THE ANALYSIS AND SIMULATION OF THE SPECTRAL AND STATISTICAL PROPERTIES OF ROAD ROUGHNESS FOR PACKAGE PERFORMANCE TESTING

by

Ben Bruscella

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Department of Mechanical Engineering
Victoria University of Technology

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ABSTRACT

The laboratory evaluation of package performance is traditionally based on the reproduction of vehicle vertical acceleration from the Power Spectral Density (PSD) estimate. The vertical vehicle response acceleration is primarily a function of vehicle suspension and speed, but is ultimately caused by fluctuations in the road surface. This thesis introduces a universal analysis and classification methodology for discretely sampled road profile data. It originates from the premise that current laboratory simulation of the transport environment, which utilises vehicle tray acceleration, is inadequate for package optimisation through performance testing. Package evaluation procedures, which utilise the road surface roughness as the fundamental excitation variable, are shown to require an accurate road profile characterisation for successful implementation.

In this study, several hundred kilometres of Victorian (Australia) road profile data are analysed with the focus on the characterisation of their non-Gaussian and non-stationary properties, for future use in the simulation of the road transportation process. Road profiles are found to be highly non-stationary, non-Gaussian, and contain transients. However, transients are difficult to locate when the data is analysed in the road profile elevation domain. The road profile spatial acceleration is adopted as the preferred analysis domain as roughness variations and transient events are identified with greater reliability and accuracy. Computer software is designed to automatically detect and extract transient events from the majority of road data, which contains short segments of constant RMS level. Transients are analysed separately from the constant RMS sections. Nine universal classification parameters are introduced to fully describe road profile spatial acceleration characteristics from the transient amplitude and stationary RMS distributions. Results from this study are applied to the areas of simulation of roads and classification of individual roads based solely on the nine classification parameters.

NOMENCLATURE

α	Spatial acceleration
ε	Spectral width parameter
λ	Wavelength
μ	Mean
η	Height of maxima
σ	Standard deviation
ρ	Density
μ_αRMS	Stationary RMS distribution mean
σ_αRMS	Stationary RMS distribution standard deviation
ρ_αT	Transient density
μ_αT	Transient amplitude distribution mean
σ_αT	Transient amplitude distribution standard deviation
Ψ^2	Mean square
$\gamma^2(n)$	Coherence
Δn	Spatial frequency resolution
a	Peak height
APD	Amplitude probability distribution
ARRB	Australian Roads Research Board
AS	Australian Standards
ASTM	American Society for Testing and Materials
bin #	Constant RMS bin number
DFT	Discrete Fourier transform
f	Frequency
FFT	Fast Fourier transform
f_s	Sampling frequency
g	Acceleration due to gravity (9.81 m/s^2)
G^*	Complex conjugate of G
G_{AA}	Auto spectrum of A
Hz	Hertz
IRI	International Roughness Index

ISO	International Organisation for Standardisation
M	Median
$M_{\alpha}RMS$	Stationary RMS distribution median
$M_{\alpha}T$	Transient amplitude distribution median
NAASRA	National Association of Australian State Road Authorities
n	spatial frequency
N	Number of samples (sample size)
N_d	Number of distinct spectral averages
p(y)	probability of variable 'y'
PDF	Probability density function
PSD	Power spectral density
R	Range
$R_{\alpha}RMS$	Stationary RMS distribution range
$R_{\alpha}T$	Transient amplitude distribution range
RMS	Root mean square
RTRRMS	Response Type Road Roughness Measurement System
RVC	Random Vibration Controller
S_D	Single Track Spectrum
S_X	Cross Track Spectrum
T	Transient amplitude
x	horizontal distance
y	Elevation
y'	Spatial velocity
y''	Spatial acceleration
$\dot{y}$	Temporal velocity
$\ddot{y}$	Temporal acceleration

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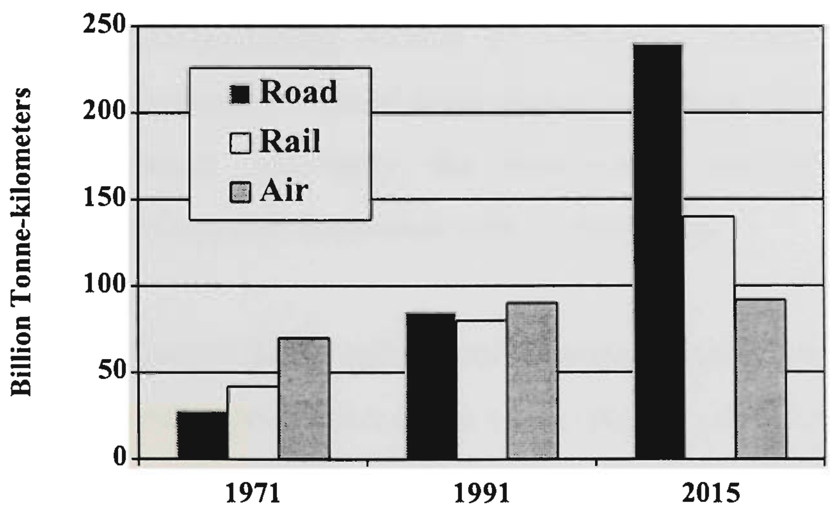
1. INTRODUCTION

Products are inevitably damaged in transportation and handling if they are not packaged adequately. Mechanical damage to products in transit is attributed to vibrations and shocks experienced in the transportation environment. The inclusion of a packaging system aims to reduce product damage but usually results in an increase to the cost of the product as deficient or excessive product protection through packaging is costly. Insufficient packaging is self evident through the incidence of damage, but the over-packaging of products is not as easily detectable. Available estimates of costs associated with over-packaging are 130 billion European Currency Units (Ostergaard, 1991). Hidden costs associated with shipment of over-packaged products may be 20 times greater than the cost of excessive packaging materials and it has been estimated that a 40% reduction in packaging volume is possible (Ostergaard, 1991).

The last 20 years have seen a dramatic increase in the movement of freight in Australia alone with activity more than doubling (VicRoads, 1995). The use of road transport has become increasingly popular and it is estimated that, by the year 2015, the shipment of products on roads will increase significantly as shown in Figure 1.1.



Source: National Transport Planning Task force, December, 1994

Figure 1.1. Growth of domestic freight transport in Australia (VicRoads 1995)

Austroads (1997) reports the split of domestic freight movement across four principle modes of road, rail, sea and air as 98.5, 95.2, 96.0 and 0.14 billion tonne-kilometres respectively. However, as observed by Silver and Szymkowiak (1979) and American President Companies (1986), road vehicles produce the highest vibration levels of all three transport modes. Consequently, the ability to design optimum protective packaging for transportation will become even more important than it is today. It will no longer be sufficient to design packaging systems based solely on the minimisation of damage to the product it encases. The influence of global environmental problems will force packaging engineers to arrive at optimum packaging configurations with substantial consideration given to minimising the use of packaging material.

Ideally, optimum package configurations should be designed and developed in conjunction with the product itself to minimise packaging material whilst ensuring the safety of the product. In practice however, package configurations are determined after product development has been completed, which demands that these configurations are validated. This is often achieved through empirical field testing methods which subjects packaged products to the actual transportation environment. If damage occurs to the package or product during field testing, the package is re-designed and tested again until a satisfactory, but not necessarily optimum, design is determined. Although field testing ensures that product-packaging systems are subjected to actual transportation hazards, it is useful only to identify cases of under-packaging. Once a package design is shown to protect a product sufficiently, the reduction of package materials is discouraged due to the cost and time associated with further testing.

Recent developments in the simulation and control of random signals have found direct application to the approximate description of the transportation environment. This has enabled laboratory testing and verification of package-product system designs which has several advantages over field verification methods. Various package configurations can be tested in a relatively short period of time without associated transport vehicle operation and staff expenses. Repeatable simulation enables results to be documented and communicated amongst organisations. The possibility for rapid testing of designs enables over-packaging to be minimised. Advantages and disadvantages of field and laboratory testing are outlined in Figure 1.2.

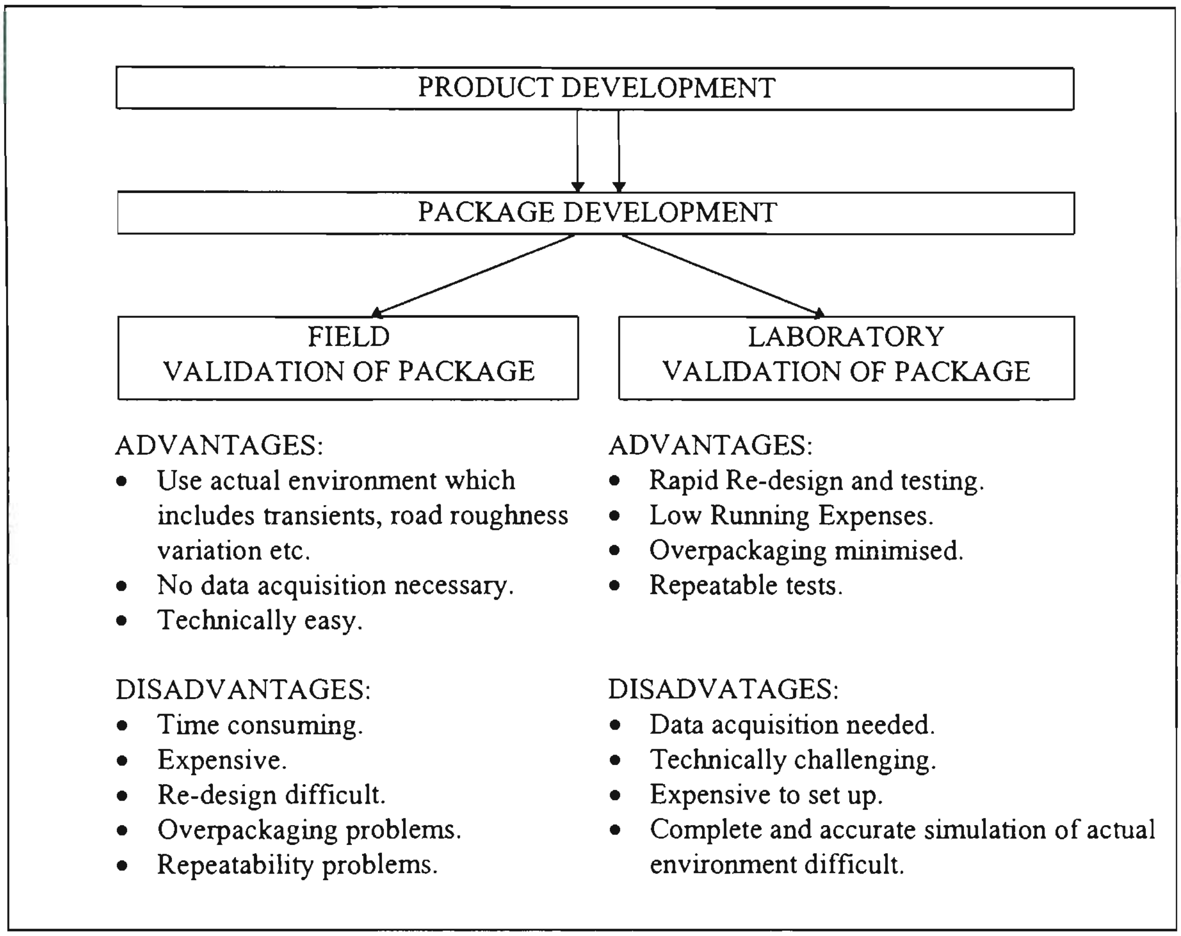


Figure 1.2. Schematic for package development and testing

The fundamental disadvantage associated with the evaluation of package configurations in the laboratory is related to difficulties with the accurate characterisation of the actual environment. Package evaluation for the road transportation environment is concerned with the design of packages to withstand the vertical motion of the vehicle primarily caused by fluctuations in the road surface. These include sporadic variations in texture and roughness as well as local defects such as potholes and cracks. When combined with typical vehicle suspension characteristics and changes in vehicle speed, these road fluctuations produce vehicle vibrations which are not readily reproduced in the laboratory. Successful implementation of laboratory testing of packages for road transportation is dependant on the accurate simulation of the actual environment.

During a typical road journey, a package/product system is subjected to both vibrations and shocks simultaneously. Parameters commonly used to describe the road transportation environment hazards, such as drop heights, shock levels and vibration levels, have been utilised as the basis for laboratory package performance testing. Testing procedures should aim at simulating the combined effects of all transportation hazards collectively rather than treating them as separate phenomena. Recent attempts made at developing standard laboratory testing procedures in accordance with this concept are discussed in the following chapter. There are standard methodologies in place for the laboratory evaluation of package performance which have major shortcomings. This is a direct result of complications encountered with the accurate characterisation of vehicle vibrations.

The contemporary methodology for simulating the road transport environment is principally concerned with the characterisation of vertical vibrations levels occurring on the loading tray of a vehicle for a particular journey. Vertical vehicle vibration is caused primarily by the road surface, and is a function of the vehicle response characteristics and vehicle speed. Consequently, the accurate simulation of the transport process requires that the vertical vibration levels of vehicles are measured for each unique journey and vehicle type, and must be recorded as a function of vehicle speed. This is an expensive and time consuming exercise which has, in some cases, led to the use of so called 'standard testing road spectra' at the expense of veracity. Since the primary causes of vehicle vibrations are the fluctuations along road surfaces, it is clear that accurate characterisation of a wide range of road surface profiles, in conjunction with knowledge of vehicle suspension properties is sufficient to predict the vibrational response of vehicles. The main advantage of this technique is that as road surfaces, for the most part, remain unchanged, characterisation needs to be undertaken only once.

2. LITERATURE REVIEW

This chapter covers three main areas of literature examination. Firstly, existing laboratory techniques for package evaluation formulated by major standard organisations is reviewed. This is followed by a review of techniques used to characterise vehicle vibrations during road transport. Thirdly, methodologies for the analysis of road surfaces, with respect to vehicle-road interactions, are critically investigated.

2.1 REVIEW OF STANDARD LABORATORY PACKAGE EVALUATION TECHNIQUES

The evaluation of package performance testing in the laboratory is sanctioned by standard organisations world wide. The major organisations involved are International Organisation for Standardisation (ISO), Australian Standards (AS) and American Society of Testing and Materials (ASTM). The development of standard methodologies has been specific so that miss-interpretation of results is minimised. A consequence of this is that the prescribed testing levels are often too high and result in the over-packaging of products. Testing levels prescribed in standard procedures are not always representative of the actual environment.

In 1980, the ISO approved ISO 4180 *'Complete, filled transport packages - General Rules for Compilation of Performance Schedules'.* The AS 2584 with the same title is technically identical. The ASTM recognised the open ended approach of ISO 4180 and the need for development of test methods that reflect the conditions that products experience in normal shipment. The ASTM implemented ISO 4180 as ASTM 4169 *'Standard Practice for Performance Testing of Shipping Containers and Systems'.* This standard is more specific than ISO 4180 and AS 2584 and helps to develop test sequences that include quantified levels of intensities.

According to ASTM D 4169, testing for effects of loose load vibration and vehicle vibration can be achieved with the use of procedures outlined in ASTM D 999 '*Standard methods for vibration testing of shipping containers*'. The ability of a shipping unit (package and product) to withstand damage caused by vertical vibrations of transport vehicles is assessed by method B - Single container resonance test or method C - Palletised load, unitised load or vertical stack resonance test. A similar procedure is incorporated in ASTM D 3580 '*Standard test methods of vibration (vertical sinusoidal motion) test of products*'.

These procedures all consist of two main parts: establishing the resonant frequencies of the packaging system and performing a resonance (sine) dwell endurance test at specific resonant frequencies for a specified length of time or until damage occurs. According to ASTM D 999, system resonances are identified by generating a constant level acceleration sinusoid with variable (sweeping) frequency at the surface on which the product is mounted while constantly monitoring the response acceleration.

The continuous type of deterministic excitation that the ASTM D 999 standard subjects a test package to leads to the possibility of over-packaging as it is unlikely that resonant frequencies are sustained for great lengths of time in an actual transport environment. Further, it is rare that actual excitations are deterministic (harmonic) in nature. ASTM D 999 is an example of 'worst case' package performance testing (Sek *et al*, 1997).

Since shipping containers are exposed to complicated dynamic stresses in the distribution environment, the approximation of product damage, or lack of it, is only possible by subjecting a test package to vibrations which emulates the unpredictable (random) actual environment. As package resonances are excited simultaneously, the resonant build up is less intense than those induced during the resonant dwell or sine sweep methods, and unrealistic damage to test specimen is minimised.

The now commonly used method for experimentally evaluating the effectiveness of packaging systems subjected to random vibrations is outlined in ASTM D 4728-95 '*Standard Test Method for Random Vibration Testing of Shipping Containers*'. This standard can be used to assess the ruggedness and performance of shipping units subjected to random vibrations representative of three common modes of transport: road, rail and air. The ASTM D 4728 standard is based on the conjecture that more accurate representation of the common modes of transport is achieved by reproducing a random signal in the laboratory based on its spectral characteristics. Test specimens are placed on a shaker system with the command signal represented by the Power Spectral Density (PSD) estimate of the transport environment. Recommended for use by the standard, transportation PSD's are shown in Figure 2.1 which represent the linear average of a large number of PSD's obtained experimentally over a long period of time.

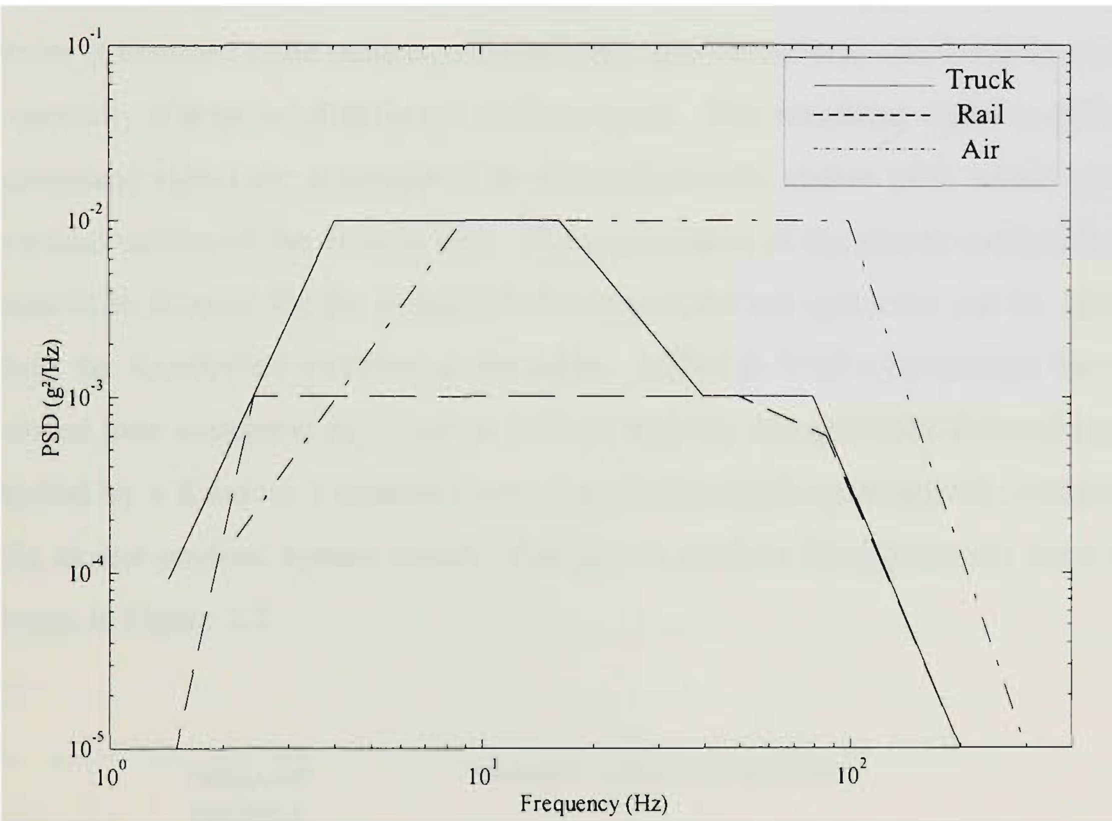


Figure 2.1. Commercial transport random vibration spectra summary, ASTM D4728-95

The transportation environment is characterised by instrumenting vehicles with accelerometers and data recorders. The accelerometer normally records the vertical acceleration levels a vehicle experiences in transit but can typically be set up to record in the lateral and longitudinal direction as well. PSD estimates, such as those shown in Figure 2.1, are used as a means of compressing the data, however, the power spectrum is, by definition, a product of the complex spectrum and its conjugate and thus, is real.

In other words, the phase information required for reproduction of the original signal is lost:

$$G_{AA} = G_A(f) * G_A^*(f) \equiv \text{Re}(G_{AA}) \qquad \textbf{(2-1)}$$

where:

G_{AA} = Folded Power Spectrum of $G_A(f)$

Although the instantaneous complex spectrum of a signal contains all relevant information for its exact reproduction, the PSD only contains magnitude and frequency information. This implies that the original signal cannot be reproduced. In order to synthesise a random signal from the PSD, usually via the inverse FFT, the phase spectrum is assumed to be random and uniformly distributed between 0 and 2π resulting in a normally (Gaussian) distributed random signal. This simulated signal is utilised as the command signal for actuation of an electro-hydraulic shaker table which emulates the vertical motion of the vehicle tray. The equalisation of the shaker command signal is required to account for the dynamic behaviour of the test specimen and the shaker to produce the appropriate vibration at the table. ASTM D 4728 recommends the use of the closed loop automatic equalisation method whereby the generated demand signal is controlled by a Random Vibration Controller (RVC) which automatically compensates for the shaker-payload system transfer function to produce the appropriate input signal as shown in Figure 2.2.

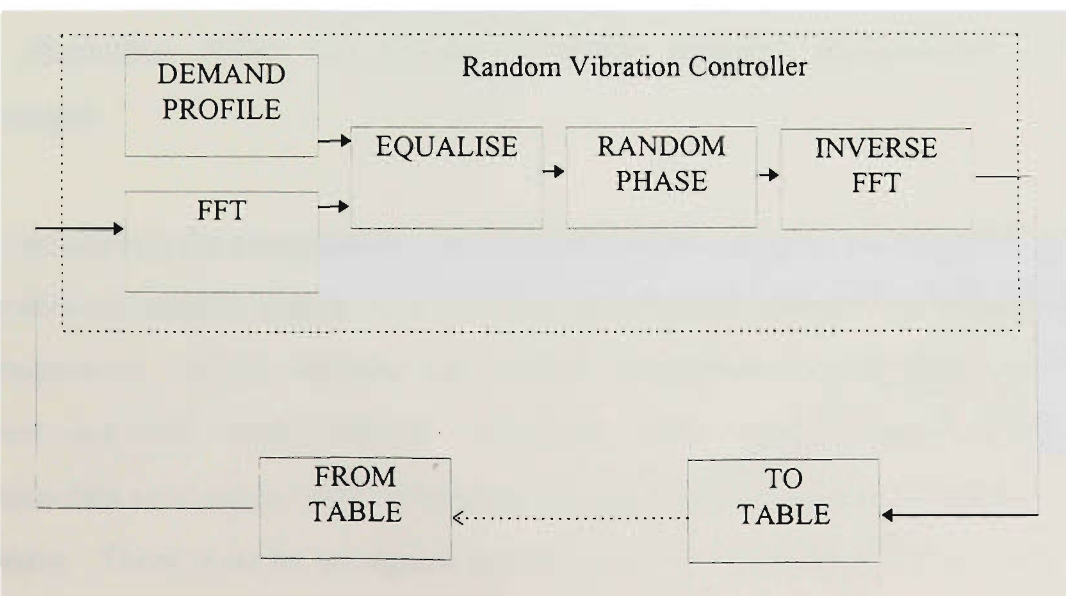


Figure 2.2. Schematic of RVC for acceleration simulation and control

When reproducing random signals from a PSD coupled with a uniformly distributed random phase spectrum, the resulting signal amplitudes will, by definition, be characterised by the Gaussian distribution with the $(RMS)^2$ equivalent to the integral of the PSD. Furthermore, the random signal will be stationary; namely the RMS level of the signal and its frequency content remain constant over time and the signal is free of transients (crest factor ≈ 3.0). Since all modes of transport are characterised, to some extent, by significant fluctuations in vibration level and contain transient events, a synthesised acceleration signal based on a single PSD is not fully adequate for simulation of the transport environment in the laboratory. In the case of road transport, fluctuations in vibration levels can be considerable as they are at least a function of road surface profiles and vehicle velocity. The procedures outlined in ASTM D 4728-95 do not account for such variations experienced in the transportation environment. One major shortcoming of the standard is that it recommends that the PSD's shown in Figure 2.1 be used in the absence of a specified PSD whilst stating that "... these PSD profiles do not purport to accurately describe a specific transportation mode or distribution environment. The user of random vibration must verify accuracy and applicability of any data of this type prior to its use.". The PSD's illustrated in Figure 2.1 are in fact representative of "... average vibration intensities measured under various loading conditions, suspension types, road conditions, weather conditions, travel speed etc." Despite these shortcomings, these PSD's are commonly treated and used as '*standard PSD's*' to simulate the transport environment in packaging laboratories. The use of these illustrative PSD's for simulation of the transport environment should be discouraged.

When simulating the transportation environment (road transport in particular) by means of a stationary random signal, it is essential that pertinent parameters such as road type (or roughness), vehicle velocity and vehicle suspension characteristics be assumed constant and their values known. Similarly, when using measured transportation vibration data to compute PSD's it must be ensured that the data, or sections thereof, are stationary. There must be no significant variations in vibration RMS level and vehicle speed and only a small number of large transients should be present in the signal. As the speed of a vehicle and the road roughness cannot be easily controlled in practice, extensive data acquisition and analysis is required in order to obtain a sufficiently large stationary record to simulate the transportation process with stationary random signals from the PSD.

Vehicle response acceleration PSD estimates, such as the one shown in Figure 2.1, are a function of five major variables, namely, the road surface type, the vehicle characteristics and speed, and the size and location of payloads. If one or all of these variables are not retained constant, the resultant process will be non-stationary and the resulting vehicle response spectra will vary in time. The recommended spectra published in the appendix of ASTM D4728-95 have evolved from an average of the compilation of field measurements made by several organisations over a period of time. Optimisation of packaging systems demands a more accurate characterisation of the actual transportation environment. Some of the limitations associated with simulating vehicle vibrations characterised by a single PSD for laboratory testing of package performance have been addressed by other researchers and are reviewed in the next section.

2.2 REVIEW OF VEHICLE VIBRATION CHARACTERISATION

Johnson (1971) analysed vibration levels on a 3-ton general purpose truck by measuring acceleration levels on a number of packages over a variety of terrains. The study was designed to investigate the effect that vehicle load, load distributions, tyre pressure, package design, driving technique and lashing had on the response spectrum generated. The data contained transient events with high crest factors, calculated from the instantaneous peak value divided by the underlying RMS, but were removed to allow analysis of the continuous background vibration signal. An extremely non-Gaussian constituent was exposed in the data. Terrain, truck speed, gross load and package position affected the vehicle vertical acceleration levels. The shock levels transmitted to a package were inversely proportional to the payload and as speed increased, so too did the RMS level of vibration. A faster vehicle speed correlated to a higher number of shock occurrences for a given peak 'g' level. Shocks (y) were shown, by Johnson (1971), to approximate to the pulse distribution model:

$$y = Ae^{k(x-x_l)} \tag{2-2}$$

where:

A = the frequency/mile of peaks,

k = a constant depending on package weight,

x = pulse peak (g's RMS),

x_l = the lower limit of the distribution of peaks.

Hoppe and Gerok (1976) measured vibration and shock levels on loading trays of various transport vehicles. Random vibrations were found to occur in all vehicles between 2 and 500 Hz, and shocks above 10 g were recorded. In the case of trucks, 68% of vibration amplitudes were below 1g, 27% between 1 g and 2 g, and 4% between 2 g and 3 g. The levels for trailers were higher.

Winne (1977) presented PSD estimates of various vehicle combinations. Truck suspension type was shown to cause the spectra to vary greatly, but the power was mainly concentrated around two major frequencies of approximately 5 and 15 Hz as illustrated in Figure 2.3. Air bag suspension reduced vibration amplitudes significantly over a frequency range of 250 Hz. Load size and its location on the loading tray affected the resultant power spectrum by causing a shift in the resonant frequencies. Largest accelerations were observed on empty or partly loaded vehicles due to the decrease in overall mass. Shocks of up to 16 g were recorded on semi trailers and up to 25 g on smaller trailers. An averaged PSD, shown in Figure 2.3, was prescribed by Winne (1977), and proposed for use in general purpose testing.

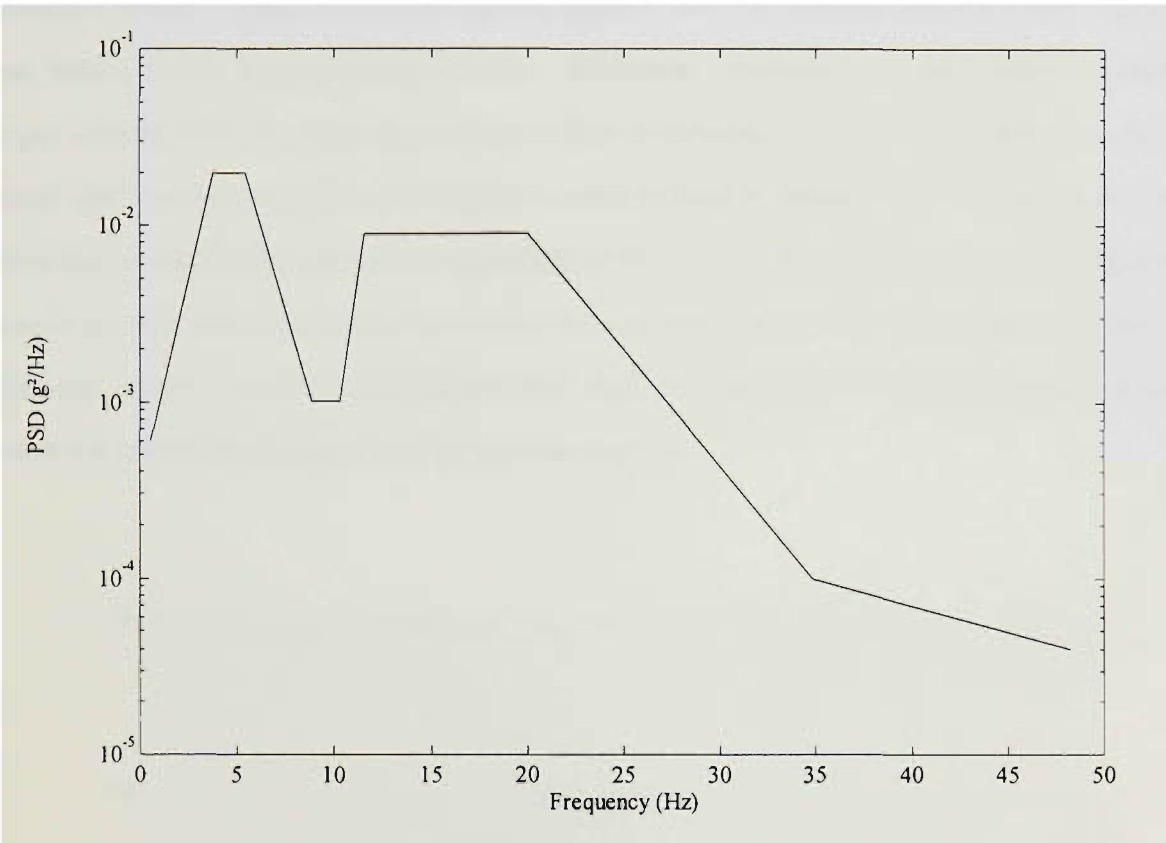


Figure 2.3. Recommended tractor-trailer vibration test spectrum (Winne, 1977)

A comprehensive study of the transport environment was conducted by the Association of American Railroads (AAR) *et al* (1991) on rail and truck shipments. It was concluded that rail and truck shipping environments were "quite similar in principle", however, rail shipments experience low vibration effects due to the energy absorptive damping characteristics of the rail car and trailers. Further, the dynamic characteristics of trucks indicate that they are less likely than rail environments to experience shocks. The reported PSD's were shown to vary both in amplitude and frequency content for various road and vehicle type. RMS acceleration distributions showed that the overall vertical accelerations were non-stationary with a non-Gaussian distribution. Further, the shocks present in the recorded data were not removed for the study.

Singh and Marcondes (1992) displayed the vibration levels in trucks as a function of suspension and payload. Their conclusion was that leaf spring trailers have high vibration levels between 3 and 4 Hz and fully loaded trailers have lower vibration levels than partially loaded trailers. Air bag suspension trailers have significantly lower vibration levels compared to leaf spring trailers and the sprung mass bounce frequency was found to be approximately 2 Hz. However, damaged air ride trailers exhibited larger vibration levels than leaf spring trailers indicating a need for regular maintenance. Panel vans exhibit significant vibration levels at higher frequencies and the most severe vibration levels in all cases were recorded at the rear of the trailers, shown in Figure 2.4. However, it is not clear from the study if transient events were removed from the PSD estimate. Pierce et al (1992) found that well functioning air ride suspension produce lower vibration levels than leaf spring suspension.

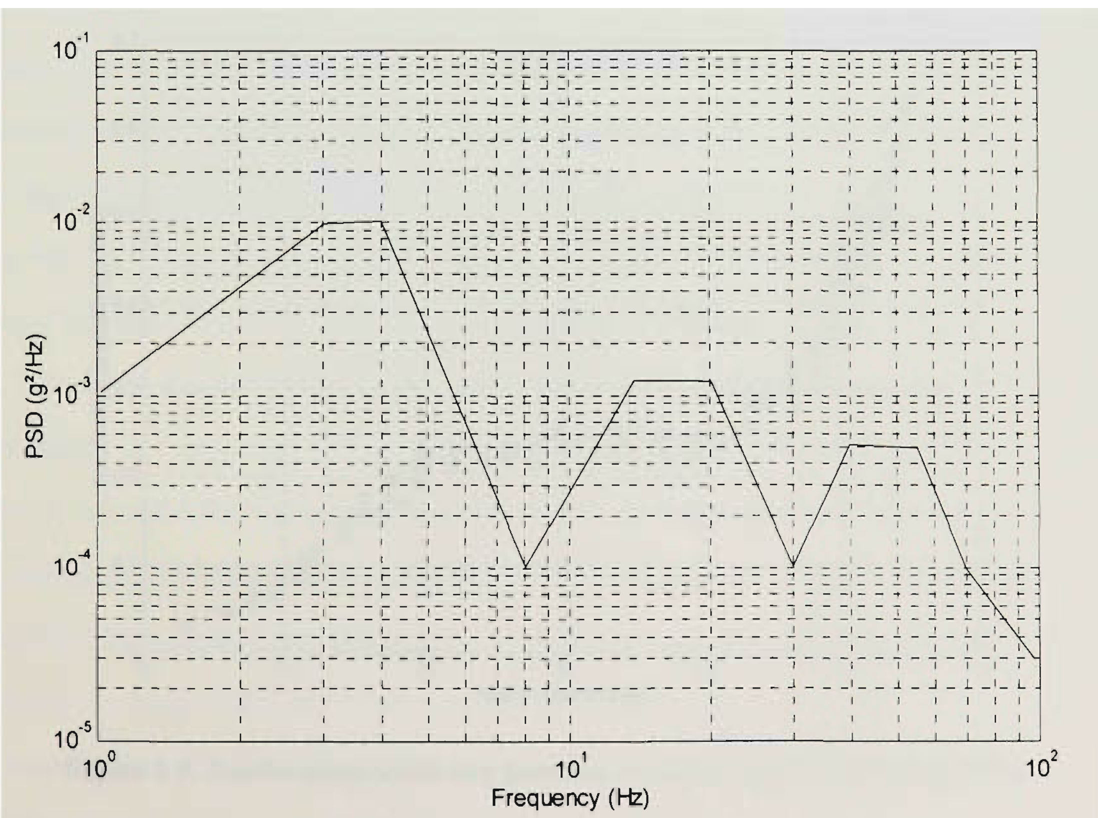


Figure 2.4. Vibration levels in trailers, 9000 kg load (Singh and Marcondes, 1992)

The research conducted by Johnson (1971), Hoppe and Gerok (1976), Winne (1977), AAR (1991), Singh and Marcondes (1992), Pierce *et al* (1992) and the ASTM D4728 standard indicates that an experimentally based PSD spectrum is insufficient for the specific description of the vehicle vibration levels of a loading tray. Vehicle response is shown to be a non-stationary, non-Gaussian process which is influenced by the road type, vehicle characteristics and payload. As a result, the response PSD's reported by various researchers can never be identical unless all the pertinent influences are retained constant. This fact often leads to a variation in laboratory testing levels and package designs.

The variation in laboratory test levels derived from actual field data was reviewed by Richards (1990) who investigated four common approaches, namely, the PSD, peak hold PSD, the so called Sandia and Cranfield[1] approach. Richards (1990) shows that measured acceleration amplitudes increase significantly with vehicle speed which results in time varying amplitudes, shown in Figure 2.5.

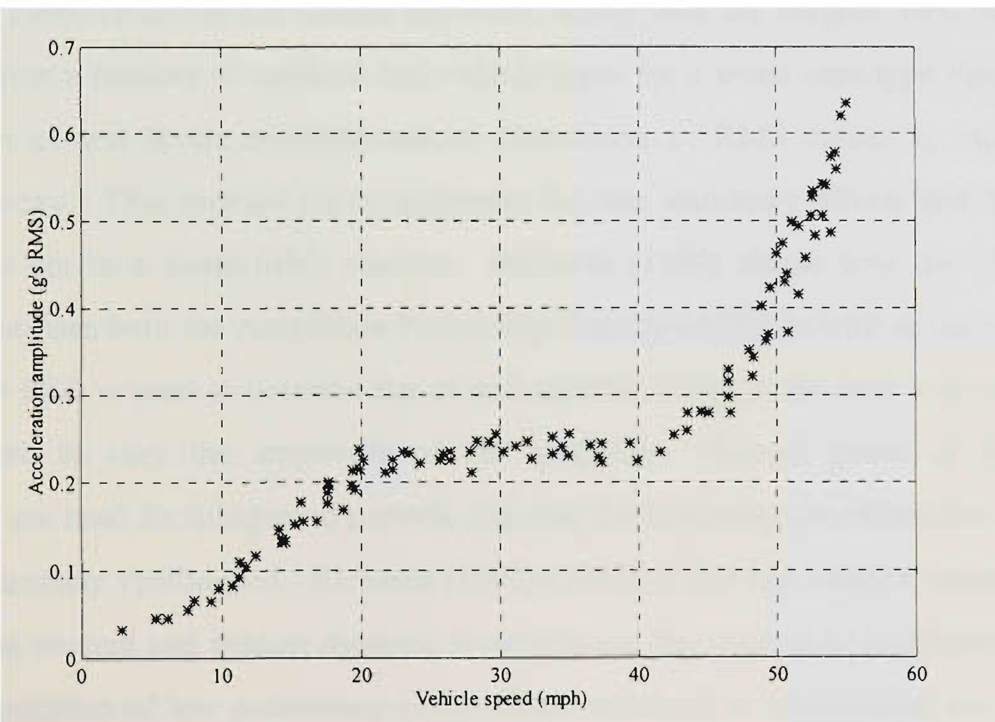


Figure 2.5. Acceleration levels as a function of vehicle speed (Richards, 1990)

[1] Named after the respective institution

In addition, the data contained both transient and continuous steady vibration level characteristics, with the transients difficult to isolate and remove due to their irregular occurrence and amplitude. Richards (1990) discussed the four mentioned acceleration data analysis procedures in detail to outline their advantages and disadvantages.

The traditional PSD approach reviewed by Richards (1990) (as employed by ASTM D 4728), is implemented extensively because of its simplicity. He identified that this method cannot cope with time variant data typically caused by vehicle speed variations and transients. Richards (1990) showed that, by utilising peak-hold PSD, an indication of the non-stationary nature of the data may be provided. This method uses the maximum PSD values over each spectral band for the entire record and is used to augment the traditional PSD method to enhance results. However, the statistical confidence in the peak hold values vary from the confidence of traditional, averaged PSD values and can produce extremely conservative test levels with a low probabilities of occurrence, leading to overpackaging.

Richards (1990) reviewed the Sandia approach, which uses the rougher 10% of values obtained over a number of surfaces and vehicle types for a worst case type simulation. Simulation of test levels revolves around conversion of RMS values to equivalent Power Spectra. This method partly addresses the non stationary effects and transient effects but not in a quantifiable manner. Richards (1990) shows how the Cranfield approach utilises both the Amplitude Probability Density (APD) as well as the response PSD. The PSD is used to describe the overall spectral shape of the data with the APD incorporated to vary the amplitude of the spectrum. Several levels of vibration amplitude are used for designated periods allowing the measured, non-Gaussian APD to be approximately synthesised. Richards (1990) indicated that this method assumes that the spectral content and vehicle dynamic responses are the same at all amplitude levels. The incorporation of low occurrence events allow transients to be included, not only as large amplitudes, but also for relatively short duration's. This method aims to include non-stationary and resultant non-Gaussian characteristics of the transportation process.

The research performed by Richards (1990) demonstrated that there is no single accepted method of deriving test severities from measured field data experiments. Test results vary throughout the investigated methodologies and there is a need for the introduction of an absolute test method.

The derivation of environment description and test severity from measured data was discussed in depth by Charles (1993). The non-stationary component of vehicle response was shown to be a function of vehicle speed. The analysed data contained prominent non-Gaussian characteristics shown with the use of amplitude probability density function (PDF) estimates plotted on semi log versus normalised signed amplitude scales. Further, Charles (1993) found that up to double the vibration severity can be introduced by running vehicles with reduced tyre pressure. He established that any environment description should include frequency response, amplitude probability and time histories of transient events. The analysis procedure used by Charles (1993) is summarised as follows:

- The data is checked for stationarity of RMS and stationary sections used for PSD estimation.
- Transients are identified from time histograms for subsequent capture and determination of shock spectra.
- Variation in vehicle speed is represented on waterfall plots to determine speed dependant peaks.

Charles (1993) noted that laboratory simulated amplitudes may be significantly lower than measured amplitudes because of the nature of many control systems and the potential for under-testing arises. He demonstrates two methods for overcoming this problem. One method derives RMS values from measured peak levels. This derived value is then used to scale a PSD plot for determination of the appropriate level based on the required probability. This method, however, assumes that the probability is constant at all frequencies. The other method is similar to the Cranfield approach which describes the non-stationary segments of the data as the superposition of Gaussian PDF estimates. This method uses the RMS level and so called Participation Factor, proportional to the probability of the RMS level. Charles (1993) addressed the fact that the averaged PSD approach alone was not adequate to describe and reproduce a transportation environment where non-stationary components were typical.

The traditional simulation method, based on the vehicle response PSD, was revised by Nordstrom *et al* (1986) who designed an enhanced physical simulation technique for vehicle vibrations based on computer simulation to include transients and multi directional vibration. Test data was analysed in terms of its vibration spectra and transients, which were treated separately, whilst allowing for large volumes of data to be compressed. They appreciated that vehicle acceleration levels exhibit distinct non-Gaussian and non-stationary characteristics. They propose that, to simulate the transportation environment in the laboratory, a synthesised steady state signal based on the measured acceleration PSD be seeded with pre-recorded transient events. Although the method proposed by Nordstrom *et al* (1986) is an improvement on previous simulation techniques, which rely solely on the PSD description of the transportation environment, there is still the need for extensive data acquisition due to the number of variables that are not retained constant.

Schoorl and Holt (1982) investigated road-vehicle-load interactions specific to fruit and vegetable transportation for which there was no vertical restraint on multi layered packaging systems. They confirmed that the factors such as road terrain, vehicle speed, suspension characteristics, vehicle axle and wheel type, tyre characteristics, and load had a significant effect on package vibration levels. The authors established that the interaction between load and vehicle body could not be neglected when simulating vehicle vibrations in the laboratory as the mechanical compliance of typical suspension systems is greater than that of electro-hydraulic shaker systems. As a consequence, simulated vibration testing will transmit larger forces to test packages, particularly for large, bouncing loads, than forces that occur in actual transit. According to Schoorl and Holt (1982), acceleration measurements on a vehicle tray were of limited use for multi-layered loads, as they were distorted estimates of the actual acceleration occurring at each layer, as depicted in Figure 2.6.

