Improved rate-of-rotation design limits

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Keywords: geometric design guidance, rate of rotation, rollover crashes, rural roads, warp factor

An important note for the reader

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Abbreviations and acronyms

ABS	anti-lock braking system
CAS	crash analysis system
CoG	centre of gravity
ESP	Electronic Stability Program
GPS	global positioning system
IRI	International Roughness Index
NAASRA	National Association of Australia State Road Authorities
NHTSA	National Highway Traffic Safety Administration
NZTA	New Zealand Transport Agency
rad/s	radian/s
RAMM	road asset maintenance management
RP	route position
SH	State Highway
SSF	static stability factor
SUV	sports utility vehicle

Contents

Executive summary

Current road design criteria used in New Zealand for rate of rotation (also referred to as warp factor) were investigated from the perspective of the safety margin they provided for the different types of vehicle found on rural roads. These criteria, which are drawn from the Austroads (2003) *Rural road design: a guide to the geometric design of rural roads*, relate to the dual requirements of appearance and comfort and are:

- 0.035 radians per second of travel time for design speeds to 70km/h
- 0.025 radians per second of travel time for design speeds for 80km/h and above.

A rate of angular rotation of 0.025 radians per second is equivalent to a rate of change of superelevation of 0.025m/m/s or 2.5% per second.

Austroads adds the qualifier 'these rate-of-rotation criteria should be regarded as reasonable values and not inherently correct'.

The research undertaken involved a combination of statistical modelling of crashes and the determination of vehicle handling behaviour using computer simulations and field measurements with instrumented vehicles for representative rural road geometries and vehicle types.

The principal objectives of the research were to:

- determine the validity of current rate-of-rotation design criteria
- establish if there was a threshold limit for the rate of rotation above which vehicle safety was significantly compromised and if this threshold limit varied with vehicle type.

A key aspect of the research was to investigate if commercially available crash reconstruction software could simulate vehicle handling behaviour to a sufficient accuracy to allow existing or proposed road geometries to be assessed from their potential to cause loss of vehicle control at design travel speeds.

Three different vehicles were instrumented to measure orthogonal accelerations (longitudinal, transverse and vertical) and orthogonal rotations (pitch, roll and yaw) as well as driving speed and driving path using global positioning system (GPS) tracking. The three vehicles comprised a passenger car, a 4-wheel drive sports utility vehicle (SUV) and a high-sided rigid truck. These vehicles were driven over a range of speeds not exceeding the legal speed limit on rural road sections that provided rate-of-rotation geometries that not only exceeded the current open road rate-of-rotation criterion of 0.025 radians per second but also the maximum rate-of-rotation criterion of 0.035 radians per second, pertaining to urban roads.

The resulting database of measured roll and yaw rates was used to assess various theoretical approaches for determining vehicle handling behaviour from road geometry inputs and to check the conformance of New Zealand rural state highways with current rate–of-rotation criteria.

The principal conclusions arising from the research are listed below.

- Rate of rotation has been shown as part of this study to be a statistically significant predictor of relative crash rate.
- There does not appear to be a critical rate-of-rotation threshold above which rollover crashes increase dramatically.
- Measured rate-of-rotation levels are typically greater than those predicted from the geometry alone, indicating the important contribution of dynamic effects associated with horizontal alignment, load shifts and suspension behaviour.

- Measured rates-of-rotation often exceed the current Austroads design criteria.
- Driver perceptions of uncomfortable ride quality were found to occur at higher rates-of-rotation than the current Austroads design criteria, typically agreeing with the 0.075radians per second threshold determined from a New Zealand study conducted in 2001 concerning the development of a truck ride indicator.
- Rate-of-rotation data from computer based vehicle handling simulations showed good agreement with corresponding data obtained from on-road measurements using instrumented vehicles.
- The behaviours of a car, a SUV and two unloaded trucks across a range of road geometries and travel speeds were dominated by sliding off the sealed lane, rather than rollover.
- Repeat simulations performed with two trucks in loaded configuration were dominated by rollover.
- When small radius horizontal curves are combined with low levels of superelevation, the rates-of-rotation for rollover were close to the existing appearance and comfort-based design criteria. For higher superelevation levels, the rates-of-rotation for rollover were typically well in excess of these criteria. This result suggests that either computer simulation is used to identify the susceptibility of specific curve geometries to rollover, or that more specific rate-of-rotation guidelines are developed that incorporate horizontal curve radius, curve superelevation and curve speed.

The recommended research actions arising from this research are as follows:

- New Zealanders' response to different levels of rate of rotation needs to be investigated. In particular, it is necessary to confirm or otherwise that an upper threshold of 0.075 radians per second derived from an investigation of truck ride is appropriate for a wide variety of vehicles and drivers.
- A more detailed examination of the crash analysis system (CAS) database should be carried out to identify common characteristics of rollover crashes occurring on the state highway network so that causative factors, additional to geometry based rate of rotation, can be identified and also their inter-relationships. These factors are likely to include horizontal curvature, superelevation, road gradient, and vehicle type/rotational stiffness.
- The effect of averaging geometry parameters over lengths shorter than the current 10m in the RAMM geometry table needs to be investigated to see if this leads to improved agreement between measured and predicted rates-of-rotation. This would require detailed surveying of specific locations, similar to what is often done at fatal crash sites.
- Typical centre of gravity heights for different truck types and load combinations need to be assessed from either static rollover threshold data or specific measurements as centre of gravity height was found to be a critical determinant of rollover performance. Having such a database will provide more confidence in the output of the computer simulation models. This, in turn, will allow better assessment of road and vehicle factors affecting the risk of a rollover crash.
- A number of reported rollover crashes in the CAS database should be reconstructed using crash simulation software to firstly verify and refine the computer modelling that has been undertaken and secondly to better quantify the contribution of road geometry and road condition variations to rollover crashes.
- Rather than blanket application of rate-of-rotation criteria, crash/vehicle handling simulation models such as PC Crash™ should be used to assess the geometry of a curve for the anticipated speed environment and traffic composition, particularly for small (< 150m horizontal radius) curves, including roundabouts, where rollover is potentially an issue.

- One section of SH58 has been identified where high crash rates coincide with poor road geometry, this being at RS0/11.6–12km in the decreasing direction. It is recommended that this section of SH58 be considered for road shape improvement works to bring the geometry within current geometric design guidelines. A before and after study should follow, which would involve both computer simulation modelling and simplified modelling using rate-of-rotation estimates derived from 'as built' superelevation data to assist in explaining any observed changes to the crash rate.
- In the rail transport industry, the track rate of rotation (change in superelevation) approaching curves and exiting curves is limited in terms of radians per metre. Similarly, the rail vehicle (rolling stock) rotational stiffness about the longitudinal axis is limited to ensure that the vehicle is capable of following this change in superelevation. There is evidence in the road transport industry to suggest that long stiff heavy commercial vehicles have a higher risk of understeer generated problems than vehicles with a more compliant chassis. Research should be carried out to determine whether current trailer designs, particularly those used in dairy and forestry industries, have an appropriate level of rotational stiffness both in the unloaded and loaded states to accommodate the changes in superelevation encountered on New Zealand state highways without wheel lift occurring.

Abstract

Rate of rotation, or 'warp factor' is a measure of the variation in crossfall of a road surface, and typically relates to a change in crossfall from that of a normal straight road to that chosen for a curve to enhance forces assisting a vehicle to stay on the road. The range of road geometries (crossfall, curvature, transition length and superelevation) typically found on the state highway network were determined, and the crash database interrogated to determine whether a critical rate-of-rotation limit corresponding to the onset of loss of control of vehicles could be established. On-road tests with instrumented vehicles were used to provide information on rates-of-rotation corresponding to occupant comfort and to provide calibration input to computer modelling. The computer modelling was used to establish rates-of-rotation resulting in loss of control for different vehicle types over ranges of road geometry and travel speed. Design criteria for rate of rotation were derived from this body of work from the perspectives of vehicle occupant comfort and safety.

1 Introduction

The objective of this research project was to improve the knowledge and design of curves and curve transitions (superelevation development lengths) on roads, and thereby develop design criteria for rate-of-rotation limits appropriate for road geometries and vehicles found on New Zealand roads. This research will be relevant to the design of new roads, as well as the redesign/realignment and maintenance of existing road sections of the New Zealand state highway network, particularly in difficult terrain.

1.1 Background

The geometric design of roads is a complex process of combining straight and curved road sections with transition curves, in order to provide for the safe, efficient and economical movement of all types of traffic. When a vehicle travels along a straight, the pavement has a relatively constant crossfall to facilitate drainage. However, around a curved path a vehicle is subject to a radial force which tends to cause it to slide outwards. To resist this force, the road is usually sloped to a greater degree than on straights and this is referred to as superelevation. The superelevation that is adopted will take into account a variety of factors, such as safety, appearance, grade, speed and drainage. The curves used to change from a straight to a constant radius curve are referred to as transition curves, or alternatively the superelevation development length. Over these transition lengths, the crossfall changes from the normal crossfall to the full superelevation crossfall. This change in crossfall over distance is called the 'rate of rotation' or 'warp factor'. It is usually specified in terms of either a rotation rate (radians/s or %/s), or a transition length (m).

The geometric design process uses a number of design standards, which have been shown to provide acceptable road design. Included among these are the Austroads (2003) *Rural road design: a guide to the geometric design of rural roads* and the NZ Transport Agency (NZTA) (2005) *State highway geometric design manual*. These guidelines specify desirable and absolute rates of rotation of 0.025 radians/s and 0.035 radians/s respectively.

Note: for consistency the rates of rotation in this report are described in units of radians/s (rad/s), as these relate to the current New Zealand design standards for comfort. Where rates of rotation are listed, they are for a vehicle speed of 100km/h unless otherwise stated. Rates of rotation relating to the actual road geometry without reference to vehicle speed can also be calculated in terms of radians/m (rad/m) as follows:

(rad/m) = (rad/s)/velocity (m/s) eg 0.0009rad/m = 0.025 rad/s at 100km/h (ie 27.7m/s)

1.2 Need for research

The topography of New Zealand is very rugged in places and the layout of roads that wind their way through this topography is often constrained by the landscape. Problems can arise when road designers attempt to design new roads, or maintain existing roads, that are topographically constrained but which also satisfy rate-of-rotation design criteria. In many instances it cannot practically be done. There is a need to test the validity of current design criteria and assess rate-of-rotation limits for both safety and comfort for New Zealand road geometries, vehicles and driving speeds.

1.3 Objectives

The primary goal of the research was to assess the validity of current rate-of-rotation guidelines, and develop more appropriate comfort and safety guidelines for rate of rotation based on New Zealand road geometries, vehicles and speeds.

The research programme actions were to:

- establish the ranges on international rate-of-rotation design values through a review of the available literature and design guidelines
- identify the range of road geometries found on the New Zealand state highway network, including curve radius, transition length, road camber and superelevation
- review the RAMM crash database to identify whether critical rate-of-rotation limits for loss of control could be established
- perform on-road trials using instrumented vehicles to establish actual rate-of-rotation levels for New Zealand roads
- carry out computer simulations to determine critical rates of rotation (loss of control) for different vehicles and road geometries
- develop recommendations for the determination of appropriate rate-of-rotation guidelines.

1.4 Scope of the report

This report presents the results of a study to assess the validity of existing rate-of-rotation guidelines, and to develop recommendations for guidelines based on New Zealand road geometries and vehicles. Chapter 2 discusses the results of the literature survey of available design rules and guidelines. Chapter 3 describes the ranges of road geometries typically found on the New Zealand state highway network. In chapter 4, the relationships between loss-of-control crashes and rate-of-rotation levels are discussed. The on-road vehicle trials are described in chapter 5 and analysis of the on-road measured data follows in chapter 6. The computer simulations on these road sections are considered in chapter 7. Comparisons of the on-road and computer simulation data, and assessment of appropriate comfort and safety rate-of-rotation guidelines are covered in chapter 8. Finally, conclusions and recommendations drawn from the research are given in chapter 9.

2 Current guidelines

2.1 Rate of rotation

A literature survey was carried out to assess the variation in the limits prescribed for rates of rotation in international rules and guidelines. Two types of criteria are often applied to rates-of-rotation limits, these being comfort and safety and these are considered in sections 2.2 and 2.3 respectively.

2.2 Comfort criteria

From the literature survey, the following table (table 2.1) has been developed to summarise the rate-of-rotation limits used internationally for comfort.

Table 2.1 Rate-of-rotation levels for comfort

Jurisdiction	Publication	Rate-of-rotation limits		
			Rad/s	%/s
Australia	Austroads (2003) *Rural road design: a guide to the geometric design of rural roads.*	Desirable Absolute maximum	0.025 0.035	2.5 3.5
Australia (ACT)	Department of Territory and Municipal Services (date unknown) *Design standards for urban infrastruct*ure. Chapter 3: Road design	Usual Maximum	0.025 0.035	2.5 3.5
New Zealand	Transit New Zealand (2005) *Highway geometric design manual*	Constrained two-lane two-way roads, design speed <= 70km/h	0.035	3.5
		Unconstrained two-lane two-way roads	0.025	2.5
		Divided roads	0.02	2.0
United Kingdom	Highways Agency (2002) *Design manual for roads and bridges*, vol 6: Road geometry, section 1	Desirable maximum Absolute maximum	0.014 0.028	1.4 2.8
United States of America (New York)	New York Dept of Transport (2003) *Design Quality Assurance Bureau recommendations for AASHTO superelevation design.*		0.028 0.032 0.035	2.8 3.2 3.5
United States of America (California)	California Department of Transportation (2006) *Highway design manua*l.		0.022 0.030 0.037 0.044	2.2 3.0 3.7 4.4

From table 2.1 it can be seen the design maximum rate of rotation for comfort is 0.044 rad/s but that the desirable levels are generally similar.

2.3 Safety criteria

As the review of literature pertaining to rate-of-rotation safety criteria progressed, it became apparent rate-of-rotation limits for comfort were much less (at least one order of magnitude) than those required for adequate roll safety. (To give numerical values, depending on the vehicle type and safety test specifications, the ratio of a rate-of-rotation limit to rollover rotation rate is approximately 0.044/0.724 (ie 1/16.5). Obviously, the effect of a roll rate will depend on the disturbance time profile, but it can be concluded that in practice comfort criteria alone rather than both comfort and safety criteria are often used to determine rate-of-rotation limits.)

Because of this observation, the roll rates presented in section 2.3.1 are not an exhaustive summary and do not cover all possible vehicle types, load configurations and test scenarios. Rather, a sample of roll rates is presented so an appreciation of ball-park roll rates likely to be a safety concern can be obtained and compared with the rate-of-rotation limits reported in section 2.2.

2.3.1 General

Ignoring suspension dynamics, fundamental vehicle roll theory indicates, provided the angle of crossfall is less than that required to cause vehicle rollover and the vehicle does not manoeuvre suddenly, a steady change in crossfall due to superelevation development in itself does not cause a vehicle to roll over. However, a fluctuating rate of change in crossfall does. This results in an angular acceleration being applied about the vehicle's roll axis, and implies vehicle rollover is most likely to occur when the superelevation has reached its maximum level and the rate of rotation reduces suddenly to zero.

There does not appear to be any literature on the relationship between road superelevation rate of rotation and vehicle rollover crashes. This suggests the typical rates of rotation employed on roads, being primarily designed for comfort levels, do not tend to cause vehicle rollover crashes.

Below are notes from representative literature on vehicle rollover crashes aimed to give an indication of vehicle roll rates:

- According to Ashby et al (2007), vehicle roll rates associated with vehicle rollover (ie once rollover has occurred) can be as low as π rad/s (ie 180 deg/s).
- To give more detail, Ashby et al (2007) studied vehicle occupant neck loads via simulation as a function of roll rate. The roll rates studied were applied to simulation of a hypothetical representative 1999–2006 sports utility vehicle (SUV) rolling about its longitudinal axis. Numerical values of the roll rates studied ranged upward from 1/2 revolution per second (ie π rad/s). (Note: this roll rate is post lift-off of all four wheels. A further note: while this value is not directly related to pavement rate of rotation, it is included here as it puts the rate-of-rotation limit magnitudes summarised in section 2.2 into useful perspective.)
- The static stability factor (SSF) is used to assess a vehicle's propensity to roll over and is given by SSF = T/2h (eg Barak and Tianbing 2003) where h= height of vehicle centre of gravity (CoG) and T = track width. Typical values as summarised by Metz et al (1992) are:
  - passenger cars: 1.33
  - SUVs: 1.08
  - (mini)vans: 1.09
  - light trucks: 1.18.

Contrary to a peer reviewer's speculation, the SSF values for passenger cars, SUVs, minivans and light trucks above do not appear to be based on the 1.20 value for trucks. (In fact, the SSF values for passenger cars, SUVs, minivans and light trucks above were calculated from a sample of 43 vehicles.) As far as the author of this section could tell, detail as to whether the vehicles were loaded or unloaded is not specified in the references.

(Note: although concerns have been expressed in some literature about assessing a vehicle's susceptibility to roll over by means of the SSF index, values for this index are presented above as it thought to provide useful initial broad-brush means of enabling comparison of the propensity of various vehicle types to rollover.)

