WAVELENGTH ANALYSIS OF STATE HIGHWAY LONGITUDINAL PROFILES

Transfund New Zealand Research Report No. 153

WAVELENGTH ANALYSIS OF STATE HIGHWAY LONGITUDINAL PROFILES

P. D. CENEK, S. FONG and M. W. McLARIN
Opus Central Laboratories,
Lower Hutt, New Zealand

Transfund New Zealand Research Report No. 153

ISBN 0-478-11561-X
ISSN 1174-0574

© 2000, Transfund New Zealand
PO Box 2331, Lambton Quay, Wellington, New Zealand
Telephone (04) 473 0220; Facsimile (04) 499 0733

P. D. Cenek, Fong, S., and McLarin M. W., 2000. Wavelength analysis of state highway longitudinal profiles.
Transfund New Zealand Research Report No. 153. 47pp.

Keywords: dynamic wheel forces, pavement loading, pavement management, ride quality, road profiles, road roughness, spectral analysis, vehicle dynamics modelling, wavelet analysis

AN IMPORTANT NOTE FOR THE READER

The research detailed in this report was commissioned by Transfund New Zealand.

Transfund New Zealand is a Crown entity established under the Transit New Zealand Act 1989. Its principal objective is to allocate resources to achieve a safe and efficient roading system. Each year, Transfund New Zealand invests a portion of its funds on research that contributes to this objective.

While this report is believed to be correct at the time of its preparation, Transfund New Zealand, and its employees and agents involved in the preparation and publication, cannot accept any liability for its contents or for any consequences arising from its use. People using the contents of the document should apply, and rely upon, their own skill and judgement. They should not rely on its contents in isolation from other sources of advice and information.

The report is only made available on the basis that all users of it, whether direct or indirect, must take appropriate legal or other expert advice in relation to their own circumstances. They must rely solely on their own judgement and seek their own legal or other expert advice in relation to the use of this report.

The material contained in this report is the output of research and should not be construed in any way as policy adopted by Transfund New Zealand but may form the basis of future policy.

CONTENTS

EXECUTIVE SUMMARY

Vertical vibrations cause the load applied by the wheels of a heavy commercial vehicle (HCV) to the road to vary above and below a nominal constant value. While such load variations occur to some extent on all parts of the road network, their magnitude will depend on the longitudinal roughness of the road section and the design of the HCV and its suspension. Generally they will increase with both speed and road roughness. Most HCVs generate their moving dynamic wheel loads because of dominant vehicle bouncing and pitching motion in the 1.5 to 4 Hz frequency range, but some poorly damped air suspensions and axle groups also generate dominant loads at frequencies in the range of 8-15 Hz, due to axle bounce motion. Wavelengths in the road surface which excite HCV bounce and pitch are in the 4-20 metre range whereas wavelengths which excite wheel bounce are in the 1-4 metre range.

Early identification of road sections that are likely to experience accelerated wear due to roughness-induced dynamic wheel loading is useful to road asset managers. This is because appropriate preventive maintenance can be undertaken to eliminate or reduce the cause of the vertical vibrations thereby prolonging the service life of the pavement, while at the same time improving ride quality. A programme of research therefore, was undertaken to develop a computationally efficient and reliable procedure for identifying from state highway road profile data, road sections that promote wheel and body bounce and body pitching in HCVs. Both latest generation spectral analysis methods including wavelet analysis, which allows local roughness features in the road surface to be identified and located, and two-dimensional vehicle models capable of accurately simulating vertical dynamics were considered.

These methods were applied to 1km sections of State Highway longitudinal profiles selected on the basis of showing significant roughness progressions (>9 NAASRA* counts/km) over a six year period (1992-1998). The resulting waveband profile spectra, simulated Root Mean Square (RMS) ride accelerations, and simulated wheel load Dynamic Impact Factors (DIF) correlations with 2, 4 and 6 year roughness changes were investigated. Wavelength band modified road profiles were also utilised to establish whether or not spectral analysis and/or the two-dimensional vehicle models can, through better discrimination of road profile features that excite HCV's, complement the International Roughness Index (IRI)/NAASRA* roughness numerics traditionally used in pavement management systems to determine maintenance intervention intervals and treatments.

The principal outcome from the research was that DIF calculated using a quarter truck (rear axle) model appears to be a better indication of dynamic pavement loading of HCVs in some situations than the NAASRA/IRI roughness numeric, and so these two indices when used together should result in improved assessment of required maintenance interventions. However, before incorporation in an asset management system such as RAMM,† it would be prudent to first analyse existing longitudinal profile data for the entire state highway network (both IRI and DIF for both wheelpaths) to establish that useful complementary information is indeed provided by the proposed DIF index. This reservation on immediate adoption of DIF has been brought about by limited evidence indicating that the roughness of chipseal surfaced state highway road sections is predominantly caused by road surface irregularities that cover a broad rather than narrow range

* NAASRA – National Association of Australian State Road Authorities (IRI – International Roughness Index)
† RAMM – Road Assessment and Maintenance Management

of wavelengths. For such situations, the DIF does not add to the information provided by the IRI/NAASRA numeric.

Secondary outcomes relate to:

(a) The recommended use at project level of either sectional power spectral density (PSD) or wavelet analysis methods whenever longitudinal wheelpath profiles are available. Thus surface irregularities that significantly contribute to overall roughness levels or dynamic pavement loading can be specifically located and their wavelength established, leading to greater discrimination of good and bad construction practices and associated deterioration mechanisms.

(b) The need to better quantify positional effects (both longitudinal and transverse) on resulting measures of roughness obtained with laser-based profilers on chipseal surfaces. In particular, there is a need to determine whether or not an automatic means for locating roughness measurements within a lane is necessary to reduce the degree of variability observed with existing time-series roughness data. The resolution of this issue is particularly important with regard to development and validation of indices and pavement deterioration models incorporated in pavement management systems such as RIMS – dTIMS.

ABSTRACT

Over the past decade, the longitudinal profiling of wheelpaths has become routine with the advent of laser-based high-speed monitoring systems. A study was undertaken in 1998 to investigate the suitability of latest generation spectral analysis methods and quarter and half-truck dynamic simulations when applied to wheelpath profile data to provide more complete information on ride quality and dynamic wheel loading of roads. The output generated by the spectral analysis and vehicle modelling approaches was assessed in terms of relevance to project and network level decision making associated with pavement maintenance management. A new index is proposed, which, when used in conjunction with IRI/NAASRA roughness, may provide earlier warning of accelerated road deterioration due to the excitation of the bounce and pitch modes of heavy trucks.

1. INTRODUCTION

Roughness or longitudinal road profiles acquired as part of annual high speed data collection undertaken by Transit New Zealand on sealed state highways and local arterial routes are stored in their pavement management system (PMS) in terms of the International Roughness Index (IRI) and converted to NAASRA roughness counts by a single linear transformation. Traditionally, the NAASRA roughness numeric has been used to monitor the condition of the state highway network, and as an indicator of the need for repair or rehabilitation. However, while a single roughness numeric for a given road section is easy to handle in present road asset maintenance management systems such as RAMM, it is clear that a single number cannot convey all of the information obtained in a road profile. For example, where two roads are characterised by the same NAASRA roughness count value, one may be very smooth except for the occasional severe pothole, while the other may have an unbroken surface with long "waves" which result from the instability of the subgrade.

From an asset management perspective, it is important to determine whether the measured roughness is associated with surface deficiencies which may be improved by the application of a thin structural overlay or structural deterioration which can only be remedied by major rehabilitation. A means of making this distinction is by wavelength analysis because surface deficiencies, such as potholes and stripping, are characterised by short longitudinal wavelengths of the order of 1-10m, whereas structural deterioration linked to subgrade settlements and construction faults are characterised by regular, long longitudinal wavelengths of the order of 10-50m.

This report presents the results of the application of four different methods of spectral analysis, proposed by Laboratoire Central des Ponts et Chaussées (LCPC) (Legeay 1994) to available state highway profile data in order to demonstrate the different information they make available for pavement management purposes. These four methods cover the waveband notation method which characterises the road profile in three wavebands covering road safety, driving comfort, and dynamic loading; a method of analysis using third octave band filtering; a method of fine band analysis and modelling of the resulting power spectral density (PSD) function by a logarithmic curve; and a wavelet method that enables accurate detection of local deficiencies.

Both the IRI and NAASRA roughness counts are based on passenger car type response and are intended to reflect the roughness as observed by the occupants of ordinary passenger cars, who generally are the majority of road users. However, it is well established that traffic related road deterioration can be substantially attributed to heavy vehicles due to the irreversible components of the load deformation response of pavement materials, caused largely by continued compaction, aggregate crushing at local contact points, and material plastic deformation. Furthermore, the dynamic response characteristics of heavy vehicles are typically different to those of passenger cars. Therefore, in addition to the spectral analysis methods, three simple, two dimensional truck models have been used to predict ride quality in terms of root mean square (RMS) accelerations of the sprung mass and pavement loading in terms of dynamic impact factors (DIF) for given road section profiles. The three 2D models used are a quarter truck, a half truck, and a half tractor semi-trailer as detailed by Todd and Kulakowski (1989). The resulting RMS and DIF values are compared and contrasted with the traditional IRI and NAASRA roughness measures and output from the spectral analysis.

The need for the reported research has been identified by Cenek(1989). This seeks to maximise the information available from longitudinal road profiles acquired as part of annual state highway surveys so that road asset managers can make more informed decisions when prioritising road maintenance and rehabilitation programmes. The research also builds on previous New Zealand research by de Pont (1994) which investigated the concept of a heavy vehicle-based roughness index but resulted in an inconclusive outcome because there were insufficient differences in longitudinal profile wavelength distributions among the five test sections used for on-road determination of dynamic wheel forces.

2 COMPUTER SIMULATION OF TRUCK RIDE COMFORT AND DYNAMIC PAVEMENT LOADING

2.1 Quarter and Half Truck Dynamic Models

Routines were developed using Matlab/Simulink software to simulate the response to longitudinal road profiles of Quarter Truck, Half Truck and Half Tractor Semi-trailer models detailed in Figures 1 to 3 and proposed by Todd and Kulakowski (1989).

Truck model parameters and the sprung mass (body) and unsprung mass (axle) response spectra for the three models on a standard sinusoidal road profile are presented in Tables A1 to A3 and Figures A1 to A7 of Appendix A. The important features of these response spectra are as follows:

(a) The tyre forces generated by heavy vehicles fall into two distinct frequency ranges due to various vibration "modes" of the vehicle, these being:

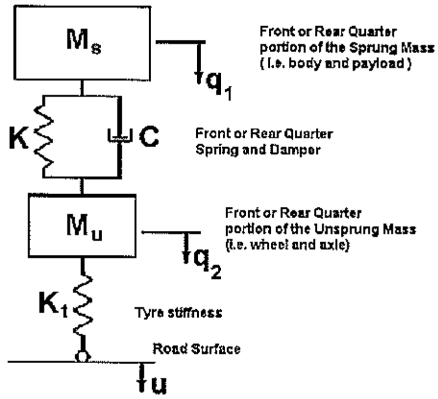
1.5-4 Hz corresponding to vehicle bounce, pitch and roll vibration modes;
8-15 Hz corresponding to axle bounce and roll, plus 'load-sharing' suspension pitch modes.

For example, at a speed of 100 km/h, these modes of vibration are excited by surface irregularities with wavelengths of approximately 7-19m and 2-4m respectively. A schematic of the principal vertical and fore and aft vibration modes of a vehicle on its suspension is given in Figure 4.

The lower frequency sprung mass mode can be regarded as producing narrow band excitation whereas the higher frequency unsprung mass mode generates broad band excitation.

(b) For the "rigid" quarter and half truck dynamic models, the lower frequency sprung mass dominates the dynamic component of tyre forces on roads. With reference to the half truck model, the dynamic tyre forces generated by the front/steering axles are insignificant when compared to those generated by the higher loaded rear axle. As expected, there appears to be little difference between the response of the quarter truck (rear axle) model, and the rear axle of the half truck model.

(c) In contrast to the "rigid" models, the articulated truck model shows higher response amplitude in the 8-15 Hz range than in the 1.5-4 Hz range. This result is a characteristic of vehicles which have axle group suspensions with poorly damped bogie pitching modes. Furthermore, for the articulated truck model, there is negligible difference in the response characteristics of the leading and trailing rear axles, apart from the leading axle displaying a slightly higher response amplitude over 15-20 Hz (wavelengths of approximately 1.5-2m at 100 km/h).



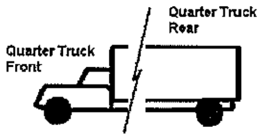
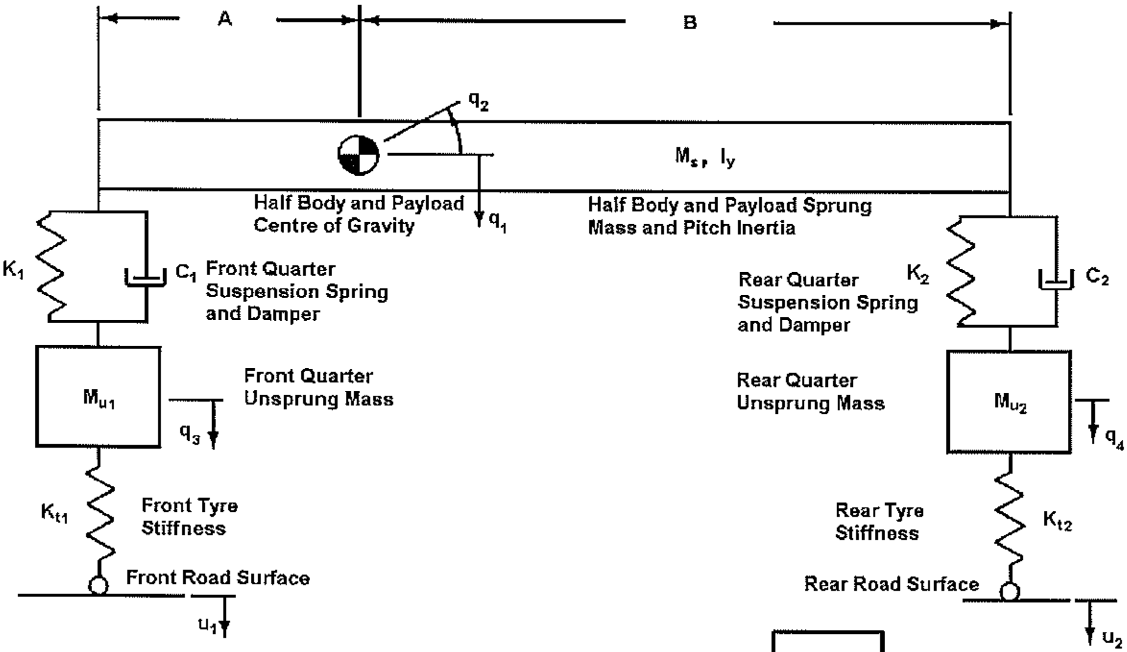


