitudinal profile energy spectra does show significant change, when there is no corresponding change in the IRI. The wavelength sub-band energy showed promising results in both roughness deterioration trend monitoring, and in identifying factors that contribute towards roughness deterioration.

Therefore it is now pertinent to consider whether roughness based on wavelength energy levels could also be used to identify maintenance needs and/or as a post-construction quality control measure. This chapter presents some of the results obtained from this research.

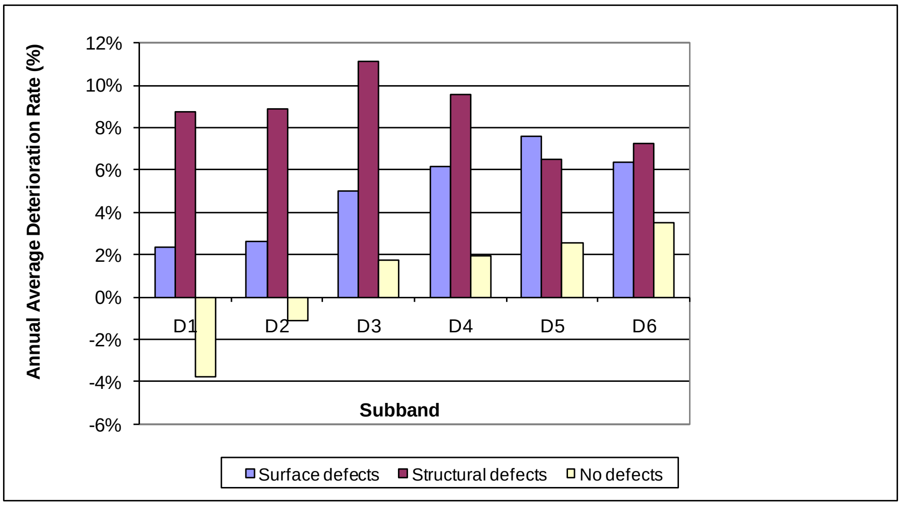
7.2 Comparing roughness change with known failure

Based on the categorisation discussed in chapter 4 the LTPP data was classified into three failure states (no defect, surface or structural). This classification was used to investigate the deterioration within each sub-band and the outcome is depicted in figure 7.1.

Some significant observations from this figure included:

- The three different failure mechanisms followed completely different patterns for the respective wavelength distributions.
- New sections or stable sections (no visible defect) showed a wavelength energy reduction for the short wavelengths (d1 and d2 or <2m). It is suspected that this trend was mostly influenced by the change in texture during the earlier years of pavement and surface life. Furthermore, initial densification due to traffic loading, takes place in the first couple of years after construction. This densification also leads to a smoothing action of the pavement surface. This also explains network trends that indicated an initial reduction in roughness on new and rehabilitated sections.
- Sections displaying structural defects mostly resulted in roughness changes in the shorter wavelengths (d1 to d3).
- Sections displaying surface defects had more effect on the long wavelength spectra (d3 to d6), although this trend was not observed in all sections.

Figure 7.1 Deterioration patterns for different failure mechanism states



The results depicted in figure 7.1 potentially have promising applications and should be explored further. For example, if these patterns applied to all typical New Zealand roads, they could be used as an indicator for the structural integrity of pavements. It is therefore recommended that this concept is tested further on network level data. The trends do match current roughness deterioration theory:

- Initial densification of flexible pavements and re-orientation of chips of thin chip seals have an expected roughness reduction during the initial years following construction. Given the nature of these changes most of the reduction would take place in the short wavelengths rather than in the longer wavelengths.
- For most of the stable phase of pavement deterioration a slow increase in roughness is expected in the longer wavelengths. The pre-dominant factors for this roughness increase would be caused by environmental impacts.
- Lastly, one of the signs of advanced pavement deterioration is a significant variation in support from both the subgrade and the pavement layers. These variations are noticed in falling weight deflectometer (FWD) tests. Therefore, a significant relative increase in roughness for the shorter wavelength sub-band would be more evident during these stages of deterioration.

7.3 Maintenance effects

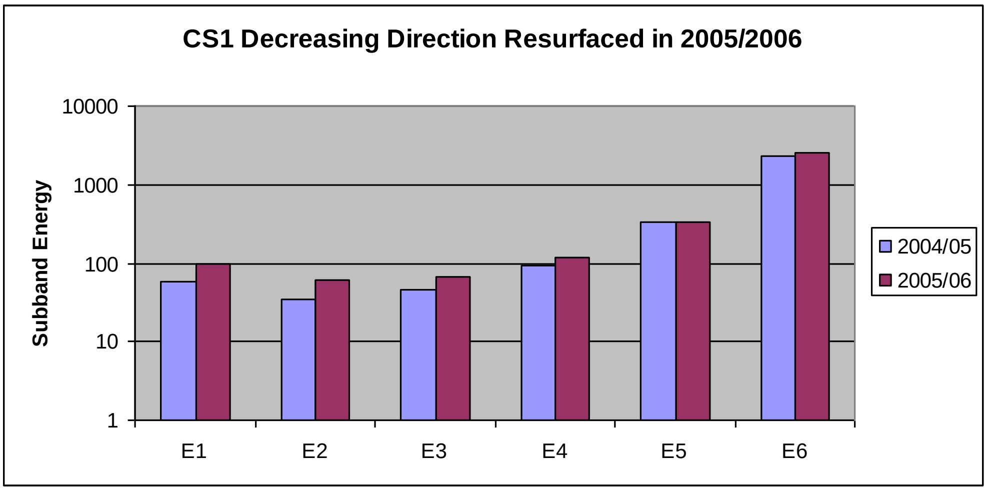
Maintenance effect is defined as the direct outcome or impact as a result of different maintenance activities. Maintenance effects have two separate impacts on pavements: first there is an immediate effect directly after the maintenance activity is completed (ie directly before and after). The second impact refers to the subsequent performance following the maintenance activity. For example, with significant strengthening treatments it is expected the pavement will deteriorate at a slower rate after maintenance compared with the rate of deterioration prior to maintenance. This section will only report on the sub-band energy changes directly after maintenance actions were applied on the pavements.