- According to experimental results reported by Marimuthu et al (2006) and simulation and experimental results reported by McCoy et al (2007), vehicle roll rates which do not result in rollover are:
  - 0.089 rad/s (ie 5.1 deg/sec) for a 1994 Ford Taurus GL Passenger car performing the 'J-turn' manoeuvre test at a constant velocity of 39.6km/h.
  - -0.279 rad/s (ie 16 deg/sec) for simulations of a typical mid-size SUV performing the 'J-turn' manoeuvre test at a constant velocity of 45km/h. (Note: the parameters of the vehicle simulated were not for a particular vehicle, but 'representative' of a mid-size SUV. Also the roll rate predicted by this SUV simulation was greater than that for the passenger car reported above. Reasons for this could be reckoned, but are not known authoritatively and so are not advanced.)
  - -0.698 rad/s (ie 40 deg/sec) for a 2001 Chevy Blazer RRR SUV performing the 'fishhook' manoeuvre test from an entrance velocity of around 60.83km/h.

  Note: descriptions of the manoeuvres named above are presented in table 2.2.

Table 2.2 Standard vehicle dynamics assessment test details

Test name	Details	Reference	Vehicle speed (km/h)	Radius of curvature (m)	Size of trip (cm)
J-turn manoeuvre	The J-turn manoeuvre involves a sudden turn of the steering wheel while the vehicle is moving along at various constant velocities. The input results in a J-shaped turning motion of the vehicle – hence the name.	McCoy, RW et al (2007) Vehicle rollover sensor test modelling. SAE 2007-01-0686	Various	Varies	Not applicable
'Fishhook' manoeuvre	The fishhook test was developed by the NHTSA and is used to evaluate vehicle safety in rollover. The path the vehicle follows is shaped like a fishhook (or an inverted question mark symbol), which gives the test its name.	Idem	Entrance speed 56.33–80.47km/h (35–50mph)	Not specified (the test path to be followed is dictated in terms of the steering wheel angle)	Not applicable

NHTSA = National Highway Traffic Safety Administration

- According to experimental results presented by McCoy et al (2007), roll rates which cause rollover of a typical mid-size SUV appear to be in excess of approximately 0.724 rad/s (ie 41.5 deg/sec) with the inherent and natural proviso that the effect of this roll-rate 'limit' on vehicle roll is very dependent on the time profile over which it acts.

2.3.2 NZTA research report 263

NZTA research report 263 'The effect of cross-sectional geometry on heavy vehicle performance and safety' (Milliken and de Pont 2004) focuses on cross-sectional geometry, not the transition in pavement cross-sectional geometry (ie rate of rotation) either side of a cross section (the focus of this report). There is, however, a portion of the Milliken and de Pont (2004) report with some relevance to the rate of rotation and this is where it addresses a sudden change in elevation of the wheels.

To summarise Milliken and de Pont (2004): its primary objective was to determine relationships between road cross-sectional geometry and heavy vehicle performance and then to use these relationships to estimate the effect of road cross-sectional geometry on heavy vehicle crash risk. This objective was achieved by reviewing truck crash data to identify where road cross-sectional geometry may have been a factor, determining the effect of various road geometry conditions on heavy vehicle performance and finally developing relationships between vehicle performance and crash rates.

Key findings of the crash data analysis were:

- Only a very small proportion (1.4%) of truck-involved crashes were reported as having a road cross-sectional geometry feature as a contributing factor.
- Some 20% of truck-involved crashes were reported as being loss of control.
- Road cross-sectional geometry can affect the likelihood of occurrence for crashes other than loss of control.
- 66% of the loss-of-control crashes occurred while cornering.

Key findings of the study into relationships between road cross-sectional geometry characteristics and vehicle performance were:

- The lateral acceleration required to cause rollover is related to the crossfall of the road by a simple relationship.
- The load transfer ratio experienced during an evasive manoeuvre depends on the specifics of the vehicle, the manoeuvre and the road profile.
- All the heavy vehicles simulated had off-tracking sensitivities to a cross slope of around 3m/g.
- A sudden drop in pavement elevation resulted in a maximum load transfer of roughly twice the steady-state load transfer.

The report concludes that the primary areas where there is potential for significant safety benefits for heavy vehicles are proper consideration of:

- banking in curves
- seal width and shoulder treatments
- road camber.

2.4 Final comments

The variation in roll rate for rollover and near-rollover crashes appears to be considerable and is obviously dependent on the type of vehicle, particularly its width relative to the height of its CoG, the manoeuvre being performed and the length of time involved. However, it can be said that the rate of rotation required to cause a rollover crash is much higher than the comfort level to which roads in most countries, including New Zealand, are designed.

3 New Zealand road geometries

3.1 Data extraction

It was not considered necessary to extract data for the entire New Zealand state highway network, but rather to obtain a representative sample that was reasonably typical and expected to cover the general range of characteristics important for this study. In particular, the dataset needed to cover a broad range of curvature and crossfall, so the rates of rotation were also likely to cover a broad range, up to and over the current guideline limits of 0.025 rad/s (design speed > 70km/h) and 0.035 rad/s (design speed < 70km/h). Accordingly, data was extracted from the RAMM database for sections of the state highway network in the lower half of the North Island. Data extracted included location, gradient, curvature and crossfall. At the same time the crash database was also interrogated to provide information on all crashes on the selected road sections.

3.2 Data variation

The data extracted from the RAMM database included the gradient curvature and crossfall for 10m increments. The data was processed to 30m moving average values of gradient, curvature and crossfall, as well as absolute rate-of-rotation values from consecutive 10m segments and for a 30m moving average. The calculation procedure used to derive rate-of-rotation estimates from data sourced from the RAMM geometry table is detailed in appendix A.

To assess the variability in the extracted data between regions, relative frequency histogram plots of the 30m moving average values of gradient, curvature, crossfall and absolute rate-of-rotation data for the Wellington and Napier regions were generated. These plots are shown in figures 3.1 to 3.4.

Figure 3.1 Comparison of horizontal curvature data – Wellington and Napier regions

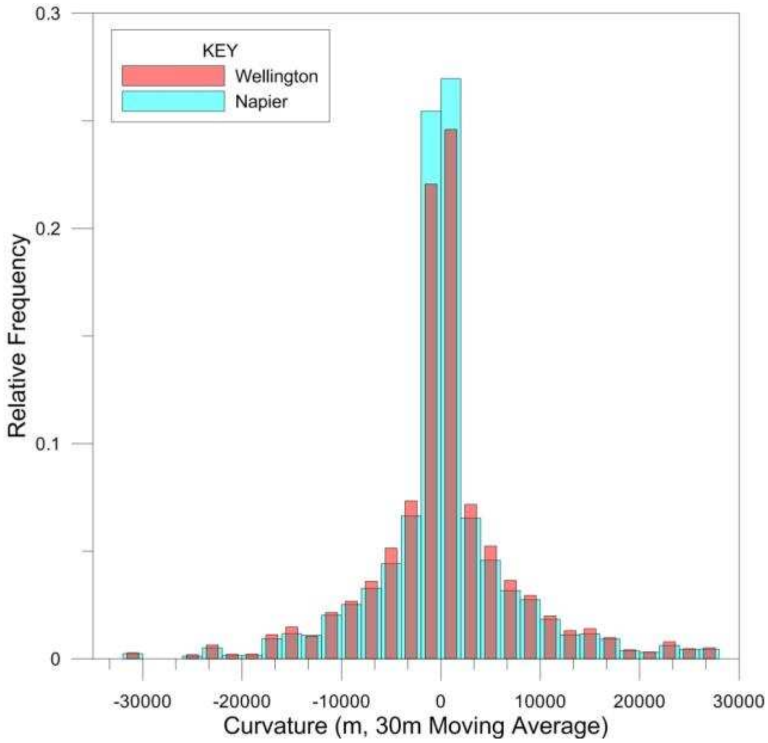


Figure 3.2 Comparison of longitudinal gradient data – Wellington and Napier regions

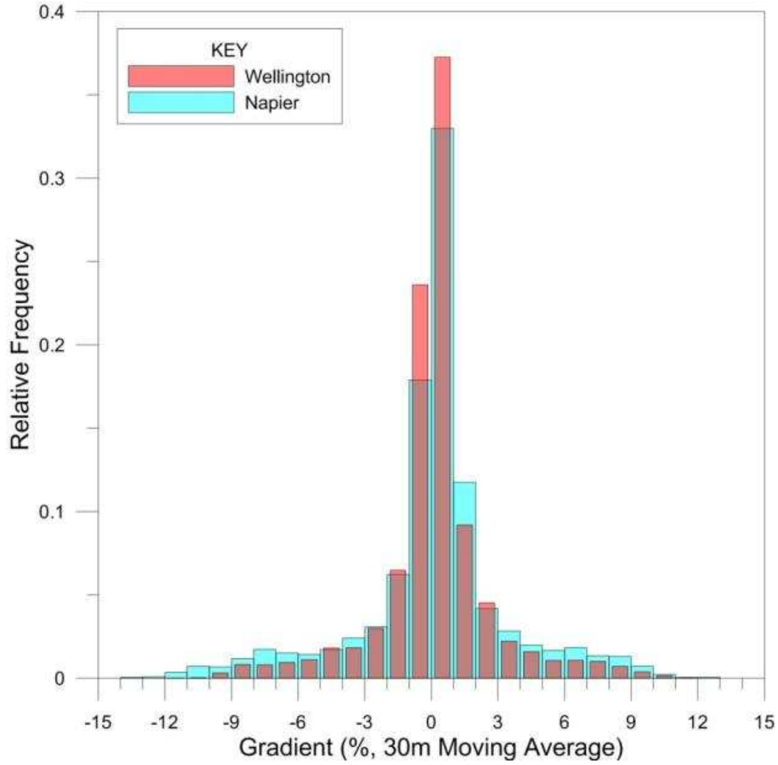


Figure 3.3 Comparison of crossfall data – Wellington and Napier regions

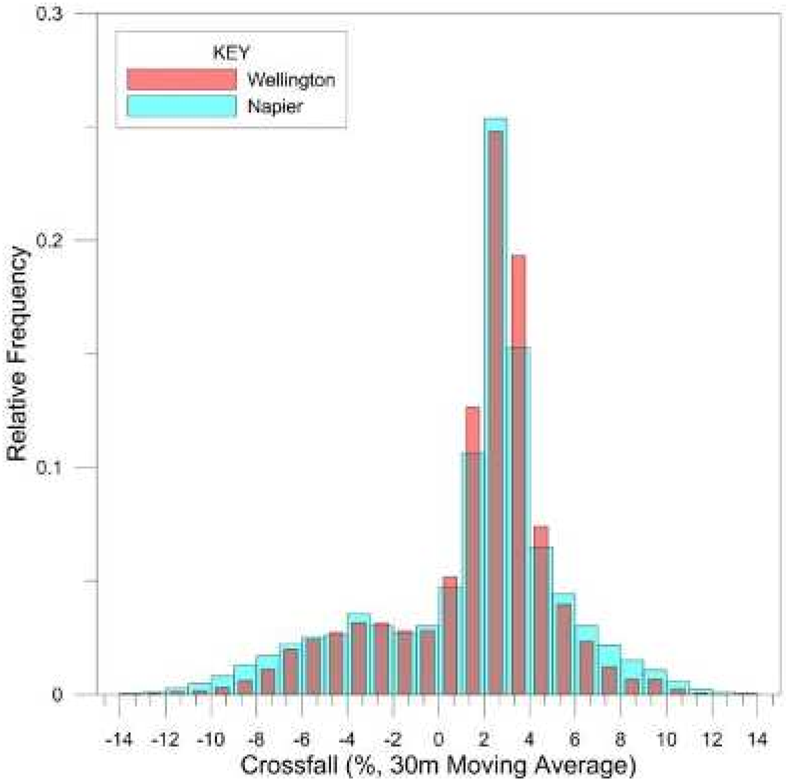
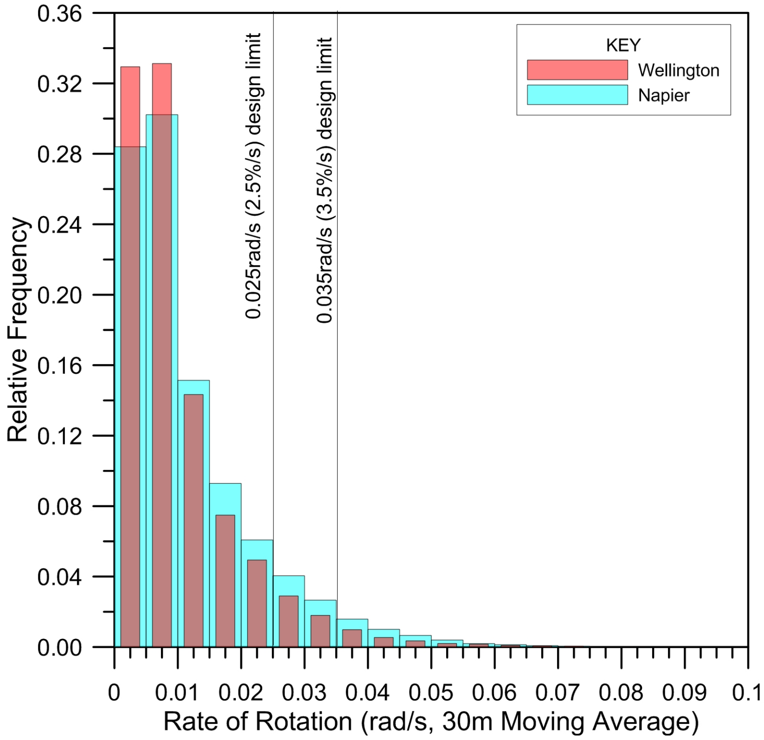


Figure 3.4 Comparison of absolute rate-of-rotation data based on theoretically derived 85th percentile speed – Wellington and Napier regions



The theoretical 85th percentile speed derived from curve radius and crossfall data stored in the RAMM geometry table using equation 3.1 has been utilised in calculating the rate-of-rotation values plotted in figure 3.4. The maximum speed for rural areas has been set to 110km/h corresponding to a 10% (10km/h) tolerance level.

$$AS = -\left(\frac{107.95}{H}\right) + \sqrt{\left(\frac{107.95}{H}\right)^2 + \left[\frac{127{,}000}{H}\right]\left[0.3 + \frac{X}{100}\right]} \qquad \text{(Equation 3.1)}$$

where AS = curve advisory speed (km/h)

R = curve radius (m)

H = absolute curvature (radians/km) = (1000/R)

X = absolute value of crossfall (%).

The following observations can be made from figures 3.1 to 3.4 and the data they present.

The gradient, curvature and crossfall distributions of the two networks are generally similar, but the Napier region shows a slightly higher proportion of steeper grades, tighter curves and higher crossfalls.

Given the slightly greater proportion of higher crossfalls in the Napier region data, it could be expected that rate-of-rotation data would also show a greater proportion of high rates of rotation. This is borne out in figure 3.4.

The proportion of the 30m moving average rates of rotation over the 0.025 rad/s comfort guidelines was 7.6% for the Wellington region and 10.9% for the Napier region.

The proportion of the 30m moving average rates of rotation over the 0.035 rad/s comfort guidelines was 2.9% for the Wellington region and 4.2% for the Napier region.

4 Road geometry and crashes

Relationships between road geometry and crashes can be very complex. To assess the effects of rate of rotation on crash rates two approaches were taken. These approaches were 1) a statistical analysis carried out by Dr Robert Davies of Statistics Research Associates and 2) a more visual approach comparing the cumulative crash distributions with the rate-of-rotation data. These different approaches are described below.

4.1 Statistical analysis

For the statistical analysis, a database comprising five years (1997–2002) of crash and geometry data for the entire state highway network was constructed. A Poisson regression model was applied to the data to determine whether there was a relationship between the crash data and the crossfall data (from which the rate of rotation is derived). This analysis showed there was a statistically significant relationship between the change in crossfall and the crash rate.

As changes in crossfall are designed into roads to deal with the radial forces exerted on vehicles when cornering, it is expected that changes in crossfall would be strongly correlated with the road curvature. Further statistical analysis showed this is the case and the correlation is very similar for right- and left-handed curves. Accordingly, it is difficult to separate out the effects on crash rate associated with (a) the road curvature and (b) the changes in crossfall that are designed into curves. However, by restricting the analysis to approximately straight rural roads (curvature > 2000m, speed limit 100km/h) the effect of change in crossfall could be assessed without the complicating issue of tight curves. This analysis showed that changes in crossfall, and hence the rate of rotation, do have a statistically significant effect on the crash rate. The relationship can be seen in figure 4.1 which shows the relative change in crash rate against the change in crossfall for each 10m road section. Also shown on the plot are the changes in crossfall that correspond to the 0.025 rad/s and 0.035 rad/s threshold limits for a vehicle travelling at 100km/h.