Figure 1: Quarter Truck Model



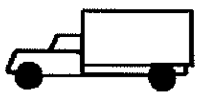


Figure 2: Half Truck Model

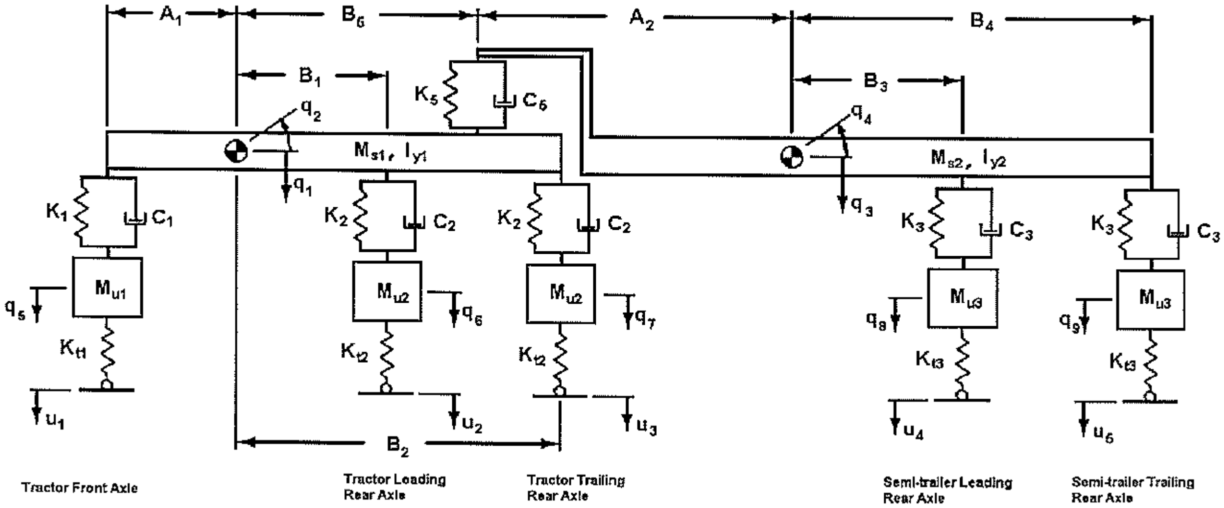
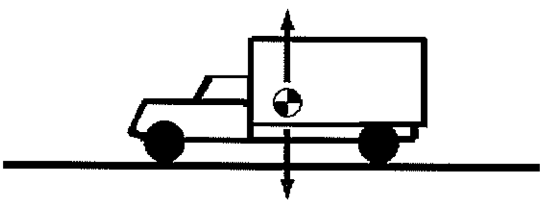
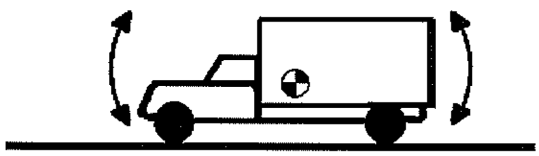


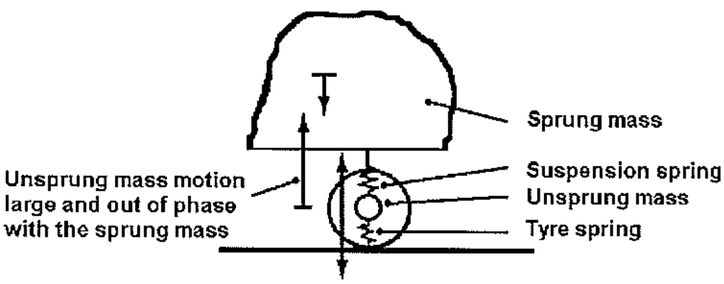
Figure 3: Half Tractor Semi-trailer Model



(a) Vertical translation or 'Bounce'



(b) Longitudinal rotation or 'Pitch'



(c) Vertical translation of the unsprung mass or 'wheel hop'

Figure 4: Vibration Modes of a Vehicle on its Suspension (after OECD, 1992)

2.2 Model Validation

The responses obtained were validated by comparison with results published by Todd and Kulakowski (1989). Although the agreement was generally good, there were some discrepancies of detail with the more complex half truck and half tractor semi-trailer models attributed to different schemes adopted to solve the differential equations.

The Matlab/Simulink schemes of this study used variable time step solvers and for the tractor semi-trailer model a solver variant suitable for "stiff" problems was employed. (A "stiff" problem is one where some solution components vary on a time scale that is very short compared to the interval of integration, but the solution of interest changes on a much longer time scale. The tractor to semi-trailer coupling produces this situation as it is very much stiffer than either the suspension springs or the tyres).

The models were further tested by their use to derive RMS sprung mass ride accelerations (ie body accelerations) and Dynamic Impact Factors (DIFs) from the tyre contact forces at each wheel position. DIF is frequently used to characterise the magnitude of wheel forces and is defined as:

$$\text{DIF} = \frac{\text{Standard Deviation of the Dynamic Tyre Force}}{\text{Mean Tyre Force}}$$

For this task, several state highway road section profiles were used that exhibited roughness values around those of the example section published by Todd and Kulakowski (1989). The road profiles were obtained by the current routine surveyors of New Zealand State Highways (WDM UK Ltd.) using their high speed data collection system and provided elevations at 100mm intervals over 0.5-100m wavelengths.

Figures 5 to 7 show the RMS ride accelerations and the corresponding tyre contact DIF values as a function of IRI for local road sections. Imperial units of IRI have been used to allow direct comparison with results published by Todd and Kulakowski (1989). The conversion to NAASRA units is as follows:[1]

$$26 \text{ NAASRA counts/km} \cong 1 \text{ IRI(m/km)} = 63.4 \text{ IRI (in/mile)}.$$

Again the agreement is generally good, although there are also discrepancies in the detail of the results, which, in consultation with Professor Kulakowski, have not yet been resolved. However, as these discrepancies can be readily explained by the differences in the response characteristics, the models were considered to be sufficiently reliable to permit their use for the purposes of the numerical studies detailed in this report.

2.3 Execution Times

Truck model simulation analyses have not been particularly optimised for execution speed and are running as fully configurable models with additional outputs. Indicative execution times (including reading in of raw profile data) are given in Table 1.

[1] Actual conversion used (from Prem 1989) is 1 IRI[m/km] = (NAASRA[counts/km] + 1.27)/26.49

Table 1: Truck Model Execution Times

Truck Model	Time for 800m of Profile (mins)
Quarter Truck Front	0.075
Quarter Truck Rear	0.075
Half Truck	0.22
Half Tractor Semi-trailer	5.4

Optimisation would be expected to reduce these times considerably and in the case of the quarter truck a transfer function formulation should reduce execution times to the same order as those reported for IRI in the next section (3.2.5).

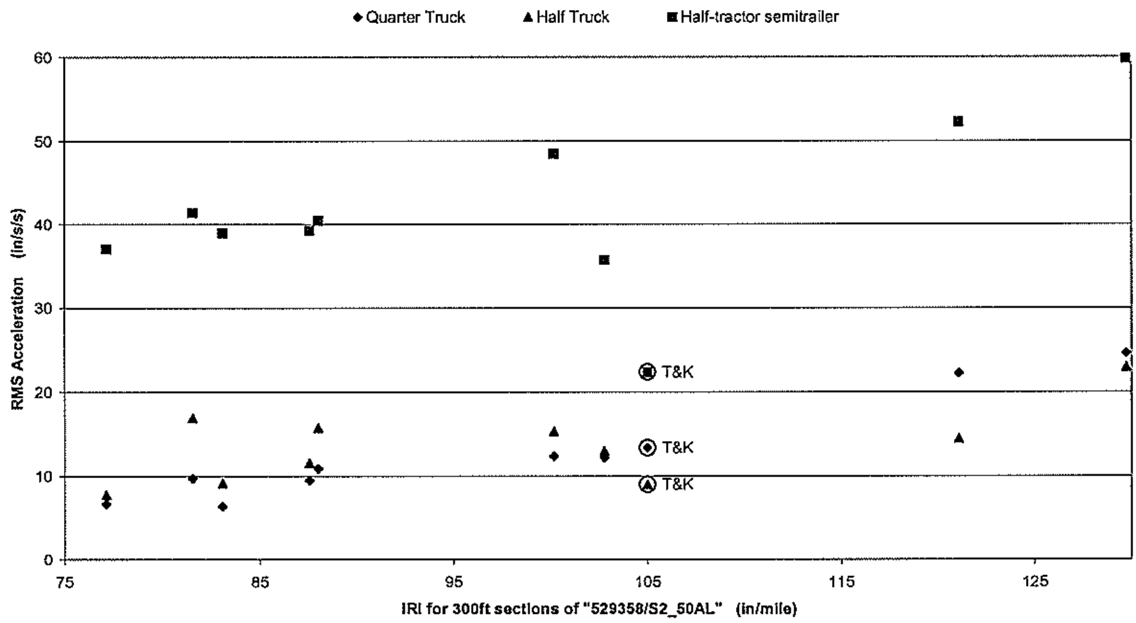


Figure 5: Sprung Mass Ride Accelerations for Roads with NAASRA Roughness Range 30-55 (T&K = Todd and Kulakowski (1989))

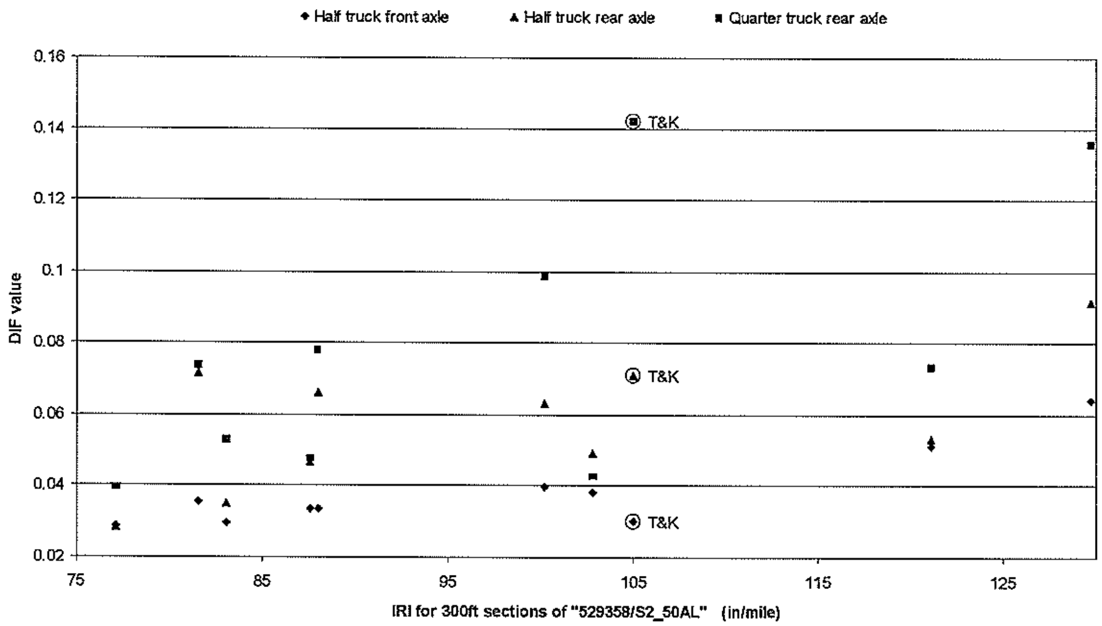


Figure 6: Quarter Truck and Half Truck Dynamic Impact Factors for Roads with NAASRA Roughness Range 30-55 (T&K = Todd and Kulakowski (1989))

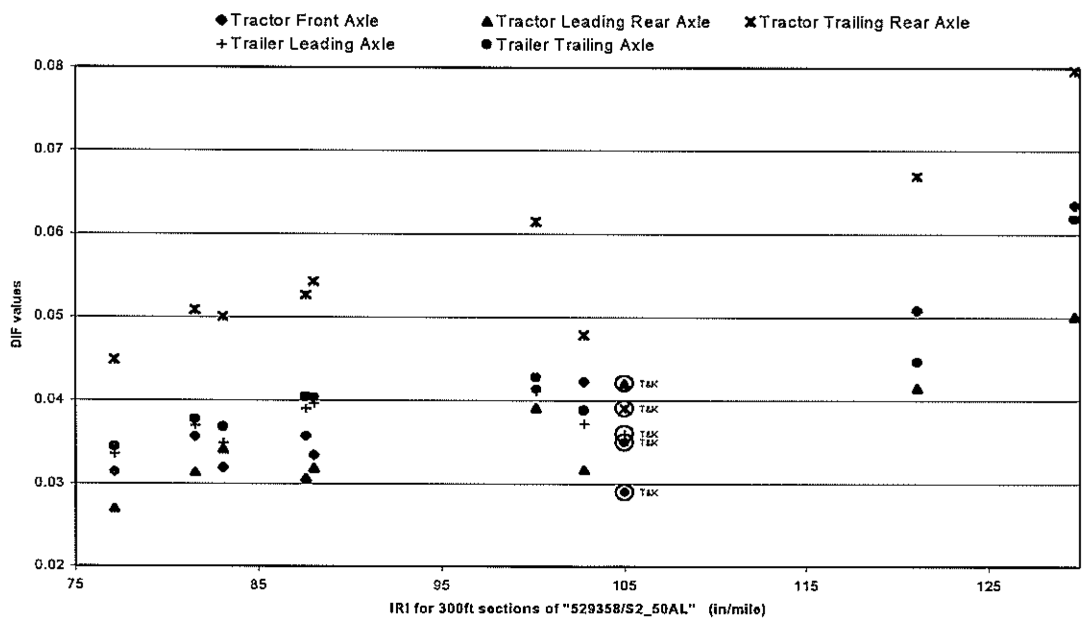


Figure 7: Half Tractor Semi-trailer Dynamic Impact Factors for Roads with NAASRA Roughness Range 30-55 (T&K = Todd and Kulakowski (1989))

3. APPLICATION OF SPECTRAL AND WAVELET ANALYSIS TO LONGITUDINAL ROAD PROFILES

3.1 Overview of Spectral Analysis

Spectral analysis techniques are widely used in mechanical and electrical engineering to analyse signals in the time and frequency domain. It describes the frequency content of a signal and is most useful in identifying signals imbedded in wide band noise. The basis of spectral analysis is to fit a series of harmonics to the signal. The harmonics are constructed from a series of sine waves of different frequencies and amplitudes. These are presented as power spectra where the signal is decomposed into sine waves of various amplitudes at a range of fixed frequencies.

In applying signal analysis to road profiles the frequency of a time series is replaced with wavelength for a spatial profile. The wavelength is the longitudinal distance along the road for a single cycle of height variation. The profile spectra show the height variation associated with each wavelength. The minimum wavelength resolution is twice the longitudinal sampling distance of the profile data.

Wavelength is related to frequency as follows:

$$\lambda = V/f$$

Where λ = wavelength (m)
V = measurement of travel speed (m/s)
f = frequency (Hz)

3.2 Matlab Application

Matlab is a commercially available, general purpose, numerical analysis package with graphical output features. A variety of toolboxes can be added to Matlab to extend its capabilities. In this case, digital signal processing (time-series analysis) and wavelet toolboxes were utilised for performing spectral analysis of road profiles acquired with laser-based profilers, namely the ARRB two laser profiler and the WDM high speed data collection system.

