Central Laboratories Report 12-529B39

Quantification of Safety Benefits Resulting from Road Smoothing

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OPUS

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Table of Contents

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Executive Summary

This report presents and discusses the results of a research project aimed at examining the relationships between road safety and road roughness parameters routinely used for road asset management purposes so that appropriate corrective actions can be identified and their benefits quantified.

A literature survey was conducted to review current international research on the effects of road roughness on safety to identify (1) critical parameters that needed to be investigated as part of the crash risk and on-road testing programmes, and (2) determine the likely form of the crash risk – roughness relationships to guide the statistical modelling.

Statistical modelling was performed to identify any significant relationships between crash risk, road geometry and routinely measured roughness parameters (IRI and profile variance).

Test track and on-road measurement programmes utilising instrumented vehicles were used to (1) establish whether isolated roughness elements were more or less safe than a uniformly rough road, (2) assess whether the output from skid testers, such as the GripTester, is affected by roughness to the same degree as passenger cars, and (3) quantify the effects of roughness on the braking distances of passenger cars and trucks.

From this study, the following conclusions and recommendations are made regarding the effects of road roughness in reducing the available tyre-road friction and the consequent impacts on crash risk and crash cost.

Conclusions

(1) The consensus in the available literature is that there is a link between roughness and crash numbers, but only limited detail on whether it is the location of the roughness or its amplitude or its spacing that contribute most to crash risk.

(2) Analysis of crash numbers showed that roughness is a statistically significant predictor variable of crash rate.

(3) Of the commonly used roughness parameters, the medium wavelength 10m profile variance is a better predictor than either the short wavelength 3m profile variance or the long wavelength 30m profile variance and only slightly better than the standard International Roughness Index (IRI) statistic.

(4) The derived crash rate model showed that by reducing the roughness of the road by 1 IRI (mm/km), a crash rate reduction of about 25% can be expected on roads where the average travel speed is 70km/h or greater.

(5) The track test measurement programme showed that:

(a) The effects of roughness increased with speed and amplitude.

(b) The effects were larger when all four wheels were affected.

(c) The effects were worst for roughness located at the apex of the corner.

(d) Roughness can affect the output from skid testers, such as the GripTester, when the wheel lifts off the surface This typically occurs for a fraction of a second and so the 10m averaged reading is not affected to any significant degree.

(6) The on-road test measurement programme showed that:

(a) At low speed (around 30km/h) roughness had no apparent effect on braking distances.

(b) At higher speed (around 50km/h) braking distances increased with increasing roughness for both the passenger car and light truck.

(c) At a speed of 50 km/h, vertical wheel loading is most affected by road surface undulations having a wavelength of about 10 metres.

(d) There were reductions in the measured wheel loads of up to 25-30% at a speed of 50km/h. The duration of these reductions in wheel loading was comparable to slide-to-stop braking events initiated at this speed.

(7) A benefit cost analysis showed that rehabilitation of low volume rural roads can be justified on the grounds of reduced crash numbers whenever the reported injury crash density exceeds:

(a) 0.5 reported injury crashes per year per kilometre for straight road sections.

(b) 1.8 reported injury crashes per year per kilometre for moderate curves (i.e. horizontal radius of curvature ≈ 400m).

Recommendations

(1) The procedures in NZTA's Economic Evaluation Manual for calculating additional costs due to roughness should be modified to include crash costs in addition to vehicle costs and vehicle occupants' willingness to pay to avoid rough road conditions wherever average vehicle speeds are 70 km/h or higher.

(2) The level of skid resistance measured by the GripTester on curves is likely to be conservative because its measuring wheel displays a higher degree of sensitivity to road roughness than a vehicle tyre. It is therefore important to determine the roughness sensitivity of other skid testers routinely used to measure skid resistance levels of the state highway network to determine if they are underestimating or overestimating the skid resistance available to motorists. Of particular concern is SCRIM , which has a measuring wheel load of 220kg compared to the GripTester's 22kg so is likely to be much less sensitive to surface roughness and so overestimate the skid resistance available to cornering and braking vehicles.

(3) Additional investigations are required to establish if the increase in braking distance with increasing roughness observed at 50 km/h continues to increase at the same or faster rate for higher brake initiation speeds. Also, will 10m wavelength road surface undulations continue to dominate wheel loading at these higher speeds? These investigations could either be performed on closed roads, or through computer simulations, provided the simulations could be suitably validated.

(4) Further work is required to identify whether any wheel load reductions on corners are similar to those on straights, and whether this translates into variations in the available friction values that are different from the requirements of straight line braking. This could be achieved either by (a) relating direct measurements of vehicle wheel loads while cornering to current measures of road roughness contained in the RAMM database, or (b) by combining on-road measurements with computer modelling, such as with PC Crash or HVE. The latter would allow calibration of the computer models against on-road measured data to be carried out for speeds that were still well within safe limits. The computer models could then be used to establish threshold levels for combinations of roughness and vehicle speed.

(5) There is need to identify (a) an appropriate threshold level of 10m profile variance above which smoothing works might be considered appropriate from a safety perspective, in a similar way that skid resistance is currently treated. The cost- benefit that might accrue from remedial smoothing works to reduce roughness levels to this threshold level also need to be assessed to provide guidance to industry.

(6) The research has shown that depending on the elevation profile of the road surface, there will be a critical vehicle speed at which a significant reduction in tyre contact occurs. Barbosa, in his 2011 paper titled “Vehicle Dynamic Safety in Measured Rough Pavement” (Journal of Transportation Engineering, Volume 137, No. 5, May 2011), provides a methodology for determining this critical speed from the power spectral density of the elevation profile of the road surface profile. This discounts its use for road maintenance management purposes but not for fatal crash investigations. It is therefore recommended that Barbosa’s methodology be validated by undertaking comparisons of measured and predicted critical speeds for test sites displaying different roughness characteristics as there are some concerns that using a quarter-car model may not replicate vehicle dynamic behaviour to an appropriate degree.

1 Introduction

1.1 Background

For the 5 year period 2004-2008, road roughness related issues were recorded as contributory factors in 428 injury crashes (including fatals) entered in the NZ Transport Agency's Crash Analysis System (CAS). A significant proportion of these crashes (22%) involved trucks or buses. Therefore, improved identification of road surface irregularities that impact on a driver's ability to control a vehicle will advance the safety of New Zealand road networks.

It is well established that rough road surfaces cause a loss of tyre-road friction, which may result in a potential hazard to the travelling public (Burns, 1981). The first issue relates to the problem of how to interpret road roughness and profile variance data routinely collected by the NZ Transport Agency as part of the annual condition survey of the state highway network to identify situations where cornering and braking could be adversely affected by fluctuations in the normal tyre force caused by a rough or undulating road surface. For example, Wambold and others (1973) have found that as the amplitude and frequency of the road roughness increased, the coefficient of friction generated between the tyre and the road surface during low speed braking decreased by as much as 80%. This finding needs to be confirmed for road conditions, tyre loads, and braking speeds typical of New Zealand rural roads.

The second issue relates to procedures in the NZ Transport Agency's Economic Evaluation Manual (EEM) for evaluating the benefits of projects that involve changing the roughness/ride characteristics of the road surface, (NZTA, 2010). The EEM procedure assumes roughness costs are made up of only two components: vehicle operating costs and values for vehicle occupants' willingness to pay (WTP) to avoid rough road conditions. However Swedish (Ihs et al, 2002) and New Zealand (Davies et al, 2005) research confirm a positive correlation between road roughness and crash frequency (crash risk). For example, the Swedish research indicates rough roads with an International Roughness Index (IRI) value of 3 mm/m (about 80 NAASRA counts/km) will have a crash rate that is 50% higher than for smooth roads with an IRI value below 0.9 mm/m (about 30 NAASRA counts/km). If crash costs were included in roughness costs, it may prove economically viable to apply smoothing treatments to lower volume roads with high levels of roughness, which are presently left to deteriorate even further on account of the target benefit cost ratio for funding not being able to be met. Therefore, there is a need to derive robust crash risk – road roughness relationships suitable for use in economic evaluations, and to establish a threshold level of roughness, which if exceeded will result in the safety of road users being severely compromised. This will allow road controlling agencies (RCA) to set an upper level of roughness in their asset management plans for road smoothing interventions to automatically take place on the grounds of safety, irrespective of the resulting economics.

1.2 Need for Research

In these times of increasing demands on the funds available for road maintenance, it is essential that appropriate decisions are made in regard to smoothing treatments, especially if an improvement in road safety results. Therefore, there is a need to be able to isolate characteristics of road surface roughness that adversely impact on cornering and braking behaviour of vehicles by reducing the available tyre-road friction so that remedial treatments can be identified and programmed.

Furthermore, a number of RCA's have been experiencing difficulty in justifying smoothing works for lower volume roads because the value of benefits is insufficient to meet or exceed the target benefit cost ratio for funding. As a consequence, these roads are often left to deteriorate further, possibly creating potential hazards for the travelling public. This points to the need to investigate the inclusion of crash costs in addition to vehicle operating and willingness to pay costs presently employed when assessing the benefits of projects in which the roughness characteristics of the road surface is changed (NZTA, 2010).

1.3 Research Aim and Objectives

The aim of this research project was to improve the safety management of road networks by examining the relationships between road safety and road roughness parameters that are routinely used for road asset management purposes so that appropriate corrective actions can be identified and their benefits quantified. This was to be achieved through the following objectives:

Objectives:

(1) To establish whether or not short wavelength or medium wavelength profile variance is a better predictor of crash risk than conventional measures of lane roughness such as the International Roughness Index (IRI) or NAASRA counts/km through an analysis of fatal/injury crashes recorded in the CAS system over the four year period 2006 to 2009.

(2) To establish whether or not the contribution of lane roughness to crash risk is greater for curved road sections than for straight road sections through an analysis of fatal/injury crashes recorded in the CAS system over the thirteen year period from 1997 to 2009.

(3) To identify whether or not there is a critical level of roughness above which crash risk increases substantially as indicated by Swedish research (Ihs et al, 2002) and if this critical level is different for passenger cars and trucks.

(4) To quantify the effects of different wavelengths and magnitudes of road surface undulations on the braking distances of passenger cars and trucks through on-road trials.

(5) To establish whether localised roughness may be less safe than a uniformly rough road when it comes to cornering through controlled off-road tests.

(6) To investigate if the output from skid testers, such as the GripTester, is affected by road surface roughness to the same degree as passenger cars by correlating friction measurements made with the skid tester at 0.4 m intervals to normal tyre forces measured on the vehicle during braking and cornering.

(7) To produce a guideline document that highlights the conditions for road surface roughness to have a significant detrimental impact on road safety through reducing the tyre-road friction available to a vehicle.

1.4 Scope of the Report

This report presents the findings of a study aimed at examining the relationships between road safety and road roughness parameters that are routinely used for road asset management purposes. The study was based on a combination of (1) statistical modelling of crash risk – roughness relationships, (2) a programme of test track measurements to compare the responses of a skid tester (GripTester) and a passenger car to isolated and uniform roughness elements, and (3) an on-road test programme to measure the effects of roughness on the braking distances of passenger cars and trucks. Chapter 2 examines the available literature on the effects of roughness on safety and crash risk, and the forms of the crash risk models that have been developed. The statistical modelling of the road condition and crash data are dealt with in Chapter 3. Chapter 4 discusses the test track programme to compare the skid tester and passenger car responses to isolated and uniform roughness elements and the results obtained. In Chapter 5 the on-road test programme to measure the effects of roughness on the braking distances of passenger cars and trucks is presented and the results discussed. The role of roughness in pavement maintenance management is presented in Chapter 6 along with the results of a benefit-cost analysis undertaken to determine the crash densities required for road smoothing treatments to become a cost-effective safety intervention. Chapter 7 combines the findings of the literature review, the results of the statistical modelling and test track and on-road testing to produce guidelines on the effects of roughness on road safety. The conclusions and recommendations derived from this study are presented in Chapter 8.

2 Literature Review

Opus International Consultants Information Service was used to generate a reference database to assess (1) the general effects of road roughness on safety, (2) critical roughness parameters that needed to be investigated as part of the crash risk quantification and on-road testing research elements and (3) the likely form of the crash risk – roughness relationships to guide the statistical modelling

2.1 General Effects of Road Roughness

The majority of research papers reported an increase in passenger car crash rates on rough road surfaces (e.g. Filippov, Smyrnova and Kyiashko, 2009; Cairney and Bennett, 2008; Chan, Huang, Yan and Richards, 2009; Ihs, 2004 and Othman, Thomson, and Lanner, 2009), and attribute this increase to the potential reduction in tyre/pavement forces caused by rougher roads. However, a small minority of research papers argued that the potential detrimental effect on passenger car safety on rough pavements is mitigated by drivers' reducing speed to maintain comfort (e.g. European Commission, date unknown; Luell, 2007and Archondo-Callao, 1999). It has been pointed out that it is likely that any reduction in speed in such situation is likely to be small for unexpected and isolated roughness elements in an otherwise smooth road.

Contrary to the situation with passenger cars, the available literature appears to (1) universally agree that increased pavement roughness increases the crash rate of trucks and motorcycles (e.g. Naraghi, 2003), (2) acknowledge that road roughness increases the rate of vehicle suspension wear, vehicle operating costs, pavement deterioration rates and vehicle emissions (e.g. Gerardi and Freeman, 2002; and Ksaibati and Al Mahmood, 2002), and (3) that the historical lack of linkages between pavement condition and crash databases (e.g. Turner, 2006) has hindered a thorough understanding of the effect of pavement roughness on vehicle crash rates.

2.2 Critical roughness parameters

The potential for roughness to contribute to differential normal tyre/pavement forces across each of the tyre-road contact points of a vehicle and the possible consequential loss of vehicle control due to differential friction availability is discussed by Burns (1976). Burns (1981) also concludes that braking and steering can be adversely affected by pavement roughness to the extent that tyre/pavement forces can become critically low and crashes can occur. These views are supported by Quinn and Hildebrand (1973), who concluded that a vehicle negotiating a tight rough corner can spin out due to diminished lateral tyre forces. More recently, Gerardi and Freeman (2002) note that rough pavements can be a safety issue, particularly during emergency braking. This is emphasised by the simulation results described by Bodevičius and Vladimirov (2006) and the recent publication of Fuentes, Gunaratne and Hess (2010), which showed that a rough pavement has a lower Locked-Wheel Tester (LWT) measured skid resistance than an equivalently textured (i.e. microtexture and macrotexture) smooth pavement.

Surprisingly, the literature review did not identify any references that discussed in any detail the effects of road roughness element geometry or spacing on vehicle braking and steering. This apparent lack of literature is also noted by Naraghi (2003). As a consequence, the literature review proved to be of little assistance in designing the experimental studies.

2.3 Crash-risk model forms

The International Roughness Index (IRI) is now commonly adopted by pavement condition and vehicle crash researchers as the best default indicator of pavement roughness. This in part may be due to the findings reported by the Washington State Transportation Centre, (Shafizadeh, Mannering and Pierce, 2002), where of the pavement roughness measures considered, the IRI statistic was found to correlate best with driver perceptions. This measure of roughness is routinely measured as part of the New Zealand Transport Agency (NZTA) annual survey of the state highway network.

Authoritative studies into the effect of pavement roughness on vehicle crash rates appear to be relatively recent. This is perhaps because, as noted previously, pavement condition and crash databases have not always been linked (e.g. Levett and Cairney, 2005). One of the first examples of linked datasets being utilised is for New Zealand State Highway's (e.g. Cenek and Davies, 2006). A later example of a study where linked datasets have been used is described by Cairney and Bennett (2008), who directly linked surveyed road surface characteristics and vehicle crash databases through a geographic information system (GIS). This direct approach has also been used on Tennessee data, as described by Chan, Huang, Yan and Richards (2009) who analysed the resulting datasets by developing negative binomial regression models. Similarly, Ihs, Velin and Wiklund (2002) have used both linear and multiple regression to relate IRI and rut depth to crash rates on Swedish State Roads, while Monsere, Bosa and Bertini (2008) used a number of methods to analyse the weather and crash data on Oregon Highways including the empirical-Bayes method where safety performance functions were generated using negative binomial regression techniques. Al-Masaeid (1997), who describes a study investigating the effect of pavement condition, roadside condition and road geometry on rural road crashes in Jordan also used a regression technique. In addition, Aeron-Thomas and Jacob (1995) predicted the reduction in crash rates resulting from road improvements in a number of developing countries. A study has also been carried out using Western Sweden road geometry, pavement condition and crash data as detailed by Othman, Thomson and Lanner (2009). Anastasopoulosa, Tarkoa and Mannering (2008) state in the abstract to their paper that while there has been an abundance of research that has used Poisson models and its variants (negative binomial and zero-inflated models), an attractive alternative is Tobit regression, whereby vehicle crash rates would be obtained directly instead of frequencies. In a later paper, two of these authors, Anastasopoulosa and Mannering (2009) comment that random-parameter count models have the potential to provide a fuller understanding of the factors determining crash frequencies. According to Linard (2009), most models where both pavement maintenance datasets and vehicle crash datasets are used tend to be simply either non-analytical or based on statistical correlations. Linard goes on to claim that a system dynamics approach would be an attractive alternative. Perhaps the most advanced of the studies using linked geometry and crash datasets is described by Brodie, Cenek, Davies and Tate (2009).