Figure 4.1 Variation of crash rate with change in crossfall

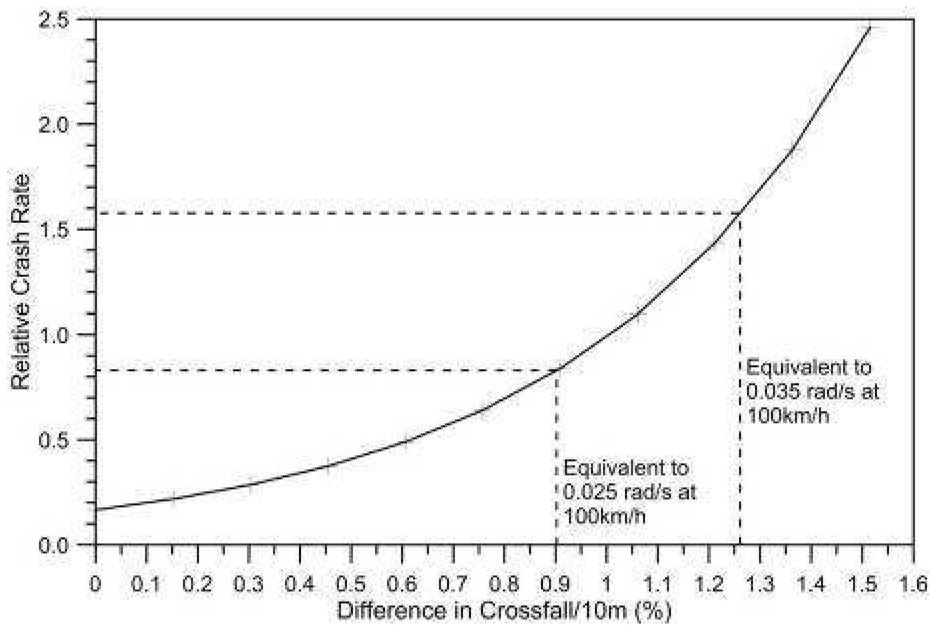


Figure 4.1 shows that varying the change in crossfall per 10m between the two threshold limits for rate of rotation corresponds to slightly less than a doubling in the crash rate. It also shows there does not appear to be a critical threshold value for rate of rotation (change in crossfall) above which the relative crash rate increases more dramatically.

4.2 Road crashes and geometry – Wellington region

Given the similarities between the geometry and rate-of-rotation data between the different regions, it was decided for logistical reasons to concentrate the extraction and assessment of crash data to one region. The Wellington region, which includes the lower North Island and upper South Island, was considered to 1) represent a sufficiently diverse range of road geometry, traffic and crash types, and 2) contain road sections suitable for the on-road measurements. Accordingly, data was extracted from the RAMM crash database for all crashes in this region between 1980 and 2008. The data included the location, direction, movement codes (eg crossing/turning, overtaking, straight-loss of control, bend-loss of control), lane, surface and weather, for a total of just under 24,500 crashes. The crash data was matched to the geometry and rate-of-rotation data via linear referencing of the crash locations to create a combined database. Note: the RAMM crash database contains only those crashes that are reported, and not those that are resolved at the scene without recourse to emergency services.

4.2.1 Crashes and rate of rotation

Given the wide variety of crashes and causes, and the focus of this project on rate-of-rotation limits, it was considered appropriate to filter the crash data to concentrate only on those which were potentially related to rate-of-rotation issues. Accordingly, the crash data was filtered to remove all but the loss-of-control crashes on bends for speed zones 70km/h and higher, leaving a total of around 3200 crashes. As described in section 3.2, the theoretical 85th percentile speed was employed in calculating the rates of rotation. Figure 4.2 shows the resulting histogram plot comparing the number of crashes with the absolute rate-of-rotation data.

Figure 4.2 Loss of control crashes on curves versus absolute rate of rotation – Wellington region

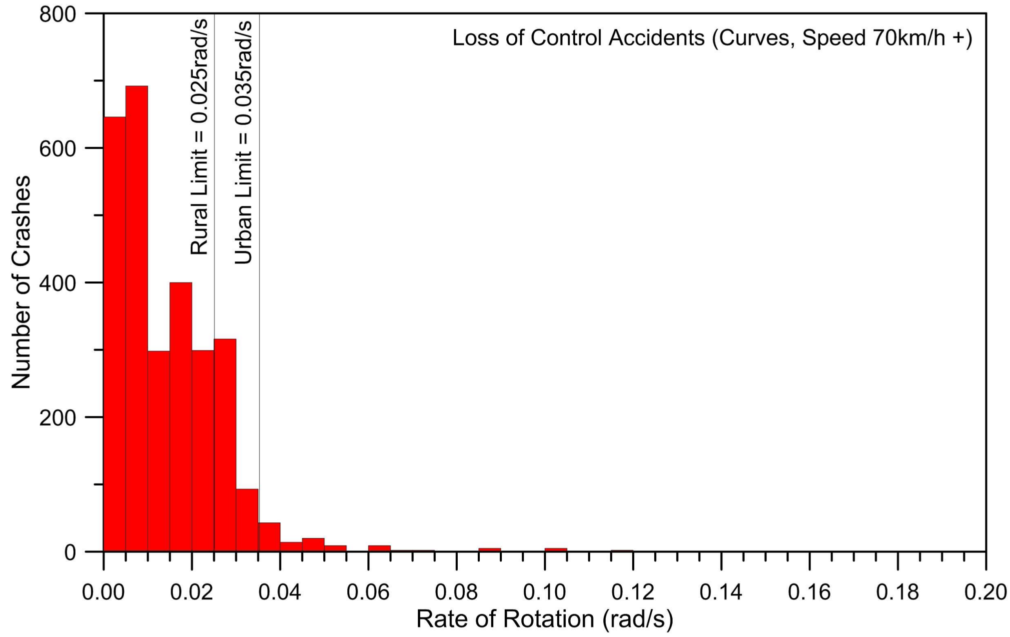


Figure 4.2 shows a significant number of the loss-of-control crashes on curves in the Wellington region for speed zones 70km/h or higher where the absolute rate of rotation was higher than the 0.025 rad/s (~17% of the loss-of-control crashes) and 0.035 rad/s (~4% of the loss-of-control crashes) guideline limits. However, from this analysis of the crash data there does not appear to be a critical limit for rate of rotation above which the number of loss-of-control crashes on curves is consistently higher. This agrees with the statistical analysis presented in section 4.1.

The crash data was further refined given the logistical considerations for the on-road testing and computer simulation objectives. An examination was made of the geometry and rate-of-rotation data for the Wellington region to assess the suitability of the state highway sections within the region for the on-road testing, with the additional requirements that 1) the rates of rotation should range from low values up to and over the current design criteria and 2) there be a reasonable range of geometries, including a range of transition lengths. It was decided that State Highway (SH) 58, between SH2 and SH1, north of Wellington, fitted these requirements. Figure 4.3 shows an aerial photo of SH58.

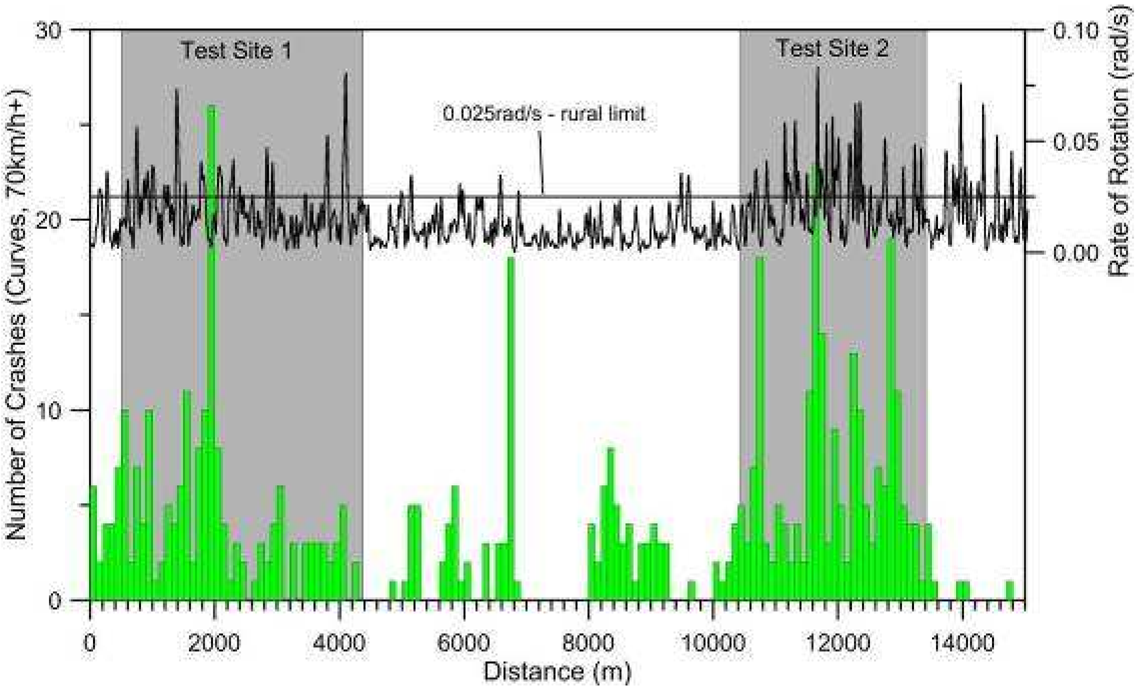
Figure 4.3 Aerial photo of SH58 (increasing direction towards west, decreasing towards east)

Accordingly, the crash database was filtered to give all the crash data for this road, in the decreasing direction, amounting to a total of around 550 crashes. Figure 4.4 shows the locations of the crashes, together with the 30m moving average rate of rotation, again based on the 85th percentile speed.

With reference to section A1 of appendix A, rate of rotation is directly proportional to vehicle speed. In the majority of the loss-of-control crashes, it is likely the speeds involved will be in excess of the 85th percentile speed. Therefore, the rate-of-rotation values plotted in figure 4.4 can be regarded as being at the lower end.

The use of 95th or 99th percentile speed would have been more appropriate but there are no validated relationships for converting theoretically derived 85th percentile speeds to these higher percentile speeds. However, this is unlikely to be an issue as locations where the rate of rotation is significantly higher than the surrounding values is of particular interest in crash analysis and this will still be highlighted irrespective of whether the 85th percentile or a higher percentile speed is used.

Figure 4.4 SH58 decreasing direction – loss of control crashes on curves and absolute rate of rotation (based on theoretical 85th percentile speed)



With reference to figure 4.4, crashes are generally clustered in areas where the rate of rotation is high, eg between 0m and 4000m, and between 10,000m and 13,000m.

4.2.2 Transition lengths

Austroads (2003) gives recommendations for the transition lengths (ie the length over which the crossfall is developed from the normal crossfall to the full curve superelevation) for different design speeds and superelevations. This means if the recommended development length or longer is used the rate of rotation should be below the recommended 0.025 rad/s guideline threshold. For example, given design speeds of 50km/h and 100km/h and a superelevation of 0.10 (10%), the Austroads recommended development lengths are 50m and 145m respectively.

Figure 4.5 plots the crossfall for SH58 in the decreasing direction. This shows that on this approximately 15km long section of road the crossfall varies considerably over relatively short distances. To test whether the existing road had adequate superelevation lengths, two short sections were extracted:

1. An 'isolated' curve – a curve between two straights (5400m to 4700m in the decreasing direction from figure 4.4)
2. A more complex combination of curves (12,000m to 11,600m in the decreasing direction from figure 4.4).

The average theoretical 85th percentile speed over these two lengths is 90km/h for the 5400m to 4700m section and 50km/h for the 12,000m to 11,600m section.

These sections were chosen more on the basis of the road geometry than the number of crashes. However, it can be seen from figure 4.4 that this second section has one of the higher crash rates along SH58.

Figures 4.6 and 4.7 show the curvature, crossfall and rate-of-rotation data (based on 85th percentile speed) for these two road sections. These figures also highlight the rate-of-rotation guideline of

0.025 rad/s. Superimposed over these plots is the Austroads recommended superelevation lengths of 130m (ie 90km/h design speed) and 50m (ie 50km/h design speed), which have been anchored on the peak superelevation (crossfall).

Figure 4.5 Variation of crossfall – SH58 decreasing direction (transition length sections are shaded)

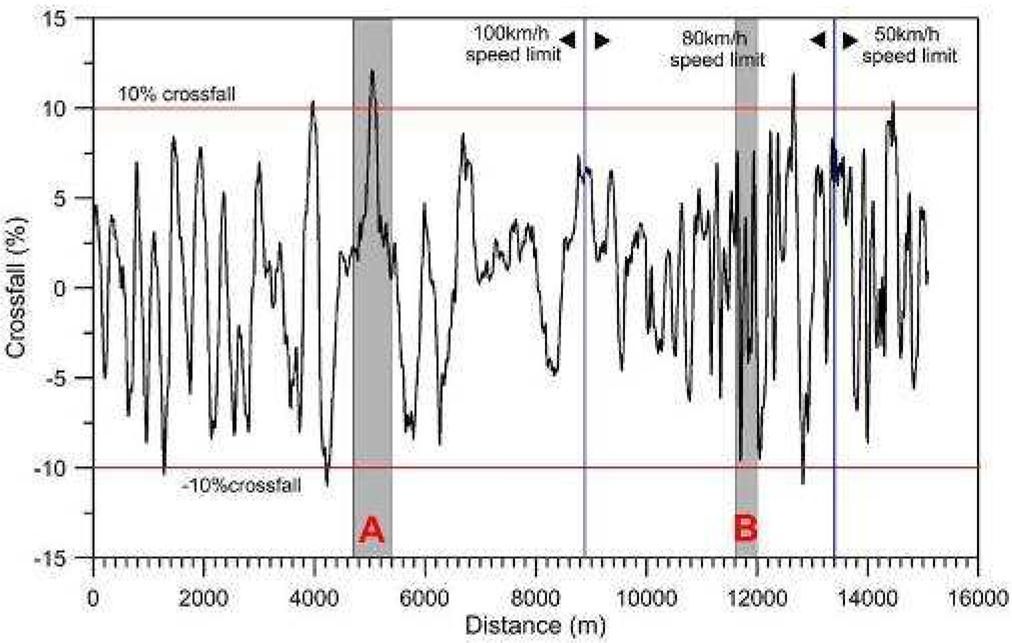


Figure 4.6 Isolated curve - curvature, crossfall and absolute rate of rotation based on 85th percentile speed – Site A, SH58 (5400–4700m – decreasing direction, 9km/h design speed)

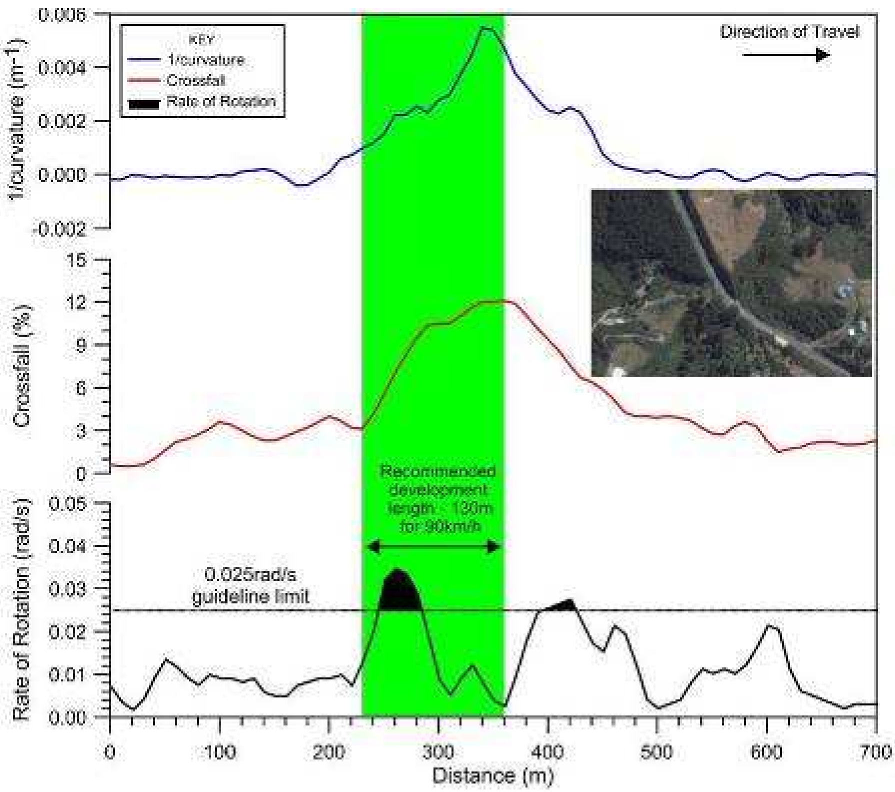


Figure 4.7 Complex curves – curvature, crossfall and absolute rate of rotation based on 85th percentile speed – Site B, SH58 (12,000–11,600m – decreasing direction, 50km/h design speed)

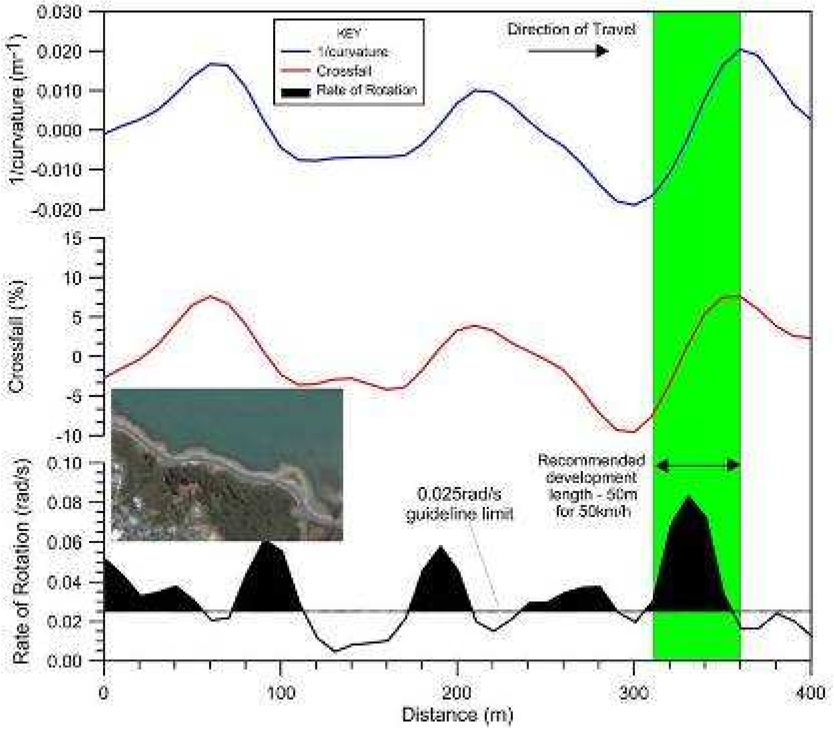


Figure 4.6 shows the isolated curve is properly designed with the crossfall rising from 3% on the straight to a maximum value of around 12% at the apex of the curve within the Austroads recommended superelevation development length of 130m. The rate of rotation reaches a maximum value of 0.035 rad/s within this development length. This marginally exceeds the lower criterion value of 0.025 rad/s applying to design speeds of 80km/h and above.