7.3.1 Impact as a result of resurfacing

As expected, resurfacing has had a small influence on the roughness. It was expected that resurfacing with larger chips might have an influence on the short wavelength initially after construction but as the chip bedded down only minor differences would exist.

Figure 7.2 illustrates a typical example of the change in roughness directly before and after a resurfacing treatment. An increase in the d1–d3 sub-band energies was observed.

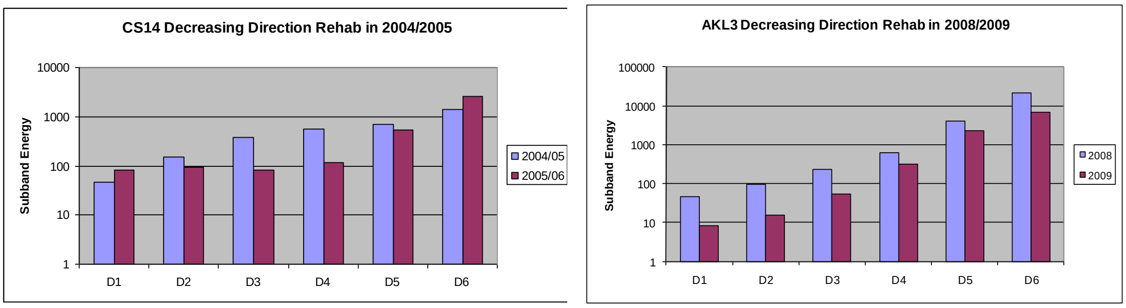
Figure 7.2 Influence of resurfacing on the sub-band energy



7.3.2 Impact as a result of rehabilitation

Other studies such as Paterson (1987) suggest that the impact of maintenance treatments is a function of the condition prevailing prior to undertaking the maintenance. This was confirmed with results from this research. Figure 7.3 shows that rehabilitation on rural chip seal pavements mostly addressed the sub-band energy levels for the mid-spectrum ranges. Rehabilitation on asphalt surface roads suggested a reduction in roughness for all sub-band energy levels (note that AKL3 was a chip sealed pavement upgraded to an asphalt surface after rehabilitation). Although more research is required in this area, it can be concluded that the sub-band energy level studies conveyed more information regarding the impact of maintenance treatments. It can therefore be assumed that this performance measure would be more effective as a post-construction monitoring tool than the IRI measurement for roughness. It also has promising applications for post-construction quality control as the wavelength sub-band energy differences gave far more detail on the profile change compared with an aggregated index such as the IRI.

Figure 7.3 Influence of rehabilitation on the sub-band energy



Rehabilitation on chip seal road

Rehabilitation on asphalt surface road

8 Conclusions and recommendations

8.1 Discussions of main findings

8.1.1 Literature review

The literature review determined that more information was needed to define the mode of roughness deterioration for different types of roads. This information would assist road controlling authorities to predict the roughness progression more accurately, and facilitate their ability to generate better forward work programmes and carry out proper maintenance actions so that a safer and smoother road network could be provided to the public.

A study of the wavelength content of the roughness profile could provide this vital information by identifying factors that contribute to the deterioration of road roughness and by providing a better understanding of the mechanisms that drive pavement deterioration.

8.1.2 Site classification

A site classification was undertaken as an input to the wavelength analysis, with the primary objective of understanding the main failure mechanisms occurring on the sites.

The site classification process demonstrated the following:

- There was good agreement between observed changes on the road and the change in energy spectra expected to influence or result from these changes.
- The IRI was most influenced by the short and medium wavelength roughness; changes in the short and medium wavelength spectra had a corresponding change in the IRI and were the only wavelength energy spectra that could be seen to have a direct correlation with changes in the IRI.
- Long wavelength spectra energy did change over time; this was more obvious on the state highway and local authority sites with high traffic volumes and heavy vehicles (Auckland and surrounds).
- There was no obvious visible distress that could be attributed to the changes in long wavelength energy spectra or evidence on the calibration sites that could be used to identify this occurrence.
- A significant portion of sites had little or no visible change in their condition, while some of these had changes in the long wavelength energy spectra.
- Maintenance undertaken on the sites was often reflected as an increase in the medium wavelength energy spectra and an increase in the IRI.

The visual review process showed it was possible to see a change in energy spectra when a particular distress occurred. The next step will be to identify a change in sub-band energy which indicates a distress is likely to occur.

8.1.3 Analyses outcomes for roughness changes over time

The results from the extensive statistical and data mining analysis suggested that the wavelength sub-band energy level was an effective measure to describe roughness changes over time.

The most significant observation was that the deterioration behaviour between local authority and state highway sections was markedly different. This was not obvious using the IRI as a performance indicator.

Local authority sections had similar changes for sub-bands d3 to d6, while sub-bands d3 and d4 had the most significant change. State highway section changes increased with increasing wavelength from sub-band d2 to d6. The longer wavelengths, d5 and d6, accounted for the majority of the changes.

It was observed that the rate of change in the energy spectra for both LTPP programmes was also significantly different. The local authority sections had a high proportion of mid-range change, while the state highway sections had a more uniform change across the categories examined. This compared to an expected annual roughness change of 0.03IRI, typical of the New Zealand network and equated to 1% annual change. It was clear the IRI masked some of the profile change occurring over time.

These findings suggested the deterioration in roughness would be similar for the longer wavelengths d5 and d6. However for the shorter wavelengths, typically the ones that were captured in the IRI calculations, there was a significant difference in performance between urban and rural sections.

8.1.4 Analyses outcomes for factors influencing roughness progression

Further analysis was undertaken to investigate factors that contributed to roughness and the progression of roughness over time. Factors considered were those formulated in the development of the LTPP experimental design matrix: environmental; location and sensitivity, or load deterioration; and traffic and strength. One of the main objectives of the research was to investigate the identification of load associated roughness progression and environmental progression. The relationship between roughness and other defects and how to identify design/construction or maintenance issues based on the information gained was also considered.

Three different statistical techniques were used for this investigation including: data mining, correlation analysis and hypothesis testing. The outcomes from all three of these methods were consistent although it was accepted that detailed results might vary slightly between the methods.

It was observed that the trends were much stronger on the local authority network than on the state highway network. The reason for this phenomenon is not completely understood other than noting the deterioration between the two networks was completely different. However, it is likely the state highway had other factors influencing roughness progression from the ones tested.