3 Statistical Modelling – Roughness and Crash Risk

3.1 Statistical Modelling - Background

The statistical modelling component of this project was carried out by Dr Robert Davies of Statistics Research Associates Ltd. In many ways it is an extension of previous work done on crash risk relationships (Davies, 2009) which related vehicle crash rates to road surface characteristics using data from 1997 to 2002 using a Poisson regression model. This current work focuses on the effects of roughness, but includes the variables identified in the earlier modelling work. It initially included the data from 1997 to 2009, but as the data was incomplete for the 1997 and 1999 years, the analysis was carried out for the years 2000 to 2009. The following sections summarise the statistical analysis that was carried out. A more complete description of the analysis is contained in Cenek et al. (2012).

3.2 Statistical Modelling - Analysis

Data Preparation

Data for the period 2000 to 2009 was extracted from the RAMM (Road Asset Management and Maintenance) and Crash Analysis System (CAS) databases. For this study the crashes considered were fatal or injury (serious or minor) crashes. The extracted data comprised the following variables:

(1) Data collected by the SCRIM+ machine at 10m intervals on each side of the road
  - (a) Geometry: gradient; curvature; crossfall; GPS coordinates (2010 only)
  - (b) Scrim coefficient for each wheel path; skid_event
  - (c) Mean texture depth for each wheel path

(2) Data collected by the SCRIM+ machine at 20m intervals on each side of the road
  - (a) IRI roughness for left and right wheel paths; 3m, 10m and 30m wavelength profile variance (2006-9 only)
  - (b) Mean rut depth and standard deviation of rut depth and related measurements

(3) Carriageway data: urban/rural; number of lanes; lane width; estimated traffic ADT (Average Daily Traffic)

(4) Road names: state highway number; road region

(5) Crash data:
  - (a) Crash location (two versions); crash details; movement code; etc.
  - (b) Crash vehicle details
  - (c) Crash causes

(6) Survey number to year correspondence (also survey vehicle type)

Initial preparation and processing of the data was carried out using the MySQL database software program. C++ routines were created to set up the data structures needed for carrying out the analyses, read in the data generated by MySQL, carry out data checking and generate the transformed data where required. In particular, they link in the 10m or 20m roughness, rutting, crash and road data and calculate the adjusted skid site, adjusted IRI, and the OOCC (Out Of

Context Curve) variables. They also check for isolated missing values in the predictor variables and attempt to estimate these from neighbouring variables.

The number of 10m data segments identified is around 1 million per year investigated and this number increases slightly over the 2000 to 2009 analysis period. This could indicate an increase in the length of road surveyed or a reduction in the number of missing values with time.

The Poisson Regression Model

The statistical modelling was based on the assumption that each side of each 10m length of road can generate injury crashes (i.e. fatal, serious injury and minor injury) over a year period that can be described by the following form:

$$\begin{gathered} \mathit{Expected\ Collective\ Risk\ or} \\ \mathit{Expected\ Crash\ Density}\ \ \mathit{injury\ crashes\ per\ year\ per}\ 10\ m \\ = a \exp\ L\ \ \ldots(3.1) \end{gathered}$$

where a is the average daily traffic (ADT) per side and L is a linear combination of the road characteristics being transformations of terms including:

- a constant term,
- gradient,
- curvature,
- out of context curve effect,
- skid-site classification,
- skid resistance,
- roughness
- $\log_{10}$
- (ADT),
- year,
- region,
- urban/rural classification.

The coefficients in the linear combination were the unknown parameters to be estimated. Since we are taking the exponential of L, a linear combination of the road characteristics, the actual model is multiplicative. The model assumes that the crashes are statistically independent and the number in each 10-metre segment follows a Poisson distribution.

The expected personal risk or crash rate (in terms of average injury crashes per year per 100 million vehicle kilometres of travel on the road) is given by:

$$\frac{10^{10}}{365} \exp\ L\ \ \ldots(3.2)$$

It should be noted that the average daily traffic (ADT) appears in the model in two places in equation 3.1 above, as α and as a $\log_{10}$ (ADT) component of L. These could have been combined into a single term in L. However, the component in L is present only if the crash risk (expected number of crashes per 100 million vehicle kilometres) depends on ADT (refer equation 3.2). When there is dependence, this dependence is modelled by the size of the coefficient of $\log_{10}$(ADT) in L.

The model fitting was done by maximum likelihood and used C++ libraries for matrix manipulation and automatic differentiation and a prototype array and statistical modelling package. The software is described on the Statistics Research Associates Ltd website www.robertnz.net.

3.3 Statistical Modelling - Results

The full statistical analysis and results are described in Dr Robert Davies report (Davies, 2011). As this project is primarily concerned with the effects of roughness, the following summary of the results of the analysis do not consider the effects of other variables included in the modelling. This summary considers the findings of the statistical modelling and analysis in terms of whether roughness is a significant predictor of crash risk, and which, if any, of the currently collected measures of roughness, is the most significant predictor variable.

The main findings of the statistical analysis relating to roughness are as follows:

(1) The results of the statistical analysis are very similar to those from the previous studies (Davies, 2009) with important predictors of crash rate including out-of-context-curve effect, curvature, ADT, skid resistance, and roughness.

(2) There is still quite a high unexplained variability in the data.

(3) The effect of roughness depends on curvature, the effect being strongest on curves with radii of curvature in the range 500 to 5000 metres.

(4) Considering the measures of profile variance, the 10m wavelength profile variance is a better predictor than either the 3m or 30m wavelength profile variances but is only slightly better than ordinary IRI.

(5) There is no strong evidence of a critical level of roughness above which crash risk increases significantly. Rather, crash risk continues to increase with increasing roughness.

(6) The skid resistance effect is stronger for crashes on wet roads rather than for all crashes and there is some evidence that it is stronger on curves than on straight or near straight roads.

(7) Repeating the analysis using only serious/fatal crashes produced results very similar to those for all casualty crashes.

(8) Including a year × region interaction has little influence on the results.

3.4 Statistical Modelling - Application

As part of the statistical analysis Dr Davies provided an illustration of the effects of reducing roughness on the number of crashes predicted by the crash model. This considered the effects of decreasing roughness on roads with absolute radius of curvature greater than 500m and less than 5000m. For this application three levels of roughness were chosen, i.e. IRI's of 2.00, 3.98 and 7.94. The effects of reducing the roughness of all lengths to the chosen value were assessed for the different levels of roughness and average daily traffic.

This illustration looked at the data for 2008, during which there were 1229 crashes related to 7348 10m long road segments in the curvature range 500m to 5000m. Table 1 shows the reduction in the predicted number of crashes for 2008 if the smoothing treatment had been done before 2008.

The first line of the table is for no smoothing treatment. The rest are for the values of maximum adjusted IRI value and ADT shown in the first two columns. It is supposed that the two sides of the road are handled independently and the column *fix length* shows the length of side that needs to be treated. The table shows, for example, that if the IRI for all road segments with an ADT of 1000 was reduced to a maximum of 2.0 mm/m, the number of crashes could be reduced by 126.

Alternatively, the Poisson regression model derived by Dr Davies can be expressed graphically in terms of the increase in crash rate as the roughness increases from a baseline roughness value of 1.6mm/m IRI. This is shown in Figure 1.

Table 1 Predicted Crash Reductions for Reduction in Roughness

Maximum Adjusted IRI (mm/km)	ADT≥	Fix Length (10m segments)	Predicted Crashes	Saved Crashes
-	0	0	1182	0
7.94	0	30	1180	2
3.98	0	815	1148	33
2.00	0	4212	1048	134
7.94	1000	20	1180	1
3.98	1000	602	1150	31
2.00	1000	3242	1055	126
7.94	5000	5	1181	1
3.98	5000	169	1163	19
2.00	5000	953	1106	76

Figure 1 Effect of Change in Roughness (IRI) on Crash Rate

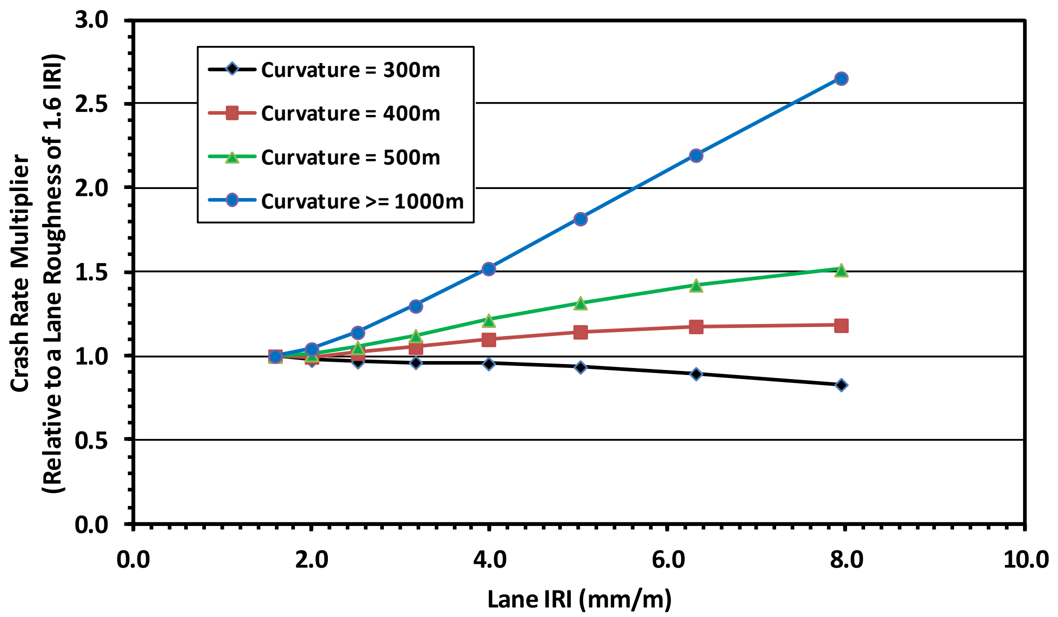


Figure 1 shows, for example, that for roads with a horizontal curvature of radius greater than or equal to 1000m, a 40% reduction in the IRI roughness from 5mm/m to 3mm/m will result in a reduction in the crash rate of about 28%. However, if the horizontal curvature is tightened to 400m, this 40% reduction in road surface roughness will result in a reduction in the crash rate of only 8%.

The key points to note in Figure 1 are as follows:

(1) There is no reduction in crash rate for reductions in IRI roughness below 2 IRI mm/m (which corresponds to a lane roughness of about 50 NAASRA counts/km).

(2) Roughness has an increasing detrimental impact on crash rate as horizontal curvature increases.

(3) For curves with horizontal curvature less than 400m i.e. tight curves, increasing roughness decreases crash rate. A possible explanation for this result is that previous research (Cenek et al, 2011) has shown that the speed vehicles are driven around tight curves is very much influenced by the lane roughness, the speed decreasing with increasing roughness.

4 Test Track Measurement Programme

This aim of this project was to examine the relationships between road safety and road roughness parameters routinely used for road asset management purposes. Accordingly, it was designed with two separate test measurement programmes, (1) a track test programme; and (2) an on-road test programme.

The objectives of the test track programme were to

(1) Establish whether localised roughness may be less safe than a uniformly rough road when it comes to cornering through tests performed on a test track under controlled conditions.

(2) Investigate if the output from skid testers, such as the GripTester, is affected by road surface roughness to the same degree as passenger cars by comparing friction measurements made with the skid tester at 0.4 m intervals to normal tyre forces measured on the skid tester's measuring wheel during cornering.

It was originally planned to carry out the test track measurement programme at Manfeild Autocourse. However, an alternative option was suggested, this being the Boomrock Test Facility located in the hills above Makara, near Wellington. The Boomrock track is a 900m long sealed testing facility that is currently used by Mercedes for some of its vehicle testing. This option was investigated and assessed to be suitable for the purposes of the testing required. It also made better logistical sense, being closer to Central Laboratories. Figure 2 shows an oblique aerial view of the facility.

Figure 2 Boomrock Test Track

4.1 Track Testing – Vehicle Instrumentation

Two vehicle/tester combinations were used for the track testing. The first of these was a Toyota Corolla hatchback, a car found on New Zealand roads in fairly large numbers. This was instrumented with four triaxial accelerometers, each one as close as possible to the wheels so that vertical wheel accelerations in particular could be accurately measured. A fifth triaxial accelerometer was also installed inside the rear luggage compartment so that the vehicle body accelerations could also be measured. The accelerometers were connected to a data acquisition system set up to record at a rate of 1200Hz. Figure 3 shows the test vehicle on the Boomrock track.

Figure 3 Toyota Corolla Test Vehicle

The second vehicle/tester was the Central Laboratories GripTester towed by a Mitsubishi L300 van. The GripTester is a small trailer based device originally designed for airport survey operations. Its mode of operation is the simultaneous measurement of drag force and load on a single treadless test tyre of 254 mm diameter (Go Kart size) inflated to 138 kPA (20psi), skidding at around 15% of the survey speed. The GripTester was instrumented to provide separate outputs of the drag, load and friction (drag/load) data. In addition, an accelerometer was fitted to the wheel mounting frame on the GripTester so that the vertical accelerations of the measuring wheel could be measured. The data outputs were connected to a data acquisition system set up to record at a rate of 100Hz. Figure 4 shows the GripTester and tow vehicle on the Boomrock track.

Figure 4 GripTester and tow vehicle at Boomrock Track

4.2 Track Testing – Measurement Programme

The sweeping corner at the southern end of the Boomrock track, seen at the bottom of Figure 2 was chosen for the testing. This is a corner of approximately 30m radius, with the entry and exit points being slightly higher than the apex of the corner. Initial testing was carried out on the corner with the track surface unaltered. Both the instrumented car and the GripTester were driven around the corner at steady speeds of either 30km/h or 50km/h to establish baseline data.

Roughness elements were then introduced by fastening combinations of timber strips to the track at selected locations. These timber strips were approximately 100mm wide, with 12mm and 24mm height options, and could be installed either as isolated elements, or as grids of up to five multiple elements. Three positions were chosen, these being (1) on the approach to the corner, (2) at the apex of the corner, and (3) on the exit to the corner. Figure 5 shows one of the single elements and one of the multiple grid element fastened to the track.

Figure 5 Views of single and multiple roughness elements

Both the car and the GripTester were driven and towed respectively around the corner for different combinations of roughness elements at speeds of either 30km/h or 50km/h. The test configurations included combinations of the following variables.

(1) baseline configuration - no added roughness elements (existing track roughness)

(2) roughness element position (approach, apex, exit)

(3) single elements
(4) multiple elements (3 elements at 1.2m spacing, 5 elements at 0.6m spacing)
(5) 12mm and 24mm heights
(6) 30km/h and 50km/h
(7) travel direction (clockwise and anti-clockwise)
(8) all wheels across roughness elements, or left or right wheels only across roughness elements (car only)

Data was recorded between fixed points on the track for each configuration, with a total test site length of 200m. The driver of the car, who was a trained NZ Police driver, was also asked to give his impressions of the relative ride quality and safety of each of the test configurations.

4.3 Data Processing

The data files were first trimmed to the test site length, and the accelerometer calibrations were applied to give measures of the accelerations in g's (1g = 9.81m/s^2). They were then processed to divide the site length of 200m into 20 approximately 10m sections, this being one of the standard lengths used for processing and presenting road geometry and condition data on the state highway network. The placements of the roughness elements, including the multiple arrays, were such that they fell within one of the 20m segments. For the GripTester data, standard deviation values of the drag, load, calculated friction (drag/load) and the vertical wheel mount acceleration were calculated for each of the 20m segments. Similarly, for the car data, standard deviation values for each of the horizontal, lateral and vertical components for each of the five accelerometers were calculated.