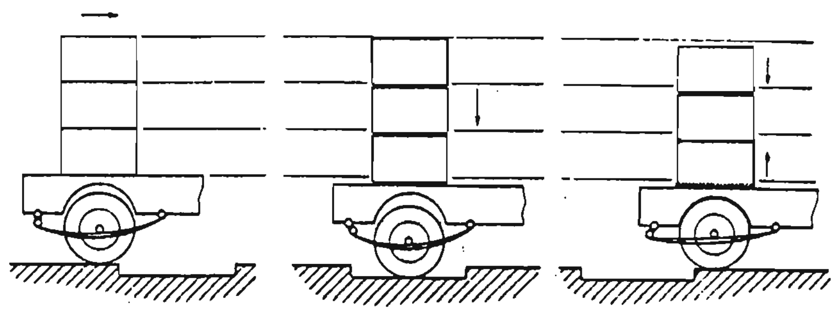


Figure 2.6. Suspension compliance with multi-layered loads (Schoorl and Holt, 1982)

So far, the research into the description of the transport environment has centred around the spectral description of vehicle response measurements for its complete description. As the simulation of these acceleration levels in the laboratory requires that assumptions be made about the statistics of the process, simulation is inadequate.

Rouillard *et al* (1996) and Sek (1995) proposed a novel method for simulating the transport environment with the use of road profiles. Vehicle vertical acceleration was replaced by the road surface elevation PSD estimate as the fundamental excitation parameter. The system also includes vehicle models. A schematic of the experimental set up used to verify the procedure is presented in Figure 2.7 in which a road profile was used as the command signal for an electro-hydraulic shaker to actuate a physical half-car.

Successful implementation of this method has distinct advantages over transport environment simulation based on vehicle tray acceleration. Stationary road profile signals could be generated from spectral and statistical parameters derived from the road profile analysis using traditional techniques. Suitable mechanical devices can be designed to represent the dynamic behaviour of typical road transport vehicles as well as provide compliance during impact in laboratory simulations. Vehicle speed could be accounted for by a shift in the road elevation PSD along the spatial frequency axis (Newland, 1993 - p 199) as given by:

$$G_y(f) = \frac{1}{v} G_y(n = \frac{f}{v}) \qquad \textbf{(2-3)}$$

where:

G_y = single track PSD,

v = vehicle transversal velocity,

n = spatial frequency,

f = frequency,

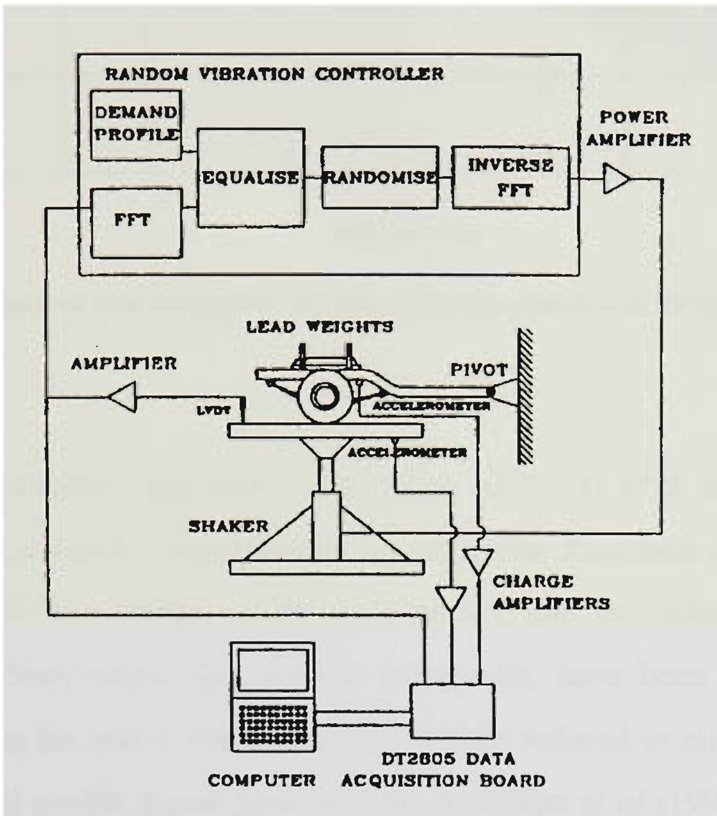


Figure 2.7. Experimental set up from Rouillard *et al*, 1996

Rouillard *et al* (1996) successfully controlled the displacement of a shaker table using a conventional RVC. The results obtained for a simulated vehicle speed of 30 m/s is shown in Figure 2.8. Unfortunately, they did not produce a command signal to incorporate the non-Gaussian, non-stationary and transient characteristics of the road profiles which were evident in the roads analysed by them. They generated a Gaussian signal based solely on the PSD of the road. Since the successful implementation of this method relies primarily on the simulation of road surfaces, the idealised Gaussian command road profile signal produced is inadequate.

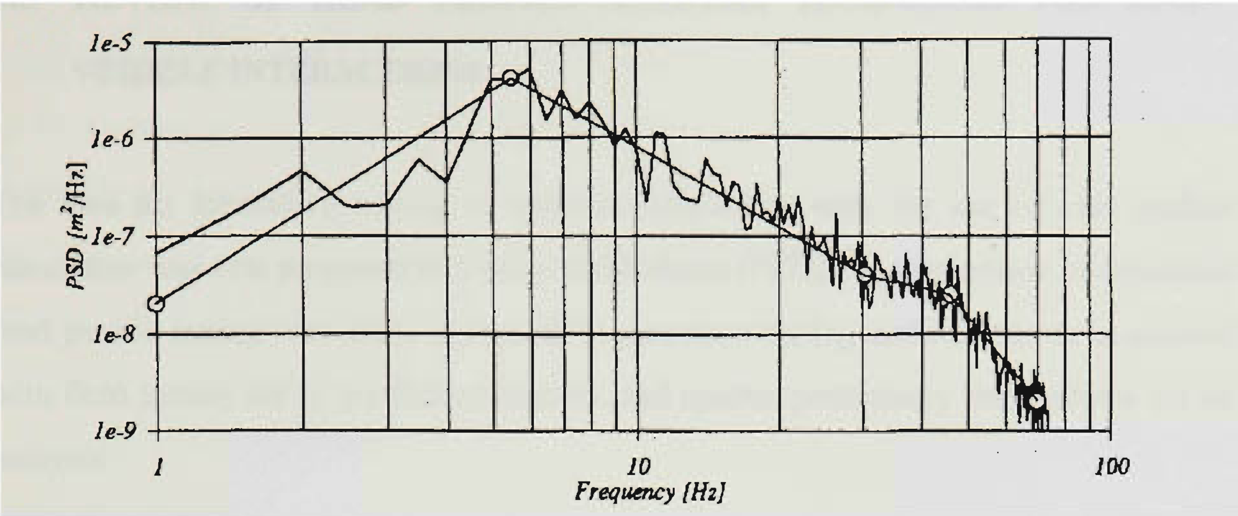


Figure 2.8. Demand and measured elevation PSD (Rouillard *et al* 1996), speed = 30m/s

In contrast to the standard approach employed by ASTM D 4728 in which the primary data is vehicle acceleration, methodologies presented by Rouillard *et al* (1996) and Sek (1995) rely on the knowledge of the road profile and the vehicle-road interaction characteristics. Once roads, and vehicle suspension, have been analysed and fully classified, the need for much data acquisition will be reduced or eliminated. However, the command road profile signal generated by Rouillard *et al* (1996) did not simulate the non-Gaussian, non-stationary characteristics inherent in road surface profiles. They identified the need for extensive analysis of road profiles before the procedure could be successfully implemented. The next section investigates previous research into the accurate characterisation of the road surface profiles with the emphasis on its use for prediction of vehicle vibration levels.

2.3 REVIEW OF ROAD PROFILE ANALYSIS TECHNIQUES FOR ROAD-VEHICLE INTERACTIONS

The idea for laboratory testing of vehicle components with the use of road surface simulation was first proposed by Dodds and Robson (1972). A comparison of simulated road profile testing was made against field prototype testing and limitations associated with field testing led to the formulation of road spectra preliminary assumptions for its analysis.

The road surface can be considered a two dimensional random surface and description of such a surface requires elaborate statistical parameters to describe it completely. A vehicle traversing this road surface is subjected to displacements inputs at each wheel, and thus any simplification of the road surface description should account for these direct inputs as well as for correlations between these inputs. Early descriptions of road surfaces considered them as two separate, uncorrelated tracks, that is the left and right track only. Cross correlations between tracks, affecting roll characteristics of a vehicle, were neglected. This did not provide an adequate description for vehicle simulation since it assumed the transverse slope to be uniform at each longitudinal position.

Dodds and Robson (1973) described the road surface as a function of two variables, the longitudinal coordinate x and transversal coordinate y, by considering the road as a homogeneous, isotropic random process having a Gaussian distribution, provided that occasional irregularities such as pot holes were removed and treated separately. This allowed cross correlations, or cross spectra, to be included in analysis procedures.

Since a homogeneous surface has statistical properties independent of coordinate translations, and assuming that the rear wheel follows the same track as the front wheel, then the road profile spectra at both wheel tracks are the same, $S_D(n)$, where 'n' is the spatial frequency. An isotropic surface has statistical properties independent of coordinate rotations, therefore the cross spectra between wheel tracks are the same, $S_X(n)$.

From a knowledge of the autocorrelation function, or power spectrum, for a single track in the x direction, the cross correlation (or cross spectrum) could be estimated from a knowledge of the vehicle geometry. The function, $\gamma(n) = S_X(n)/S_D(n)$, defined by Dodds and Robson (1973), reinforced practical considerations as the coherence, $\gamma^2(n)$, approaches unity for small spatial frequency and approaches zero for large spatial frequency. This implies that the admissible range of spatial frequency extend through $0 < n < \infty$ and since the phase between the two signals is zero, it also implies that the cross spectrum is real.

Verification of these assumptions allowed for a multi-track response to be obtained from a single track PSD estimate, knowledge of traversal velocity, and dynamic properties of the vehicle.

The shape of the log PSD versus log spatial frequency estimate was found to be independent of road type but a function of the RMS level. A new road classification system based on a single track PSD function was proposed:

$$S(n)=\begin{cases} S(n_0)\left(\dfrac{n}{n_0}\right)^{-w_1}, & n\le n_0 \\ s(n_0)\left(\dfrac{n}{n_0}\right)^{-w_2}, & n\ge n_0 \end{cases} \qquad \text{(2-4)}$$

where

n = spatial frequency

S(n) = elevation spectral density estimate (m^3/cycle)

w = roughness parameters

n_0 = discontinuity spatial frequency = ($\pi/2\ m^{-1}$)

The values of the above parameters for typical road types are shown in Table 2.1.

Table 2.1. Classification of roads (Dodds and Robson, 1973)

			w1		w2	
Road Class	**Condition**	**$S(n_0)$ $(x10^{-6})m^3$/cycle**	**Mean**	**Standard Deviation**	**Mean**	**Standard Deviation**
Motorway	Very Good Good	2-8 8-32	1.945	0.464	1.360	0.221
Principal Road	Very Good Good Average Poor	2-8 8-32 32-128 128-512	2.05	0.487	1.440	0.266
Minor Road	Average Poor Very Poor	32-128 128-512 512-2048	2.28	0.534	1.428	0.263

The model proposed by Dodds and Robson (1973) could not be fully validated because of the lack of real road profile data. It is understandable that subsequent attention has been focussed at validating these initial assumptions. Kamash and Robson (1977, 1978) examined the implications and restrictions that this assumption imposed on the admissible range of the subsequent spectra generated.

Robson (1979) further investigated this isotropic model and revised the initial model proposed by Dodds and Robson (1973). The range of spatial frequency considered was restricted to $n_a \leq n \leq n_b$ and made no assumption about the behaviour of the spectra outside of this specified range given by:

$$S(n)=\begin{cases} c(n_a)^{-w} & , 0<|n|<n_a \\ c|n|^{-w} & , n_a<|n|<n_b \\ 0 & , n_b \geq |n| \end{cases} \tag{2-5}$$

where:

$w = 2.5$.

Experimentally obtained values for c based on the road class, are shown in Table 2.2. The values of n_a and n_b defined the typical spatial bandwidth, $0.01 < n < 10\ m^{-1}$. The International Standards Organisation (ISO) used this assumption to develop a classification system which is based on the PSD of the road profile, depicted in Figure 2.9. The lower lines of this figure represent very good road condition with the upper lines representing increasingly rougher roads.

Table 2.2. Revised classification of roads (Robson, 1979)

Road Class	Range (x 10^{-8} m^3/cycle)	'c' (x 10^{-8} m^3/cycle)
Motorway	3 - 50	10
Principal Road	3 - 800	50
Minor Road	50 - 3000	500

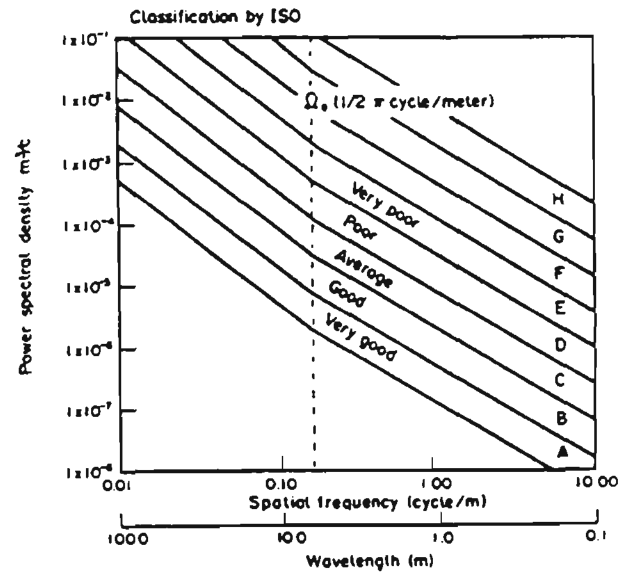


Figure 2.9. Classification of roads by ISO (1982)

Cebon and Newland (1983) further developed the isotropic assumption for roads and proposed to digitally simulate the complete road surface from a single track profile using two-dimensional FFT techniques. Procedures were presented for the digital simulation of heights profiles of a number of correlated parallel tracks and also of entire two dimensional surfaces. Profiles of a number of correlated tracks were generated by the one-dimensional Fourier transform but two-dimensional Fourier transforms are required to generate a fully isotropic surface. Heath (1987a) introduced formulae which involved single integration and subsequent closed form solutions of the cross spectra:

$$S_X(n) = \int_n^{\infty} S'_D(n_1)\, J_0(2\pi nc\sqrt{n_1^2 - n^2}).dn \qquad \text{(2-6)}$$

where

S_X = Cross Spectrum

n = spatial frequency

S_D = Single track spectrum

which implies that the cross spectrum at a particular wavelength is independent of the single track spectrum at a lower spatial frequency. Therefore, the calculation of the cross spectrum requires a measured single track spectrum of a considerably larger spatial frequency bandwidth. Heath (1987b) assessed the accuracy of the isotropic road roughness assumption using spectral techniques on real road data. He found that spectral analysis supported a hypothesis of real cross spectra between tracks, consistent with the isotropic assumption. Coherences $(S_x(n) / S_D(n))^2$ calculated via isotropy agreed well with experimentally determined coherences for asphaltic pavements, but over-predicted measured values for spatial frequency below 0.1 m^{-1}.

With a further modification to the basic isotropic model, Heath (1989) was able to increase the range of spatial frequency in which the experimental and calculated values were in close agreement. These improvements meant that increasingly accurate cross spectra could be generated from knowledge of single track spectra and vehicle dimensions, which reinforced the Dodds and Robson (1973) proposition that road surface classification could be based on a single track profile spectra.

Heath (1989) demonstrated a means of synthesising a single track road profile using the Fourier transform technique in which a spectral array of randomised phase is used in conjunction with the single track spectra to produce, by definition, a Gaussian signal, similar to the method employed by Rouillard *et al* (1996). However, this specifies that analysis and simulation is limited to the first and second order moments of road roughness statistics.

Several conclusions can be reached as a result of treating the road as an isotropic random surface. Once single track spectra of typical roads are analysed and classified, simulation of road surfaces for vehicle multi-track analysis could be performed with sufficient accuracy (Heath 1988) and would justify the ISO classification method. The equations derived by Heath (1989) are applicable for a homogeneous random process only. However, investigation into the homogeneous nature of road surfaces has been neglected. It can be suggested that the road surface profile is not truly homogeneous but can be shown to be weakly homogeneous in certain sections.

Road profile analysis and simulations found in literature is predominantly based on a Gaussian distribution assumption and thus is limited to the first and second order statistical moments. Road data analysed by Heath (1988) and Rouillard *et al* (1996) was shown to have a substantial non-Gaussian component. Rouillard *et al* (1996) used higher order statistical moments, such as kurtosis and skewness, as an indication of the degree of non-Gaussianity. They also demonstrated the independence of the road elevation spectral shape to road type, but the data was shown to be non-stationary. Further, calculated crest factors showed the significance of transient events in the road profile but statistical analysis techniques (PDF) of the road profile elevation itself failed to locate these events due to the large amplitude of the low spatial frequency.

The extensive analysis of road profiles relies on their accurate measurement. The research conducted by Dodds and Robson (1973), Cebon and Newland (1983) and Heath (1988) shows that once single track profiles are accurately measured, analysed and characterised, complete surfaces can be generated based on the isotropic model.

2.3.1 Measurement of road surface profiles

Road roughness has traditionally been collected and analysed for the purpose of road maintenance. This has proven important in areas such as road pavement performance and determination of road user costs. Numerous devices have been created to record 'road profile roughness' but they can be classified into two main categories:

- Response Type Road Roughness Measurement Systems (RTRRMS),
- Road profilometers.

2.3.1.1 Response type road roughness measuring systems (RTRRMS)

RTRRMS provide a cheap, easy method of obtaining an indication of the road roughness. These devices are transducers that accumulate the motion of suspension systems induced by traversing the road surface. A typical arrangement, used in the Bureau of Public Roads (BPR) Roughometer, is shown in Figure 2.10. It is a single wheeled trailer with a one way clutch mechanism, or integrator, to record the motion of its suspension. The roughness is determined by cumulative displacement of suspension stroke per unit distance.

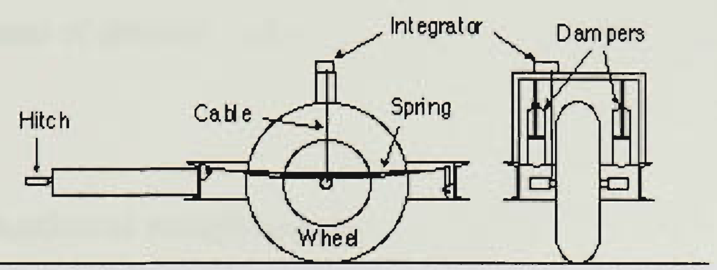


Figure 2.10. The BPR roughometer

The results obtained from RTRRMS are inevitably influenced by the properties of the host vehicle/trailer. Even with careful calibration and standardisation, the roughness measurements are not stable with time or transportable to other systems.

RTRRMS allow a repeatable road roughness profile to be obtained at highway speeds and thus they have proved popular as a means of indicating general road surface condition. This type of measurement system is not suitable for detailed road profile analysis. To provide an accurate description of the road profile elevation, actual longitudinal profile elevation is required.

2.3.1.2 Measurement of longitudinal profile

Static methods of profile measurement include:

- Staff and level survey,
- Transport and Roads Research Laboratory (TRRL) beam.

Staff and level survey is extremely time consuming and labour intensive and the process is prone to errors. The TRRL beam is more rapid and less time consuming than manual survey, but its use is limited to validation of profilometers and RTRRMS readings.

The advent of laser technology led to the development of laser based dynamic road profile measuring systems to acquire road data at highway speeds. The Australian Roads Research Board (ARRB) have designed and implemented a laser based profilometer that records actual road profile at highway speeds. The vertical measurement resolution of this system is 0.2 mm and the spatial resolution is approximately 50 mm (Prem, 1987 or see Appendix A). The acquisition method is suitable for the purpose of detailed road profile analysis needed in this thesis.

2.3.2 The international roughness index (IRI)

The World Bank initiated a project to calibrate and standardise roughness measurements and provide a means of correlation between the various measuring systems. The project resulted in the introduction of the International Roughness Index (IRI). The IRI is a standardised version of the RTRRMS readings and provides a methodology to compare the readings from different RTRRMS which are invariably a function of the host vehicle suspension characteristics. Unfortunately, this methodology renders the IRI insufficient for detailed road profile analysis of short wavelength variation and transients.

However, since the advent and extensive use of high speed profilometers, IRI calculation has been modified to allow their readings to be directly compared with RTRRMS readings. The procedure is as follows. The data is filtered with a moving spatial domain filter of 250 mm base length. The data is further filtered with the quarter-car model shown in Figure 2.11 to simulate a travel speed of 80 km/h. The filtered profile is then accumulated by summing absolute values of the filtered points and then divided by the base length. The resultant IRI has units of slope.

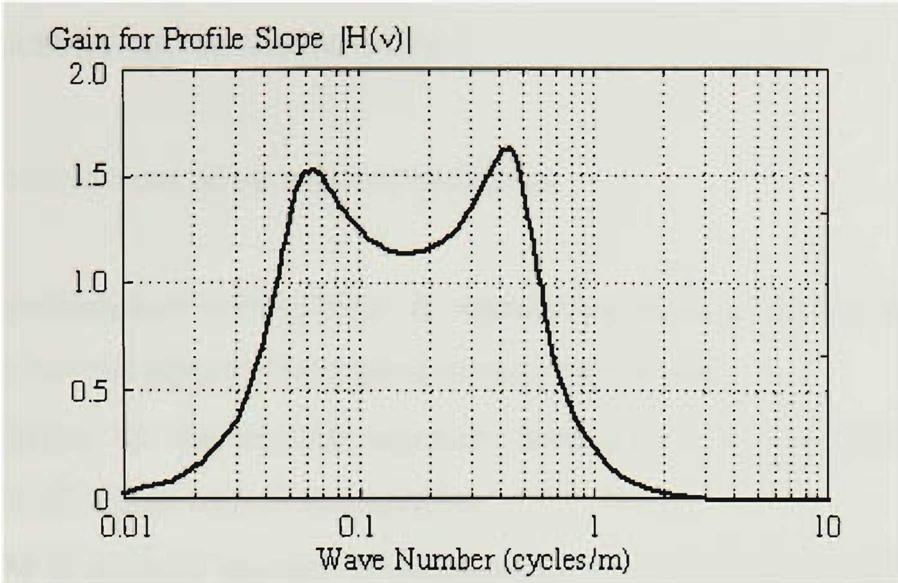


Figure 2.11. Spatial frequency response of quarter-car model

IRI provides a suitable methodology for comparison between various RTRRMS readings as well as road profilometer acquisition systems. However, due to the post-processing involved, an absolute road profile cannot be obtained. The IRI does not take advantage of the information attainable from high speed laser profilometers which gives absolute road profile. Therefore, the use of IRI is not suitable for accurate road profile analysis and may become redundant in the future.

An attempt has been made by Marcondes (1990) to relate the IRI to vehicle tray PSD. The study aimed at development of a procedure to predict vehicle PSD as a function of IRI, pavement roughness, vehicle dynamics and speed. A quarter car simulation was used to compute IRI and spectral analysis used for pavement elevation and truck acceleration.

Since the IRI is not a complete description of road profiles, there was little or no correlation between the IRI and road elevation RMS levels. The subsequent results of the study were hindered due to the limitations of the IRI.

2.4 LITERATURE REVIEW SUMMARY

The literature review can be summarised as follows:

- Package performance testing aims at reproducing loading environments in the laboratory, but relevance to actual environments vary greatly.
- The simulation of the random transport environment has centred around the description of vehicle vertical accelerations.
- The ASTM D-4728-95 specifies a methodology to simulate random vibration test levels, prescribes recommended PSD's, and outlines the procedure for laboratory simulation. However:
    - The level of acceleration experienced by a vehicle has been shown to be a function of five main variables, namely road surface type, suspension characteristics, vehicle speed and payload type and distribution.
    - The recommended PSD levels are not indicative of the real transport environment.
    - In general, laboratory simulation of the vehicle vibrations based on PSD's produce, by definition, a stationary, Gaussian signal which contain no transient data. This produces vibration levels which vary greatly from the levels obtained in field measurements.
    - In order to account for variation in the parameters affecting the vehicle vibrations, much data must be collected for each unique combination of road, vehicle and load.
- The Amplitude Probability Density (APD) of acceleration data has shown that non-stationary and non-Gaussian characteristics cannot be neglected. Recent techniques include these properties for laboratory simulation, but not in a quantifiable manner.
- Differences between mechanical compliance of the vehicle suspension and shaker systems may affect the force levels applied to test packages, introducing errors in the simulation process which may lead to conservative package designs and over-packaged products.

- The current method of using acceleration response PSD for simulation is inadequate. A method has been outlined which will improve laboratory simulation, but relies on accurate road profile and vehicle characteristic descriptions. This description must account for variations in road surfaces (non-stationarities) as well as irregular, but damaging transient events (non-Gaussian).

- Typical road surfaces have been measured and classified in terms of their spatial PSD only. The characteristic slope of the elevation PSD seems to be independent of the road surface but a function of the RMS (roughness) value of the road.
- No attempt has been made to classify and include transient events or investigate the non-Gaussian characteristic of the road profile elevation data.
- Road surfaces can be determined from single track and cross spectra. Thus, single track description is a sufficient representation of the total road surface.
- RTRRMS values are not an indication of the road profile elevation and can be used only as a guideline for road condition.
- Road profile data can be acquired by laser profilometers at highway speeds with accuracy and resolution suitable for detailed road profile analysis.
- The IRI is not suitable for accurate road profile elevation analysis, when considering short wavelength variations and transients.
- The road profile elevation is, in general, non-Gaussian and non-stationary.
- The use of the road profile (IRI) to predict the acceleration of truck trays has been attempted but with limited success.
- Road profile data has not been used as a control parameter for package performance evaluation.
- Extensive road profile analysis is required for prediction of vehicle vibration.

3. HYPOTHESIS

3.1 GENERAL AIMS

The overall aim of this project is to develop a universal road profile analysis and classification strategy for discretely sampled road data to represent all road profiles. This project is based on the premise that road profile data, coupled with comprehensive vehicle suspension models (physical or numerical), can be used to simulate a wide range of road transportation environments for package performance evaluation and optimisation.

3.2 SPECIFIC AIMS

The specific aims of this thesis are to:

- Comprehensively investigate characteristics of discretely sampled, single track road profile data in both the amplitude and frequency domains.

- Develop an analysis methodology for road profile data to characterise their non-stationary, non-Gaussian and transient properties.

- Develop pertinent parameters for the universal classification of single track road profiles for the purpose of signal synthesis and simulation.

4. FUNDAMENTAL CHARACTERISTICS OF ROAD PROFILES

The analysis of road surface profiles for the purpose of devising a universal classification strategy, for the majority of road types, initially requires a large sample of road profile data representative of a wide range of road surfaces. These prototype road data can be used to establish the fundamental statistical and spectral characteristics of roads, in general, as well as to validate the introduction of statistical classification parameters.

Actual data used in this project is a subset of over 20,000 km of Victorian (Australia) road profile data measured with the ARRB laser profilometer (see Appendix A). Twenty one road sections, totalling approximately 415 km, were selected to represent a wide range of bituminous sealed roads, based on the measured NAASRA roughness (NAASRA, 1981). Information on these 21 different road sections is shown in Table 4-1.

Table 4-1. Road profile data information

Road Name	Location (Victoria)	File Name	Length (km)	NAASRA Roughness (counts/km)
Princes Highway East	Metro S E	25101a	22.85	37
Princes Highway East	Metro S E	25102a	20.30	37
Princes Highway East	Metro S E	25103a	3.26	52
Princes Highway East	Metro S E	25103b	3.41	52
Northern Highway	N	25401b	5.03	64
Murray Valley Highway	N	25704a	47.65	41
Murray Valley Highway	N	25704b	43.77	41
South Gippsland Highway	E	25803a	11.28	65
South Gippsland Highway	E	25803b	21.82	65
South Gippsland Highway	E	25803c	14.96	65
South Gippsland Highway	E	25805b	60.82	88
Midland Highway	S W	25901a	13.99	72
Goulburn Valley Highway	N E	26404b	20.57	68
Maroondah Highway	Metro S E	27203a	14.57	N/A
Pyrenees Highway	N	27401a	12.38	121
Timboon - Port Campbell Rd.	S W	50381a	8.00	132
Wiltshire Lane	W	51881a	2.28	120
Daylesford - Malmsbury Rd.	W	51971a	25.41	91
Bendigo - Maryborough Rd.	N	52001a	22.25	104
Euroa - Mansfield Road	N E	55051a	8.33	93
Lismore - Skipton Road	S W	59621a	32.63	104

The file name given to these roads is arbitrary and used by the ARRB to identify its geographical position. The roughness values were computed by the ARRB to classify the condition of a particular road, with lower numbers indicative of smoother roads. Analysis for this study was conducted on the road profile elevation data acquired at the passenger wheel track.

All figures generated in the subsequent chapters are the result of the analysis of the entire 415 km road profile data with the use of MATLAB®. Results presented herein are typical of the results obtained from the analysis of the entire 415 km sample.

4.1 PRELIMINARY ANALYSIS

Initial examination of the raw road profile elevation data indicated that the amplitudes associated with long wavelengths were prominent. Two typical road profiles are shown in Figure 4.1. It can be assumed that these large fluctuations are the result of the continuous integration of residual acceleration due to a non-zero mean output of the acceleration sensors of the laser profilometer. Moreover, it has been shown by Prem (1987) that the ARRB profilometer is accurate for wavelengths ranging between 33m and 0.1m. The profilometer was designed to record wavelengths between 100 and 0.5m.

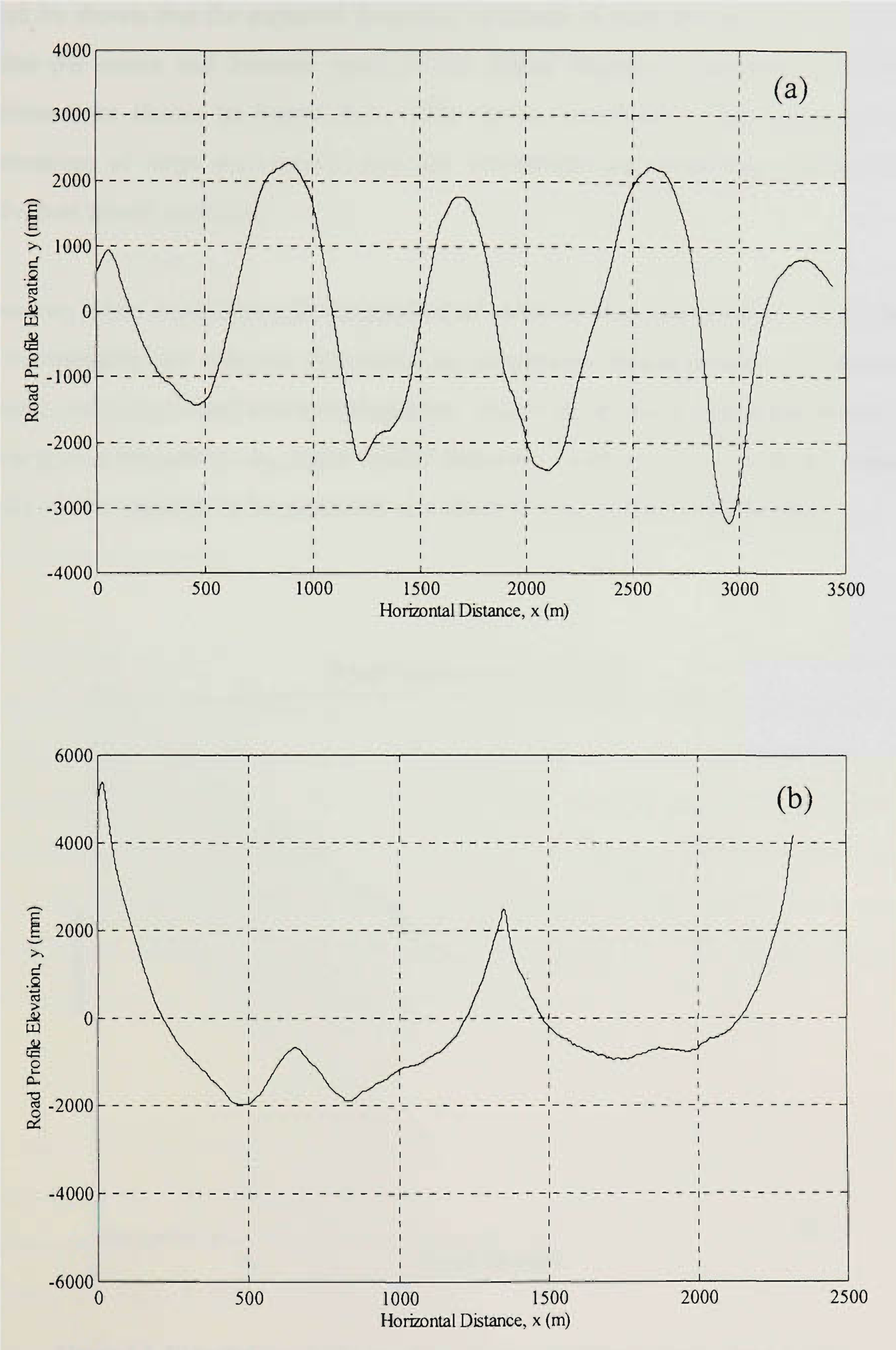


Figure 4.1. Road profile elevation (a) Road 25103b and (b) Road 51881a

It can be shown that the expected frequency spectrum of road profiles are large at zero cycles per metre and become small as the spatial frequency increases (wavelength decreases) as shown in Figure 4.2. This can be visualised by the large, hill type fluctuations of large wavelengths and low wavelength and amplitude fluctuations of individual gravel particles.

However, when considering the interaction of vehicles with road profiles, only a range of wavelengths are relevant depending on suspension characteristics of vehicles in general, including wheel and tyre properties. Figure 4.2 shows a spatial bandwidth, (n_L, lower spatial frequency - n_U, upper spatial frequency) within which significant vibration levels can be expected to be generated as a result of road surface irregularities.

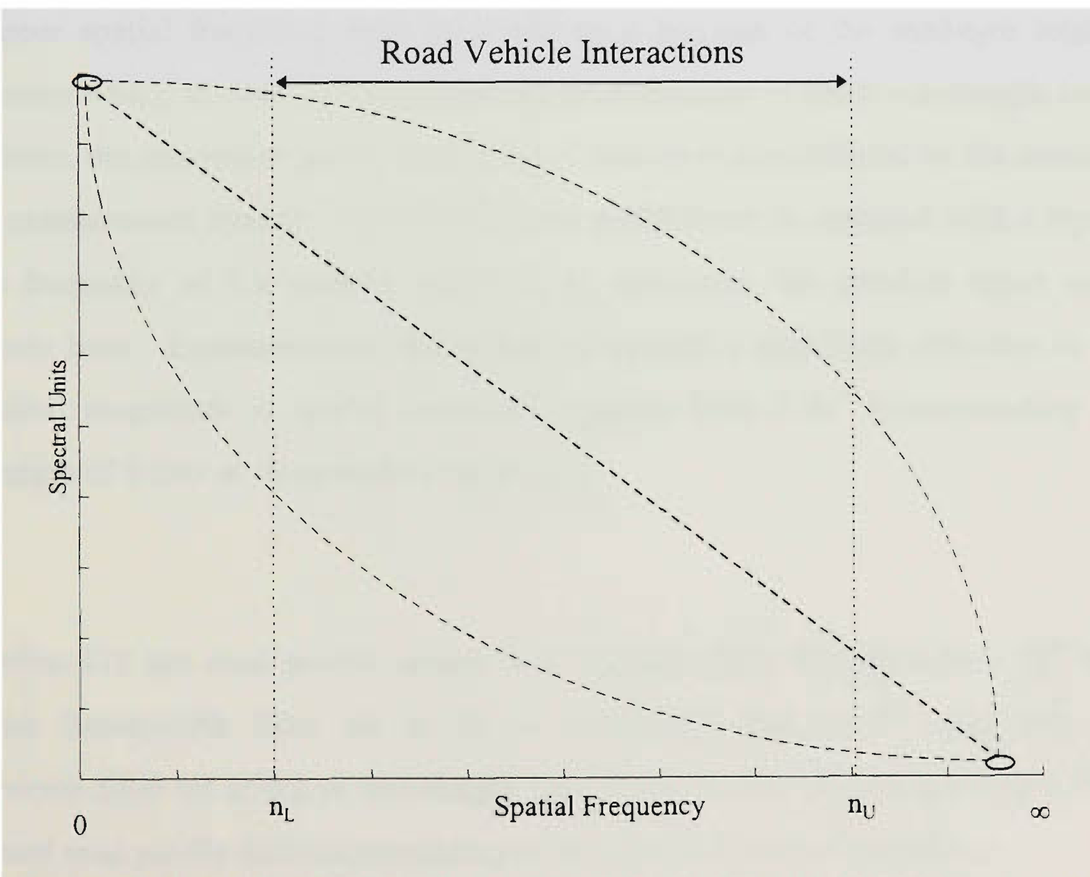


Figure 4.2. Expected amplitude as a function of spatial frequency for road profiles

When considering road profiles as the main source of damage for packages during road transit, it is essential that those wavelengths which induce vehicle resonances are included in the analysis. Several researchers (for example, Marcondes (1990), ASTM D4728 (1995), Singh and Marcondes (1992), Pierce et al (1992) and AAR (1991)) document the first vertical resonant frequency of commercial vehicles as typically 3 to 4 Hz. In order to account for all types of road vehicles, road fluctuations wavelengths of up to 33m will be used for the analysis of road profiles in this study. This corresponds to the inclusion of all excitation frequencies greater than at least 1 Hz for a vehicle speed of up to 120 km/h. In the worst case the amplitude of road fluctuations at 33m wavelengths is such that vehicles travelling at speeds not exceeding 120 km/hr will experience negligible acceleration. The raw road profile elevation spectra for two typical roads is shown in Figure 4.3 which demonstrates that, as expected, the fluctuation amplitude decreases as spatial frequency increases.

The upper spatial frequency limit (n_U) will be a function of the road-tyre interface mechanism which, in itself, will provide natural attenuation of small wavelength events. In addition, the maximum spatial frequency of interest is also affected by the resolution of the measurement system. The ARRB laser profilometer is designed with a Nyquist spatial frequency of 9.8 cycle/m which is, by definition, the absolute upper spatial frequency limit. Examination of the spectrum revealed a significant reduction in road fluctuation magnitude at spatial frequencies greater than 5 m^{-1} (corresponding to a wavelength of 0.2m) as illustrated in Figure 4.3.

The entire 415 km road profile sample was digitally (IIR) filtered with a 12th order highpass Butterworth filter set at 33 m wavelength and an 8th order low pass Butterworth filter set at 0.2 m wavelength (see Appendix B). Figure 4.4 shows 100 m of filtered road profile data corresponding to the spectra shown in Figure 4.3.

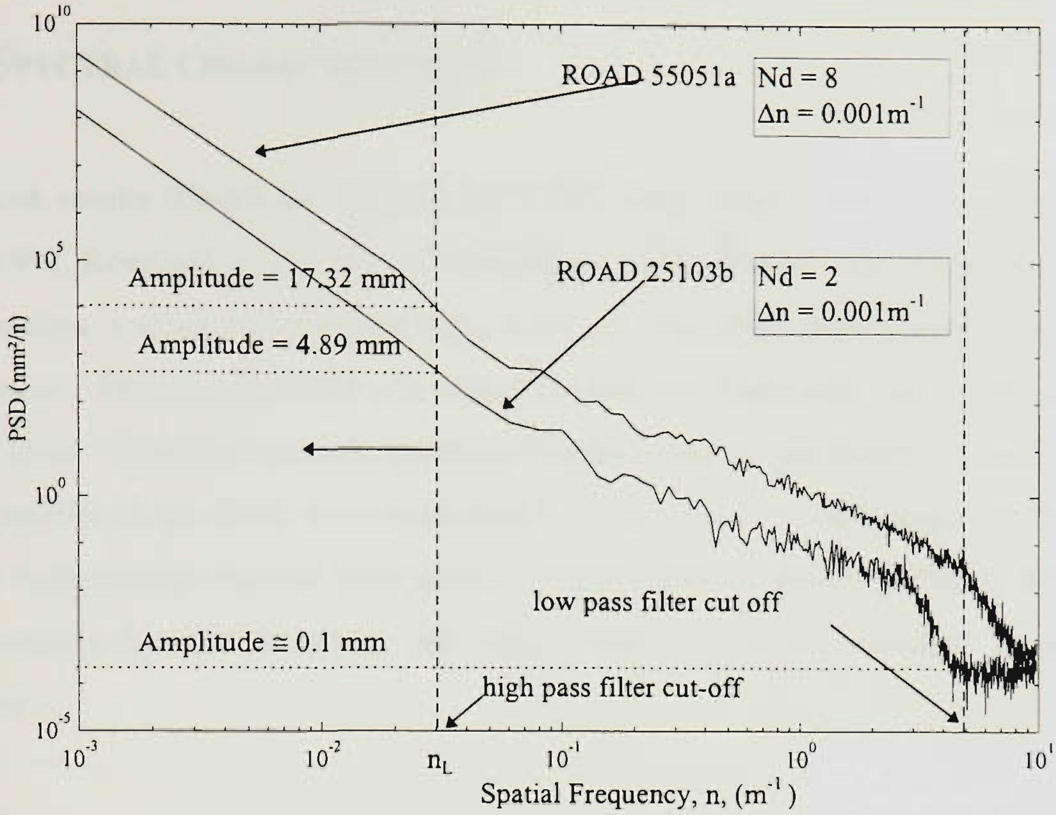


Figure 4.3. PSD for two typical roads

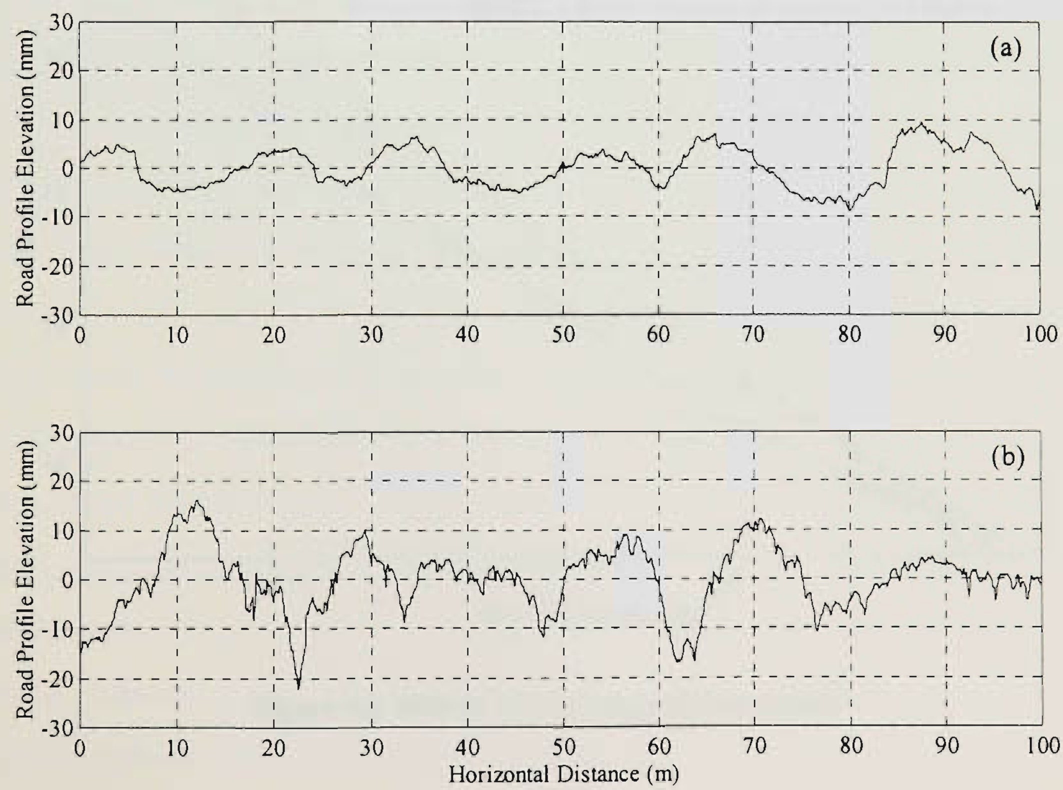


Figure 4.4. 100 m extract of filtered road elevation data, (a) 25103b, (b) 55051a

4.2 SPECTRAL CHARACTERISTICS

Research results (Dodds and Robson 1973, ISO 1982, Heath 1988, Hegmon, 1993, Xu *et al* 1992, Rouillard *et al* 1994 and Bruscella *et al* 1997) show that, while the shape of road spectra is independent of road type, the level of the PSD varies proportional to road roughness. This is manifested as a vertical translation of the road spectra based on the RMS level. Therefore the sole pertinent variable used to describe the spatial PSD of road profiles is the RMS level since RMS^2 is equivalent to the integral of the PSD. Three typical road sections were used to confirm this as shown in Figure 4.5. This phenomenon has the advantage that road roughness can be classified by a single number.

