Quantification of Safety Benefits Resulting from Road Smoothing

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Abstract

Relationships between road safety and road roughness parameters routinely used for road asset management purposes were examined to allow identification of appropriate road maintenance interventions and their benefits to be quantified. Statistical modelling was employed to identify significant relationships between crash risk, road geometry and routinely measured roughness parameters, such as the International Roughness Index (IRI) and road profile variance. Test track and on-road measurement programmes utilising instrumented vehicles were used to establish whether isolated roughness elements were more or less safe than a uniformly rough road for cornering manoeuvres and to quantify the effects of roughness on the braking distances of passenger cars and trucks. The key findings were that (1) road roughness had an increasing detrimental impact on crash risk as horizontal curvature increased; (2) the roughness parameter shown to be the best predictor of crash risk was 10m wavelength profile variance, although it was only marginally better than IRI; (3) at speeds greater than 50 km/h, braking distances increased with increasing roughness for both passenger cars and light trucks; (4) during cornering, roughness effects were greatest when encountered at the apex of the curve and on all four wheels; (5) a significant reduction in tyre contact occurs at a critical speed that depends on the elevation profile of the road surface; and (6) smoothing of low volume rural roads was shown to be a cost effective safety intervention whenever the existing reported injury crash density exceeds 0.5 reported injury crashes per year per kilometre for straight road sections and 1.8 reported injury crashes per year per kilometre for moderate curves.

Key words: braking distance; cornering; crash risk; road profile variance; road roughness

1. Introduction

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). However, there are two issues that needed to be addressed in these times of increasing demands on the funds available for road maintenance to enable appropriate decisions to be made in regard to smoothing treatments.

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 m/km (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 m/km (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 if there is 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.

This paper summarises the main findings of a research project funded by the Road Safety Trust (Cenek and Jamieson, 2012), which utilised statistical modelling and test track and on-road measurement programmes to examine the relationships between road safety and road roughness parameters routinely used for road asset management purposes.

2. Statistical modelling

2.1. Background

The statistical modelling component was in many ways an extension of previous work done on crash risk relationships (Davies, 2009), which used data from NZ Transport Agency's Road Assessment and Maintenance Management (RAMM) database over the period from 1997 to 2002 to derive a Poisson regression model to relate reported injury road crash rates to road condition and road geometry. The current work focussed on the effect of roughness on crash rate, but included the variables identified in the earlier modelling work. It initially covered RAMM data from 1997 to 2009, but as the data was incomplete for the 1997 and 1999 years, the statistical modelling was confined to the period from 2000 to 2009. The following sections summarise the statistical analysis that was carried out and associated results. A more complete description of the analysis is given in Cenek et al (2012).

2.2. Model description

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:

$$\begin{aligned}&\mathit{Expected\ Collective\ Risk\ or}\\&\mathit{Expected\ Crash\ Density}\ (\mathit{injury\ crashes\ per\ year\ per}\ 10\ m)\\&= a\exp(L)\ \ldots(1)\end{aligned}$$

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:

$$\frac{10^{10}}{365}\exp(L) \ldots (2)$$

It should be noted that the average daily traffic (ADT) appears in the model in two places in equation 1 above, as a 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 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.

2.3. Results

The results of the statistical modelling pertaining to roughness are summarised below:

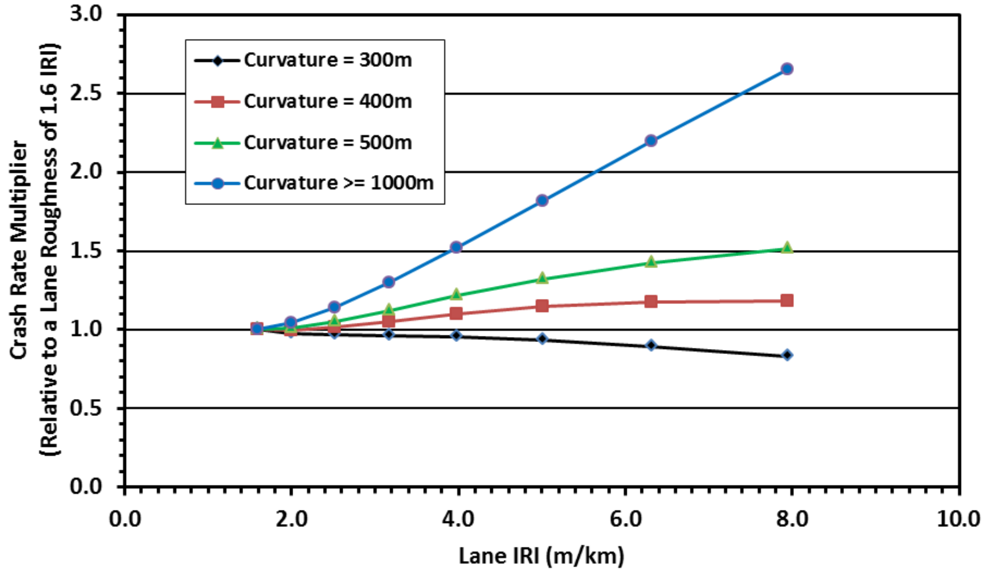
- The results of the statistical analysis are very similar to those from the previous studies (Davies, 2009) with important predictors of crash rate being out-of-context-curve effect, horizontal curvature, ADT, skid resistance, and roughness.
- There is still quite a high unexplained variability in the data.
- The effect of roughness depends on curvature, the effect being strongest on curves with radii of curvature in the range 500 to 5000 metres.
- 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 IRI.
- 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.
- Repeating the analysis using only serious/fatal crashes produced results very similar to those for all casualty crashes.
- Including a year × region interaction has little influence on the results.