4.4 Driver Observations

The test driver was asked to provide his impressions during the testing. He was asked to consider the effects of the different test configurations on the natural line of the turning circle when cornering. The main observations from this were:

(1) deviations increased with speed – 50km/h is worse than 30km/h
(2) no difference between travelling clockwise or anticlockwise
(3) deviations increased with roughness element height – 24mm is worse than 12mm
(4) deviations were higher when all four wheel passed over the roughness elements, compared to only the left or right side wheels
(5) deviations were larger for the roughness elements located on the apex of the corner compared to either before or after the corner
(6) the largest deviations occurred at 50km/h for the 24mm high roughness elements located at the apex of the corner.

4.5 Results

The primary objectives of the track test programme were (1) to establish whether localised roughness may be less safe than a uniformly rough road when it comes to cornering through controlled off-road tests, and (2) to investigate if the output from skid testers, such as the GripTester, is affected by road surface roughness to the same degree as passenger cars.

Localised and Uniform Roughness

The driver of the car indicated that the array of roughness elements produced more deviation in the natural driving line than the single elements. Figure 6 shows a plot comparing the 20m standard deviation values for test runs at 50km/h over three single 24mm high roughness elements located before the corner, at the apex, and on the exit of the corner, and the array of three 24mm high elements located at the apex of the corner.

Figure 6 Comparison of Standard Deviation of Vertical Accelerations – Single and Multiple Elements

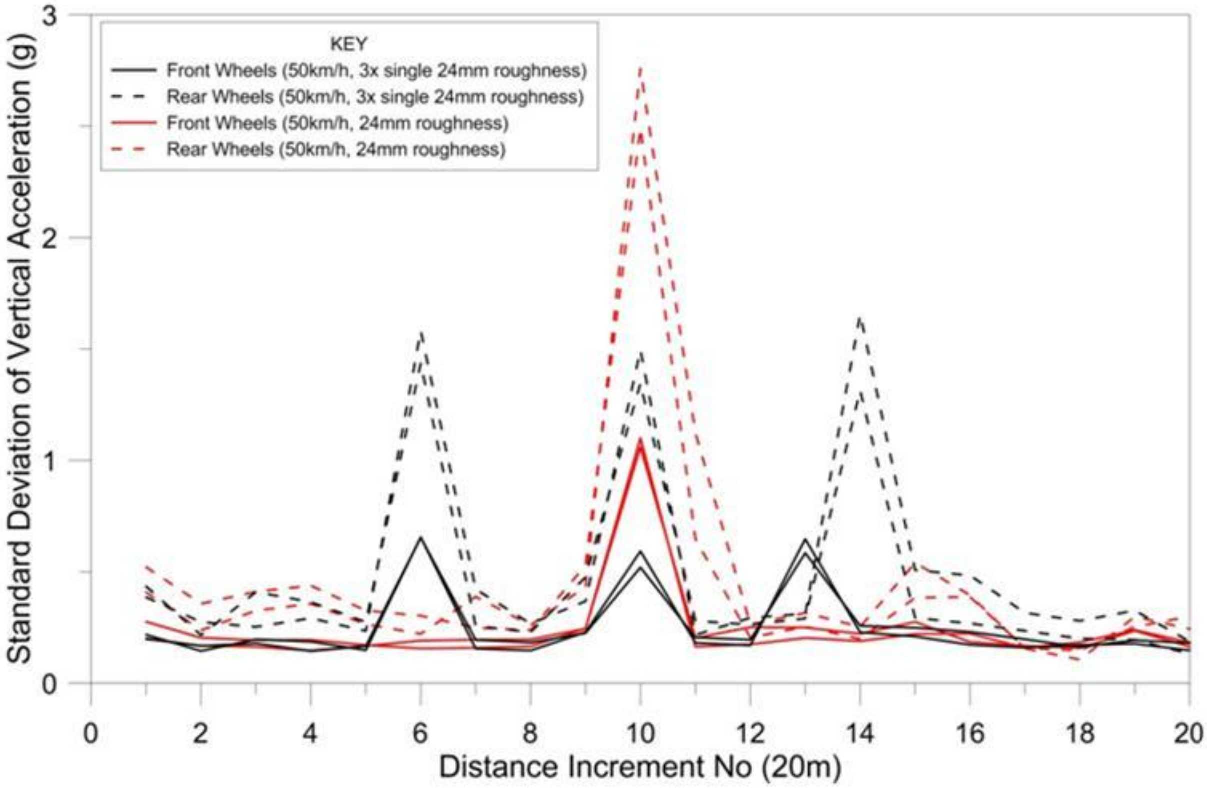
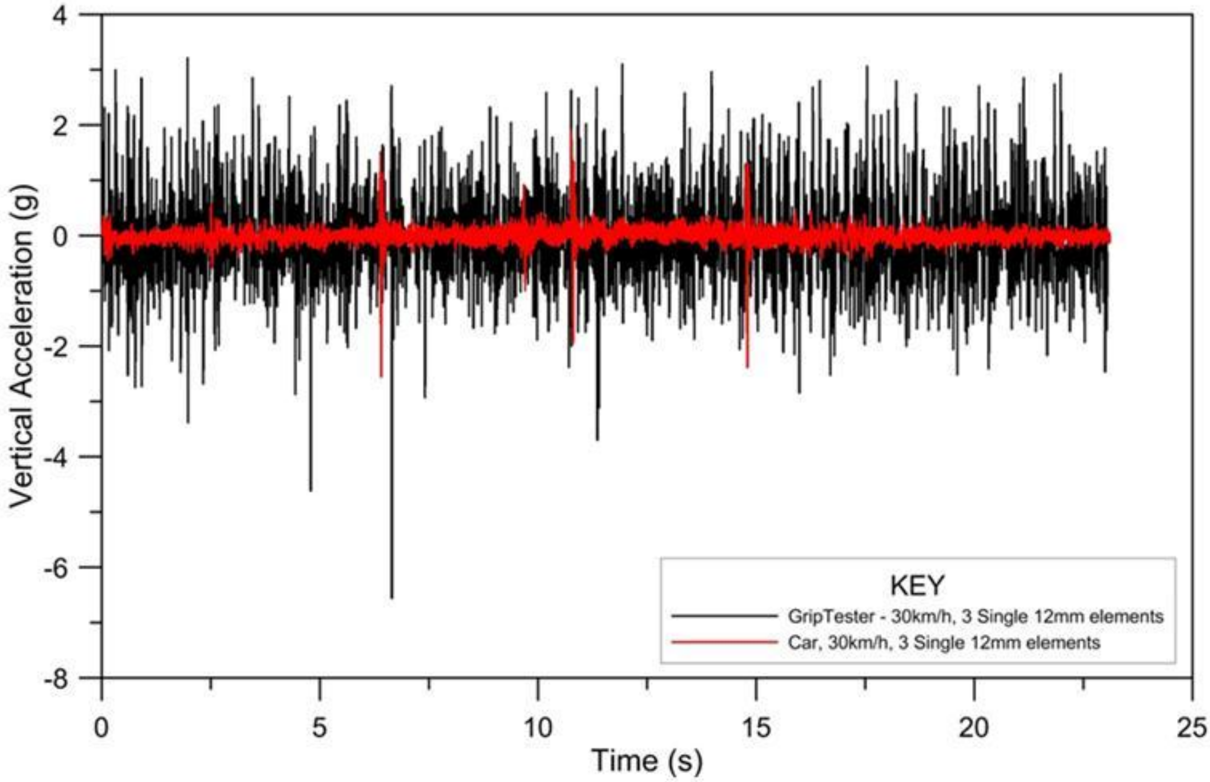


Figure 6 supports the driver's view that the multiple elements located on the apex of the corner produced a greater response than the single elements, either before on or after the corner, and are therefore potentially less safe.

GripTester Output and Roughness

The GripTester uses the simultaneous outputs of drag and load on the measuring wheel to provide a measure of the surface friction, called the Grip Number, by calculating the ratio of the drag to the load. On a perfectly smooth road, it would be expected that the load on the measuring wheel would be approximately constant, and that any variation in the friction value would arise primarily from changes in the drag values. However, on a rough road, both the drag and the load will vary as the GripTester measuring wheel and suspension respond to the roughness elements. The issue is whether the GripTester responds in the same way to significant surface roughness as a passenger car does. This was investigated initially by simply comparing the vertical acceleration of the GripTester wheel with one of the car wheels. Figure 7 compares the vertical acceleration of the two tyres passing over three single isolated roughness elements.

Figure 7 Vertical Accelerations - GripTester and Car Wheel 12mm roughness



This shows that while the GripTester's measuring wheel generally experiences greater accelerations over most of the 200m test site than the car wheel, the GripTester's measuring wheel does not appear to respond to the roughness elements to the same relative degree. Accordingly, it was decided to compare the car and GripTester accelerations for the configuration that the driver identified as causing the most concern about ride and potentially safety, i.e. the array of 3 spaced 24mm roughness elements located at the apex of the corner.

Figure 8 shows the vertical accelerations of the two wheels passing over these configurations. Here, the effects of the 24mm high roughness elements are more pronounced for the GripTester than they were for the 12mm elements. However, the peak acceleration levels are similar over the elements themselves for both the GripTester and the car. Figure 7 and Figure 8 indicate relative responses of the car and GripTester are different, with the GripTester having a higher response to low levels of roughness, but approximately the same at higher levels. This raised the question: What was the effect of roughness on the actual outputs (drag load and friction) of the GripTester?

Figure 9 shows the load, drag and friction outputs for an array of 3, 12mm high roughness elements on the apex of the corner. This shows that the GripTester outputs are affected, with the load output increasing as the wheel hits the roughness element, and the drag output reducing. The consequence can be seen in the friction output, which reduces significantly by around 0.6 Grip Number. This is perhaps consistent with the likely effects on the friction available to a car, as the load on its wheel also reduces with this type of roughness (i.e. hump rather than depression).

Figure 8 Vertical Accelerations - GripTester and Car Wheel 12mm roughness

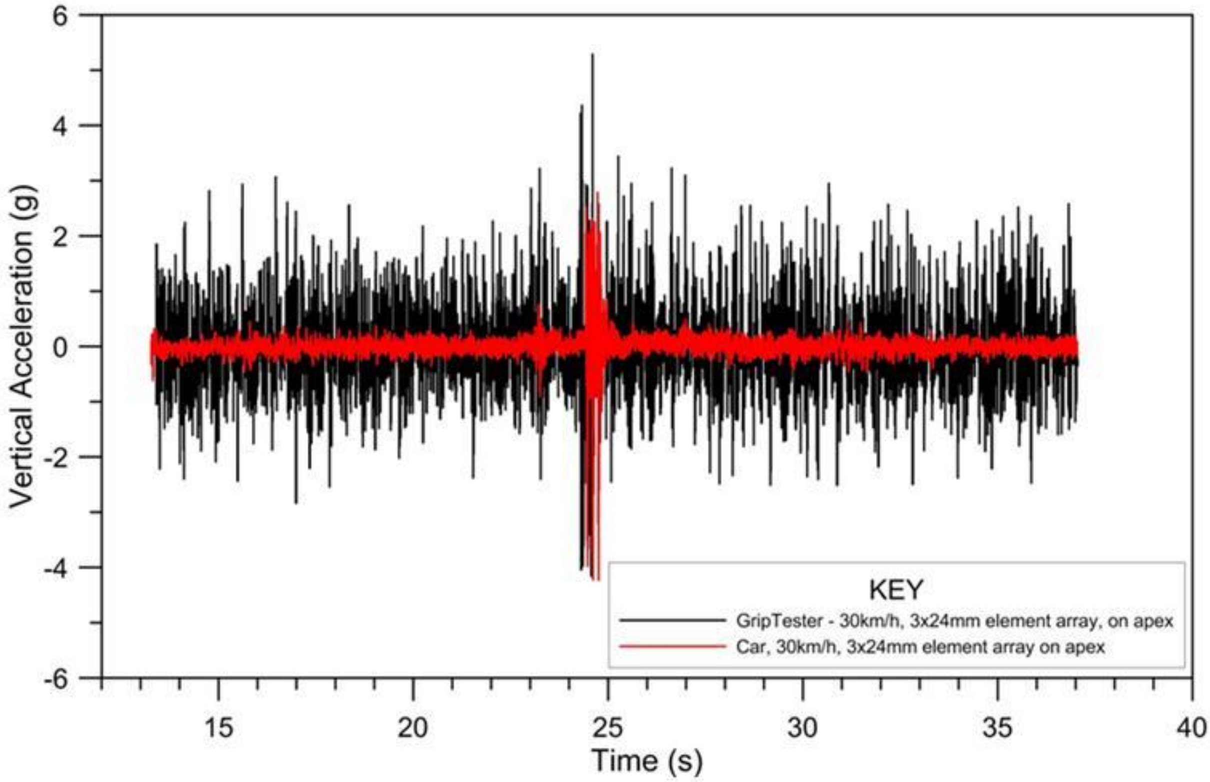
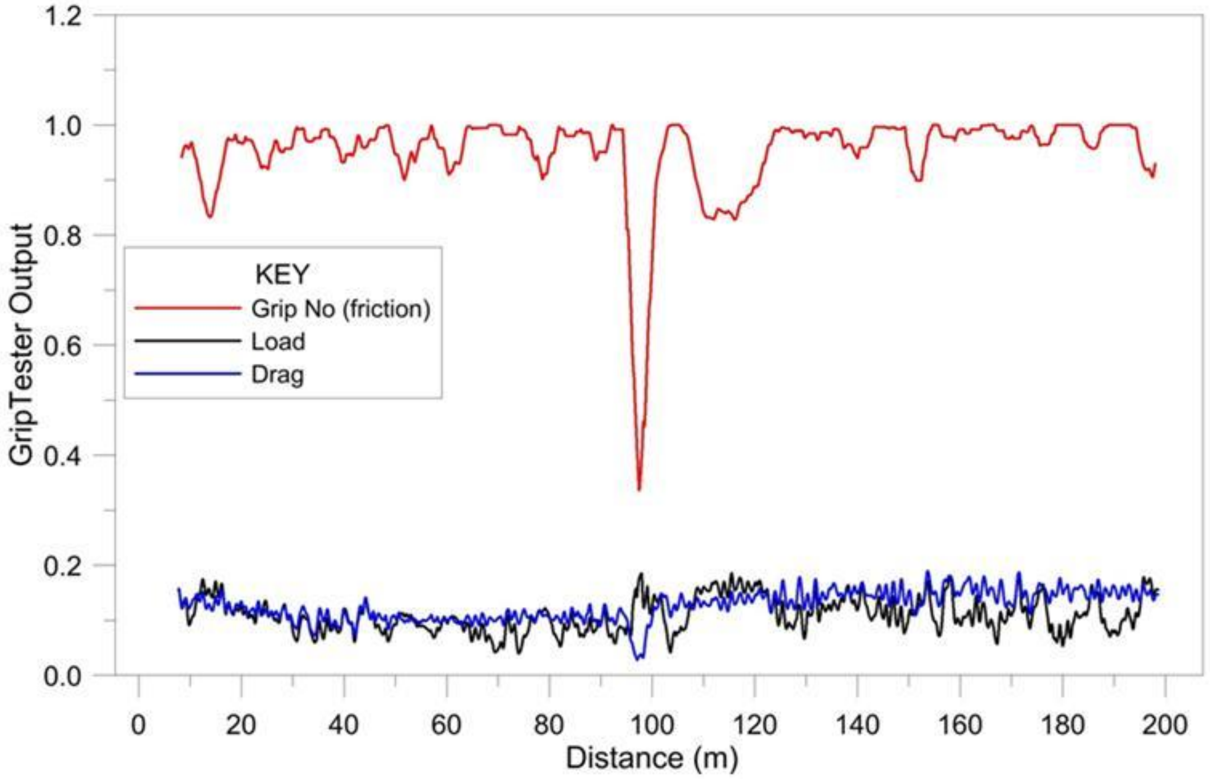


Figure 9 GripTester Outputs (friction, load and drag) – array of 3 24mm high roughness



5 On-road Test Measurement Programme

The objective of the on-road test programme was to quantify the effects of different wavelengths and magnitudes of road surface undulations on the braking distances of passenger cars and trucks through on-road trials.

5.1 On-road Testing – Vehicle Instrumentation

Two vehicles were chosen for the on-road test programme. These were (1) the same Toyota Corolla hatchback that was used for the track testing at the Boomrock facility and which is shown in Figure 3, and (2) a light truck. The truck selected for the testing is shown in Figure 10. Both of these vehicles were equipped with ABS (anti-lock braking system), which could be disabled by removing the appropriate fuses.