Some encouraging results were obtained from these sections, with the influence of traffic loading, pavement strength and environmental classification being identified as contributors to roughness decay. With these factors established, it was considered that the development of a roughness progression model based on wavelength energy would be more feasible than attempting to build a prediction model based on the IRI definition.

8.1.5 Analysis outcome for failure mechanisms and maintenance practices

The most promising result from the research was the identification of a potential pattern of failure mechanisms, and therefore of the stages of road deterioration, through the wavelength energy change over time. For example, as a road progresses from being new to a stage where it has surface defects, and then ultimately to a stage of pavement associated failures, the wavelength energy distribution changes. If this result could be replicated on network data it would have tremendous application potential. This would allow for performance monitoring of road networks based on roughness data and illustrate the percentage of the overall network that was failing on surface-related issues versus the portion of the network showing advanced deterioration in pavement structure.

Lastly, the wavelength energy changes for maintenance activities were also investigated. Apart from this analysis giving completely expected results for both resurfacing and rehabilitation, it demonstrated the potential of using wavelength analysis of roughness data as a quality assurance tool for rehabilitation construction.

8.2 Implications of current data collection, processing and management

The results from this research indicate that the decomposition of the longitudinal profile using wavelet analysis methodology provides additional information which can be used to define the deterioration process occurring within pavements – information that is not available in the current IRI.

The analysis software has been developed into a simple executable package and could be utilised by researchers and pavement engineers to enhance their understanding of the deterioration process.

Even though data has been collected for eight years on the calibration sites it is evident there are sites which have changed very little and some which have changed significantly. Clearly the data collection process should continue to better define the modes of deterioration when all the LTPP sites display deterioration.

Although this research has highlighted some issues needing further investigation, it is recommended to start trialling this approach on network data. The implications of this would be:

- The high-speed data collection operators or clients need to start undertaking wavelength energy transformation of roughness profiles.
- Provision has to be made within road asset management databases to include these additional roughness measures.
- On confirmation of network reporting feasibility, a framework for the performance reporting needs to be developed.

8.3 Recommendations for further work

Recommended further work on this topic matter is summarised in table 8.1.

Table 8.1 Summary of further work on roughness wavelength energy utilisation

Items	Description	Data and resource considerations
Test findings on network pilot data	Although part of the research deliverables included a process of linking LTPP data to network trend data, it is still believed that the process needs to be tested on the network data.	To apply it to network data using a small sample such as a maintenance area.
State highway vs local authority results	Investigate factors leading to different results between state highway and local authority networks	Based further research on a combination of LTPP and network data
Link this research finding with strength research	Some research has been undertaken that aimed at better understanding pavement strength. Replicating some of the results in this research should be undertaken using new strength indices	This work can be undertaken only using LTPP data.
Confirm failure mode patterns	Some further analysis would be required. Attempt to replicate this research results	Sample of network data where failure modes are known

Items	Description	Data and resource considerations
	identifying failure patterns on network data	
Quantify the implications of the change in long wavelength energy on roughness	One approach could be to instrument a truck to measure vehicle response on a selection of sites with different long wavelength energy. Alternatively, as the long wavelength energy level is thought to be related to pavement base strength, measure pavement strength at the same selected sites to see if a relationship between the high long wavelength energy and the base strength can be defined.	Combination of LTPP and network data
Commence roughness progression model development	Sufficient evidence exists to suggest developing a roughness deterioration model based on wavelength would be feasible.	LTPP and network data

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Appendix A: Correlation matrices for LTPP sections