The reader is referred to Cenek et al (2012) for a discussion on how the other modelled variables impact on crash rate.

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 1.6 m/km IRI as in Figure 1.

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 5m/km to 3m/km 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%.

Figure 1: Effect of change in roughness (IRI) on crash rate



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

- There is no reduction in crash rate for reductions in IRI roughness below 2 IRI m/km (which corresponds to a lane roughness of about 50 NAASRA counts/km).
- Roughness has an increasing detrimental impact on crash rate as horizontal curvature increases.
- 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.

3. Test track programme

3.1. Overview

The objective of the test track programme was to 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.

The test track measurement programme was carried out at the Boomrock private car test circuit. This sealed circuit is 900m long and located in the hills above Makara, near Wellington. Figure 2 shows an oblique aerial view of the facility.

The test vehicle was a late model 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 2 Boomrock test circuit

3.2. Methodology

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. The instrumented car was driven around the corner at steady speeds of 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 3 shows one of the single elements and one of the multiple grid element fastened to the track.

Figure 3: Views of single and multiple roughness elements

The instrumented test vehicle was driven around the corner for different combinations of roughness elements at speeds of either 30km/h or 50km/h. The corner test configurations comprised combinations of the following variables:

- baseline configuration - no added roughness elements (existing track roughness)
- roughness element position (approach, apex, exit)
- single elements
- multiple elements (3 elements at 1.2m spacing, 5 elements at 0.6m spacing)
- 12mm and 24mm heights
- 30km/h and 50km/h travel speeds
- travel direction (clockwise and anti-clockwise)

- all wheels across roughness elements, or left or right wheels only across roughness elements

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.

3.3. 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:

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

3.4. Measured vehicle accelerations

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 4 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 4: Comparison of vertical accelerations – single and multiple roughness elements

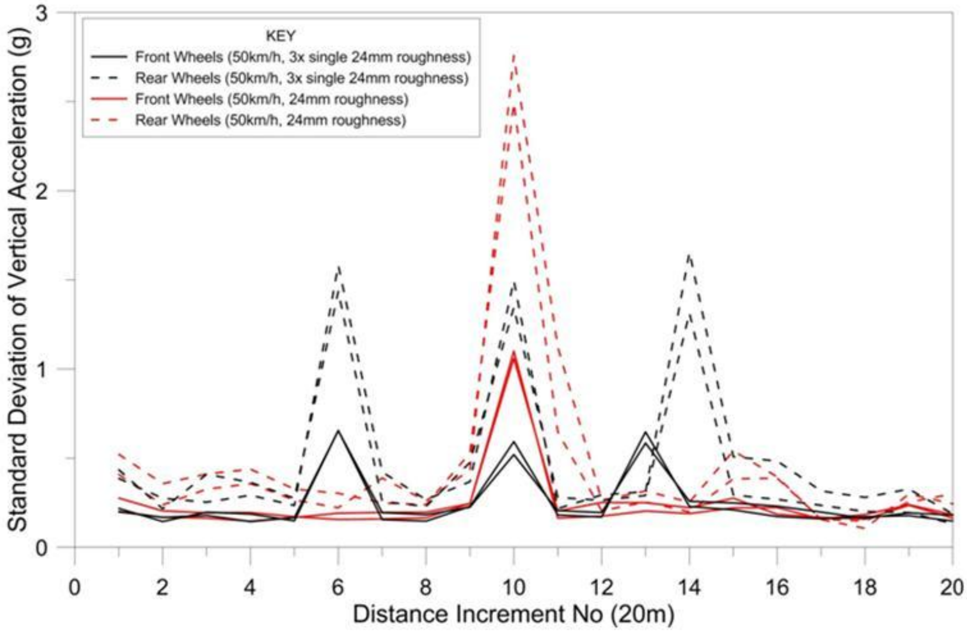


Figure 4 supports the driver's view that the multiple elements located on the apex of the corner produced a greater response than the single elements, either before, on, or after the corner, and are therefore potentially less safe.