Figure 10 Test Vehicle 2 – Light Truck

For the on-road testing the vehicles were both instrumented with a Vericom VC2000 that was loaned by the NZ Police. This is an accelerometer based unit that attaches to the inside windscreen of the test vehicle, and is routinely used by the NZ Police in locked wheel braking tests to measure braking distances and coefficients of friction at crash sites. In braking mode the unit is triggered on a threshold deceleration of 0.25g. The unit records the ensuing braking manoeuvre at a rate of 100Hz. The car and truck were also instrumented with triaxial accelerometers in a similar manner to the track testing carried out at Boomrock. In addition, all four of the wheels on the car, and the front wheels on the truck were instrumented with strain gauged load cells to provide a measure of the wheel loads during the driving and braking tests. The outputs from the accelerometers and load cells were recorded using a data acquisition system at a rate of 1200Hz.

5.2 Site Selection

The site originally chosen for the on-road test programme was a section Mangaroa Valley Road, west of Upper Hutt. This road section was used by the SCRIM vehicle as one of its calibration/validation sites for the annual state highway condition survey, having been chosen for its wide range of roughness levels. However, with all of the vehicle instrumentation installed for the test programme, it was found out at the last minute that the site had recently been resealed, and that Upper Hutt City Council would not allow locked wheel braking tests to take place on it. An alternative site had to be found at short notice. The site chosen was an approximately 570m long northbound section of Parkes Line Road, which is similar to Mangaroa Valley Road in that it contains a range of roughness levels. The chosen section was straight and overall relatively flat. Figure 11 shows a view of a section of the Parkes Line Road site.

Figure 11 View of the Parkes Line Road Site (note the undulations)

For the purposes of the testing and the analysis of the results, the site was divided into 11 equal lengths, each approximately 50m long.

5.3 On-Road Test Programme

The on-road test programme comprised friction measurements made with the GripTester, and locked wheel braking test made with the instrumented car and instrumented truck. These measurements and the results of the tests are described below.

Skid Resistance – Griptester

Wet surface friction measurements were made in both the left and right wheelpaths with the GripTester, at a survey speed of 50km/h. As for the earlier testing at the Boomrock test track, these measurements comprised the simultaneous measurement of the drag, load, friction and vertical accelerometer outputs. The intention was to identify any changes in skid resistance along the site, so that the results of the locked wheel braking tests could be normalised with respect to the baseline skid resistance and any variations in the vehicle speeds. Figure 12 shows plots of the measured GripTester data. Table 2 lists the average Grip Number data for the eleven subsections of the site length.

Figure 12 Measured Skid Resistance Data - GripTester

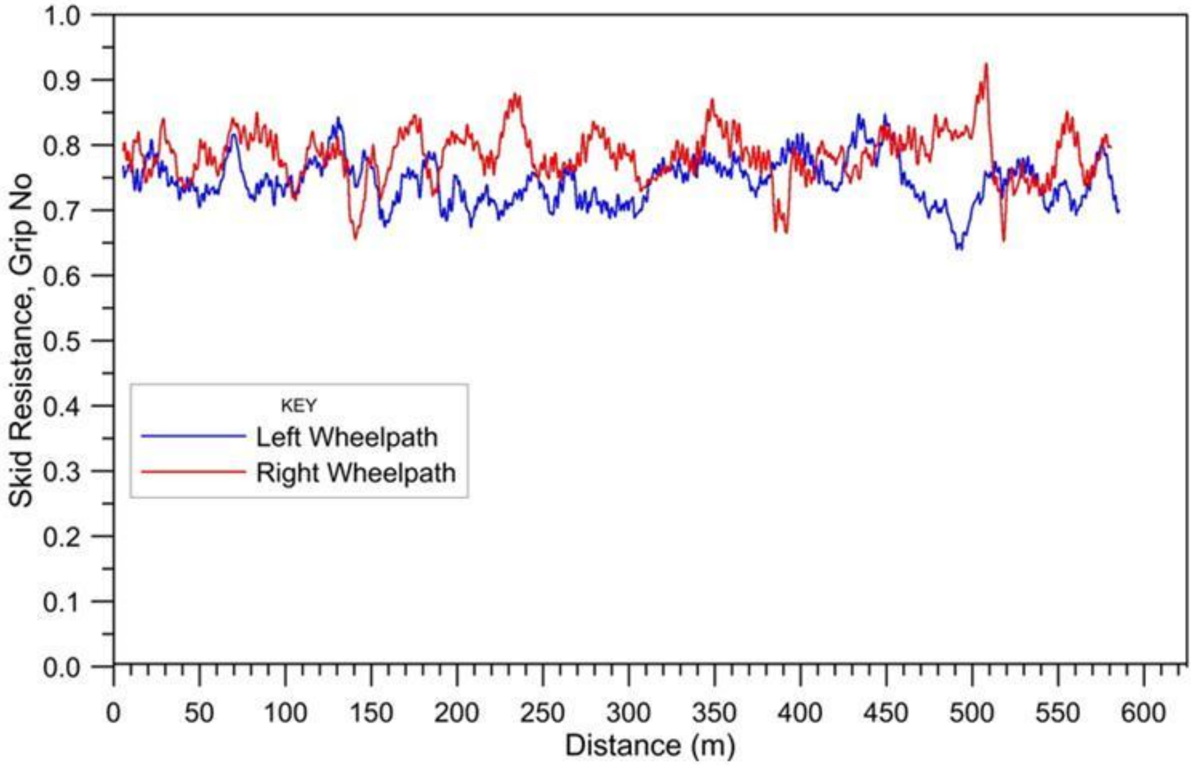


Table 2 GripTester Skid Resistance Data – 50m lengths

Section No. (from start)	Average Grip No. Left Wheelpath	Average Grip No. Right Wheelpath
1	0.77	0.74
2	0.79	0.74
3	0.75	0.76
4	0.79	0.73
5	0.79	0.72
6	0.78	0.74
7	0.80	0.76
8	0.75	0.77
9	0.79	0.76
10	0.80	0.72
11	0.77	0.73
Overall Site Average	**0.78±0.03**	**0.74±0.03**

The figure and table show that, while there is some variation of friction along the site length, the variations are relatively small. However, there does appear to be a slight difference between the left and right wheelpaths.

Driveover Tests

To establish the response of the car and the truck to the roughness content of the site, both vehicles were driven over the site at steady speeds, and data recorded. For the car these speeds were 50km/h, 70km/h and 100km/h. For the truck the speeds were 50km/h, 70km/h and 90km/h. To compare how the responses to the site roughness varied along the site and assess how this varied with speed, the vertical acceleration data from the left front wheels of both vehicles were plotted, and these are shown in Figure 13 and Figure 14 for the car and truck respectively. These have been plotted with the same scales to illustrate the differences between the vehicle responses.

These two figures show that the car and truck respond differently to the roughness content of the site. The car response is much lower than that of the truck, but appears to have significant lower frequency components. The truck response is much higher than the car, and this is assumed to be due to its stiffer tyres and suspension.

The other reason for the driveover tests was so that the test site and the 11 subsections could be characterised in terms of their roughness and this could then be related to the braking distances. Accordingly, the vertical acceleration data for the driveover tests was split into the 11 subsections and analysed for maximum, minimum and root-mean-square (RMS) values. These are listed in Table 3.

Figure 13 Vertical Wheel Acceleration for Steady Speed Driveover - Car

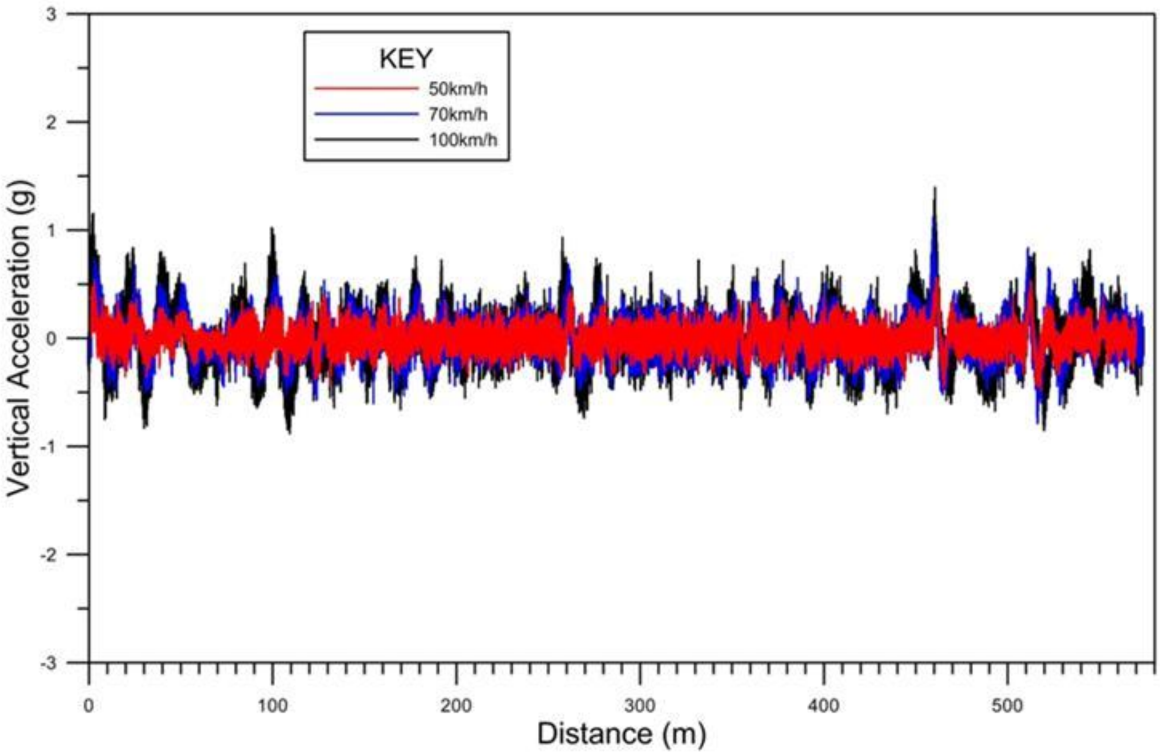


Figure 14 Vertical Wheel Acceleration for Steady Speed Driveover - Truck

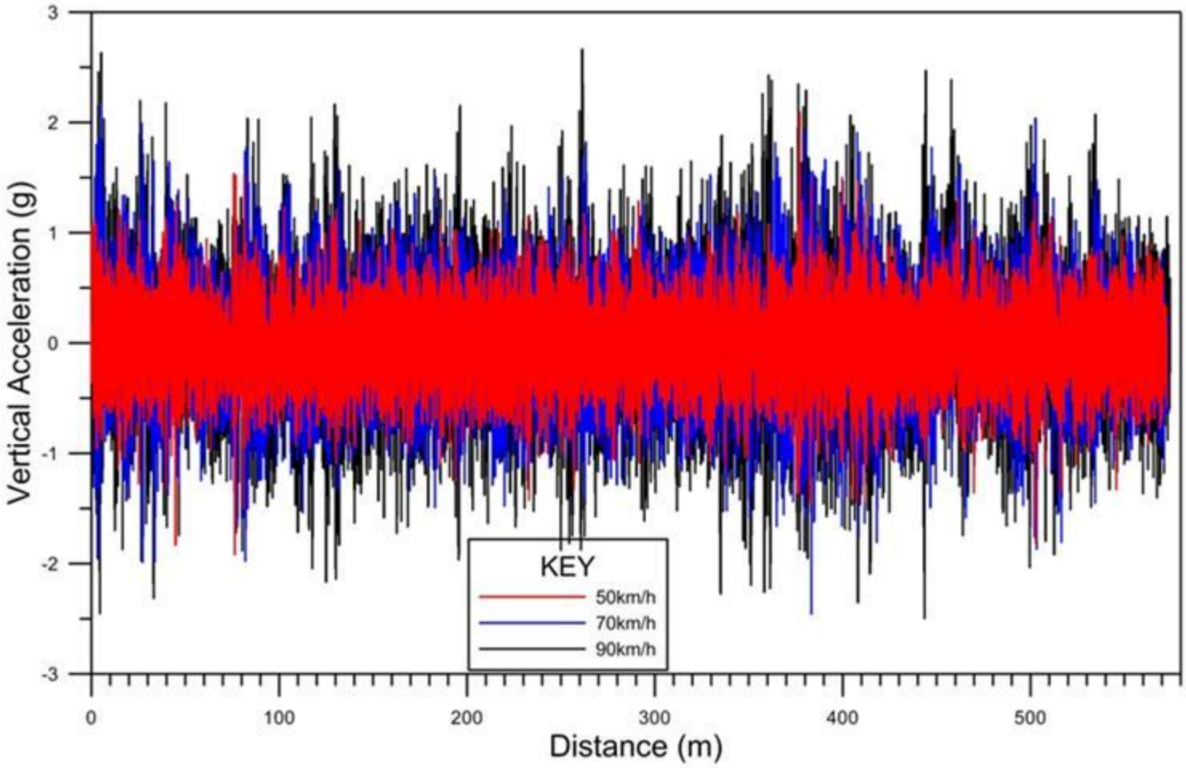


Table 3 Vertical Accelerations – 50m lengths

Vehicle	Section No. (from start)	50km/h			70km/h			100km/h - Car 90km/h - Truck		
		Max (g)	Min (g)	RMS (g)	Max (g)	Min (g)	RMS (g)	Max (g)	Min (g)	RMS (g)
Car	1	0.54	-0.36	0.12	0.74	-0.55	0.24	1.16	-0.83	0.36
	2	0.37	-0.38	0.10	0.51	-0.42	0.18	1.02	-0.64	0.29
	3	0.41	-0.44	0.12	0.58	-0.52	0.19	0.62	-0.88	0.25
	4	0.37	-0.36	0.10	0.54	-0.57	0.17	0.76	-0.66	0.24
	5	0.35	-0.36	0.09	0.52	-0.60	0.16	0.93	-0.51	0.21
	6	0.44	-0.34	0.11	0.44	-0.52	0.13	0.74	-0.74	0.24
	7	0.35	-0.34	0.11	0.46	-0.42	0.13	0.72	-0.66	0.19
	8	0.39	-0.36	0.11	0.68	-0.48	0.18	0.72	-0.65	0.24
	9	0.57	-0.46	0.14	0.45	-0.42	0.13	1.40	-0.70	0.34
	10	0.52	-0.44	0.13	0.54	-0.48	0.16	0.79	-0.85	0.27
	11	0.39	-0.48	0.11	0.58	-0.58	0.17	0.82	-0.65	0.22
Truck	1	1.29	-1.83	0.39	2.17	-1.99	0.58	2.63	-2.45	0.72
	2	1.54	-1.92	0.37	1.78	-1.98	0.48	2.04	-1.88	0.54
	3	1.21	-1.09	0.30	1.59	-1.54	0.42	2.16	-2.17	0.63
	4	1.12	-1.24	0.32	1.50	-1.49	0.42	2.15	-1.97	0.59
	5	1.14	-1.42	0.34	1.49	-1.48	0.43	2.10	-1.88	0.58
	6	1.29	-1.09	0.31	1.82	-1.40	0.44	2.66	-1.75	0.58
	7	1.18	-1.11	0.33	1.82	-1.66	0.48	2.43	-2.28	0.72
	8	2.09	-1.47	0.42	1.93	-2.46	0.62	2.35	-2.35	0.72
	9	1.31	-1.08	0.33	1.77	-1.81	0.48	2.47	-2.50	0.61
	10	1.31	-1.81	0.37	2.04	-1.87	0.48	1.97	-2.04	0.58
	11	0.97	-1.33	0.30	1.48	-1.45	0.39	2.07	-1.49	0.49

Figure 15 and Figure 16 graphically compare the RMS vertical acceleration values on the test segments for the car and truck respectively. These figures and Table 3 show that there is considerable variation in the maximum, minimum and RMS acceleration values over the different segments of the test site. As expected there was generally an increase in the RMS values with speed. However, there were some differences on individual segments, e.g. segment 9 for the car and segment 3 for the truck, indicating that the vehicles respond differently to the roughness content within the site, and also with speed.