Table A.1 Correlation matrix for local authority LTPP

	AADT	pc_heavy	SNP	Deflectio	AGE2	PaveWidt	Avg_LWP_	Avg_RWP_	Avg_LWP_	Avg_RWP_	SIRutting	SIRoughne	SIFlexure	SIShear	AIWT.N	Flush.Mid	Flush.Hig	Sensitivity
AADT	⇧ 1	⇨ -0.215	⇧ 0.7061	⇩ -0.449	⇨ -0.094	⇧ 0.8236	⇨ -0.15	⇨ -0.101	⇨ -0.167	⇨ -0.008	⇧ 0.637	⇧ 0.5301	⇧ 0.6253	⇧ 0.6548	⇨ 0.0019	⇩ -0.338	⇨ -0.169	⇨ 0.0059
pc_heavy	⇨ -0.215	⇧ 1	⇨ -0.248	⇨ -0.044	⇨ 0.0392	⇩ -0.319	⇨ 0.1879	⇨ 0.1107	⇨ 0.0159	⇨ 0.0219	⇨ -0.135	⇨ -0.005	⇩ -0.348	⇨ -0.148	⇨ -0.115	⇨ 0.2091	⇨ 0.0159	⇩ -0.39
SNP	⇧ 0.7061	⇨ -0.248	⇧ 1	⇩ -0.819	⇨ -0.255	⇧ 0.6744	⇨ -0.047	⇨ 0.0097	⇨ 0.0374	⇨ 0.1992	⇧ 0.9214	⇧ 0.8529	⇧ 0.8777	⇧ 0.8178	⇨ 0.0729	⇩ -0.359	⇨ -0.293	⇨ -0.185
Deflection_0	⇩ -0.449	⇨ -0.044	⇩ -0.819	⇧ 1	⇨ 0.2607	⇩ -0.517	⇨ -0.026	⇨ -0.106	⇨ -0.188	⇩ -0.367	⇩ -0.841	⇩ -0.937	⇩ -0.705	⇩ -0.757	⇨ -0.099	⇨ 0.2036	⇨ 0.3089	⇧ 0.4103
AGE2	⇨ -0.094	⇨ 0.0392	⇨ -0.255	⇨ 0.2607	⇧ 1	⇨ -5E-04	⇨ 0.1099	⇩ -0.349	⇨ 0.1516	⇨ -0.116	⇨ -0.189	⇨ -0.203	⇨ -0.283	⇨ -0.125	⇨ 0.2099	⇨ -0.083	⇨ 0.1356	⇨ 0.0958
PaveWidth	⇧ 0.8236	⇩ -0.319	⇧ 0.6744	⇩ -0.517	⇨ -5E-04	⇧ 1	⇨ -0.094	⇨ -0.066	⇨ -0.032	⇨ 0.2787	⇧ 0.6481	⇧ 0.5733	⇧ 0.7007	⇧ 0.7187	⇨ 0.0296	⇩ -0.451	⇨ -0.291	⇨ 0.1513
Avg_LWP_rut.yr	⇨ -0.15	⇨ 0.1879	⇨ -0.047	⇨ -0.026	⇨ 0.1099	⇨ -0.094	⇧ 1	⇧ 0.6281	⇧ 0.6319	⇨ 0.2654	⇨ 0.0645	⇨ 0.0882	⇨ -0.044	⇨ -0.086	⇨ -0.07	⇨ -0.158	⇨ -0.037	⇨ -0.184
Avg_RWP_rut.yr	⇨ -0.101	⇨ 0.1107	⇨ 0.0097	⇨ -0.106	⇩ -0.349	⇨ -0.066	⇧ 0.6281	⇧ 1	⇨ 0.2378	⇨ 0.2972	⇨ 0.0952	⇨ 0.1461	⇨ 0.0188	⇨ -0.005	⇨ -0.002	⇨ -0.04	⇨ -0.07	⇨ -0.166
Avg_LWP_IRI.yr	⇨ -0.167	⇨ 0.0159	⇨ 0.0374	⇨ -0.188	⇨ 0.1516	⇨ -0.032	⇧ 0.6319	⇨ 0.2378	⇧ 1	⇧ 0.4954	⇨ 0.0892	⇨ 0.1611	⇨ 0.0418	⇨ 0.0592	⇨ 0.0391	⇨ -0.107	⇨ -0.079	⇨ -0.154
Avg_RWP_IRI.yr	⇨ -0.008	⇨ 0.0219	⇨ 0.1992	⇩ -0.367	⇨ -0.116	⇨ 0.2787	⇨ 0.2654	⇨ 0.2972	⇧ 0.4954	⇧ 1	⇨ 0.2016	⇨ 0.298	⇨ 0.2898	⇨ 0.3289	⇨ 0.2743	⇨ -0.028	⇨ -0.142	⇨ -0.086
LWP_d1	⇨ -0.101	⇨ -0.047	⇨ 0.005	⇨ -0.091	⇨ 0.2287	⇨ -0.017	⇧ 0.4897	⇨ 0.1288	⇧ 0.8862	⇨ 0.2725	⇨ 0.0125	⇨ 0.0673	⇨ 0.0081	⇨ -0.01	⇨ 0.0075	⇨ -0.115	⇨ -0.078	⇨ -0.048
LWP_d2	⇨ -0.08	⇨ -0.042	⇨ 0.0213	⇨ -0.099	⇨ 0.2329	⇨ -0.002	⇧ 0.4836	⇨ 0.0996	⇧ 0.8908	⇨ 0.2361	⇨ 0.0343	⇨ 0.0802	⇨ 0.0137	⇨ -0.007	⇨ 0.009	⇨ -0.151	⇨ -0.066	⇨ -0.047
LWP_d3	⇨ -0.077	⇨ -0.03	⇨ 0.0372	⇨ -0.111	⇨ 0.2264	⇨ -0.029	⇧ 0.5373	⇨ 0.1459	⇧ 0.8895	⇨ 0.2108	⇨ 0.0463	⇨ 0.0922	⇨ 0.0042	⇨ -0.023	⇨ 0.0373	⇨ -0.137	⇨ -0.045	⇨ -0.074
LWP_d4	⇨ 0.049	⇨ 0.058	⇨ 0.1234	⇨ -0.17	⇨ 0.1418	⇨ 0.0729	⇧ 0.7561	⇧ 0.3823	⇧ 0.7922	⇨ 0.1962	⇨ 0.1612	⇨ 0.1908	⇨ 0.0743	⇨ 0.0155	⇨ -0.013	⇨ -0.178	⇨ -0.072	⇨ -0.163
LWP_d5	⇨ -0.044	⇨ 0.1017	⇨ -0.027	⇨ -0.035	⇨ 0.277	⇨ -0.073	⇧ 0.5774	⇨ 0.2183	⇧ 0.7604	⇨ 0.157	⇨ 0.0044	⇨ 0.0464	⇨ -0.077	⇨ -0.081	⇨ 0.2459	⇨ -0.027	⇨ -0.026	⇨ -0.15