4. On-road Test Programme

4.1. Overview

The aim 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. Two vehicles were utilised for the on-road test programme: (1) the same Toyota Corolla hatchback that was used for Boomrock circuit tests and (2) a light truck. Both of these vehicles were equipped with anti-lock braking systems (ABS).

The vehicles were instrumented with a Vericom VC2000, which was loaned by the NZ Police. This is an accelerometer based device 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 Boomrock circuit tests. 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.

The selected test site was a straight and relatively flat 570m long northbound section of Parkes Line Road, Maymorn, Upper Hutt. As can be seen from Figure 5, the site covered a range of roughness levels. However, the variation in wet skid resistance as determined by the GripTester was relatively small, the site average left and right wheelpath GripNumber (GN) values being 0.78±0.03 and 0.74±0.03, respectively. For the purposes of the testing and the analysis of the results, the site was divided into 11 equal lengths, each approximately 50m long.

Figure 5: Panoramic view of Parkes Line Road – note undulations

4.2. Methodology

To establish the response of the test vehicles to the roughness content of the test site, both vehicles were driven over the site at different speeds and the vertical accelerations and vertical wheel loads recorded. This data was split into the 11 subsections and the descriptive statistics of maximum, minimum and root-mean-square (RMS) values were calculated for each subsection. Power spectra of the vertical wheel accelerations and loads were also generated to determine the relative contributions of the different roughness wavelengths.

The locked wheel braking tests were carried out at initiation speeds between 30km/h and 50km/h for safety reasons as the test site was a residential street. 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 as measured by vertical wheel accelerations and loading. 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.

4.3. Locked-wheel braking results

Figures 6 and 7 compare the normalised braking distances with the RMS vertical acceleration data for the car and truck respectively.

Figure 6: Normalised braking distance as function of RMS vertical acceleration - car

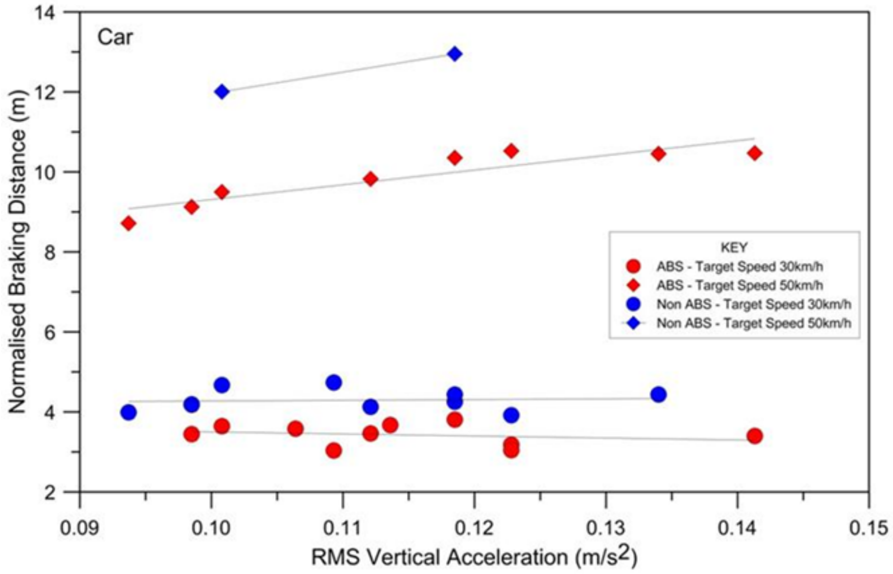
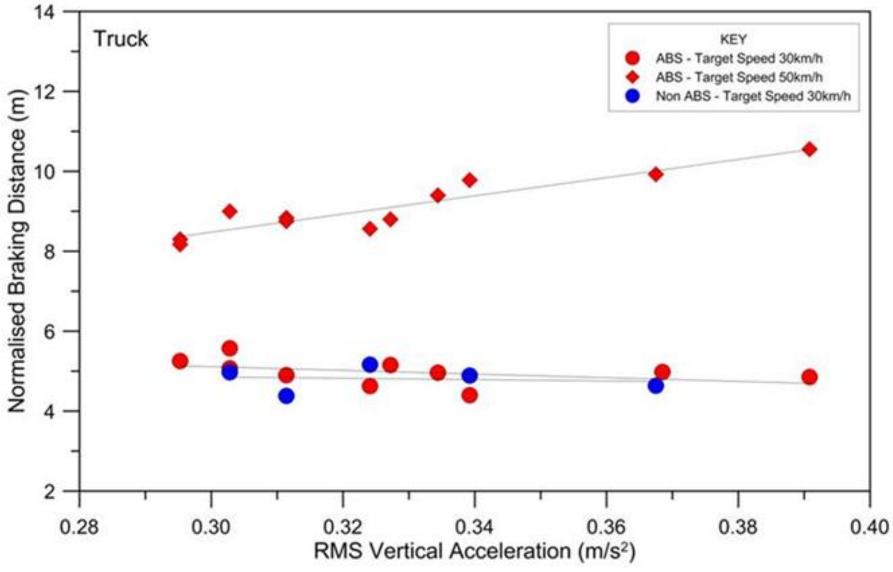