Figure 15 Segment RMS Vertical Acceleration Levels - Car

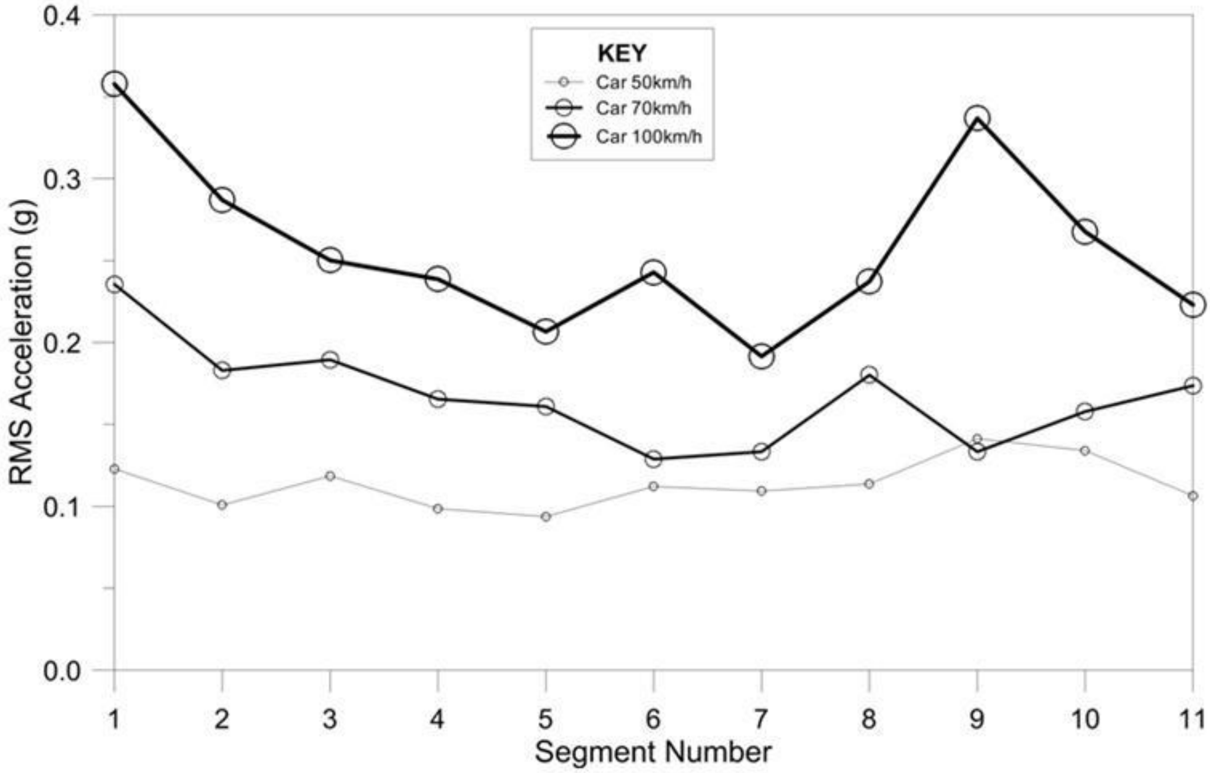
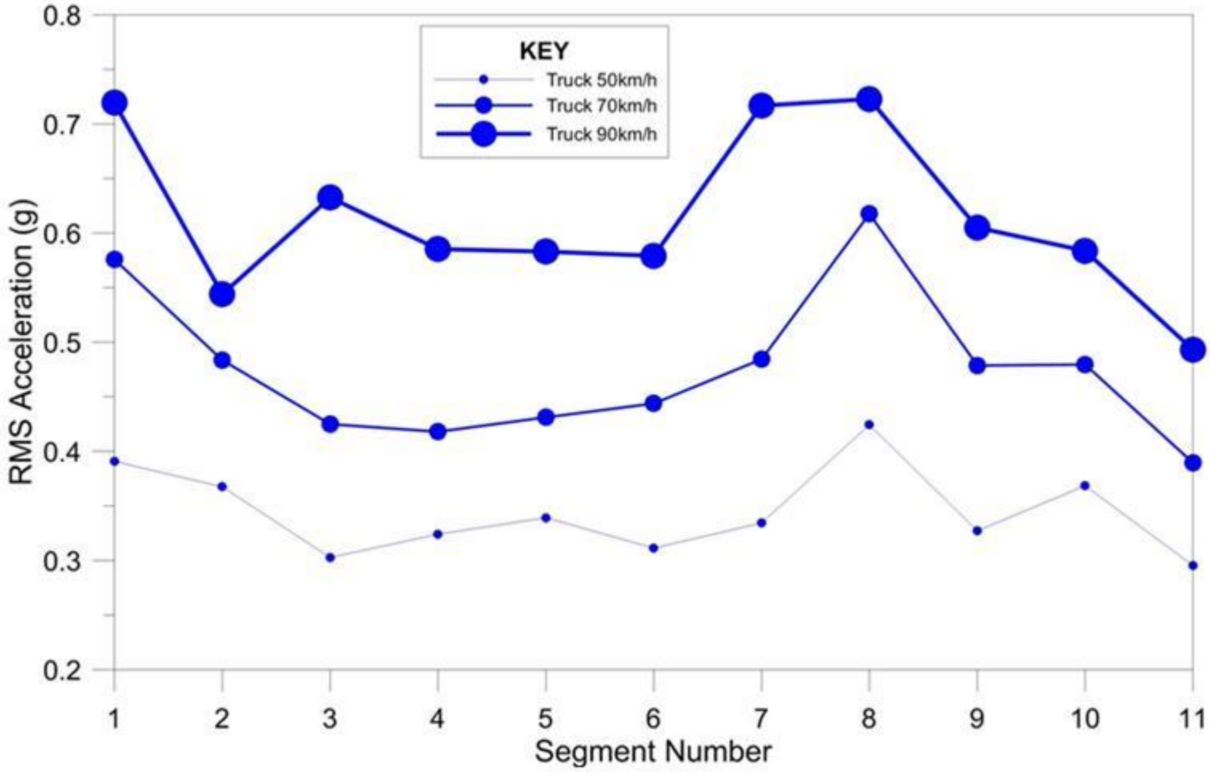


Figure 16 Segment RMS Vertical Acceleration Levels - Truck



Locked Wheel Braking Tests

Locked wheel braking tests were carried out on the test site using both the instrumented car and truck at speeds between 30km/h and 50km/h. Speeds were limited to these initiation speeds for safety reasons. The braking tests were initiated at random locations throughout the site, and the location of the braking points recorded so that the braking tests could be related to the segment roughness content. The elapsed time, braking initiation speed, braking distance and average coefficient of friction data were also recorded for each test. Most of the testing was carried out with the ABS (Anti-lock Braking System) in the default ON configuration. However, a limited number of test runs were carried out with the ABS turned off by removing the appropriate fuses.

As the braking initiation speeds typically varied from the target speeds by up to 4-5km/h, the braking distance data was then normalised to a common speed and common average coefficient of friction. This was to allow comparison of the data measured on the different test segments. Figure 17 and Figure 18 compare the normalised braking distances with the RMS vertical acceleration data for the car and truck respectively.

Figure 17 Normalised Braking Distance and RMS Vertical Acceleration Levels - Car

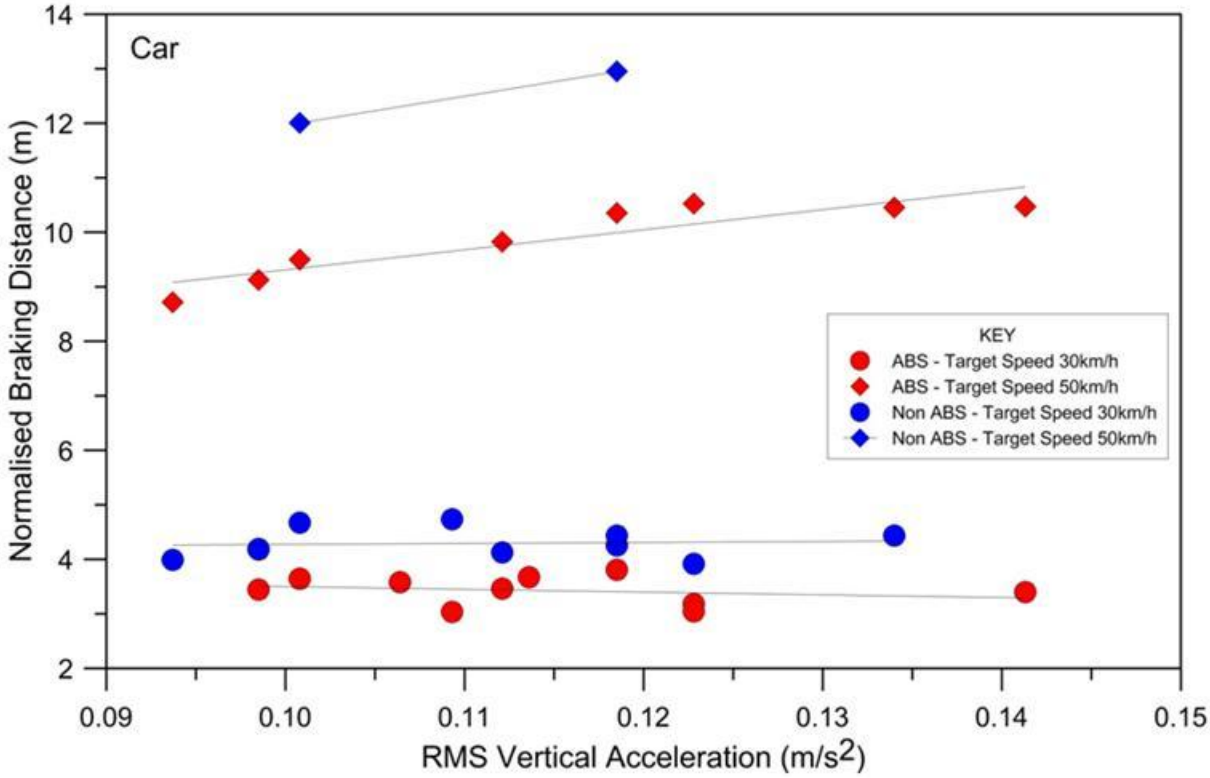
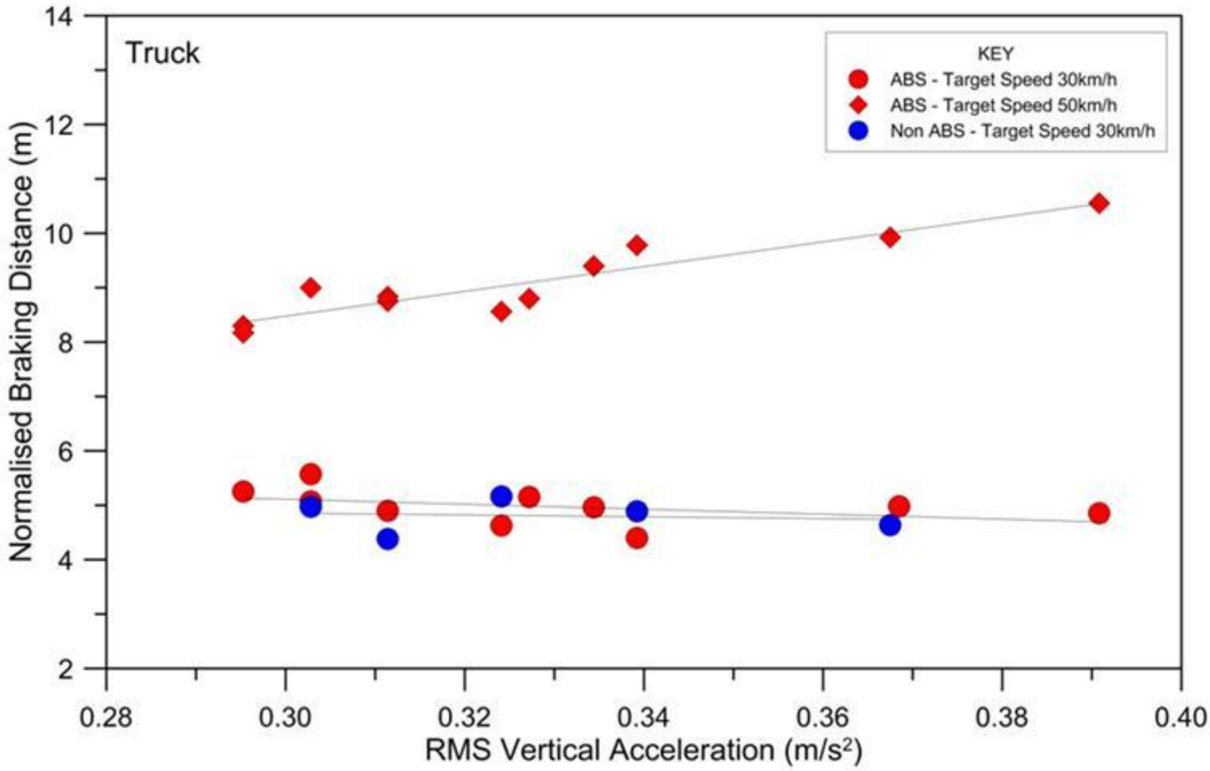


Figure 18 Normalised Braking Distance and RMS Vertical Acceleration Levels - Truck



These figures show that at the lowest braking initiation speed of 30km/h there was effectively little difference in the normalised braking distance for both the car and the truck across the different roughness content of the site segments as typified by the RMS vertical accelerations. In contrast, for the higher braking initiation speeds of around 50km/h both the car and the truck showed an increase in braking distance with increasing RMS vertical acceleration.

Site Wavelength Content

Figure 17 and Figure 18 identified an increase in the braking distance with increasing roughness for the higher range of test speeds. This would appear to be consistent with rougher road sections causing the load to decrease on one or more of the wheels, thereby reducing the friction available for emergency braking manoeuvres. One of the questions raised before this study commenced was, if roughness has an effect on braking distances, could this be attributed to a specific roughness type or wavelength. The earlier statistical analysis of the crash database suggested that roughness was a contributing parameter in the crash statistics and, of the wavelength measures of roughness currently available in the RAMM database, the 10m wavelength profile variance was slightly better than either the 3m or 30m wavelength profile variance or the standard IRI statistic. Accordingly, it was considered appropriate to analyse the data from the steady speed driveover tests to determine whether particular wavelengths were more dominant.

Figure 19 and Figure 20 present power spectral density plots of the vertical wheel acceleration and the corresponding wheel loads for the car and the truck respectively for a constant speed of 50km/h. These show the relative contributions of the different wavelengths to the vertical acceleration and wheel load signals.

Figure 19 Power Spectral Density – Car at 50km/h

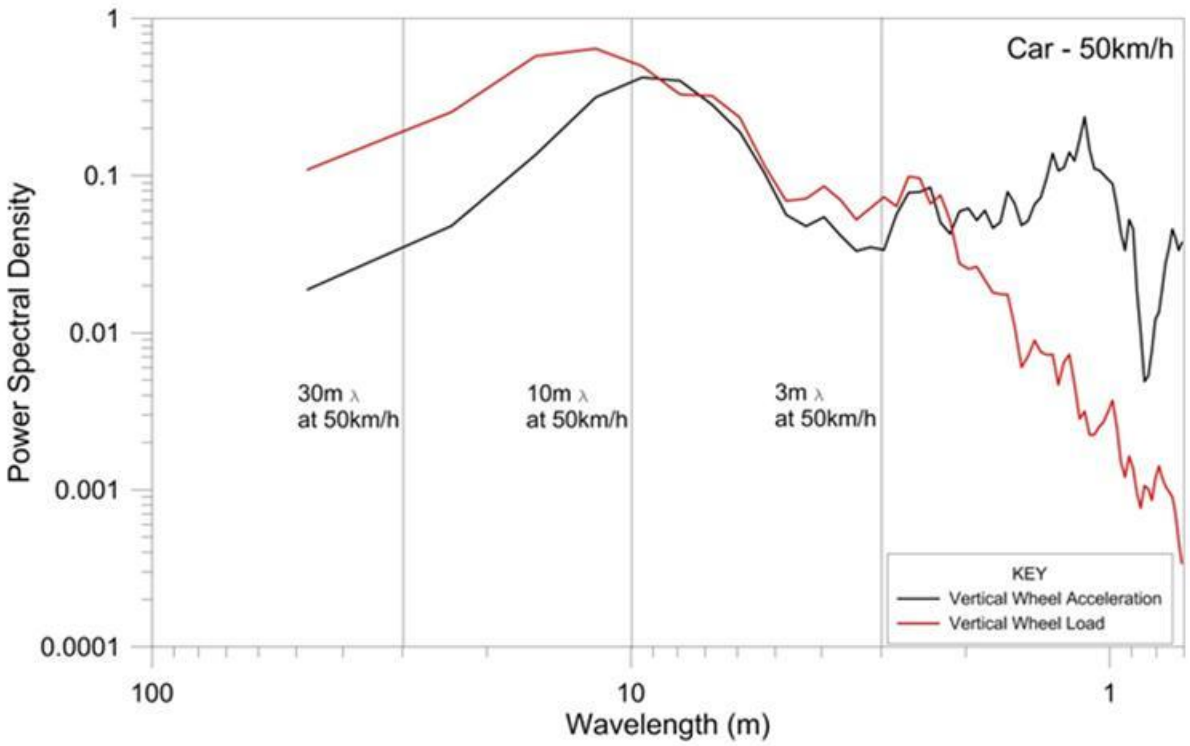
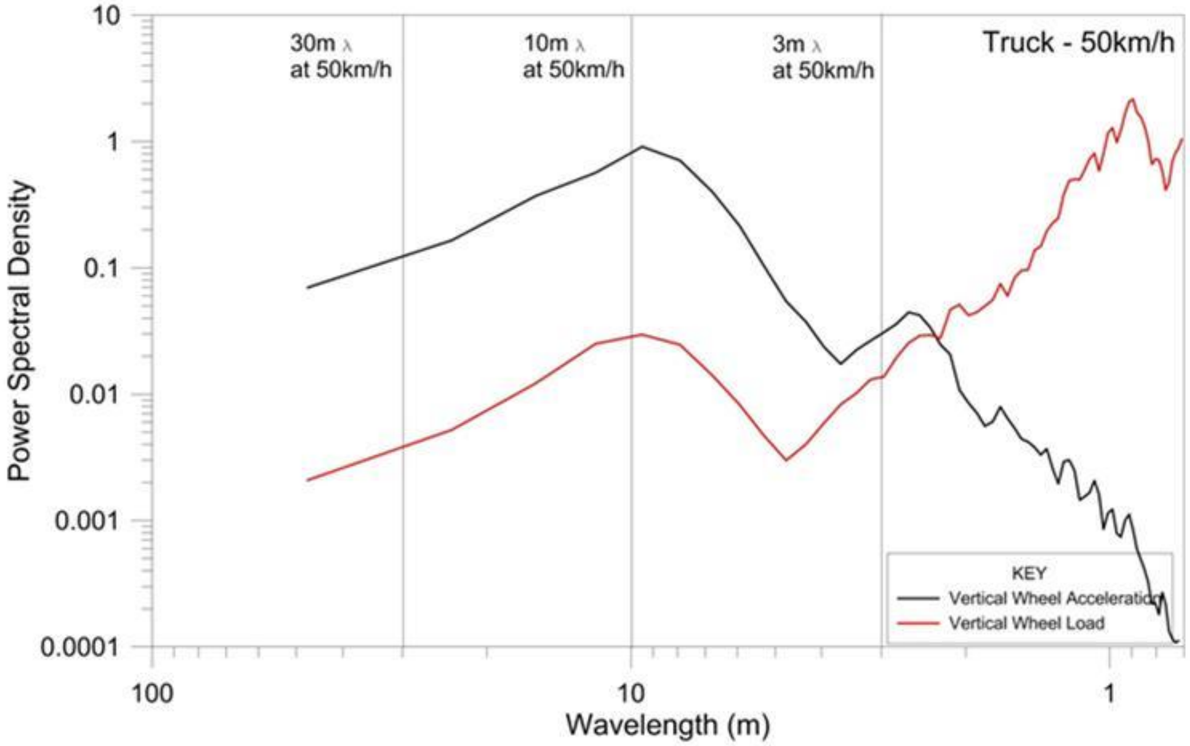