For the multiple curve situation shown in figure 4.7, which is not atypical of SH58, the crossfall is again shown to increase continuously within the Austroads recommended superelevation development length of 50m. However, in this case the maximum rate-of-rotation value is 0.085 rad/s. This is a factor of 2.5 times greater than the criterion value of 0.035 rad/s applying to design speeds less than 70km/h.

For the other curves shown in figure 4.7, all but one have a maximum rate-of-rotation value within their superelevation development length that exceeds the criterion value of 0.035 rad/s, with the typical value being around 0.06 rad/s. As can be seen from figure 4.4, this section of SH58 has a high frequency of crashes compared with the rest of this state highway.

Given that SH58 carries many thousands of vehicles each day without large numbers of complaints being registered about ride comfort or safety concerns, the rate-of-rotation values shown in figure 4.7 raise a number of questions such as the appropriateness of the current rate-of-rotation design criteria; road users' unwillingness to complain about road geometry matters; and road users' seeming acceptance of substandard road geometry in complex terrain.

5 On-road measurements of rate of rotation

The on-road test programme to measure actual levels of rate of rotation, including the site and vehicle selections and the instrumentation and data acquisition system used, is detailed below.

5.1 Site selection

As discussed in chapter 1, road geometry data (gradient curvature and crossfall) for the lower North Island was extracted from the RAMM database. Rates of rotation were calculated for the state highways within this area, and these were compared with the design criteria of 0.025 rad/s for rural roads (speed limits of 80–100km/h) and 0.035 rad/s for urban roads (speed limits of 70km/h and under). All of the state highways within this area showed rate-of-rotation values that ranged up to and exceeded these criteria values. Accordingly, selection of the sites for the on-road measurement programme was based primarily on logistical requirements. Two sections of SH58, between SH2 and SH1 north of Wellington, were selected.

Figures 5.1 and 5.2 show the rates of rotation for the entire ~15km length of this state highway in both the increasing and decreasing directions. The two sections chosen for testing were 1) route position (RP) 0/0.48 – 0/4.36, and 2) 0/10.40 – 0/13.44. Section 1 operates under a 100km/h posted speed limit, while section 2 operates under an 80km/h posted speed limit.

Both of these figures show that, over the selected 15km length of SH58, there are a significant number of locations where the rate of rotation exceeds the current design criteria.

Figure 5.1 SH58 – rate of rotation based on 85th percentile speed (increasing direction)

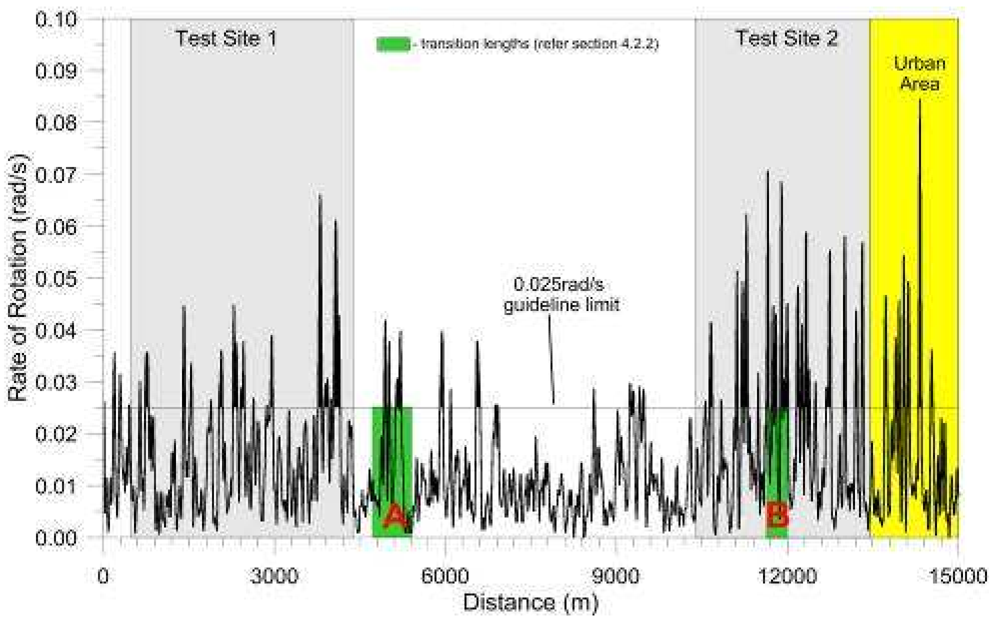
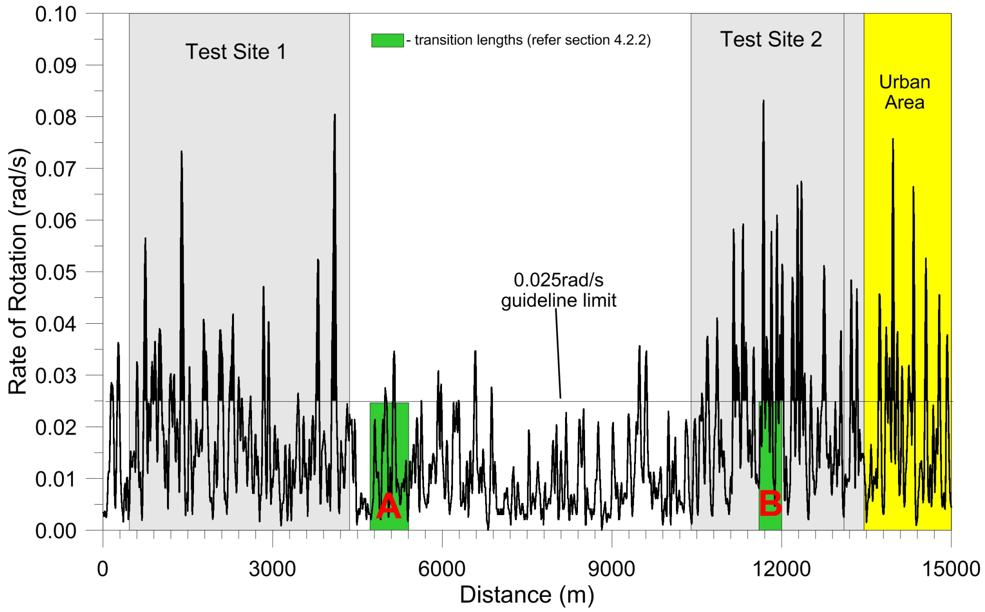


Figure 5.2 SH58 – rate of rotation based on 85th percentile speed (decreasing direction)



5.2 Vehicle selection and instrumentation

Three vehicles were selected for the on-road test programme, these being a passenger car (Toyota Corolla wagon), a four-wheel drive (Isuzu Bighorn), and a light truck (Isuzu Model FRR 5T). Views of these vehicles are shown in figures 5.3 to 5.5.

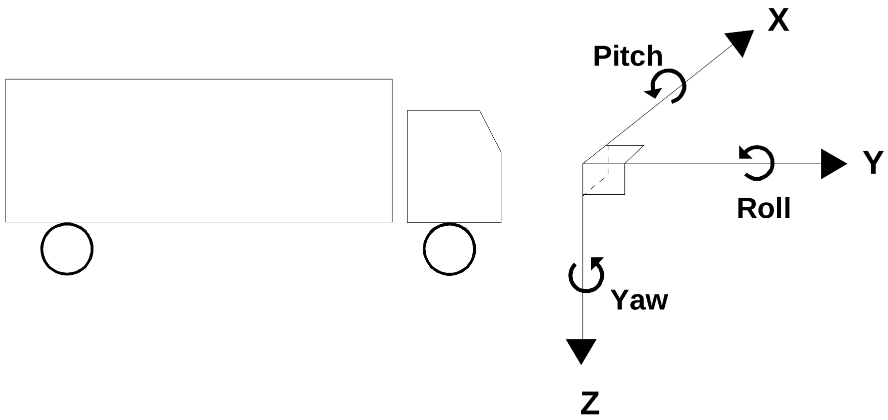
Figure 5.3 Test vehicle 1 – Toyota Corolla wagon

Figure 5.4 Test vehicle 2 – Isuzu Bighorn 4WD

Figure 5.5 Test vehicle 3 – Isuzu Model FFR 5T truck

Each of the vehicles was instrumented in turn with three orthogonal gyroscopes to measure pitch roll and yaw, as shown in figure 5.6, and three accelerometers to measure longitudinal, lateral and vertical accelerations (Ay, Ax and Az). An event marker was used to record the start and ends of the test sections. Data was recorded using a PC-based data acquisition system at a rate of 100Hz. At a travel speed of 100km/h, this corresponded to acceleration and rotation readings being taken every 0.28m along the state highway.

Figure 5.6 Measurement system coordinate axes



5.3 On-road testing

Each of the three test vehicles was driven over the two test sections in both the increasing and decreasing directions at set speeds. The vehicle speed was maintained at as constant a speed as possible, given the geometry and traffic conditions. Sampling was initiated prior to entering the test section and the event marker used to mark the start and end points of the test section. A number of the test runs at the highest speed were repeated.

The matrix of test speeds for each vehicle and test section is given in table 5.1. On section 1, the test speeds for the truck were set at 10km/h lower than for the other vehicles to account for the maximum allowable speed for trucks being 90km/h instead of 100 km/h for the other two vehicles.

Table 5.1 Test section measurement speeds

Vehicle	Measurement speed (km/h)	
	Section 1 (RP 0/0.48 – 0/4.36)	Section 2(0/10.40 – 0/13.44)
Car	80, 90, 100	60, 70, 80
4WD	80, 90, 100	60, 70, 80
Truck	70, 80, 90	60, 70, 80

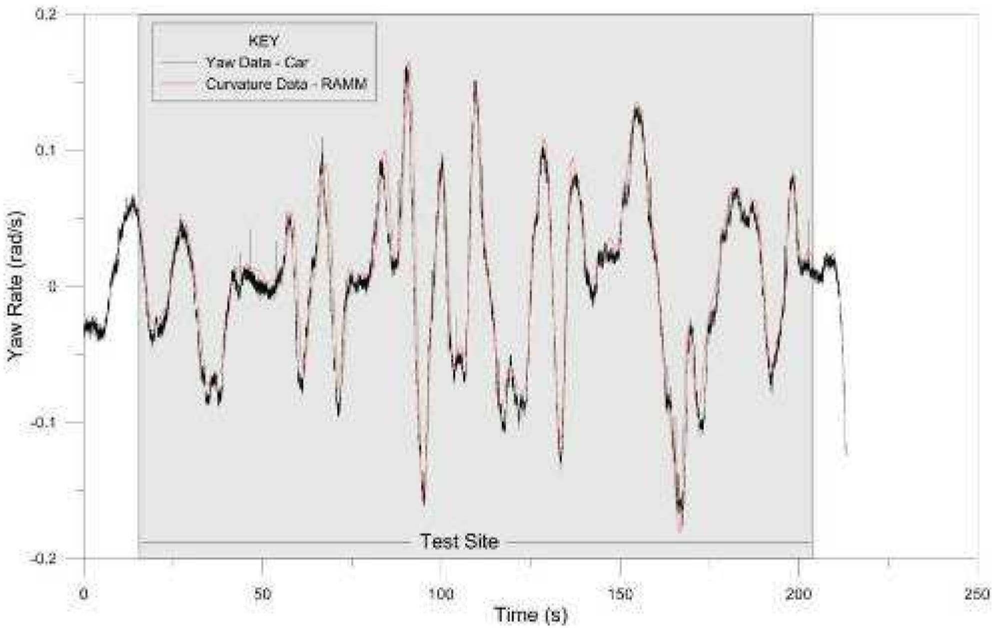
6 Processing and analysis of field data

6.1 Initial processing

Each of the data files for the test runs was edited to the event marked start and end points. Calibration equations were applied to the accelerometer and gyroscope signals to provide Ax, Ay and Az accelerations in m/s^2, and pitch, roll and yaw in degrees/s (deg/s).

Before any further analysis was carried out, an initial check on the data was carried out to compare the measured yaw data in the first test vehicle (the car) on one of the two test sites at 60km/h with the corresponding data derived from the RAMM database curvature data. The results of this comparison are shown graphically in figure 6.1.

Figure 6.1 Example comparison of measured yaw data and RAMM curvature data



With reference to figure 6.1, close agreement is observed between the yaw rates measured in the car for a constant speed and those derived from curvature data in the RAMM geometry table using the calculation procedure given in appendix A.

6.2 Overall data summary and trends

Presenting 36 plots of the rate-of-rotation data for each of the three vehicles, each of the test speeds and both of the test sections was considered to be not beneficial in highlighting differences between the vehicles. Therefore, it was decided to first assess the overall differences in the rates of rotation between the vehicles for the different speeds and test sites and then investigate in more detail the rates of rotation for the vehicle found to be most sensitive to the road geometry variations.

Table 6.1 presents for each of the test sites the absolute maximum rate-of-rotation values measured for each of the test runs for each of the vehicles.

Figures 6.2 and 6.3 summarise this data graphically for each of the two test sites, with trend lines to identify variations between vehicles and with speed.

Table 6.1 Summary of rate-of-rotation data

Vehicle speed (km/h)	Absolute maximum (rad/s)					
	Section 1 (RP 0/0.48 – 0/4.36)			Section 2 (0/10.40 – 0/13.44)		
	Car	4WD	Truck	Car	4WD	Truck
Increasing direction						
60	–	–	–	0.070	0.074	0.074
70	–	–	0.078	0.078	0.064	0.080
80	0.072	0.070	0.090	0.074	0.072	0.072
80	–	–	–	–	0.068	0.084
90	0.072	0.070	0.096	–	–	–
90	–	–	0.092	–	–	–
100	0.078	0.068	–	–	–	–
100	0.076	0.072	–	–	–	–
Decreasing direction						
60	–	–	–	0.080	0.092	0.114
70	–	–	0.078	0.078	0.070	0.118
80	0.078	0.090	0.100	0.078	0.080	0.112
80	–	–	–	–	0.066	0.112
90	0.088	0.094	0.094	–	–	–
90	–	–	–	–	–	–
100	0.090	0.092	–	–	–	–
100	0.084	0.090	–	–	–	–

Figure 6.2 Absolute maximum rate-of-rotation data (vehicles and speed) – site 1

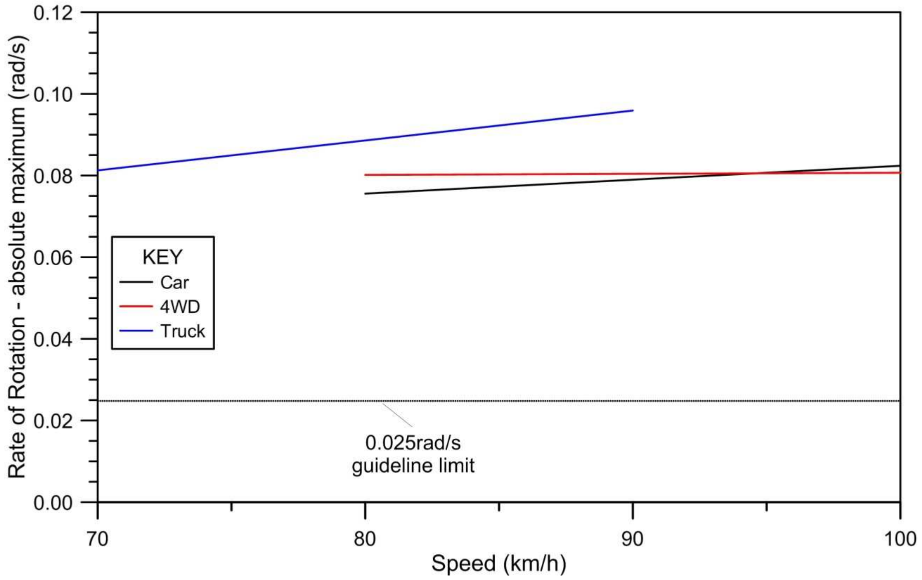
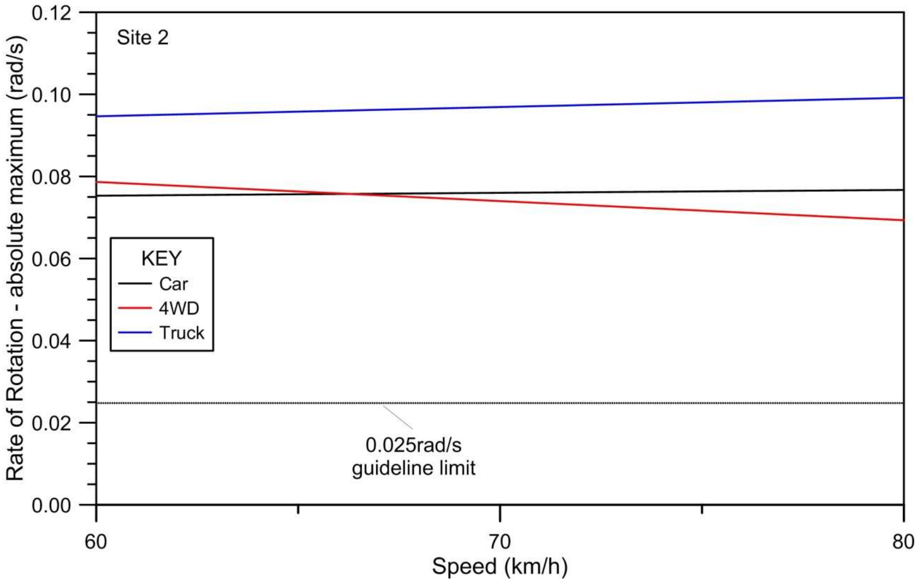


Figure 6.3 Absolute maximum rate-of-rotation data (vehicles and speed) – site 2



The two main points to note are as follows:

For each of the vehicles, there are locations on both sites where the rate of rotation exceeds the design criterion of 0.025 rad/s for rural roads.