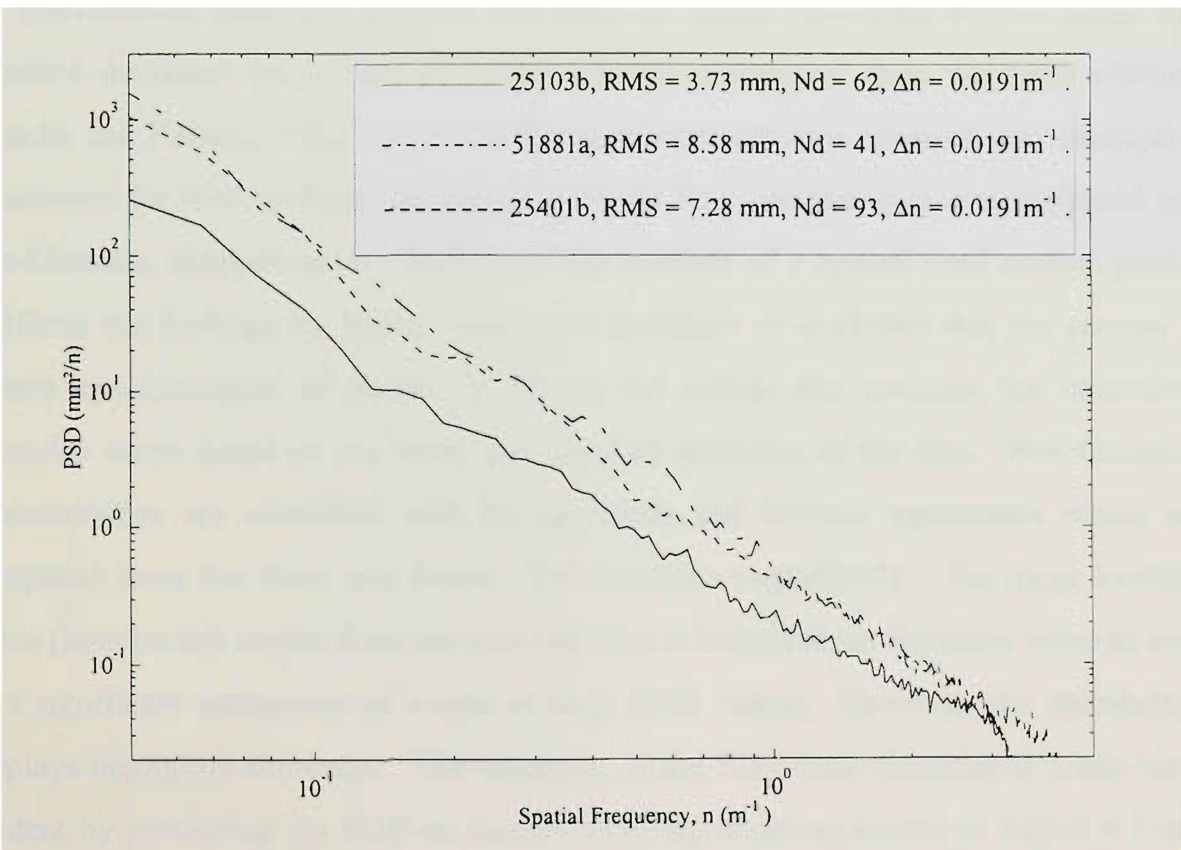


Figure 4.5. PSD of three road profile elevations

However, when computing the averaged PSD of a random process it is important to ensure that the samples are stationary and free from transients. As vehicle vibrations are rarely constant, even at a constant vehicle speed, it is presumed that road surface profiles exhibit non-stationary characteristics and contain transients. Before computing the average PSD, the data should be prepared such that any transient events are removed and that stationary sections be combined and analysed separately. The next section investigates the fundamental amplitude domain characteristics of road profiles.

4.3 AMPLITUDE DOMAIN CHARACTERISTICS

The representation of a random process by a PSD only describes the distribution of energy with respect to frequency. The distribution of energy in relation to amplitude is best shown by the probability density function (PDF). It has often been assumed that road surface fluctuations can be considered as a Gaussian process. This is usually done for convenience since the process can then be simply described by the mean and standard deviation only, both of which can be determined from the PSD estimate (Bendat and Piersol, 1986). It is therefore understandable that research into descriptive parameters for road surfaces has focussed on the PSD estimate only and neglected any non-Gaussian characteristics. Results of the analysis of a typical road surface profile confirms the findings by Heath (1988) and Rouillard *et al* (1996) that the process is clearly non-Gaussian, as shown in Figure 4.6 which also includes the equivalent Gaussian curve based on the mean and standard deviation of the data. Non-Gaussian characteristics are identified with the skewness and kurtosis parameters which are computed from the third and fourth PDF moments respectively. The large kurtosis value (leptokurtic) results from the concentration of events about the mean value as well as a significant occurrence of events at large RMS values. However, the distribution displays negligible skewness. The departure of the PDF from Gaussian is made more evident by presenting the PDF on various semi-log scales as shown in Figure 4.7 and Figure 4.8. The deviation from the Gaussian distribution at RMS values greater than $\pm 3\sigma$ in both figures which indicates the presence of high crest factor events.

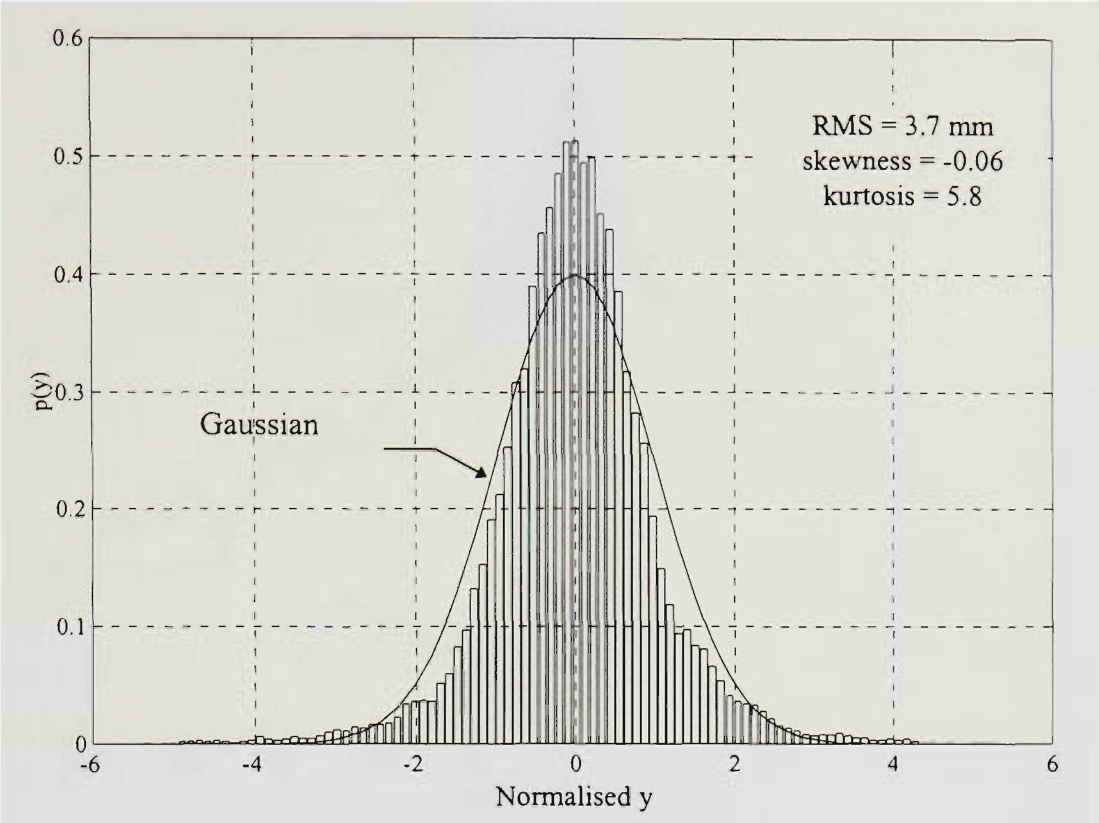


Figure 4.6. PDF of road 25103b (bars) with equivalent Gaussian (lines) based on the μ and σ

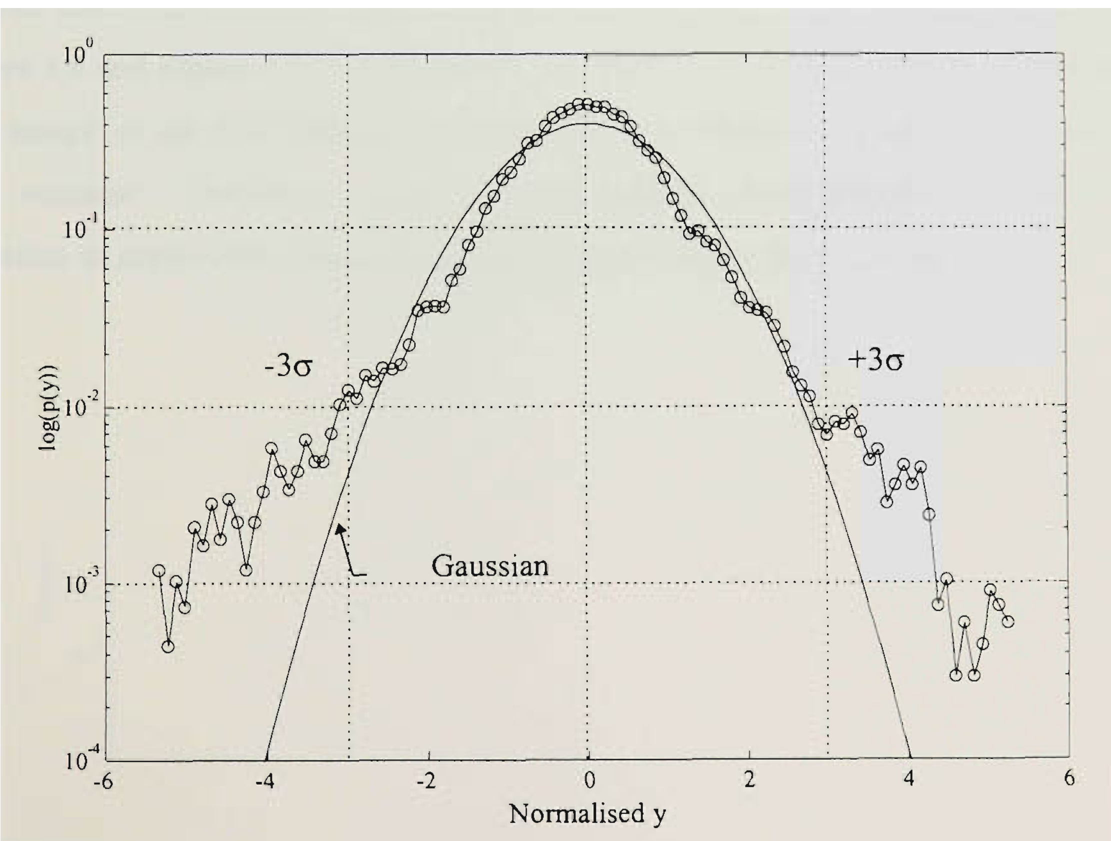


Figure 4.7. PDF of road 25103b on a semi log scale with equivalent Gaussian

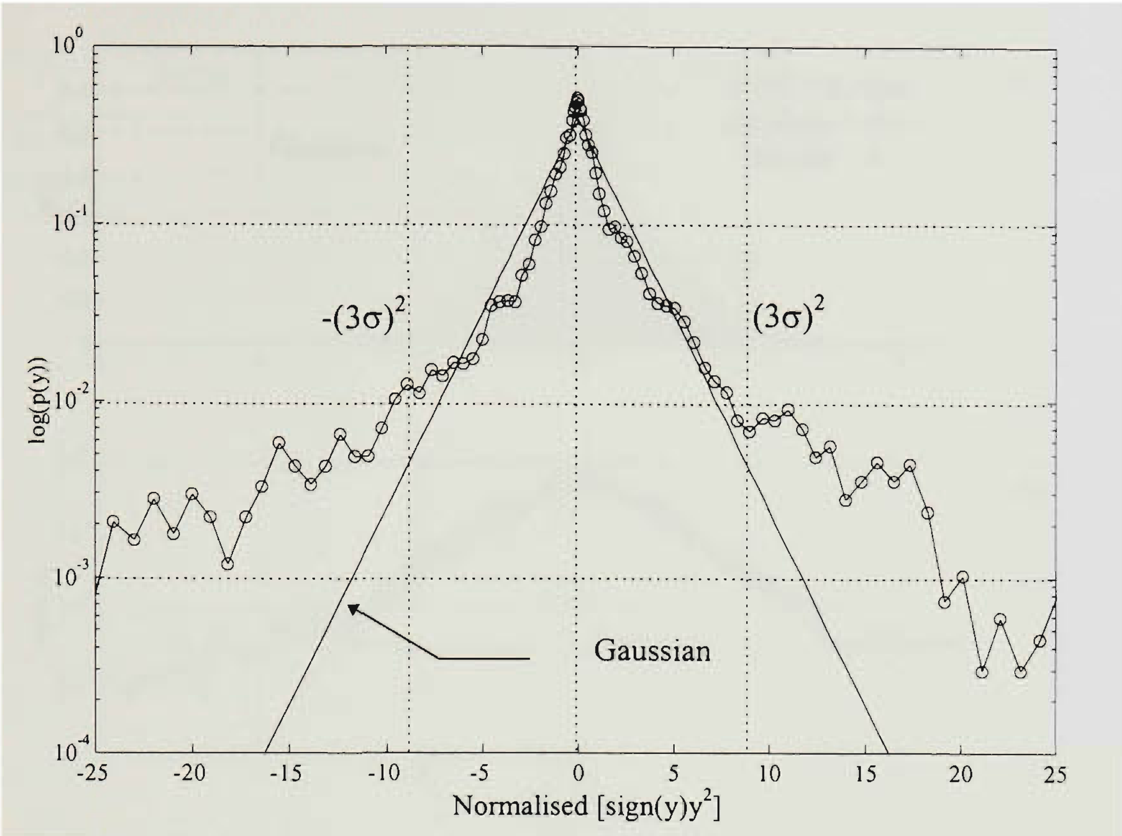


Figure 4.8. PDF of road 25103b on a semi log scale with equivalent Gaussian

Further confirmation of the non-Gaussian characteristics of road surfaces can be seen in Figure 4.9 and Figure 4.10 which contain the PDF of another two typical road surfaces. The nature of the non-Gaussian characteristic was consistent throughout all analysed road sections. Therefore, it can be stated that the characterisation of road profile elevation as approaching Gaussian properties is not valid, shown in Table 4-2.

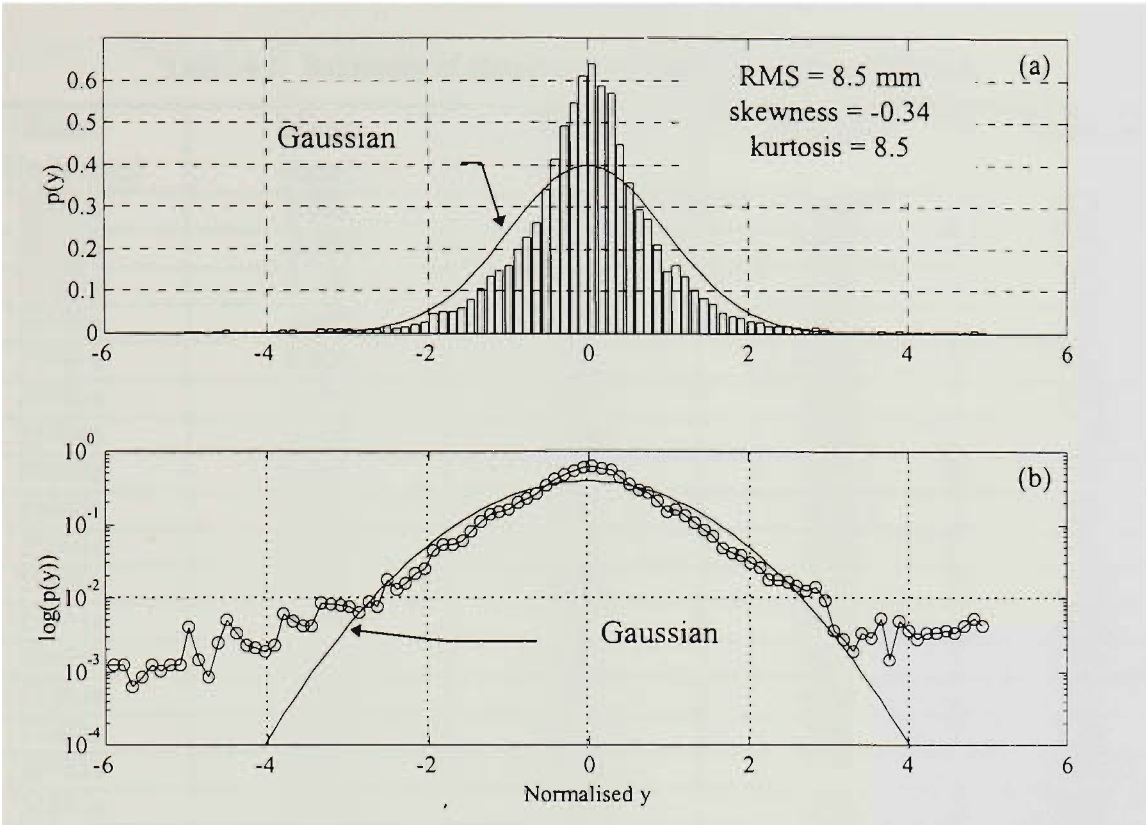


Figure 4.9. PDF of road 51881a with equivalent Gaussian (a) linear scale (b) semi log scale

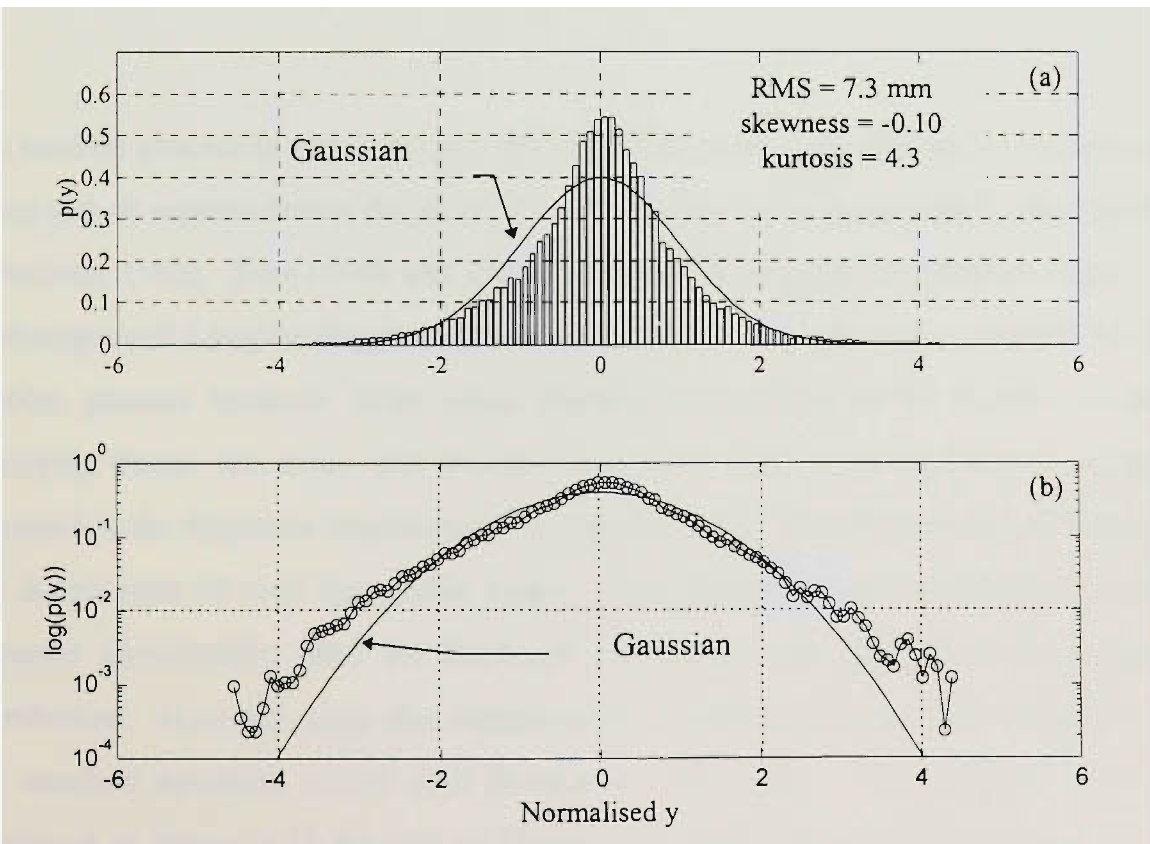


Figure 4.10. PDF of road 25401b with equivalent Gaussian (a) linear scale (b) semi log scale

Table 4-2. Summary of statistics for ARRB elevation profile data

Road (File Name)	Mean (mm)	RMS (mm)	Skewness	Kurtosis
25101a	0.003	3.13	-0.04	7.43
25102a	-0.002	2.03	-0.01	9.74
25103a	-0.003	2.65	-0.01	5.65
25103b	-0.003	3.73	-0.06	5.77
25401b	0.008	7.29	-0.10	4.33
25704a	-0.001	3.45	-0.06	6.51
25704b	0.000	2.98	-0.27	11.84
25803a	0.003	4.07	0.07	5.73
25803b	0.001	4.84	-0.14	5.24
25803c	-0.002	5.19	0.02	6.53
25805b	0.000	5.38	-0.16	5.12
25901a	-0.001	5.23	-0.04	4.45
26404b	0.000	4.80	-0.34	15.08
27203a	-0.003	7.86	-0.14	5.19
27401a	-0.002	8.47	0.05	3.88
50381a	-0.001	14.01	3.77	128.87
51881a	-0.028	8.54	-0.34	8.50
51971a	-0.002	6.93	-0.17	5.40
52001a	0.002	6.14	-0.16	15.02
55051a	-0.001	9.46	-0.13	5.59
59621a	0.001	7.89	-0.07	4.97

If a random process is classified as narrow banded, namely all maxima occur above the mean and all minima below the mean, the distribution of the peaks follows the Rayleigh (Newland, 1993). Rice (1944 and 1945), in the study of noise in electrical signals and Cartwright and Longuet-Higgins (1956), in the study of ocean waves, showed that as a random process becomes more broad banded (an increase in the number of peaks occurring below the mean and troughs above the mean), the distribution of peaks approaches the Gaussian distribution (see Appendix C). Rouillard *et al* (1996) studied the distribution of road fluctuation peaks. They found that the distribution of peaks departed significantly from the Rayleigh distribution and approached the Gaussian distribution. However, they also suggested a correlation between road roughness and the standard deviation of the road fluctuation amplitudes. Three typical results are displayed in Figure 4.11 through to Figure 4.13 which show the distribution of peak heights together with best fitting Gaussian and Rayleigh distributions. From these results, there appears to be no definite relationship between road roughness and the standard deviation of the road fluctuation amplitudes. However, there appears to be a relationship between the kurtosis of the peak distribution and the nominal road roughness.

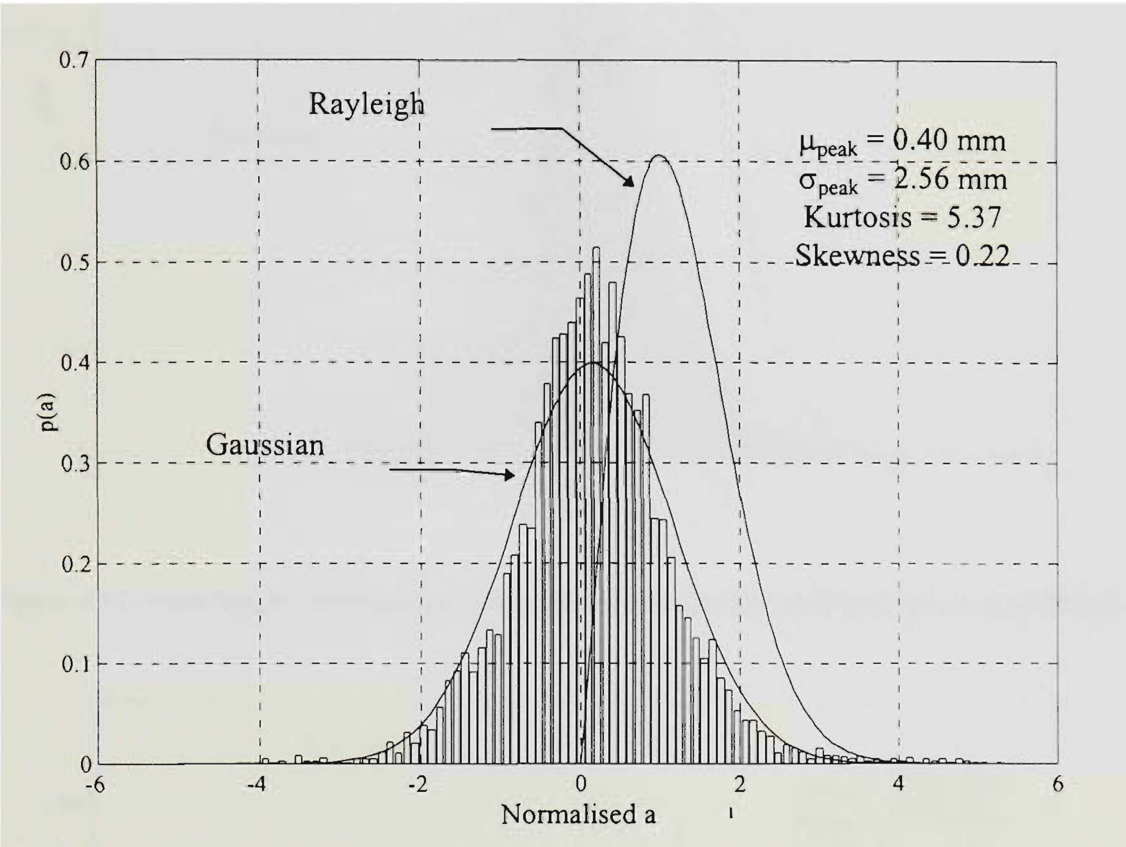


Figure 4.11. Peak height distribution with equivalent Gaussian and Rayleigh (road 25103b)

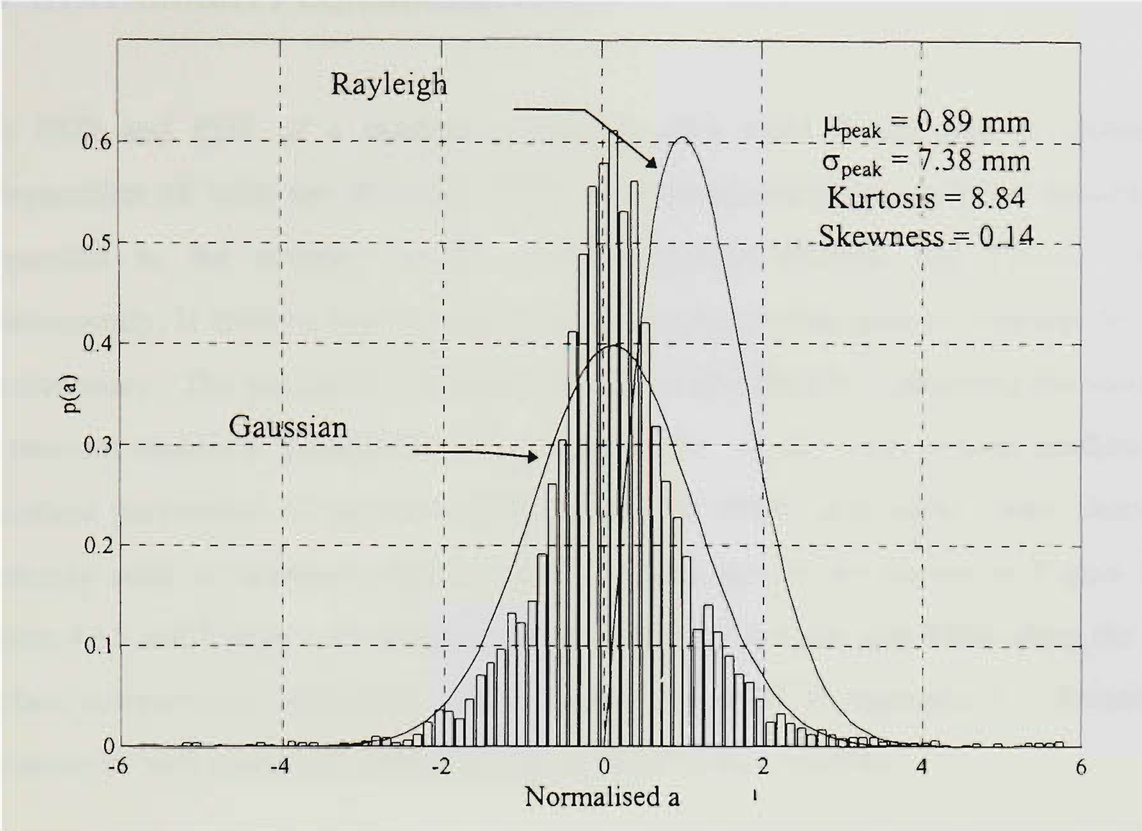


Figure 4.12. Peak height distribution with equivalent Gaussian and Rayleigh (road 51881a)

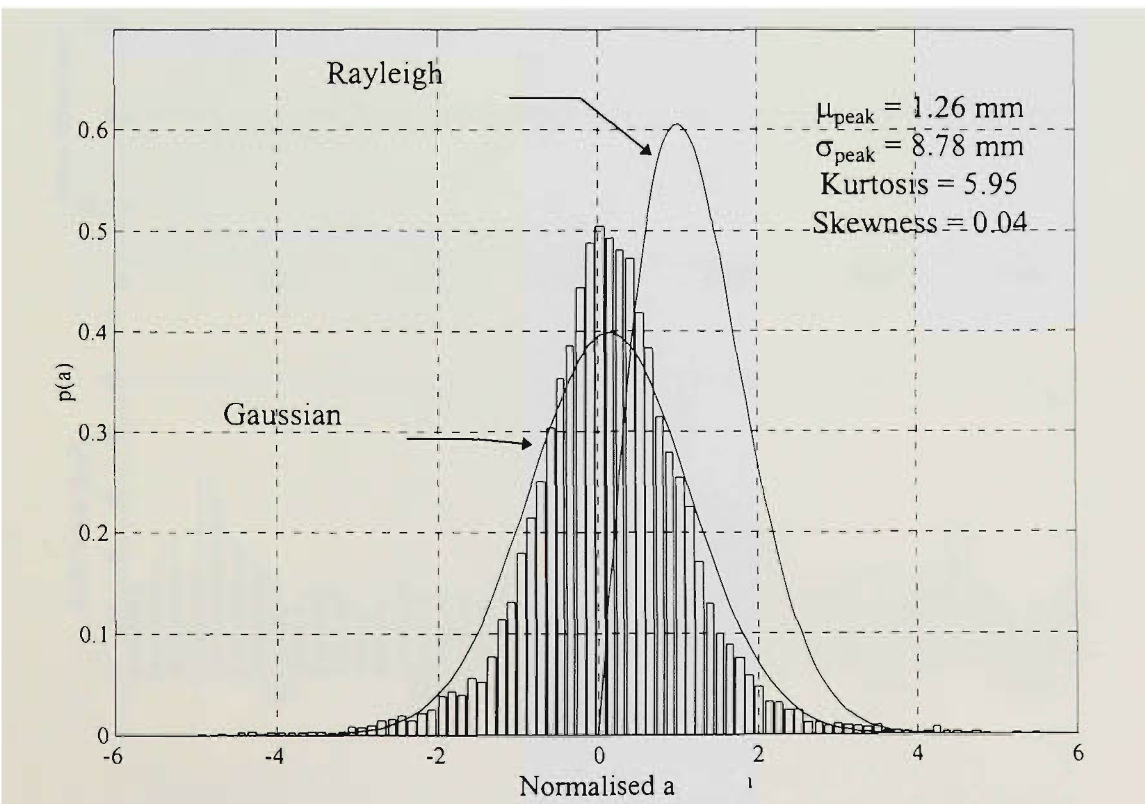


Figure 4.13. Peak height distribution with equivalent Gaussian and Rayleigh (road 55051a)

4.4 STATIONARITY CONSIDERATIONS

The PSD and PDF of a random process is only valid if the data is stationary. Computation of both the PSD and PDF of non-stationary data will be distorted in proportion to the severity of the non-stationarities (Bendat and Piersol, 1986). Consequently, It must be ensured that sections of road profile used to compute the PDF are stationary. The stationarity of a process can be identified by computing the variation of relevant statistical parameters along the sample. In the case of road profiles, the statistical parameters of interest are the mean, the RMS, and higher order statistical moments such as skewness and kurtosis. Typical results are shown in Figure 4.14, Figure 4.15 and Figure 4.16 which show the variation in mean and RMS along the road surface computed in accordance the procedures outlined in Appendix C. Substantial variation in both mean and RMS indicate strong non-stationarities.

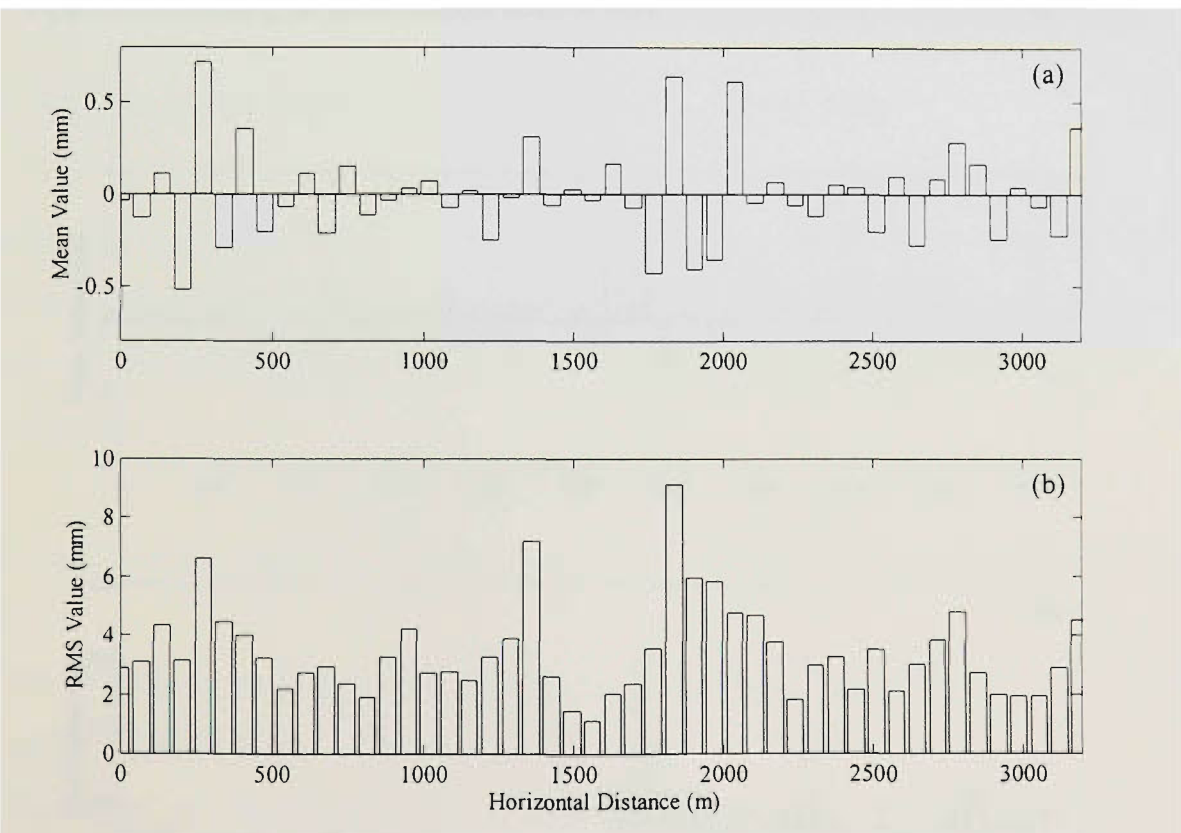


Figure 4.14. Moving (a) mean and (b) RMS of road 25103b, window = 66.5m, overlap = 0%

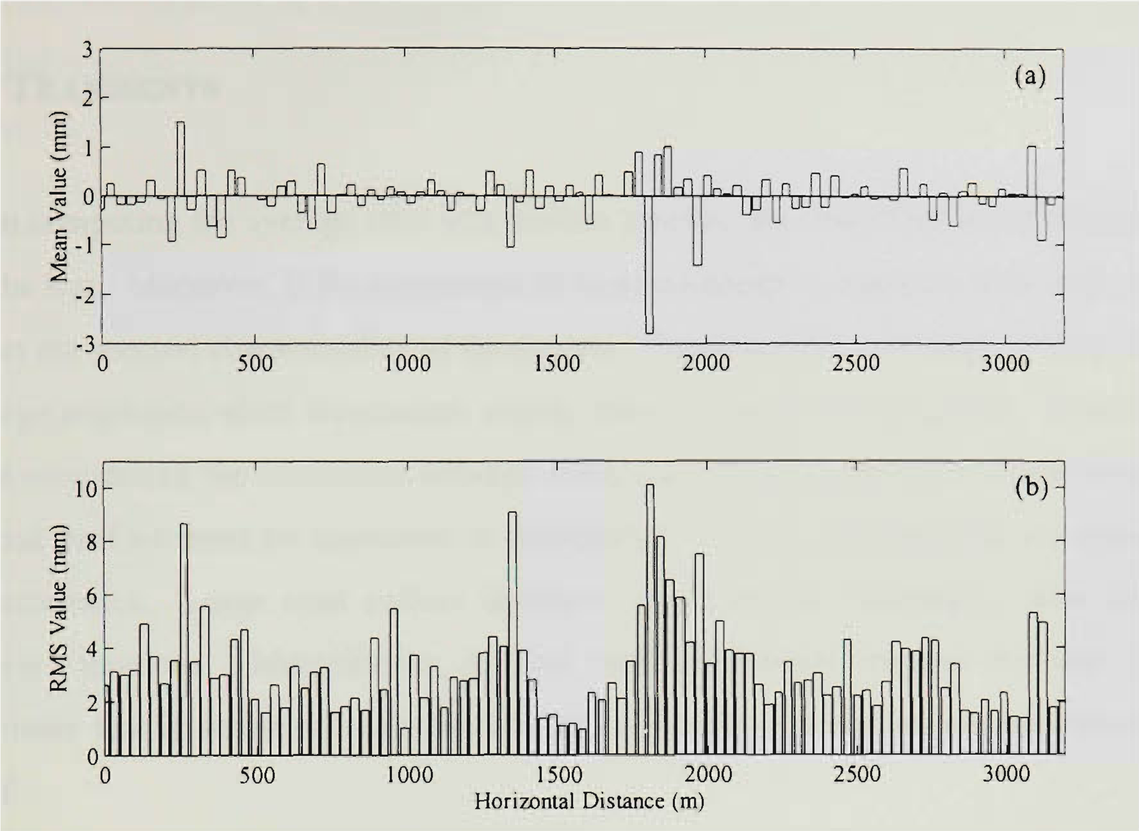


Figure 4.15. Moving (a) mean and (b) RMS of road 25103b, window = 33m, overlap = 0%

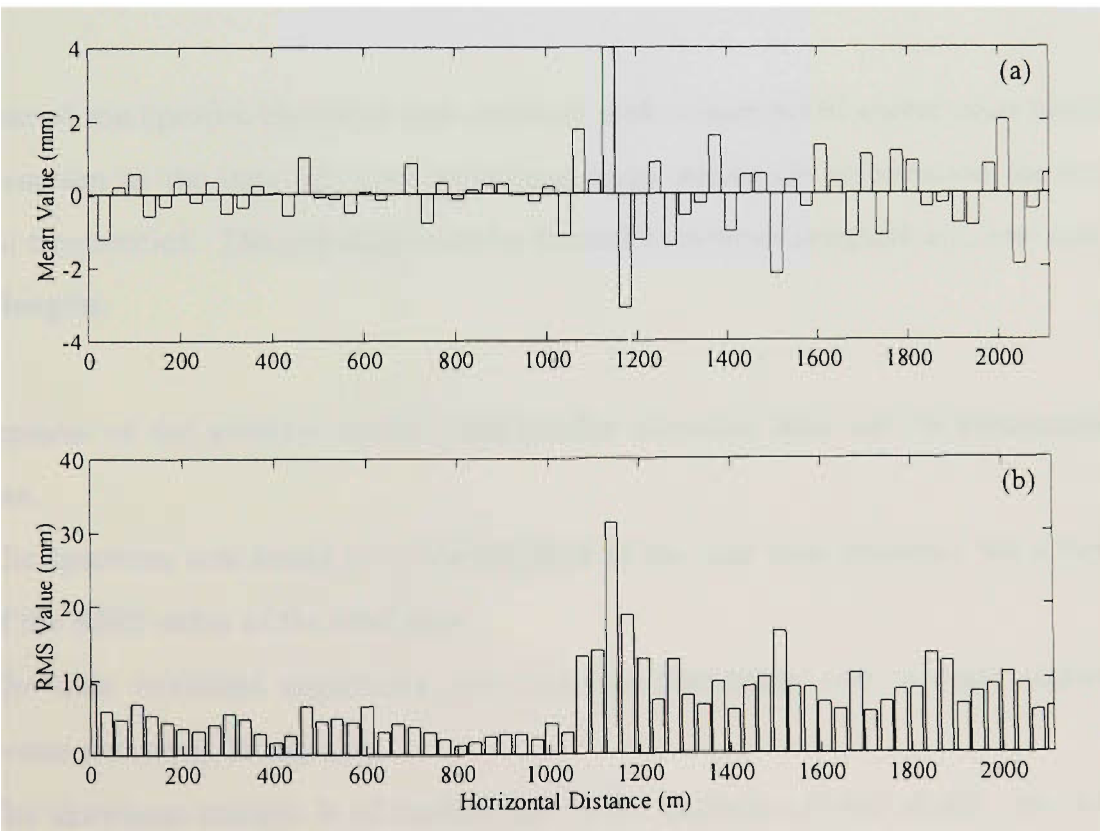


Figure 4.16. Moving (a) mean and (b) RMS of road 51881a, window = 33m, overlap = 0%

4.5 TRANSIENTS

When computing the average PSD of a random process, the characteristics of transients will be lost. Moreover, if the occurrence of large transients is common, they may even distort the spectral characteristics of the process. Consequently, transients, defined here as large amplitude, short wavelength events, should be analysed separately. However, when considering the interaction between roads and vehicles, amplitude characteristics of road profiles must be examined in conjunction with its corresponding wavelength characteristics. Large road surface elevation values do not necessarily cause large vehicle vibrations. Identification of road profile transients requires the use of a parameter that is sensitive to the spatial rate of change in elevation, not the elevation itself.

