Use of roadside barriers versus clear zones February 2013

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Abbreviations and acronyms

ABS	anti-lock braking system
ADT	average daily traffic
ARRB	Australian Road Research Board
CAS	crash analysis system
EEM	*Economic evaluation manual volume 1*
ESC	electronic stability control
EVT	effective traffic volume
FSI	fatal or serious injury
KiwiRAP	the New Zealand Road Assessment Programme
NZTA	New Zealand Transport Agency
OOCC	out-of-context curve
RAMM	road asset management and maintenance
SHGDM	*State highway geometric design manual*

Contents

Executive summary

This study was undertaken in 2011–12 to quantify the effects of roadside barriers and clear zones on the mitigation of run-off-road crash numbers and crash severity for New Zealand road and roadside characteristics. The aim was to provide practitioners with information that would assist them in making safe, more appropriate and cost-effective treatments for specific conditions. It reflected the change, both by the New Zealand government and the New Zealand Transport Agency (NZTA), to a Safe System approach to road safety and the need to best target the limited funding available.

This research was based on the extension of an existing crash risk model that had been successfully used to investigate the effects of horizontal alignment, out-of-context curves, skid resistance and roughness on New Zealand state highway crash rates. The existing model database containing the geometry, road condition and crash data was updated to reflect the latest information. It was extended to include the relevant clear zone and barrier information available in KiwiRAP (eg roadside hazard severity and offset (worst hazard), road protection score, horizontal and vertical alignment and terrain). Statistical analyses were carried out on the database using a modified Poisson regression model to identify the effects of different roadside treatments on the crash rate. Note that this study did not consider the pavement surface condition or the width of the sealed shoulder. Limited computer simulation modelling was also carried out to 1) support and test the validity of the statistical analysis and 2) assess the use of simulation modelling where either crash numbers or barrier provision or type were relatively low.

The main conclusions of this study are given below, followed by recommendations for further work.

Conclusions

Literature review

- Current barrier and clear-zone practices do not necessarily reflect the advances that have been made in recent years in road design, skid resistance, vehicle safety features (eg airbags, anti-lock braking system, electronic stability control), vehicle performance and delineation.
- For a 100km/h speed environment, up to 70% of vehicle encroachments are accommodated within the first 6m of lateral distance. However, up to 20% of vehicles that run off the road will encroach further than 9m, and can still have a high forward speed, even under braking.

Analysis database

- The main issues with the RAMM barriers and railings data, the crash data and the KiwiRAP concerned the accuracy of the locations.
- There is some evidence in the KiwiRAP data that there are differences in the subjective evaluation of the roadside hazard offsets between the left and right sides of the road.

Statistical analysis

- The roadside, which can comprise a combination of clear zones and barriers or other hazards, as defined in KiwiRAP, was found to have a statistically significant effect on the crash rate.
- Crash rates were predicted for different roadside conditions, where these are described in terms of either the type of barrier/railing (rigid, short-rail, semi-rigid or flexible (wire rope)), or roadside

condition risk categories (tiny, low, medium, high or extra high). These roadside risk categories relate to the physical makeup of the roadside through the KiwiRAP severity outcomes and their descriptions. They essentially progress through increasing severity of the hazard and increasing proximity to the road. The predicted crash rates are listed in the following table.

Classification type	Barrier/rail or road-side risk category	Predicted crash rate (per 100 million vehicle.km)
Derived from KiwiRAP	Tiny	0.4
	Low	6
	Medium	10
	High	13
	Extra high	14
Barrier/rail	Rigid	17
	Short rail	23
	Semi-rigid	13
	Flexible (wire rope)	10

- While the lateral offset distance of the hazard from the road is important, ie the width of the clear zone, it is also the type of hazard that is encountered at the far side of this offset distance that is important in determining the crash rate.
- Analysis of crash severity showed that across the different roadside conditions defined in terms of either the type of barrier/railing (rigid, short-rail, semi-rigid, or flexible (wire rope)), or roadside condition risk categories (tiny, low, medium, high or extra high) there was very little significant variation. The proportions of fatal and serious crashes were around 0.3 with only the tiny category having a significantly lower risk of a fatal or serious crash. This may be due to the lack of data, particularly for some roadside categories and/or that some barriers are only used in certain road environments.
- Consideration of additional factors including curvature, terrain and horizontal alignment, as well as wet road crashes did not add anything significant to the statistical model that was not already included. This is assumed to be because these factors were largely accounted for in other model variables, eg the horizontal alignment is strongly correlated with the out-of-context curve factor, which is already included in the model.

Simulation modelling

- Both straight and corner simulations showed that for run-off-road encroachments either under constant speed or emergency braking, normal speeds at lateral distances of 2m, 4m and 9m, ie the typical distances for the placement of barriers and clear zones, were generally 40km/h or less. If the available literature is correct, this would suggest that properly designed barriers placed in this range should not cause serious injuries or fatalities.
- For both the straight and corner model simulations, the forward speeds remained high at offsets of 2m, 4m and 9m, even under emergency braking, irrespective of whether the vehicle was trying to stay on the road or not. This supports the view from the statistical analysis that not only is the lateral distance to the hazard important, so is the type of hazard.

- The corner simulations suggest that placing the barriers further out, for example at 4m offset instead of 2m, would accommodate a greater proportion of encroaching vehicles without a significant increase in the risk of serious injury because of high normal speeds and incident angles. However, placing barriers at much greater distances does raise the possibility of increased risk of rollover crashes, and also removes the potential route delineation that barriers can provide, particularly at night.
- Additional simulations showed that the forward and normal speeds, and incident angles, are significantly affected by the surface friction of the roadside.

Cumulative approach

- The findings of this study support the view that for a Safe System approach, it is important to consider the overall safety within the road reserve, starting with the road itself, eg in terms of geometry and friction, and carrying on to the roadside, including all roadside conditions, eg friction, slope, gradient, offset to hazard and type of hazard.

Recommendations

The recommendations for further work from this study on the effects of clear-zone and barrier treatments for New Zealand roadsides are as follows:

- An economic evaluation should be carried out on the cost implications of the different roadside barrier/rail risk categories of rigid, short rail, semi-rigid and flexible (wire rope), or roadside risk categories of tiny, low, medium, high and extra high, given the calculated crash rates. This would allow the variations in crash rate and crash severity for different roadside conditions to be incorporated in the NZTA's (2010) *Economic evaluation manual volume 1*. For example, it is likely that flexible (wire rope) barriers at around 4m offset will be more cost effective in most situations than a wide clear zone (>9m) when the purchase and construction costs are balanced against the crash costs.
- The uncertainties in the crash rates need to be reduced. This requires either more crash data, which would mean waiting for a number of years, or the lesser applied roadside treatments need to be used more frequently. The relatively good performance of the flexible (wire rope) barriers would suggest that their use should be expanded, particularly in those areas where barriers are contemplated.
- The findings of the Austroads study completed in 2012 should be reviewed, and the results of its statistical analysis compared with the crash rate predictions from this study.
- A limited selection of KiwiRAP data, including the video records if possible, should be assessed to investigate the effects due to mapping the 100m data onto 10m increments as was done for this statistical analysis. If this suggests that refinement of the KiwiRAP data would improve the confidence limits of the statistical analysis, further options should be considered.
- The apparent bias between the left and right roadside hazard offset in the KiwiRAP data should also be investigated further to determine the magnitude of the effect, and identify likely causes for the differences. One possible source of bias may be due to the video record being taken in only one direction.
- Additional work is needed to identify the effective frictional values for New Zealand roadsides, including grasses and other vegetation, beyond the limited amount of data that is currently available.

Abstract

This report summarises research carried out in 2011–12 to quantify the effects of roadside barriers and clear zones on mitigation of run-off-road crash numbers and crash severity for New Zealand road and roadside characteristics through statistical and computer simulation modelling. The purpose of the research was to provide practitioners with information that would allow them to make safe, more appropriate and cost-effective treatments for specific conditions.

The statistical modelling included extending an existing crash risk model to cover the available parameters relating to barriers and clear zones, eg offset from the road and barrier type. Limited computer simulation modelling of run-off-road scenarios on selected straight and corner road sections was used to confirm and supplement the findings of the statistical modelling.