1. The car and truck show increases in the maximum rate of rotation with speed for both sites, but the trend with speed for the 4WD is flat for one site and down for the other. This suggests the suspension of the 4WD is either set up or responds differently to the road geometry, particularly the variation in crossfall and roughness.
2. The rate-of-rotation levels are higher on both sites for the truck, while those for the car and 4WD are generally similar.

Plots that compare the similarities and differences between the measured rate-of-rotation data for all three vehicles at one speed, and for the truck at all three test speeds are given in appendix C. These plots show that, while there are similarities between the locations where the rate of rotation exceeds the design criterion for rural roads of 0.025 rad/s, there are also noticeable differences, where one or more, but not all three, vehicles exceed the limit. These differences may be due to dynamic (suspension and tyres) characteristics of the vehicle or driver steering inputs.

As the truck produced the highest measured rates of rotation on site 2, the rate-of-rotation data for the lowest and highest test speed are presented in figures 6.4 and 6.5. These figures graphically illustrate the similarities and differences typically found in the measured data across the different test sites, vehicles and speeds.

Figure 6.4 Rate of rotation and yaw rate, site 2, decreasing direction – truck (60km/h)

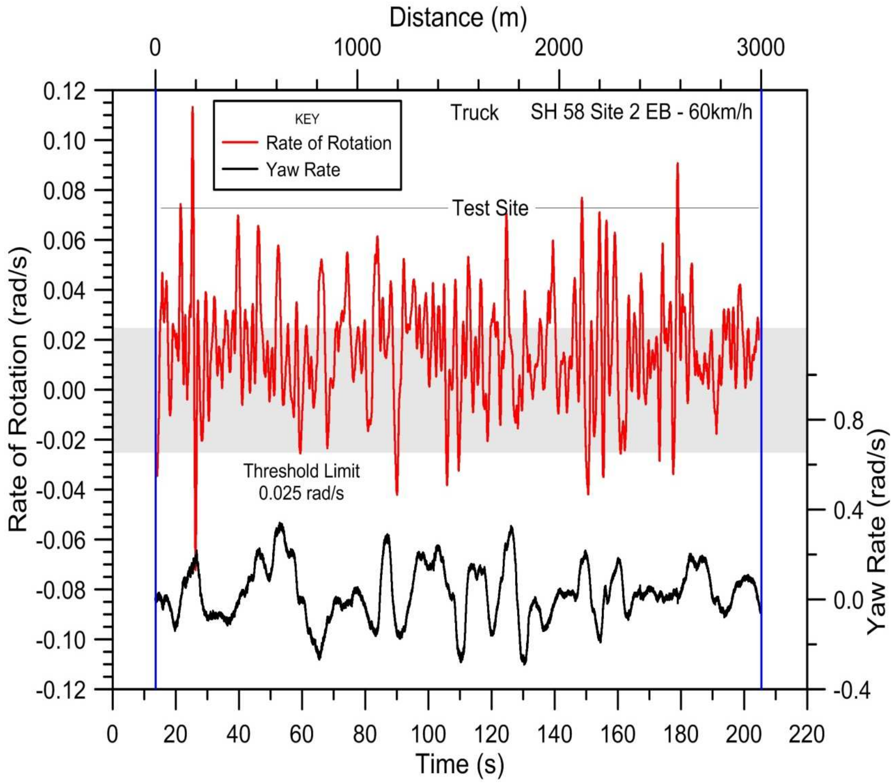
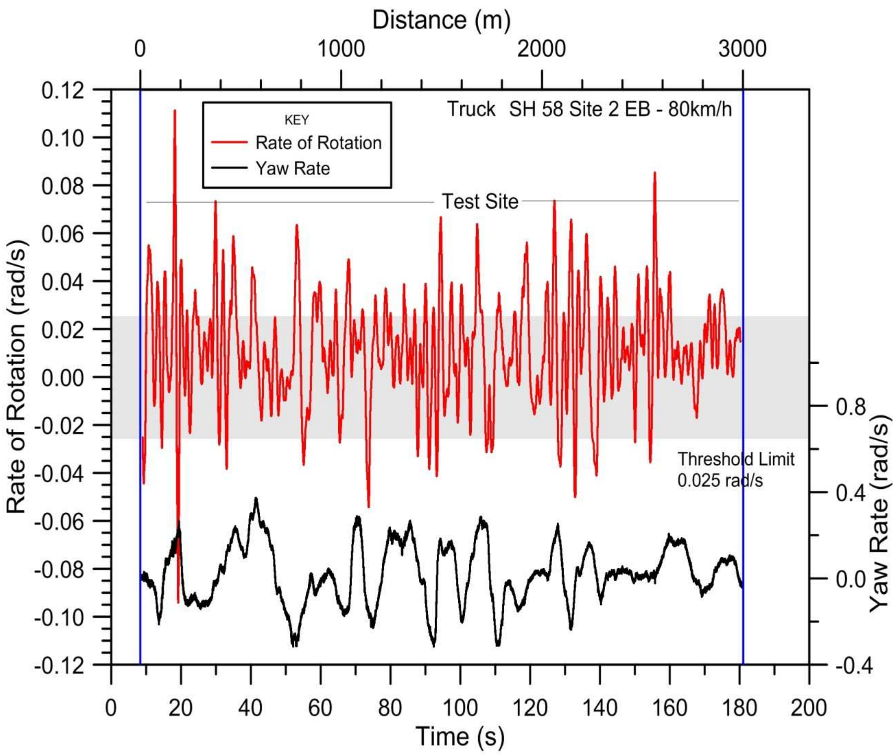


Figure 6.5 Rate of rotation and yaw rate, site 2, decreasing direction – truck (80km/h)



The main points to note from these plots are:

1. There are many locations where the rate of rotation exceeds the design criterion of 0.025 rad/s and there are also locations where they exceed the 0.075 rad/s level proposed by Jamieson and Cenek (2001) for comfortable ride quality.
2. The locations where the 0.025 rad/s criterion is exceeded are generally consistent, but the actual values vary, most likely because of the dynamic interactions between the undulating road surface and the vehicle suspension.
3. There does not appear to be a large effect on the peak values due to the vehicle speed. Again, this is thought to be due to the effects of the vehicle suspension.

6.3 Comparison of measured and geometry-based data

Earlier figures showed the rates of rotation calculated from the changes in crossfall listed in the RAMM database. These rates were based on the differences in crossfall between adjacent 10m sections and an assumed design speed of 110km/h. They only take account of the road surface, not the dynamic effects of the vehicle tyres and suspension. However, we can compare the measured rate-of-rotation data with that predicted from the crossfall data by using the survey speed as the design speed.

A comparison between the measured data on site 2 for the truck at 60km/h and the rate of rotation estimated from the geometry data, also for a travel speed of 60km/h are given in figure 6.6.

Figure 6.6 Calculated and measured rotation and yaw rates, site 2, decreasing direction – truck at 60km/h

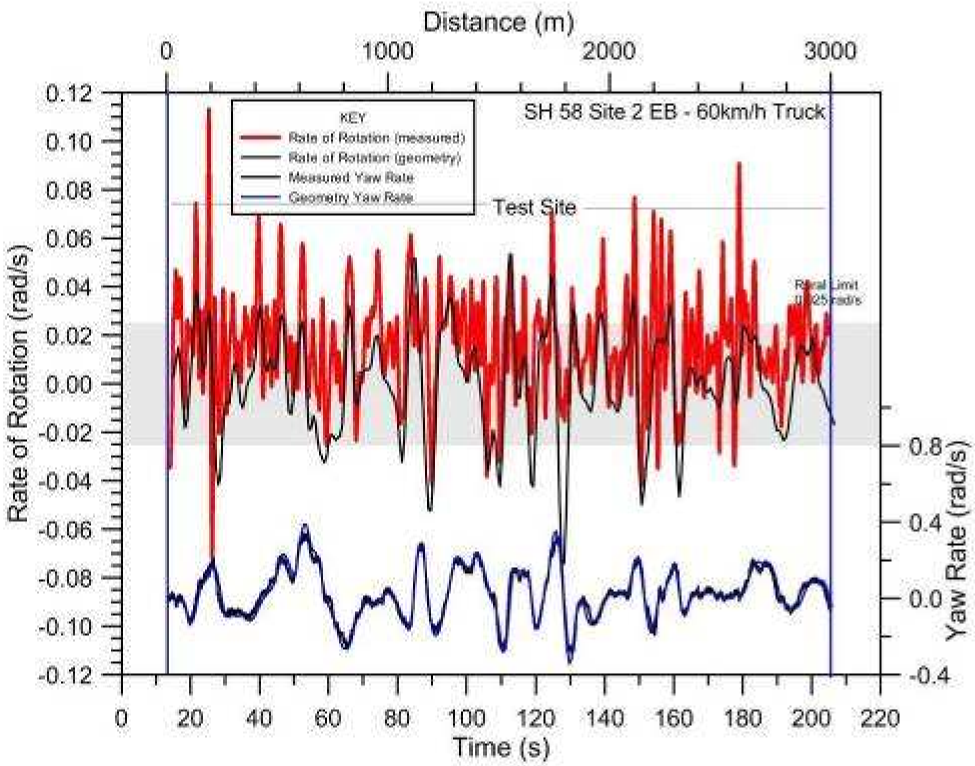


Figure 6.6 shows:

- the geometry calculated rate of rotation is generally, but not always, less than the measured rotational response of the vehicle
- as expected, the truck is sensitive to crossfall changes, with a larger number of locations where the 0.025 rad/s criterion was exceeded
- numerous locations where the geometry-calculated rate of rotation also exceeded the 0.025 rad/s criterion.

Of particular interest on site 2 is one section where the measured response for all three vehicles was significantly greater than the 0.025 rad/s and 0.035 rad/s criteria and also the geometry-derived rate-of-rotation value. This can be seen in the plot for the truck shown in figure 6.6 at around 200m after the start of the test site. This section was noted by the both driver and passenger as having an uncomfortable ride and being one the worst locations on the two test sections. Here, the magnitude of the rate of rotation was around 0.11 rad/s.

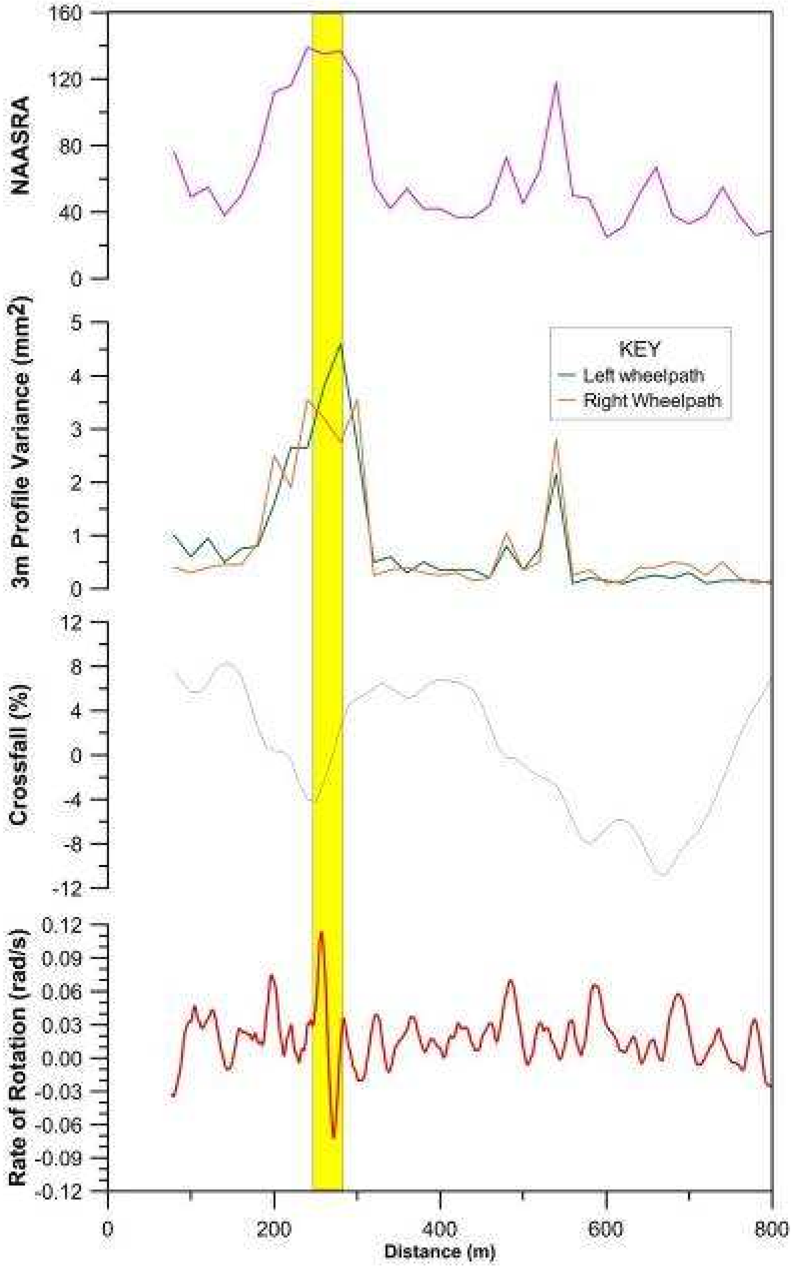
In figure 6.7, the crossfall and roughness (National Association of Australian State Road Authorities ((NAASRA)) lane roughness and 3m wheelpath profile variance) data has been plotted together with the rate-of-rotation data for a short length of site 2 in the vicinity of where the high measured rate of rotation occurred for the decreasing direction only. Profile variance is a measure roughness that records the difference between the actual road profile and its moving average over selected moving average lengths (Jamieson 2008).

The 3m profile variance value reflects the unevenness associated with profile features that have a wavelength of 3m or less. High values of 3m profile variance typically arise from short wavelength features such as potholes and poor reinstatements.

Figure 6.7 shows there is nothing special about the variation of crossfall that would necessarily account for the high measured rate of rotation seen at this location. However, both the NAASRA roughness and 3m profile variance are consistently higher than elsewhere on this section, and indeed all of site 2, apart from some isolated locations.

It should be noted the roughness levels are by no means high compared with other locations on the state highway network although both the NAASRA lane roughness and 3m profile variance values are close to the threshold values adopted for maintenance intervention of rural single carriageway roads (ie 110 NAASRA counts/km and 5.5mm^2 3m profile variance). Therefore, it appears the combination of roughness and geometry is exacerbating the rate of rotation at this location. This is consistent with previous work by Jamieson and Cenek (2001) on truck ride quality, which found that according to drivers, roll (rate of rotation) was of most concern, particularly when combined with pitch. The work on truck ride quality suggested a comfort threshold value of 4.25 deg/s (~0.075rad/s) based on the resultant of the pitch and roll rates.

Figure 6.7 Comparison of geometry and roughness data with measured rate-of-rotation data, site 2, decreasing direction



7 Computer simulations

Having looked at the measured rates of rotation from the on-road testing at different speeds, and the derived values from geometry data, the next steps were to 1) use these values to calibrate the computer simulation model, and then 2) extend the speed and geometry parameters in the computer simulation model to establish whether rate-of-rotation limits for safety could be determined.