4.6 SUMMARY OF ROAD PROFILE ELEVATION ANALYSIS

The use of road profile elevation data obtained with a laser profilometer must be treated with caution as the data has very prominent large amplitude information for the low spatial frequencies. The raw data must be filtered to remove insignificant, low and high wavelengths.

The results of the analysis on the road profile elevation data can be summarised as follows.

- The spectrum was found to be independent of the road type generally but a function of the RMS value of the road data.
- The data exhibited significant non-Gaussian properties with a large number of events occurring above $\pm 3\sigma$.
- The skewness statistic is of limited use in the analysis of road profile elevation as results show it to be negligible.

- There was found to be a correlation between the kurtosis of the peak amplitudes and road roughness. The distribution of peaks of the road profile do not approximate to the Rayleigh distribution.
- Moving statistics indicate substantial non-stationary characteristics of road profile elevation data.
- An alternative method must be developed in order to include transients in the analysis and classification of road surface.

The description of the road profile which provides the greatest relevance to vehicle simulation is the spatial rate of change of the slope of the road profile elevation (the derivative of the velocity profile) or 'spatial acceleration'. The concept of the road profile spatial acceleration is introduced in the next section.

5. FUNDAMENTAL CHARACTERISTICS OF ROAD PROFILE SPATIAL ACCELERATION

The use of road profile elevation data was shown to be limiting for analysis of transients and consequently, the spatial acceleration of road profile data was adopted as the fundamental variable for characterisation and universal classification.

Spatial acceleration is the double derivative of the road elevation with respect to its horizontal distance, or 'rate of change of the slope'.

By definition, the road profile spatial acceleration y'' is:

$$y'' = \frac{d^2 y(x)}{dx^2} \tag{5-1}$$

where:

y = road profile elevation,

x = horizontal distance

The temporal velocity is related to the road elevation by:

$$\dot{y} = \frac{dy}{dt} = \frac{dy}{dx} \cdot \frac{dx}{dt} = y' v \tag{5-2}$$

where:

t = time

y' = spatial velocity

$\frac{dx}{dt} = v =$ vehicle transverse velocity.

Therefore, the temporal acceleration is:

$$\ddot{y} = \frac{d}{dt}\left(y' . v\right) \tag{5-3}$$

or $$\ddot{y} = \frac{dy'}{dt} v + y' . \frac{dv}{dt} \tag{5-4}$$

where $$\frac{dy'}{dt} = \frac{dy'}{dx} \cdot \frac{dx}{dt} \quad \text{(5-5)}$$

therefore $$\ddot{y} = v^2 \, y'' + y' \, \ddot{x} \quad \text{(5-6)}$$

where $\ddot{x}$ = longitudinal acceleration (that is: vehicle acceleration).

For a constant vehicle longitudinal velocity (zero vehicle acceleration), the temporal acceleration is calculated from the expression:

$$\ddot{y} = v^2 \, y'' \quad \text{(5-7)}$$

where:

v = constant transverse (vehicle) velocity.

The road profile elevation, *y*, as a function of the horizontal distance *x*, may also be expressed as an Nth order polynomial approximation:

$$y = c_0 + c_1 x + \sum_{n=2}^{N} c_n x^n \quad \text{(5-8)}$$

The double derivative (spatial acceleration) has the effect of forcing the mean to zero and removing first order trends, represented respectively by the constants c_0 and c_1:

A 10 m section of typical road profile data, and its corresponding spatial acceleration, is shown in Figure 5.1 to illustrate the transformation from the displacement domain to the spatial acceleration domain. The spatial acceleration at 'x' was estimated from the tangent at 'x', calculated from the polynomial approximation of points *'x-1', 'x' and 'x+1'*. As expected, long wavelengths are suppressed and short wavelengths are accentuated.

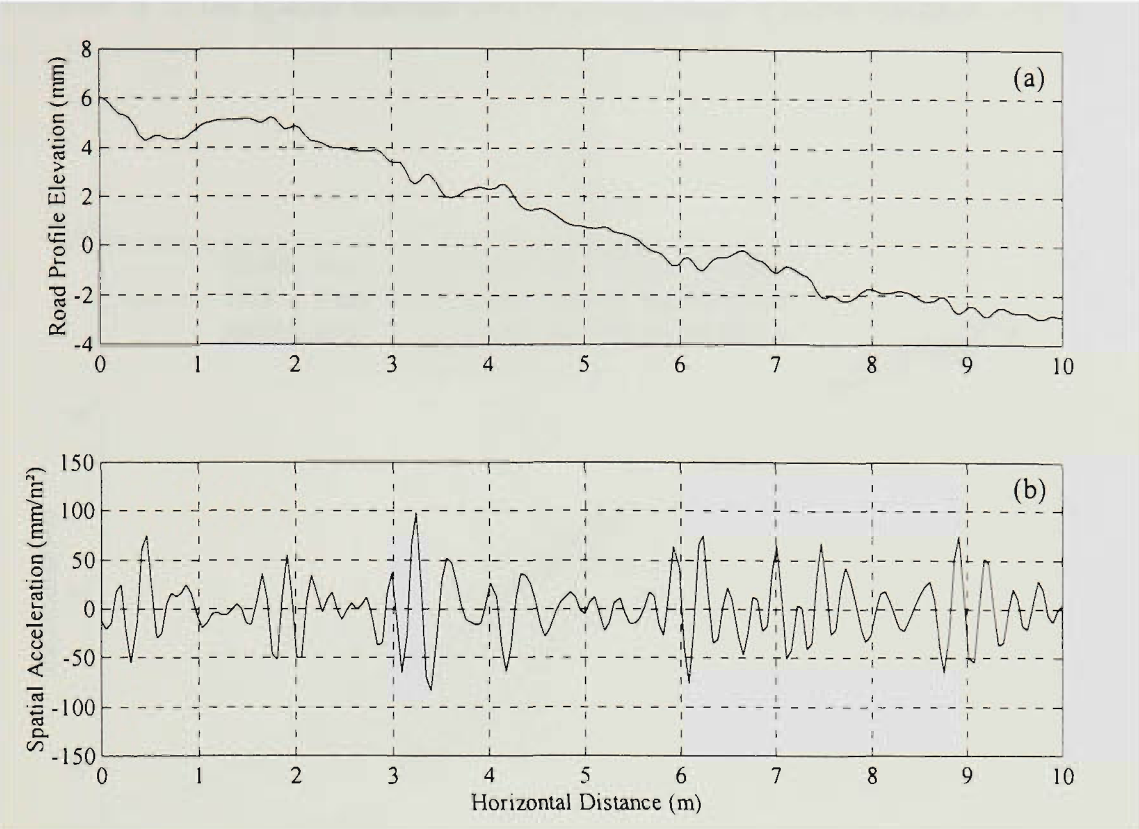


Figure 5.1. (a) Elevation and (b) spatial acceleration for a 10 m extract from road 25103b

5.1 SPECTRAL CHARACTERISTICS

In order to verify that the basic spectral properties of road profile data are retained after transformation into the spatial acceleration domain, the PSD of roads 25103b, 51881a and 25401b were computed and displayed in Figure 5.2. As can be seen, the basic spectral shape remains independent of nominal road roughness. Newland (1993), shows that the spatial acceleration spectrum is related to the elevation spectrum by:

$$S(y'') = S(y) \times (2\pi n)^2 \qquad \textbf{(5-9)}$$

where

y = road profile elevation,

y'' = road profile spatial acceleration,

S( ) = spectrum,

n = spatial frequency

The variable 'n' in the spatial domain can be compared to 'f' in the temporal domain.

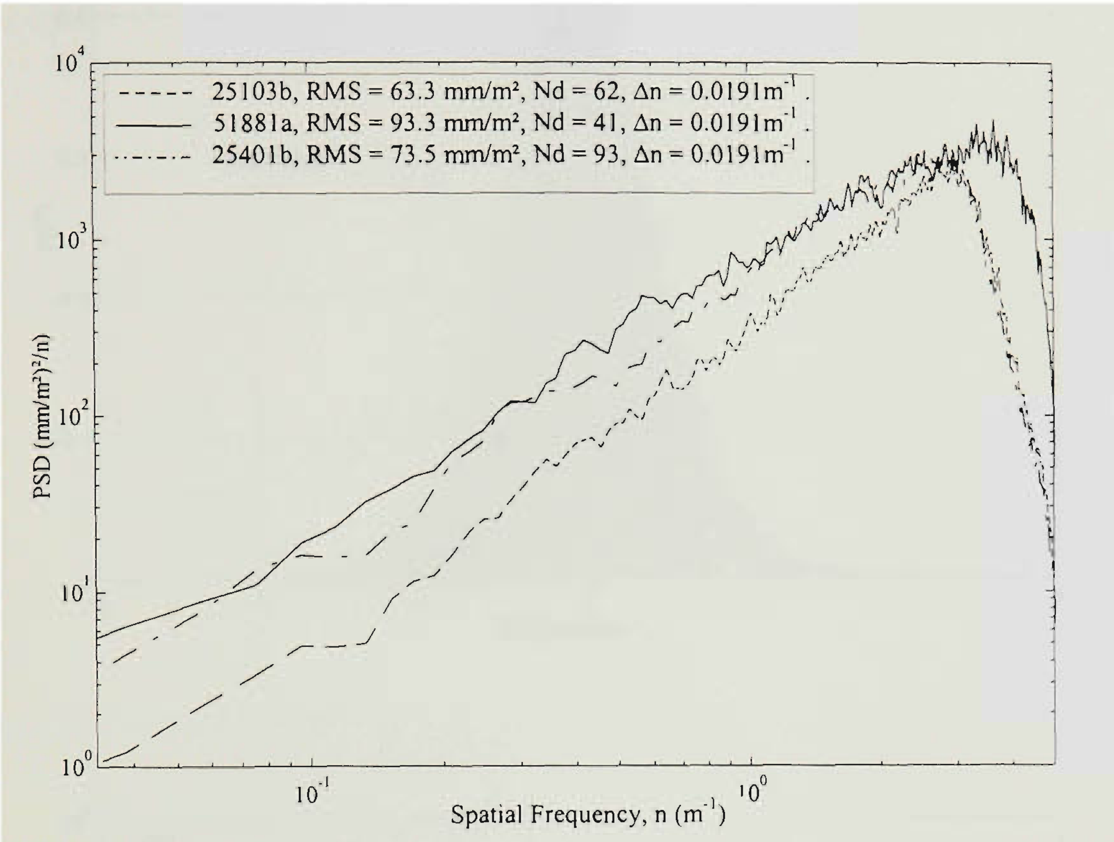


Figure 5.2. PSD estimate for three typical road spatial acceleration

(c/f corresponding Road Profile Spectra Figure 4.5)

5.2 AMPLITUDE DOMAIN CHARACTERISTICS

The effect of transition from the road elevation domain to the spatial acceleration domain on the statistical properties of roads needed to be assessed. The fundamentally non-Gaussian characteristics of road profiles are not affected as shown in Figure 5.3, Figure 5.4 and Figure 5.5.

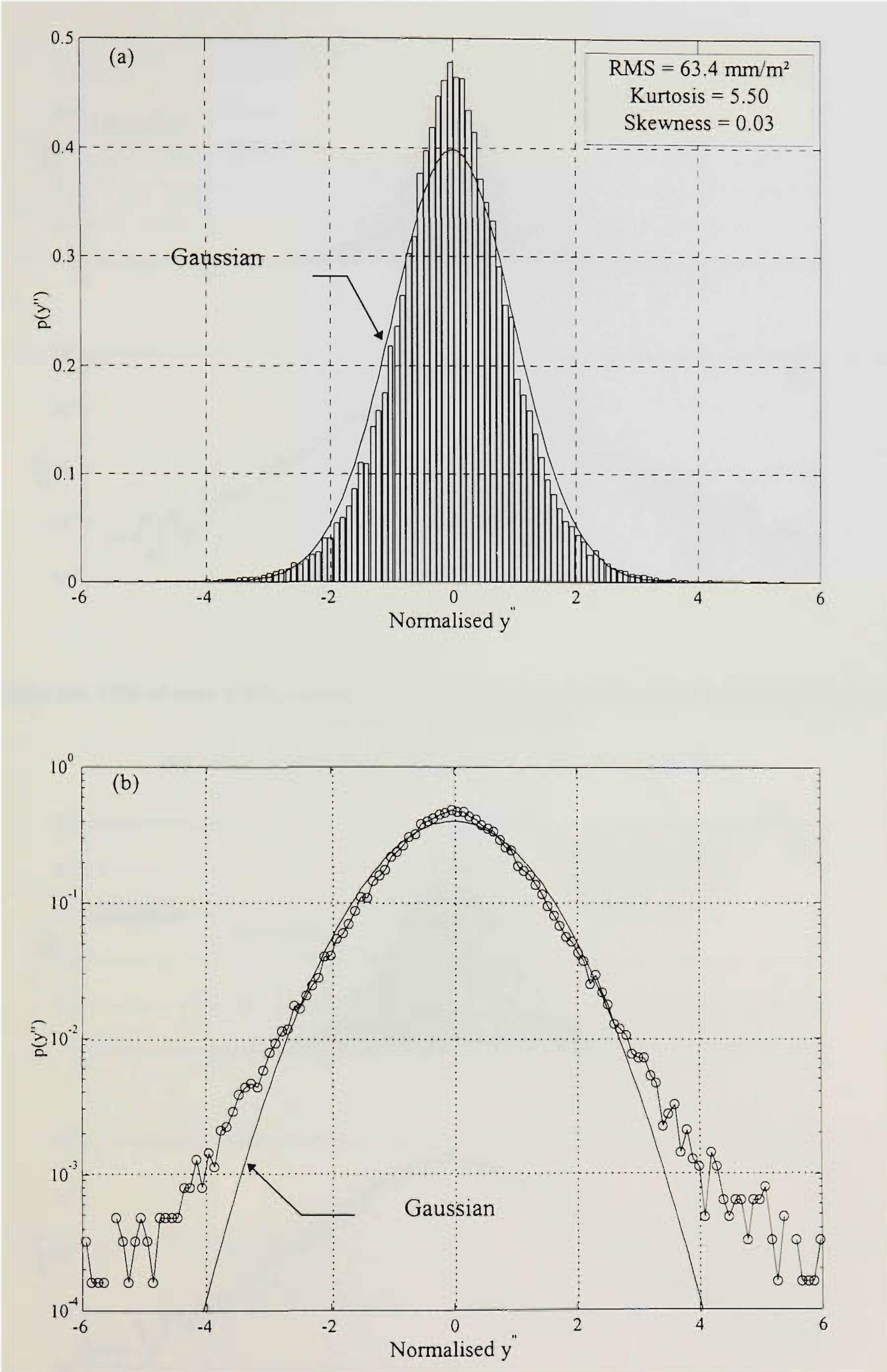


Figure 5.3. PDF of road 25103b spatial acceleration (bars) with equivalent Gaussian (lines) (a) linear scale (b) semi log scale

(c/f corresponding Road Profile PDF in Figure 4.6 & Figure 4.7)

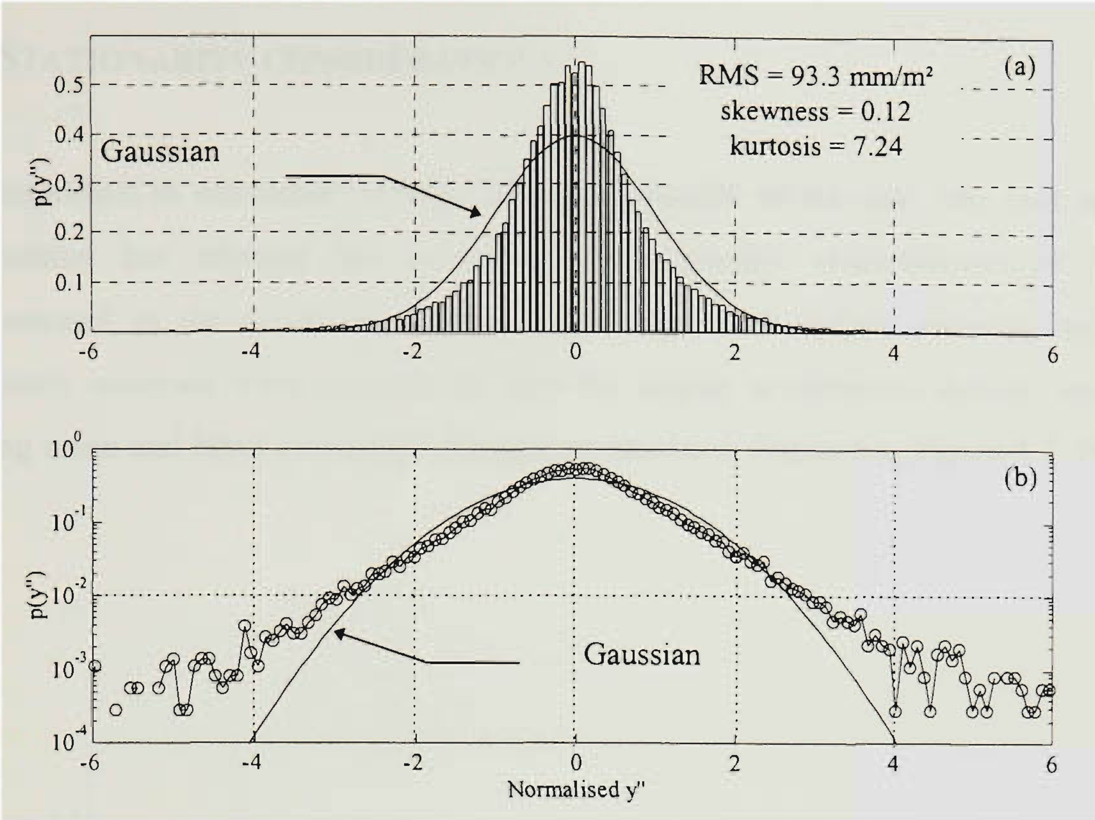


Figure 5.4. PDF of road 51881a spatial acceleration (bars) with equivalent Gaussian (lines) (a) linear scale (b) semi log scale

(c/f corresponding Road Profile PDF in Figure 4.9 and 4.10)

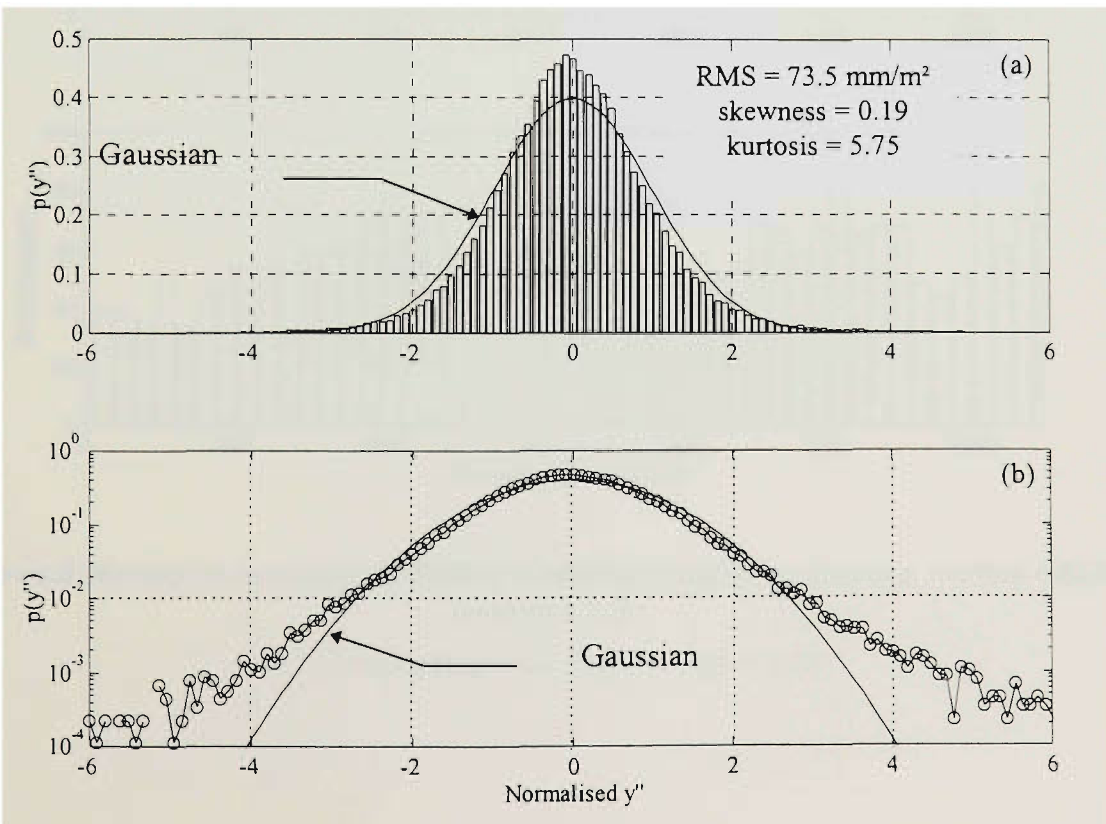


Figure 5.5. PDF of road 25401b spatial acceleration (bars) with equivalent Gaussian (lines) (a) linear scale (b) semi log scale

5.3 STATIONARITY CONSIDERATIONS

It is important to determine whether the transformation of the data into road spatial acceleration has affected the underlying non-stationary characteristics of roads demonstrated in the preceding chapter. The same road surface elevation sections previously analysed were transformed into the spatial acceleration domain and the moving mean and RMS evaluated. Results are shown in Figure 5.6, Figure 5.7, Figure 5.8.

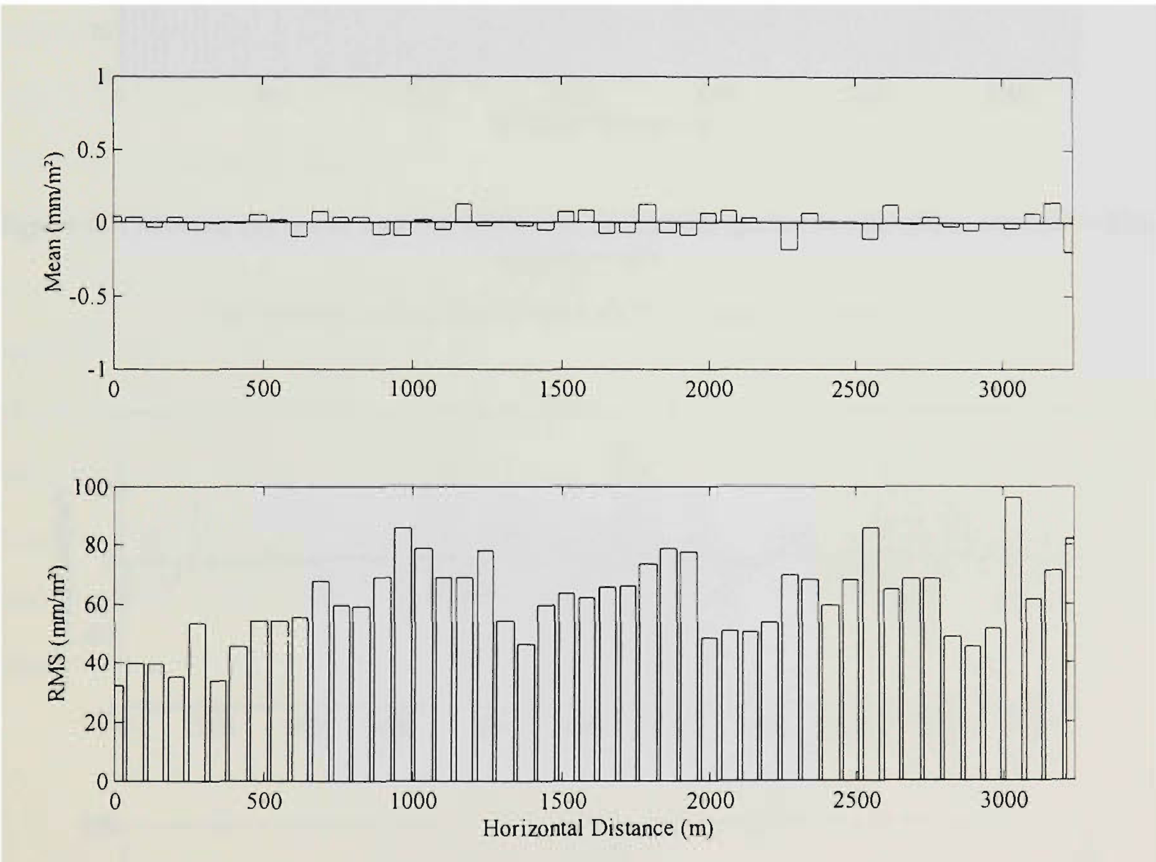


Figure 5.6. Moving (a) mean and (b) RMS of road 25103b spatial acceleration, window = 66.5m, overlap = 0%

(c/f corresponding Road Profile in Figure 4.14)

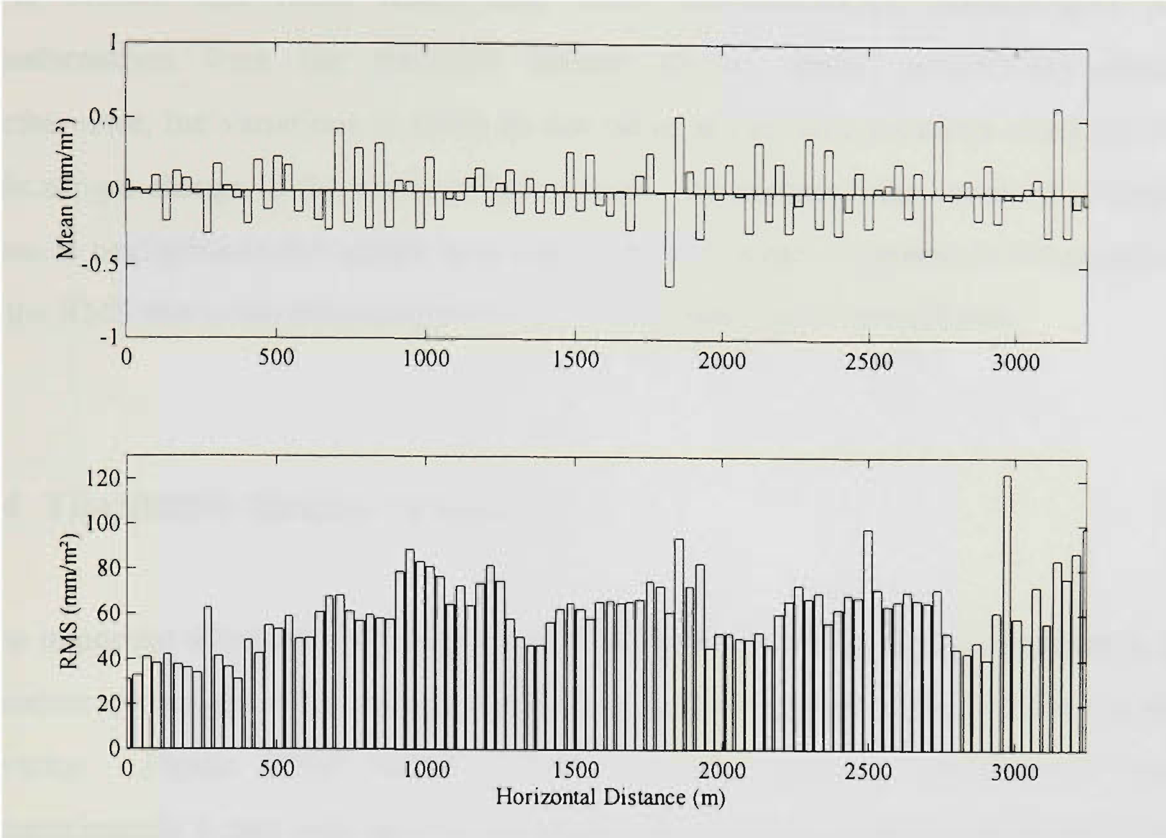


Figure 5.7. Moving (a) mean and (b) RMS of road 25103b spatial acceleration, window = 33m, overlap = 0%

(c/f corresponding Road Profile PDF in Figure 4.15 and 4.16)

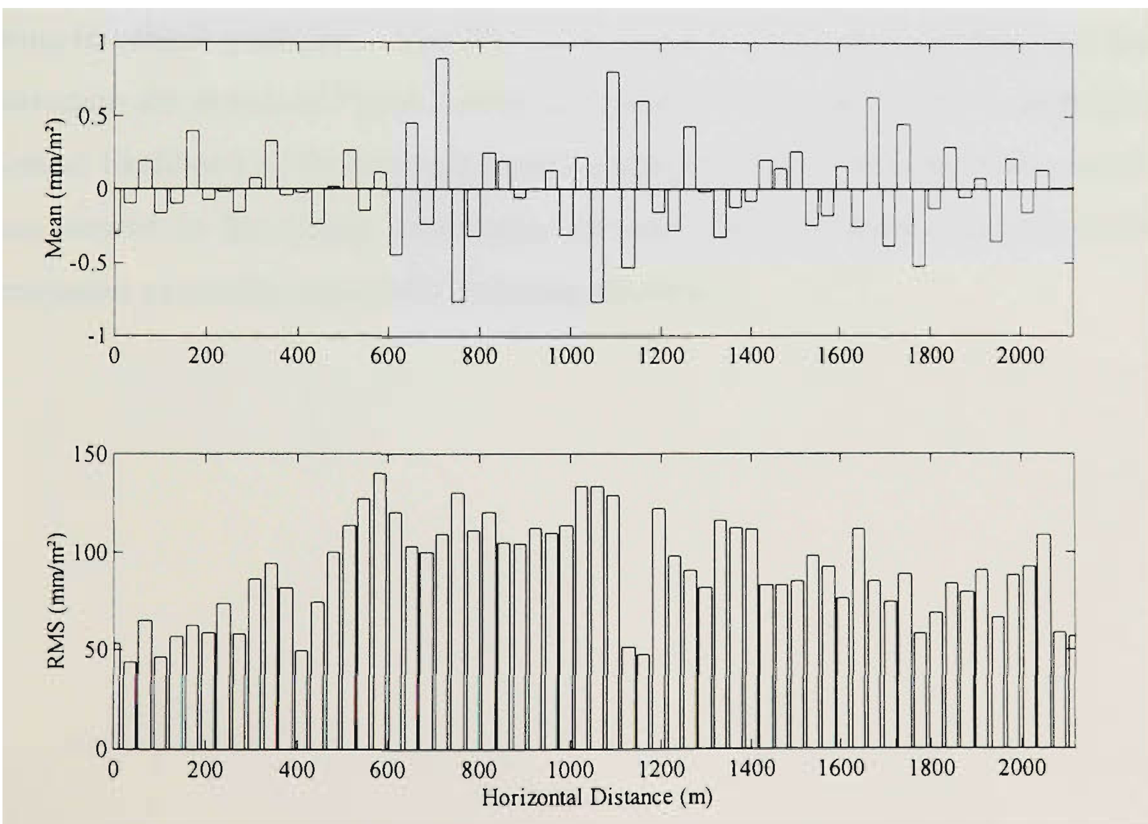


Figure 5.8. Moving (a) mean and (b) RMS of road 51881a spatial acceleration, window = 33m, overlap = 0%

It is evident that roads retain their RMS non-stationarity characteristics after transformation from the elevation domain to the spatial acceleration domain. Furthermore, the variations in RMS do not occur at the same locations along the road indicating a change in the nature of the process. As expected, the variation in moving mean is negligible in the spatial acceleration domain when compared to the magnitude of the RMS due to the attenuation of long wavelengths (first order effects).

5.4 TRANSIENT CHARACTERISTICS

One important advantage of transforming road elevation into spatial acceleration is that transient events are more easily identified and representative of the vehicle vibration severity. Figure 5.9(a) shows a typical section of road containing a bump (approximately 6 mm high and 0.5 m length) while Figure 5.10(a) displays the spatial acceleration (double derivative) of the same road section. These plots clearly highlight the main advantage of analysing roads in the spatial acceleration domain as high amplitude, short wavelength events are amplified in proportion to their severity in relation to vehicle excitation. The PDF of the entire 3.24 km road elevation and spatial acceleration are shown in Figure 5.9(b) and Figure 5.10(b) respectively to highlight the statistical likelihood of the transient event compared to the remainder of the road data. When viewed in the spatial acceleration domain, the PDF shows that the transient events occur extremely outside the Gaussian distribution.

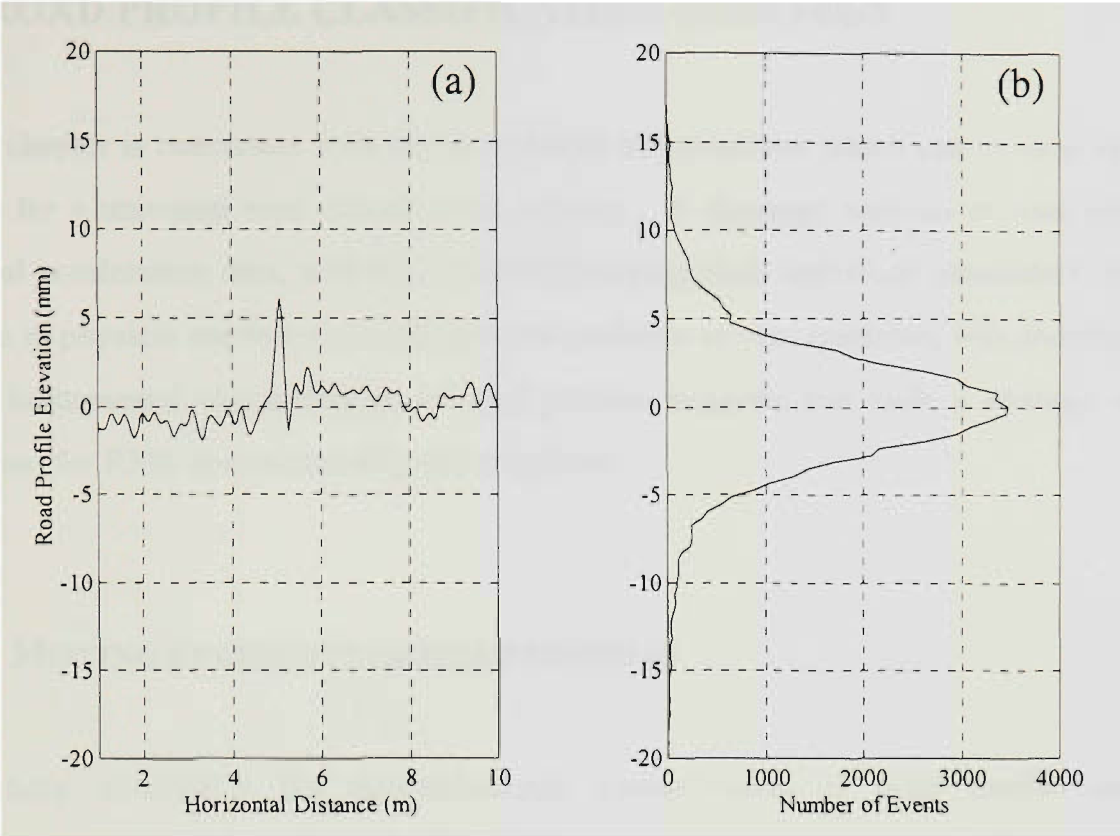


Figure 5.9. (a)10 m extract from road 25103b, with large 'bump' and (b) overall PDF

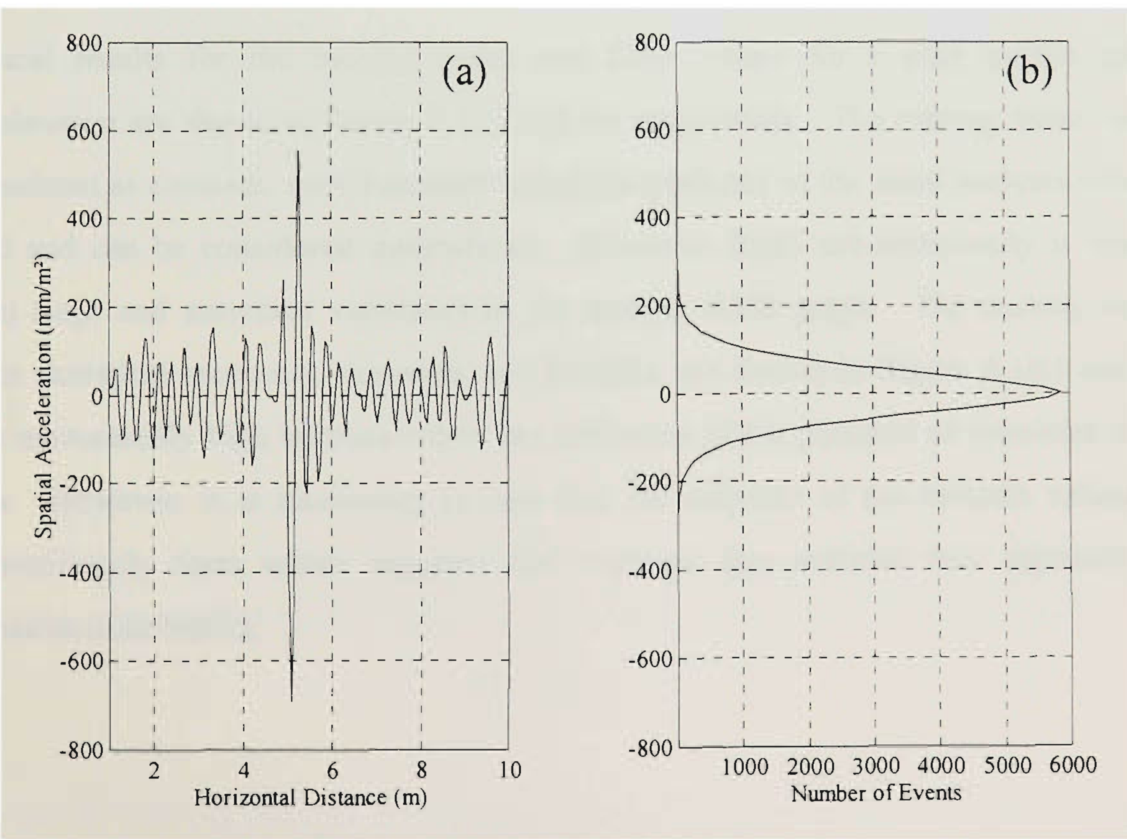


Figure 5.10. (a)10 m extract from road 25103b - transient spatial acceleration (b) overall PDF

6. ROAD PROFILE CLASSIFICATION STRATEGY

This chapter is concerned with the formulation of parameters which can be used as the basis for a universal road classification strategy. A thorough analysis of road profile spatial acceleration data, with the aim of identifying those statistical parameters which relate to physical attributes of road surfaces pertinent to road transport, was undertaken. The fundamental characteristics of road profiles suggests that such a strategy must account for RMS non-stationarity and transients.

6.1 MOVING STATISTICS OF ROAD PROFILES

To fully investigate the non-stationarity characteristics of road profile spatial acceleration, a window size of ≈2.5m (50 samples) was used along with maximum window overlap for transient analysis (crest factors) and 0% overlap for other statistical parameters. Refer to Appendix C for techniques used in dealing with non-stationarities.

Typical results for the moving mean and RMS values for a road profile spatial acceleration are shown in Figure 6.1(a) and (b) respectively. The moving mean can be considered as constant, with localised variations attributed to the small analysis window used and can be considered insignificant. However, RMS non-stationarity is evident from large and sustained variations in the moving RMS graph. The moving higher order statistical moments, skewness and kurtosis, are shown in Figure 6.1(c) and (d). The momentarily high kurtosis values are indicative of the presence of transients in the data. However, it is interesting to note that the majority of the kurtosis values are approximately three which suggests that transient free sections may approach the Gaussian distribution.

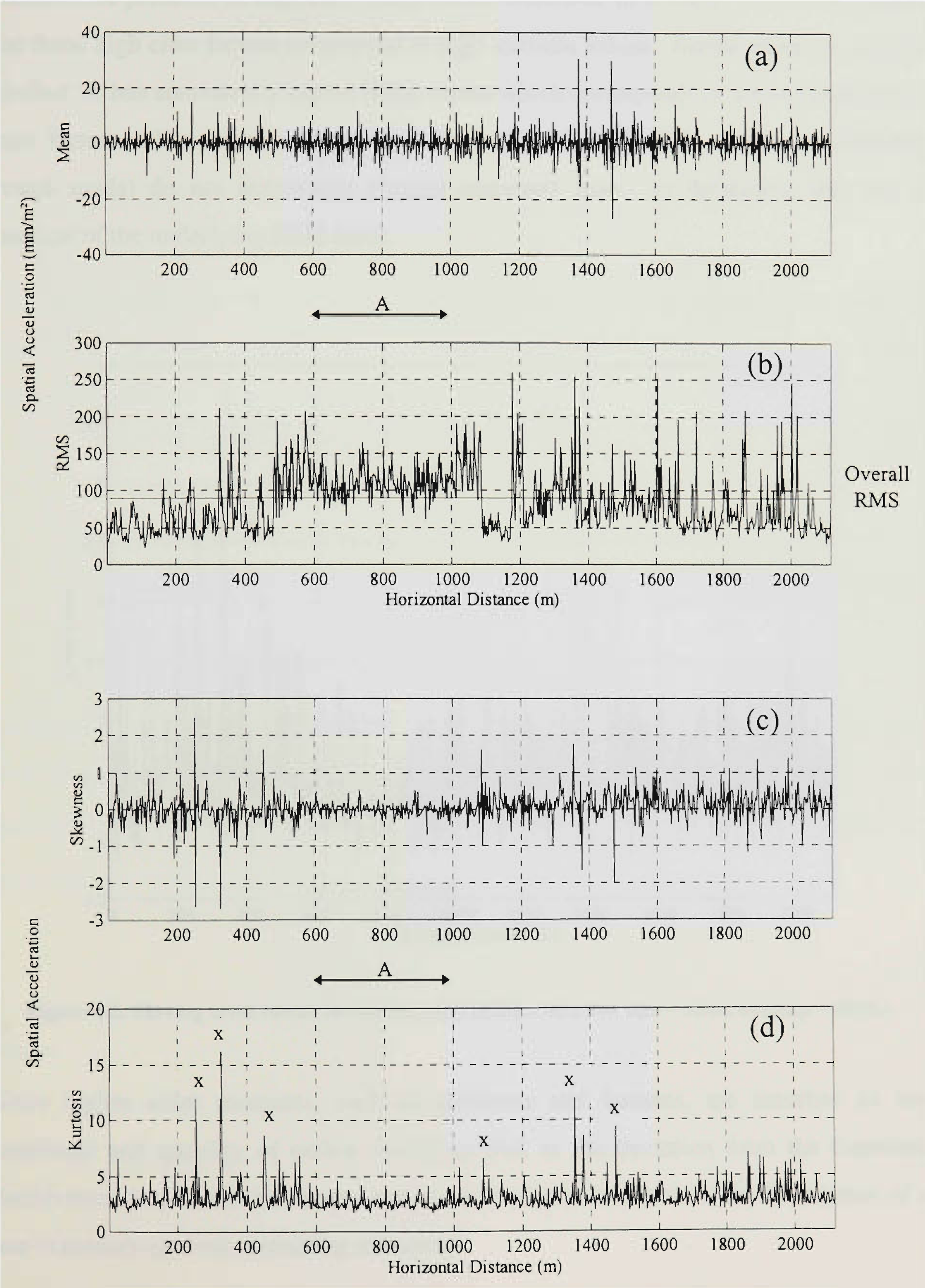


Figure 6.1. Moving (a) mean, (b) RMS, (c) skewness and (d) kurtosis for entire length of road 51881a (ensemble = 2.5m, overlap = 0%)

The moving crest factor for the same road section is shown in Figure 6.2 which indicates the presence of high crest factor events indicated by crosses. It is worth noting that these high crest factors correspond to high kurtosis values. Furthermore, the region labelled 'A' has consistently higher RMS values which corresponds to a low kurtosis and crest factors. This indicates that road sections with high RMS spatial acceleration (rough roads) do not necessarily contain transients since, by definition, they are a function of the underlying RMS level.