Matlab provides the facility to write programs as "scripts" to perform complex analysis using the toolbox functions. A Matlab script was written to process the profile data from the 1998 Transit New Zealand High Speed Survey archives and perform the analyses detailed below.

3.2.1 IRI Roughness and Profile Wavelengths

The wavelength content of the profile is highly relevant to the calculation of road roughness. The International Roughness Index (IRI) is effectively a filter that applies weightings to specific profile wavelengths and sums the result. The weightings at each wavelength are illustrated in Figure 8. Wavelengths around the response peaks at 2.3m and 15.9m have a large influence on IRI. Below

0.1m and above 100m there is no significant influence on IRI. Roughness as summarised by IRI, and equivalently NAASRA[2], reduces the wavelength content of the profile to a single number.

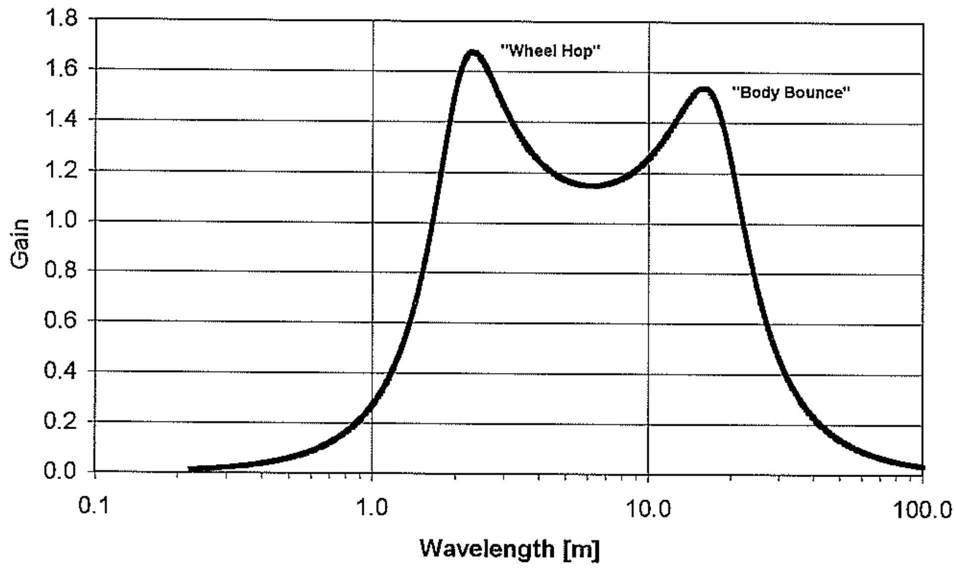


Figure 8: IRI Wavelength Weighting

The following profiles in Figures 9 and 10 are synthetic profiles with the same roughness but are constructed from two different pure sine wavelengths, 1m and 10m.

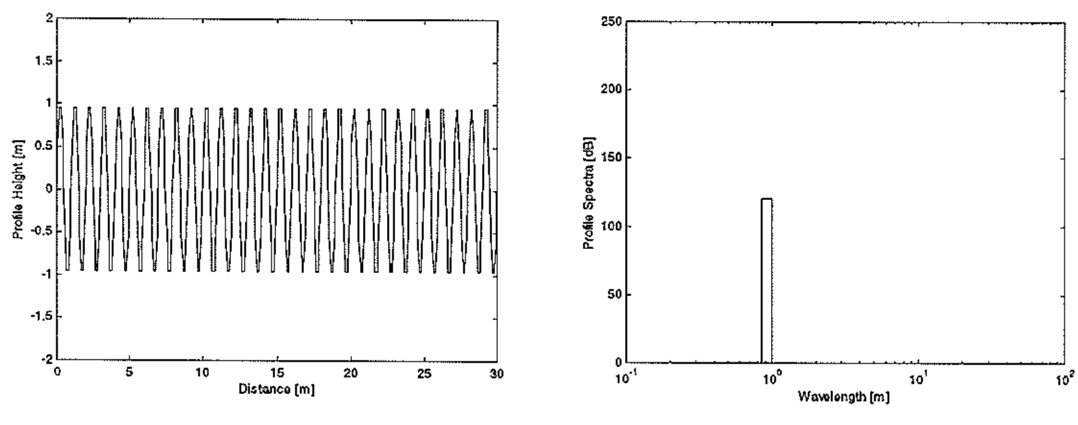


Figure 9: Pure 1m Wavelength Profile, IRI=1m/km

2 1 IRI ≅ 26 NAASRA counts/km

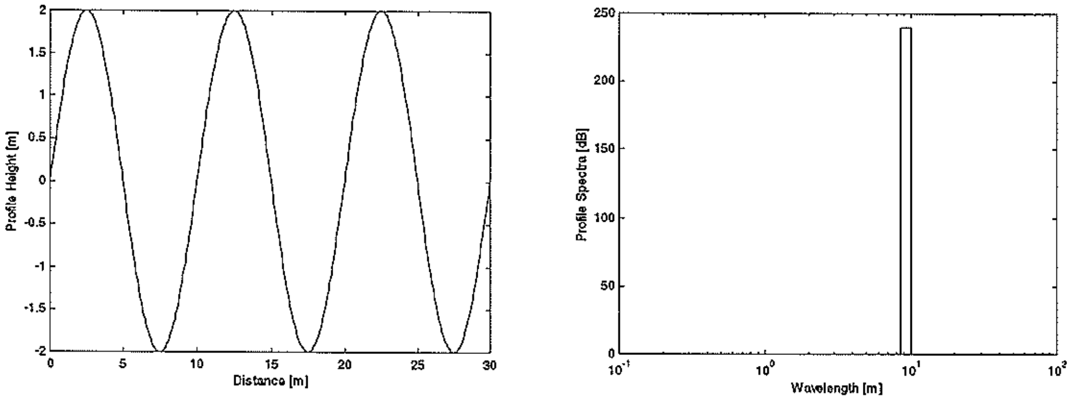


Figure 10: Pure 10m Wavelength Profile, IRI=1m/km

The spectra for the pure wavelength profiles in Figures 9 and 10 show a single value of 120dB and 240dB at 1 and 10 m respectively. A 1 m amplitude variation in profile is equivalent to 120dB. Spectra are usually reported at fixed wavelengths and the most commonly used is the third octave spectra where they are averaged into wavelength bands centered on powers of 2 raised to increments of 1/3. (e.g. the 28 third octave bands used here for road longitudinal profiles have center wavelengths that range from 0.2m to 100m according to the following series: 2^{N1} ; 2^{N2} ; ...... ; 2^{N28} where Ni = (i – 8)/3 .)

3.2.2 Reporting to ISO 8608:1995

An averaged profile spectra is used to classify the road roughness according to the International Organisation for Standardisation (ISO) standard ISO 8608:1995. A logarithmically averaged profile spectrum is fitted with a straight line and classified according to predefined classes. The classes range from A for the smoothest surface to H for the roughest. The profile spectrum is classified according to where the logarithmic line fit falls in the classes, as shown in Figure 11.

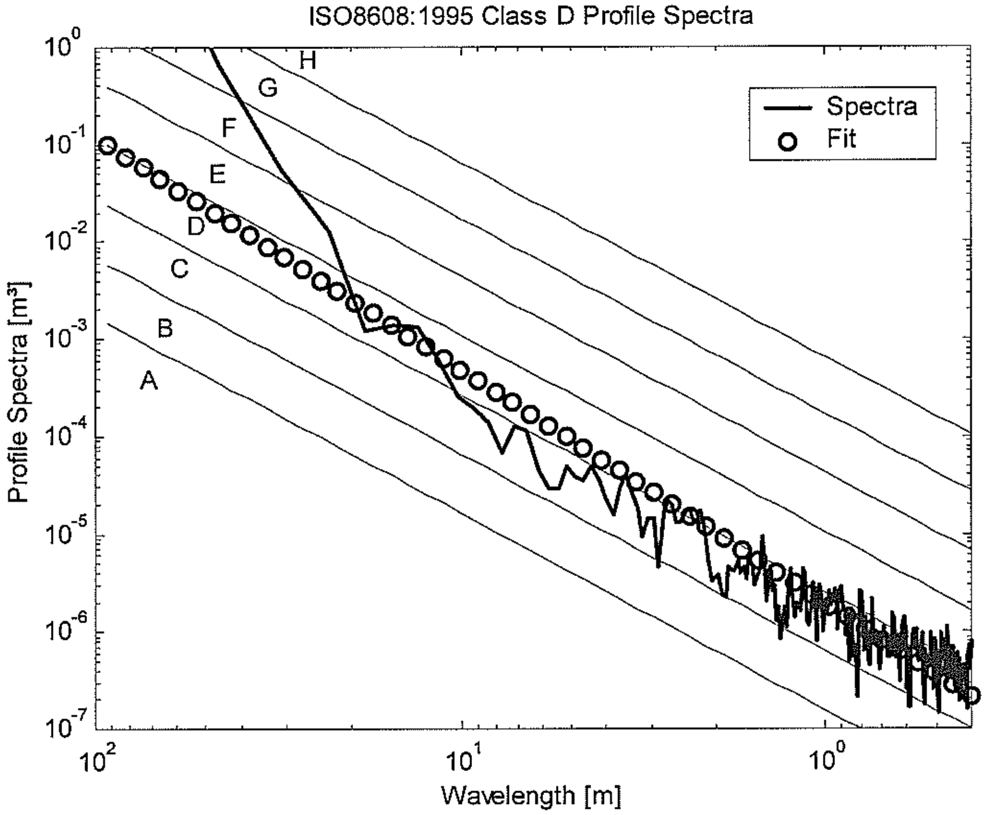


Figure 11: ISO8608:1995 Profile Spectra Classes

3.2.3 RMS Waveband Filtering Summary

Road roughness is influenced by different wavelengths in the road longitudinal profile. Therefore the profile may be characterised by the height deviations in certain wavelength bands.

Butterworth filters in Matlab were used to isolate the profile variations in particular wavelength bands. The bands chosen are listed in Table 2. The filtered profiles are summarised as individual filtered variances or RMS (Root Mean Squared) values.

Table 2: Filtering Wavelength Limits

Filtered RMS	Low Wavelength Limit (m)	High Wavelength Limit (m)
0-Infinity	0	None
0.5-5	0.5	5
5-15	5	15
15-50	15	50
50-100	50	100

3.2.4 Wavelet Analysis

Wavelet analysis is similar to spectral analysis, the difference being that the spatial position of the height variation at each wavelength is preserved. This allows the position of disturbances to be located. Spectral analysis tends to lose localised features while wavelet analysis does not.

The best way to describe wavelet analysis is by example. With reference to Figure 12, the analysis breaks down the input signal into a series of "detail" reconstructions. The reconstructions follow a decomposition tree where the signal is broken into cascading levels of detail at each wavelength band. The reconstructions are centered on the 1, 2, 4, 8, 16, 32 and 64 m wavelengths. A comparison of an original profile and its reconstruction is given in Appendix B.

The graphical representation of wavelet analysis in Figure 12 highlights the strength of the method in that height variations in each wavelength band that significantly contribute to the overall roughness can be precisely located. However, as automatic analysis of graphical output cannot be readily achieved, the wavelet analysis is summarised as RMS values in each wavelength band of Table 3. Therefore wavelet analysis can be considered to be the same as the wavelength filtering described in section 3.2.3.

Table 3: Wavelet RMS Summary

Wavelet RMS	Low Wavelength Limit (m)	High Wavelength Limit (m)
1	0.75	1.5
2	1.5	3
4	3	6
8	6	12
16	12	24
32	24	48
64	48	96

3.2.5 Execution Times

The times for the Matlab analysis are listed in Table 4. The times are taken from the median, lower and upper quartile of times to avoid the extremes from the minimums and maximum times. These times are for the analysis of 62 1-km-long wheel-path profiles at a nominal sampling distance of 100 mm, giving approximately 10,000 profile points. They do not include the time for reading the input profile.

Table 4: Processing Times for 1-km-long Road Elevation Profile

Time (sec)	IRI	Filter	ISO	Wavelet
Minimum	0.7100	0.1700	0.2700	0.3300
Mean	0.7200	0.2200	0.2800	0.3823
Maximum	1.0400	0.2800	0.3800	0.5000

The IRI times in Matlab will be longer than a specialised calculation program as Matlab cannot efficiently perform the recursive sum needed for IRI.

3.2.6 Sample Output

Both graphical and numerical outputs are produced from the Matlab analysis. Figures 12-14 illustrate the graphical characteristics of road profiles achieved by spectral and wavelet analysis.

Figure 12 contains four plots showing the profile spectra for the entire length of profile, IRI roughness, RMS values of each wavelength band and ISO8608:1995 classification summarised in 100 m lengths. Figure 13 shows the details of the wavelet decomposition while Figure 14 shows the profile spectra every 100m along the profile length.

As can be seen, different information is provided in the graphs, with Figure 12 more suitable for network level analysis whereas Figures 13 and 14 would have more application at a project level.

An example of the numerical output is given in Table 5. The first set of lines give the road section name, the profile length, and number of profile sample points. The second set of data gives the mean roughness value of the road section in both IRI and NAASRA. The calculation time is also given. The following three blocks give the times for calculating the wavelength filtering, ISO8608 profile spectra classification and wavelet RMS summary. The final block of data contains the full numerical data for the analysis summarised in rows at every 100 m and overall for the road section length. The columns are in the following order:

- Distance in metres.
- IRI roughness in m/km.
- Filtered RMS Summary of the wavelength bands, 0 to infinity, 0.5 to 5.0, 5.0 to 15, 15 to 50, 50 to 100 m.
- ISO8608:1995 Profile Spectra Classification
- Wavelet RMS Summary of the wavelength bands centred on 1, 2, 4, 8, 16, 32, 64, and 128 m (only first three shown in Table 5).
- Third Octave Profile Spectra decibel levels in columns of third octave wavelengths (only the first four are shown in Table 5).