7.1 Background – PC Crash™ V9.0

The computer simulation software package selected for the simulation models was PC Crash™ V9.0. This is an internationally recognised three-dimensional vehicle collision and trajectory simulation tool used by police and civilian crash investigators and analysts. Three-dimensional (3D) road models can be created in computer-aided design packages from surveyed data and imported in the simulation software, or created within the software by either drawing contours then laying a surface over them, or by generating a 3D road element by modifying elevation, radius, crossfall and width parameters. Surface friction values can also be defined either as a standard value for the entire surface, or as friction polygons with specific defined dimensions and values. Vehicles, including cars, trucks, buses, vans and motorcycles can then be imported from a number of different databases covering a wide range of vehicle manufacturers. Vehicle paths and speeds, including sequences of acceleration and braking can then be defined. When the simulation is run using the default kinetic model, the vehicle will obey the laws of physics and will follow the specified path unless the speed becomes too great for the simulation conditions, eg if the friction is too low, or if rollover occurs. Appendix B contains a summary listing of the features of PC Crash™ V9.0.

7.2 3D road simulation

It was not considered necessary to simulate the entire lengths of the two on-road test sections to calibrate the PC Crash™ model. Rather, it was only necessary to select a section where the ranges of curvature and crossfall spanned those found on these two test sections. Accordingly, a 700m long section of the SH58 RP 0/10.40 – 0/13.44 site (ie test site 2) was chosen for the calibration simulation. Figure 7.1 shows an aerial view of this section. Data extracted from the RAMM database showed the horizontal curvature within this section varies from around -2000m to +2000m, and gets as low as -60m and +40m, while the crossfall varies between around -12% and +12%. Full surveying of this section was beyond the scope and budget of this project. The only feasible alternative was to use the existing RAMM geometry data. However, this data is given in 10m increments, which was deemed to be too coarse for the calibration of the computer simulation model, given that the model is constructed from a series of polygon surfaces. Accordingly, spline interpolations of the geometry at 1m increments were generated from the 10m geometry data. These were used to generate a 3D model of the road section in the PC Crash™ simulation. Figure 7.2 shows a plan view of the generated road section. Note: the orientation differs from the aerial photo because the 3D model is progressively generated from an initial origin point and curvature. Also included on this view is the drive path (red line) for one of the simulated vehicles travelling in the increasing direction (left to right across figure 7.1 corresponding to a compass direction of east to west).

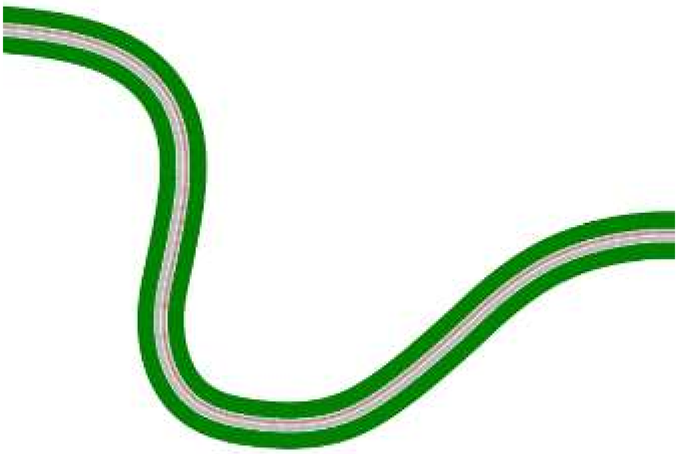
7.3 Simulation testing – PC Crash™ calibration

Having set up the 3D road simulation within PC Crash™, the next step was to determine whether PC Crash™ could replicate the yaw and rate-of-rotation data measured during the on-road testing. Again, rather than running simulations for each of the three test vehicles and each of the three test speeds, the car and truck at travel speeds of 60km/h and 80km/h were selected as representing the extremes of the vehicle responses, including the rate of rotation.

Each of the two vehicles was imported into the simulation and placed on the surface at the start of the 3D road model. The vehicle simulation includes parameters relating to the geometry (size, shape, dimensions), suspension, weight, moments of inertia, CoG location, tyres, steering and braking inputs, passenger weights and locations, and safety features, such as anti-lock braking system (ABS) and electronic stability program (ESP), among others. Many of these parameters can be individually tailored to the specific scenario being modelled. For example, the suspension properties can be varied from soft, to normal, to hard, each of which affects the suspension stiffness and damping.

Figure 7.1 Aerial view of corner section selected for simulation

Figure 7.2 Plan view of 3D road model constructed for simulation



A standard path following the centre of the lane was drawn for each vehicle to follow. Options within the program allow vehicles to be anchored to this path at selected points, including the CoG, or any of the four wheels. The CoG location was used in all simulation runs.

Once the vehicle is positioned and aligned, the velocity for the simulation can be set, and the run initiated. The simulation will run for either a specified time or distance. Displays of output parameters, including pitch, roll and yaw rates, can be generated and the data for these written to files for later plotting or analysis.

Simulations were run for the Toyota Corolla station wagon and the Isuzu truck for speeds of 60km/h and 80km/h. Data files were generated for the yaw and roll rates in each case. Figures 7.3 to 7.6 compare the yaw and roll rates derived from geometry data in RAMM, on-road measurements and the PC Crash™ simulations.

It was expected there would be differences between the on-road measured and PC Crash™ derived vehicle responses because of 1) the somewhat variable travel speed of the vehicles that affects measured data, and 2) the necessary use of the RAMM road geometry data, which represents smoothed data because of the 10m averaging utilised. The latter is the most likely explanation for some of the short duration spikes that are seen in the plotted on-road measured vehicle responses but absent in the PC Crash™ derived vehicle responses. However, there is sufficient agreement between the measured and simulated vehicle response data to suggest PC Crash™ can be used with a degree of confidence to explore rate-of-rotation issues relating to safety.

The other point to note from figures 7.3 to 7.6 is that while yaw rates derived purely from geometry data from RAMM agree well with the measurements and simulations, the same cannot be said for rates of rotation, with the RAMM geometry-derived values being significantly less. This result highlights the need for on-road measurements or computer simulations when investigating potential safety issues arising from sudden changes in superelevation.

Figure 7.3 Comparison of geometry, on-road and computer simulation data – car (60km/h)

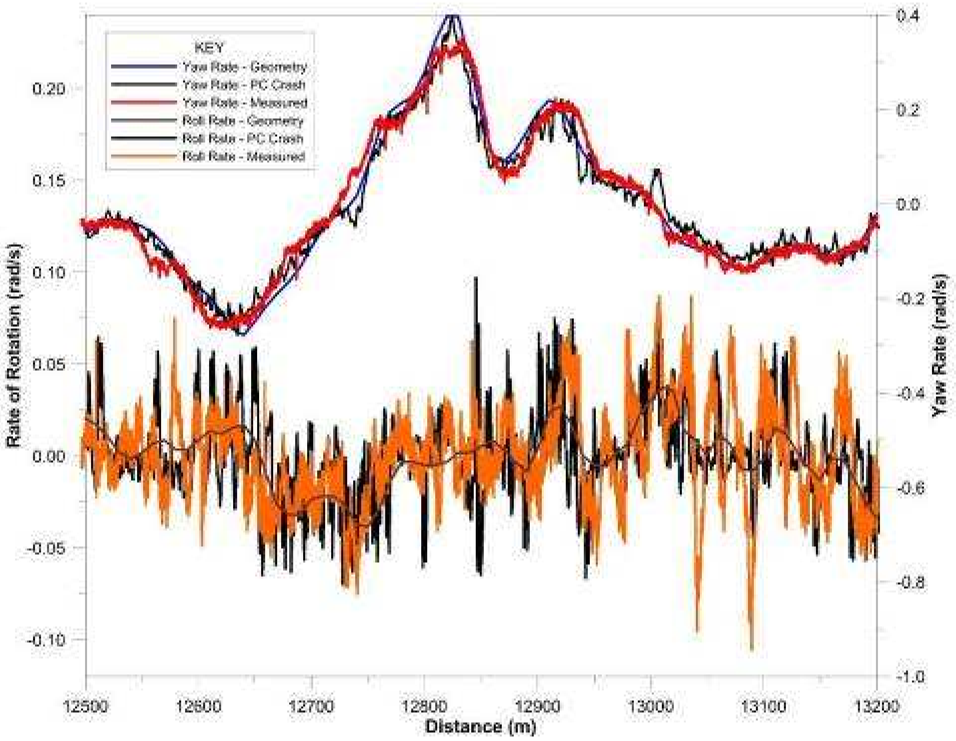


Figure 7.4 Comparison of geometry, on-road and computer simulation data – car (80km/h)

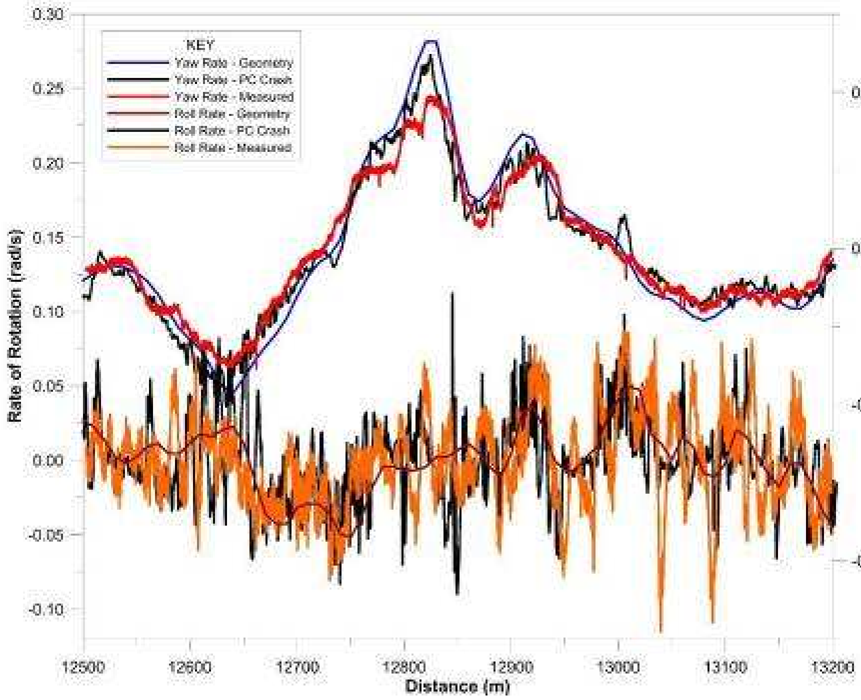


Figure 7.5 Comparison of geometry, on-road and computer simulation data – truck (60km/h)

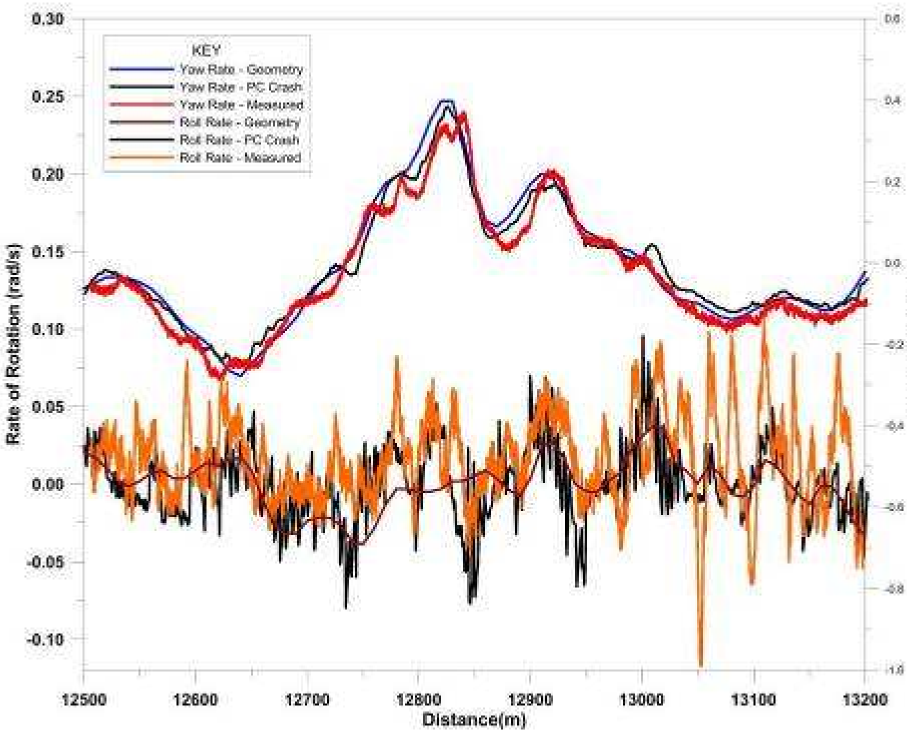
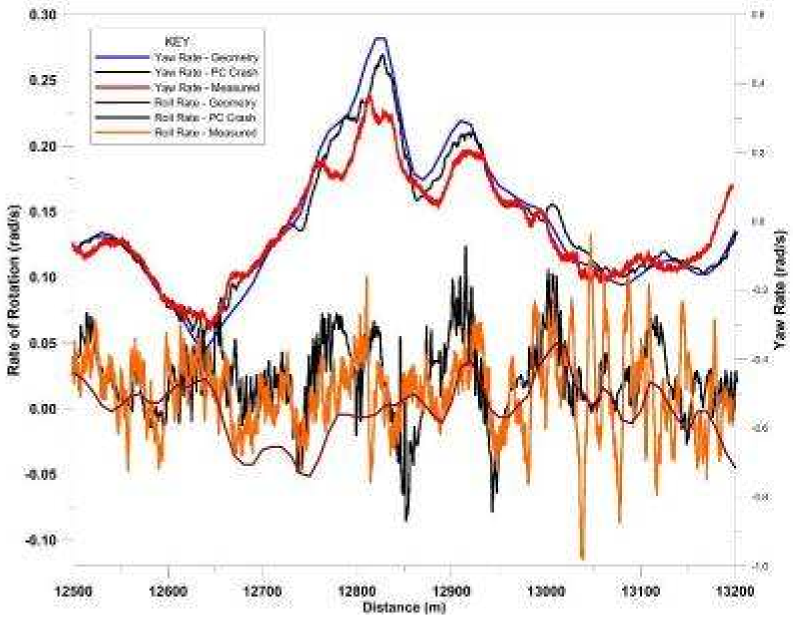


Figure 7.6 Comparison of geometry, on-road and computer simulation data – truck (80km/h)



7.4 Simulation testing - safety

Given the abundance of vehicle models and the wide variations in vehicle speeds and road geometry that can be found on New Zealand roads, there is potentially a huge number of combinations that could be modelled in computer simulations. Therefore, choices had to be made regarding the vehicles, speeds and road geometries.

The vehicles chosen were those used in the on-road testing and for the PC Crash™ simulation calibration, ie a car (Toyota Corolla), an SUV (Isuzu Bighorn), and a medium truck (Isuzu FRR), with the further inclusion of a heavy truck in the form of an Isuzu Gigamax EXY (see figure 7.7). These four vehicles were considered to represent a good coverage of the New Zealand vehicle fleet.

For each of the simulations, it was assumed the vehicles had a driver and front seat passenger. For each of the two trucks, simulations were run empty and loaded, with consequent assumptions about the change in the CoG.

The road geometries for the safety-related simulations were chosen based on a combination of:

- the range of geometries found on existing curves on the state highway network
- the Austroads (2003) *Rural road design – guide to the geometric design of rural roads*
- issues identified within the trucking industry, eg roundabouts.

To have an appreciation of the degree of variation in crossfall for a given radius of horizontal curvature that can be expected on the state highway network, a plot of curvature versus crossfall has been provided in figure 7.8 for a typical 16km section of rural state highway. Figure 7.9 shows how the crossfall varies between consecutive 10m lengths over the same 16km section of rural state highway.