The key finding was that the roadside condition, whether comprising clear zones of varying widths, or different barrier types, had an impact on the crash rate that was statistically significant. However, the results of both the statistical analysis and the computer simulation modelling showed that while the lateral distance offset to the nearest hazard or barrier was important, the type of hazard that was encountered at the far side of this offset distance was also important in determining the crash rate.

1 Introduction

1.1 Objectives

The purpose of this research project, undertaken in 2011–12, was to understand and quantify the effects of different roadside barrier types and offsets and clear-zone widths on the mitigation of crash numbers and crash severity for New Zealand road and roadside characteristics. This will allow practitioners to make safer, more appropriate and cost-effective choices of treatment/s for specific conditions.

The principal objectives of the research were:

1. To determine the reduction in crash numbers and crash severity resulting from roadside treatments for different combinations of road conditions and environments, where these treatments include types and offsets of roadside barriers and widths of clear zones.
2. To provide information on reduction rates for the numbers and severity of run-off-road crashes for inclusion in the NZTA (2010) *Economic evaluation manual volume 1* (EEM).
3. To identify specific areas where sufficient information to provide statistically significant reduction factors relating to New Zealand specific road and roadside characteristics is lacking, and provide guidance for remedying this.

1.2 Background

Two of the objectives of MoT (2010) *Safer journeys*, the New Zealand government's strategy to guide improvements in road safety in the period 2010–2020 are 1) accommodating human error, and 2) managing the forces in vehicle crashes to avoid serious injury. They recognise that drivers do make mistakes, that crashes may occur as a result and that we need to find ways to not only reduce the number of crashes, but also the number and severity of injuries and fatalities in such crashes. While we try to prevent crashes by ensuring that the road is well designed and maintained, crash statistics continue to show that run-off-the-road crashes are a very significant proportion of the total number of crashes on our roads. Accordingly, we need to be able to provide appropriate treatments in the space extending out from the road edgeline that will help to reduce the numbers of crashes, or at least mitigate the effects so as to avoid deaths and serious injuries. This is referred to as a Safe System approach to road safety.

Clear zones and barriers (rigid, semi-rigid or wire rope) are all intended to reduce the consequences for vehicles that depart from the road. The clear zone is generally defined as an area extending from the edge of the travelled road lane that is free of hazards and obstacles that allows errant vehicles to traverse this area with minimum damage to the vehicle and its occupants. It can also include various widths of sealed and unsealed shoulder.

The idea of providing a clear zone for errant vehicles to recover or stop without serious damage or injuries to occupants was developed through the 1960s and 70s in response to issues on sections of the early Interstate roading system in the United States. Through a combination of studies of roadside encroachments and crashes, statistical analysis and early computer simulation modelling, the concept of a 9m wide clear zone was developed and enshrined in various American Association of State Highway and Transportation Officials (AASHTO) publications and design guides. The most recent of these is the

AASHTO (2006) *Roadside design guide* – 3rd edition. Both the New Zealand and Australian design guides have typically tended to follow design methodologies similar to those used in the US and are largely based on those from AASHTO.

Significant improvements have occurred since the 1970s in general geometric road design, skid resistance, vehicle safety features (anti-lock braking system (ABS) and electronic stability control (ESC)), vehicle handling performance and road delineation. Accordingly, given the change in expectations with the adoption of a Safe System approach questions are being asked about whether current design procedures produce the safest practical design and whether they do represent a Safe System approach.

1.3 Need for research

The need for this research was driven by a combination of 1) the adoption in New Zealand of the Safe System approach to road safety, the intention of which is to reduce the number of crashes, or at least minimise the effects so as to avoid fatalities and serious injuries and 2) the need to target the limited amount of funding available for road safety improvements. Critical to the ability to target this funding is the need to understand the effects of different safety treatment options on the crash rate and the crash outcomes. For example, is it better to install barriers, or provide a larger clear zone?

1.3.1 Methodology

The primary goal of this research was to quantify the effects of roadside barriers and clear zones on crash numbers and crash severity for New Zealand road and roadside characteristics, so that practitioners can make safer, more appropriate and cost-effective choices of treatment(s) for specific conditions.

The research programme actions were to:

- review the available literature on barriers and clear zones, with a particular focus on research and practice in Australia and New Zealand
- generate an updated database for the entire state highway network, combining road geometry, condition, and barrier data from RAMM, clear-zone data from KiwiRAP and crash data from CAS
- use statistical analysis to extend the existing crash risk model to quantify the effects of roadside barriers and clear zones on mitigation of crash numbers and crash severity for New Zealand road and roadside characteristics, including terrain, horizontal alignment and roadside slope
- supplement the statistical analysis with limited computer simulation modelling of selected scenarios to 1) test the validity of the statistical analysis and 2) assess the use of simulation modelling where crash numbers may be insufficient to provide data for different combinations of variables
- quantify crash/severity reduction rates for roadside barriers and clear zones under New Zealand conditions for possible inclusion in the EEM.

1.4 Scope of the report

After this introduction, chapter 2 presents the results of a literature review that examines current practices in New Zealand and Australia and discusses the re-examination of these practices that is currently taking place, with reference to recent and current research. Chapter 3 describes the extraction of the relevant data from the RAMM, CAS and KiwiRAP databases and its incorporation into a combined analysis dataset. Chapter 4 covers the statistical analysis of the combined dataset. Computer simulation modelling of selected road and vehicle configurations designed to supplement the statistical analysis is described in chapter 5. In chapter 6, the literature review, results of the statistical analysis and the computer simulation modelling are discussed with respect to the effects of barrier and clear zones and their selection for a given situation. Chapter 7 presents the conclusions and recommendations drawn from the research.

2 Literature review

2.1 Background

Opus International Consultants' Information Service was used to generate a reference database for a survey of current international research and best practice regarding clear zones and barriers. This identified a considerable body of literature on run-off-road crashes and the use of clear zones and barriers in mitigating their severity. The following is not intended to be a comprehensive review of this body of literature. Rather, the intention is to describe the current practices in New Zealand and Australia and discuss the re-examination of clear zone and barrier practices that is currently taking place in both countries, with reference to 1) recent and current research, both in New Zealand, Australia and internationally and 2) the project objective of assisting practitioners in choosing the most appropriate treatment for any particular section of roadside.

2.2 Run-off-road crashes

Vehicles do occasionally run off the road, even with the best care and attention to the geometric road design (gradient curvature and crossfall), skid resistance, and the use of other safety devices such as pavement markings and traffic signs. The reasons vehicles leave the road can include:

- driver fatigue, distraction or inattention
- excessive speed
- the influence of alcohol or drugs
- medical conditions, eg heart attack
- collision avoidance
- surface conditions, eg snow, ice or rain, or diesel spillage
- vehicle element failure, eg steering
- poor visibility, eg rain or fog.

When a vehicle runs off the road, there are a number of possible outcomes. With a minor encroachment, the driver may easily be able to return the vehicle to the road. Alternatively, the driver may be able to stop without hitting anything and then return to the road, or be towed back to the road. Or, the vehicle may strike an obstacle or hazard, of which there can be a wide variety, eg banks, cliffs, poles, trees, fences, ditches, road signs, barriers or bridge abutments. Or the vehicle may roll. Or it may over-correct and cross the centreline. The consequences can range from minor vehicle and property damage through to serious injuries or fatality.

There have been numerous studies conducted around the world on run-off-road crashes. A number of these are included in the reference list in chapter 8. Some of these studies have led to or fed into the various geometric design guides used in many countries, including the United States (US), New Zealand and Australia. McLean (2002) provides a good review of the development of roadside design standards in the US, including an assessment of the implications for Australian practice. Australia and New Zealand have typically tended to follow design methodologies similar to those used in the US. There are also good reviews of run-off-road crashes in Australia and New Zealand and clear-zone and barrier research and practice contained in the stage 1, 2 and 3 reports (Austroads 2010b, 2011a and 2011b) of the multi-year Austroads research project that is currently in progress.