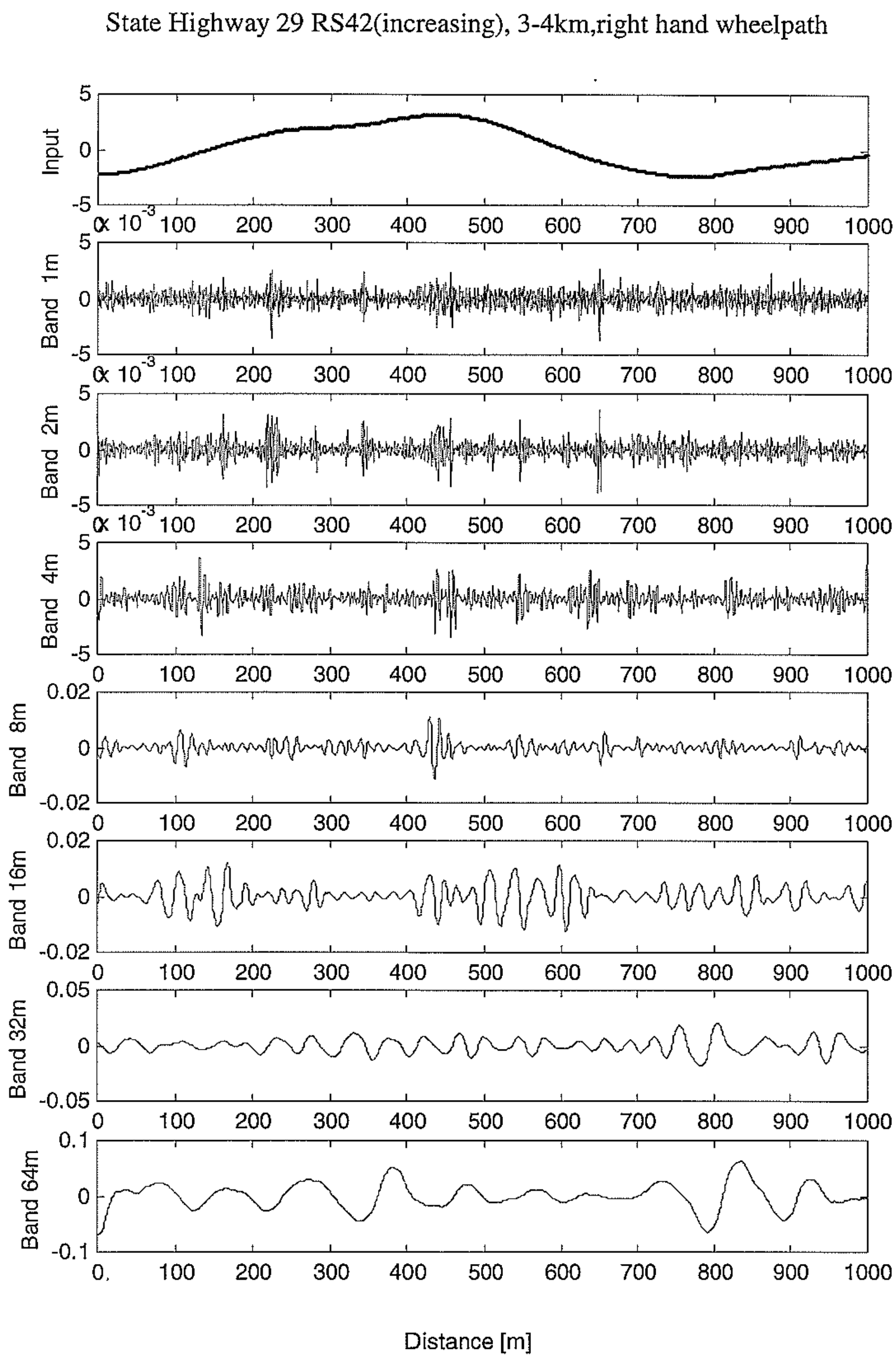


Figure 12: Wavelet Decomposition

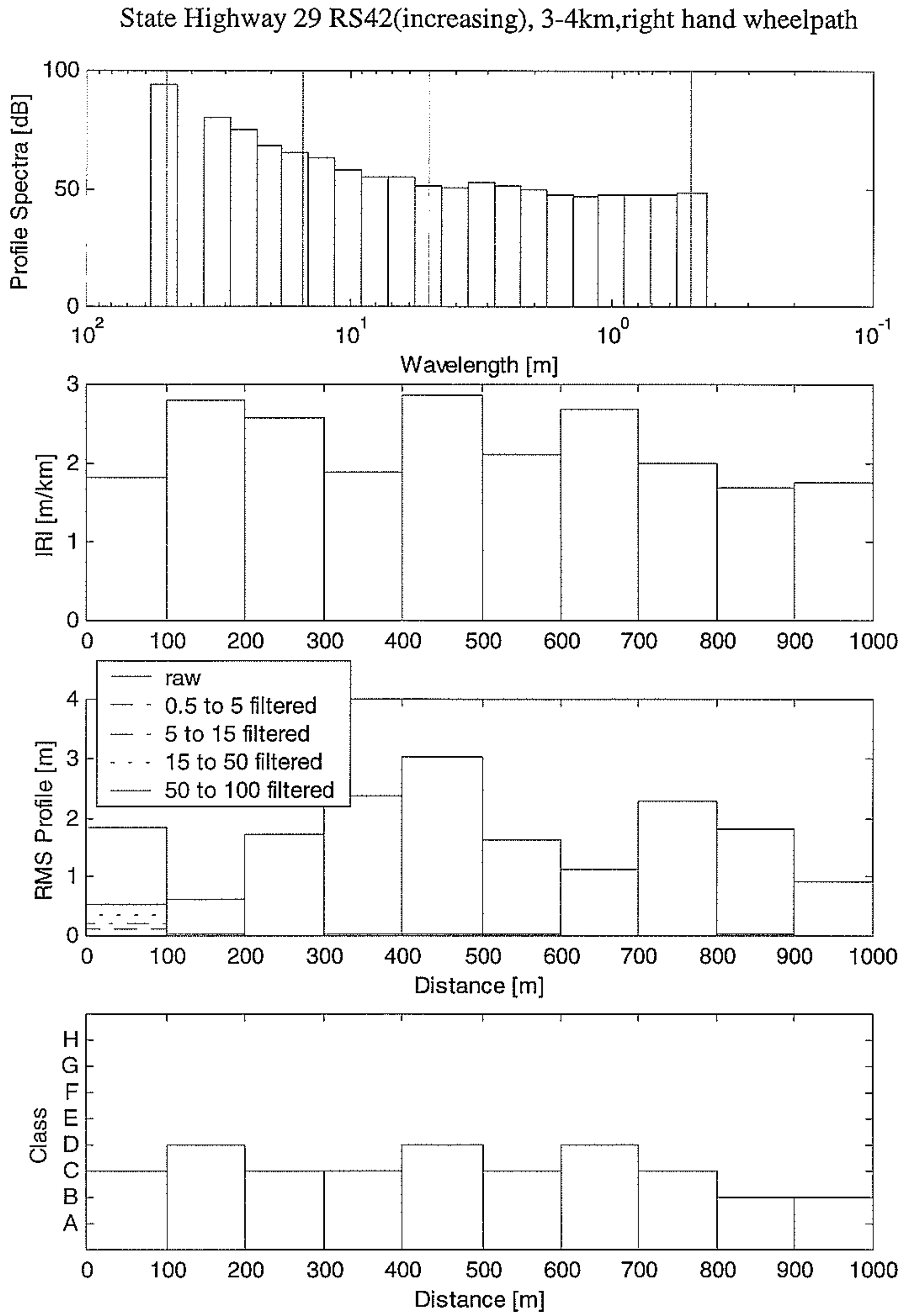


Figure 13: Roughness, Spectral and ISO Classification Plots

State Highway 29 RS42(increasing), 3-4km,right hand wheelpath

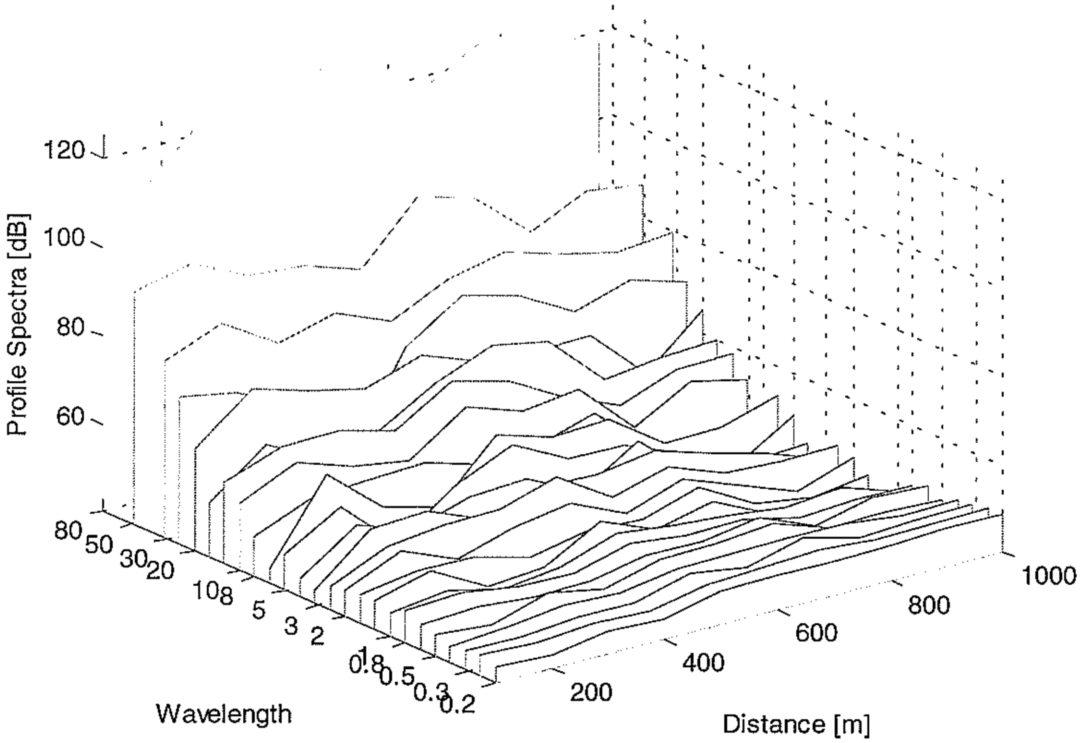


Figure 14: Sectional Spectra

Table 5: Numerical Output from MATLAB Analysis (State Highway 29 RS42(increasing), 3-4km,right hand wheelpath)

```
Name 029-0042i,3000,4000 rhp
Profile length    =  1000.09 m
Number of samples = 11101

Mean IRI         =   2.2199 m/km
Mean NAASRA      =  60.0759 counts/km
Calculation Time =   0.7100 seconds

Wavelength Filtered Profile
Calculation Time =   0.2100 seconds

ISO Classification
Calculation Time =   0.2800 seconds

Wavelet Summary
Calculation Time =   0.3300 seconds
```

		Filtered RMS Summary						Wavelet RMS Summary				Third Octave Profile Spectra				
Dist	IRI	0-Inf	0.5-5	5-15	15-50	50-100	ISO	1.000e+000	2.000e+000	4.000e+000	...	1.984e-001	2.500e-001	3.150e-001	3.969e-001	...
100	1.812e+000	1.824e+000	1.142e-001	1.979e-001	3.619e-001	5.239e-001	C	4.996e-004	5.274e-004	5.966e-004	...	4.455e+001	4.563e+001	4.533e+001	4.446e+001	...
200	2.803e+000	6.153e-001	1.179e-003	2.742e-003	7.617e-003	3.249e-002	D	5.628e-004	7.601e-004	9.601e-004	...	4.402e+001	4.524e+001	4.485e+001	4.576e+001	...
300	2.586e+000	1.712e+000	1.225e-003	2.200e-003	5.712e-003	1.247e-002	C	6.823e-004	8.745e-004	6.776e-004	...	4.607e+001	4.630e+001	4.632e+001	4.728e+001	...
400	1.884e+000	2.382e+000	9.064e-004	1.578e-003	7.039e-003	2.272e-002	C	5.185e-004	6.123e-004	4.987e-004	...	4.530e+001	4.569e+001	4.612e+001	4.688e+001	...
500	2.866e+000	3.028e+000	1.302e-003	3.280e-003	8.490e-003	2.173e-002	D	7.281e-004	7.869e-004	9.792e-004	...	4.843e+001	4.823e+001	4.959e+001	4.898e+001	...
600	2.116e+000	1.638e+000	1.041e-003	2.160e-003	9.284e-003	1.741e-002	C	6.324e-004	5.978e-004	6.721e-004	...	4.882e+001	4.881e+001	4.745e+001	4.926e+001	...
700	2.696e+000	1.137e+000	1.247e-003	2.720e-003	6.731e-003	1.375e-002	D	7.409e-004	8.022e-004	8.782e-004	...	4.867e+001	4.956e+001	5.094e+001	4.941e+001	...
800	2.005e+000	2.282e+000	9.827e-004	1.765e-003	9.076e-003	1.443e-002	C	5.385e-004	6.148e-004	4.753e-004	...	4.875e+001	4.851e+001	4.762e+001	4.915e+001	...
900	1.680e+000	1.798e+000	9.327e-004	1.680e-003	8.557e-003	2.721e-002	B	5.891e-004	5.291e-004	6.555e-004	...	4.956e+001	4.901e+001	4.836e+001	4.785e+001	...
1000	1.750e+000	9.244e-001	9.153e-004	1.657e-003	8.966e-003	1.407e-002	B	5.825e-004	5.041e-004	6.813e-004	...	4.920e+001	4.904e+001	4.860e+001	4.792e+001	...
All	2.220e+000	1.734e+000	1.239e-002	2.177e-002	4.334e-002	7.002e-002	C	6.123e-004	6.714e-004	7.373e-004	...	4.771e+001	4.772e+001	4.784e+001	4.823e+001	...

4 ANALYSIS OF STATE HIGHWAY ROAD SECTIONS DISPLAYING SIGNIFICANT ROUGHNESS PROGRESSIONS

4.1 Application of Truck Dynamic Models and Matlab Script

Thirty-one 1km sections of State Highway profile were selected for which the past six years of RAMM data showed roughness progressions between 9 and 30 NAASRA counts per km in six years. Initially more sections were chosen but many were eliminated when it was found that the current roughness as reported in RAMM was not reasonably well matched by roughness values calculated from the current recorded longitudinal profiles. The RAMM road identifications associated with each of the thirty-one 1km sections are given in Appendix C.

IRI and ISO roughness ratings, spectra, and wavelet parameters were derived for each wheelpath in each 100m of each 1km section as detailed in Section 3.2.

The profiles were filtered to remove wavelengths greater than 100m which are essentially topographical features, and do not influence vehicle response. Vehicle response parameters were then derived for the left hand wheelpath in each 100m of the centre 800m of each 1km section. The 100m each end was used for lead-in and run-out in the truck dynamic model simulations.

ISO ratings ranged from "B" to "F" with most being class "C" or "D" and were not discriminating enough to be considered any further here.

A database of left hand wheelpath vehicle response and profile spectra parameters (31x8=248 100m entries) was compiled and parameter correlations checked for expected outcomes. Table 6 shows the regression coefficients obtained, with R^2 values equal to 0.8 or more highlighted. IRI, RMS ride accelerations, and tyre contact DIF values correlate often within themselves and with the shorter wavelength bands of the profile spectra. Correlation of vehicle parameters with the 5-15m band is prevalent and is to be expected since these wavelengths are known to excite the "body bounce" mode of traversing vehicles. Body bounce will be the prime cause of ride discomfort and because of the body mass inertia, it will also be the prime cause of high dynamic tyre contact forces. There is also some correlation with the 0.5-5m band which is associated with safety as it includes wavelengths that excite vehicle "wheel hop" modes. Road roughness influences the actual useable friction that is provided by the road surface and tyre by adding a random vertical force applied to the tyre which can result in friction variations during turning and braking manoeuvres. As expected, this phenomenon is particularly involved when road surface irregularities cause "wheel hop". There are no practical correlations outside these two lower wavelength bands.