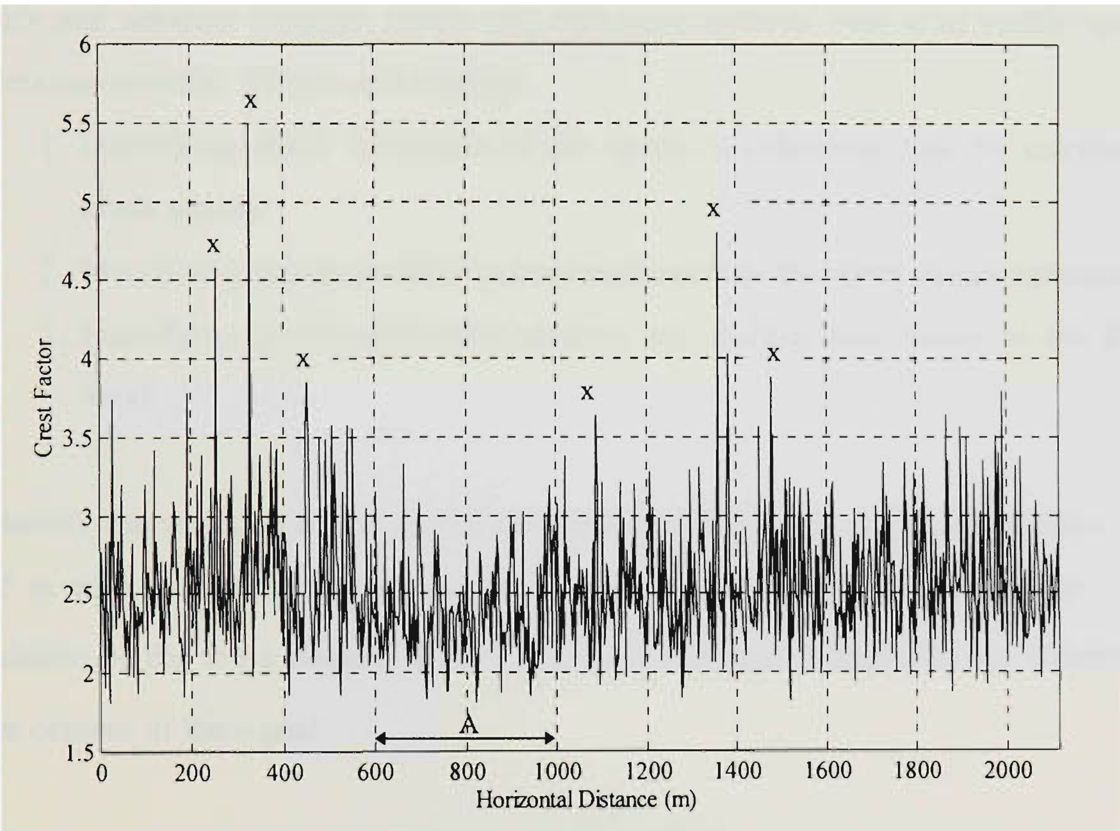


Figure 6.2. Moving crest factor for entire road 51881a (window size = 2.5m, overlap =100%)

Since higher order moments, such as skewness and kurtosis, are sensitive to the amplitude and quantity of outlier events as well as the deviation from the Gaussian distribution, they cannot be used as reliable statistical parameters for the description of a non-stationary process containing transients.

The identification of the highly non-stationary and transient attributes associated with the analysis of road spatial acceleration requires that a suitable methodology be introduced to separate transients from sections of constant RMS, discussed in the next section.

6.2 CONSTANT RMS ROAD SECTIONS AND TRANSIENTS - SEPARATION TECHNIQUE

This section presents the development of a method and computational techniques to identify and separate transient events and stationary sections from road profile spatial acceleration records. This is achieved by:

1. Identifying RMS variations of the spatial acceleration data by calculating mean square
2. Identifying and removing transient sections from the mean square estimate
3. Identifying pseudo-stationary sections and storing them based on the RMS level

To identify the variation of the spatial acceleration RMS value, a moving window size of 0.5 m with maximum overlap was used to estimate the mean square variation. The calculation of the mean square, $\hat{\psi}_y^2(x)$, gives an unbiased estimate of the $(\mathrm{RMS})^2$ or power content of the signal:

$$\hat{\psi}_y^2(x) = \frac{1}{N}\sum_{i=1}^{N} y_i^2(x) \tag{6.1}$$

where:

$\hat{\psi}_y^2(x)$ = mean square,

N = window size,

$y^2{}_i(x)$ = instantaneous square value.

Extensive analysis showed that the mean square estimate was useful in identifying significant changes in RMS level as well as detection of transients in road profile spatial acceleration data. Subsequently, the mean square estimate of the entire 415 km road spatial acceleration sample was computed. A typical section of road exhibiting non-Gaussian and non-stationary characteristics is shown in Figure 6.3(a), with the corresponding moving mean square results shown in Figure 6.3(b).

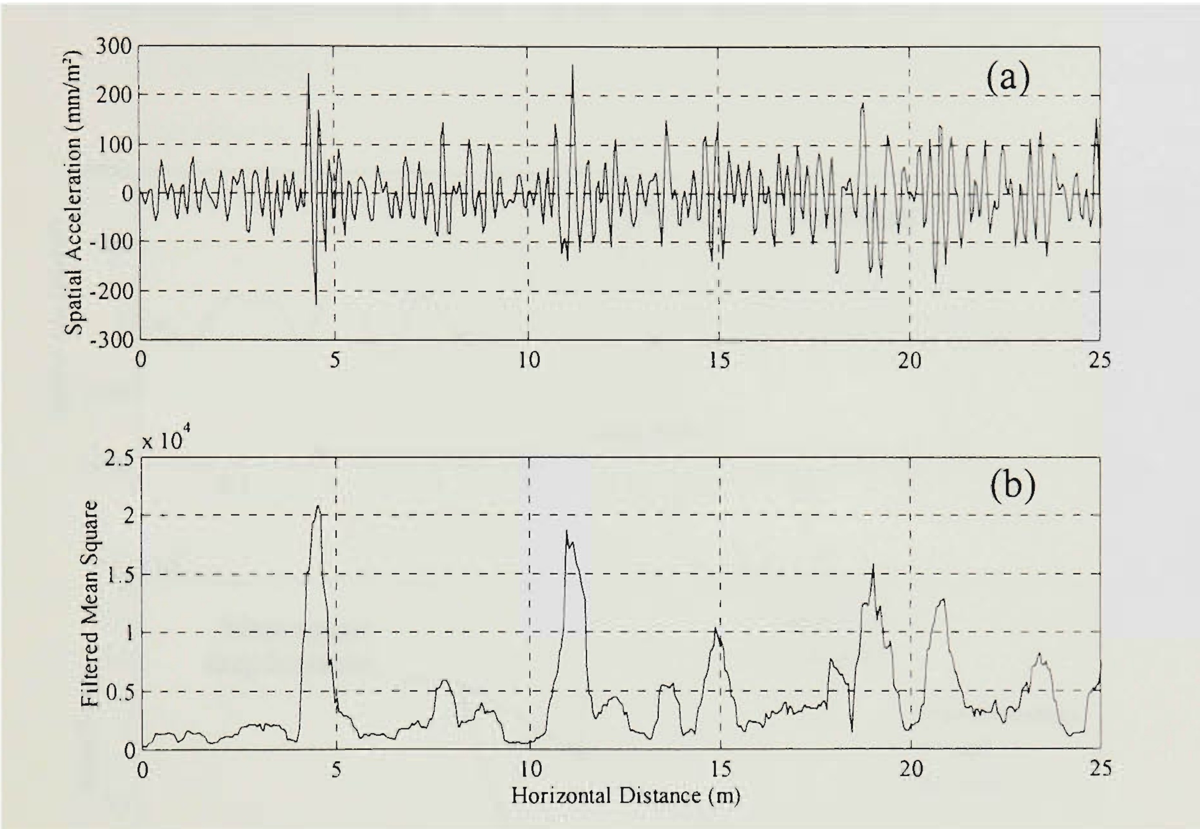


Figure 6.3. A 25 m extract from road (a) 51881a spatial acceleration and (b) mean square (window = 0.5m, overlap = max)

Transient events can be distinguished from the underlying oscillations as they comprise large amplitude and short width. Therefore, two criteria were used to identify transient spatial acceleration sections from the moving mean square:

1. sufficiently short moving mean square drop-off distance, and
2. sufficiently large spatial acceleration local crest factor[1].

The methodology used for transient identification is (see Figure 6.4):

- Identification of maximum moving mean square value in the record.

[1] *As opposed to the crest factor, which is defined as the ratio of the highest peak to the RMS of the entire signal, the local crest factor is based on the ratio of the highest peak to the RMS of that portion of the signal adjacent to the maxima.*

- Estimation of drop-off distance (the locations at which the mean square reaches 10% of the maximum) - if the drop-off distance is less than 2.5m, then the mean square drop-off distance criterion is met.
- Doubling the drop-off window size to calculate the local RMS and local crest factor - if local crest factor is larger than 3.0, the crest factor criterion is met

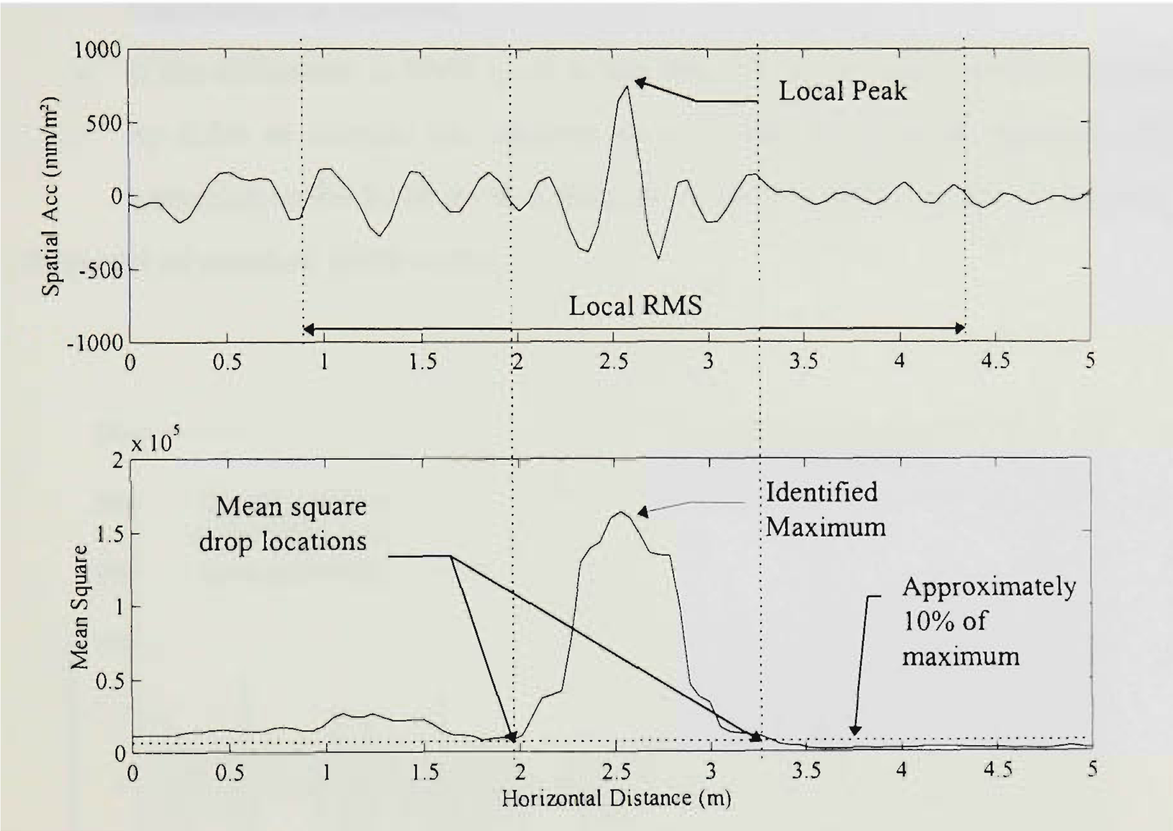


Figure 6.4. Illustration of transient identification criteria

If both of these criteria are met, the section is classified as transient and removed from the data for separate analysis.

If either transient criteria were not met, the section was re-analysed to determine the region of constant RMS[2].

[2] *As in practice roads will exhibit continual variations in the RMS value, constant RMS, in this case, is defined as variations smaller than 10 mm/m². This RMS bin size (see Appendix C) was selected to produce approximately 25 bins over the entire RMS range obtained during analysis. Therefore, sections of road in a single RMS bin will be considered as stationary.*

Identification of stationary sections was accomplished by Figure 6.5:

- Estimation of the initial local RMS, based on an initial window size of 3.5 m centred on the mean square maximum
- Calculation of RMS in adjacent 0.5 m sections on each side of the initial window
- Computing the difference in RMS between the initial window and adjacent sections
    - if the difference is greater than 50%, then a transition in the RMS level (non-stationarity) is detected.
    - If the difference in RMS level is less than 50 %, the initial width is increases by 0.5m to include the adjacent sections and the process repeated until a transition in the RMS level is detected or the end of the record is reached.
- Removal of constant RMS section.

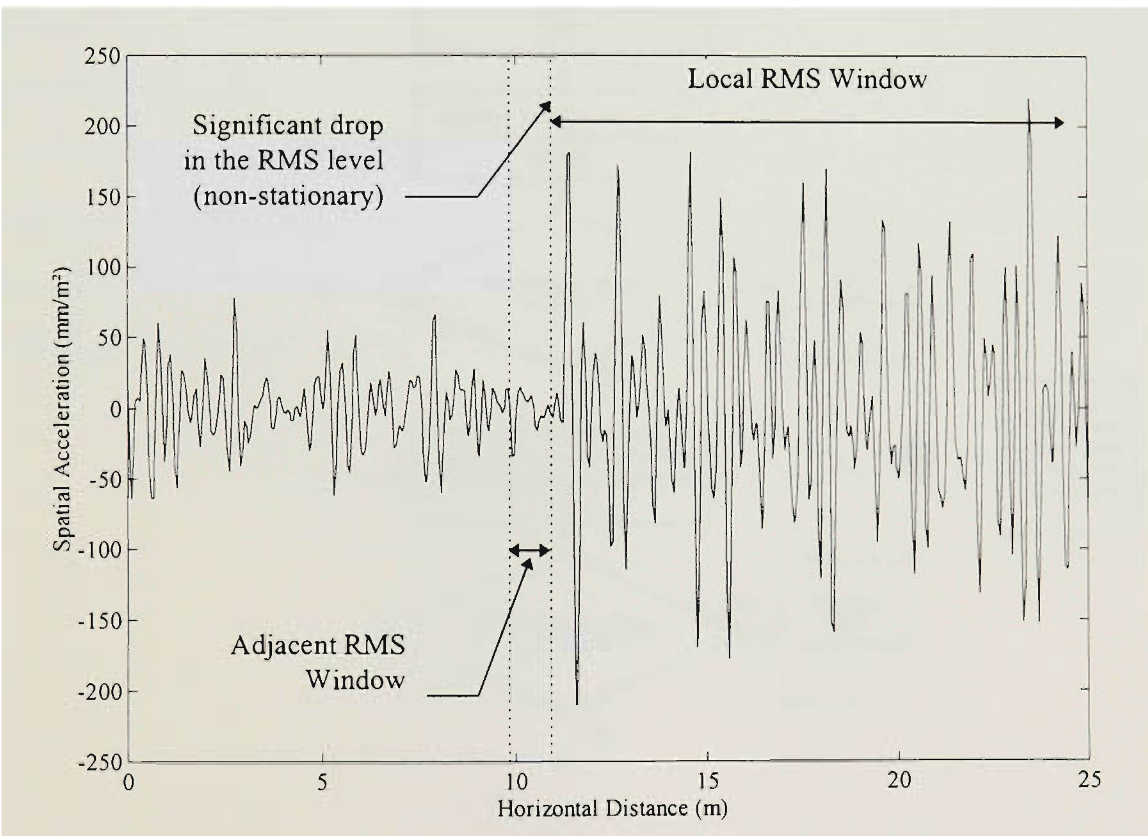


Figure 6.5. Illustration of locating RMS transition (non-stationarity) region

A flow chart algorithm used in the analysis of moving mean square data to separate transient and stationary sections is shown in Figure 6.6 which was implemented in MATLAB®.

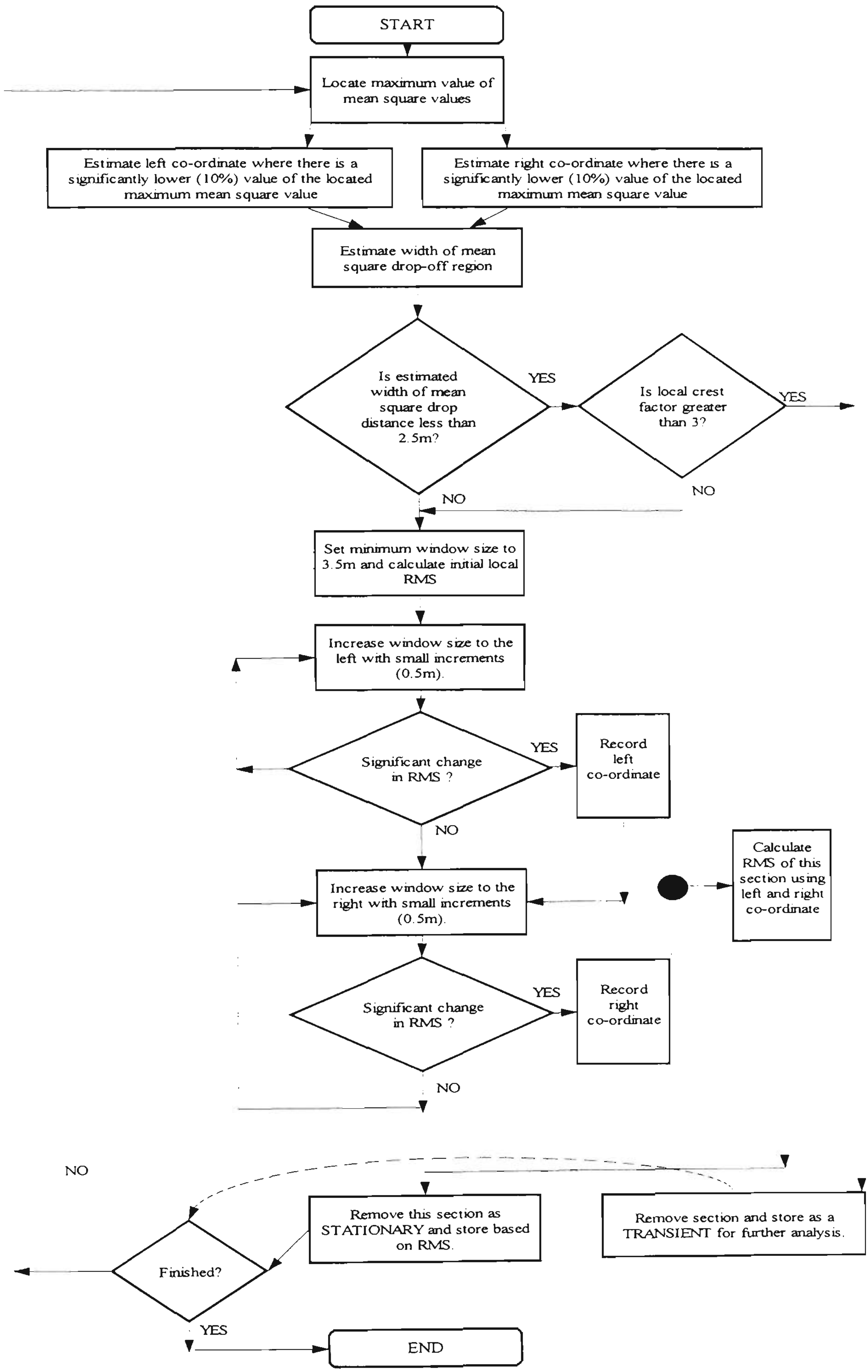


Figure 6.6. Flow chart for stationary and transient identification

6.3 RESULTS

The entire 415 km sample was analysed with computer software developed according to the flow chart outlined in Figure 6.6.

6.3.1 Properties of constant RMS segments

The analysis of the entire 415 km road sample yielded a series of road segments of constant (stationary) RMS levels. Each segment consists of concatenated road sections extracted from the entire 415 km road sample based on their RMS level. The PSD estimates for constant RMS road segments from bin #1 (0 - 10 mm/m^2 RMS) to #6 (50 - 60 mm/m^2 RMS) are shown in Figure 6.7. It can be seen that the PSD's retain their shape while translated vertically according to the RMS level. It can also be concluded that extraction of transients from spatial acceleration data and regrouping the data into constant RMS segments did not affect the basic shape of the spectra.

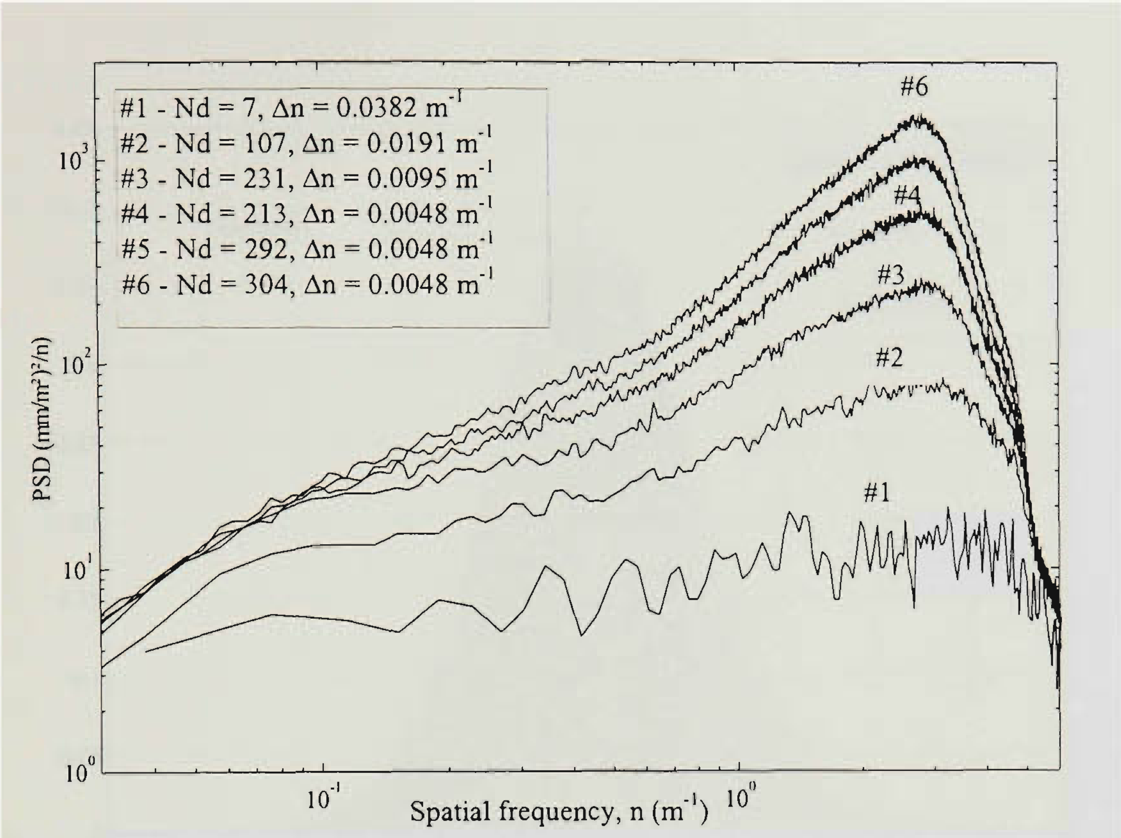


Figure 6.7. PSD estimates for RMS bin #1 to #6

The PDF for constant RMS segments (bin #2 and bin #3) are shown in Figure 6.8 to Figure 6.11.

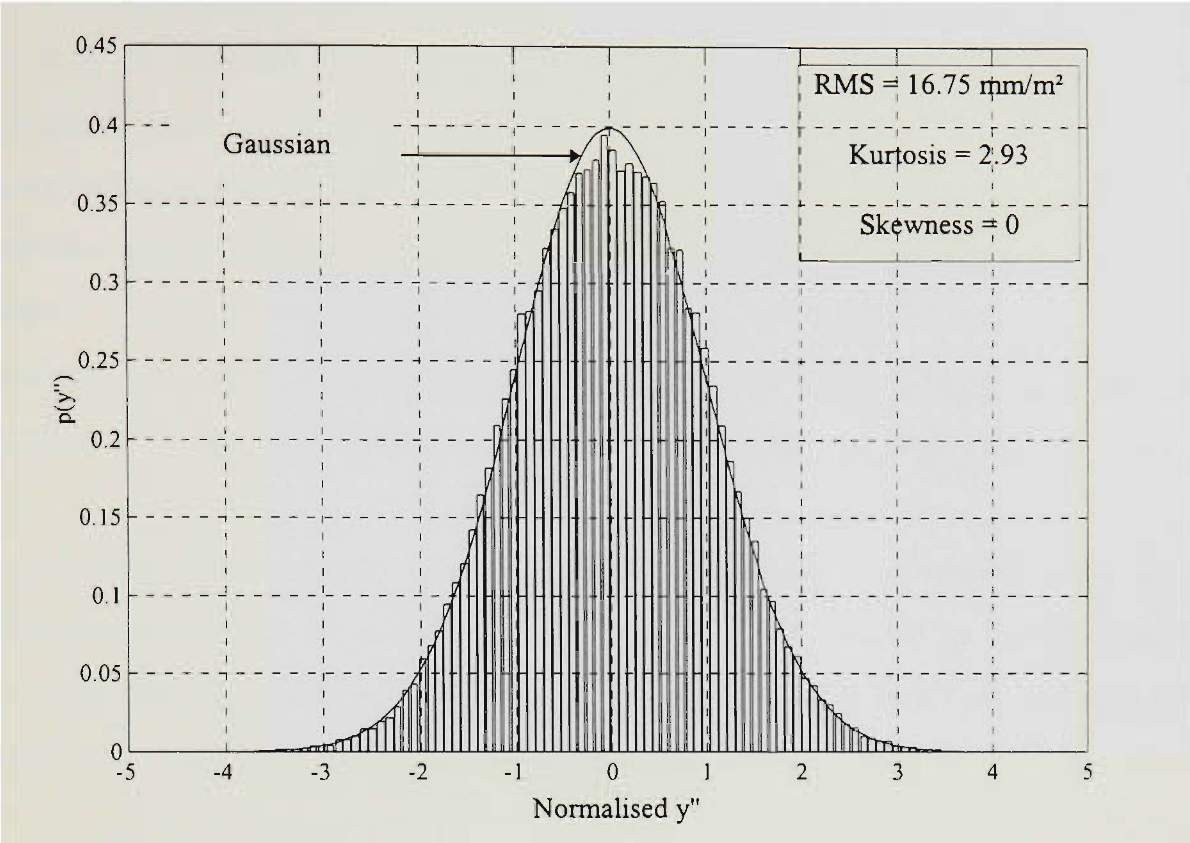


Figure 6.8. Stationary bin #2 PDF for entire sample with equivalent Gaussian, linear scale

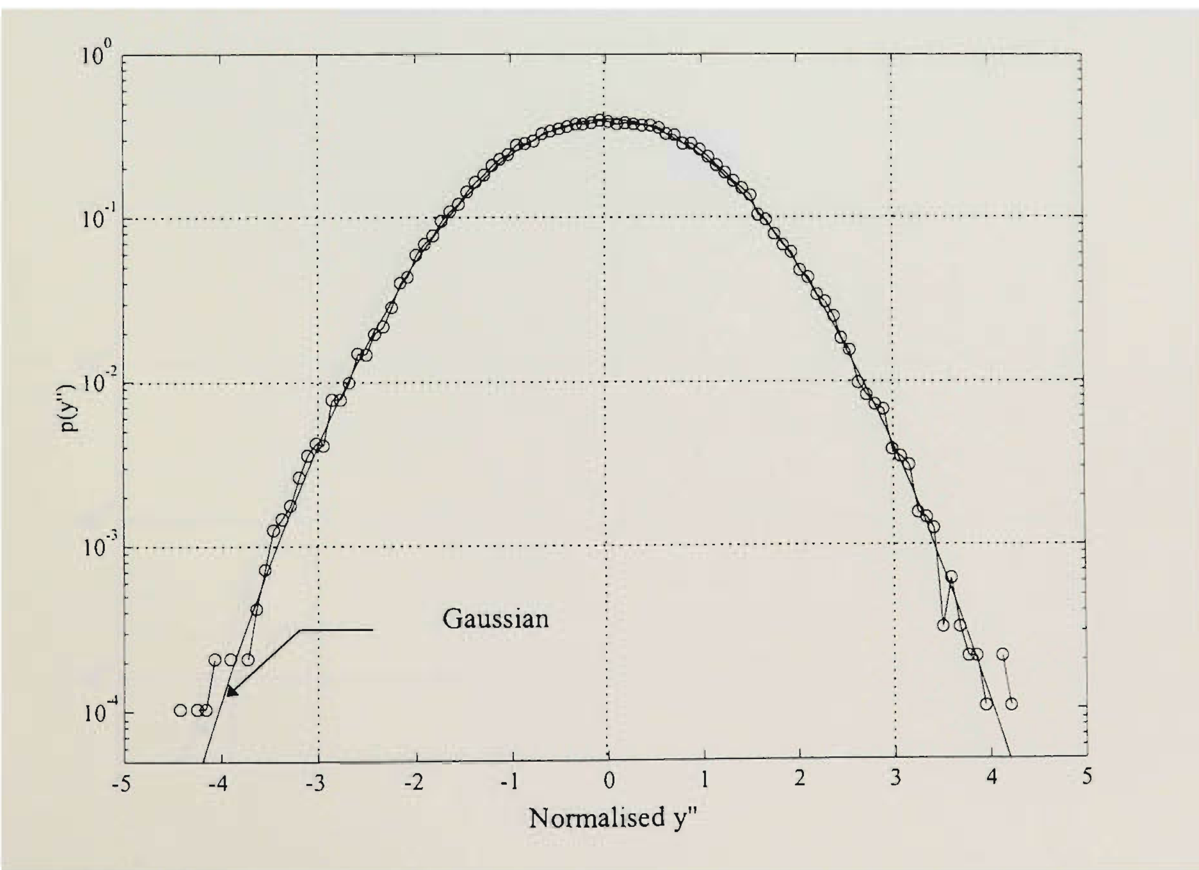


Figure 6.9. Stationary bin #2 PDF for entire sample with equivalent Gaussian, semi log scale

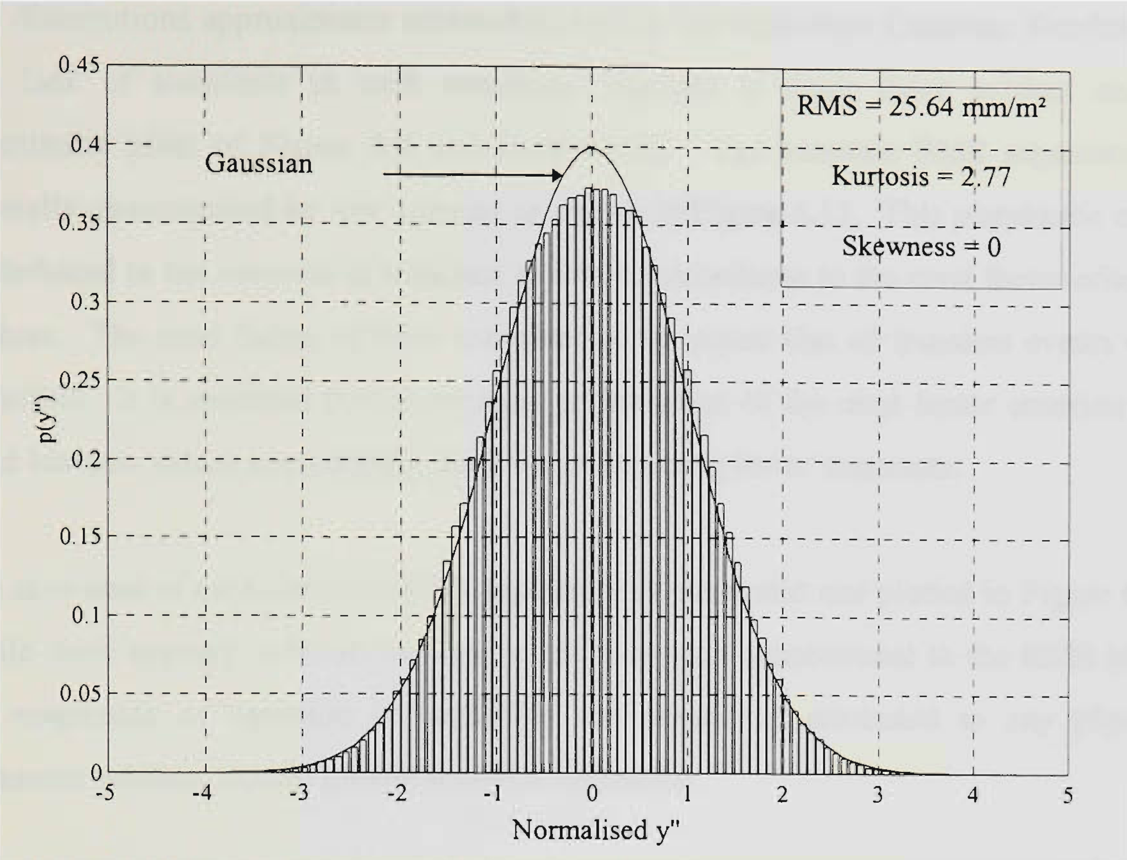


Figure 6.10. Stationary bin #3 PDF for entire sample with equivalent Gaussian, linear scale

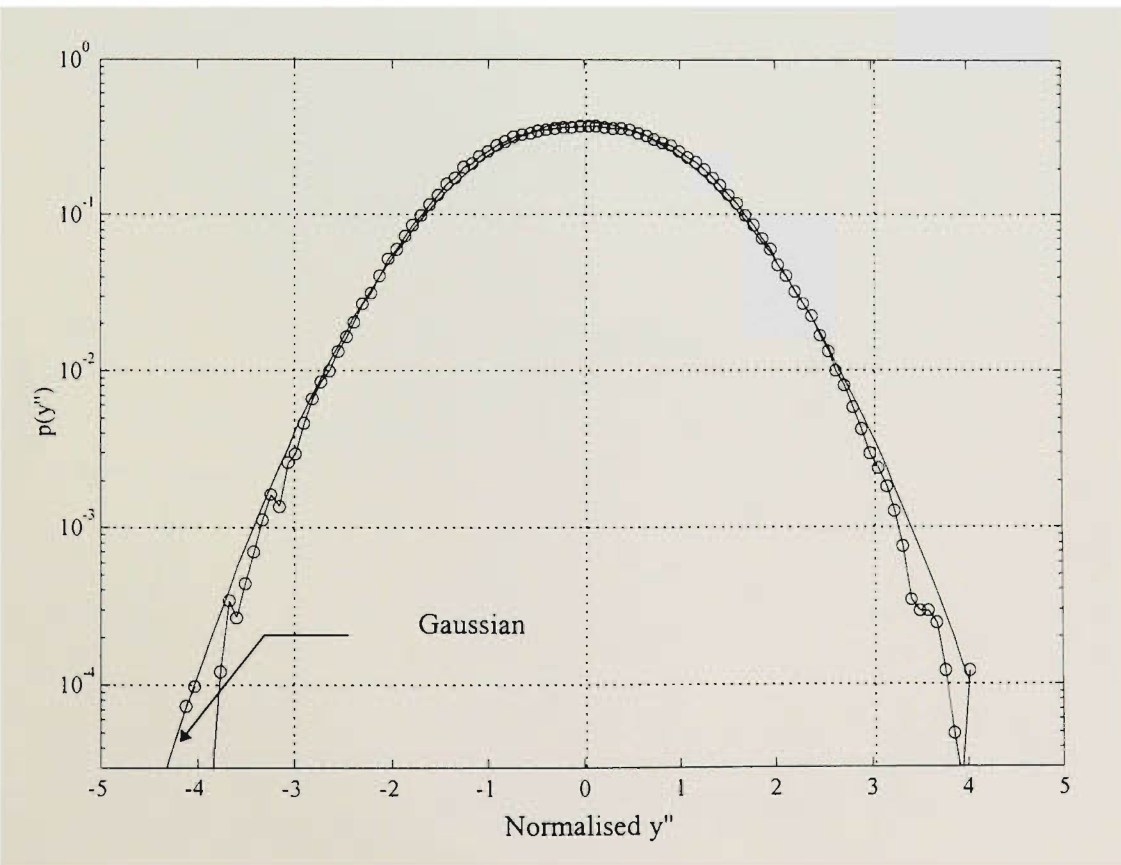


Figure 6.11. Stationary bin #3 PDF for entire sample with equivalent Gaussian, semi log scale

The distributions approximates reasonably well to the equivalent Gaussian distribution. The lack of transients in each stationary segment is made more evident on the logarithmic plots of Figure 6.9 and Figure 6.11. The constant RMS segments are generally characterised by low kurtosis as shown in Figure 6.12. This platykurtic effect is attributed to the removal of transient events in accordance to the crest factor criterion of three. The crest factor of three was selected to ensure that all transient events were identified. It is expected that an increase in the value of the crest factor criterion will yield kurtosis values approaching three while detecting fewer transients.

The skewness of each constant RMS segment was computed and plotted in Figure 6.13. While there appears to be an increase in the skewness proportional to the RMS bin #, the magnitude of variation is negligible and cannot be attributed to any physical parameter relating to road profile spatial acceleration .

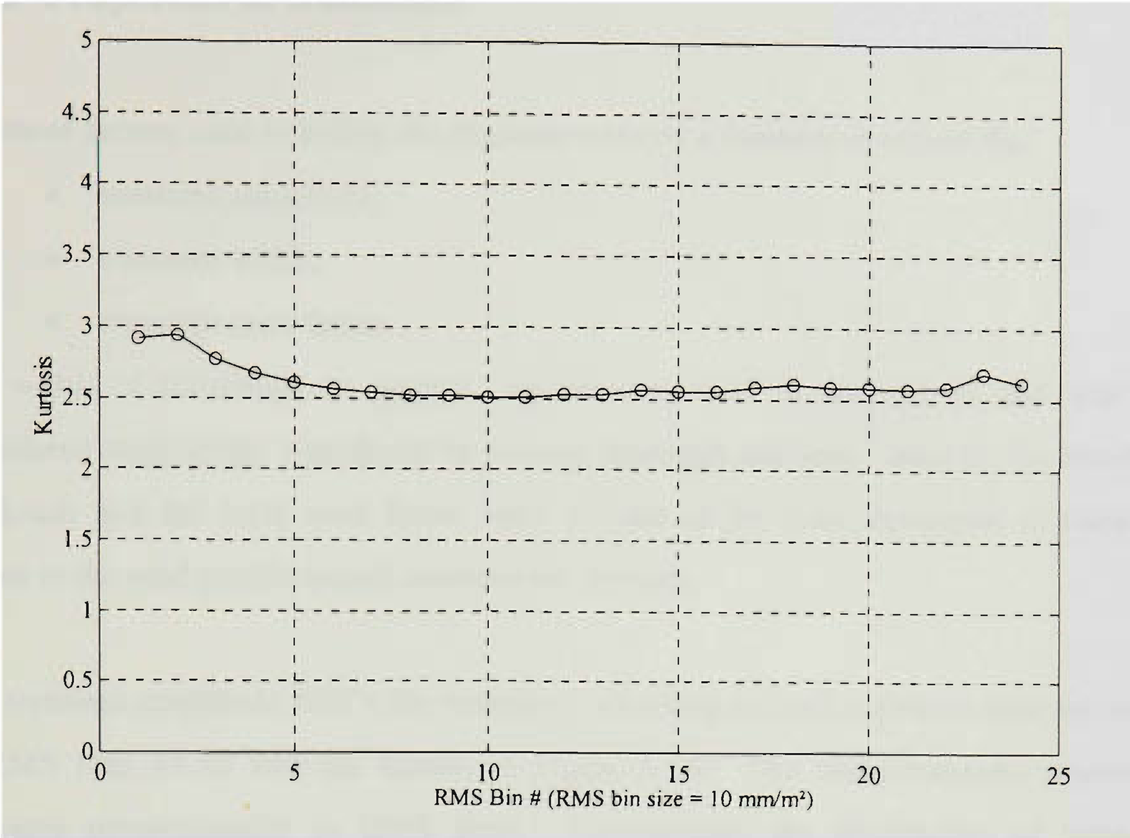


Figure 6.12. Kurtosis as a function of RMS bin number

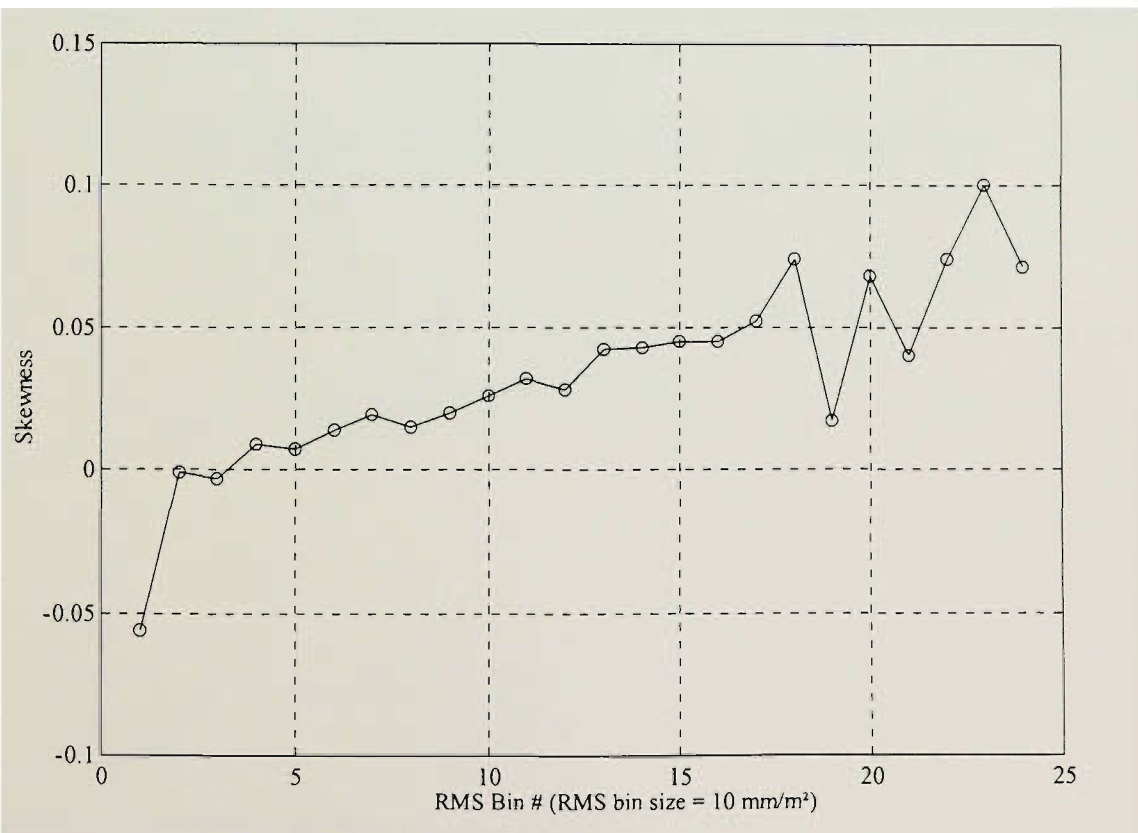


Figure 6.13. Skewness as a function of RMS bin number

6.3.2 Properties of transients

The three factors used to define the characteristics of a transient event are the:

- transient amplitude,
- transient width,
- transient crest factor.

The width of transients, in general, lay between 0.25 m and 0.5 m and was not considered sufficiently significant to warrant thorough analysis. Instead, the transient amplitude and the local crest factor were utilised as the main descriptor of transient events in the road profile spatial acceleration domain.