The plots in figures 7.8 and 7.9 were used to derive the ranges of geometry parameters examined with the PC Crash™ simulations, as tabulated in table 7.1

Figure 7.7 View of typical Isuzu Gigamax model EXY heavy truck

Figure 7.8 Variation of crossfall for a specified value of horizontal curve radius found on a representative 16km section of rural state highway

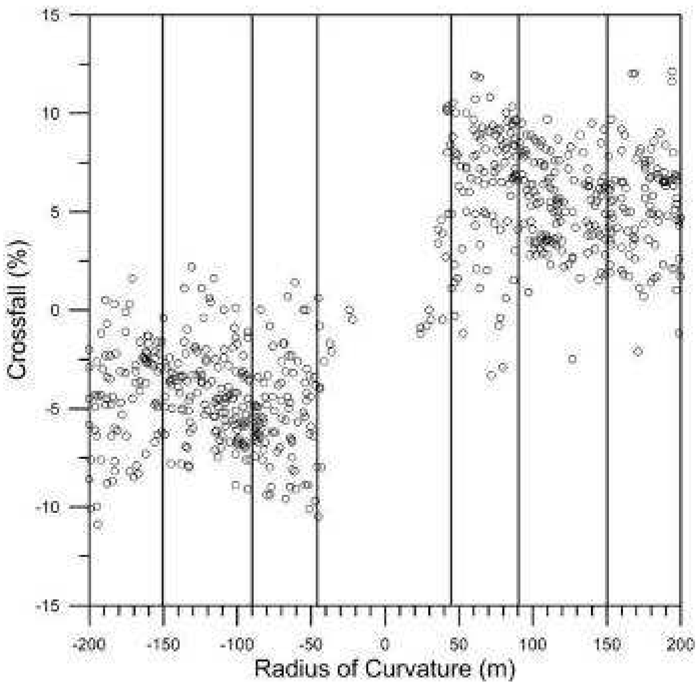


Figure 7.9 Typical crossfall variation over consecutive 10m sections of rural state highway

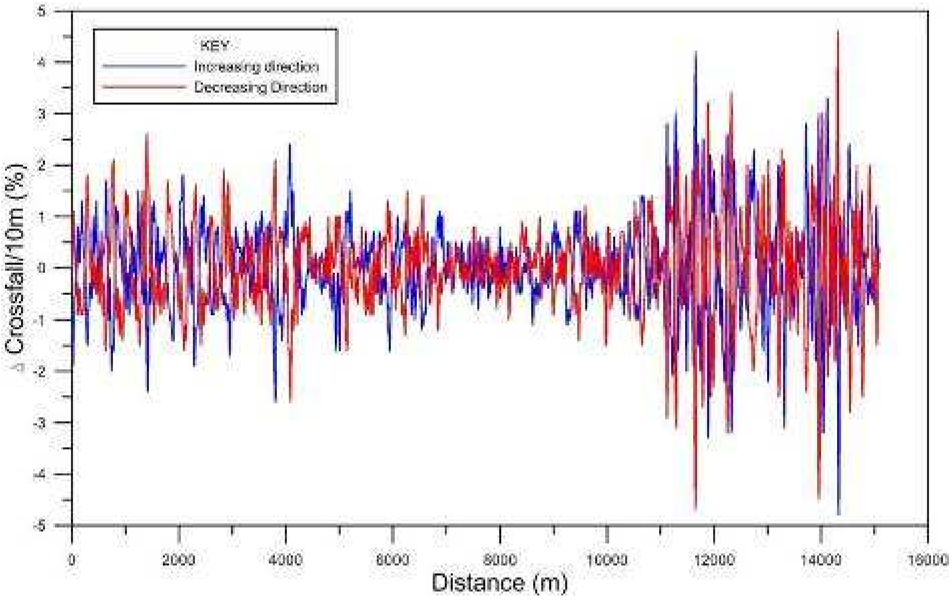


Table 7.1 Range of geometry parameter for computer simulation models

Road type	Radius of curvature (m)	Maximum superelevation (% crossfall)					
Open	45	-3[(a)]	0	3	6	12	12[(b)]
Open	90	-3[(a)]	0	3	6	12	12[(b)]
Open	150	-3[(a)]	0	3	6	12	12[(b)]
Open	200	-3[(a)]	0	3	6	12	12[(b)]
Roundabout	25	-3[(a)]	0	3	6	–	–

Notes:
[(a)] modelled with a constant -3% crossfall
[(b)] a shorter superelevation development length used

The first step in the simulation testing for safety was the generation of the 3D road models based on the ranges of geometry variables give in table 7.1. The surfaces were generated to sweep through a minimum length of 30m at the minimum radius. The entry and exit surfaces were given appropriate alignments and normal drainage crossfall of 3%, while the crossfall was varied through the curve to give the desired level of superelevation. A uniform surface friction value of 0.7 was applied to simulate a dry road condition. The dry road friction level was used, as a vehicle would be more likely to slide if the road surface became wet.

Simulations were run at each of the chosen test speeds for the particular geometry configuration. The simulations were then run at increasing speeds until the vehicle either slid off the road, or rolled off, whichever occurred first. No steering inputs were applied to the vehicle. Neither was any consideration given to any surface elements either on the road surface or on the roadside that might act as trip elements to cause rollover. In these simulations, the intent was to identify combinations of speed and road geometries (curvature and crossfall) that might cause rollover because of the combination of crossfall and lateral accelerations resulting from speed and weight shift. Speeds were stepped in 10km/h increments until the vehicle either slid off the sealed lane or rolled off.

7.5 Simulation testing – results

Table 7.2 summarises the results on the simulations in general terms, identifying the speed at which the vehicle either slid partially or completely off the sealed lane, or rollover occurred.

Table 7.2 Simulation results – rollover or encroachment speeds
XXX = rollover, XXX = slides off, – = not simulated

Vehicle	Radius (m)	Maximum superelevation (%)					
		-3	0	3	6	12	12*
Car (Corolla)	25	–	–	–	–	–	–
	45	70	80	80	80	80	80
	90	90	90	100	100	110	110
	150	–	–	–	–	–	–
	200	–	–	–	–	–	–
SUV (Bighorn)	25						
	45	70	70	70	80	80	80
	90	90	90	100	100	110	110
	150	–	–	–	–	–	–
	200	–	–	–	–	–	–
Truck (Isuzu FRR) Unloaded	25	50	50	50	60	–	–
	45	70	70	70	80	80	80
	90	90	90	100	100	100	100
	150	110	120	–	–	–	–
	200	120	120	130	130	140	140
Truck (Isuzu FRR) Loaded	25	50	50	50	50	60	–
	45	60	70	70	70	80	80
	90	90	90	90	90	100	100
	150	110	110	–	–	–	–
	200	120	120	130	130	140	140
Truck (Gigamax) Unloaded	25	50	50	50	50	–	–
	45	70	70	70	80	80	80
	90	90	90	100	100	100	100
	150	–	–	–	–	–	–
	200	130	130	130	130	140	140
Truck (Gigamax) Loaded	25	50	50	50	60	–	–
	45	60	60	60	60	70	70
	90	80	80	80	80	90	90
	150	–	–	–	–	–	–
	200	110	110	120	120	130	130

* A shorter superelevation development length was used.

Cornering simulations for the car and SUV were not carried out for the 150m and 200m radius curves. This was because these vehicles were already sliding off before rollover occurred on the tighter curves (45m and 90m radius) and so similar results were expected on the 150m and 200m radius curves.

With reference to table 7.2, the following observations were made:

- With no steering or surface element triggers, the behaviour of the car and SUV for all road geometry configurations investigated was dominated by the vehicles sliding off without rolling. Limited additional simulations with additional rear-seat passengers and substantial but reasonable boot or roof luggage or both, showed similar trends.
- With no steering or surface element triggers, the behaviour of both unloaded trucks on all road geometry configurations investigated was dominated by the vehicles sliding off either without rolling or before they rolled.
- In the loaded condition, the behaviour of both trucks was dominated by rollover. The speed required for rollover increased with increasing superelevation.

The critical rate of rotation for a loaded truck to roll over while cornering can be estimated by combining the rollover travel speeds given in table 7.2 with the maximum difference in crossfall between consecutive 10m segments for the corresponding curve configuration. The results of this calculation are tabulated in table 7.3 and also shown graphically in figure 7.10. Superimposed on figure 7.10 are the urban and rural rate-of-rotation thresholds of 0.035 rad/s and 0.025 rad/s respectively.

Table 7.3 Critical geometry based rate of rotations for rollover of loaded truck from PC Crash™ simulations

Vehicle	Radius (m)	Rate of rotation (rad/s, for superelevations –3% to 12%)					
		-3[a]	0	3	6	12	12[b]
Truck (Isuzu FRR) Loaded	25	0	0.028	0.028	0.028	0.050	–
	45	0	0.039	0.039	0.039	0.067	0.100
	90	0	0.050	0.050	0.050	0.083	0.167
	150	0	0.061	–	–	0.100	0.200
	200	0	0.067	0.072	0.072	Sliding	Sliding
Truck (Gigamax) Loaded	25	Sliding	Sliding	Sliding	Sliding	–	–
	45	0	0.033	0.033	0.033	0.058	–
	90	0	0.044	0.044	0.044	0.075	–
	150	–	–	–	–	–	–
	200	0	0.061	0.067	0.067	0.108	–

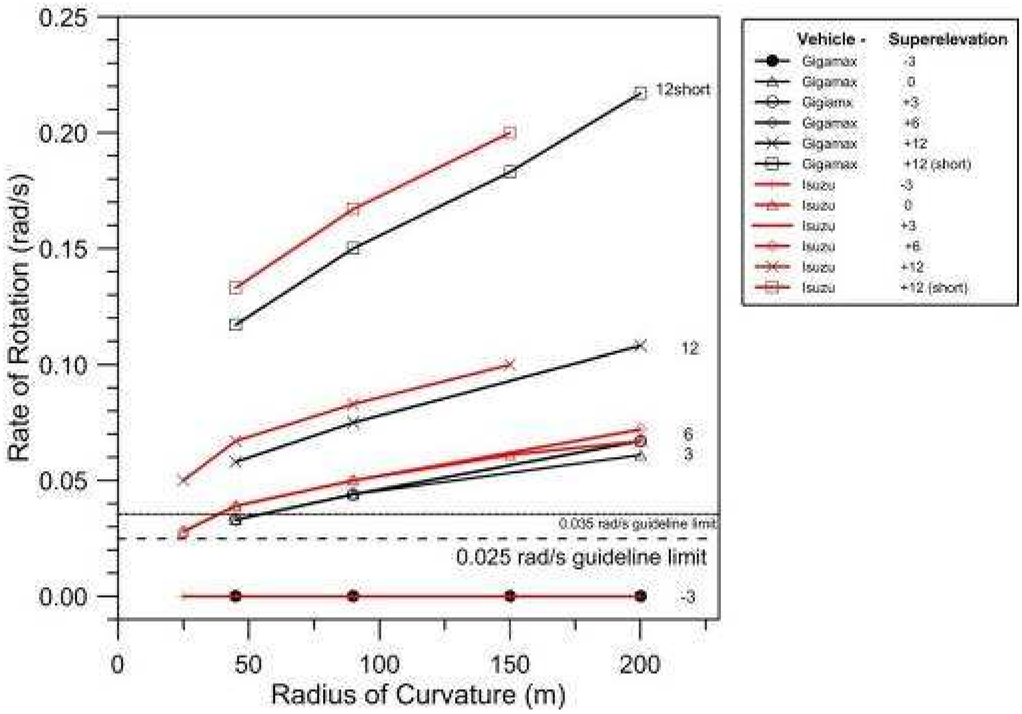
Note:

[a] simulation at constant 3% crossfall has no geometry-based rate of rotation so rollover caused by lateral acceleration and load shift

[b] a shorter superelevation development length was used

– indicates not simulated

Figure 7.10 Relationship between critical rate of rotation and curve radius for loaded trucks



Note: short implies shorter superelevation development length was used

With reference to table 7.3 and figure 7.10, the following additional observations are made regarding the relationship between curve geometry and vehicle rollover:

- Under dry road conditions, represented by the level of friction chosen for the simulations, it is possible for loaded trucks to roll due to curvature and speed alone.
- As the superelevation increases, the rate of rotation required to cause rollover increases significantly.
- The critical rate of rotation for rollover to occur was found to be below or around the existing rural and urban comfort limits of 0.025 rad/s and 0.035 rad/s whenever curves with small radius (≤ 50m) were combined with low superelevation (up to 6%).
- The critical rate of rotation for rollover is comparatively insensitive to truck size for low superelevations (up to 6%). However, the effect of a truck's size becomes apparent at higher superelevation values or when superelevation development lengths are shorter than prescribed in geometric design guides.
- When the horizontal radius of curvature is small, rollover of loaded trucks can occur at relatively low speeds across a range of superelevations. This finding from the PC Crash™ simulations highlights that roundabouts may be particularly susceptible to truck rollover crashes and so care must be taken to minimise the centrifugal force effect and any sudden changes in radius and in particular crossfall.

8 Discussion of results

8.1 Existing rate-of-rotation limits

The current New Zealand guidelines for rate-of-rotation limits contained in Austroads (2003) of 0.025 rad/s for rural roads and 0.035 rad/s for urban roads are aimed at providing reasonable ride comfort levels. They are generally consistent with current international practice in Australia, the UK and the USA. However, they are also based on vehicle technology that is generally more than 20 years old. There are currently no guidelines or limits for rate of rotation with respect to safety, the assumption being if the comfort guidelines are used for design, any safety limits would be far in excess of these.

8.2 New Zealand road geometries

New Zealand's complex and often rugged topography means roads are often constrained by the landscape, and roading designers may face compromises between creating or maintaining roads that are topographically constrained and also meeting current design guidelines, such as for superelevation development lengths. There are existing sections of the New Zealand roading network where the crossfall geometries produce rates of rotation in excess of the current guideline limits for comfort. However, there does not appear to be any significant degree of complaint from the driving public. This would suggest the current guideline limits may be too conservative. Previous work by Jamieson and Cenek (2001) has suggested a threshold of 0.075 rad/s for unpleasant truck ride quality is appropriate, but there is a need to investigate and validate this limit for a wider variety of vehicles and drivers.

8.3 Road geometries and rollover crashes

There is little literature on the relationship between the rate of rotation and vehicle rollover crashes. Statistical analysis of crash and geometry data for the state highway network showed that, as expected, changes in crossfall were strongly correlated with horizontal curvature because of the need to deal with radial forces on cornering vehicles. Removing curvature as a variable showed rate of rotation remained a significant predictor of crash rate. It also showed there did not appear to be a critical rate of rotation above which crash rates increased significantly.

8.4 Measured rate-of-rotation data

On-road measurements of rate of rotation were made on selected road sections covering a wide range of road geometries using a car, SUV and a light truck. The results showed the measured rates of rotation were mostly, but not always, greater than those derived from the crossfall geometry alone, indicating the contributing effects of travel speed variations, horizontal alignment and consequent load shifts. This suggests that either the vehicles are not responding well to the road geometry variations, or the combinations of horizontal curvature and crossfall in particular locations are generating larger vehicle responses than is desirable. As expected, the truck was most sensitive to crossfall variations, given the higher CoG and different suspension characteristics. The driver's subjective assessment of ride quality on the test routes agreed reasonably well with the proposed threshold criteria of 0.075 rad/s for uncomfortable ride quality proposed by Jamieson and Cenek (2001).

8.5 Computer simulations

Safety considerations meant the on-road testing was limited to speeds that, while possibly being uncomfortable at times, were within the legal limits and within the capabilities of the driver and vehicle. Therefore, the only option available for investigating the likely effects of pushing vehicle speeds beyond safe levels and reaching rollover conditions was computer simulation, using crash reconstruction software. Such software has become increasingly sophisticated as a result of the advances in computer hardware and processing power.

The data from the on-road testing provided a ready database for confirming the accuracy and validity of the computer simulations. Comparative test simulations of selected vehicle and curve combinations showed the chosen simulation package, PC Crash™, provided good agreement with the corresponding measured yaw and rate-of-rotation data.

Although it was thought even better agreement could be achieved if the detail of the road model used was improved through direct survey rather than using the 10m averaged geometry data from the RAMM database, output from PC Crash™ was considered to be more than suitable for the purpose of investigating road geometry induced vehicle rollover.

Simulations were run for a combination of curve geometries (radius and variation of crossfall) and vehicles to determine the speeds at which either rollover occurred or the vehicles slid off the sealed lane. The results of these simulations showed that, ignoring radical driver steering inputs and surface-related rollover triggers, the loss of control behaviour of the car, SUV and unloaded truck was dominated by sliding across a wide range of curve geometries.

By comparison, loaded trucks were shown to roll off the road sections investigated rather than slide off as travel speeds increased. For low radius curves and low levels of superelevation the critical rates of rotation for rollover were close to the existing comfort level guideline limits, while for higher levels of superelevation they were typically well in excess of these guideline limits.

The results of this study suggest, rather than setting specific guidelines for safety limits for rate of rotation, it may be more appropriate to use computer simulation to assess specific geometric designs for risk of rollover crashes at the design speed. This approach also lends itself to the 'safe system' approach to road safety by allowing vehicle speed and vehicle loading extremes to be modelled. By doing this any deficiency in the road geometry can be highlighted thereby enabling road users to be protected from death and serious injury.

8.6 Suggestions for further work

The findings of the rate-of-rotation study suggest a number of avenues for further work. These include carrying out:

- a study to better assess New Zealanders' comfort levels with respect to ride quality and rate of rotations, particularly to establish whether the threshold of 0.075 rad/s proposed by Jamieson and Cenek (2001) is appropriate for a wider variety of vehicles and drivers
- a more detailed examination of the crash database to identify the locations of rollover crashes, and thereby the other potential causative factors such as curvature, crossfall and gradient
- an investigation of the effects of the geometry over averaging lengths shorter than the current 10m values used in the RAMM database. This would require detailed surveying of specific locations, similar to that carried out at serious crash sites

- an assessment of the range of typical CoG heights for different trucks and load combinations so that input parameters for computer simulation models could be refined and the relative risks of rollover crashes better assessed
- an investigation of the ability of long, torsionally stiff, road vehicles to adequately follow the changes in superelevation that currently occur on New Zealand roads.

9 Conclusions and recommendations

Conclusions drawn from the comparison of measured and computer modelled rate-of-rotation results for a limited range of vehicles are presented below along with associated recommendations for additional work.