Average parameters for each of the thirty-one 1km sections were derived for inter-correlation as above and for correlation with rate of roughness changes for each 1km. Three measures of this rate (last 2yrs, last 4yrs, and last 6yrs) were calculated from the six years of RAMM data obtained for the sections. Regression coefficients for correlations of these rates with the averaged vehicle response and profile spectra parameters are shown in Table 7. Again the

Table 6: Regression Coefficients (R^2) for 100m data points (refer Appendix A for truck model abbreviations)

			RMS sprung mass accelerations					Dynamic pavement loading DIF values									Profile spectra wavebands				
		IRI	QTF	QTR	HT	Htrac	Hsemi	QTF	QTR	HTF	HTR	HtracF	HtracR1	HtracR2	HsemiR1	HsemiR2	0-Inf	0.5-5m	5-15m	15-50m	50-100m
IRI		1																			
RMS sprung mass accelerations	QTF	**0.89**	1																		
	QTR	0.59	0.72	1																	
	HT	0.58	0.71	**0.89**	1																
	Htrac	**0.89**	0.78	0.52	0.51	1															
	Hsemi	0.71	**0.81**	0.68	0.72	0.69	1														
Dynamic pavement loading DIF values	QTF	**0.91**	**1.00**	0.71	0.69	**0.81**	**0.80**	1													
	QTR	0.58	0.72	**1.00**	**0.89**	0.51	0.68	0.70	1												
	HTF	**0.87**	**0.94**	0.78	**0.84**	0.79	**0.85**	**0.95**	0.77	1											
	HTR	0.55	0.69	**0.89**	**0.99**	0.48	0.70	0.67	**0.89**	**0.82**	1										
	HtracF	**0.91**	**0.94**	0.66	0.67	**0.87**	**0.89**	**0.94**	0.65	**0.92**	0.63	1									
	HtracR1	**0.82**	**0.85**	0.68	0.71	**0.83**	**0.96**	**0.85**	0.68	**0.89**	0.68	**0.94**	1								
	HtracR2	0.74	**0.83**	0.71	0.74	0.73	**0.99**	**0.82**	0.70	**0.88**	0.72	**0.90**	**0.97**	1							
	HsemiR1	**0.81**	**0.89**	0.67	0.70	0.77	**0.97**	**0.88**	0.67	**0.90**	0.68	**0.94**	**0.96**	**0.95**	1						
	HsemiR2	0.77	**0.86**	0.64	0.68	0.74	**0.95**	**0.85**	0.64	**0.88**	0.65	**0.91**	**0.94**	**0.94**	**0.97**	1					
Profile spectra wavebands	0-Inf	0.14	0.16	0.07	0.06	0.11	0.09	0.16	0.07	0.13	0.06	0.15	0.10	0.10	0.11	0.13	1				
	0.5-5m	**0.90**	0.73	0.45	0.45	**0.92**	0.62	0.77	0.45	0.75	0.42	**0.82**	0.76	0.65	0.72	0.68	0.10	1			
	5-15m	**0.86**	**0.99**	0.75	0.74	0.74	**0.84**	**0.98**	0.75	**0.95**	0.72	**0.93**	**0.86**	**0.85**	**0.90**	**0.87**	0.15	0.70	1		
	15-50m	0.23	0.32	0.17	0.15	0.19	0.18	0.32	0.17	0.26	0.14	0.26	0.19	0.20	0.23	0.29	0.33	0.15	0.30	1	
	50-100m	0.14	0.18	0.09	0.08	0.11	0.10	0.18	0.09	0.15	0.08	0.15	0.10	0.11	0.13	0.18	0.29	0.09	0.17	0.78	1

Table 7: Regression Coefficients (R^2) for 800m averages (refer Appendix A for truck model abbreviations)

		Roughness Changes				RMS sprung mass accelerations					Dynamic pavement loading DIF values									Profile spectra wavebands				
		1998-1992	1998-1994	1998-1996	**IRI**	QTF	QTR	HT	Htrac	Hsemi	QTF	QTR	HTF	HTR	HtracF	HtracR1	HtracR2	HsemiR1	HsemiR2	0-Inf	0.5-5m	5-15m	15-50m	50-100m
Roughness changes	1998-1992	1																						
	1998-1994	0.30	1																					
	1998-1996	0.38	0.49	1																				
IRI		0.03	0.01	0.00	1																			
RMS sprung mass accelerations	QTF	0.06	0.00	0.00	**0.92**	1																		
	QTR	0.01	0.00	0.00	**0.82**	**0.90**	1																	
	HT	0.02	0.00	0.00	**0.84**	**0.91**	**0.95**	1																
	Htrac	0.03	0.01	0.00	**0.97**	**0.90**	**0.82**	**0.83**	1															
	Hsemi	0.05	0.00	0.01	**0.82**	**0.89**	**0.87**	**0.92**	**0.85**	1														
Dynamic pavement loading DIF values	QTF	0.05	0.00	0.00	**0.94**	**1.00**	**0.90**	**0.91**	**0.92**	**0.89**	1													
	QTR	0.01	0.00	0.00	**0.82**	**0.90**	**1.00**	**0.95**	**0.81**	**0.87**	**0.89**	1												
	HTF	0.04	0.00	0.00	**0.94**	**0.98**	**0.91**	**0.96**	**0.93**	**0.93**	**0.98**	**0.91**	1											
	HTR	0.02	0.00	0.00	**0.83**	**0.90**	**0.95**	**1.00**	**0.81**	**0.91**	**0.89**	**0.95**	**0.95**	1										
	HtracF	0.06	0.00	0.00	**0.94**	**0.97**	**0.88**	**0.91**	**0.95**	**0.95**	**0.98**	**0.87**	**0.98**	**0.89**	1									
	HtracR1	0.05	0.00	0.00	**0.89**	**0.92**	**0.88**	**0.92**	**0.92**	**0.98**	**0.92**	**0.88**	**0.96**	**0.90**	**0.98**	1								
	HtracR2	0.05	0.00	0.01	**0.85**	**0.91**	**0.88**	**0.93**	**0.87**	**1.00**	**0.91**	**0.88**	**0.95**	**0.91**	**0.96**	**0.99**	1							
	HsemiR1	0.05	0.00	0.00	**0.88**	**0.94**	**0.89**	**0.93**	**0.90**	**0.99**	**0.94**	**0.89**	**0.97**	**0.92**	**0.98**	**0.99**	**0.99**	1						
	HsemiR2	0.07	0.00	0.01	**0.87**	**0.94**	**0.86**	**0.91**	**0.88**	**0.98**	**0.94**	**0.86**	**0.96**	**0.89**	**0.98**	**0.98**	**0.99**	**0.99**	1					
Profile spectra wavebands	0-Inf	0.12	0.00	0.00	0.45	0.52	0.36	0.38	0.37	0.37	0.52	0.36	0.47	0.37	0.46	0.37	0.38	0.41	0.43	1				
	0.5-5m	0.01	0.02	0.01	**0.94**	**0.81**	0.72	0.74	**0.96**	0.76	**0.83**	0.72	**0.85**	0.73	**0.87**	**0.85**	0.79	**0.82**	**0.80**	0.32	1			
	5-15m	0.05	0.00	0.00	**0.91**	**1.00**	**0.91**	**0.93**	**0.89**	**0.91**	**0.99**	**0.91**	**0.98**	**0.91**	**0.97**	**0.93**	**0.93**	**0.96**	**0.95**	0.51	**0.80**	1		
	15-50m	0.19	0.06	0.03	0.46	0.59	0.41	0.40	0.44	0.41	0.58	0.41	0.51	0.39	0.53	0.42	0.44	0.46	0.53	0.55	0.32	0.55	1	
	50-100m	0.21	0.08	0.02	0.36	0.44	0.30	0.30	0.33	0.31	0.44	0.30	0.38	0.28	0.41	0.32	0.33	0.35	0.42	0.46	0.24	0.41	**0.94**	1

expected parameter correlations show up (0.8 or more highlighted). However there is no evidence of correlation of RMS accelerations, DIF values, or profile wavelength with the roughness rate measures. Even when DIF values were factored by "%heavies*AADT" for each section to best reflect the damage potential of the wheel loading, there was no sign of correlation with the roughness progression rates.

With reference to Table 7, the poor inter-correlation between the last 2 years, last 4 years and last 6 years roughness changes was unexpected given the extent of the roughness changes over the 6 year measurement period. The correlations suggest that only 30 to 50% of the observed variations in the roughness progressions are time related, with the remaining variation most likely caused by measurement variability.

The possible causes of this variability are:

1. Location referencing relative to State Highway Reference Stations as the specified tolerance on measured survey lengths between stations is 20m ± 0.5%. A typical average distance between stations is 15km, so acceptable location errors can be on average about 95m. Where raw data are "rubber-banded" to match the actual Reference Station spacing, this error will be minimised.
2. Transverse positioning of the roughness measurements relative to the wheel tracks.
3. Differences in the response characteristics of different roughness meters used since 1992. This is in spite of laser profilers being used from 1994 onwards to measure road elevation profiles, in preference to less stable response type meters such as the NAASRA roughometer used between 1992 and 1994.

The poor correlation between the three rates of roughness change suggests that special care must be taken when making time series measurements to ensure compatibility between the different roughness measurement systems employed and tight control of both longitudinal and transverse location referencing.

4.2 Discussion

Correlation of roughness rates of change with both ride accelerations and dynamic pavement loadings was expected on the basis that high rate of change sections had been selected for the study. Of any, these sections would be most likely to exhibit banded wavelength roughness development in the 0.5-5m band for predominantly surface deterioration and in the 5-15m band for predominantly structural deterioration. In the event all sections exhibited a fairly even mix of these two profile wavelength bands and consequently no correlation with ride and dynamic loading was obtained. To illustrate the effect expected, the left hand wheelpath profile from one of the sections was modified to increase the 0.5-5m band (at the expense of all others). The same was done for the 5-15m band. In both cases profile amplitudes were adjusted to keep the IRI (average for the centre 800m) the same as the unmodified section profile. The results of RMS accelerations, and dynamic pavement loading (DIF) analyses are shown in Table 8. Note that although IRI is unchanged there are significant changes in the truck model response parameters, illustrating that these parameters could be used to refine IRI results in network surveys. To be useful in network surveys, additional analysis procedures need to be simple and efficient yet correctly reflect the additional information being sought. From the data obtained in this study the use of a Quarter Truck model is indicated as the most suitable since the Half Truck and Half Tractor Semi-trailer models do not add enough to warrant their added complexity.

Table 8 also shows the complexity of the changes in truck model response parameters to the wavelength and speed changes tabulated. It can be argued from this that a network survey parameter, such as a quarter truck DIF response, should be evaluated for a speed that fairly reflects prevailing truck speeds on the network. At a project level this should be refined to use a truck speed appropriate to the road section under consideration. To illustrate, Figure 15 contrasts the Quarter Truck and IRI quarter car sprung mass and DIF response spectra for a vehicle speed of 20m/s (72km/h). The dominance of the body bounce mode is shown as are the differences between the "resonance" wavelengths for this mode. The Quarter Truck Rear DIF peak gain of 15.3 occurs at a wavelength of 11.5m whereas the IRI quarter car DIF peak gain is at 17.7m. At a vehicle speed of 30m/s (108km/h), these peaks shift to the longer wavelengths of 17.3m and 26.6m respectively.

Table 8: Truck models response to wavelength modified profiles (refer to Appendix A for truck model abbreviations)

Truck Speed		**20 m/s** (72 km/h)			**30 m/s** (108 km/h)		
Boosted Wavelength		2m	None	10m	2m	None	10m
IRI (m/km)		4.05	4.05	4.05	4.05	4.05	4.05
RMS Sprung mass accelerations (%g)	QTF	6.48	7.26	9.58	8.51	10.26	20.02
	QTR	15.67	25.33	19.92	18.74	30.66	63.36
	HT	7.90	12.24	10.00	9.17	14.03	30.55
	Htrac	15.72	13.72	11.76	48.43	30.78	30.30
	Hsemi	5.85	7.79	8.11	15.33	22.95	18.42
Dynamic pavement loading DIF values (%)	QTF	6.40	7.24	9.25	8.91	10.22	19.02
	QTR	14.61	24.06	18.96	17.46	29.10	60.23
	HTF	6.57	7.47	8.13	8.73	9.68	17.29
	HTR	11.96	19.51	14.81	13.19	21.57	49.34
	HtracF	7.31	7.57	8.84	11.91	13.72	18.80
	HtracR1	6.60	7.32	6.65	16.45	18.76	15.09
	HtracR2	9.51	11.86	12.05	29.49	35.97	28.03
	HsemiR1	7.94	9.47	10.80	19.67	24.19	20.27
	HsemiR2	7.29	9.11	11.29	19.56	23.10	19.84

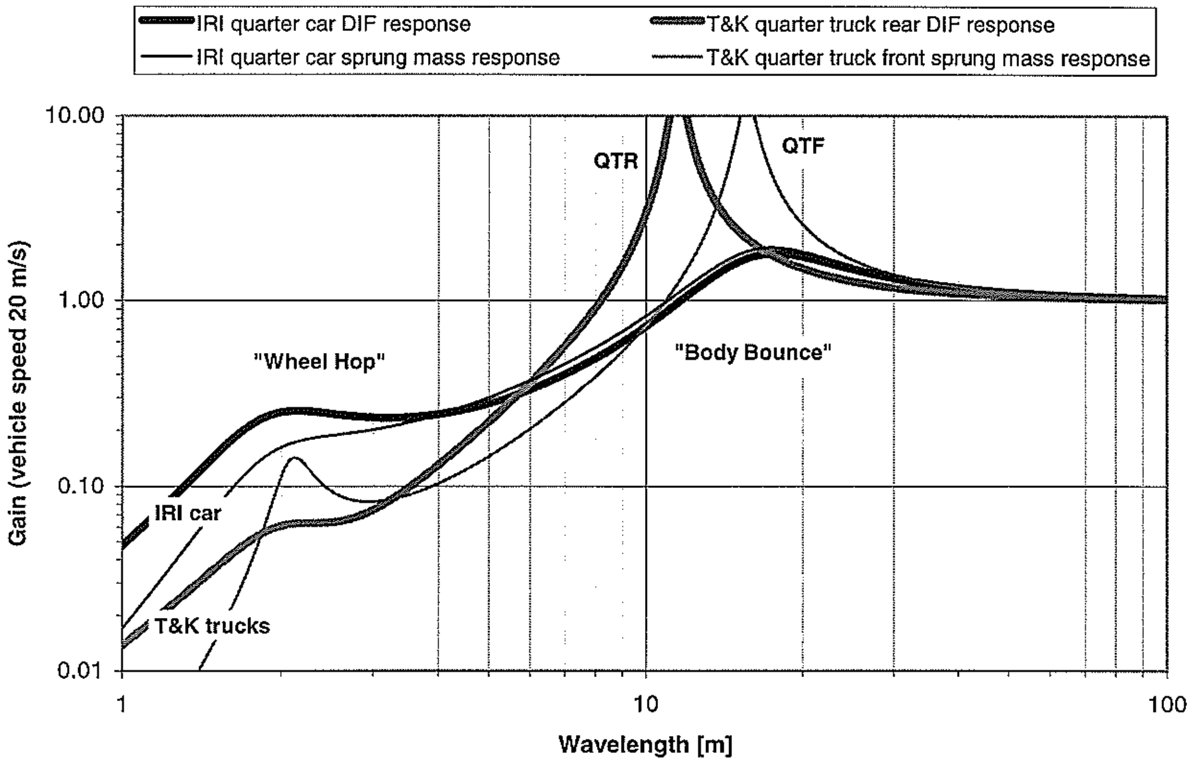


Figure 15: Quarter Car and Quarter Truck Responses (T&K = Todd and Kulakowski (1989))

5. CONCLUSIONS AND RECOMMENDATIONS

The following conclusions and recommendations have been derived from a limited application of quarter and half truck dynamic models and spectral analysis techniques to road elevation profiles obtained with WDM Limited's high speed data capture system as part of the annual road roughness survey of the sealed state highway network.