The transient amplitude PDF's for transients occurring in road segments corresponding to RMS bins #5 to #10 are shown in Figure 6.14. The mean transient amplitude increases proportionally to RMS level. Furthermore, the distribution of transient amplitudes exhibit good agreement with the equivalent Gaussian distribution. Finally, the standard deviation of the transient amplitude appear to correlate with the RMS level.

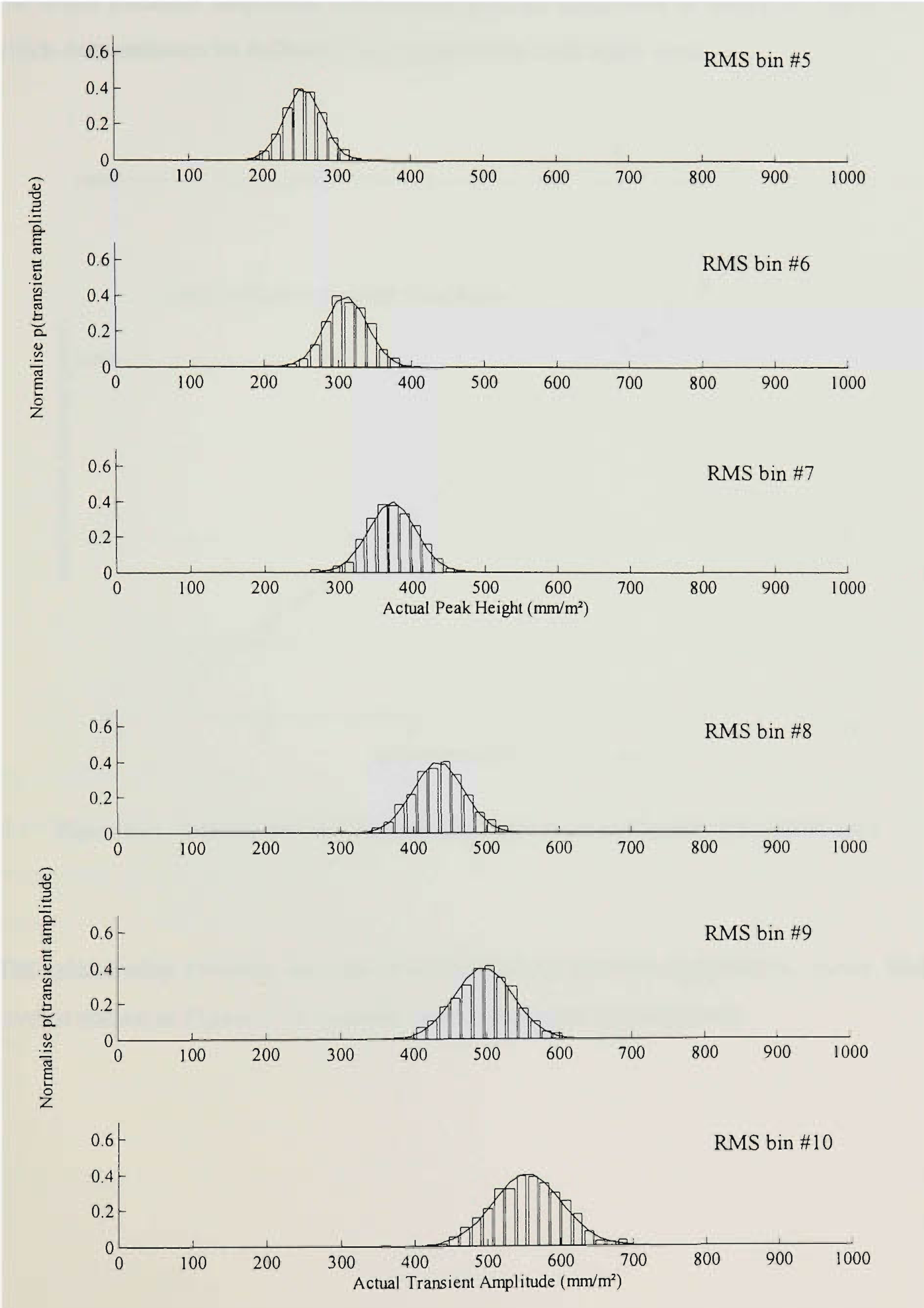


Figure 6.14. Transient amplitude PDF corresponding to RMS bin #5 to # 10 (bars) together with equivalent Gaussian (lines)

The mean transient amplitude corresponding to all RMS bins is shown in Figure 6.15 which demonstrates its definite linear relationship with RMS level.

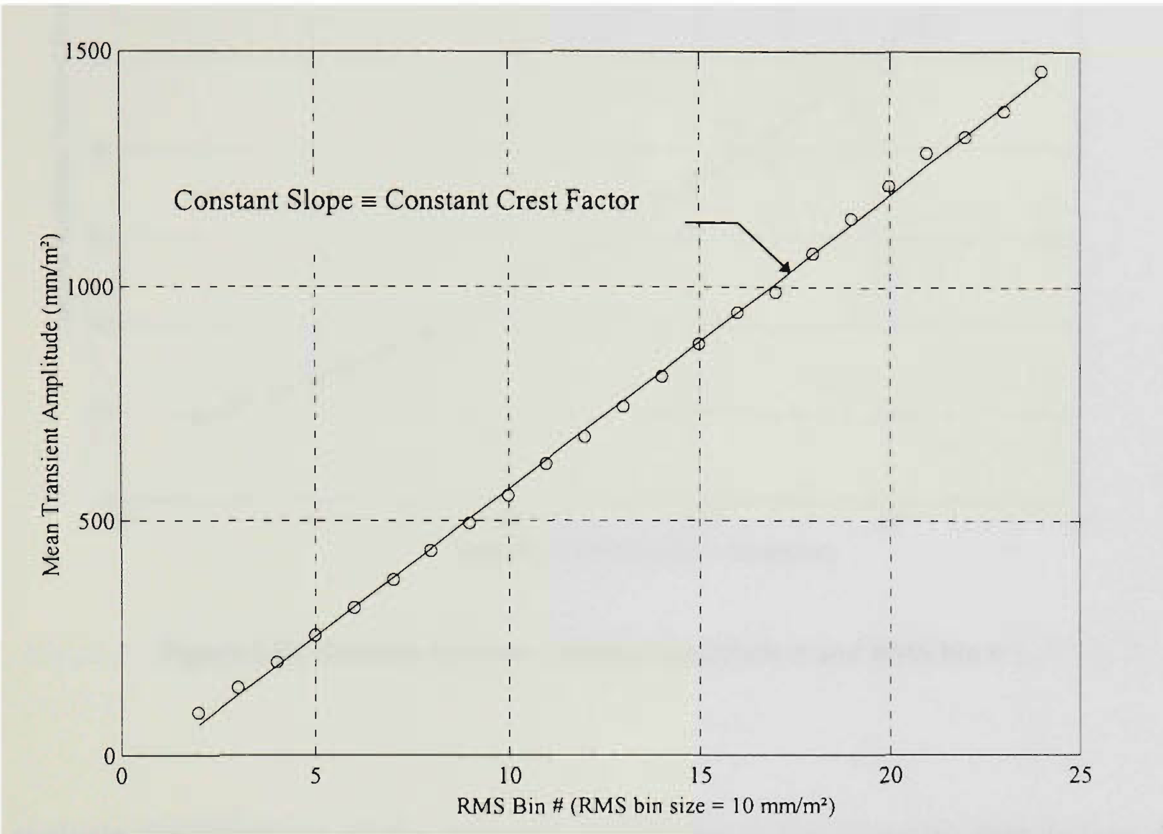


Figure 6.15. Relation between transient amplitude mean and corresponding RMS bin #

The relationship between the standard deviation of transient amplitudes, versus RMS level is shown in Figure 6.16, together with a quadratic line of best fit.

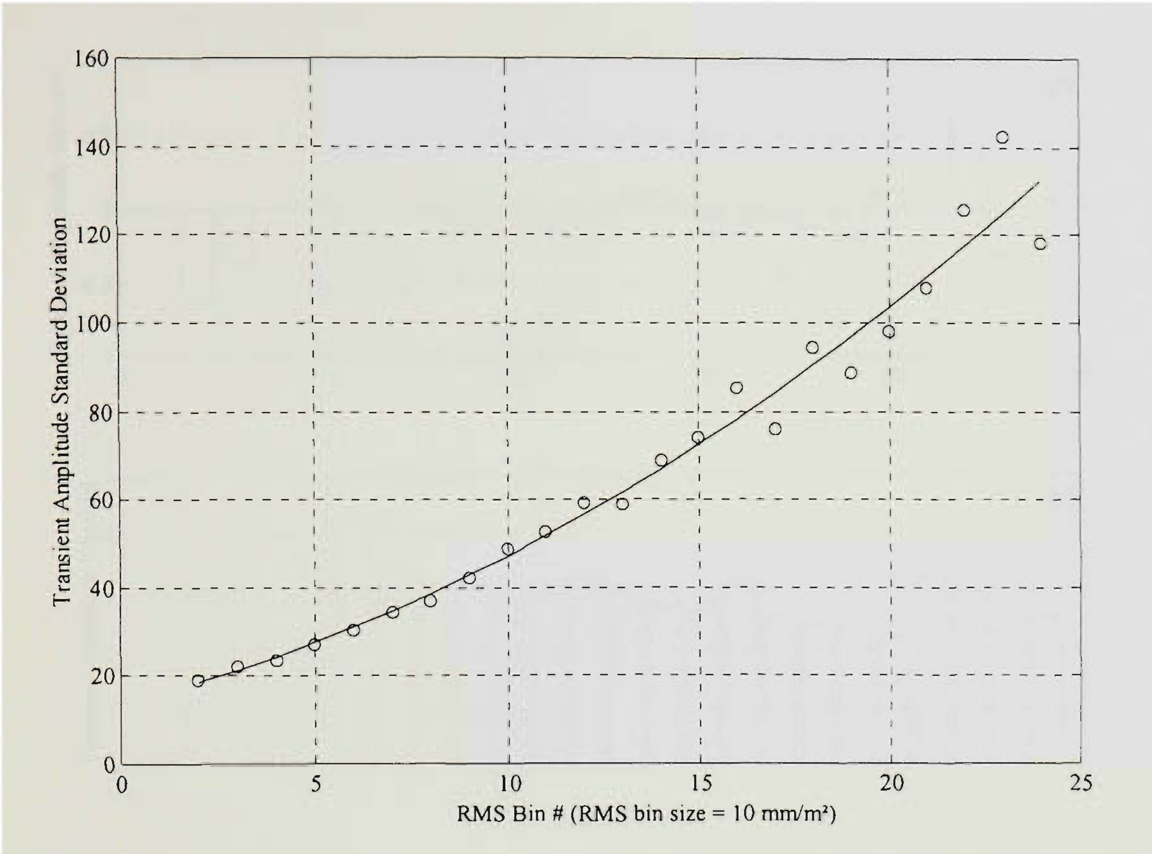


Figure 6.16. Relation between transient amplitude σ and RMS bin #

To evaluate the closeness of the transient amplitudes to the Gaussian distribution, the skewness and kurtosis of transient amplitudes, as a function of the underlying RMS level, were calculated and results shown in Figure 6.17. This figure demonstrates that generally, the skewness and kurtosis remain close to zero and three respectively for all RMS bins and therefore can be assumed to approximate a Gaussian process.

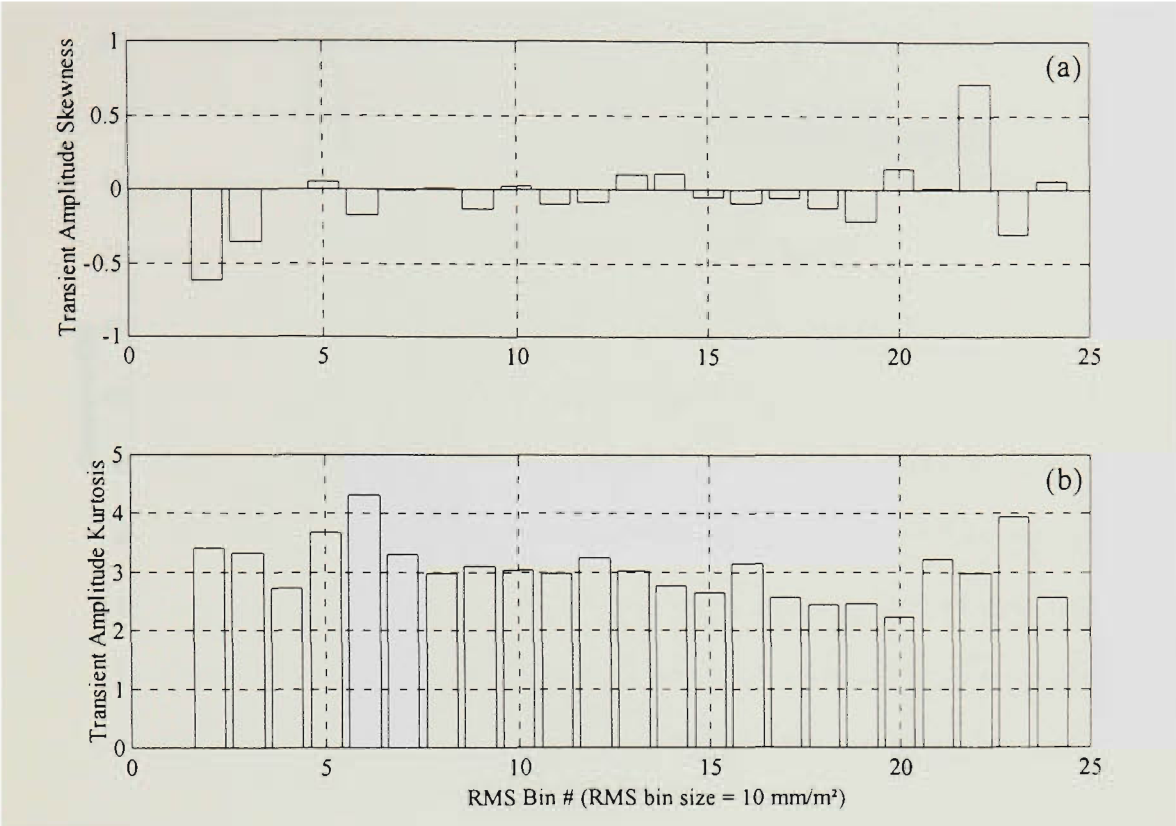


Figure 6.17. (a) Skewness and (b) kurtosis of transient amplitude PDF's for all RMS bin #

6.3.3 Constant (stationary) RMS and transient amplitude distributions

Typical results, showing the constant RMS (stationary) and transient amplitude distribution of three representative roads[3] are shown in Figure 6.18 to Figure 6.23, while the RMS and transient amplitude distribution for the entire 415 km road sample are shown in Figure 6.24 and Figure 6.25 respectively. Also shown is the overall (raw) RMS value and the transient density which relates the total number of transients to a unit length. These results show that the shape of both the RMS and transient amplitude distributions exhibit similarities.

[3] It must be noted that these roads were analysed according to the procedure set out in section 6.2 whereby the transient events and transient free, constant RMS section are treated separately.

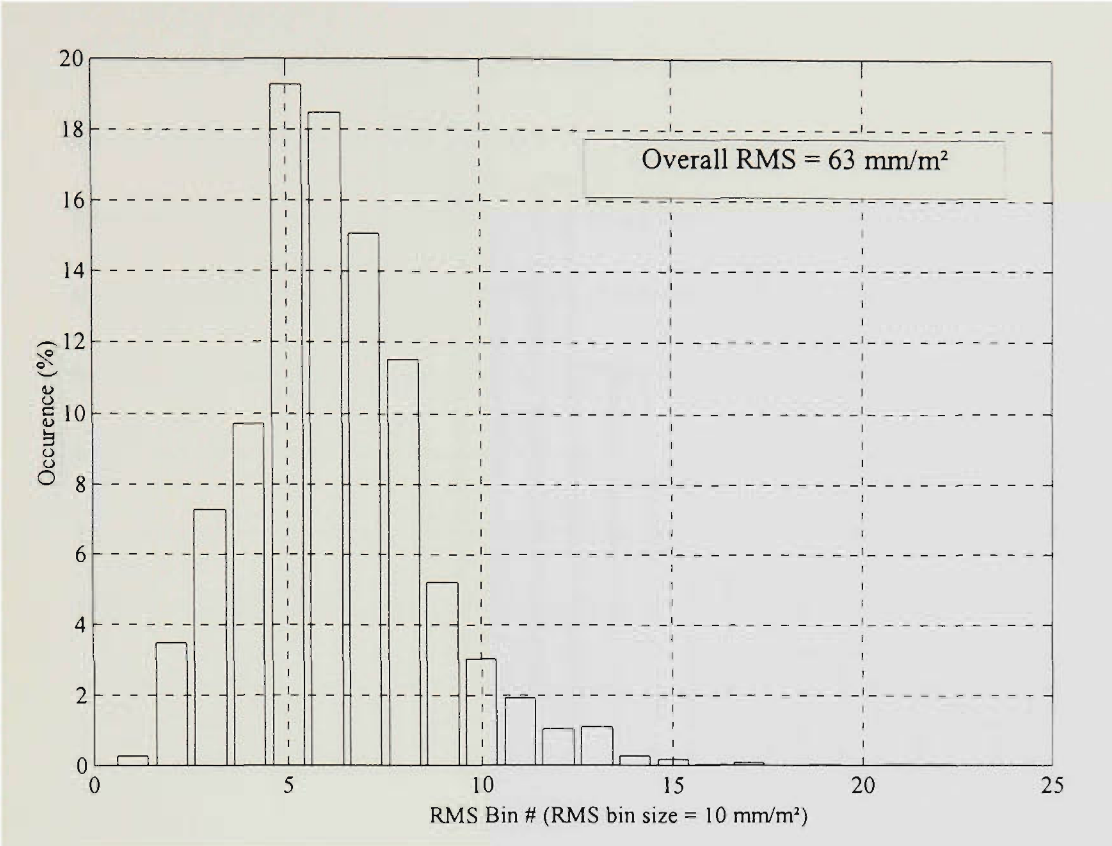


Figure 6.18. Stationary RMS distribution for road 25103b

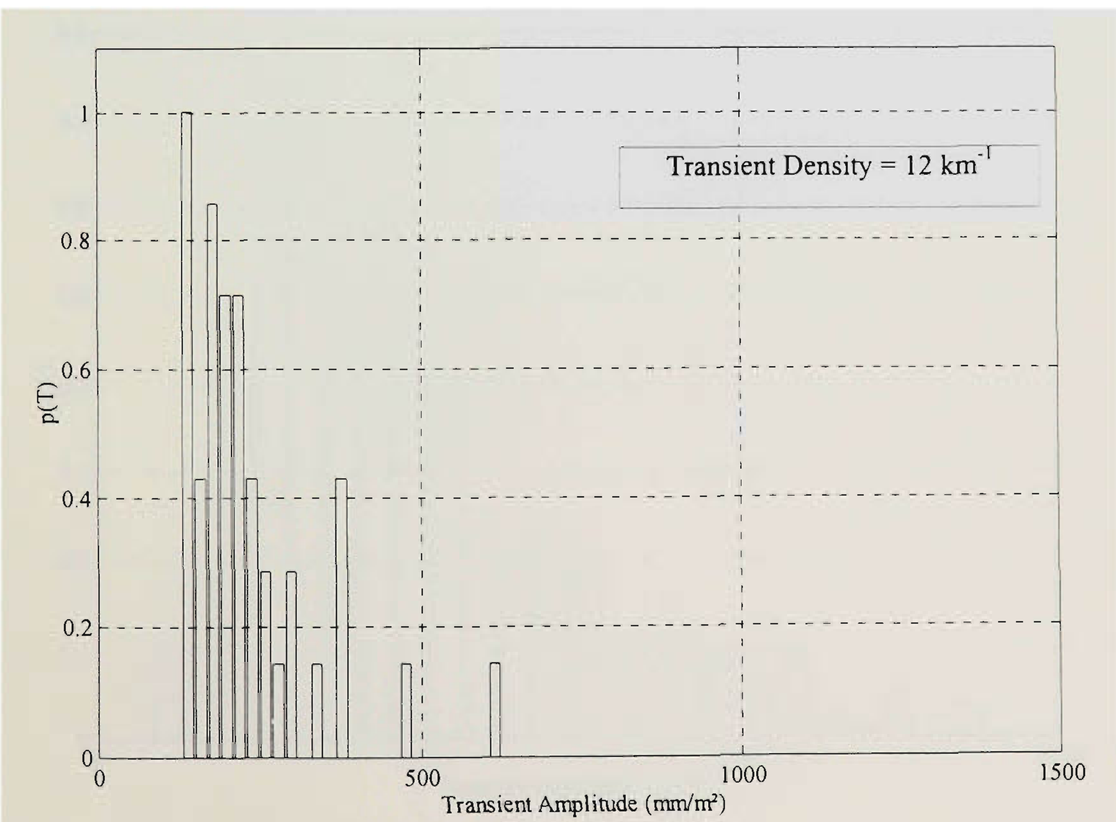


Figure 6.19. Transient amplitude distribution for road 25103b

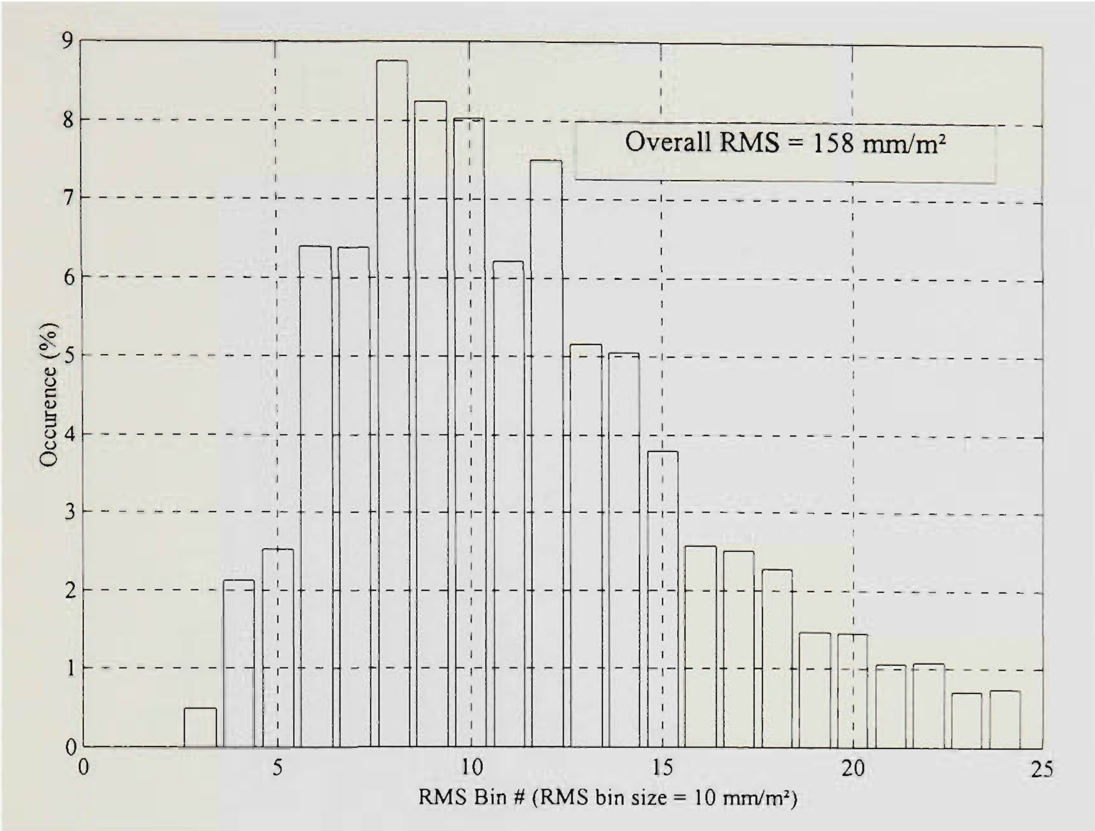


Figure 6.20. Stationary RMS distribution for road 55051a

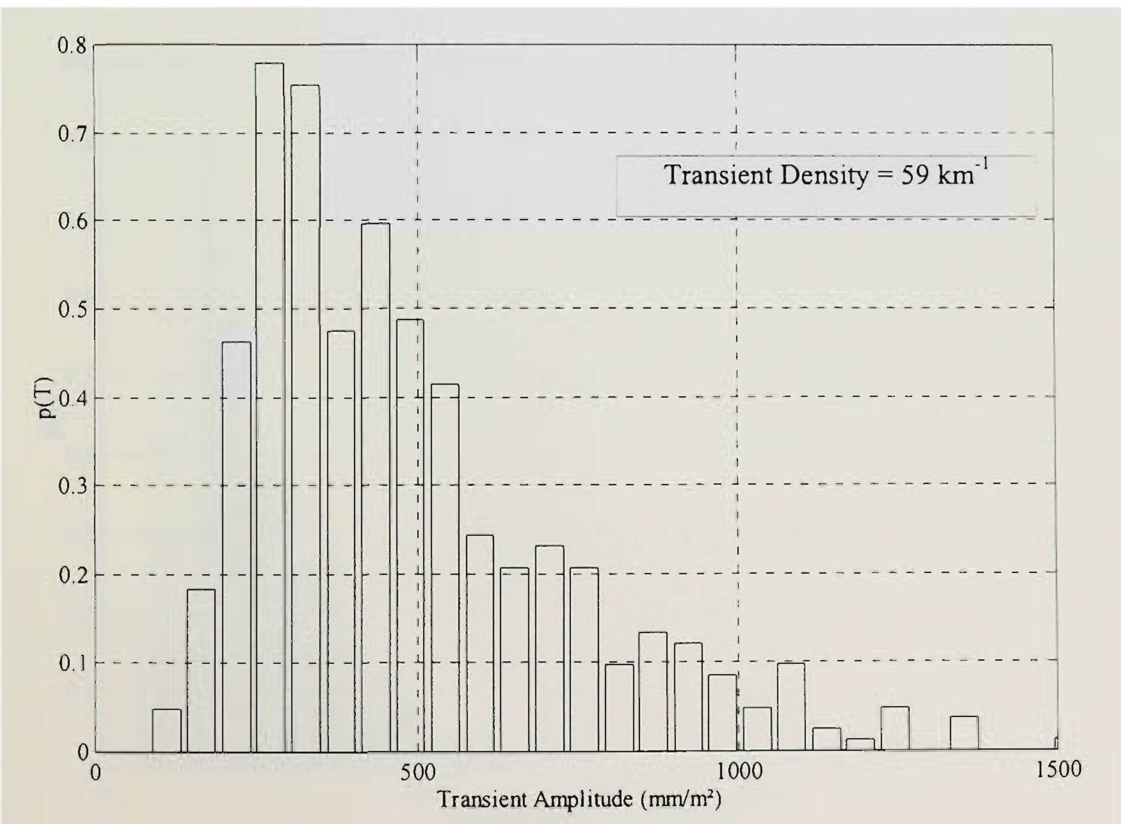


Figure 6.21. Transient amplitude distribution for road 55051a

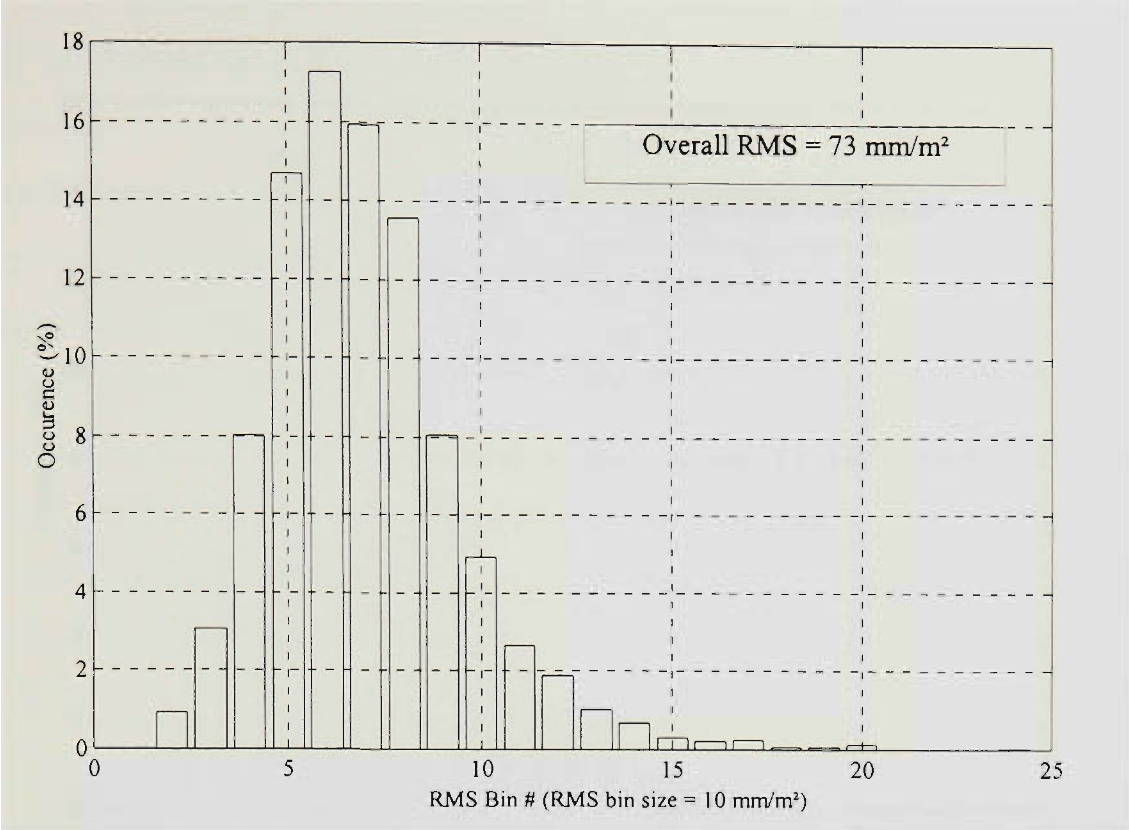


Figure 6.22. Stationary RMS distribution for road 25401b

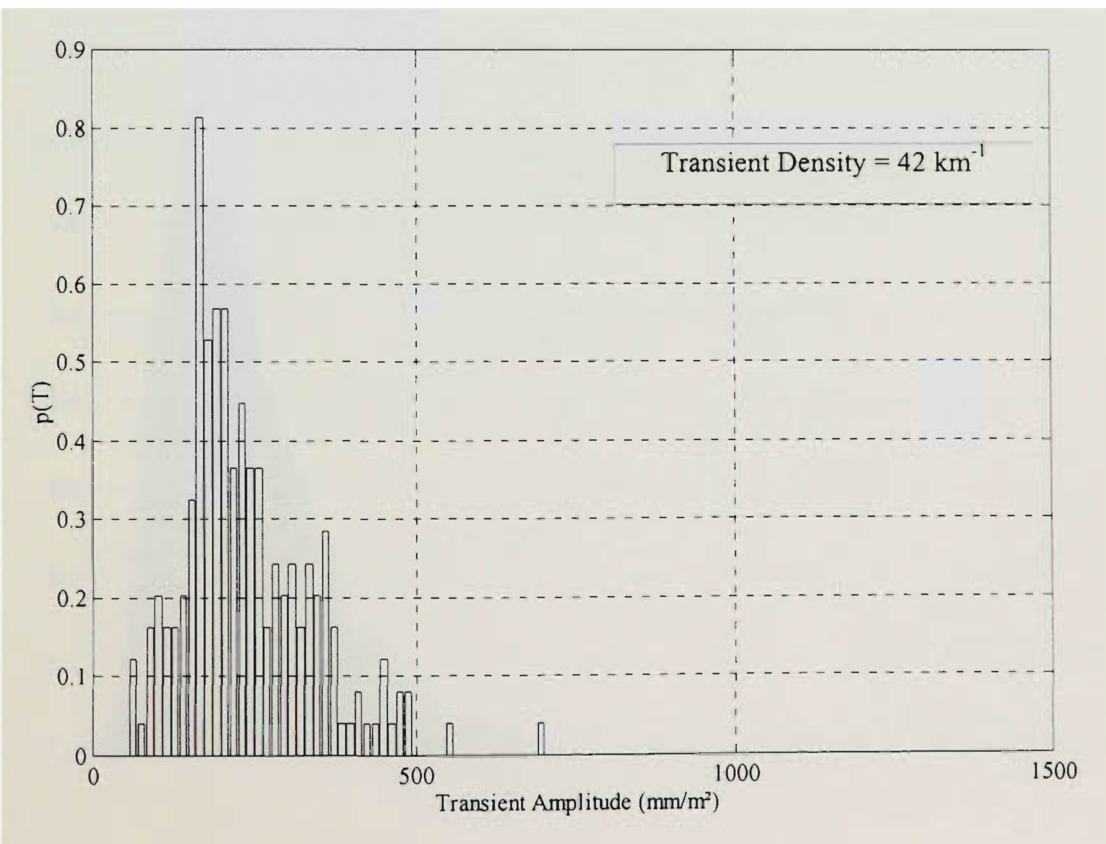


Figure 6.23. Transient amplitude distribution for road 25401b

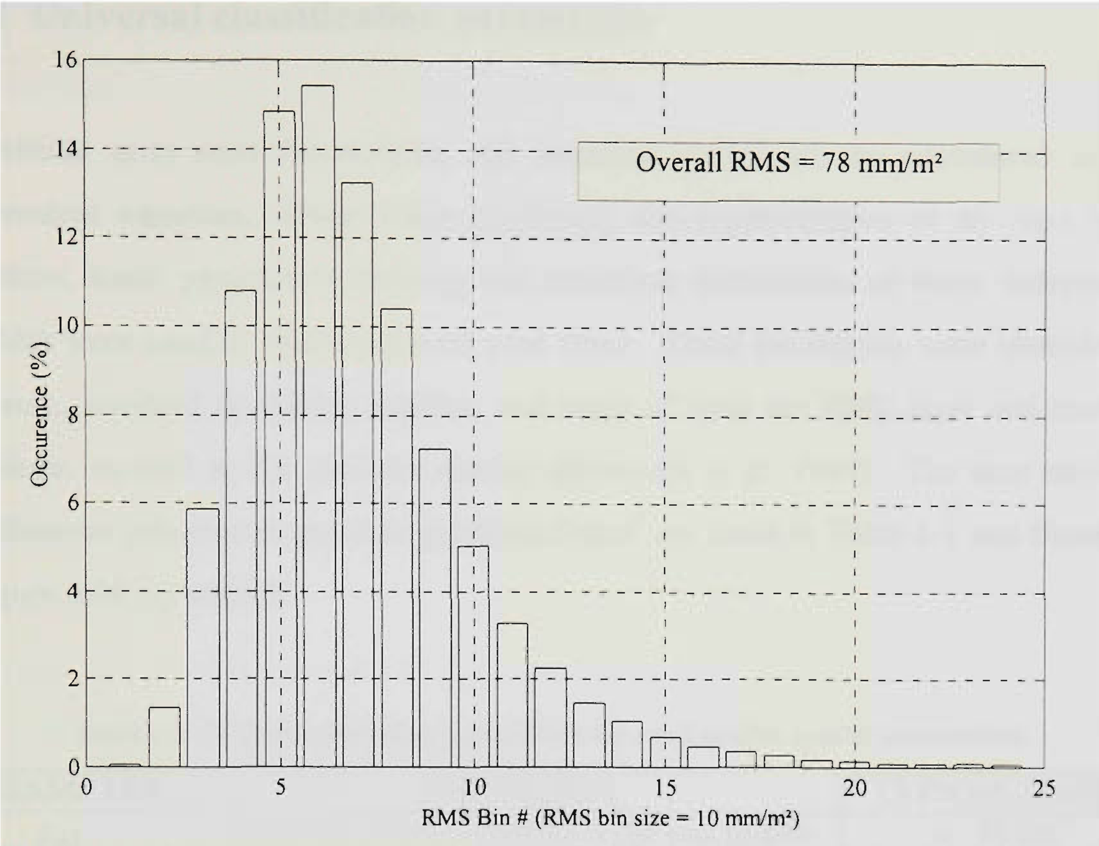


Figure 6.24. Overall stationary RMS distribution for all roads

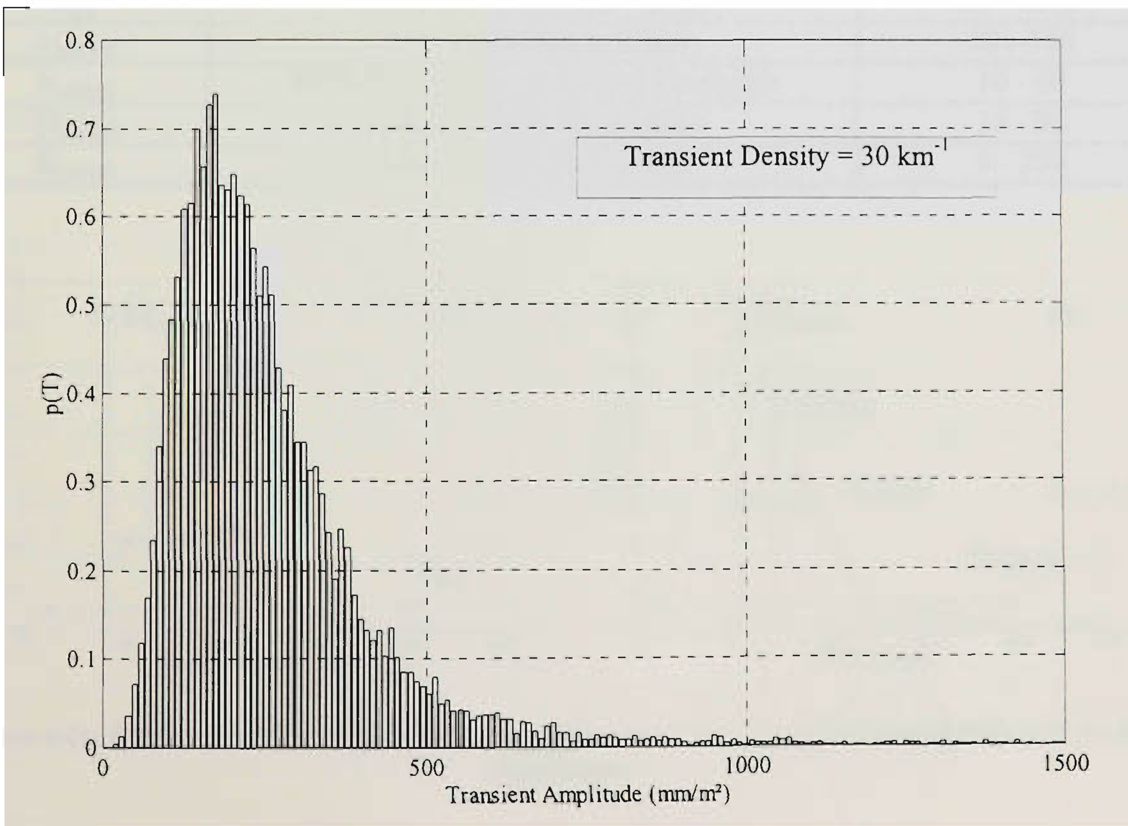


Figure 6.25. Overall transient amplitude distribution for all roads

6.3.4 Universal classification parameters

The steady state road fluctuations and transient events can be considered as two independent variables, which when combined, are representative of all road types. Therefore, basic parameters defining the statistical distribution of these independent variables were used to characterise all road types. These parameters were identified as the mean, standard deviation, median, and range of both the RMS level and transient amplitude, as well as the transient density (Bruscella *et al*, 1997). The nine universal classification parameters and their practical limits[4] are listed in Table 6-1 and illustrated in Figure 6.26 (a) and (b).

Table 6-1. Nine classification parameters for road profile spatial acceleration

PARAMETER	DEFINITION	TYPICAL LIMITS
$\rho_{\alpha T}$	*Transient Density (Transients per unit length)*	0 - 80 km^{-1}
$\mu_{\alpha T}$	*Transient Amplitude Mean*	100 - 600
$\sigma_{\alpha T}$	*Transient Amplitude Standard Deviation*	50 - 800
$M_{\alpha T}$	*Transient Amplitude Median*	50 - 400
$R_{\alpha T}$	*Transient Amplitude Range*	20 - 1500
$\mu_{\alpha RMS}$	*RMS Distribution Mean*	30 - 110
$\sigma_{\alpha RMS}$	*RMS Distribution Standard Deviation*	10 - 60
$M_{\alpha RMS}$	*RMS Distribution Median*	15 - 95
$R_{\alpha RMS}$	*RMS Distribution Range*	5 - 250

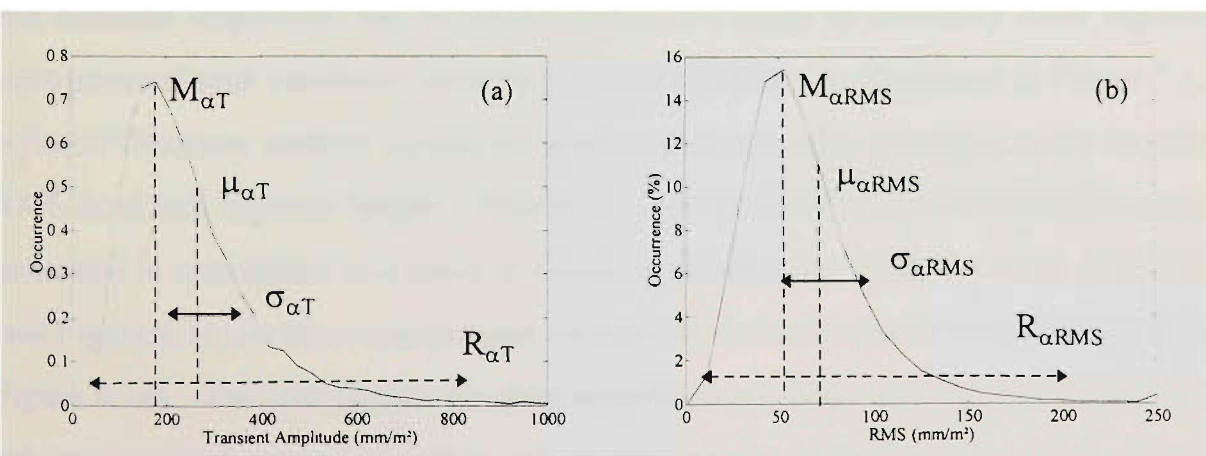


Figure 6.26. Illustration of nine classification parameters for (a) transient amplitudes and (b) RMS distributions

[4] Based on the analysis of the entire 415 km sample.

7. DISCUSSION AND APPLICATION

It is envisaged that the newly developed universal road classification parameters can be utilised for two main applications

1. Simulation of road profiles for package performance evaluation
2. Characterisation and classification of specific road surfaces for transportation and maintenance purposes.

7.1 SIMULATION OF ROAD PROFILES

It has been shown that the process used to describe road surfaces can be dismantle into its two fundamental components, namely, steady state road fluctuations and transient events. These components can be recombined (superimposed) in any sequence to create an altogether new (artificial) process. The analysis has shown that individual constant RMS segments can be represented by a Gaussian random process defined by a PSD function, RMS level, and segment length. Similarly, transient events corresponding to that segment can be considered as a random process, which is defined by the mean and standard deviation transient amplitude (Gaussian), as well as the number of transients to occur per unit length. Consequently an artificial road containing a range of RMS level and transient amplitudes can be reconstructed as a series of stationary RMS segments superimposed with randomly occurring transient events. As illustrated in Figure 7.1, a series of Gaussian random signals are generated sequentially according to the specified RMS level and segment length[1]. Similarly, corresponding random transient events are generated in accordance to a series of Gaussian distributions while the mean crest factor (see Figure 6.15) remains constant and standard deviation increases with RMS level (see Figure 6.16). The two signals are then superimposed, dissected into sufficiently large sub-sections and randomly rearranged to emulate the undeterministic nature of road fluctuations while retaining the specified spectral and statistical properties.

[1] These Gaussian signals are synthesised from a typical spatial acceleration frequency spectrum (see Figure 6.7) coupled with a uniformly distributed random phase spectrum.