Figure 20 Power Spectral Density – Truck at 50km/h



These figures show that for the longer wavelengths (greater than 3m) there are consistent peaks at around 10m wavelength in both the vertical wheel accelerations and the wheel loads for both the car and truck. The appearance of this peak in the wheel load power spectra suggests that this wavelength is more strongly transferred through the suspension to the body of the vehicle than the shorter 3m wavelength or longer 30m wavelength. This is consistent with the findings of the earlier statistical analysis.

Variation in Wheel Load

Having established that the 10m wavelength was more dominant in the vertical wheel acceleration and vertical wheel load data than either the 3m or 30m wavelengths it was considered useful to investigate the variation in the wheel load relative to the stationary load, with respect to the magnitude of the variations, the time over which these could occur and what the variation was with vehicle speed.

Figure 21 and Figure 22 show the variation in one of the vertical wheel loads for the car and the truck for speeds of 50km/h and 100km/h. These have been plotted against distance to assess the effects of the roughness at the same locations throughout the site. Additional axes have been added to show the time for the different speeds.

Figure 21 Variation in Wheel Load - Car

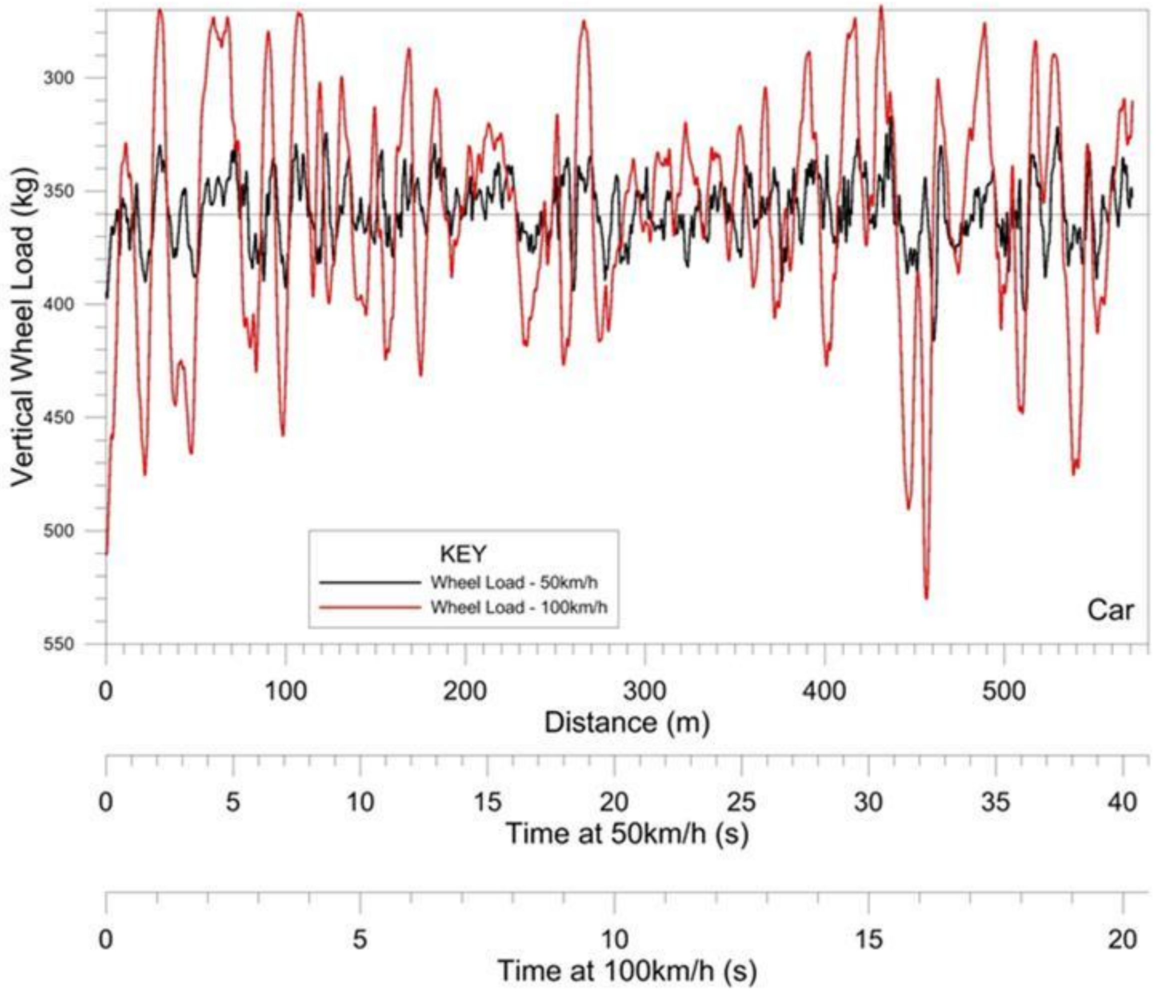
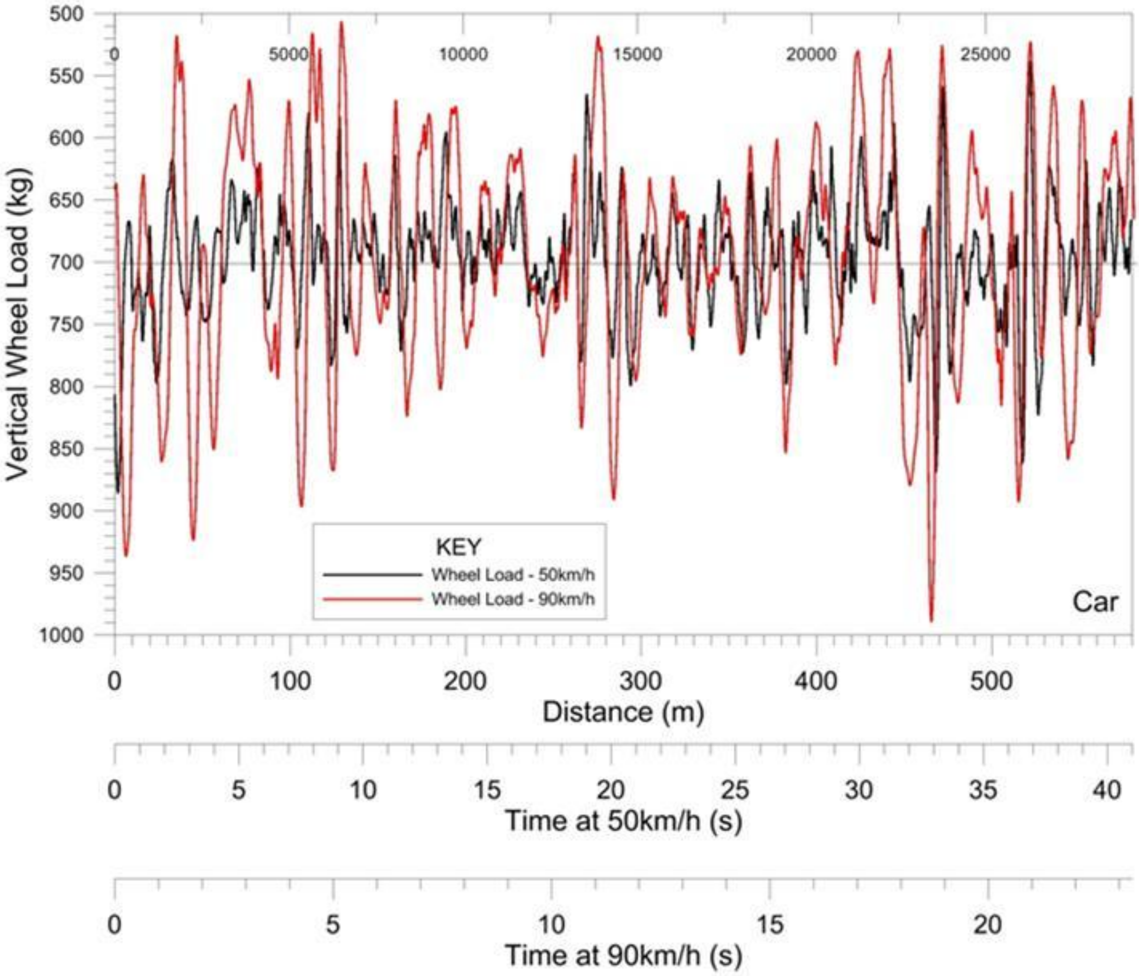


Figure 22 Variation in Wheel Load - Truck



From these figures, we can make the following observations regarding the variation in wheel load:

(1) At 50km/h the wheel load for the car varied between around 325kg (reduced load) to around 420kg (increased load), from the base load of 360kg. This equates to a variation of around -10% to +17%.

(2) At 100km/h the wheel load for the car varied between around 270kg (reduced load) to around 530kg (increased load), from the base load of 360kg. This equates to a variation of around -25% to +45%.

(3) For the car the ratio of the RMS wheel load to the mean wheel load went from around 5% at 50km/h to around 25% at 100km/h.

(4) At 50km/h the wheel load for the truck varied between around 530kg (reduced load) to around 880kg (increased load), from the base load of 700kg. This equates to a variation of around -25% to +13%.

(5) At 90km/h the wheel load for the truck varied between around 500kg (reduced load) to around 990kg (increased load), from the base load of 700kg. This equates to a variation of around -29% to +41%.

(6) For the truck the ratio of the RMS wheel load to the mean wheel load went from around 6% at 50km/h to around 13% at 90km/h.

(7) The wheel load for both vehicles is reduced for significant amounts of time over the length of the site, this being up to 2 seconds at a time, but mostly around 1 second. With the average time for the braking tests at 50km/h being around 1.5 seconds, this suggests that the wheel load can be significantly reduced during most if not all of the braking period. At 90-100km/h the wheel load is also reduced for significant amounts of time over the length of the site, this being up to 2 seconds at a time, but mostly around 1 second. These times are expected to be at the lower end as the effects of pitching present during braking manoeuvres were absent in the constant speed runs.

The above results indicate that there is an effect on braking distance, and thereby safety, due to road roughness. This effect is related to the time and magnitude of the reduction in wheel loads, most notably for wavelengths of around 10m. The question is: How can we identify sections of the New Zealand state highway network that may be considered “at-risk” due to roughness effects?

One option would be to instrument a vehicle and survey the entire network. This would be relatively expensive. Other options could be (1) use the 10m profile variance currently listed in the RAMM database, or (2) use computer models to “drive” over the measured road profiles. The use of such a computer model is described in the work of Barbosa (2011), who used a “quarter-car” model to investigate the load variation on an unpaved road. He found that on this unpaved road, there was a significant loss of contact pressure beginning from around 25km/h. There are also alternative computer models, such as PC Crash and HVE, which could potentially replicate this work, with the added benefit that they are full vehicle models that may also be able to investigate the effects of changes in superelevation on wheel loading.

6 Road Smoothing as a Cost Effective Safety Intervention

A benefit-cost analysis (BCA) according to the procedures detailed in the EEM (NZTA, 2010) and utilising the relationship between road roughness and crash rate (personal risk) given in Figure 1 was undertaken to determine the crash densities required for smoothing treatments to become a cost-effective safety intervention. However, prior to presenting the results of this BCA, the role of roughness in pavement maintenance management is first considered to provide the necessary background to the calculations performed.

6.1 Roughness as a Performance Indicator

Road roughness is a function of structural deformation and surface irregularities. Because it is a measure of both how road users perceive a road and the remaining useful life of the pavement, roughness is a key driver of the pavement management process.

For the New Zealand state highway network, the roughness policy is to provide a comfortable riding surface appropriate to the traffic volume and class of highway. Road roughness is measured by recording irregularities in the road surface along the length of each 100m section of road and is reported in either NAASRA or International Roughness Index - quarter car (IRI_{qc}) roughness units where from Prem (1989):

$$NAASRA\ \ counts\ \ km\ = -1.27 + 26.49\ lane\ IRI_{qc}\ (m\ \ km)\ \dots(6.1)$$

Roughness performance is measured by the proportion of the state highway system which exceeds the upper threshold levels of roughness given in Table 4. The performance target for road roughness are for not more than 1% of the roughness counts to exceed the upper threshold values tabulated in Table 4 by (i) length and (ii) vehicle kilometres (NZTA, 2009).

Table 4 NZTA Upper Threshold Roughness Levels

National State Highway Strategy (NSHS) Hierarchy Classification		Lane Roughness	
Classification	**Description**	**NAASRA (counts/km)**	**IRI_{qc} (m/km)**
Motorway	Motorway & Expressway	100	3.82
R1	Rural (>10,000 AADT)	110	4.20
R2	Rural (4,000 – 10,000 AADT)	120	4.58
R3	Rural (1,000 – 4,000 AADT)	130	4.96
R4	Rural (< 1,000 AADT)	150	5.71
Urban	Urban (≤ 70 km/h)	150	5.71

6.2 Time-Profile of Pavement Roughness and Maintenance

From Paterson (1987), the typical roughness progression of a pavement involves the following phases.

During the early phase of a pavement's life, prior to the occurrence of surface distress, there is only a slight increase in roughness. There are no related costs except the small annual routine maintenance cost and there are only slight changes in the average vehicle operating cost due to the small increase in roughness.

Following the initiation of surfacing distress, the roughness and the associated vehicle operating costs increase more rapidly. Patching maintenance reduces the roughness and vehicle operating costs slightly, but not back to the levels that would be applied in the absence of surfacing distress because the patching itself is a defect, deviating in profile from the perfect planar surface.

A thin resurfacing or reseal has the immediate effects of reducing the area of surfacing distress to nil, and reducing the roughness by an amount dependent on the thickness and technique applied. A surface treatment reseal causes only a minor or negligible reduction in roughness (except when preliminary shape correction by spot patching has been carried out). A thin overlay causes an appreciably greater reduction in roughness, primarily in the short wavelength band. Neither of these thin resurfacing options adds appreciably to the stiffness of the pavement and so their impacts on future performance are the benefits derived primarily from the repair and control of surfacing distress, and the initial rate of deterioration is likely to be similar to, or slightly less than that for the equivalent maintenance-free pavement.