2.3 Current practice – clear zones

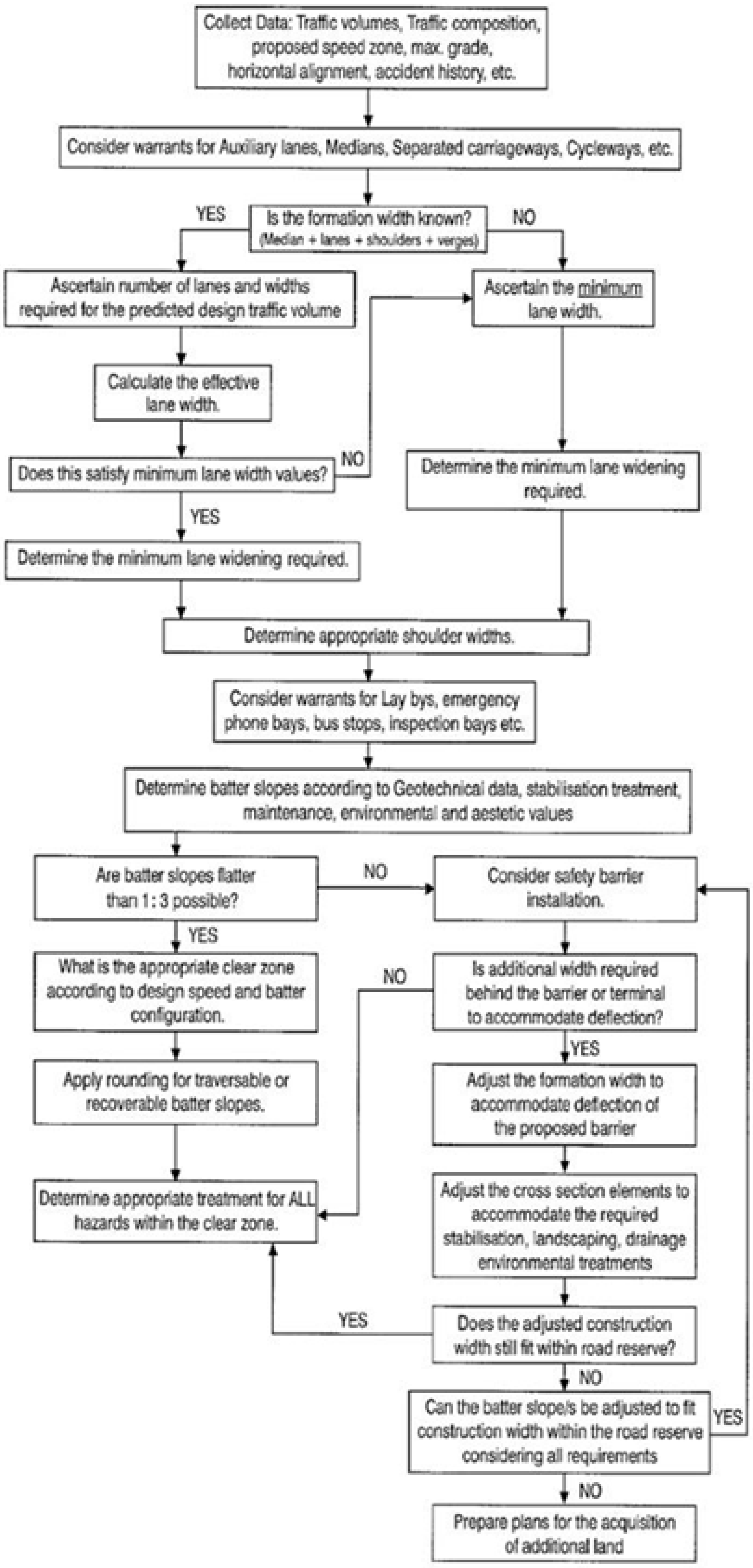
The concept of providing a clear zone for errant vehicles to recover or stop without serious damage or injuries to occupants was developed through the 1960s and 70s in response to issues on sections of the early interstate roading system in the US. Through a combination of studies of roadside encroachments and crashes, statistical analysis and early computer simulation modelling, the concept of a 9m wide clear zone was both developed and enshrined in various American Association of State Highway and Transportation Officials (AASHTO) publications and design guides. The most recent of these is AASHTO (2006). Both the New Zealand and Australian design guides have been largely based on those from AASHTO.

2.3.1 New Zealand

In New Zealand the current methods for determining the clear zone required on retrofitting, construction or reconstruction projects are outlined in the NZTA (2002) *State highway geometric design manual* (SHGDM), part 6 – cross section. These methods, including the figures and tables that relate traffic volume, roadside batter slope and design speed to required clear-zone width, have largely been taken directly from AASHTO (2006).

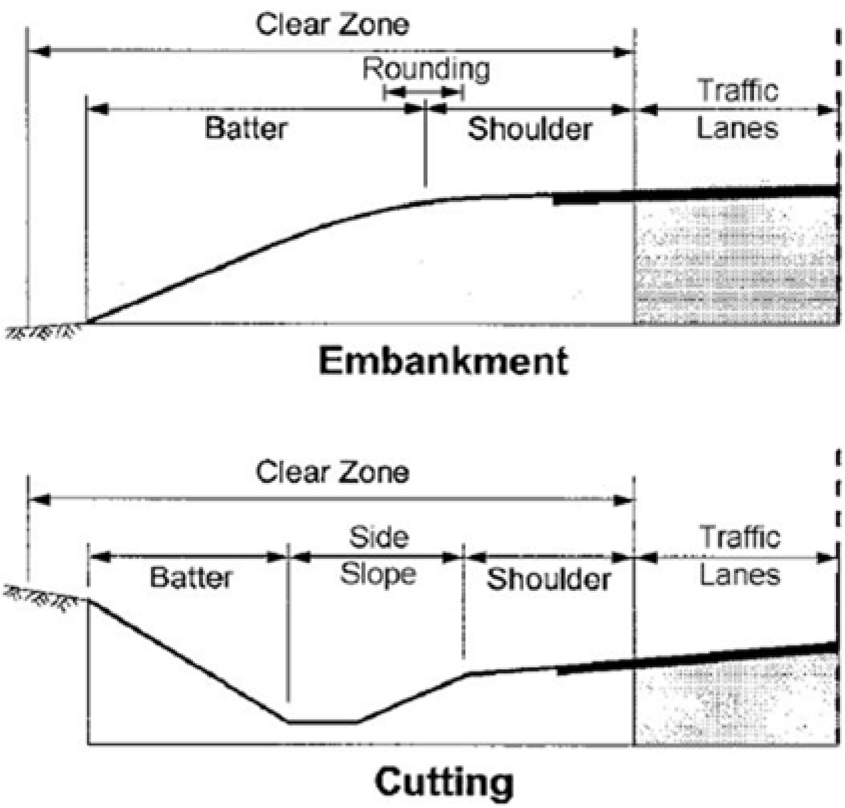
The first stage in the SHGDM methodology in establishing the appropriate clear zone is the determination of the cross section and whether there is a need for a clear zone or a barrier. This process is shown in figure 6.2 of the SHGDM which is given in figure 2.1.

Figure 2.1 Cross section determination flow chart (figure 6.2 from SHGDM)



This shows that the need for a clear zone or a barrier is determined by whether the batter slope (roadside slope) is flatter than 1:3. If it is steeper than this, a barrier should be considered; otherwise the appropriate clear-zone width needs to be determined. Figure 2.2 shows the cross-section details for typical situations found on the rural New Zealand state highway network.