Figure 7: Normalised braking distance as function of RMS vertical acceleration – truck



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.

Analysis of the vertical wheel load data showed that for both vehicles, wheel load 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.

The above results indicate that road roughness does have an effect on braking distance and thereby safety. This effect is related to the time and magnitude of the reduction in wheel loads, most notably for wavelengths of around 10m.

5. Benefit-Cost Analysis

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.

The procedures in the EEM were employed to determine the average daily traffic (ADT) required on a two lane (single carriageway) state highway (i.e. “rural other” road category) to generate sufficient crash reduction 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)).

The key assumptions in carrying out the BCA were as follows:

- The cost of road smoothing treatments ranged between NZ$20 per m^2 to NZ$30 per m^2 so as to cover in-situ stabilisation, overlay and rip and remake. 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$30).
- The rehabilitation treatment will reduce the lane roughness of the carriageway from 5.71 IRI (150 NAASRA counts/km) to 3.03 IRI (79 NAASRA counts/km).
- The reduction in lane roughness from 5.71 IRI to 3.03 IRI will, with reference to Figure 1, bring about a 36.4% decrease in reported injury crashes occurring on straight roads (i.e. horizontal radius of curvature ≥ 1000m) reducing to a 10% decrease in reported injury crashes occurring on moderate curves (i.e. horizontal radius of curvature = 400m).
- The reported injury crashes occur mid block on 100 km/h remote rural roads, the cost per reported injury crash ($ 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 3:

$$BCR = 4 = \frac{5.9736 \times Crash\ Density\ \times (\%\ reduction\ in\ crashes/100)\ \times \$957{,}600}{Cost(\$)} \quad \dots (3)$$

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.

6. Conclusions

The results from the statistical modelling and field testing using instrumented vehicles have confirmed that road roughness can cause a significant reduction in tyre contact forces, thereby detrimentally affecting braking and cornering performance of vehicles. Medium (10m) wavelength roughness was identified as being particularly problematic in this regard.

For low volume rural roads with high roughness levels, road smoothing was shown to be a cost effective safety intervention whenever the reported injury crash density exceeded 0.5 reported injury crashes per year per kilometre for straight road sections and 1.8 reported injury crashes per year per kilometre for moderate curves (i.e. horizontal radius of curvature ≈ 400m).

Acknowledgements

The funding of this research project by the Road Safety Trust is gratefully acknowledged.

References

Burns, J.C. (1981) Roughness and Roadway Safety, Transportation Research Record 836, pp. 8-14.

Cenek, P.D., Herrington, P.K., Henderson, R.J., Holland, B.J.H., McIver, I.R. and Walton, D.K. (2011) High Stress Corners, NZ Transport Agency Research Report 466.
from http://www.nzta.govt.nz/resources/research/reports/466/index.html

Cenek, P.D. and Jamieson, N.J. (2012) Quantification of Safety Benefits Resulting from Road Smoothing, Central Laboratories Report 12-529B39

Cenek, P.D., Henderson, R.J. and Davies, R.B. (2012) Modelling Crash Risk on the New Zealand State Highway Network, NZ Transport Agency Research Report 477.
from http://www.nzta.govt.nz/resources/research/reports/477

Davies, R.B., Cenek, P.D. and Henderson, R.J. (2005) The Effect of Skid Resistance and Texture on Crash Risk. Proceedings Surface Friction Roads and Runways, Christchurch. 1-4 May 2005.

Davies, R.B. (2009) Crash-Risk Model for Curves
from http://www.robertnz.net/pdf/report_curves3.pdf

Ihs, A., Velin, H. and Wiklund, M. (2002) The Influence of Road Surface Condition on Traffic Safety: Data from 1992-1998. VTI Report 909.

NZTA (2010) NZ Transport Agency's Economic Evaluation Manual, Volume 1. NZ Transport Agency, Wellington, New Zealand from http://www.nzta.govt.nz/resources/economic-evaluation-manual/volume-1/

Wambold, J.C., Brickman, A.D., Park, W.H. and Ingram, J. (1973) Effect of Road Roughness on Vehicle Braking, Highway Research Record 471, pp. 76-82.