Rehabilitation works such as a thick overlay (whether asphaltic or granular with bituminous surfacing) have the immediate effects of reducing the roughness to approximately the level of new pavements and the surfacing distress to nil, and the future effect of reducing the rate of deterioration through strengthening the pavement.

6.3 Road Smoothing Treatments

Treatments utilised on New Zealand's state highway network that result in a significant reduction in road roughness all relate to pavement rehabilitation, which is a major surfacing action for the purpose of returning the structural condition of the pavement to its as-constructed or design condition, or to exceed the as-constructed condition. These treatments comprise:

(1) In-situ stabilisation using lime, cement or foam bitumen. This involves the treatment of a road pavement or subgrade material by the introduction of a binder to improve it or to correct a known deficiency and thereby enhance its ability to perform its function in the pavement.

(2) Overlay, which is the addition of one or more courses of pavement material to an existing road surface, generally to increase strength/stiffness and/or improve riding quality.

(3) Rip and remake, which is the removal of existing surfacing materials, followed by placement and compaction of unbound basecourse to an acceptable shape, and sealing.

The cost of these treatments typically range between NZ$20 per m^2 and NZ$30 per m^2 (Hudson, 2012).

The reduction in roughness following application of these rehabilitation treatments can be estimated using the following relationship (TNZ, 2006):

$$A = 0.36B + 25 \ldots (6.2)$$

where: A = predicted "after" lane NAASRA roughness (counts/km)
B = the measured "before" lane NAASRA roughness (counts/km)

6.4 Benefit-Cost Analysis

The only roughness related costs presently accounted for in the EEM pertain to vehicle operating costs (VOC) and vehicle occupants' willingness to pay (WTP) to avoid rough road conditions. The WTP values reflect the preference of road users for driving on smooth roads. The combined VOC and WTP costs due to roughness are provided in Table A5.15 of the EEM for the standard traffic composition applying to the three road categories urban, rural strategic, rural other.

The NZ Transport Agency considers any 20m length of state highway with a lane roughness of 150 NAASRA counts/km (5.71 IRI_{qc}) as unacceptable and requires fixing immediately if practical (NZTA, 2009). Using 2009 data, 2.2% of New Zealand's sealed state highways exceed this 20m lane-roughness threshold, equating to some 505 lane-kms.

The procedures in the EEM were employed to determine the annual average daily traffic (AADT) required on a two lane (single carriageway) state highway (i.e. "rural other" road category) to generate sufficient VOC and WTP benefits to result in a benefit-cost-ratio (BCR) of 4 from the rehabilitation of a 20m section of carriageway. The BCR of 4 was selected because this value has traditionally been used as the target for small construction projects.

To simplify the BCA, the analysis period has been confined to the first eight years of the rehabilitated pavement's life, where changes in roughness are expected to be minimal as are pavement maintenance costs and vehicle operating costs. The analysis period of 8 years has been selected to coincide with the average seal life on NZ state highways. Therefore, benefits arising from smoothing the road occur continuously over this eight year period and so need to be discounted back to time zero using the uniform series present worth factor (USPWF) to calculate their present value (PV). Based on the discount rate of 8 percent specified in the EEM, the USPWF for a time period of 8 years is 5.9736 (refer Table A1.1 of EEM (NZTA, 2010)).

Considering the cost side of the BCA, the typical sealed carriageway width for rural state highways is 8.5m. Therefore the lower and upper cost of the rehabilitation works is $3,400 (i.e. 20x8.5x$20) and $5,100 (i.e. 20x8.5x$30).

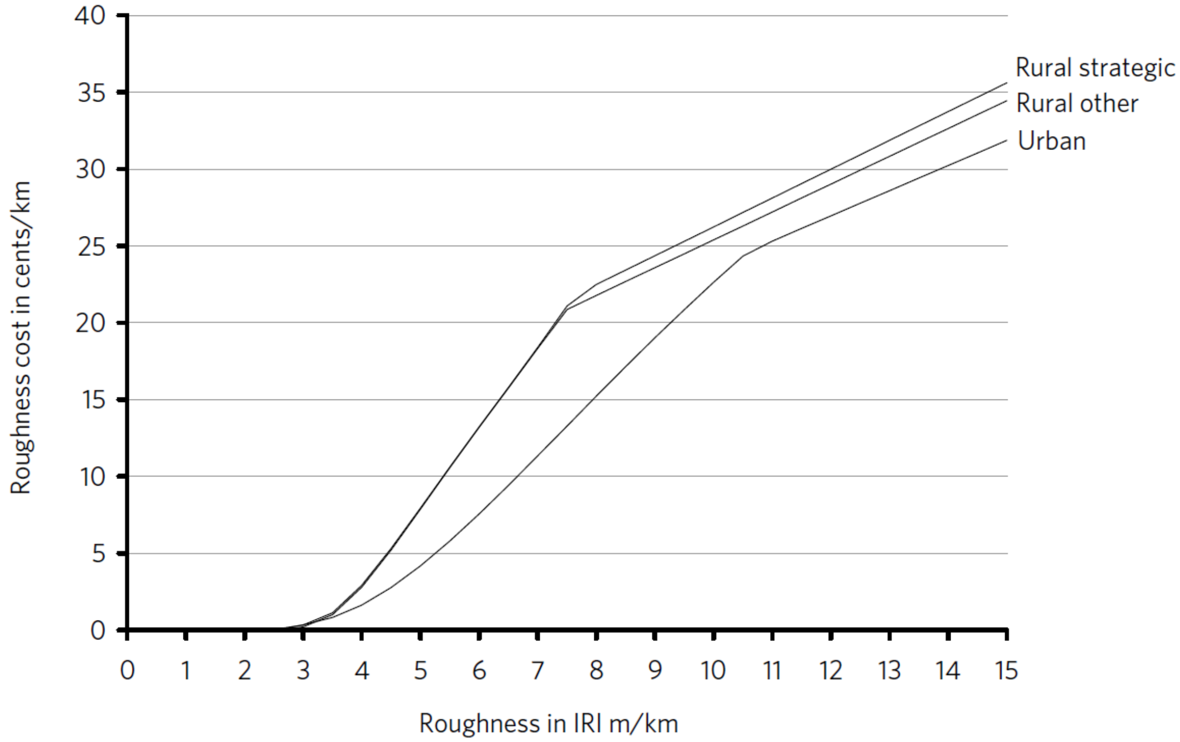
Applying equation 6.2, this rehabilitation works will result in a reduction in the 20m lane roughness from 150 NAASRA counts/km (5.71 IRI_{qc}) to 79 NAASRA counts/km (3.03 IRI_{qc}) With reference to Table A5.14 of the EEM (reproduced as Figure 23 below for ready reference), this reduction in roughness corresponds to a reduction in VOC of 10.3 cents/km (July 2009).

The AADT required to generate $4 in benefits for every $1 spent can be calculated from equation 6.3.

$$BCR = 4 = \frac{5.9736 \times 365 \times AADT \times Benefit(\$)}{Cost(\$)} \quad \ldots (6.3)$$

Therefore, for the lower cost estimate of $3,400, the required traffic volume is 3028 AADT whereas for the upper cost estimate of $5,100 this increases to 4542 AADT.

Figure 23 Additional VOC due to Roughness by Road Category (from NZTA, 2010)



This BCA highlights that it is impossible to justify rehabilitation works on low volume state highways (i.e. R3 and R4 category state highways) on VOC savings alone and recourse to projected savings in maintenance costs is necessary. However, the saving from reduced maintenance costs can be problematic to quantify without historical roughness and maintenance records.

With reference to Figure 1, a reduction in roughness from 150 NAASRA counts/km (5.71 IRI_{qc}) to 79 NAASRA counts/km (3.03 IRI_{qc}) is estimated to bring about a 36.4% decrease in reported injury crashes occurring on straight roads (i.e. horizontal radius of curvature ≥ 1000m) reducing to a 9.97% decrease in reported injury crashes occurring on moderate curves (i.e. horizontal radius of curvature = 400m).

Assuming the reported injury crashes occur mid block on 100 km/h remote rural roads, the cost per reported injury crash ($ July, 2009) from table A6.22 of the EEM is 1.14×$840,000 = $957,600.The crash density in terms of reported injury crashes per year per 20m) required to generate $4 in benefits for every $1 spent can be calculated from equation 6.4:

$$BCR = 4 = \frac{5.9736 \times Crash\ Density\ \times (\%\, reduction\ in\ crashes/100)\ \times \$957{,}600}{Cost(\$)} \quad \ldots (6.4)$$

Therefore, for straight roads the required reported crash density is 0.0065 injury crashes per year per 20m (= 0.33 injury crashes per year per km) for the lower rehabilitation cost estimate of $3,400 increasing to 0.0098 injury crashes per year per 20m (=0.49 injury crashes per year per km) for the upper rehabilitation cost estimate of $5,100.

For moderate curves, the required reported crash density is 0.024 injury crashes per year per 20m (= 1.19 injury crashes per year per km) for the lower rehabilitation cost estimate of $3,400 increasing to 0.0358 injury crashes per year per 20m (= 1.79 injury crashes per year per km) for the upper rehabilitation cost estimate of $5,100.

From this BCA of crash cost savings resulting from rehabilitation works, we can conclude that rehabilitation of low volume rural roads can be a cost effective safety intervention whenever the existing reported injury crash density exceeds:

(a) 0.5 reported injury crashes per year per kilometre for straight road sections.

(b) 1.8 reported injury crashes per year per kilometre for moderate curves (i.e. horizontal radius of curvature ≈ 400m).

To put these crash densities in context, the Karangahake Gorge (SH2 RS 73/0.65 – 18.4) between Paeroa and Waihi, had a crash density of 0.82 reported injury crashes per year per kilometre at the time it was recognised as being a section of SH2 notorious for crashes.

It should be noted that the target reported injury crash densities of 0.5 injury crashes per year per kilometre for straight road sections and 1.8 injury crashes per year per kilometre for moderate curves are on the conservative side. This is because no account has been taken of VOC benefits. However, VOC benefits can be aggregated with the crash reduction benefits. Therefore, if VOC benefits that would give a BCR <4 were aggregated with crash reduction benefits resulting from smoothing also giving a BCR <4, then the resultant BCR may be ≥ 4

7 Discussion

7.1 Existing Value of Roughness

Currently the only ways that the NZTA values differences in road roughness in evaluating projects are (1) the vehicle operating costs, e.g. wear and tear on vehicles, and (2) users willingness to pay for smoother road conditions. Accordingly, it is difficult for road controlling authorities to justify smoothing works on lower volume roads.

7.2 International Experience

A large proportion of the available literature agrees that car crash rates are higher on rough road surfaces. This is generally attributed to a reduction in the tyre pavement forces on rougher roads. While a small number argue that this is likely to be mitigated by drivers reducing their speed on rougher roads, such speed reductions are thought to be small or unlikely on unexpected or isolated rough sections. In contrast to this, there is consistent agreement in the literature that increased pavement roughness increases the crash rate for trucks and motorcycles.

While the available literature indicates a link between crash numbers and roughness, there is very little detail on quantification of the effects of roughness element spacing or geometry on the driving, steering or braking elements that can make up any vehicle crash. Accordingly, there is little information on whether it is the location of the roughness, its amplitude or spacing, that contribute most to crash risk. One of the reasons for this has been that the historical lack of linkages between pavement condition and crash databases has hindered the development of relationships between specific road roughness condition parameters and crash rates.

7.3 Crash Risk Modelling

The linking of road condition and crash databases to investigate relationships between different parameters is relatively recent. One of the most recent and advanced studies that linked geometry and crash databases was carried out in New Zealand by Brodie, Cenek, Davies and Tate (2009). This used a Poisson regression model to relate vehicle crash rates to road surface characteristics, such as road geometry (gradient, curvature and crossfall) and skid resistance. It did not include roughness.

This current study essentially extended this model to cover a longer period of crash statistics and to include the road roughness parameters currently stored in the RAMM database. While this project was specifically intended to assess the effects of road roughness, the other road geometry parameters such as skid resistance, gradient, crossfall and curvature were included in the modelling so that relative contributions could be assessed. The main issues to be addressed were whether roughness is a significant predictor of crash risk and which, if any, of the currently measured roughness parameters is the most significant predictor variable.

The model found that roughness was a statistically significant predictor of crash risk and, of the existing roughness parameters, the medium wavelength 10m profile variance data was slightly better than either the short wavelength, 3m, profile variance, the long wavelength, 30m, profile variance, or IRI. However, there was no critical level of roughness above which crash risk increased dramatically. Rather, crash risk was found to increase with increasing roughness. The effects of roughness on crash risk were also found to be highest on curves between 500m and 5000m radius.

7.4 Test Track Measurement Programme

The test track programme carried out at the Boomrock track had two objectives, (1) to establish whether localised roughness was more or less safe than a uniformly rough road, and (2) to assess whether the output from skid testers, such as the GripTester, is affected by roughness and whether any effects identified were smaller or larger than for a passenger car.

From this test programme of measurements made using instrumented vehicles, and which included opinions from a trained Police driver, a number of observations were made. These included the following observations, some of which are intuitively evident:

(1) The effects of roughness increased with speed and amplitude.

(2) The effects were larger when all four wheels were affected.

(3) The effects were worst for roughness at the apex of the corner.

(4) Acceleration levels on the GripTester wheel were higher than the car for low levels of roughness, but similar for rougher sections.

(5) Roughness affects both the GripTester load and drag outputs, with this significantly affecting the friction value (drag/load) when the wheel lifts off the surface (drag drops to zero). This typically occurs for short periods of time, typically equivalent to much less than 10m at the standard survey speed of 50km/h.

7.5 Road Test Measurement Programme

On-road measurements of braking distances with the passenger car and light truck were intended to identify whether the different wavelengths and magnitudes of road surface undulations had a significant effect. Previous work by Barbosa (2011) on the mathematical modelling of the response of a quarter-car model to road roughness suggests that “at speeds faster than 25km/h the likelihood of tire contact loss is possible”, and also that “what is desirable is the minimum variation of contact forces that allows the largest horizontal force available for a given friction coefficient”.

The on-road braking tests showed the following:

(1) At low speed (around 30km/h) there was no apparent effect on braking distances due to roughness.

(2) At higher speed (around 50km/h) there was an increase in the braking distance with increasing vertical wheel acceleration for both the car and the light truck. Spectral analysis indicated that medium wavelengths of around 10m were more dominant than shorter wavelengths of around 3m, or longer wavelengths of around 30m. This is consistent with the finding of the statistical analysis of crash rates.

(3) There were significant variations in both the car and truck wheel loads during constant speed driving over the site used for the braking tests, with reductions ranging up to 25-30%. These often occurred for lengths of time similar to the durations of the locked wheel braking tests.

These findings are consistent with the modelling work carried out by Barbosa (2011). They suggest that for low speed regimes, roughness is potentially not a major issue in terms of safety. However, these results suggest that, at higher speeds, roughness, and particularly undulations of around 10m in wavelength, can contribute to longer stopping distances, and that these effects are most likely to be due to a reduction in the wheel load and consequently in the horizontal forces that can be generated during a braking manoeuvre. Both the statistical analysis and the on-road braking tests indicate that there is a potential to reduce crash numbers and related costs by reducing roughness. However, further work is needed to identify (1) an appropriate threshold level of 10m profile variance, and (2) the cost benefits that might accrue from remedial smoothing works to reduce roughness levels to this threshold level.

The findings of the track testing and the on-road testing also have potentially significant implications for cornering vehicles. The track testing identified roughness at the apex of a corner as having the most significant safety issues for the driver. This is also where the friction demand required to keep the vehicle on the road is highest. If the available friction is reduced, either by a change in the skid resistance of the surface, or by a reduction in the wheel loads, then the consequences are potentially very serious. In New Zealand, significant resources are used to try to maintain or increase skid resistance levels in high demand situations, such as corners and intersections. However, there is currently no consideration of whether this effort maybe being compromised in some areas by high levels of roughness. Further work is required to identify whether the wheel load reductions on corners are similar to those on straights, and whether this translates into variations in the available friction values that are different from the requirements of straight line braking. This could be achieved either by (1) relating direct measurements of vehicle wheel loads while cornering to current measures of road roughness contained in the RAMM database, or (2) by combining on-road measurements with computer modelling, such as with PC Crash or HVE. The latter would allow calibration of the computer models against on-road measured data to be carried out for speeds that were still well within safe limits. The computer models could then be used to establish threshold levels for combinations of roughness and vehicle speed.