Figure 2.2 Typical clear-zone cross section details (figure 6.10 from SHDGM)



According to the SHGDM, to be regarded as part of the clear zone, the roadside area should:

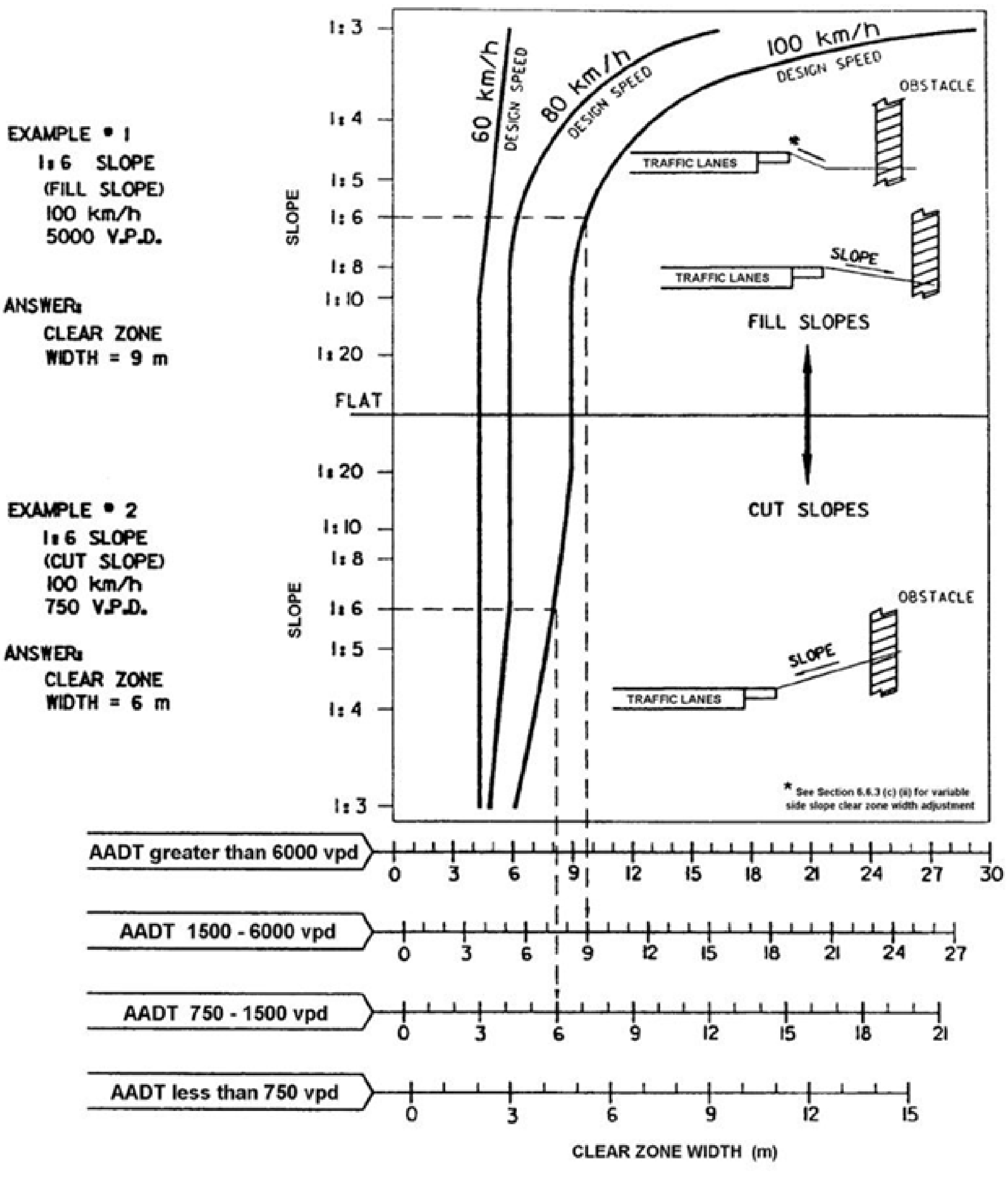
- be traversable and relatively flat, ie side slopes must be ≤1:6
- have side slopes that are not steeper than 1:4 on embankments and 1:3 on cuttings
- have side slopes where changes are rounded to ensure that all wheels of an encroaching vehicle remain on the ground
- be clear of large fixed objects, eg trees, poles, or objects must be frangible.

Table 2.1 (table 6.10 from the SHGDM) and figure 2.3 (figure 6.12 from the SHDGM) show the lateral clearance, or clear-zone width, required on a straight level section of road for a range of design/operating speeds and average annual daily traffic (AADT). This also shows the clear-zone widths required in two typical situations.

Table 2.1 Required clear-zone width (m) – straight flat road (table 6.10 from SHGDM)

DESIGN SPEED	DESIGN ADT	FILL SLOPES			CUT SLOPES		
		1:6 OR FLATTER	1:5 TO 1:4	1:3	1:3	1:5 TO 1:4	1:6 OR FLATTER
60 km/h or Less	UNDER 750	2.0-3.0	2.0-3.0	• •	2.0-3.0	2.0-3.0	2.0-3.0
	750-1500	3.0-3.5	3.5-4.5	• •	3.0-3.5	3.0-3.5	3.0-3.5
	1500-6000	3.5-4.5	4.5-5.0	• •	3.5-4.5	3.5-4.5	3.5-4.5
	OVER 6000	4.5-5.0	5.0-5.5	• •	4.5-5.0	4.5-5.0	4.5-5.0
70-80 km/h	UNDER 750	3.0-3.5	3.5-4.5	• •	2.5-3.0	2.5-3.0	3.0-3.5
	750-1500	4.5-5.0	5.0-6.0	• •	3.0-3.5	3.5-4.5	4.5-5.0
	1500-6000	5.0-5.5	6.0-8.0	• •	3.5-4.5	4.5-5.0	5.0-5.5
	OVER 6000	6.0-6.5	7.5-8.5	• •	4.5-5.0	5.5-6.0	6.0-6.5
90 km/h	UNDER 750	3.5-4.5	4.5-5.5	• •	2.5-3.0	3.0-3.5	3.0-3.5
	750-1500	5.0-5.5	6.0-7.5	• •	3.0-3.5	4.5-5.0	5.0-5.5
	1500-6000	6.0-6.5	7.5-9.0	• •	4.5-5.0	5.0-5.5	6.0-6.5
	OVER 6000	6.5-7.5	8.0-10.0 •	• •	5.0-5.5	6.0-6.5	6.5-7.5
100 km/h	UNDER 750	5.0-5.5	6.0-7.5	• •	3.0-3.5	3.5-4.5	4.5-5.0
	750-1500	6.0-7.5	8.0-10.0 •	• •	3.5-4.5	5.0-5.5	6.0-6.5
	1500-6000	8.0-9.0	10.0-12.0 •	• •	4.5-5.5	5.5-6.5	7.5-8.0
	OVER 6000	9.0-10.0 •	11.0-13.5 •	• •	6.0-6.5	7.5-8.0	8.0-8.5
110 km/h	UNDER 750	5.5-6.0	6.0-8.0	• •	3.0-3.5	4.5-5.0	4.5-4.9
	750-1500	7.5-8.0	8.5-11.0 •	• •	3.5-5.0	5.5-6.0	6.0-6.5
	1500-6000	8.5-10.0 •	10.5-13.0 •	• •	5.0-6.0	6.5-7.5	8.0-8.5
	OVER 6000	9.0-10.5 •	11.5-14.0 •	• •	6.5-7.5	8.0-9.0	8.5-9.0

Figure 2.3 Required clear-zone width –straight flat road (figure 6.12 from SHGDM)



Adjustments to the clear-zone width must then be made for horizontal curvature, gradient and side slope. The SHGDM uses a series of adjustment factors to derive an effective traffic volume (EVT), where:

EVT = K * AADT	and	***AADT***	=	AADT in the design year
		K	=	volume adjustment factor

The volume adjustment factor, ***K***, is determined by applying the encroachment adjustment factor (***M***) shown in figure 2.4 to the traffic volume adjustment factor diagrams shown in figure 2.5 (for two-lane, two-way roads).