LWP_d6	⇨ 0.0627	⇨ 0.1339	⇨ 0.0482	⇨ -0.167	⇨ 0.1301	⇨ 0.1148	⇨ 0.2319	⇨ 0.2469	⇨ 0.2349	⇨ 0.0897	⇨ 0.1041	⇨ 0.1631	⇨ 0.0292	⇨ 0.1491	⇨ 0.0014	⇨ 0.0063	⇨ -0.054	⇩ -0.343
LWP_max	⇨ -0.026	⇨ -0.02	⇨ 0.0603	⇨ -0.13	⇨ 0.2373	⇨ 0.0344	⇧ 0.5278	⇨ 0.1581	⇧ 0.8788	⇨ 0.2332	⇨ 0.068	⇨ 0.1178	⇨ 0.0362	⇨ 0.0112	⇨ 0.0251	⇨ -0.14	⇨ -0.068	⇨ -0.105
RWP_d1	⇨ 0.2035	⇨ -0.026	⇨ 0.193	⇨ -0.191	⇨ 0.0541	⇨ 0.2845	⇨ 0.2172	⇨ 0.2483	⇨ 0.2522	⇧ 0.567	⇨ 0.1219	⇨ 0.1688	⇨ 0.2808	⇨ 0.2795	⇨ 0.2858	⇨ -0.057	⇨ -0.153	⇨ -0.086
RWP_d2	⇨ 0.2381	⇨ -0.037	⇨ 0.2462	⇨ -0.222	⇨ 0.1883	⇨ 0.3221	⇨ 0.2084	⇨ 0.1482	⇧ 0.3839	⇧ 0.568	⇨ 0.1636	⇨ 0.1953	⇨ 0.3116	⇨ 0.2752	⇧ 0.6211	⇨ -0.216	⇨ -0.162	⇨ -0.005
RWP_d3	⇨ 0.0343	⇨ -0.038	⇨ 0.0104	⇨ 0.0277	⇨ 0.1012	⇨ 0.0976	⇨ 0.0855	⇨ 0.1193	⇨ 0.2293	⇧ 0.5249	⇨ -0.051	⇨ -0.043	⇨ 0.109	⇨ 0.1189	⇨ 0.3013	⇨ 0.0095	⇨ -0.127	⇨ 0.1219
RWP_d4	⇨ 0.1276	⇨ 0.0573	⇨ 0.1258	⇨ -0.173	⇨ -0.168	⇨ 0.1119	⇨ 0.1454	⇧ 0.3716	⇨ 0.1949	⇨ 0.3555	⇨ 0.1041	⇨ 0.171	⇨ 0.2046	⇨ 0.1848	⇨ 0.2313	⇨ 0.1669	⇨ -0.088	⇨ -0.118
RWP_d5	⇨ 0.2719	⇨ 0.046	⇨ 0.1297	⇨ -0.074	⇨ -0.108	⇨ 0.2076	⇨ 0.0329	⇨ 0.1496	⇨ -0.037	⇨ 0.1416	⇨ 0.0673	⇨ 0.0975	⇨ 0.1435	⇨ 0.0848	⇨ -0.005	⇨ 0.2135	⇨ -0.096	⇨ -0.191
RWP_d6	⇨ 0.0452	⇨ 0.0706	⇨ -0.045	⇨ 0.0365	⇨ -0.118	⇨ -0.062	⇨ -0.148	⇨ 0.0789	⇨ -0.207	⇨ -0.192	⇨ -0.057	⇨ -0.014	⇨ -0.059	⇨ -0.082	⇨ 0.0051	⇨ 0.2394	⇨ -0.002	⇨ -0.133
RWP_max	⇨ 0.0818	⇨ -0.017	⇨ 0.0159	⇨ -0.006	⇨ -0.03	⇨ 0.0138	⇨ 0.0026	⇨ 0.1756	⇨ -0.025	⇨ 0.0962	⇨ -0.026	⇨ 0.0238	⇨ 0.022	⇨ -0.006	⇨ 0.2055	⇨ 0.2073	⇨ -0.093	⇨ -0.136
SIRutting	⇧ 0.637	⇨ -0.135	⇧ 0.9214	⇩ -0.841	⇨ -0.189	⇧ 0.6481	⇨ 0.0645	⇨ 0.0952	⇨ 0.0892	⇨ 0.2016	⇧ 1	⇧ 0.9503	⇧ 0.8015	⇧ 0.7988	⇨ 0.0409	⇩ -0.373	⇩ -0.308	⇨ -0.207
SIRoughness	⇧ 0.5301	⇨ -0.005	⇧ 0.8529	⇩ -0.937	⇨ -0.203	⇧ 0.5733	⇨ 0.0882	⇨ 0.1461	⇨ 0.1611	⇨ 0.298	⇧ 0.9503	⇧ 1	⇧ 0.7252	⇧ 0.7462	⇨ 0.0714	⇨ -0.296	⇨ -0.28	⇩ -0.363
SIFlexure	⇧ 0.6253	⇩ -0.348	⇧ 0.8777	⇩ -0.705	⇨ -0.283	⇧ 0.7007	⇨ -0.044	⇨ 0.0188	⇨ 0.0418	⇨ 0.2898	⇧ 0.8015	⇧ 0.7252	⇧ 1	⇧ 0.8457	⇨ 0.0516	⇩ -0.365	⇨ -0.296	⇨ -0.004
SIShear	⇧ 0.6548	⇨ -0.148	⇧ 0.8178	⇩ -0.757	⇨ -0.125	⇧ 0.7187	⇨ -0.086	⇨ -0.005	⇨ 0.0592	⇨ 0.3289	⇧ 0.7988	⇧ 0.7462	⇧ 0.8457	⇧ 1	⇨ 0.0196	⇩ -0.299	⇩ -0.35	⇨ -0.101
AIWT.N	⇨ 0.0019	⇨ -0.115	⇨ 0.0729	⇨ -0.099	⇨ 0.2099	⇨ 0.0296	⇨ -0.07	⇨ -0.002	⇨ 0.0391	⇨ 0.2743	⇨ 0.0409	⇨ 0.0714	⇨ 0.0516	⇨ 0.0196	⇧ 1	⇨ -0.112	⇨ -0.047	⇨ -0.007
Flush.Mid	⇩ -0.338	⇨ 0.2091	⇩ -0.359	⇨ 0.2036	⇨ -0.083	⇩ -0.451	⇨ -0.158	⇨ -0.04	⇨ -0.107	⇨ -0.028	⇩ -0.373	⇨ -0.296	⇩ -0.365	⇩ -0.299	⇨ -0.112	⇧ 1	⇧ 0.4822	⇨ -0.094
Flush.High	⇨ -0.169	⇨ 0.0159	⇨ -0.293	⇨ 0.3089	⇨ 0.1356	⇨ -0.291	⇨ -0.037	⇨ -0.07	⇨ -0.079	⇨ -0.142	⇩ -0.308	⇨ -0.28	⇨ -0.296	⇩ -0.35	⇨ -0.047	⇧ 0.4822	⇧ 1	⇨ -0.006
Sensitivity	⇨ 0.0059	⇩ -0.39	⇨ -0.185	⇧ 0.4103	⇨ 0.0958	⇨ 0.1513	⇨ -0.184	⇨ -0.166	⇨ -0.154	⇨ -0.086	⇨ -0.207	⇩ -0.363	⇨ -0.004	⇨ -0.101	⇨ -0.007	⇨ -0.094	⇨ -0.006	⇧ 1