5.1 Incorporation of Quarter Truck Pavement Loading Index in Pavement Management Systems

5.1.1 Conclusions

The NAASRA roughness numeric which is linearly related to the International Roughness Index (IRI) is used in pavement management systems to determine maintenance intervention intervals and treatments. NAASRA roughness is also used for the estimation of road user costs and as a measure of ride quality of all vehicle classes. However, the research described in this report has established that in some situations NAASRA/IRI is not a reasonable indicator of pavement loading of heavy trucks. This is because the quarter car model used for calculating IRI has resonances at wavelengths of 2.3m and 16m (approximately 1.4 and 9.7 Hz at 80 km/h), and the latter is not typical of heavy trucks. At the legal speed limit, heavy trucks are excited by road surface profile wavelengths around 2.5m and 11m with the longer wavelengths usually dominating the dynamic component of wheel forces on roads.

The options available for analysing road elevation profiles to identify road sections that promote excessive wheel and body bounce are therefore to apply a digital high-pass filter corresponding to the wavelengths of interest or to use a truck dynamic model which effectively is applying a mechanical filter to the road elevation profile. The latter is preferred from a practitioner's perspective, as the calculated body accelerations and tyre forces can be more readily related to truck ride comfort and pavement loading than a filtered RMS displacement value.

From this study, the use of a quarter truck (rear axle) model has been identified as being most suitable, because the half truck and half tractor semi-trailer models do not add enough extra information to warrant their added complexity which translates into longer processing times. The dynamic impact factor (DIF) utilised in this report appears to be a suitable index for pavement management purposes, as it not only provides a measure of dynamic pavement loading but also correlates well with truck ride quality. The DIF is expected to indicate damage to the road at an earlier state than IRI/NAASRA roughness.

5.1.2 Recommendations

To maximise the benefit from state highway road roughness surveys performed with profilers, the "dynamic impact factor" calculated using a quarter truck (rear axle) model should be stored in a pavement management system such as RAMM along with the IRI/NAASRA numeric already obtained. Together, these two indices will allow better assessment of networks for priority maintenance and reconstruction forecasting purposes. By transfer function formulation, a quarter truck DIF analysis could be made as computationally efficient as the current IRI analysis, and therefore inclusion in routine survey data processing would not pose significant problems. However, before routine implementation it would be prudent to analyse existing longitudinal profile data for the complete state highway network (both IRI and DIF for both wheelpaths and at two speeds) as a check that complementary information is provided by the proposed DIF index.

5.2 Application of Spectral Analysis Methods to Special Roughness Related Investigations and Deterioration Modelling

Two spectral analysis methods evaluated in this report show considerable promise for special investigations of pavement roughness, since longitudinal profile features that significantly contribute to overall roughness levels or dynamic pavement loading can be specifically located. In addition, the wavelength of each feature is known so appropriate remedial measures can be identified. These methods are wavelet analysis and sectional power spectral density (PSD) whereby a cascade plot of profile spectra at fixed intervals along the profile length is produced. Any non-homogeneous lengths along a road section are readily highlighted, since both methods are graphically based.

By using either method, greater discrimination of bad and good construction and maintenance practices, and associated deterioration mechanisms, is possible than from the IRI/NAASRA numeric.

5.2.1 Recommendation

Whenever longitudinal elevation profiles are available, either wavelet analysis or sectional power spectral density should be employed in special investigations to aid the interpretation of pavement deterioration leading to more efficient management of the road network through adoption of more appropriate rehabilitation strategies and better formulated pavement deterioration models.

5.3 Integrity of RAMM Roughness Records

It is a matter of some concern that current (1998) IRI/NAASRA roughness as recorded in RAMM was not reasonably well matched by IRI/NAASRA roughness values independently derived from the source longitudinal elevation profiles. This outcome suggests problems with the matching of the raw profiles to RAMM state highway network reference stations. The other outcome of note was the high degree of variability in the 1992-1998 time series roughness measurements over the selected 31 road sections despite the use of laser-based profilers. Profilers are supposedly much less susceptible to mechanical system changes than response-type meters. This result suggests that particular care must be taken when roughness measurements are made on long term performance monitoring sites to ensure that any changes in observed roughness levels due to pavement distress are not masked by measurement system variability introduced by factors such as inaccurate positioning or changes to operational characteristics.

5.3.1 Recommendation

Roughness data acquired as part of the annual automatic condition survey of the state highway network appear to be too unreliable for developing and refining road asset management tools such as the proposed dynamic impact factor and pavement deterioration models. Research is, therefore, urgently required to quantify positioning effects (longitudinal and transverse) on resulting measures of roughness to establish whether or not an automatic means for locating roughness measurements along and across a lane is necessary. The sensitivity of profiler-based roughness measurements on coarse textured chipseal surfaces to lateral position, is an area that merits particular attention given the size difference between the laser spot footprint and a vehicle tyre footprint.

6. REFERENCES

Cenek, P.D.. 1996. Review of instruments for measuring the texture profile of road surfaces. *Transit New Zealand Research Report No. 63*. 88pp.

Daubechies, I. 1988. Orthonormal bases of compactly supported wavelets. *Communications in Pure and Applied Mathematics* 41: 909-996.

de Pont, J. 1994. Road profile characterisation. *Transit New Zealand Research Report No. 29*. 45pp.

Heywood, R.J., Ramsay, E.D., McLean, J.R., Karagania, R.M. 1996. Road roughness – infrastructure damage based standards. *Proceedings Roads '96 Conference 4, Asset Management and Freight,* [ARRB Transport Research Ltd, Australia]: 307-321.

ISO.1995. Mechanical vibration – road surface profiles – reporting of measured data. International Standard ISO/DIS 8608: 1995.

Legeay, V. 1994. Examples of applications of methods of spectral analysis of the length profile analyser. *Bulletin de Liaison des Laboratoire des Ponts et Chaussées, No. 192:* 11-17.

Mann, A.V., McManus, A.M., Holden, J.C.. 1997. Power spectral density analysis of road profiles for road defect assessment. *Road and Transport Research* 6(3): 36-47.

OECD Road Transport Research. 1992. Dynamic loading of pavements. 184pp OECD, Paris.

Prem, H. 1989: NAASRA roughness meter calibration via the road-profile-based international roughness index (IRI). *Research Report ARR164,* Australian Road Research Board (ARRB), Vermont South, Victoria, Australia.

Todd, K.B., Kulakowski, B.T. 1989: Simple computer models for predicting ride quality and pavement loading for heavy trucks. *Transportation Research Record 1215:* 137-150.

APPENDIX A Response Characteristics of Quarter and Half Truck Models.

Table A1: Quarter and Half Truck Model Parameters

	Quarter Truck (QT)		**Half Truck** (HT)	
	Front (QTF)	Rear (QTR)	Front (HTF)	Rear (HTR)
Sprung mass - M_s (kg)	2447	4010	6457	
Sprung mass pitch moment of inertia - I_y (kg–m^2)	-		46406	
Distances to sprung mass C of G - A, B (m)	-		3.786	2.310
Unsprung mass - M_u (kg)	272	521	272	521
Suspension spring stiffness - K (kN/m)	198.2	1138	198.2	1138
Suspension damping* - C (kN/m/s)	2.627	2.627	2.627	2.627
Tyre vertical stiffness - K_t (kN/m)	788.0	875.6	788.0	875.6

* Value increased to 17.1 kN/m/s (more typical of heavy commercial vehicle suspension damping) for use in profile traverse response simulations.

Table A2: Half Tractor Semi-trailer Model Parameters

	Tractor (Htrac)			Semi-trailer (Hsemi)	
	Front (HtracF)	Leading Rear (HtracR1)	Trailing Rear (HtracR2)	Leading Rear (HsemiR1)	Trailing Rear (HsemiR2)
Sprung mass - M_{s1} , M_{s2} (kg)	1,821			14,314	
Sprung mass pitch moment of inertia - I_{y1} , I_{y1} (kg–m^2)	22,653			10,234	
Distances from coupling to C of G - B_5 , A_2 (m)	3.014			5.984	
Distances to sprung mass C of G - A_1 , B_1 , B_2 , B_3 , B_4 (m)	1.527	3.209	4.507	5.599	6.817
Unsprung Mass - M_{u1} , M_{u2} , M_{u3} (kg)	271.9	521.2	521.2	339.9	339.9
Suspension Spring Stiffness - K_1 , K_2 , K_3 (kN/m)	198.2	1261	1261	1313	1313
Suspension Damping* - C_1 , C_2 , C_3 , (kN/m/s)	2.627	2.627	2.627	2.627	2.627
Tyre Vertical Stiffness - K_{t1} , K_{t2} , K_{t3} (kN/m)	788.0	1576	1576	1751	1751
Coupling Stiffness - K_5 (kN/m)	17,510				
Coupling Damping - C_5 (kN/m/s)	175.1				

* Value increased to 17.1 kN/m/s (more typical of heavy commercial vehicle suspension damping) for use in profile traverse response simulations.