Figure 2.4 Encroachment adjustment factor, M (figure 6.13 from SHGDM)

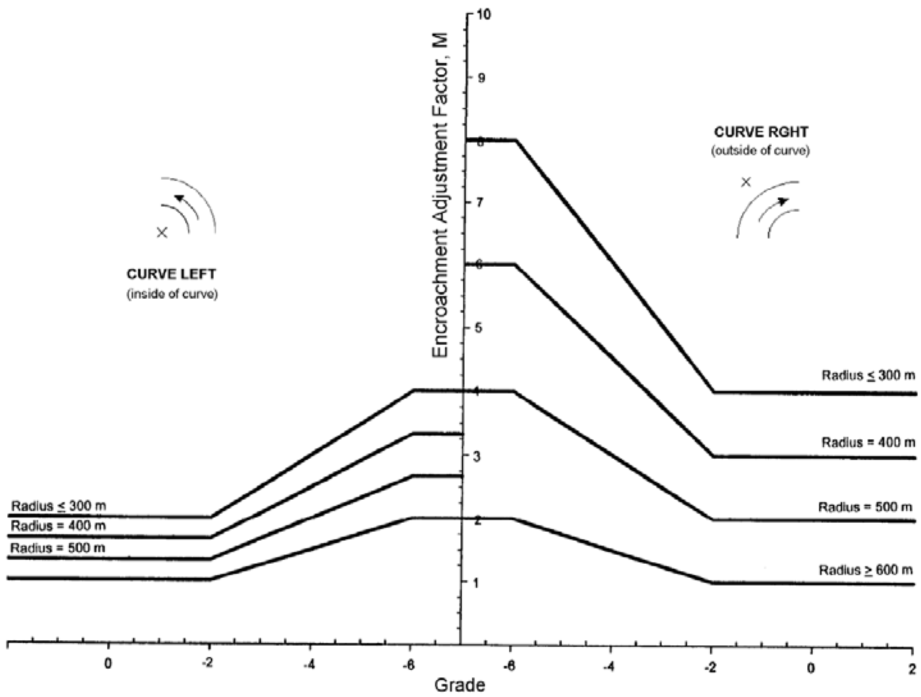
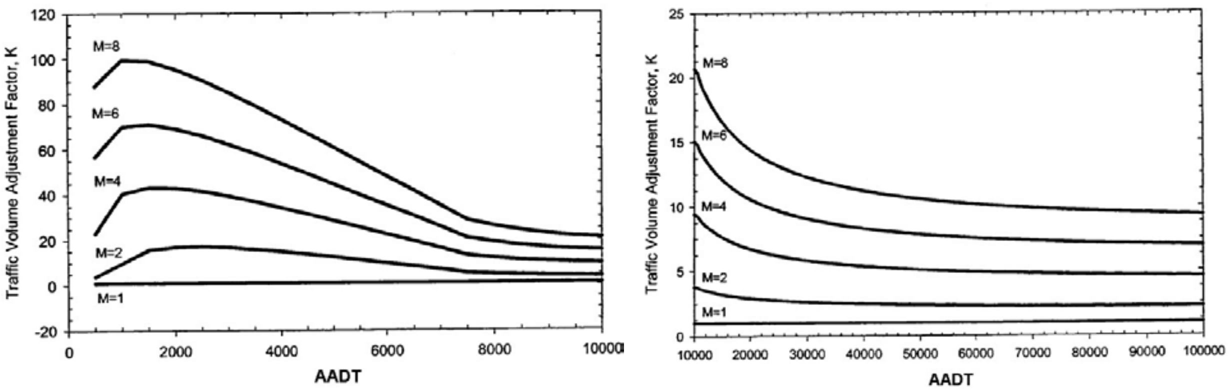


Figure 2.5 Traffic volume adjustment factor – two-lane two-way roads (figure 6.14 from SHGDM)



To illustrate the calculation, consider example 1 in figure 2.3 (fill slope of 1:6, design speed of 100km/h, and an AADT of 5000 vehicles/day). On a straight road this produces a required clear-zone width of 9m. If this was instead a right-hand (curve right) corner with a radius of 300m on flat terrain, according to figure 2.4 it would give:

$$M = 4$$

Looking at figure 2.5, with an AADT of 5000, this would give a value of ***K*** ~ 30. The calculated ***EVT*** would then be 150,000. Going back to figure 2.3 and equating ***EVT*** with AADT, this produces a clear-zone width of just under 10m, instead of the original 9m.

It is important to note that the SHGDM supports the use of engineering judgement in that it states ‘the widths and slopes of the various cross section elements may be varied within acceptable limits to achieve a balanced, economical, functional and aesthetic result’, and ‘a holistic approach must therefore be taken with road design and the cross section needs to be designed in conjunction with all other aspects of the road design, including landscaping'.

2.3.2 Australia

Current Australian practice for determining clear-zone widths is also largely based on the research and practices discussed in AASHTO (2006). This practice is described in section 17.3 of Austroads (2003) *Rural road design: a guide to the geometric design of rural roads*. Figure 2.6 shows the appropriate clear-zone widths on straights from the Austroads guide. Figure 2.7 shows how to determine the appropriate clear-zone width on different batter slopes, while figure 2.8 shows the modification factors used for the clear-zone width on the outside of corners.

Figure 2.6 Clear zone widths on straights (figure 17.2 from Austroads 2003)

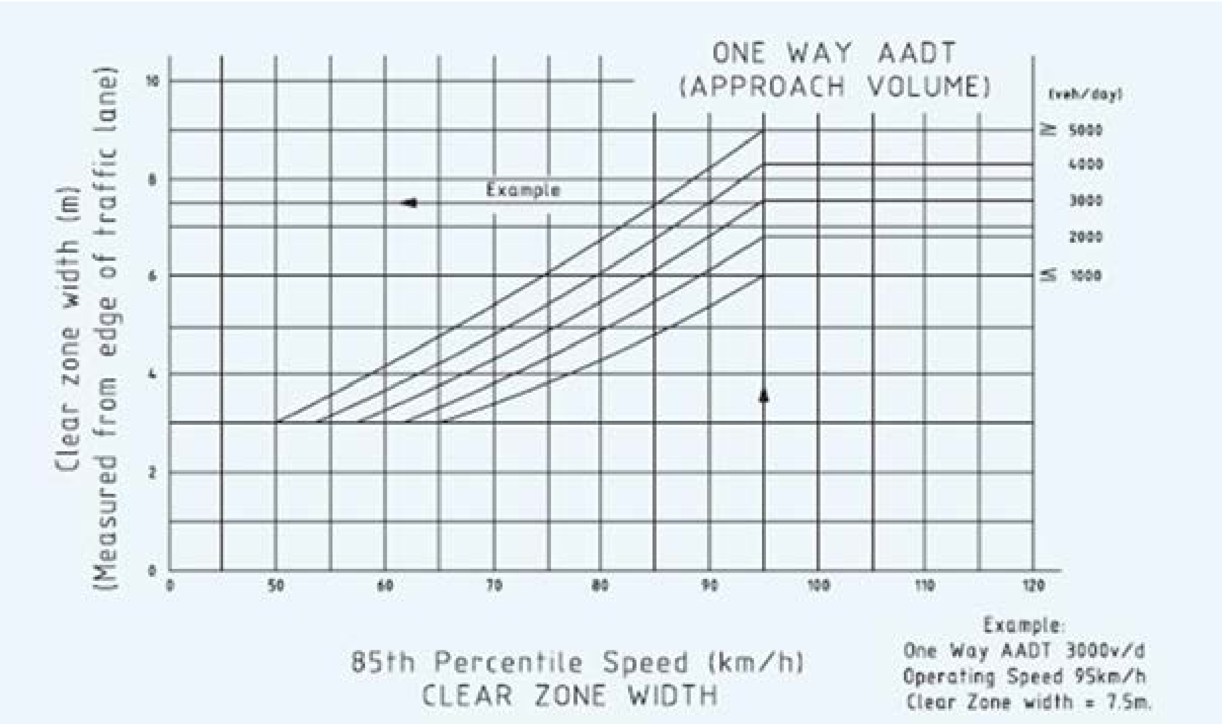


Figure 2.7 Effective clear-zone widths on batters (figure 17.5 from Austroads 2003)