Table A.2 Correlation matrix for state highway LTPP

	TMS_AAD	Total_pc_	BackAnaly	AGE2	PaveWidt	Avg_LWP_	Avg_RWP_	Avg_LWP_	Avg_RWP_	SIRutting	SIRoughne	SIFlexure	SIShear	AlWT.N	Flush.Mid	Flush.Hig	Sensitivity
TMS_AADT	⇧ 1	⇩ -0.17	⇨ 0.4499	⇩ -0.017	⇨ 0.4213	⇩ -0.147	⇨ 0.0634	⇩ 0.0123	⇨ 0.0613	⇨ 0.3549	⇧ 0.5302	⇨ 0.3605	⇨ 0.4079	⇨ 0.0727	⇩ -0.162	⇩ -0.049	⇩ -0.053
Total_pc_heavy	⇩ -0.17	⇧ 1	⇩ -0.007	⇨ 0.3024	⇩ -0.055	⇨ 0.1005	⇩ -0.114	⇨ 0.0795	⇨ 0.0681	⇨ 0.0554	⇨ 0.1546	⇩ -0.276	⇩ -0.451	⇩ -0.15	⇨ 0.2451	⇩ -0.162	⇨ 0.1728
BackAnalysedSNP_Average	⇨ 0.4499	⇩ -0.007	⇧ 1	⇩ 0.0189	⇨ 0.193	⇩ -0.262	⇩ -8E-04	⇩ -0.153	⇩ -0.07	⇧ 0.801	⇧ 0.7271	⇨ 0.2721	⇨ 0.2072	⇩ -0.005	⇩ -0.232	⇩ -0.09	⇨ 0.0693
AGE2	⇩ -0.017	⇨ 0.3024	⇩ 0.0189	⇧ 1	⇩ -0.086	⇨ 0.0868	⇩ -0.086	⇨ 0.1111	⇨ 0.143	⇨ 0.158	⇨ 0.2317	⇩ -0.102	⇩ -0.31	⇨ 0.1769	⇨ 0.1909	⇩ -0.193	⇨ 0.2657
PaveWidth	⇨ 0.4213	⇩ -0.055	⇨ 0.193	⇩ -0.086	⇧ 1	⇩ -0.021	⇨ 0.1811	⇨ 0.1955	⇨ 0.1601	⇨ 0.1168	⇨ 0.1244	⇨ 0.0818	⇨ 0.1913	⇩ -0.023	⇩ -0.02	⇨ 0.3284	⇨ 0.1051
Avg_LWP_RUT.yr	⇩ -0.147	⇨ 0.1005	⇩ -0.262	⇨ 0.0868	⇩ -0.021	⇧ 1	⇨ 0.375	⇨ 0.0464	⇨ 0.089	⇩ -0.211	⇩ -0.091	⇩ -0.214	⇨ 0.0452	⇨ 0.1606	⇩ -0.105	⇩ -0.176	⇩ -0.192
Avg_RWP_RUT.yr	⇨ 0.0634	⇩ -0.114	⇩ -8E-04	⇩ -0.086	⇨ 0.1811	⇨ 0.375	⇧ 1	⇨ 0.1598	⇨ 0.1188	⇩ -0.072	⇩ -0.018	⇩ -0.127	⇨ 0.1981	⇩ -0.055	⇩ -0.267	⇩ -0.106	⇩ -0.061
Avg_LWP_IRI_yr	⇩ 0.0123	⇨ 0.0795	⇩ -0.153	⇨ 0.1111	⇨ 0.1955	⇨ 0.0464	⇨ 0.1598	⇧ 1	⇧ 0.8757	⇩ -0.046	⇩ -0.041	⇩ -0.169	⇩ -0.157	⇨ 0.0681	⇨ 0.1391	⇨ 0.1054	⇨ 0.061
Avg_RWP_IRI_yr	⇨ 0.0613	⇨ 0.0681	⇩ -0.07	⇨ 0.143	⇨ 0.1601	⇨ 0.089	⇨ 0.1188	⇧ 0.8757	⇧ 1	⇨ 0.048	⇨ 0.0376	⇩ -0.042	⇩ -0.08	⇨ 0.0306	⇨ 0.079	⇨ 0.0712	⇨ 0.0784
LWP_d1	⇨ 0.1049	⇩ -0.029	⇨ 0.0515	⇨ 0.0892	⇨ 0.0984	⇩ -0.041	⇨ 0.2198	⇨ 0.3959	⇨ 0.2923	⇨ 0.2212	⇨ 0.2393	⇩ -0.217	⇨ 0.1664	⇨ 0.0346	⇩ -0.156	⇩ -0.026	⇨ 0.1174
LWP_d2	⇨ 0.0857	⇩ -0.021	⇩ 0.021	⇨ 0.0595	⇨ 0.1649	⇩ 0.0133	⇨ 0.154	⇨ 0.4472	⇨ 0.3394	⇨ 0.1452	⇨ 0.1828	⇩ -0.267	⇨ 0.0821	⇨ 0.0637	⇩ -0.111	⇩ -0.008	⇨ 0.0636
LWP_d3	⇨ 0.0382	⇩ -0.062	⇩ -0.062	⇨ 0.0508	⇨ 0.1611	⇩ -0.015	⇨ 0.1917	⇧ 0.6016	⇨ 0.3837	⇩ 0.0195	⇨ 0.0426	⇩ -0.273	⇩ 0.0041	⇨ 0.141	⇩ -0.005	⇨ 0.0426	⇩ 0.0014
LWP_d4	⇨ 0.0511	⇩ -0.041	⇩ -0.085	⇩ -0.041	⇨ 0.1327	⇩ -0.091	⇨ 0.153	⇨ 0.4578	⇨ 0.3036	⇩ -0.02	⇨ 0.0363	⇩ -0.085	⇨ 0.1035	⇨ 0.098	⇩ -0.074	⇩ -0.037	⇩ 0.0188
LWP_d5	⇨ 0.0929	⇨ 0.0354	⇩ 0.0043	⇨ 0.1716	⇨ 0.2117	⇩ -0.122	⇨ 0.0821	⇨ 0.2822	⇨ 0.0845	⇨ 0.1717	⇨ 0.2275	⇩ -0.085	⇨ 0.1037	⇨ 0.1834	⇨ 0.0932	⇩ -0.012	⇨ 0.0742
LWP_d6	⇨ 0.2343	⇩ -0.043	⇨ 0.2236	⇨ 0.0812	⇨ 0.265	⇩ -0.027	⇩ 0.0274	⇨ 0.3108	⇨ 0.2902	⇨ 0.4027	⇨ 0.4023	⇩ -0.196	⇨ 0.0655	⇨ 0.2656	⇩ -0.074	⇨ 0.1177	⇨ 0.2149