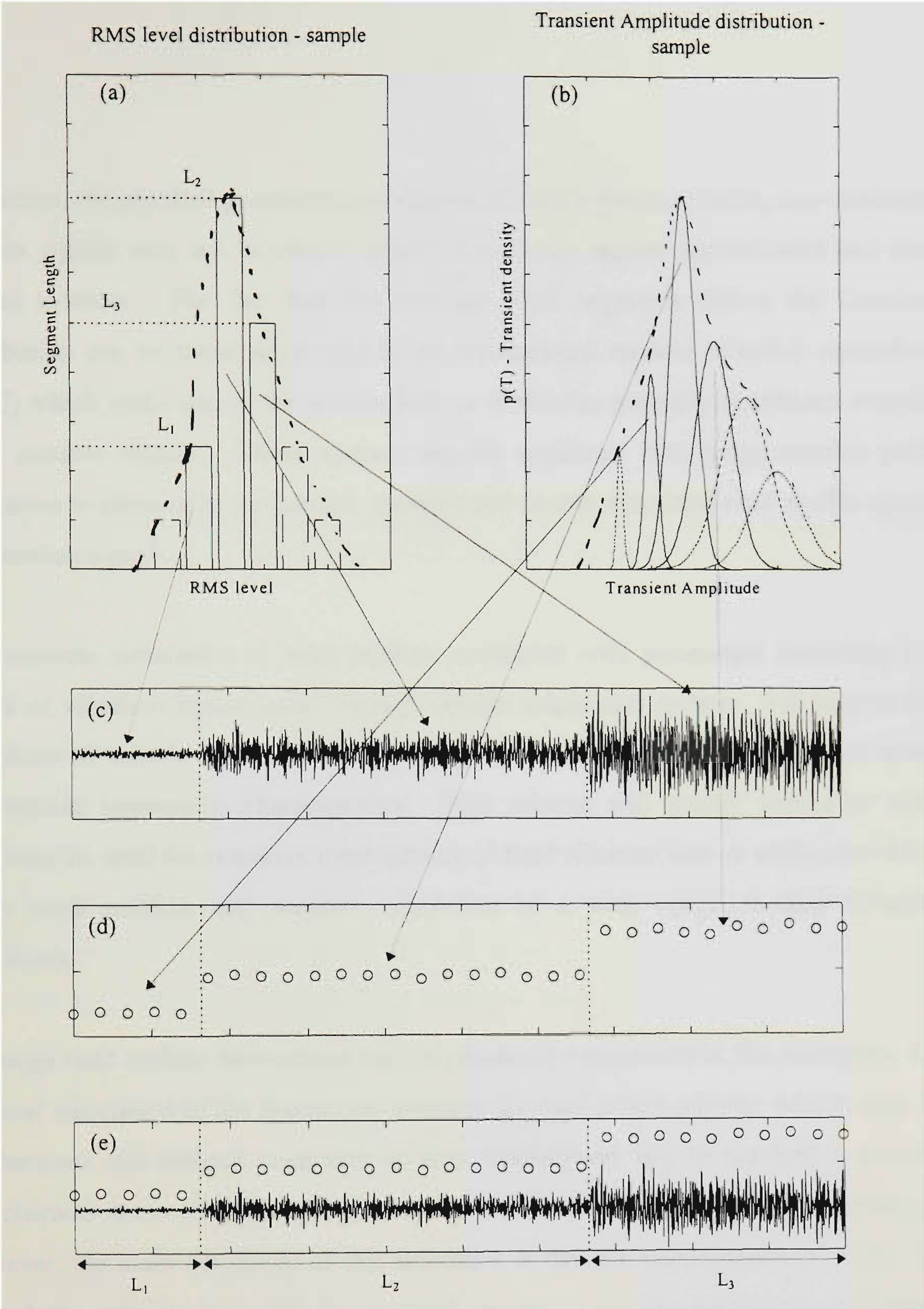


Figure 7.1. Reconstruction of a section of road profile. ***(a) RMS level PDF - each vertical bar represents a stationary (constant RMS), Gaussian segment. (For typical RMS distribution properties, see Figure 6.26(b)). (b) Transient amplitude PDF and density. (For typical transient amplitude distribution properties, see Figure 6.26(a)). (c) Each RMS level produces a stationary, Gaussian signal for the specified segment length - L. (d) Transients are generated according to the transient amplitude distribution. The generation of transient amplitudes is random (normally distributed), corresponding to the underlying RMS level. (e) The stationary, transient free data is superimposed with the transients to produce the characteristics of the original profile.*** **This profile is simulated in a random order to reproduce the original profile.**

In practice, the physical generation and control of such a transient-laden, non-stationary random signals may not be readily achieved and may require sophisticated real time control systems. The fact that the constant RMS segments follow the Gaussian distribution can be taken advantage of by conventional random vibration controllers (RVC) which make use of the inverse FFT to synthesise normally distributed variable RMS random signals. These systems can be combined with programmable pulse generators to physically reconstruct, generate and control simulated road profile spatial acceleration signals.

The accurate simulation of road profiles, combined with parameters describing the nature of vibration transmission through vehicle suspension systems, will lead to the prediction of vehicle vibration levels for any combination of road type, vehicle speed and vehicle suspension characteristics. This scheme will greatly reduce or even eliminate the need for extensive measurement of field vibration data as well as provide a much more realistic and accurate simulation of a wide range of road transport conditions.

Although road surface fluctuations can be physically reproduced in the laboratory, the physical simulation of the interaction between the road profile and the vehicle may be cumbersome and difficult to achieve as large mechanisms may be required to emulate the characteristics of large vehicles (such as natural frequency and compliance). However, the main advantage of this technique is that the transmissions of vibrations through the vehicle suspension is accurately modelled and the suspension compliance effects during impact or bouncing of heavy packages are accounted for. Figure 7.2 shows a schematic for utilisation of the road profile coupled with physical vehicle models for transportation simulation.

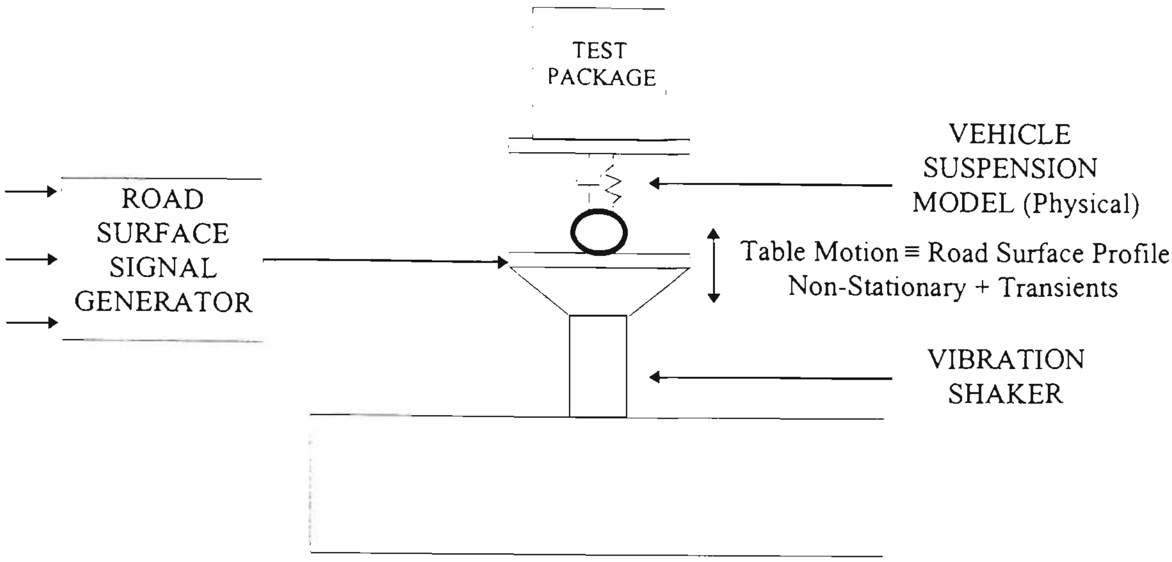


Figure 7.2. Schematic of road transport vibration simulation with road surface command signal and physical vehicle suspension model

The use of physical vehicle suspension models during vibration tests can be eliminated by empirically and/or mathematically modelling the dynamic characteristics of such systems. This would involve accurate characterisation of the interactions between road surfaces and vehicles, including tyre characteristics and non-linear suspension effects. In such cases, realistic simulation could be achieved by specifying road profile and vehicle suspension characteristics so that the vertical acceleration can be numerically computed and subsequently physically simulated in the laboratory as illustrated in Figure 7.3.

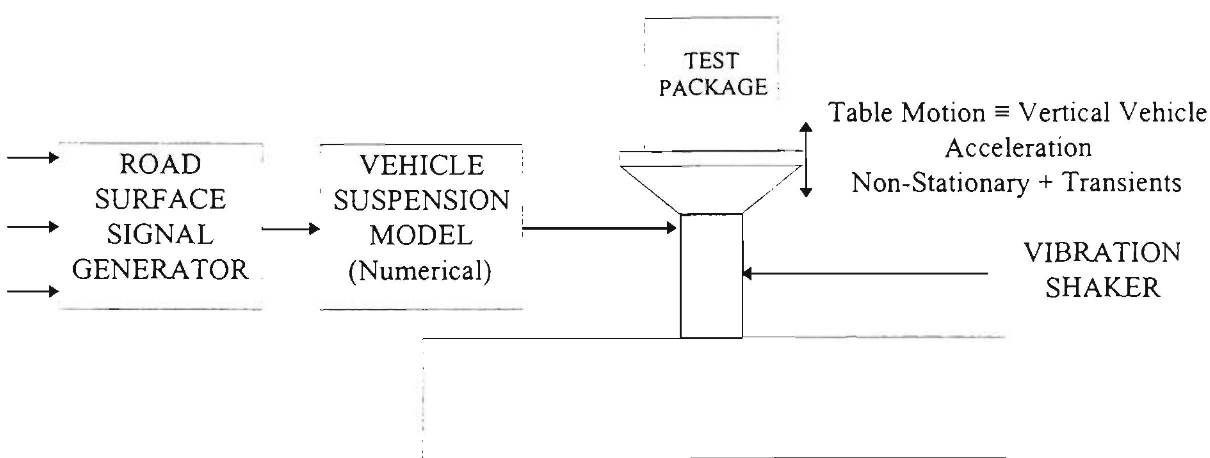


Figure 7.3. Schematic of road transport vibration simulation with vertical acceleration command signal and numerical vehicle model

However, the typically low compliance of an electro-hydraulic shaker produces unrealistic simulation of package-vehicle interaction when the product 'bounces'. A control strategy to overcome this problem is proposed in Figure 7.4.

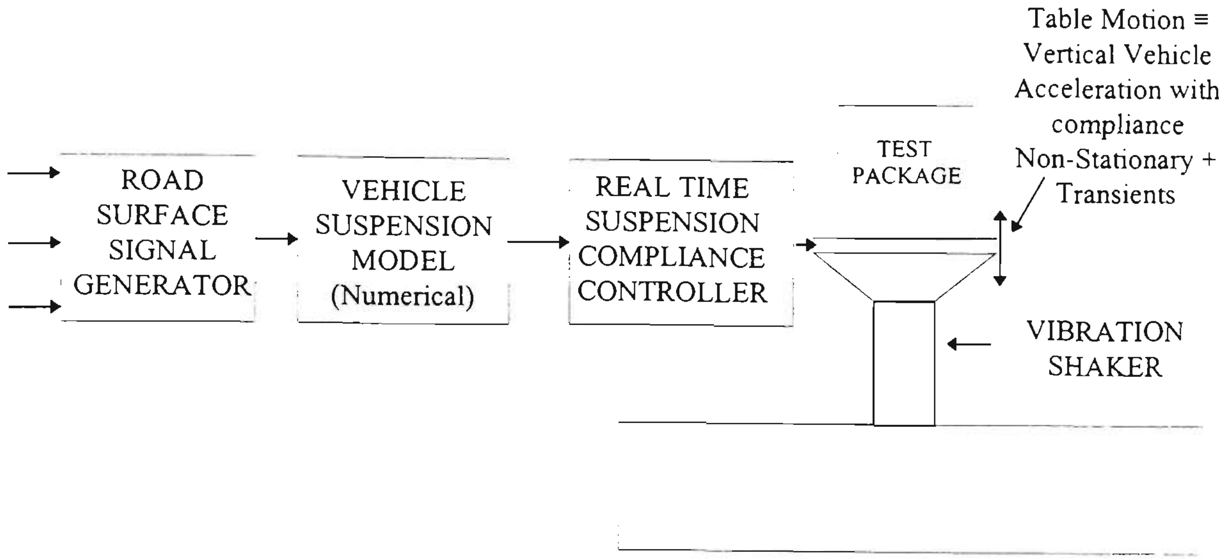


Figure 7.4. Schematic of road transport vibration simulation with vertical acceleration command signal with compliance of suspension system controller.

Therefore, the implementation of accurate road transport simulation relies not only on the accurate characterisation of road profiles but also on the precise modelling of vehicle suspension characteristics and investigation into suspension compliance effects.

7.2 CLASSIFICATION OF SPECIFIC ROADS

The universal road spatial acceleration classification parameters (Table 6.1) are also useful in evaluating the condition of actual roads. More specifically, they indicate variation in road roughness (spatial acceleration RMS level) and transient severity along the road. This characterisation of actual roads can be used to manage and plan transport routes in order to minimise journey duration and product damage by optimising vehicle speed and avoiding rough roads. Furthermore, road management and maintenance organisations can use this scheme as a tool to monitor and manage road conditions as well as specify the surface quality of new and repaired road.

Figure 7.5 shows a 100 m extract of spatial acceleration from a typical road. The results of analysis are shown in Figure 7.6 where the RMS variation, and the location and amplitude of transients are plotted versus horizontal distance. The distribution and parameters describing the transient amplitudes for the entire road section (8.33 km) are shown in Figure 7.7. For comparison, the transient amplitude distribution for the entire 415 km sample is also shown. The RMS level distribution for the entire road section (8.33 km) is shown in Figure 7.8 together with the parameters used to characterise the distribution. Also shown for comparison is the RMS distribution for the entire 415 km sample. Similar results for another representative road are shown in Figure 7.9 to Figure 7.12.

The parameters describing each individual road section from the entire 415 km sample analysed in this study are shown in Appendix D.

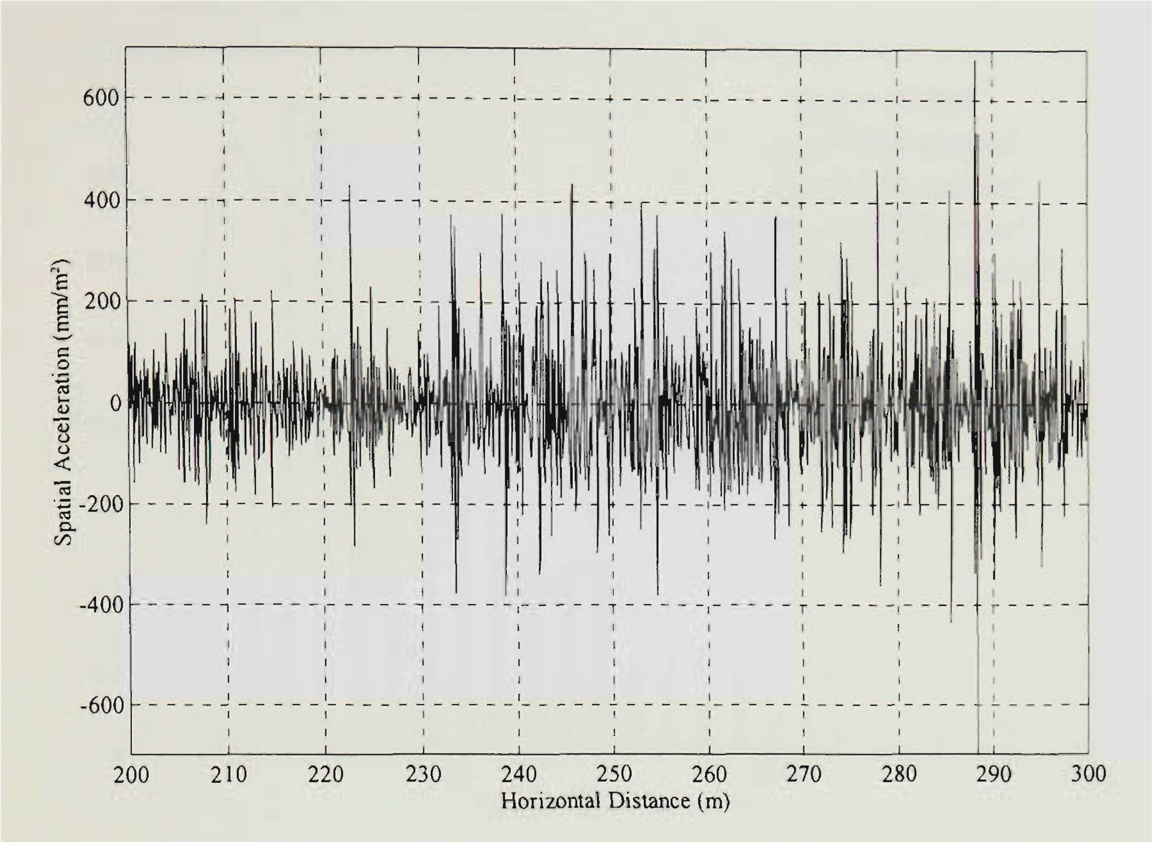


Figure 7.5. 100 m extract of spatial acceleration, road 55051a, 100 m

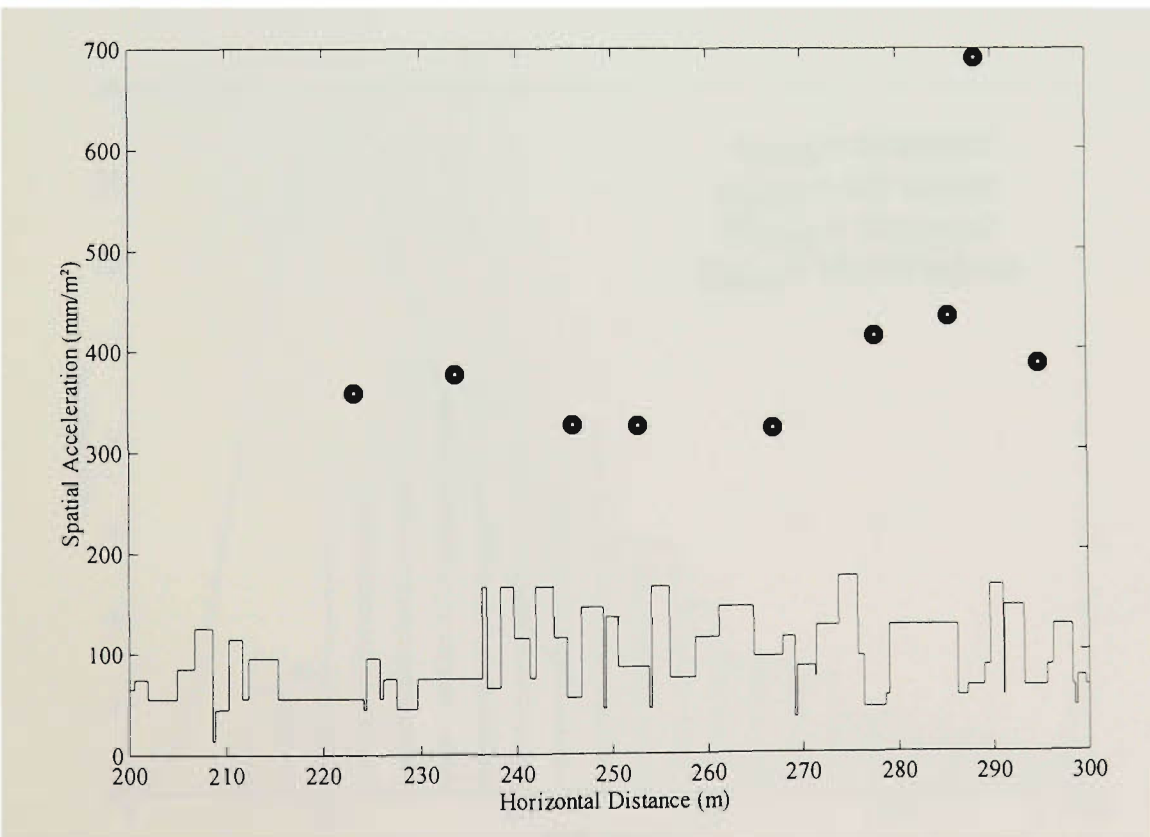


Figure 7.6. Results from computer software, road 55051a, 100 m (line = RMS history, dots = transient location and amplitude)

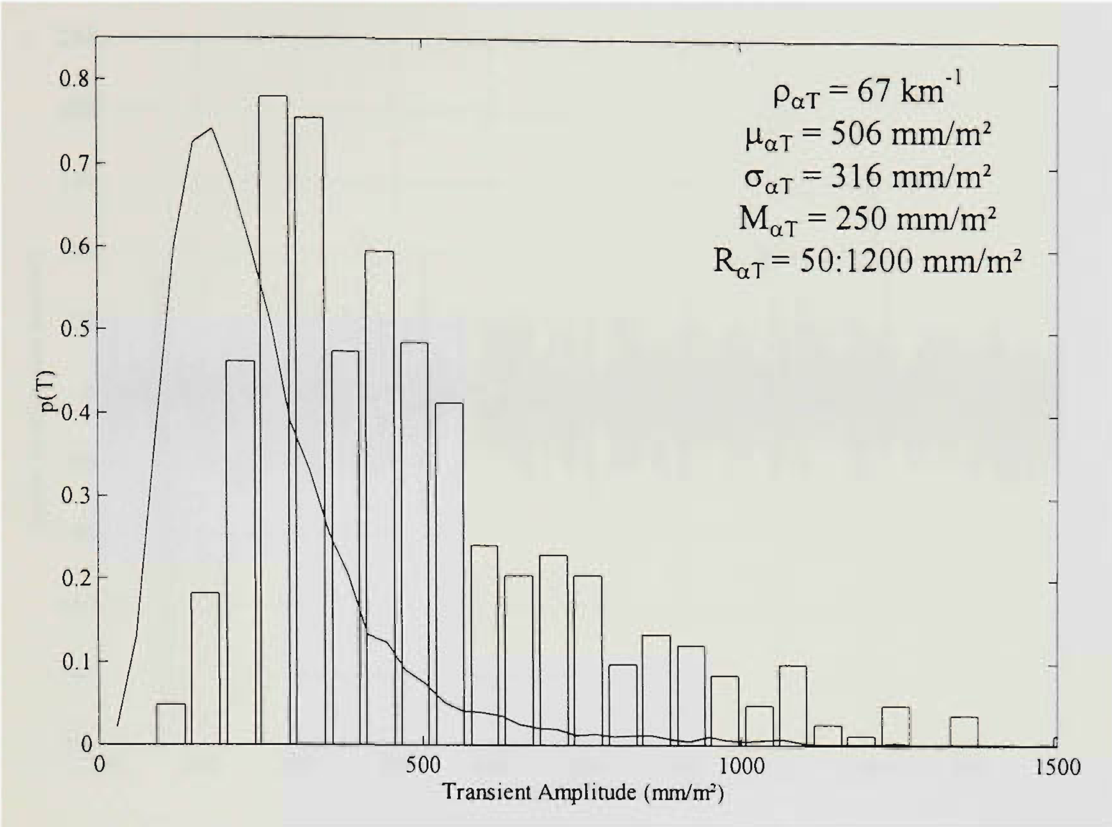


Figure 7.7. Transient amplitude distribution (bars = entire road 55051a - 8.33 km, line = entire 415 km sample) with classification parameters

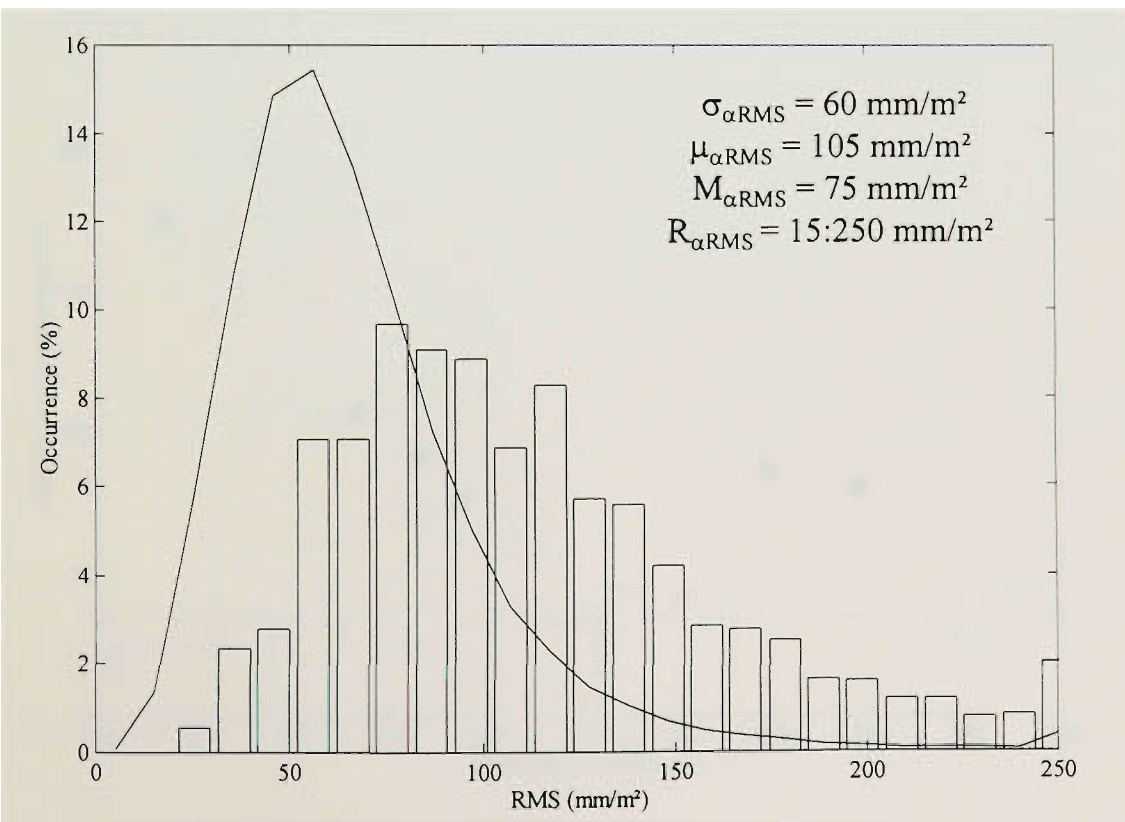


Figure 7.8. Stationary RMS distribution (bars = entire road 55051a - 8.33 km, line = entire 415 km sample) with classification parameters

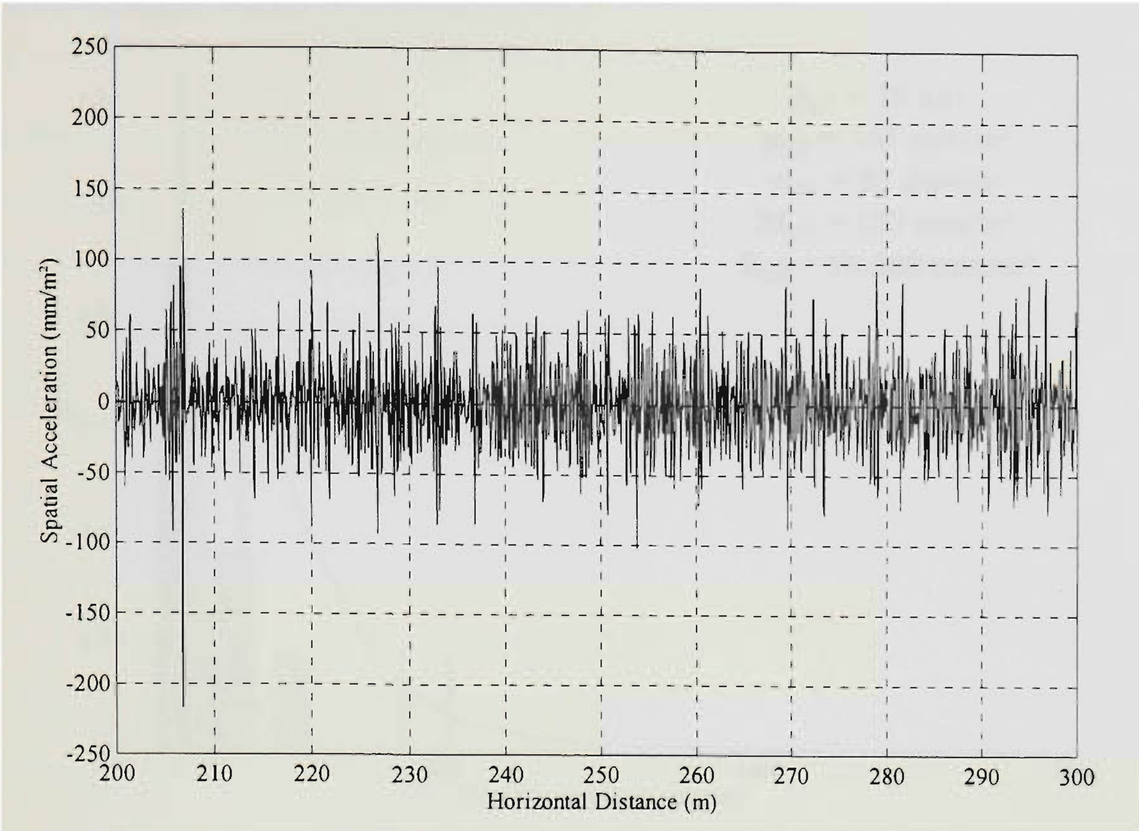


Figure 7.9 100 m extract of spatial acceleration, road 25103a, 100 m

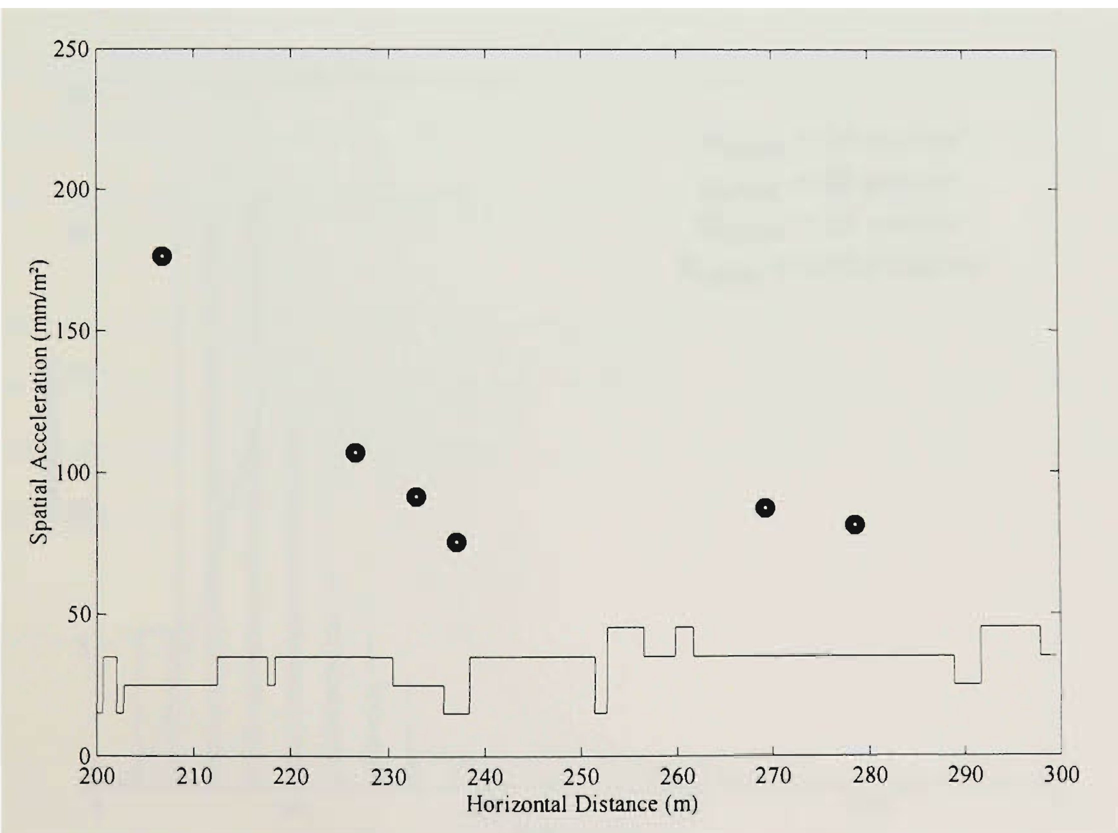


Figure 7.10 Results from computer software, road 25103a, 100 m (line = RMS history, dots = transient location and amplitude)

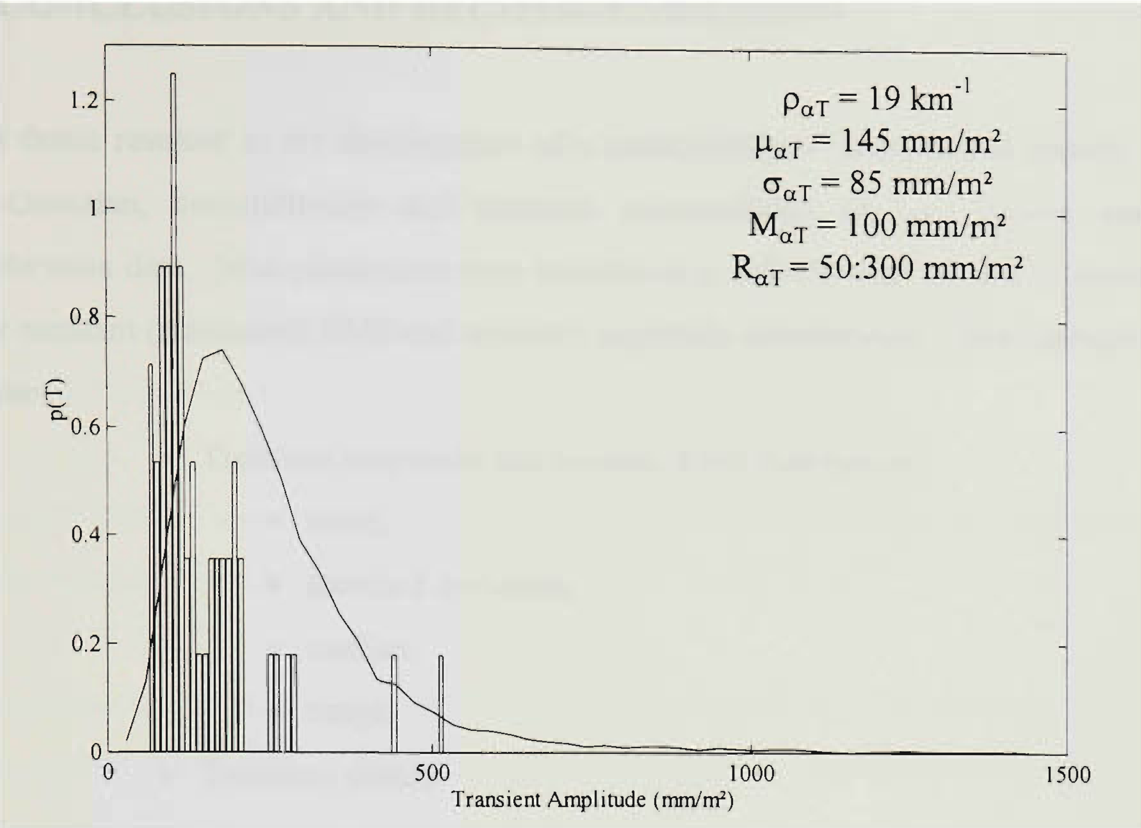


Figure 7.11. Transient amplitude distribution (bars = entire road 25103a - 3.26 km, line = entire 415 km sample) with classification parameters

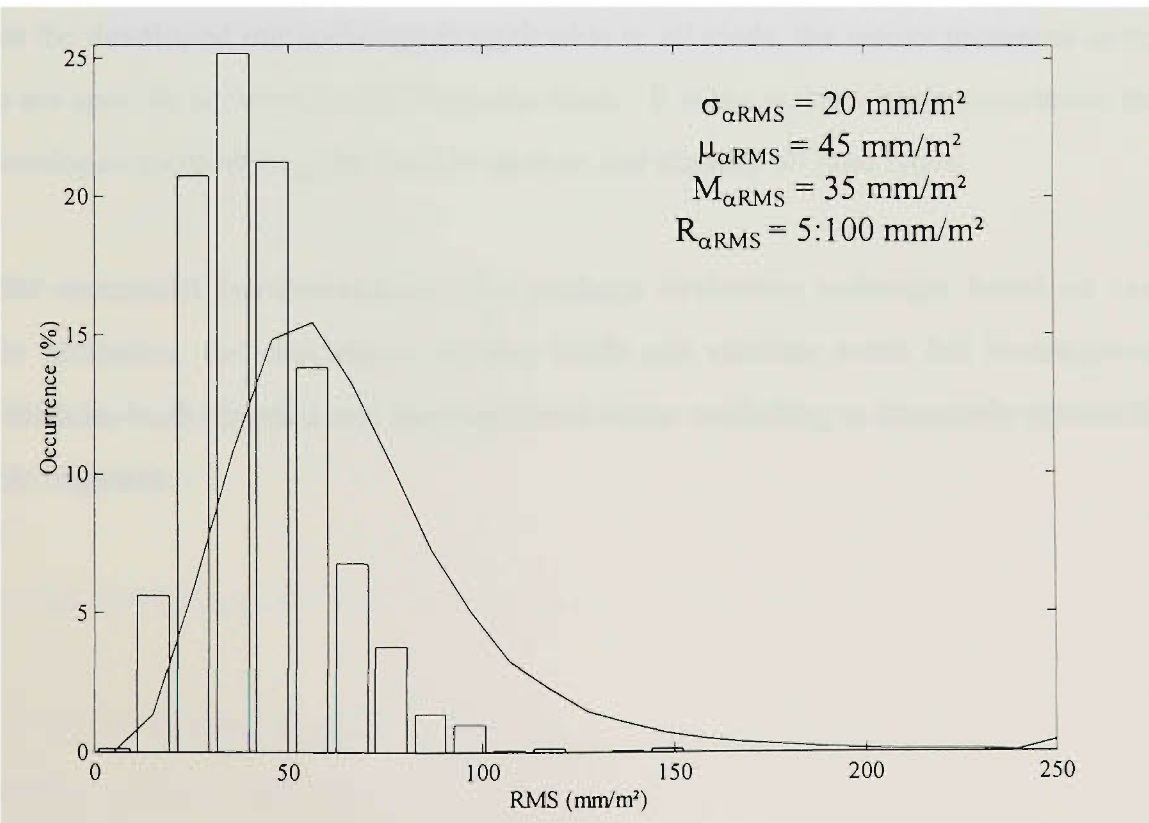


Figure 7.12. Stationary RMS distribution (bars = entire road 25103a - 3.26 km, line = entire 415 km sample) with classification parameters

8. CONCLUSIONS AND RECOMMENDATIONS

This thesis resulted in the development of a methodology to analyse and classify the non-Gaussian, non-stationary and transient characteristics of road profile spatial acceleration data. Nine parameters were introduced to classify road profiles in terms of their constant (stationary) RMS and transient amplitude distributions. These parameters are the:

- Transient amplitude and constant RMS distribution:
    - mean,
    - standard deviation,
    - median,
    - range,
- Transient density

These classification parameters were useful in both the simulation of the non-stationary, transient-laden characteristics of roads and the evaluation of road condition.

Whilst the developed methodology is applicable to all roads, the results presented in this thesis are specific to bituminous, Victorian roads. It is the author's recommendation that the developed methodology be used to analyse and classify all road types.

For the successful implementation of a package evaluation technique based on road profile excitation, the interaction between roads and vehicles needs full investigation. This includes both physical and numerical non-linear modelling to accurately predict the vehicle response.

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Appendix A - MEASUREMENT OF ROAD PROFILE DATA

Experimental data analysed in this project was acquired with the laser profilometer developed by the Australian Roads Research Board (ARRB). The system consists of two accelerometers, three laser based non-contact displacement transducers, a precision fifth wheel, signal conditioners and a digital data logger. All transducers, except for the fifth wheel, are mounted on a rigid beam which is fixed in place of the front bumper. The signal conditioners and the data logger are carried in the host vehicle.

The accelerometers are oriented to sense vertical acceleration and are mounted directly above the laser transducers, which are positioned above the left and right wheel tracks and measure the transducer to road surface vertical distance. The data from the accelerometers are double integrated to establish the vertical distance with respect to the inertial reference and combined with the data from the relevant transducer to produce wheel-track profile.

The laser transducers have a range of 256 mm and a resolution of 0.2 mm. The sampling interval for all measured road profiles is 51.13 mm producing a Nyquist spatial frequency of 9.8 m^{-1}. The accelerometer measurement range is ±2g. The data from the accelerometers is digitally high pass filtered before the first integration and again before the second integration. The filtered and double integrated accelerometer data are combined with the displacement data with corrections for lags associated with transducers (4 ms) and the accelerometer analog filter (8 ms) to achieve an overall signal free from phase distortion. The data is over-sampled at a frequency of 16 kHz and the fifth wheel data is used to decimate the data and convert temporal data into the spatial domain.

The performance of the laser profilometer was validated against a manual survey of the road surface, and results are shown in Figure A.1 and Figure A.2. The profile slope (derivative of road elevation or 'spatial velocity') spectra was used in preference to elevation spectra to minimise spectral leakage errors. However, due to the lack of data used, the number of spectral averages appears to be low, increasing the random error associated with the spectra. The conclusion is that the profilometer agrees well with the manual survey in the range of 34m up to 1m.

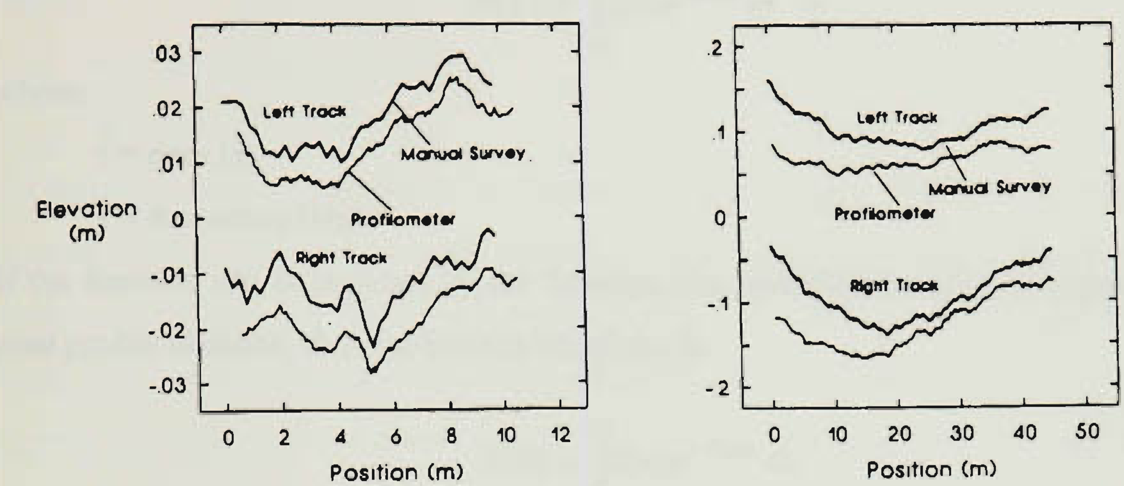

Figure A.1. Comparison of profilometer to manual survey (Prem, 1987)

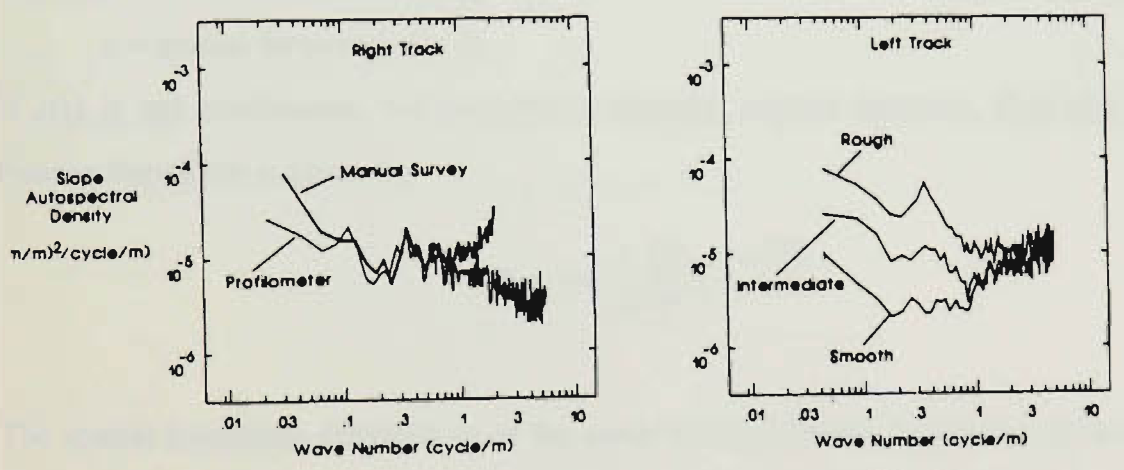

Figure A.2. Spectral analysis from profilometer (Prem, 1987)

Appendix B - FREQUENCY ANALYSIS FOR ROADS

Given the function *s(t)* specified for all *t*, then the Fourier transform, *S(f)*, of *s(t)*, is:

$$S(f) = \int_{-\infty}^{+\infty} s(t) e^{-j2\pi f t}\, dt \tag{B-1}$$

where:

t = time (s)

f = frequency (Hz).