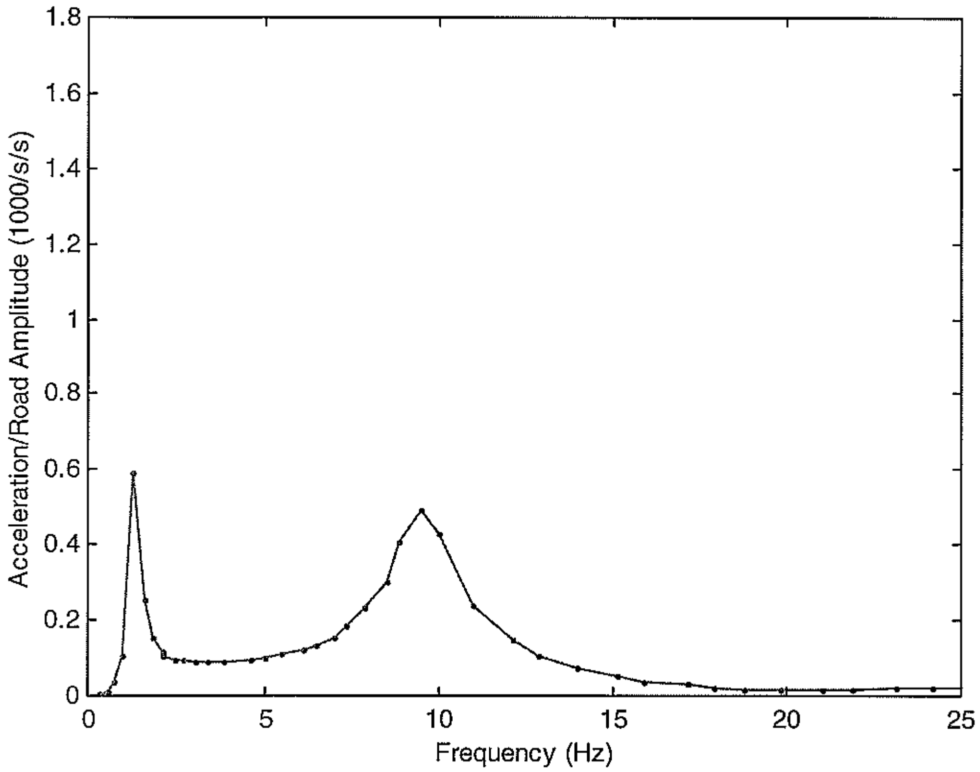


Figure A1: Quarter Truck Front Axle Sprung Mass Response

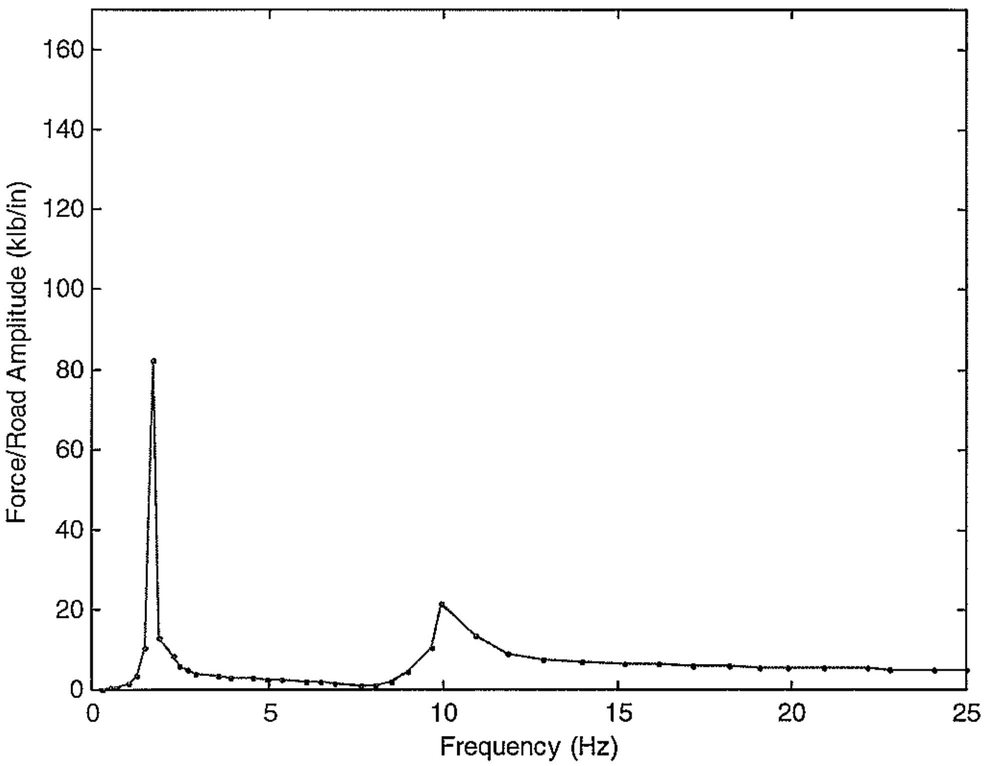


Figure A2: Quarter Truck Rear Axle Tyre Force Response

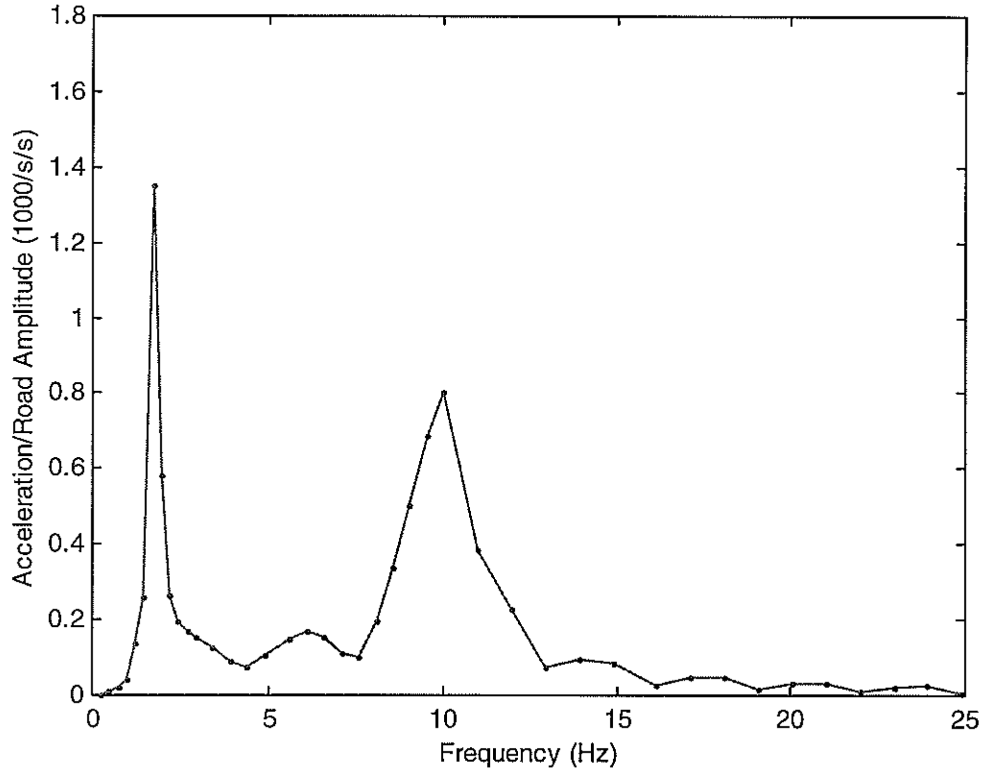


Figure A3: Half Truck Sprung Mass Response

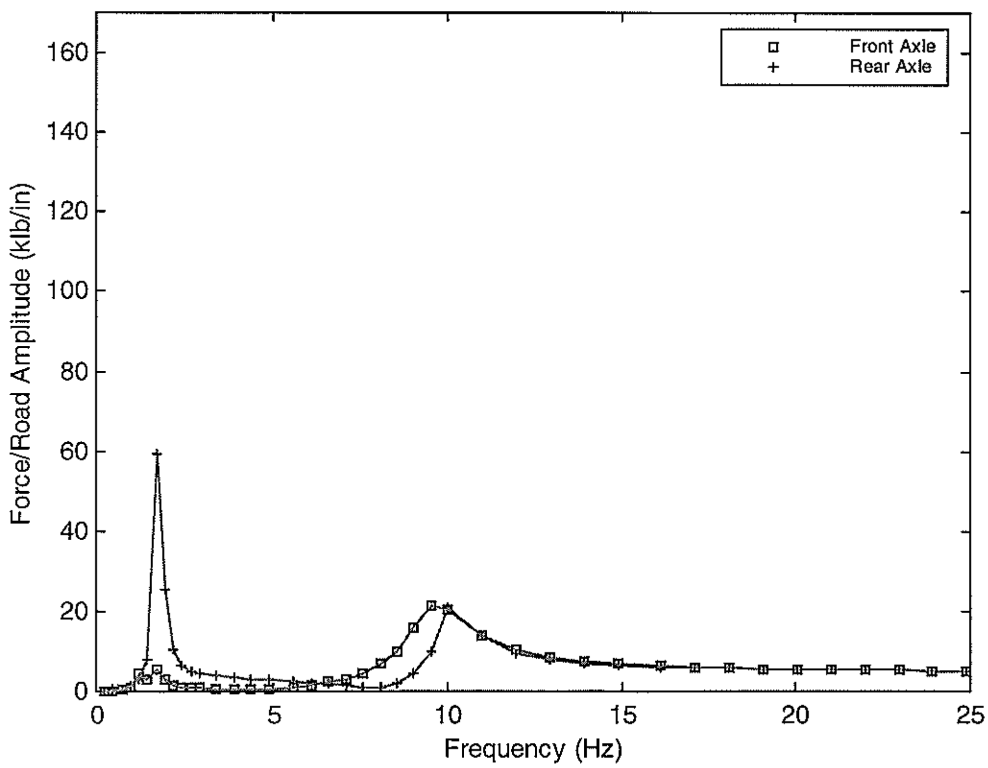


Figure A4: Half Truck Tyre Force Response

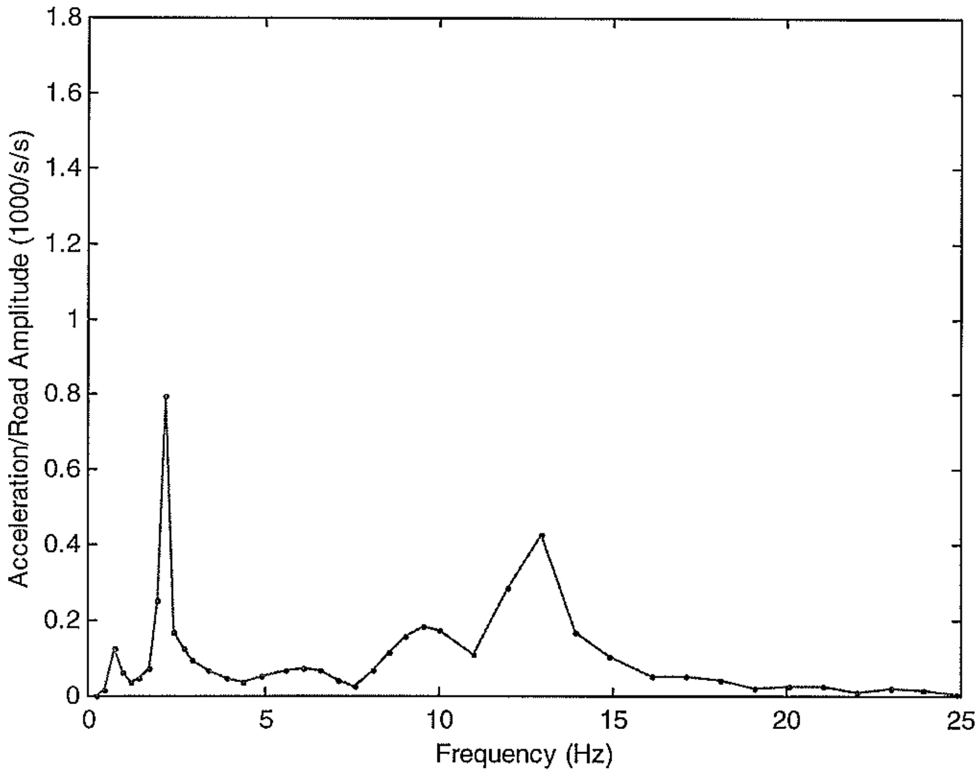


Figure A5: Half Tractor Semi-trailer Sprung Mass Responses

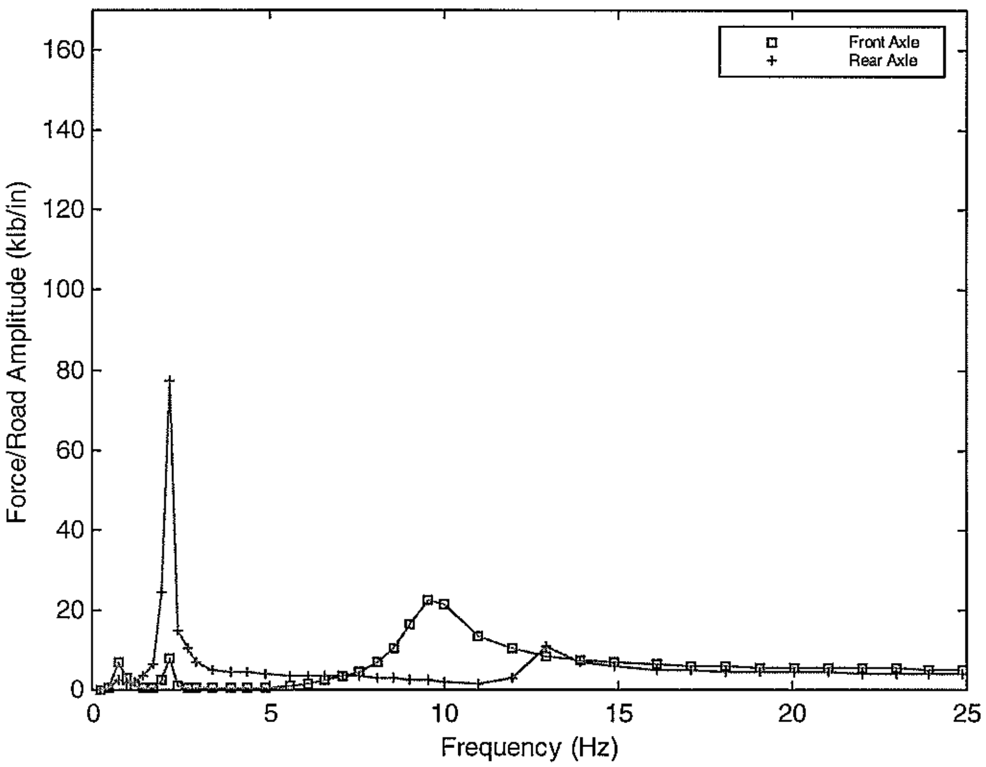


Figure A6: Half Tractor Semi-trailer Tyre Force Responses (Tractor)

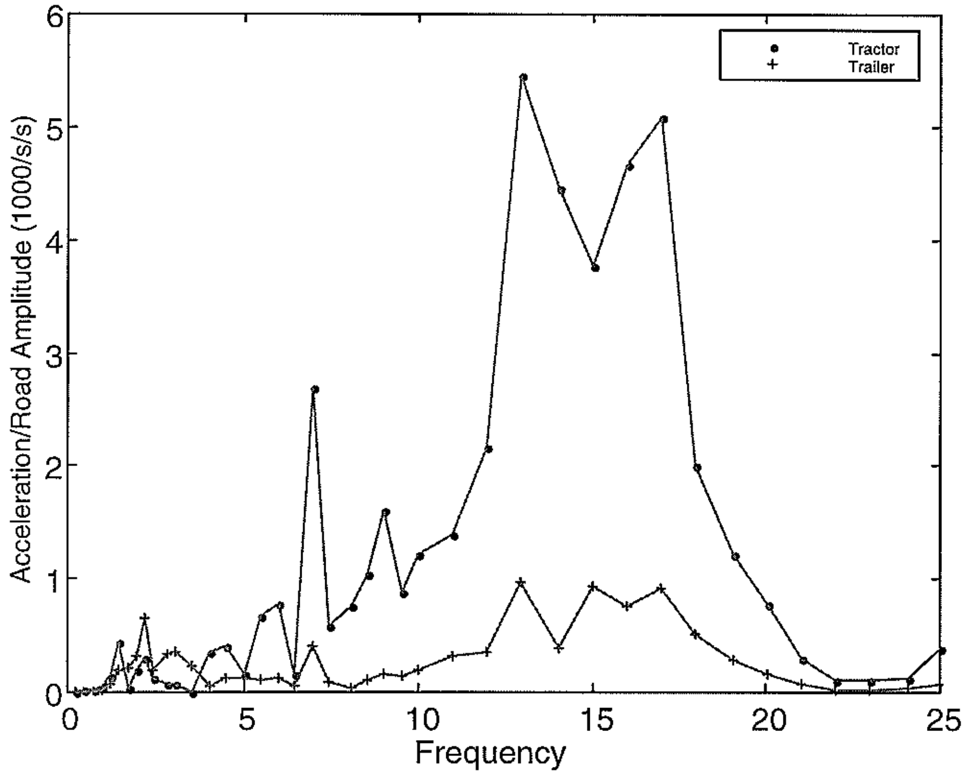


Figure A7: Half Tractor Semi-trailer Tyre Force Responses (Trailer)

APPENDIX B Wavelet Reconstruction.

Wavelet Reconstruction

The following figures show the integrity of the wavelet reconstruction. The wavelet function used for the analysis is that proposed by Daubechies (1988). An order 5 Daubechies wavelet function as shown in Figure B1, was chosen to give satisfactory resolution in both position and frequency. The order 5 wavelet is stretched and scaled to produce a decomposition of the input profile. A multi-level reconstruction is shown in Figure B2. Each successive level has double the wavelength band content of the previous level. The sum of the reconstruction levels can be used to reproduce the original input profile. Figure B3 and the filtered profiles of Figure B4 show that the reconstruction is virtually indistinguishable from the original profile. Ride acceleration and dynamic wheel loadings were calculated for all truck models traversing the original and reconstructed profiles. No discernible differences were found in any of these truck response parameters, providing further confirmation of the integrity of the wavelet reconstruction.