LWP_max	⇨ 0.1141	⇩ 0.028	⇨ 0.049	⇨ 0.0824	⇨ 0.1545	⇩ -0.154	⇨ 0.142	⇨ 0.3159	⇨ 0.1076	⇨ 0.2303	⇨ 0.2822	⇩ -0.162	⇨ 0.1	⇨ 0.1586	⇩ -0.033	⇩ -0.005	⇨ 0.1639
RWP_d1	⇨ 0.1472	⇩ -0.008	⇨ 0.1084	⇨ 0.0677	⇨ 0.0431	⇩ -0.011	⇨ 0.1547	⇨ 0.1973	⇨ 0.3274	⇨ 0.3283	⇨ 0.3256	⇩ -0.149	⇨ 0.1978	⇩ 0.0146	⇩ -0.188	⇩ -0.005	⇨ 0.142
RWP_d2	⇨ 0.1646	⇩ -0.009	⇨ 0.1402	⇨ 0.1377	⇨ 0.0507	⇩ -0.041	⇨ 0.1547	⇨ 0.3709	⇨ 0.4892	⇨ 0.3481	⇨ 0.3365	⇩ -0.095	⇨ 0.1054	⇨ 0.0289	⇩ -0.216	⇩ -0.005	⇨ 0.1425
RWP_d3	⇨ 0.186	⇨ 0.0329	⇨ 0.0373	⇨ 0.1395	⇨ 0.0964	⇨ 0.0307	⇨ 0.2408	⇨ 0.4775	⇧ 0.5982	⇨ 0.2118	⇨ 0.2452	⇩ -0.154	⇩ -0.003	⇩ 0.013	⇩ -0.148	⇩ -0.029	⇩ 0.0179
RWP_d4	⇨ 0.3479	⇩ -0.06	⇨ 0.2407	⇨ 0.0356	⇨ 0.4066	⇩ -0.109	⇨ 0.2451	⇨ 0.4648	⇧ 0.5814	⇨ 0.2434	⇨ 0.2439	⇨ 0.0488	⇨ 0.1274	⇩ -0.004	⇩ -0.092	⇨ 0.1753	⇨ 0.1563
RWP_d5	⇨ 0.0661	⇩ -0.076	⇨ 0.1692	⇨ 0.0573	⇨ 0.467	⇩ -0.013	⇨ 0.2584	⇨ 0.29	⇨ 0.3405	⇨ 0.2028	⇨ 0.1192	⇨ 0.0935	⇨ 0.1487	⇩ -0.002	⇩ -0.005	⇨ 0.2281	⇨ 0.1428
RWP_d6	⇩ 0.0229	⇩ -0.006	⇩ 0.0081	⇩ 0.0122	⇩ -0.022	⇩ -0.012	⇨ 0.0763	⇨ 0.0723	⇨ 0.2263	⇨ 0.215	⇨ 0.1717	⇨ 0.1184	⇨ 0.1556	⇩ 0.0272	⇩ -0.148	⇩ -0.049	⇨ 0.1405
RWP_max	⇨ 0.0882	⇩ -0.054	⇨ 0.1181	⇨ 0.0326	⇨ 0.2525	⇩ -0.021	⇨ 0.2155	⇨ 0.166	⇨ 0.304	⇨ 0.2742	⇨ 0.206	⇨ 0.1493	⇨ 0.2146	⇩ 0.0063	⇩ -0.126	⇨ 0.0899	⇨ 0.1703
SIRutting	⇨ 0.3549	⇨ 0.0554	⇧ 0.801	⇨ 0.158	⇨ 0.1168	⇩ -0.211	⇩ -0.072	⇩ -0.046	⇨ 0.048	⇧ 1	⇧ 0.869	⇨ 0.2875	⇨ 0.2389	⇨ 0.1102	⇩ -0.236	⇩ -0.05	⇨ 0.2421
SIRoughness	⇧ 0.5302	⇨ 0.1546	⇧ 0.7271	⇨ 0.2317	⇨ 0.1244	⇩ -0.091	⇩ -0.018	⇩ -0.041	⇨ 0.0376	⇧ 0.869	⇧ 1	⇨ 0.2153	⇨ 0.3109	⇨ 0.149	⇩ -0.109	⇩ -0.137	⇨ 0.1392
SIFlexure	⇨ 0.3605	⇩ -0.276	⇨ 0.2721	⇩ -0.102	⇨ 0.0818	⇩ -0.214	⇩ -0.127	⇩ -0.169	⇩ -0.042	⇨ 0.2875	⇨ 0.2153	⇧ 1	⇧ 0.5827	⇩ -0.006	⇩ -0.188	⇩ -0.193	⇨ 0.0346
SIShear	⇨ 0.4079	⇩ -0.451	⇨ 0.2072	⇩ -0.31	⇨ 0.1913	⇨ 0.0452	⇨ 0.1981	⇩ -0.157	⇩ -0.08	⇨ 0.2389	⇨ 0.3109	⇧ 0.5827	⇧ 1	⇨ 0.0519	⇩ -0.264	⇩ -0.126	⇩ -0.194
AlWT.N	⇨ 0.0727	⇩ -0.15	⇩ -0.005	⇨ 0.1769	⇩ -0.023	⇨ 0.1606	⇩ -0.055	⇨ 0.0681	⇨ 0.0306	⇨ 0.1102	⇨ 0.149	⇩ -0.006	⇨ 0.0519	⇧ 1	⇩ 0.0104	⇩ -0.041	⇩ -0.008
Flush.Mid	⇩ -0.162	⇨ 0.2451	⇩ -0.232	⇨ 0.1909	⇩ -0.02	⇩ -0.105	⇩ -0.267	⇨ 0.1391	⇨ 0.079	⇩ -0.236	⇩ -0.109	⇩ -0.188	⇩ -0.264	⇩ 0.0104	⇧ 1	⇨ 0.2965	⇨ 0.1752
Flush.High	⇩ -0.049	⇩ -0.162	⇩ -0.09	⇩ -0.193	⇨ 0.3284	⇩ -0.176	⇩ -0.106	⇨ 0.1054	⇨ 0.0712	⇩ -0.05	⇩ -0.137	⇩ -0.193	⇩ -0.126	⇩ -0.041	⇨ 0.2965	⇧ 1	⇨ 0.177
Sensitivity	⇩ -0.053	⇨ 0.1728	⇨ 0.0693	⇨ 0.2657	⇨ 0.1051	⇩ -0.192	⇩ -0.061	⇨ 0.061	⇨ 0.0784	⇨ 0.2421	⇨ 0.1392	⇨ 0.0346	⇩ -0.194	⇩ -0.008	⇨ 0.1752	⇨ 0.177	⇧ 1