9.1 Rate-of-rotation limits

The conclusions from this study of rate-of-rotation limits for comfort and safety are:

9.1.1 Existing rate-of-rotation design criteria

- The existing Austroads design criteria for rate of rotation revolve around appearance and comfort considerations and are based on research that does not necessarily account for the handling performance of latest generation vehicles.
- There are currently sections of the state highway network where, based on geometry alone, rate-of-rotation levels exceed the existing design criteria.

9.1.2 Rate of rotation and crashes

- Rate of rotation is a statistically significant predictor of crash rate.
- There does not appear to be a critical rate-of-rotation threshold above which rollover crashes increase dramatically.

9.1.3 Measured rate-of-rotation data

- Measured rate-of-rotation levels are typically greater than those predicted from crossfall geometry alone, indicating the important contribution of dynamic effects associated with horizontal alignment, load shifts and suspension behaviour.
- Measured rates of rotation also often exceed the current design criteria for urban and rural roads.
- Driver perceptions of uncomfortable ride quality were found to occur at higher rates of rotation than the current design criteria, typically agreeing with the 0.075 rad/s determined from a New Zealand study (Jamieson and Cenek 2001) concerning the development of a truck ride indicator.

9.1.4 Computer simulation of the rate of rotation for rollover

- Rate-of-rotation and yaw-rate data from computer simulations showed very good agreement with corresponding data obtained from on-road measurements using instrumented vehicles.
- The behaviour of a car, a SUV and two unloaded trucks across a range of road geometries and travel speeds were dominated by sliding off the sealed lane rather than rollover.
- Repeat simulations performed with the two trucks in loaded configuration were dominated by rollover.
- When small radius horizontal curves were combined with low levels of superelevation, the rates of rotation for rollover were close to the existing appearance and comfort-based design criteria. For higher superelevation levels, the rates of rotation for rollover were typically well in excess of these criteria. This result suggests either computer simulation is used to identify the susceptibility of specific curve geometries to rollover, or more specific rate-of-rotation guidelines are developed that incorporate horizontal curve radius, curve superelevation and curve speed.

9.2 Recommendations

The recommendations for further work arising from this study of the validity of current rate-of-rotation design criteria are as follows:

- New Zealanders' response to different levels of rate of rotation needs to be investigated. In particular, it is necessary to confirm or otherwise that an upper threshold of 0.075 rad/s derived from an investigation of truck ride is appropriate for a wide variety of vehicles and drivers.
- A more detailed examination of the CAS database should be carried out to identify common characteristics of rollover crashes occurring on the state highway network so that causative factors, additional to geometry-based rate of rotation, can be identified and also their inter-relationships. These factors are likely to include horizontal curvature, superelevation, road gradient and vehicle type/rotational stiffness.
- The effect of averaging geometry parameters over lengths shorter than the current 10m in the RAMM geometry table needs to be investigated to see if this leads to improved agreement between measured and predicted rates of rotation. This would require detailed surveying of specific locations, similar to what is often done at fatal crash site.
- Typical CoG heights for different truck types and load combinations need to be assessed either from existing static rollover threshold data or from specific measurements because CoG height was found to be a critical determinant of rollover performance. Having such a database will provide more confidence in the output of the computer simulation models. This, in turn, will allow better assessment of road and vehicle factors affecting the risk of a rollover crash.
- A number of reported rollover crashes in the CAS database should be reconstructed using crash simulation software to first verify and refine the computer modelling that has been undertaken and second to better quantify the contribution of road geometry and road condition variations to rollover crashes.
- Rather than blanket application of rate-of-rotation criteria, crash/vehicle handling simulation models such as PC Crash™ should be used to assess the geometry of a curve for the anticipated speed environment and traffic composition, particularly for small (< 150m horizontal radius) curves, including roundabouts, where rollover is potentially an issue.
- One section of SH58 has been identified where high crash rates coincide with poor road geometry, this being at RS0/11.6–12km in the decreasing direction. It is recommended this section of SH58 be considered for road shape improvement works to bring the geometry within current geometric design guidelines. A before and after study should follow, which would involve both computer simulation modelling and simplified modelling using rate-of-rotation estimates derived from 'as built' superelevation data to assist in explaining any observed changes to the crash rate.
- In the rail transport industry, the track rate of rotation (change in superelevation) approaching curves and exiting curves is limited in terms of radians per metre. Similarly, the rail vehicle (rolling stock) rotational stiffness about the longitudinal axis is limited to ensure the vehicle is capable of following this change in superelevation. There is evidence in the road transport industry to suggest long stiff heavy commercial vehicles have a higher risk of understeer generated problems than vehicles with a more compliant chassis. Research should be carried out to determine whether current trailer designs, particularly those used in dairy and forestry industries, have an appropriate level of rotational stiffness both in the unloaded and loaded states to accommodate the changes in superelevation encountered on New Zealand state highways, without wheel lift occurring.

10 References

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Appendix A: Calculation of rate of rotation and yaw rate

Approximate values for the rate of rotation and yaw rate can be derived from the 10m average data contained in RAMM'S geometry table. The calculation procedures that have been used are summarised below.

A1 Calculation of rate of rotation

The 10m average crossfall values in RAMM are given in terms of a percentage value (%), eg 10% crossfall equates to a 1:10 slope from the centreline to the edge of the lane. An approximate rate of rotation for a vehicle travelling at a particular speed can be derived by relating the variation if the crossfall (roll) to the vehicle speeds, as in the following example:

Vehicle speed	= V = 60 km/h = 16.66 m/s
Crossfall in first 10m section	= C1 = 2%
Crossfall in second 10m section	= C2 = 12%
Change in crossfall over 10m	= C2-C1
	= (12-2) = 10% = 5.74° ~ 0.1 radians
	= 0.1 radians/10m
	= 0.01 radians/m

Therefore at a speed of 16.66m/s, the rate of rotation

= 0.01 radians/m x 16.66m/s

= 0.1666 radians/s

Note: this value is approximate and does not show the maximum variation in crossfall that may occur within the 10m averaging length that is used in RAMM.

A2 Calculation of yaw rate

The road curvature for each 10m road segment is given in RAMM. An approximate yaw rate (rate of change of horizontal direction) can be derived from this for each vehicle speed as in the following example:

- Vehicle speed = V = 60km/h = 16.66m/s
- Radius of curvature for 10m section = R = 100m
- A circle of radius R has a circumference of C = 2πR = 628.3m

Therefore, a vehicle travelling at 16.66m/s will take C/V = 628.3m/16.66m/s = 37.7s to travel around a 100m radius circle. There are 2π radians in a full circle and so the yaw rate = 2π radians/37.7s = 0.167 radians/s.

Appendix B: Features of PC Crash™ V9.0

B1 Standard features

- Simultaneous simulation of up to two vehicles (PC Crash™ 2D) or 32 vehicles (PC Crash™3D)
- Interface to specs (North American), ADAC, Vyskocil, DSD (European and Japanese) and KBA (as of October 2008) vehicle databases
- 2D or 3D kinetic calculation model
- Front/rear brake force distribution model
- ABS braking model
- Electronic Stability Program model
- Specification of driver reaction, accelerating, braking, steering and other parameters, in the form of sequences
- Steering can also be specified with kinematic and kinetic (default mode) vehicle paths, with various kinetic steering model options
- Definition of different road elevations, slopes and friction coefficients in specific polygonal areas
- Impact model by Kudlich-Slibar, based on conservation of linear and angular momentum, with 'full' and 'sliding' impacts
- Specification of impact elasticity with restitution or separation velocity
- 2D or 3D impact model, with unlimited number of impacts
- Automatic calculation of all secondary impacts
- Collision optimiser, for the automatic determination of impact speeds and seven other impact parameters, based on rest and/or up to five intermediate vehicle positions
- Crash backwards calculation, using post-impact velocities
- Automatic kinematic calculation of accident avoidance
- Forwards automatic avoidance simulation (velocity decrease, brake increase)
- Various diagrams for wheel forces, etc
- Kinematic and kinetic (default mode) specification of vehicle paths
- Backtracking tyre marks with a kinematic skidding calculation to determine post-impact velocities, based on up to six post-impact positions and braking levels for each vehicle
- Automatic kinematic calculation of crash avoidance
- Automatic kinetic calculation of crash avoidance, with either gradual decrease of speed or increase of braking level until impact is avoided
- Measurement tool
- Printout of report of input/output values, including all collision and trajectory parameters and character counting

- Detailed vehicle shapes can be specified using DXF files, with possible optional change of shape at impact
- Scene DXF and VRML drawings and/or bitmaps can be imported into the simulation
- Integrated drawing program for drawing/modifying scene drawings and vehicle DXF shapes, with 256 layers, extrude feature, and tool for constructing intersections and roads
- Calculation of rollovers and vaults
- Choice of two tyre models (linear or TM-Easy)
- Calculation of acceleration due to engine power and air resistance with up to 16 transmission ratios and the ability to gear down when going up grades
- Calculation of the effects of wind and air resistance, including down force and uplift
- Direct switching between different units systems (eg km/h, mph, m/s, f/s)
- Direct switching between different languages
- Auto save feature, with user-definable intervals
- ‘Undo’ up to 50 prior operations
- Interactive help
- Improved vehicle suspension bump-stop model
- Interface to optional Madymo® occupant modeler
- Collision Optimizer Monte Carlo (random) algorithm
- New AZT EES catalogue of European vehicle damage photographs
- Individual damaged wheel steering and positioning
- Additional kinetic path steering model features
- Up to five axles per vehicle
- North American symbol library
- Additional drawing tool features
- Multiple scene bitmap importing
- Revamped user manual with more detailed explanations
- Improved templates for simple exchange of data between PC Crash™ and WinWord
- Extended wizard for kinematics simulation
- New simulation model for electronic stability control systems
- Mouse wheel support for all input windows
- Updated Crash 3 database (Stand 02/2007)
- KBA 2008
- Bitmaps can also be projected on slopes
- Measurement grid can be extended at arbitrary edge

- Improved representation and expression of bitmaps (interpolation and smoothing)
- Transparency option for bitmaps
- Mirrate-of-rotation function for limit method
- Drawing program toolbar
- User defined menus and toolbars
- Bitmap toolbar for handling of bitmaps
- Adjustable indication sequence for bitmaps (foreground/background)
- Friction polygons and road slope toolbar
- Default settings consolidated

B2 Additional features of PC Crash™ 3D

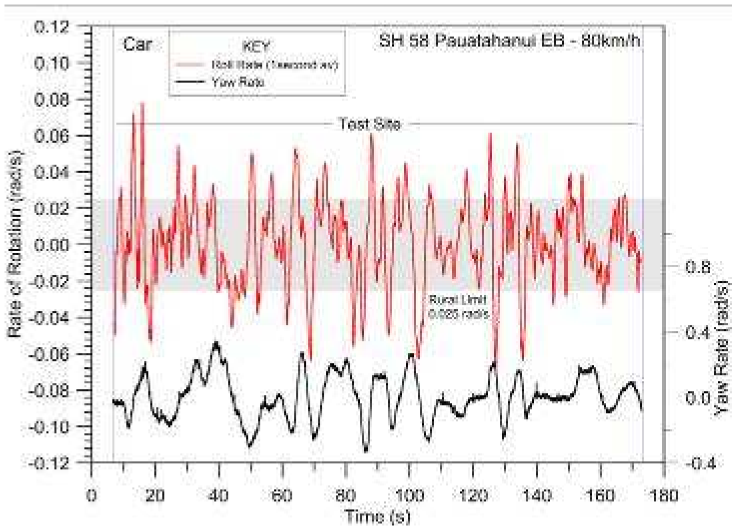
- Simulation and collision analysis of trailers (steered, non-steered, semi-trailer), with more than one trailer per tow vehicle possible. Offsets at the hitch point can be specified
- Multiple collisions between different vehicles
- New high resolution 3D vehicle models
- 3D perspective view, with display of 3D vehicles and scene 2D or 3D DXF drawings and rectified bitmaps
- VRML and FCE vehicle models can be imported
- Generation of 3D video animations with fixed or moving camera position, playable with Windows Media Player
- Tool for constructing or importing complicated 3D scenes, including those created from total station survey files or car interior
- Multibody pedestrian model
- Multibody motorcycle, bicycle and unrestrained occupant models
- Multiple multibody objects in one simulation, and on sloped surfaces
- Simulation of movable load
- Belt modelling
- Trailer steering model (based on articulation angle)
- Crash 3 impact module with interface to NHTSA vehicle database
- Visualisation of Crash 3 deformations
- Side view window for analysing vehicle interaction in rear-end impacts, with European vehicle side view bitmaps
- 2D and 3D vehicle DXF automatic deformation model
- 3D window dynamic viewing
- Direct X 3D graphics, for improved rendering

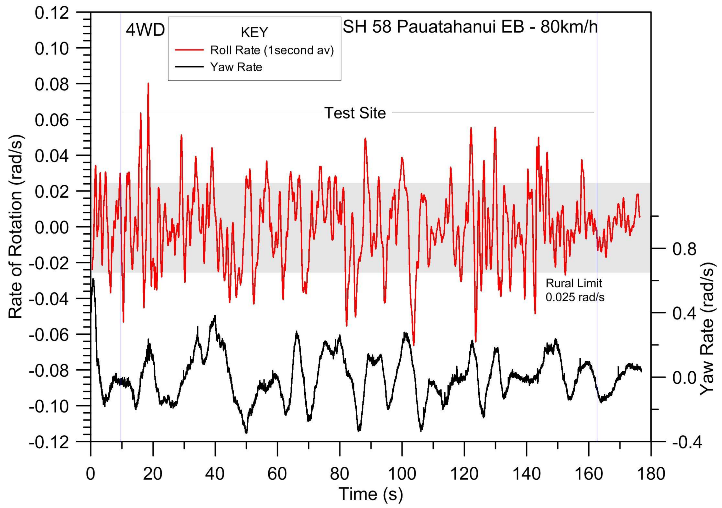
- New stiffness-based crash simulation model
- New stiffness database with real crash test to be used in stiffness based crash simulation
- Improved occupant simulation in PC Crash™ including safety belts and car interior.
- New mesh based impact model with improved structural stiffness and deformation calculation at vehicle/vehicle and vehicle/slope collisions.
- Key-numbers searching for KBA-database
- Calculation of tracks caused by tire contact
- Bounds method within the Drawing Tool
- Square measurement grid within the Drawing Tool
- Crash backwards calculation with momentum/angular momentum combination
- Adapted impact analysis backwards
- Possibility to save PC Crash™ project files for different versions (7.0, 7.1, 7.2, 7.3, Pocket Crash)
- Refresh-display of point of impact (POI) velocities
- Refresh-display of intersection areas of momentum mirrate-of-rotation method (backward method), with momentum diagram (scale 0.001:1 m for 1000 Ns)
- Adapted v-s-t window (point of reaction, reaction time, lag time adjustable)
- Camera rotation with roll and pitch
- Vehicle administration (copy, delete, exchange)
- Mesh model with X61/FCE vehicles
- Expansion of FCE vehicles
- EES calculation for Crash 3 model
- 64 bit version of PC Crash™ available
- Adapted multi-body simulation model (faster calculation, new joint types)
- Sort function within Crash 3 data base
- Sort function within EES catalog
- Apply function within measurement grid
- Apply function within limit method
- New 3D vehicle models
- Selection of the pre-impact impulse direction for EES backwards procedures
- Support of DFF files for 3D vehicles (Renderware format)
- Rest- and intermediate position can be switched on and off separately
- Optimisation of multi body calculations (further optimisation in progress)
- Preview for vehicle DXF dialogue

Appendix C: Measured rate-of-rotation comparisons

The following figures present the measured rates of rotation and yaw rates for 1) the three vehicles on site 2 in the decreasing direction for a speed of 80km/h, and 2) the truck on site 2 in the decreasing direction at all three test speeds.

Figure C.1 Vehicle response at 80km/h, site 2 decreasing direction, for each test vehicle





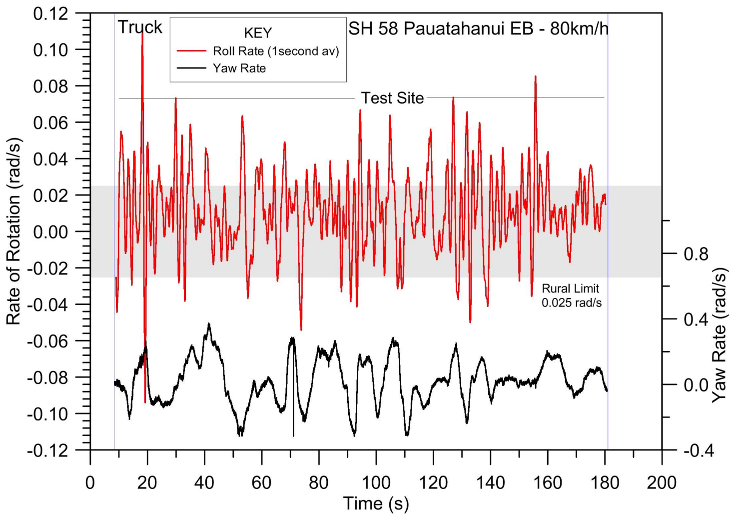


Figure C.2 Truck response, site 2 decreasing direction, at travel speeds 60, 70 and 80km/h