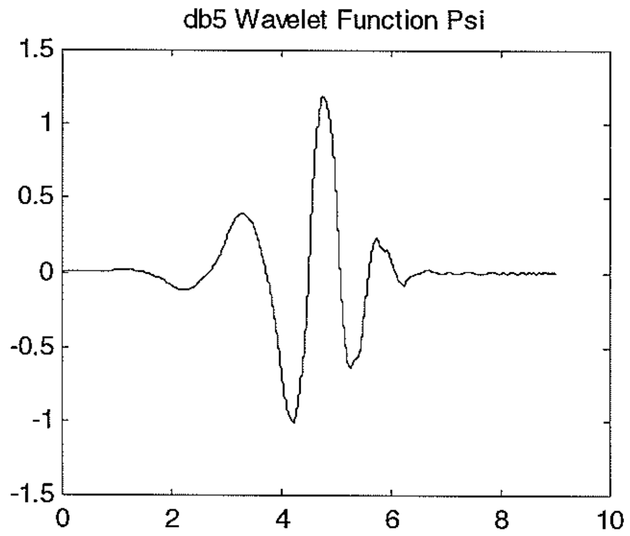


Figure B1: Daubechies Order 5 Wavelet

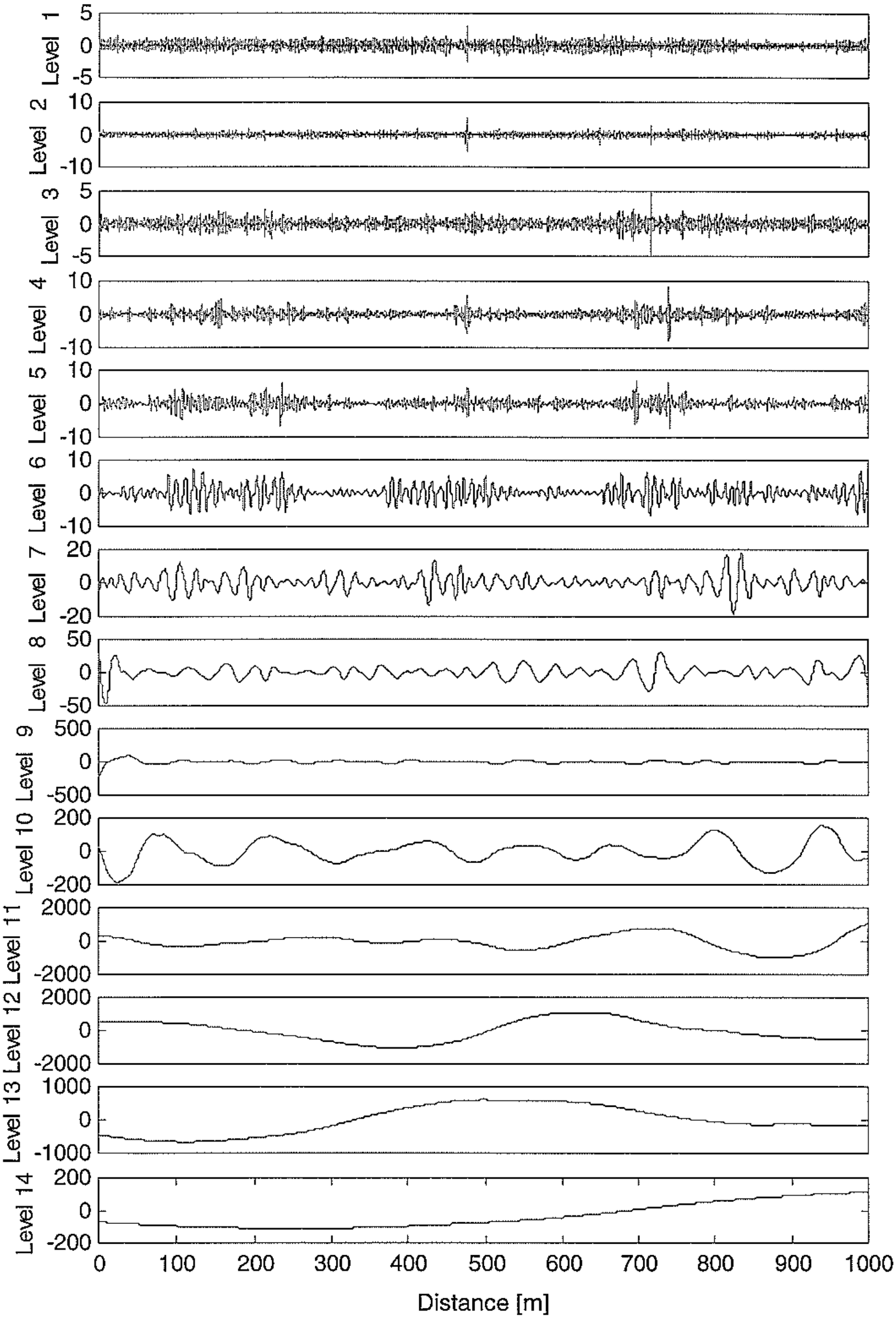


Figure B2: Wavelet Reconstruction Levels

State Highway 1N RS83(increasing), 0-1km,left hand wheelpath

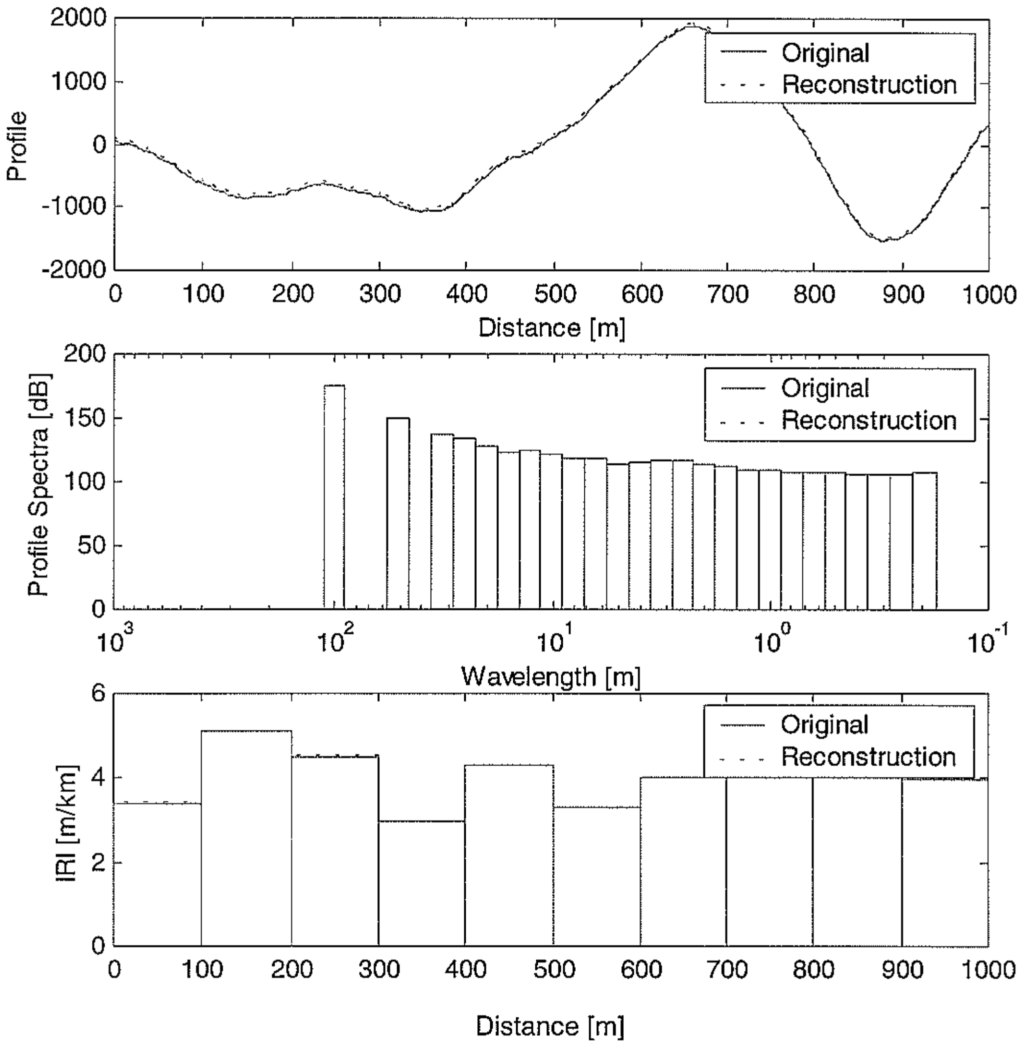


Figure B3: Original Profile and Wavelet Reconstruction Properties

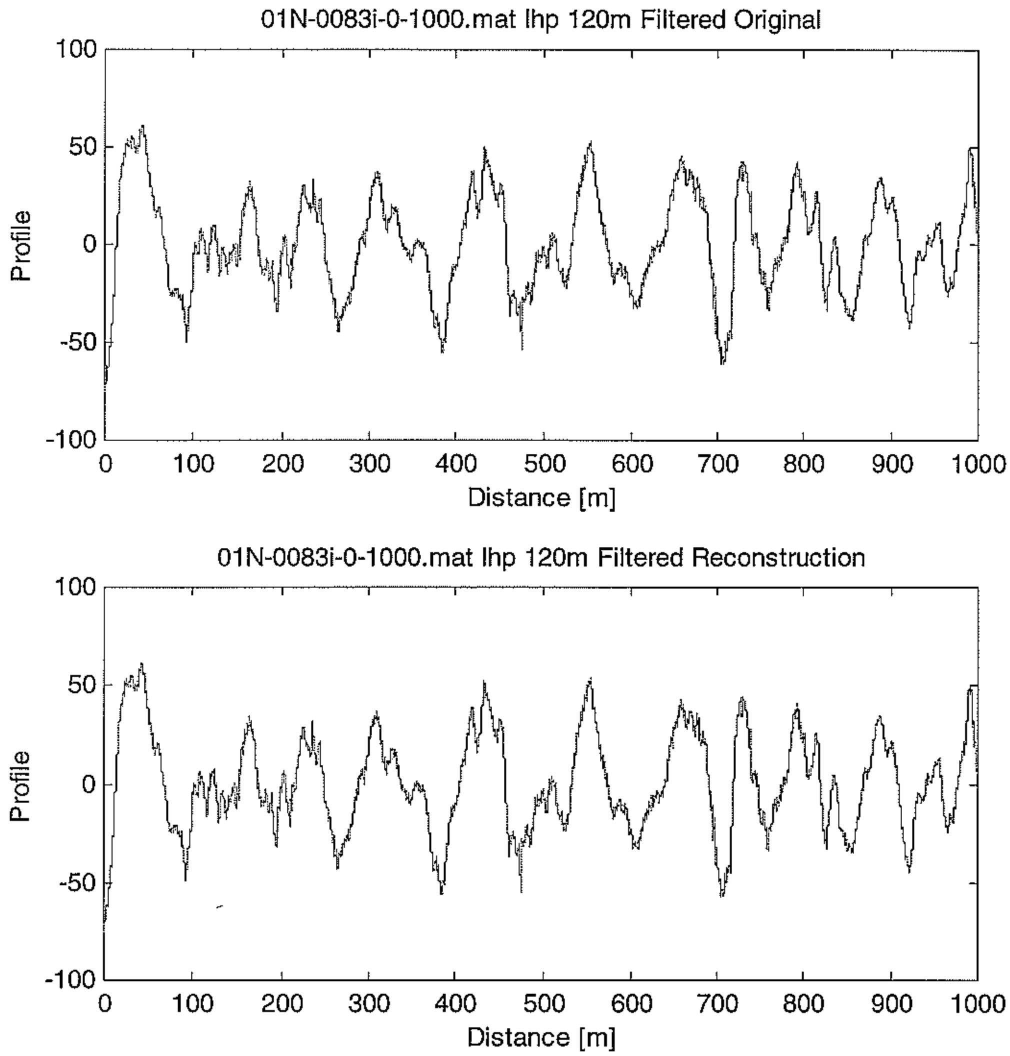


Figure B4: Filtered Original and Reconstructed Profiles

APPENDIX C Thirty-one 1km State Highway Sections Studied.

Table C1: Road Sections (1km) with Significant Roughness Progressions

Table C1: Road Sections (1km) with Significant Roughness Progressions

Region Name	road_id	road_name	sh	rs	startm	endm	1992	1993	1994	1995	1996	1997	1998	LHP NAASRA Profile	RHP NAASRA Profile	AVG NAASRA Profile
Bay Of Plenty	1725	002-0146d	002	146	1000	2000	68.60	72.89	80.00	77.44	78.11	95.33	96.11	91.02	93.17	92.09
Northland	10	01N-0083d	01N	83	1000	2000	70.00	69.22	66.00	81.11	79.89	85.11	87.33	80.54	68.65	74.60
Waikato	1562	025-0024d	025	24	5000	6000	51.71	48.57	51.31	60.44	61.89	61.78	80.22	88.72	89.09	88.90
Waikato	1562	025-0024d	025	24	12000	13000	59.56	60.67	57.11	58.67	60.89	73.67	79.67	74.72	60.53	67.63
Waikato	1562	025-0024d	025	24	14000	15000	46.00	48.00	49.10	46.56	48.44	62.67	71.00	75.72	74.80	75.26
Waikato	1562	025-0024d	025	24	13000	14000	45.11	47.11	43.88	46.56	51.22	65.56	74.67	96.01	82.59	89.30
Waikato	1427	027-0067d	027	67	4000	5000	41.33	40.44	41.22	41.67	48.00	62.11	61.44	60.76	63.23	62.00
Waikato	1427	027-0067d	027	67	3000	4000	51.11	49.44	51.67	50.33	49.67	58.44	70.67	90.88	50.52	70.70
Waikato	1423	027-0027d	027	27	1000	2000	55.89	53.67	55.89	56.11	63.44	73.11	75.33	88.25	74.29	81.27
Waikato	1423	027-0027d	027	27	0	1000	54.56	58.00	54.00	55.30	56.40	66.40	69.00	93.76	66.21	79.98
Waikato	1426	027-0046d	027	46	18000	19000	46.89	43.44	42.67	50.33	47.50	50.63	58.89	87.72	55.93	71.83
Waikato	1443	029-0061d	029	61	2000	3000	64.00	60.11	63.44	65.11	65.78	82.11	80.33	92.11	76.17	84.14
Waikato	1580	031-0015d	031	15	0	1000	114.60	109.50	114.00	117.67	118.11	128.00	133.78	147.88	121.59	134.74
Waikato	228	002-0018i	002	18	0	1000	59.20	61.18	62.09	64.30	63.60	68.60	77.22	64.63	71.82	68.23
Northland	10	01N-0083i	01N	83	0	1000	70.18	65.91	69.00	75.22	76.56	79.78	85.11	109.69	87.04	98.37
Waikato	1417	026-0070i	026	70	8000	9000	65.78	70.33	69.89	75.67	74.33	84.44	86.67	88.33	76.10	82.22
Waikato	1423	027-0027i	027	27	0	1000	52.30	46.90	53.90	53.90	55.20	73.90	81.44	74.79	69.65	72.22
Waikato	1426	027-0046i	027	46	5000	6000	50.20	51.60	52.00	49.30	48.40	51.20	79.78	84.29	65.49	74.89
Waikato	1426	027-0046i	027	46	10000	11000	37.70	41.80	49.00	52.30	51.50	56.60	66.00	53.74	49.74	51.74
Waikato	1426	027-0046i	027	46	17000	18000	43.70	38.70	43.50	53.80	51.60	64.00	62.11	77.35	67.97	72.66
Waikato	1441	029-0042i	029	42	3000	4000	49.38	50.67	51.89	59.78	62.00	64.11	69.44	68.21	60.08	64.14
Waikato	1441	029-0042i	029	42	4000	5000	46.89	55.33	52.60	54.89	56.44	59.67	70.56	61.19	66.18	63.68
Waikato	1443	029-0061i	029	61	3000	4000	52.89	57.00	51.67	57.89	57.00	63.00	66.89	79.45	76.78	78.11
Waikato	1443	029-0061i	029	61	2000	3000	67.78	63.33	59.78	69.67	67.56	75.00	77.22	82.39	65.75	74.07
Waikato	1580	031-0015i	031	15	0	1000	94.50	96.33	100.20	101.33	100.89	117.22	119.33	142.89	124.40	133.64
Waikato	1580	031-0015i	031	15	1000	2000	94.78	97.67	97.50	100.44	99.11	107.89	116.00	125.13	86.53	105.83
Waikato	1581	031-0031i	031	31	1000	2000	87.22	95.00	95.50	104.33	104.44	108.78	113.33	134.29	80.54	107.42
Waikato	1581	031-0031i	031	31	3000	4000	98.90	106.80	110.50	111.56	113.22	125.33	129.00	163.52	102.34	132.93
Waikato	1864	032-0015i	032	15	2000	3000	87.00	84.44	90.89	93.33	98.22	113.22	110.67	132.28	108.86	120.57
Waikato	1864	032-0015i	032	15	9000	10000	89.78	94.11	101.56	107.56	105.11	115.00	117.67	116.53	118.31	117.42
Waikato	1864	032-0015i	032	15	10000	11000	105.00	105.78	103.25	106.67	112.33	121.22	121.22	116.75	110.38	113.56