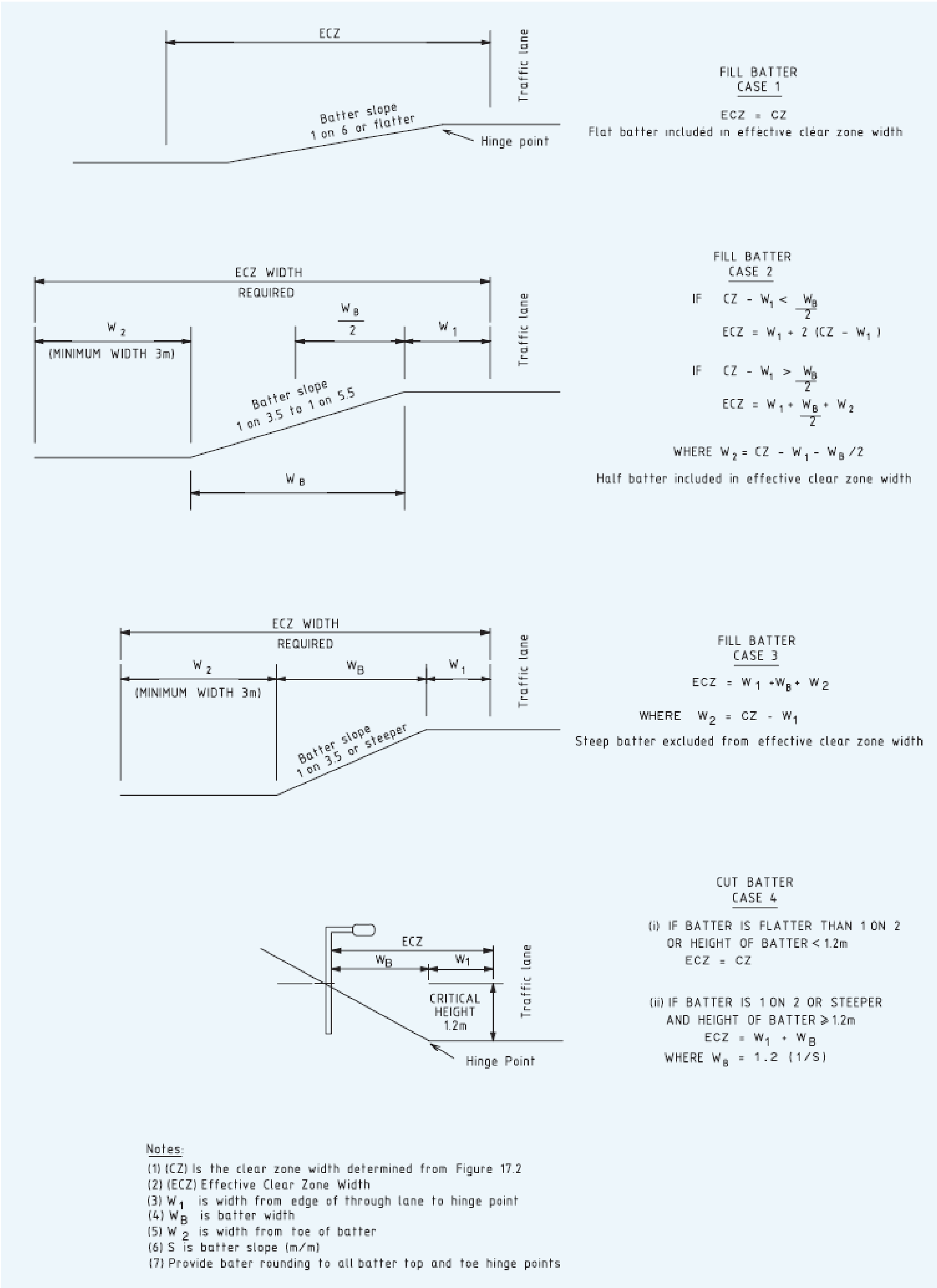
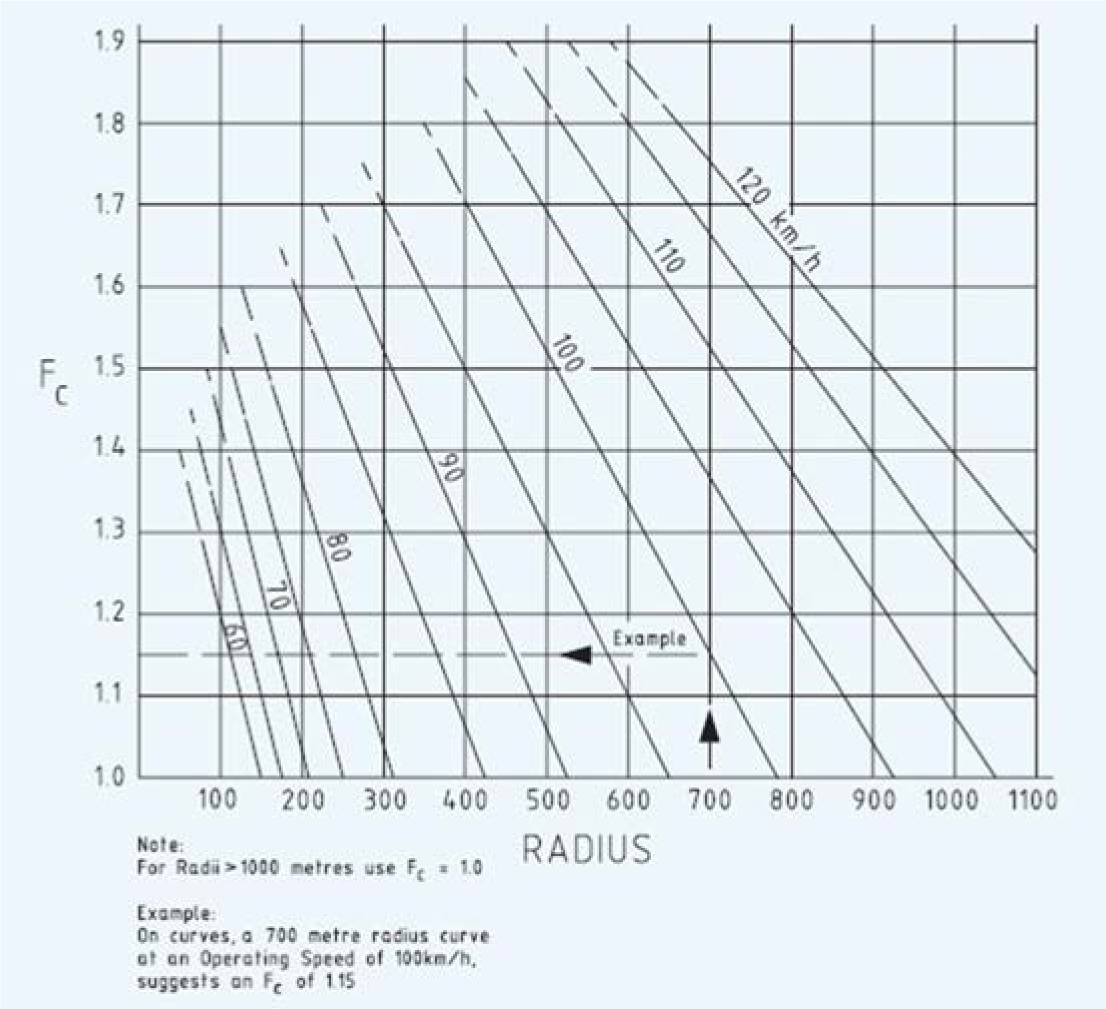


Figure 2.8 Adjustment factors – clear zones on corners (figure 17.3 from Austroads 2003)



Comparing the New Zealand and Australian approaches it can be seen that they are very similar, with both being based around the principle of having a clear zone of around 9m on open roads with a 100km/h posted speed limit.

2.4 Current practice – barriers

Both the New Zealand SHGDM (NZTA 2002 and 2003) and the Australian Austroads (2003) consider roadside barriers first as hazards, in the same way poles and trees are considered hazards. In general terms, their use is supposed to be avoided unless geometric circumstances warrant their use, or they are used to shield an even greater hazard.

2.4.1 New Zealand

In New Zealand, the joint Australian and New Zealand standard *AS/NZS 3845:1999 – Road safety barrier systems* (AS/NZS 3845:1999) provides specific requirements for the installation and maintenance of road safety barriers, while the NZTA's *M23: 2009 Specification for road safety barrier systems* (M23:2009) sets out the approval, design layout and installation requirements for permanent barrier systems on state highways. Only the barriers listed in this specification are approved for use in New Zealand as safety barrier systems. In terms of roadside barriers these consist of the following three types:

1 Flexible, eg wire rope barriers, comprising tensioned wire ropes supported by closely spaced lightweight poles

2 Semi-rigid, eg W beam barriers, comprising steel rails attached to closely spaced posts

3 Rigid, eg concrete barriers, comprising rigid blocks designed to slide across the ground.

Figure 2.9 presents photos of some of the barrier systems currently in use in New Zealand.