7.6 Crash Reduction as a Justification for Pavement Rehabilitation

A benefit cost analysis was undertaken, which demonstrated the difficulty in justifying rehabilitation works on low volume state highways on VOC and WTP savings alone. However, by introducing the relationship between road roughness and crash rate given in Figure 1, it was shown that BCR's in excess of 4 will result when rehabilitation treatments are applied to road sections where the existing reported injury crash density exceeds:

(a) 0.5 reported injury crashes per year per kilometre for straight road sections.

(b) 1.8 reported injury crashes per year per kilometre for moderate curves (i.e. horizontal radius of curvature ≈ 400m).

This result highlights the need for the EEM to account for crash costs due to roughness, either by incorporating Figure 1 of this report or some variant, thereby providing a means for economically justifying rehabilitation treatment of sections of low volume state highway displaying a combination of high roughness level and high injury crash density.

8 Conclusions and Recommendations

The following conclusions and recommendations have been derived from the statistical modelling and on-road testing performed to investigate relationships between vehicle handling performance and road roughness parameters that are routinely used for road asset management purposes.

8.1 Conclusions

(1) The consensus in the available literature is that there is a link between roughness and crash numbers, but only limited detail on whether it is the location of the roughness or its amplitude or its spacing that contribute most to crash risk.

(2) Analysis of crash numbers showed that roughness is a statistically significant predictor variable of crash rate.

(3) Of the commonly used roughness parameters, the medium wavelength 10m profile variance is a better predictor than either the short wavelength 3m profile variance or the long wavelength 30m profile variance and only slightly better than the standard International Roughness Index (IRI) statistic.

(4) The derived crash rate model showed that by reducing the roughness of the road by 1 IRI (mm/km), a crash rate reduction of about 25% can be expected on roads where the average travel speed is 70km/h or greater.

(5) The track test measurement programme showed that:

(a) The effects of roughness increased with speed and amplitude.

(b) The effects were larger when all four wheels were affected.

(c) The effects were worst for roughness located at the apex of the corner.

(d) Roughness can affect the output from skid testers, such as the GripTester, when the wheel lifts off the surface This typically occurs for a fraction of a second and so the 10m averaged reading is not affected to any significant degree.

(6) The on-road test measurement programme showed that:

(a) At low speed (around 30km/h) roughness had no apparent effect on braking distances.

(b) At higher speed (around 50km/h) braking distances increased with increasing roughness for both the passenger car and light truck.

(c) At a speed of 50 km/h, vertical wheel loading is most affected by road surface undulations having a wavelength of about 10 metres.

(d) There were reductions in the measured wheel loads of up to 25-30% at a speed of 50km/h. The duration of these reductions in wheel loading where comparable to slide-to-stop braking events initiated at this speed.

(7) A benefit cost analysis showed that rehabilitation of low volume rural roads can be justified on the grounds of reduced crash numbers whenever the reported injury crash density exceeds:

(a) 0.5 reported injury crashes per year per kilometre for straight road sections.

(b) 1.8 reported injury crashes per year per kilometre for moderate curves (i.e. horizontal radius of curvature ≈ 400m).

8.2 Recommendations

(1) The procedures in NZTA's Economic Evaluation Manual for calculating additional costs due to roughness should be modified to include crash costs in addition to vehicle costs and vehicle occupants' willingness to pay to avoid rough road conditions wherever average vehicle speeds are 70 km/h or higher.

(2) The level of skid resistance measured by the GripTester on curves is likely to be conservative because its measuring wheel displays a higher degree of sensitivity to road roughness than a vehicle tyre. It is therefore important to determine the roughness sensitivity of other skid testers routinely used to measure skid resistance levels of the state highway network to determine if they are underestimating or overestimating the skid resistance available to motorists. Of particular concern is SCRIM , which has a measuring wheel load of 220kg compared to the GripTester's 22kg so is likely to be much less sensitive to surface roughness and so overestimate the skid resistance available to cornering and braking vehicles.

(3) Additional investigations are required to establish if the increase in braking distance with increasing roughness observed at 50 km/h continues to increase at the same or faster rate for higher brake initiation speeds. Also, will 10m wavelength road surface undulations continue to dominate wheel loading at these higher speeds? These investigations could either be performed on closed roads, or through computer simulations, provided the simulations could be suitably validated.

(4) Further work is required to identify whether any wheel load reductions on corners are similar to those on straights, and whether this translates into variations in the available friction values that are different from the requirements of straight line braking. This could be achieved either by (a) relating direct measurements of vehicle wheel loads while cornering to current measures of road roughness contained in the RAMM database, or (b) by combining on-road measurements with computer modelling, such as with PC Crash or HVE. The latter would allow calibration of the computer models against on-road measured data to be carried out for speeds that were still well within safe limits. The computer models could then be used to establish threshold levels for combinations of roughness and vehicle speed.

(5) There is need to identify (a) an appropriate threshold level of 10m profile variance above which smoothing works might be considered appropriate from a safety perspective, in a similar way that skid resistance is currently treated. The cost- benefit that might accrue from remedial smoothing works to reduce roughness levels to this threshold level also need to be assessed to provide guidance to industry.

(6) The research has shown that depending on the elevation profile of the road surface, there will be a critical vehicle speed at which a significant reduction in tyre contact occurs. The paper by Barbosa provides a methodology for determining this critical speed from the power spectral density of the elevation profile of the road surface profile. This discounts its use for road maintenance management purposes but not for fatal crash investigations. It is therefore recommended that Barbosa's methodology be validated by undertaking comparisons of measured and predicted critical speeds for test sites displaying different roughness characteristics as there are some concerns that using a quarter-car model may not replicate vehicle dynamic behaviour to an appropriate degree.

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Appendix A: Glossary of Terms

The following terms have been used in this report:

AADT	Annual Average Daily Traffic
ABS	Anti-lock Braking System
ADT	Average Daily Traffic
BCA	Benefit Cost Analysis
BCR	Benefit Cost Ratio which is the ratio of benefits ($) to costs ($)
CAS	Crash Analysis System
EEM	Economic Evaluation Manual
frequency (Hz)	Number of waves that pass a given point per second
g	Acceleration due to gravity ≈ 9.81 m/s^2
IRI	A mathematical model of the dynamic response of a real vehicle travelling along a single wheelpath of longitudinal road profile (referred to as the quarter-car, or World Bank, model). It is expressed in terms of accumulated displacement of the simulated suspension in either metres per measured kilometre (m/km) or millimetres per measured metre (mm/m).
LTSA	Land Transport Safety Authority (now superseded by NZTA)
NAASRA	The National Association of Australian State Road Authorities
NAASRA Roughness Meter	A standard mechanical device used for measuring road roughness by recording the upward movement of the rear axle of a standard stationwagon relative to the vehicle's body as the vehicle travels at a standard speed along the road being tested. A cumulative upward vehicle movement of 15.2mm corresponds to 1 NAASRA Roughness Count.
NZTA	New Zealand Transport Agency
OOCC	Out-of-context-curve indicator, which is the difference between the local speed (the speed averaged over the 10m road section of interest and the 2 preceding 10m sections) and the approach speed (the speed averaged over 50, 10m sections preceding the 3 used to calculate the local speed).
Profile Variance	Profile variance is a method of interpreting and summarising longitudinal evenness of a road surface in terms of variance of profile about moving average lengths (3m, 10m and 30m). High levels of 3m variance typically arise from short wavelength features such as potholes and poor reinstatements. 10m variance is influenced by short undulations, possibly arising from localised subsidence of reinstatements and subsurface utilities. High levels of 30m variance may be due to long undulations in the pavement associated with pavement distress.

PSD	Power Spectral Density (PSD) function of a measured parameter is the variance of the parameter divided by the spatial frequency of the measured parameter. Therefore, where the parameter to be described is the evaluation profile of a road in units of m, then the variance of the profile has units m^2 and the spatial frequency (the inverse of the wavelength) may have units of cycles/m, resulting in a PSD function with units of m^3/cycle.
PV	Present Value i.e. benefits and costs occurring during the life of a project discounted back to time zero.
RAMM	Road Assessment and Maintenance Management
RCA	Road Controlling Agencies
RMS	Root- mean-square or quadratic mean, which is equivalent to standard deviation when the mean is equal to zero.
SC	SCRIM coefficient, a measure of the skid resistance of a road when wet
SCRIM	Sideways-force coefficient routine inspection machine (the skid resistance tester employed by NZTA to undertake annual high speed condition surveys of the state highway network.
SCRIM+	The SCRIM survey vehicle fitted with additional equipment to enable it to perform measurements in addition to skid resistance (e.g. roughness, rutting, texture, and geometry)
SD	Standard Deviation
SE	Standard Error
SH	State Highway
SQL	Structured Query Language
TNZ	Transit New Zealand (the crown entity previously responsible for New Zealand's SH network, prior to merging on 1 August 2008 with the LTSA to form the NZTA)
USPWF	Uniform Series Present Worth Factor i.e. factor applied to a series of equal benefits or costs that arise each year or continuously over a period to calculate their PV.
VOC	Vehicle Operating Costs
wavelength	Equals the distance between two successive wave crests or troughs. It is equal to the speed of the wave divided by its frequency.
WTP	Willingness-to-pay

Appendix B: Details of Statistical Crash Prediction Model

Basic details of the crash prediction model used to generate the data presented in Figure 1 are provided below for ready reference. However, the reader is referred to Cenek et al. (2012) for a comprehensive explanation as to how the model was derived.

B1 Ranges of Input Parameters

Table B1 summarises the model input variables and their bounds.

Table B.1 Predictor variables

Predictor variable	Bounds	Notes
year		discrete variable, 10 levels
region		discrete variable, 14 levels
urban_rural		discrete variable, 2 levels
adj_skid_site		discrete variable, 3 levels
poly3_bound_OOCC	0, 35	3rd degree polynomial of bounded version of OOCC
poly2_bound_log10_abs_curvature	2,4	2nd degree polynomial of bounded version of log of absolute curvature
poly2_log10_ADT		2nd degree polynomial of ADT
poly2_scrim-0.5000		2nd degree polynomial of (scrim – 0.5)
poly3_bound_abs_gradient	4,10	3rd degree polynomial of bounded version of absolute curvature
poly3_bound_adj_log10_iri	-0.3, 1.2	3rd degree polynomial of bounded version of adjusted log IRI
poly2_bound_log10_abs_curvature × poly2_bound_adj_log10_iri	as above	interaction between 2nd degree polynomial of bounded version of absolute curvature and 2nd degree polynomial of bounded version of adjusted log IRI

B2 NZTA Regions

Table B.2 lists the 14 NZ Transport Agency regions used for regionalising data contained in the RAMM database.

Table B.2 NZ Transport agency regions and their statistical modelling identifier

NZ Transport Agency Region	Identifier for Statistical Modelling
Northland	R01
Auckland	R02
Waikato	R03
Bay of Plenty	R04
Gisborne	R05
Hawkes Bay	R06
Taranaki	R07
Manawatu-Whanganui	R08
Wellington	R09
Nelson-Marlborough	R10
Canterbury	R11
West Coast	R12
Otago	R13
Southland	R14

B3 Model Coefficients

Predictor Variable	Model Statistics		
	Coefficient	S.E.	Ratio
constant	-8.91855	1.5417	-5.785
year:2000	0		
year:2001	0.109205	0.032422	3.3683
year:2002	0.247343	0.031694	7.804
year:2003	0.238247	0.031266	7.62
year:2004	0.232857	0.031305	7.4384
year:2005	0.235531	0.031055	7.5842
year:2006	0.295369	0.030688	9.625
year:2007	0.365291	0.030352	12.035
year:2008	0.202345	0.031429	6.4382
year:2009	-0.25118	0.034691	-7.2405
region:R01	0		
region:R02	-0.3796	0.043852	-8.6564
region:R03	-0.14205	0.027619	-5.1432
region:R04	-0.14638	0.034058	-4.298
region:R05	-0.1046	0.054999	-1.9019
region:R06	0.047882	0.037183	1.2877
region:R07	0.053738	0.037214	1.444
region:R08	-0.06228	0.031594	-1.9713
region:R09	-0.01674	0.040607	-0.41217
region:R10	-0.0313	0.036024	-0.86887
region:R11	-0.24174	0.032098	-7.5312
region:R12	-0.28411	0.046289	-6.1377
region:R13	0.039511	0.03157	1.2515
region:R14	0.096712	0.039059	2.4761
urban_rural:U	0		
urban_rural:R	0.119504	0.022661	5.2736
adj_skid_site:4	0		
adj_skid_site:3	1.610236	0.025046	64.291
adj_skid_site:1	1.871158	0.050226	37.255
bound_OOCC**1	-0.01228	0.011831	-1.0376
bound_OOCC**2	0.00319	0.000927	3.443
bound_OOCC**3	-5.5E-05	1.81E-05	-3.0522
bound_log10_abs_curvature**1	-3.48945	0.67689	-5.1551
bound_log10_abs_curvature**2	0.491136	0.11127	4.414
log10_ADT**1	0.36854	0.24587	1.4989
log10_ADT**2	-0.12283	0.034023	-3.6103
scrim-0.5000**1	-1.77861	0.12049	-14.762
scrim-0.5000**2	1.168532	1.0013	1.167
bound_abs_gradient**1	0.164931	0.53955	0.30569
bound_abs_gradient**2	-0.01713	0.084138	-0.20356
bound_abs_gradient**3	0.000751	0.004139	0.18145
bound_adj_log10_iri**1	0.118761	6.3295	0.018763
bound_adj_log10_iri**2	-27.8012	9.1483	-3.0389
bound_adj_log10_iri**3	-1.57226	0.93719	-1.6776
bound_log10_abs_curvature**1.bound_adj_log10_iri**1	-0.26655	4.3747	-0.06093
bound_log10_abs_curvature**1.bound_adj_log10_iri**2	18.8887	6.3699	2.9653
bound_log10_abs_curvature**2.bound_adj_log10_iri**1	-0.03185	0.71379	-0.04462
bound_log10_abs_curvature**2.bound_adj_log10_iri**2	-2.79786	1.0265	-2.7257

B4 Example Calculation of Crash Risk

To see how the model is applied, the parameter values tabulated in Table B.3 have been used as input to the "all injury" crash model summarised in section B3.**Error! Reference source not found.**

Table B.3 Parameter values used for example calculation

Parameter	Value
year	2008
region	R03
urban_rural	R
adj_skid_site	4
OOCC	0
curvature	5000
ADT	1000
gradient	0
scrim	0.5
adj_log10_iri	0.3

Table B.4 shows the results of applying the "all injury" crash rate model. As can be seen the estimated personal risk (i.e. crash rate) is 12.63 injury crashes per 100 million kilometres travelled (calculated using equation 3.2) and the estimated collective risk (i.e. crash density in terms of all reported injury crashes per year per 10m of lane) is 0.00046 (calculated using equation 3.1).

Table B.4 Calculation of personal and collective risks

Predictor Variable	Model Coefficient	Value of Variable	Product (Value × Coefficient)
constant	-8.91855	1	-8.91855
year:2008	0.202345	1	0.202345
region:R03	-0.14205	1	-0.14205
urban_rural:R	0.119504	1	0.119504
adj_skid_site:4	0	1	0
bound_OOCC**1	-0.01228	0	0
bound_OOCC**2	0.00319	0	0
bound_OOCC**3	-5.5E-05	0	0
bound_log10_abs_curvature**1	-3.48945	3.69897	-12.9074
bound_log10_abs_curvature**2	0.491136	13.68238	6.719914
log10_ADT**1	0.36854	3	1.105619
log10_ADT**2	-0.12283	9	-1.1055
scrim-0.5000**1	-1.77861	0	0
scrim-0.5000**2	1.168532	0	0
bound_abs_gradient**1	0.164931	4	0.659725
bound_abs_gradient**2	-0.01713	16	-0.27404
bound_abs_gradient**3	0.000751	64	0.048069
bound_adj_log10_iri**1	0.118761	0.290289	0.034475
bound_adj_log10_iri**2	-27.8012	0.084268	-2.34275
bound_adj_log10_iri**3	-1.57226	0.024462	-0.03846
bound_log10_abs_curvature**1.bound_adj_log10_iri**1	-0.26655	1.073772	-0.28622
bound_log10_abs_curvature**1.bound_adj_log10_iri**2	18.8887	0.311705	5.887697
bound_log10_abs_curvature**2.bound_adj_log10_iri**1	-0.03185	3.971851	-0.12649
bound_log10_abs_curvature**2.bound_adj_log10_iri**2	-2.79786	1.152987	-3.22589
			Σ=-14.59
	Personal Risk (injury crashes per 10^8 vkt)		12.63
	Collective Risk (injury crashes per 10m)		0.00046

OPUS