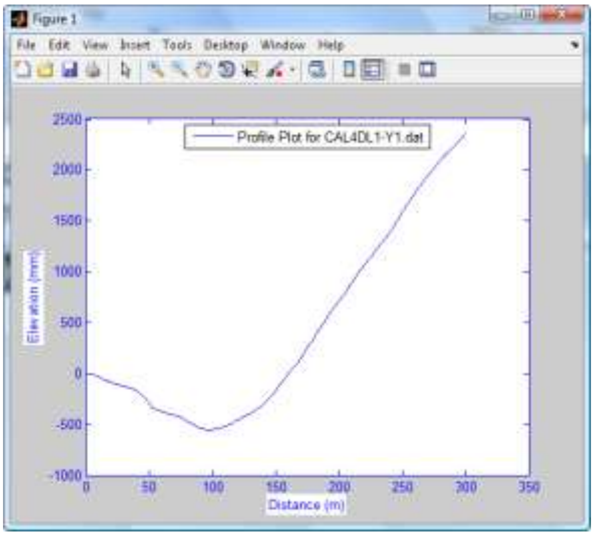
Note: Wavelength sub-band energy columns were removed

Appendix B: Database and analysis software used in this research

Figure B.1 Instrument used to record the pavement profile for the analysis

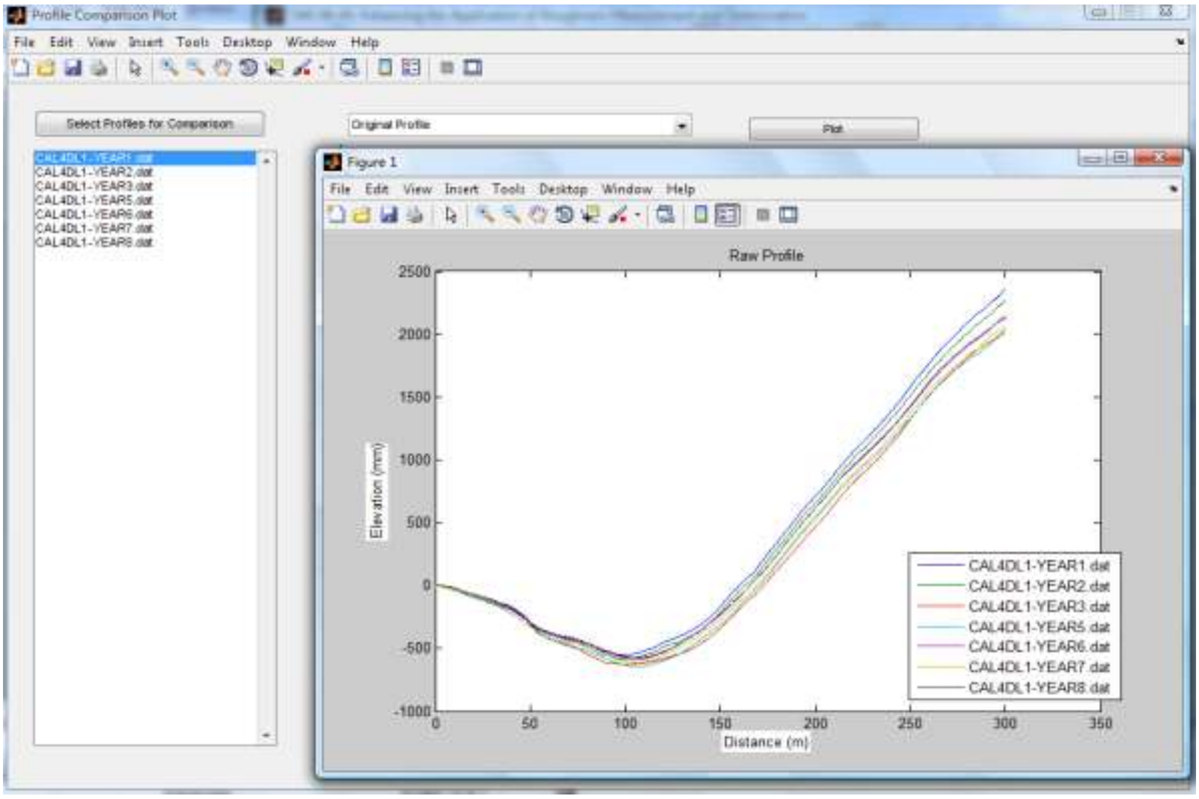
The computer program was developed to open and view the raw profile data in a two-dimensional graph. Figure B.2 is an example of a typical profile; this review capability allows the user the ability to examine the profile data visually.

Figure B.2 Computer program example profile plot



The computer program can also plot multiple profiles and so allow a visual inspection to identify any difference between the profiles. Figure B.3 is an example of profile comparison plot for data collected over eight years at the same LTPP section.

Figure B.3 Example multiple profiles comparison plot



The key function of the computer program is to decompose the raw profile data into sub-bands and calculate the energy within each sub-band. This represents the wavelength content characteristics of the profile. Figure B.4 shows an example of sub-band energy calculation for one profile measured at LTPP section CAL27.

A batch processing function was developed to automatically process multiple profiles stored within a single directory. This function displays the energy calculated; graphically displays the results and automatically uploads the calculation results into a corresponding database table.

An MS Access database was developed to store and organise the data used in this research. Various database tables were designed to store different type of data, such as sub-band energy for local authority LTPP sections, sub-band energy for state highway LTPP sections, sub-band IRI for local authority LTPP sections, sub-band IRI for state highway LTPP sections, and profile IRI results from the walking profiler survey. SQL queries were designed to find out the average value of sub-band energy and IRI for each wheelpath of each LTPP sections.

Figure B.4 Example sub-band energy calculation