Figure 2.9 Examples of barrier systems in use in New Zealand

a) Wire rope barrier

b) Semi-rigid barrier

c) Rigid barrier

According to the M23:2009 specification, the minimum requirement for road safety barrier systems on state highways is based on *NCHRP report 350* (1999) (test level 3 (TL3)). This requires that such a barrier must be able to perform adequately in crash tests with a 700kg car travelling at 100km/h impacting at an angle of 20°, or a 2000kg pick-up also travelling at 100km/h impacting at an angle of 25°. Note that in New Zealand, *NCHRP report 350* was superseded in November 2012 by the AASHTO (2009) *Manual for assessing safety hardware* (MASH-1), on the instructions of the NZTA. This contains changes to the procedures and criteria used to evaluate and test various types of road safety devices. It is designed to reflect changes in the vehicle fleet, eg size, height and weight.

The M23:2009 specification requires that the layout of such road safety barrier systems is in accordance with the requirements of section 7.3: Roadside features, of the SHGDM. This covers location and layout factors such as 1) the offset from the edge of traffic lane, 2) deflection requirements, 3) any terrain effects, 4) flare rate (the rate of change of offset from the road) and 5) the length of need.

In most cases, according to section 7.3 of the SHGDM, 'a longitudinal safety barrier should be placed as far from the edge of the traffic lane as conditions permit'. Usually, this means that a barrier should be placed beyond the 'shy line offset', ie the offset distance beyond which roadside features do not cause drivers to 'shy' away from them. Therefore, the shy line avoids affecting driver behaviour and maintains speeds and capacity, but is not necessarily safety related. Table 2.2 lists the shy line offsets from section 7.3 of the SHGDM that should be provided wherever possible.

Table 2.2 Shy line offsets (table 7.1 from SHGDM)

Design or 85th percentile speed (km/h)	Shy line offset (m)	
	Nearside (left)	Offside (right)
≤70	1.5	1.0
80	2.0	1.0
90	2.5	1.5
≥100	3.0	2.0

In general, the consideration of the use of roadside barriers is based on the cross section determination flow chart from the SHGDM shown in figure 2.1. However, it is also based on a subjective analysis of roadside elements or conditions. In most situations, roadside barriers are placed at between 2m and 4m from the edge of the travelled lane. This is considered sufficient to accommodate a medium-sized commercial vehicle.

In New Zealand, the use of median and roadside barriers, particularly wire rope barriers, has become more frequent in recent years. As noted earlier, roadside barriers are considered a hazard, in that they represent another obstacle that a vehicle can hit if it runs off the road. Nevertheless, given the topographical issues (cliffs, embankments, and rivers) found adjacent to many roads in New Zealand, and also funding issues, they can often represent an appropriate choice depending on the circumstances.

2.4.2 Australia

In Australia, as in New Zealand, barriers are used to shield 'hazards that cannot be removed or made more forgiving' (Austroads 2002). In the past all road safety barriers in Australia were required to comply with the joint Australian and New Zealand Standard AS/NZS 3845: 1999, which is based on the testing standards of *NCHRP report 350* (1999). As in New Zealand, *NCHRP report 350* is to be replaced by MASH-1 (AASHTO 2009). Flexible, semi-rigid or rigid barriers similar to those used in New Zealand are selected in accordance with Austroads (2010a) *Guide to road design: part 6: roadside design, safety and barriers*.

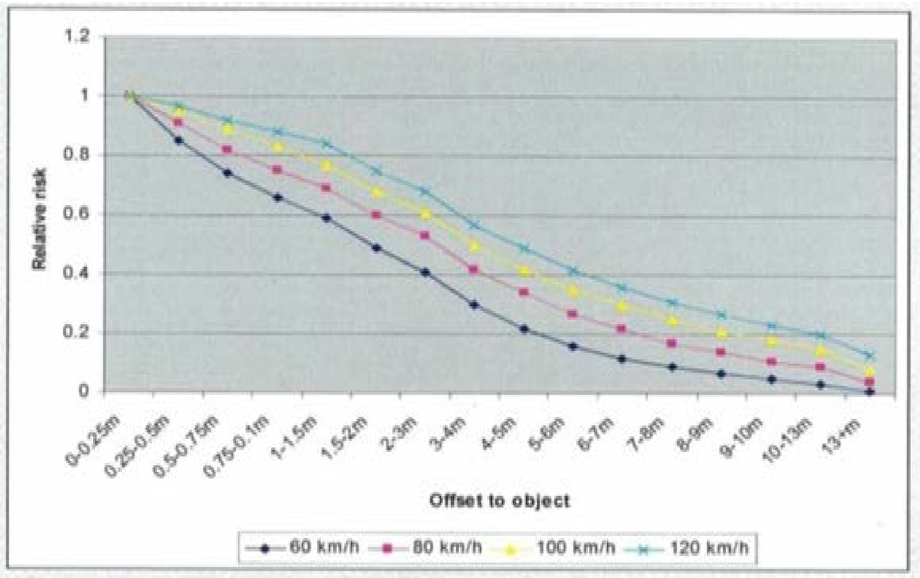
2.5 Recent and current research

Recent and current research, internationally and in Australia and New Zealand, is raising questions about the most appropriate safety treatments for roadsides, particularly given the adoption of the Safe System approach to road safety that seeks to minimise crash severity, and the need to best allocate existing and limited resources.

Much of the work involved in developing the clear-zone concept and many of the current design practices relating to clear zones and barriers, are based on research and analysis carried out in the 1970s. Questions are currently being asked, not only about whether these practices reflect the improvements in general geometric design, skid resistance, vehicle mechanical reliability, safety features (eg airbags, ABS, ESC), performance and road delineation, but also whether the clear-zone concept is the most appropriate for a Safe System approach to road safety. There is an increasing perception that a holistic approach, where combinations of a variety of safety features are used, is desirable.

There have been a number of recent studies that have investigated run-off-road crashes, eg Shaw-Pin (2001), ASSHTO (2006), Levett (2007). Some of these have looked at the probability of vehicles involved in run-off-road events exceeding different encroachment distances. Figure 2.10 shows a plot of the relative risk (from AASHTO) of different levels of encroachment.

Figure 2.10 Relative risk and encroachment distance (AASHTO 2006)



This shows that for typical speeds on New Zealand state highways around 20% of encroachments could exceed the basic recommended clear-zone width of around 9m. This does not give any indication of the crash outcomes found for vehicles reaching or exceeding this encroachment distance. There have been a number of studies that have looked at crash severity in such cases. One of the most recent of these was reported in Jurewicz and Pyta (2010). This study of crash data on rural roads in Victoria, Australia, showed that even for very wide clear zones (>9 m) there were still a significant number of run-off-road casualty crashes. Accordingly, even very wide clear zones cannot be considered a total solution under the Safe System approach. Rather, clear zones represent a 'harm reduction supporting solution'. The results of this analysis of crash statistics are also supported by the work of Doecke and Woolley (2010; 2011) and Jamieson (2012). The Doecke and Woolley studies involved analysis of selected run-off-road crashes, followed by computer simulation modelling using the HVE (Human Vehicle Environment) simulation package to assess clear-zone widths and the appropriateness of barrier protection. They showed 'that it would be rarely feasible to provide a clear zone wide enough to accommodate a vehicle that left the road out of control', that 'barrier protection has the potential to meet the requirements of a Safe System' and that 'roadside barrier protection in combination with narrower clear zones may provide the most cost effective way to treat rural roadsides to achieve a Safe System'. Jamieson (2012) showed similar results, using the computer simulation package PC-Crash to investigate vehicle encroachments on corners, stating that 'vehicles in wet conditions can pass through a standard 9m clear zone, reaching the far side with relatively high speed, even under emergency braking'.