If the function *s(t)* is replaced by the function *s(x)*, specified for all *x*, to represent the road profile distance, then the Fourier transform is:

$$S(n) = \int_{-\infty}^{+\infty} s(x) e^{-j2\pi n x}\, dx \tag{B-2}$$

where:

x = horizontal distance (m)

n = spatial frequency (m^{-1}).

If *s(x)* is not continuous, but sampled at discrete, regular intervals, then the discrete Fourier transform is given by:

$$S(n_k) = \frac{1}{N} \sum_{0}^{N-1} s_k\, e^{-j\frac{2\pi nk}{N}} \tag{B-3}$$

The spatial frequency distribution of the sampled road profile data was estimated using the Discrete Fourier Transform (DFT) with the Fast Fourier Transform (FFT) algorithm, whereby the number of samples, *N*, is a power of 2. The random nature of the road profile elevation indicated that the spatial frequency content should be expressed in terms of its Power Spectral Density (PSD), to ensure constant values regardless of the spatial frequency resolution of the spectra, providing that the signal is stationary.

When calculating the PSD estimate of a random process, it is essential that the two main factors affecting the result are specified:

1. the number of distinct spectral averages (N_d) used and the

2. spatial frequency resolution (Δn) that is linked to the so-called picket fence effect (Randall, 1987) and given by:

$$\Delta n = \frac{f_s}{N} \quad \textbf{(B-4)}$$

where:

f_s = sampling frequency

N = Number of samples

An increase in Δn will decrease N_d for a certain sample size. However, an increase in N_d may result in an increase in the so-called spectral leakage. Leakage can be reduced with the use of spectral windows to ensure that road sections used for spectral estimates begin and end at zero. All road data was windowed with a Hanning window with 50 % overlap and relevant corrections made for the reduction in magnitude (Randall 1987) to estimate the PSD.

The spatial frequency bandwidth of interest in this study was limited to those relevant to road transportation in accordance with the designed acquisition system. The characteristics of the filter used is shown in Figure B.1. The data was filtered and reverse filtered to ensure there was minimal phase distortion.

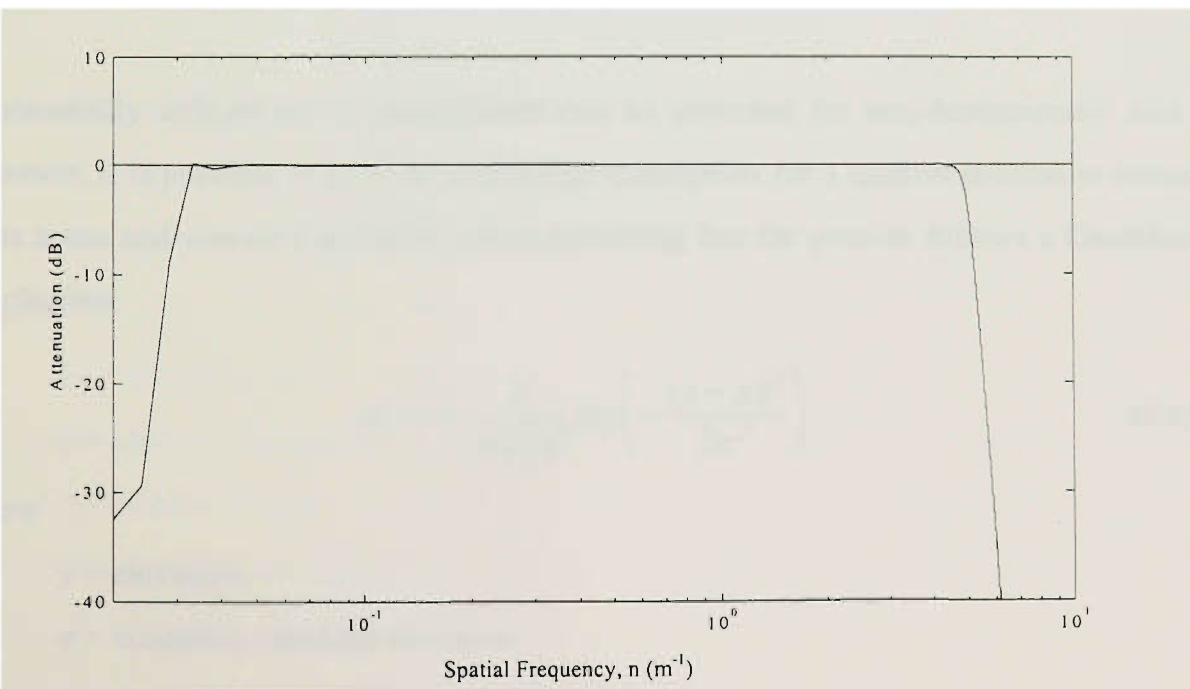

Figure B.1. Butterworth filter characteristics

Appendix C - AMPLITUDE DOMAIN ANALYSIS - STATISTICS

BACKGROUND INFORMATION

Data representing a physical phenomenon, such as road profile data, can be broadly grouped into two basic categories, deterministic and non-deterministic. Deterministic data can be described by an explicit mathematical relationship. However, non-deterministic random data cannot be described in such a manner and rather, must be described in terms of probability statements and statistical properties. As with road surface profiles, each new spatial history will be unique. The distribution of the fluctuations of the single track profile elevation data is important in the description of such a signal.

The concept of amplitude domain analysis is to predict the probability of a certain variable. In the case of road profile descriptions, the vertical amplitude fluctuations mainly determine the mechanical effects a vehicle will be exposed to as it traverses a surface. Therefore, the adaptation of amplitude domain analysis for road data analysis is appropriate as it is typically a non-deterministic process.

A potentially infinite set of descriptions can be provided for non-deterministic data. However, it is possible to provide a complete description for a random process in terms of its mean and standard deviation values assuming that the process follows a Gaussian distribution:

$$p(y) = \frac{1}{\sigma\sqrt{2\pi}} \exp\left(-\frac{(y-\mu)^2}{2\sigma^2}\right) \tag{C-1}$$

where

y = elevation,

σ = ensemble standard deviation,

μ = ensemble mean value.

NOTE: σ = RMS when μ = 0.

The Gaussian distribution with a mean value of zero and standard deviation value of one is shown in Figure C.1.

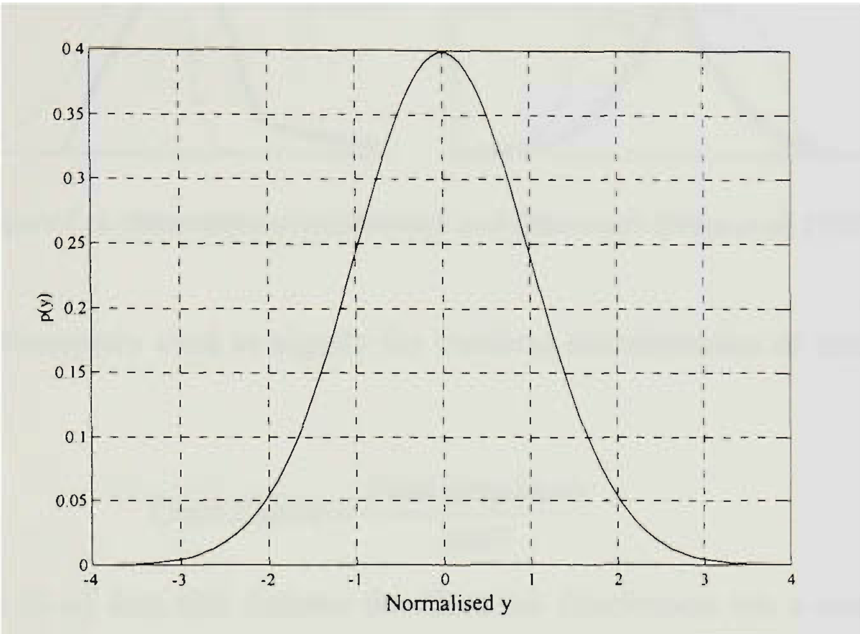

Figure C.1. Gaussian distribution ($\mu = 0, \sigma = 1$)

The degree of variation from a Gaussian distribution can be described by higher order moments such as skewness and kurtosis (Press *et al,* 1992):

$$Skewness = \frac{1}{N}\sum_{j=1}^{N}\left[\frac{y_j - \bar{y}}{\sigma}\right]^3 \qquad \textbf{(C-2)}$$

$$Kurtosis = \frac{1}{N}\sum_{j=1}^{N}\left[\frac{y_j - \bar{y}}{\sigma}\right]^4 \qquad \textbf{(C-3)}$$

where:

N = ensemble size,

j = element number,

y = road elevation

σ = standard deviation.

Skewness and kurtosis are illustrated in Figure C.2.

The Gaussian distribution has a skewness of zero and kurtosis of three.

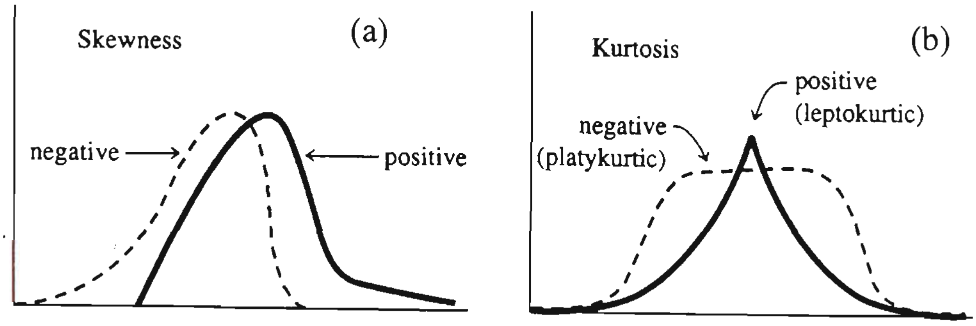

Figure C.2. Illustration of (a)skewness and (b)kurtosis (Press *et al*, 1992)

A parameter commonly used to signify the transient characteristics of data is the crest factor:

$$Crest\ Factor = \frac{Peak\ Amplitude}{RMS} \qquad \text{(C-4)}$$

such that 99.7 % of data that follows the Gaussian distribution has a crest factor less than three.

The distribution of peak heights of a narrow banded Gaussian random processes approximates to the Rayleigh distribution:

$$p(a) = \frac{a}{\sigma^2} \exp\left(-\frac{(a^2)}{2\sigma^2}\right) \quad x > 0 \qquad \text{(C-5)}$$

where

a = peak height.

The normalised Rayleigh distribution is shown in Figure C.3.

Cartwright and Longuet-Higgins (1956) found that, as the spectral characteristics of a process changes from narrow banded to broad banded (spectral width parameter, ε changes from zero to one), the distribution of peak heights changes from Rayleigh to Gaussian as shown in Figure C.4.

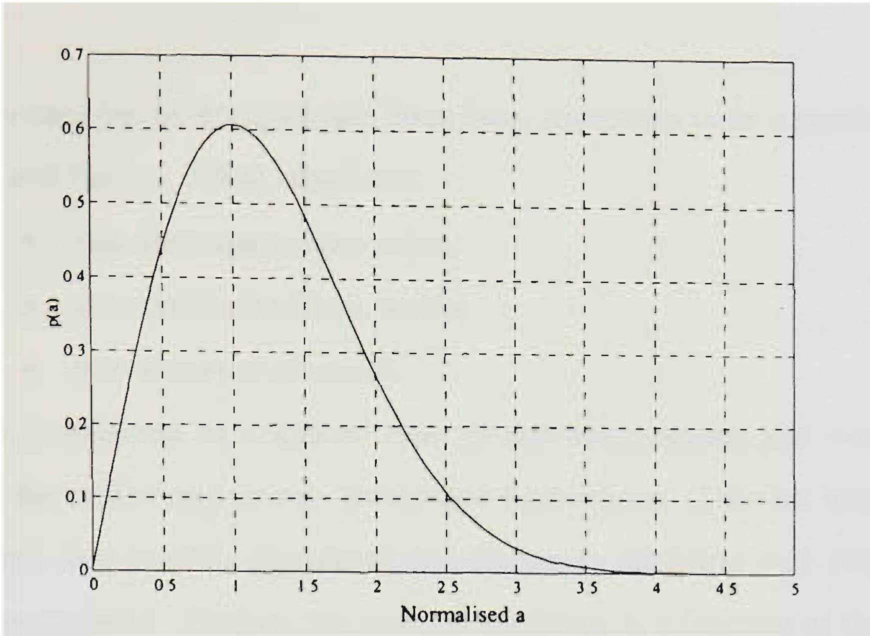

Figure C.3. Rayleigh distribution for peak heights

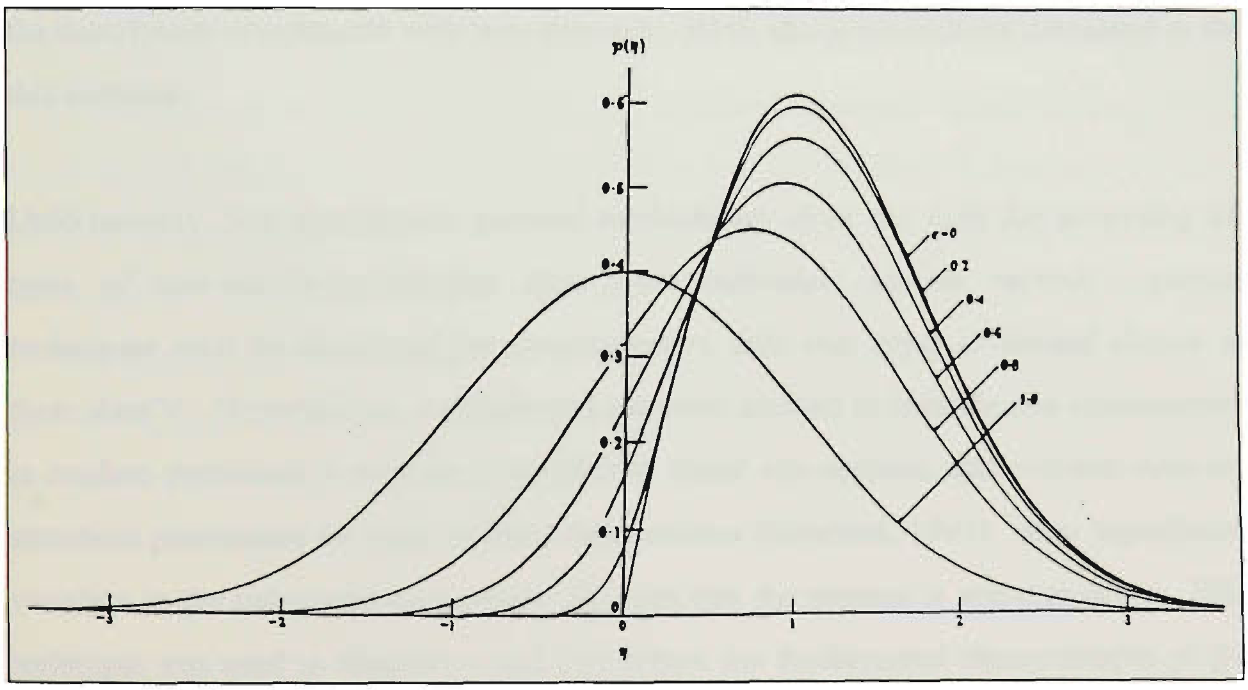

Figure C.4. Graphs of p(η) (probability distribution of heights of maxima) for different values of spectral width parameter, ε (Cartwright and Longuet-Higgins, 1956)

DEALING WITH NON-STATIONARITIES

Non-stationary data can be grouped into three basic categories or be a combination of all three (Bendat and Piersol, 1986) which are:

- non-stationary mean value,
- non-stationary RMS, and/or
- non-stationary frequency.

Transients are considered as a special type of non-stationarities and were dealt with separate from the underlying (steady-state) road fluctuations. The vast majority of road profile elevation data exhibits significant non-stationary attributes with respect to mean and RMS characteristics. Further, the spectral amplitude is a function of the RMS level. Conversion of the elevation profile to the spatial acceleration domain removes the DC and first order effects whilst retaining the RMS variations. Further, the shape of the PSD remains solely a function of the RMS level. Consequently, road profile spatial acceleration must be considered as a non-stationary RMS process. Methodologies for the description of a process with non-stationary RMS characteristics are discussed in the this sections.

Unfortunately, "*an appropriate general methodology does not exist for analysing all types of non-stationary random data from individual sample records......special techniques must be developed for non-stationary data that apply to limited classes of these data*"[1]. Nevertheless, a simple and common method to identify non-stationarities in random processes is to slice a record into 'short' sub-sections and evaluate relevant statistical parameters for each of these sub-sections (Newland, 1993). Any 'significant' variation in the calculated parameters indicates that the process is non-stationary. This technique was used in chapters 4 and 5 to obtain the fundamental characteristics of the non-stationarities associated with road profile elevation and spatial acceleration. However, the interpretation of the results obtained are highly dependent on the width of the sub-sections (window size) as well as the amount of overlap across sub-sections. The effect of these parameters on the interpretation of non-stationarity analysis is discussed in the following sections where results should be treated as illustrative only.

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1 *Bendat and Piersol, 1986, Page 426*

Effect of window size

A reduction in the window size used to calculate a statistical parameter will provide a detailed description of the non-stationarity of the process. However, a window size which is too small will be approach the instantaneous value, resulting in miss-interpretation of the statistical estimates. Conversely, an window size which is too large will approach the overall statistical value for the process and will fail to identify non-stationarity. In this study, a cumulative estimation procedure was used to determine the minimum window size required for meaningful analysis of non-stationary data. In this procedure, the statistical parameter of interest is calculated for a single event (instantaneous value) and recorded. The number of events used to estimate the statistic is gradually increased and re-calculated upon addition of each event to determine the minimum window size to ensure stable results.

The cumulative mean value of a typical road, with four randomly chosen starting points, is shown in Figure C.5. From the graphs it can be concluded that, as the mean approaches a constant value of zero within approximately 20 points ($\approx$1m), window sizes smaller than this should not be used in the computation of moving statistics. However, more accurate results are obtained if a window size of at least 40 points ($\approx$2m) are used as there is noticeable fluctuations in the cumulative mean in the region between 20 and 40 points (Figure C.5(b) & (d)).

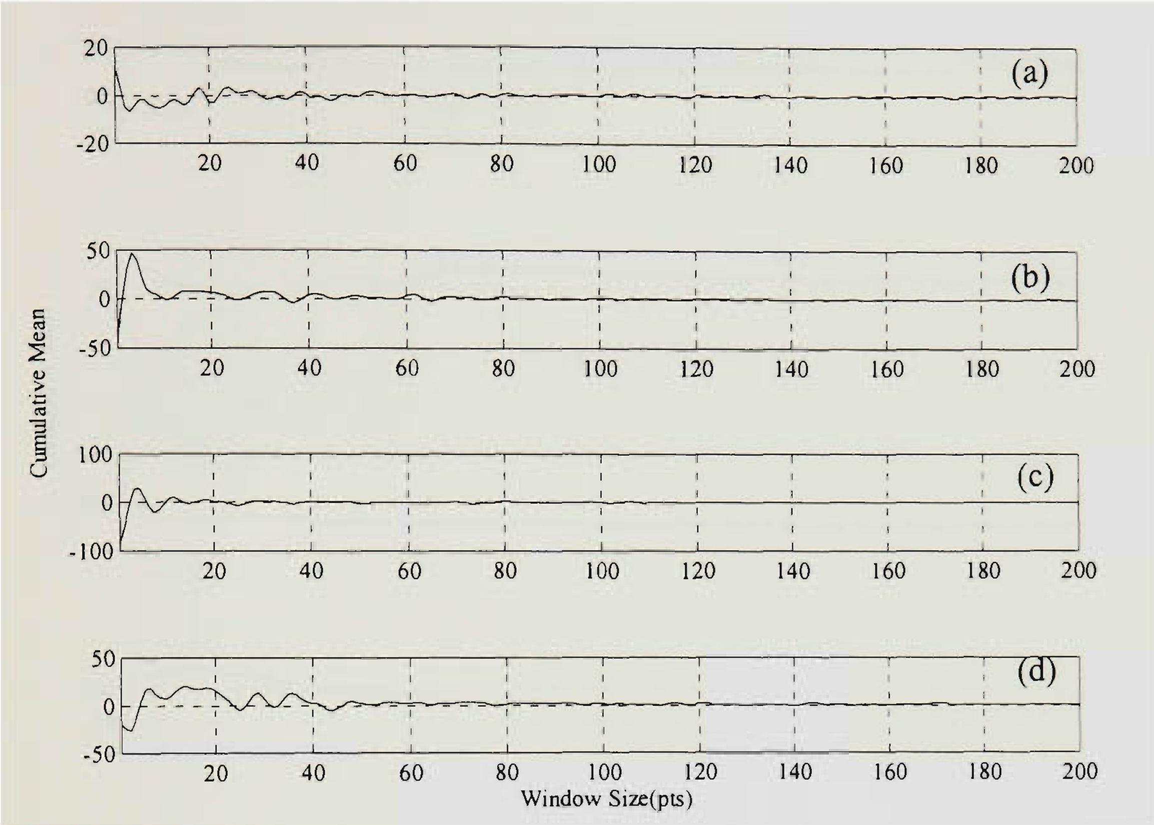

Figure C.5. Cumulative mean versus window size (points) for four different locations

The cumulative RMS estimate of the same typical road, with four randomly chosen starting points is shown in Figure C.6 where it can be seen that the RMS reaches a steady value between at 20, 120, 25 and 80 points respectively. This is probably due to the fact that the road profile spatial acceleration is inherently non-stationary with respect to the RMS level. When computing cumulative quantities, it must be noted that early variations in the variable, relative to the starting point, will appear more prominent than late variations. Evidence of non-stationarity can be seen in Figure C.6(b) by a sudden change in the RMS level followed by a steady state region. Consequently, it is not possible to define the minimum window size from the data shown in Figure C.6. However, as shown in Figure C.5, 2 m is the absolute minimum window size for which the mean of the road profile spatial acceleration can be considered stationary.

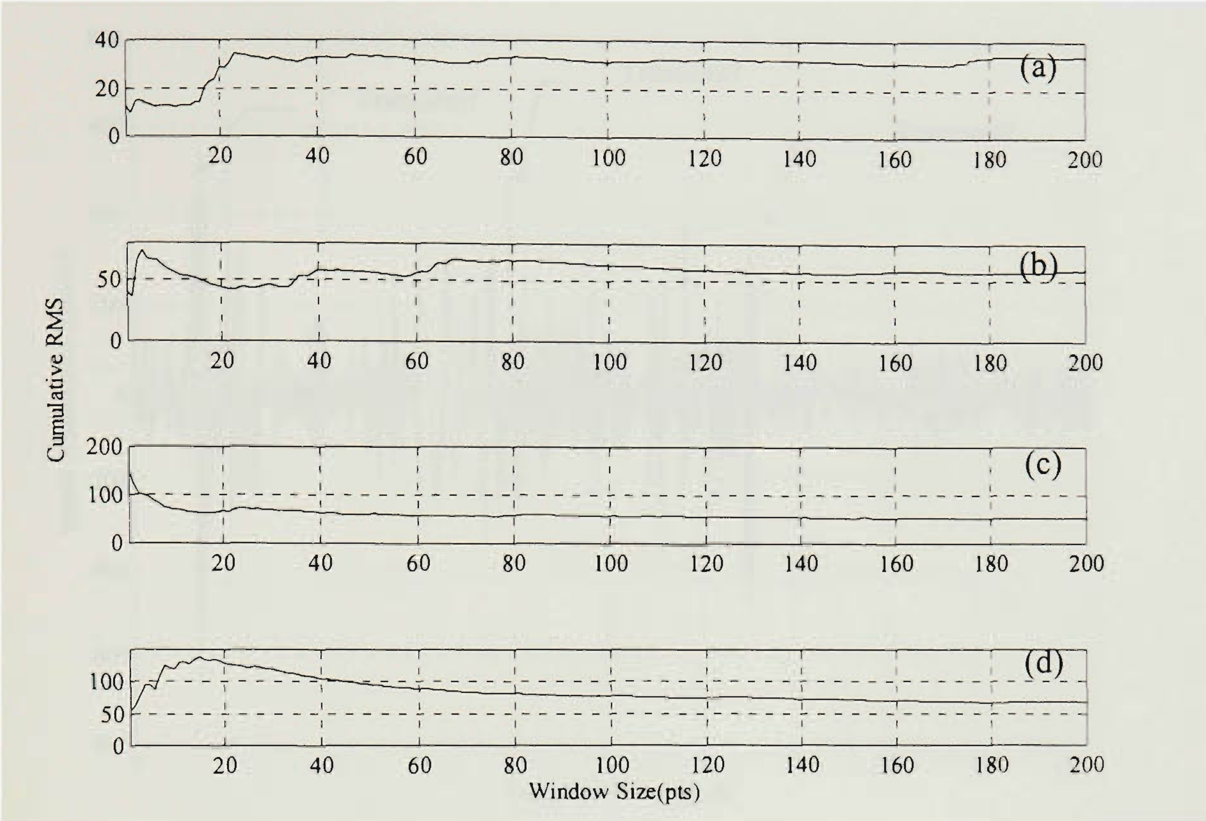

Figure C.6. Cumulative RMS versus window size (points) for four different locations

Effect of window overlap

Window overlap is defined as the degree of overlap across two adjacent windows. To investigate the effect of variation in overlap on estimated statistical results, the RMS and crest factor of a typical section of road spatial acceleration (see Figure C.7) was analysed with the window size retained constant at 60 points (≈3m).

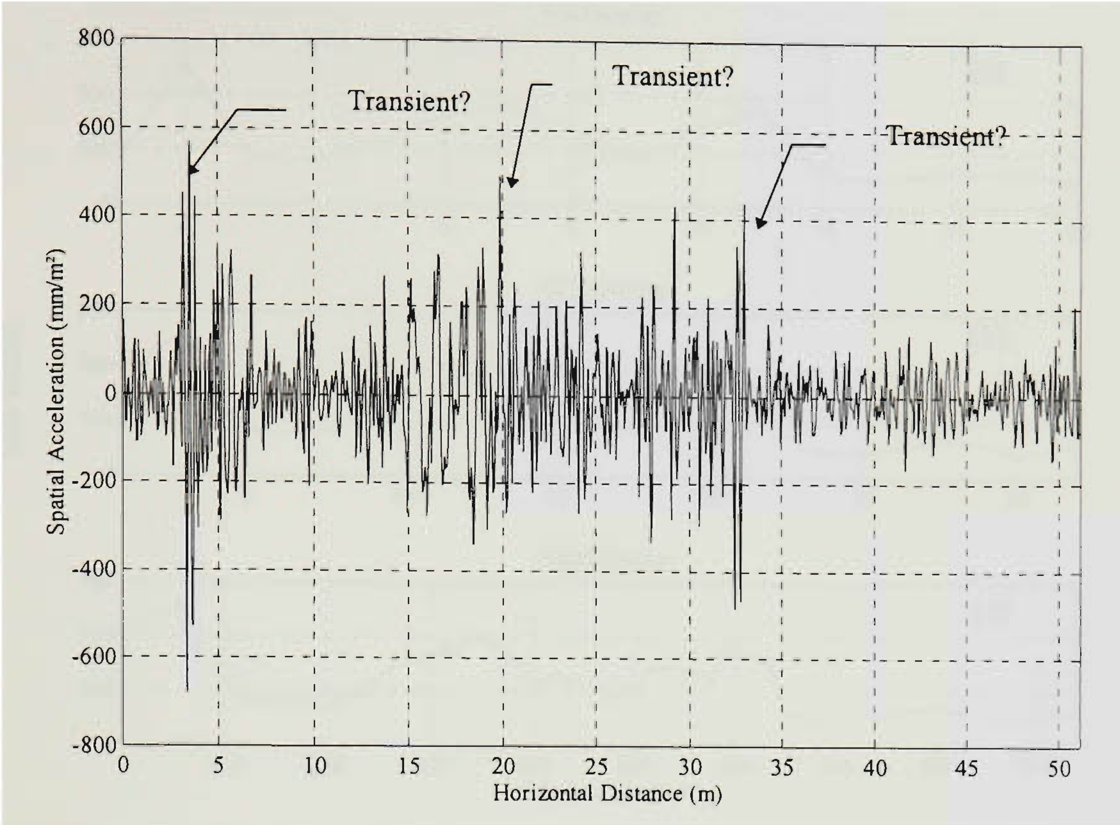

Figure C.7. 50 m of spatial acceleration for analysis of window overlap (road 51881a)

The effect of variation in window overlap on the estimated RMS value is depicted in Figure C.8. While an adequate description of the RMS variation is obtained from the use of smaller overlap percentages, maximum[2], overlap provides a more detailed description of the RMS variation sensitive to local deviations.

[2] Maximum overlap - statistics estimated by moving entire ensemble by 1 point only.

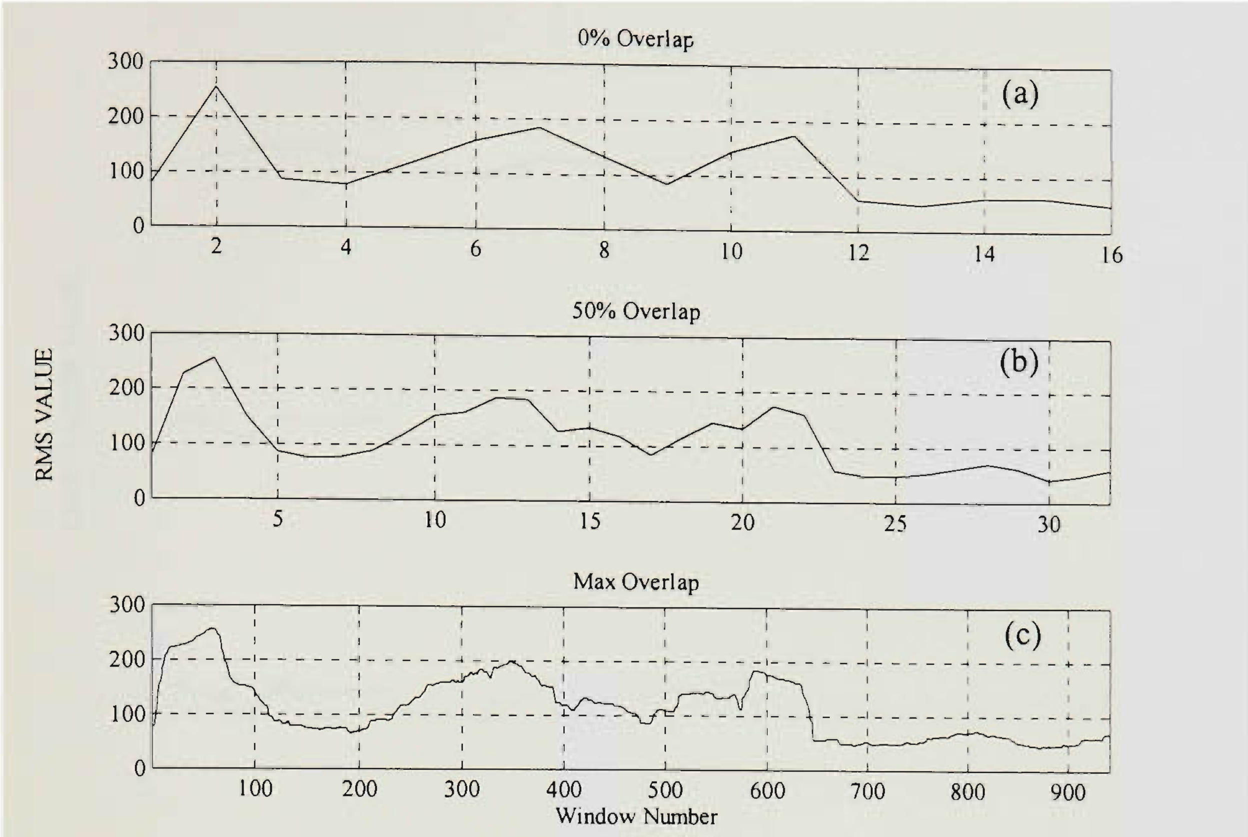

Figure C.8. Effect of moving RMS for various overlap (ensemble size = 3m)

The identification of transient events can be achieved by computing the moving crest factor of a record. It can be seen from Figure C.9 that, contrary to small window overlap, maximum window overlap in the computation of moving crest factors provides the sensitivity to localised events required for the identification of transient events.

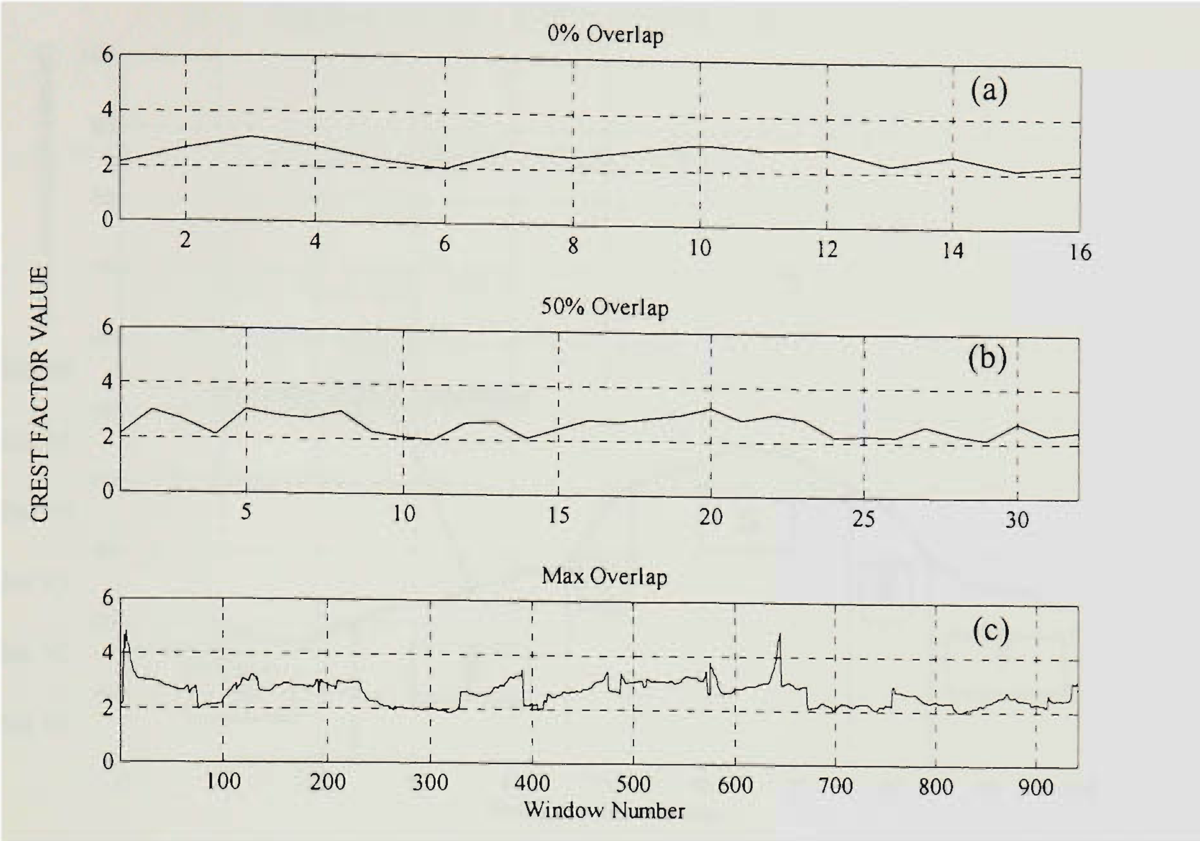

Figure C.9. Effect of ensemble overlap on the moving crest factor estimate (ensemble size = 3m)

Concept of RMS bin size

Throughout the analysis, an arbitrary RMS bin size of 10 mm/m² was used for identification of pseudo-stationary sections, which enables grouping of stationary sections based on RMS bin numbers, defined as:

$$RMS\,bin\,number = \mathrm{mod}\left(\frac{RMS}{RMS\,bin\,size}\right) + 1 \qquad \textbf{(C-6)}$$

The use of the RMS bin size is depicted in Figure C.10, which shows the variation in RMS for a road profile. This section of road contains four uniquely different pseudo-stationary sections based on an RMS bin size of 10 mm/m².

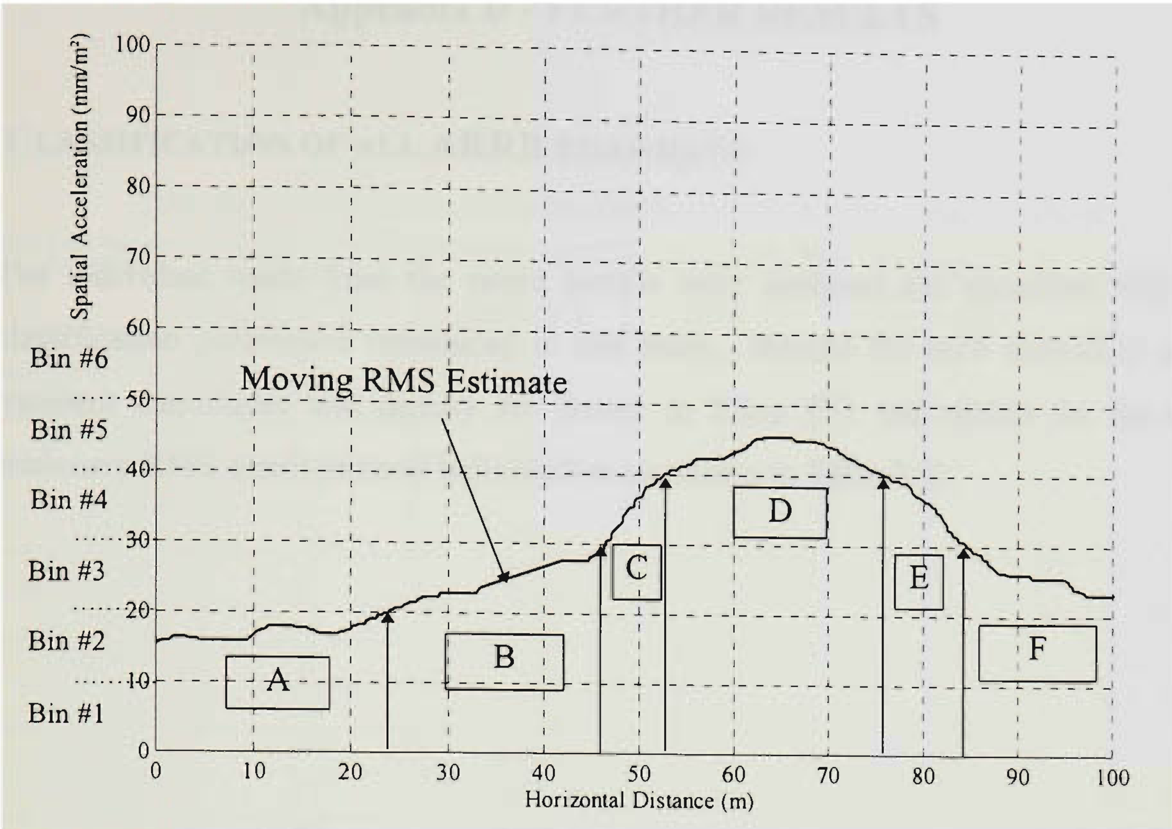

Figure C.10. Use of RMS bin size to identify stationary sections (transients removed)

The use of an RMS bin size enables the constantly varying characteristics of road profile spatial acceleration RMS to be describe with fewer parameters. An increase in the RMS bin size reduces the number of required parameters but increases the non-stationarity of each identified pseudo-stationary section.

Appendix D - FURTHER RESULTS

CLASSIFICATION OF ALL ARRB ROAD DATA

The individual roads from the entire sample were analysed and classified with the classification parameters introduced in this study. Results for each individual road[3] transient amplitudes and density are shown in Table D-1 and results for the non-stationary RMS distribution of individual roads shown in Table D-2.

[3] Due to their length, some road sections were separated for classification. For example, road 59621a has two sets of classification parameters, 59621a(1), (representing the first half) and 59621a2 (representing the second).

Table D-1. Transient amplitude distribution parameters for all roads analysed

ROAD	DENSITY (km^{-1})	MEAN (mm/m^2)	STD (mm/m^2)	MEDIAN (mm/m^2)	RANGE (mm/m^2)
25101a	21	148	86	128	40-350
25102a	20	182	107	114	45-460
25103a	17	145	85	88	65-280
25103b	12	231	101	143	135-385
25401b	40	238	101	171	60-495
25803a	22	181	129	99	40-410
25803b	22	261	130	202	50-710
25803c	35	254	182	118	40-780
25901a	18	202	96	120	50-420
26404b	39	266	168	218	40-680
27203a	31	353	289	192	80-730
27401a	29	240	160	160	40-600
50381a	48	385	370	132	40-1100
51881a	44	305	158	368	115-620
51971a	32	351	321	144	45-950
52001a	43	273	134	228	60-640
55051a	59	506	316	268	90-1250
59621a(1)	23	327	748	113	75-1040
59621a(2)	23	251	135	144	120-560
25704a(1)	20	198	84	175	25-450
25704a(2)	19	204	108	143	50-480
25704a(3)	28	204	113	119	50-480
25704b(1)	36	233	130	212	60-630
25704b(2)	29	213	140	140	60-620
25805b(1)	40	262	114	148	60-580
25805b(2)	43	236	95	217	55-540
25805b(3)	31	217	110	174	80-470
OVERALL	30	258	170	170	30-1000

Table D-2 RMS distribution parameters for all roads analysed

ROAD	OVERALL (mm/m^2)	MEAN (mm/m^2)	STD (mm/m^2)	MEDIAN (mm/m^2)	RANGE (mm/m^2)
25101a	54	47	31	25	5-135
25102a	67	58	37	34	15-135
25103a	46	41	18	35	15-85
25103b	63	56	26	44	15-115
25401b	74	65	26	55	15-135
25803a	57	48	23	44	15-125
25803b	74	63	29	55	15-175
25803c	79	65	32	54	15-165
25901a	69	63	25	54	15-155
26404b	78	66	29	54	15-175
27203a	102	86	36	75	15-195
27401a	73	65	24	65	15-155
50381a	106	59	38	44	15-215
51881a	93	78	43	55	15-175
51971a	113	73	39	55	15-195
52001a	86	74	37	54	15-205
55051a	158	106	54	74	25-235
59621a(1)	94	64	27	55	15-155
59621a(2)	72	63	30	45	15-155
25704a(1)	69	63	24	65	15-145
25704a(2)	69	63	23	55	15-145
25704a(3)	60	52	23	44	15-145
25704b(1)	73	62	34	44	15-125
25704b(2)	63	53	24	44	15-145
25805b(1)	83	73	30	64	25-165
25805b(2)	80	70	33	54	15-175
25805b(3)	73	64	30	54	15-175
OVERALL	78	65	33	55	15-225