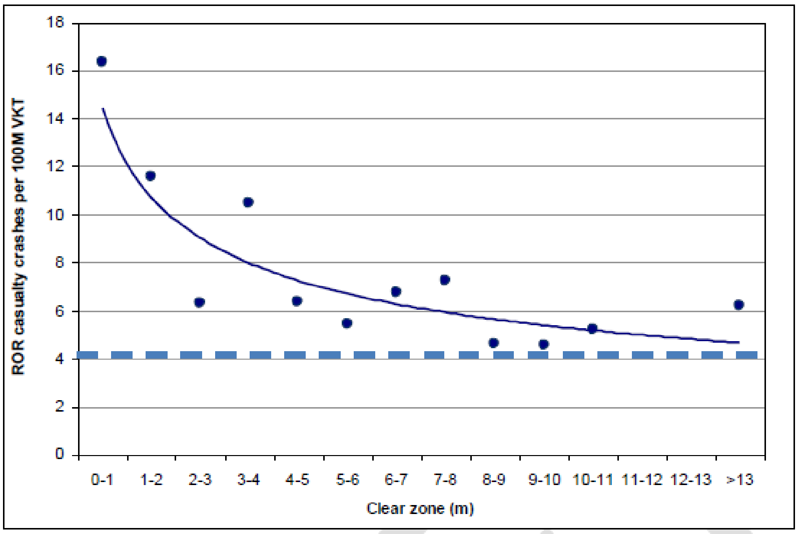
2.5.1 Improving roadside safety – ARRB study

Research studies, including those above, combined with the adoption by Australian roading authorities of the Safe System approach to road safety, led the Australian Road Research Board (ARRB) to instigate a four-year study aimed at gaining a greater understanding of how to best treat roadside hazards. This broad and detailed study, currently in its final year, has resulted in three reports (Austroads 2010b; 2011a and 2011b, 2012). These reports contain a great deal of information, covering much broader subject areas than this current study is focused on. They have tended to look at the effects of clear zones and barriers as separate aspects of roadside safety. With specific reference to the objective of this project, which was to help choose the most effective roadside safety treatment, the results of the Australian study to date are described in the following sections.

2.5.1.1 ARRB study – clear zones

The ARRB study (Austroads 2011a) analysed the risk of run-off-road crashes for different clear-zone widths on the left-hand side. Figure 2.11 shows the variation in crash risk with clear-zone width.

Figure 2.11 Run-off-road casualty crash rate for various clear-zone widths (Austroads 2011)



This shows that the crash rate reduces significantly over the first 8m–9m and then is relatively flat. This 'residual' crash risk may be due to other factors within the clear zone not linked to the clear zone width, eg rollover crashes or impacts with ground features such as drains or culverts. Table 2.3 presents these results in various clear-zone width ranges, together with confidence limits.

Table 2.3 Run-off-road casualty crash likelihood changes with varying clear-zone width (from Austroads 2011a)

Clear zone range (m)	ROR casualty crashes per 100M VKT	95% confidence limits ($p \leq 0.05$)	Relative risk of a ROR casualty crash
0–2	13.3	9.8–17.7	2.4
2–4	8.9	7.1–11.0	1.6
4–8	6.4	5.4–7.4	1.1
>8	5.6	4.8–6.4	1.0

The suggestion from Austroads (2011a) is that 'only clear zones exceeding 4m should be permitted on the 100km/h rural road network, if safety barriers are not an option'.

2.5.1.2 2.5.1.2 ARRB study – safety barriers

The Austroads study (Austroads 2011a; 2011b) involved detailed analysis of crashes into common roadside hazards, including safety barriers. It focused on defining two severity indices: 1) the risk of a fatal or serious injury (FSI), and 2) the risk of a fatal outcome (F). These are described in the following equations:

$$\text{FSI ratio} = \Sigma(\text{Fatalities} + \text{Serious injuries})/\Sigma(\text{All vehicle occupants}) \quad \text{(Equation 2.1)}$$

$$\text{F ratio} = \Sigma(\text{Fatalities})/\ \Sigma(\text{All vehicle occupants}) \quad \text{(Equation 2.2)}$$

$$\text{Injury ratio} = \Sigma(\text{All injuries})/\ \Sigma(\text{All vehicle occupants}) \quad \text{(Equation 2.3)}$$

In the final Austroads report (Austroads 2012), an alternative definition of the FSI ratio was proposed:

$$FSI_{2012}\ \text{ratio} = \Sigma(\text{Fatalities} + \text{Serious injuries})/\Sigma(\text{All casualties}) \quad \text{(Equation 2.4)}$$

A roadside hazard with a low or zero FSI ratio can be said to perform close to a Safe System condition, ie all crashes are either property damage only, minor injuries or not recorded.

An analysis of urban and rural crashes over 10 years across Victoria (Austroads 2011a; 2011b) was used to develop severity indices for different types of barriers (rigid, semi-rigid and flexible). These are shown in table 2.4. Also included in this table is the corresponding FSI_{2012} data from the Austroads (2012) report.

Table 2.4 Crash severity levels by road safety barrier type (from Austroads 2011b; 2012)

Barrier type	F ratio	FSI ratio	FSI_{2012} ratio	Injury ratio	Casualty crashes
Rigid	0.03	0.32	0.50	0.84	113
Semi-rigid	0.07	0.40	0.60	0.81	108
Flexible	0.01	0.23	0.33	0.59	46

The relatively high crash severity levels for semi-rigid barriers, which could be expected to be more forgiving than rigid barriers in crashes, are considered to be due to the road locations to which they are applied, compared with the other barrier types. Nevertheless, the data suggests that flexible barriers perform better than the other barrier types.

To provide a better context for these results, severity indices were also calculated for a range of other roadside hazards commonly encountered in run-off-road crashes. For comparison, this included the no-object-hit scenario, ie where the vehicle comes to a stop without hitting a roadside hazard, but may impact for example with the roadside surface, drains or batter slopes. These severity indices are shown in table 2.5. The Austroads (2012) FSI_{2012} data is also included in this table.

Table 2.5 Crash severity levels by common roadside hazards (from Austroads 2011b; 2012)

Hazard type	F ratio	FSI ratio	FSI_{2012} ratio	Injury ratio	Casualty crashes
Pole (power/phone)	0.07	0.55	0.81	0.93	252
Tree/shrub/scrub	0.07	0.52	0.75	0.89	2589
Fence/wall/gate	0.03	0.47	0.55	0.86	484
Embankment	0.02	0.41	0.53	0.89	802
No object hit	0.02	0.38	0.55	0.82	1686

Comparing tables 2.4 and 2.5 it can be seen that flexible barriers had the lowest injury severity ratios, better even than those for the no-object-hit scenario. Furthermore, the data shows that both semi-rigid and rigid barriers have lower FSI ratios than many commonly hit objects on the roadside. These relationships hold when the proportion of fatalities and serious injuries to either the total number of vehicle occupants or to the total number of casualties is considered.

2.5.2 Full-scale barrier crash testing

The improvement of existing barrier systems and the development of new ones is a continuing process of research and testing. Recent research involving full-scale testing of barriers (Hammonds and Troutbeck 2012) suggests that based on some limited testing with crash dummies, there appeared to be little practical difference in crash severity reduction between wire rope and W-beam semi-rigid barriers. However, the amount of testing appears to have been constrained by funding.

Also, as a general comment within that research, the relative performance of some semi-rigid barriers might improve with further development and become closer to flexible wire rope barriers rather than remaining at a similar performance level to rigid barriers. However, this would need to be confirmed through further research, product development and a more extensive testing programme. It may be worth noting that at the time of this research Bernard Hammonds was the Chair of the Austroads National Safety Barrier Assessment Panel. Rod Troutbeck was the co-Chair of the International Research sub-committee of the US TRB Committee AFB20 ‘Roadside Safety Design’.

2.5.3 Cumulative approach

This project focused on assessing the best treatment, in terms of clear zones or barriers, for any given section of roadside. However, the work of Jurewicz and Pyta (2010) and Jamieson (2012) suggests that the roadside should not be treated in isolation from other factors that affect crash risk and that a cumulative approach is most appropriate. In particular, both these studies also emphasise consideration of the width of the lane and sealed shoulder.

3 Creation of analysis dataset

3.1 Background

This project was based around the crash risk model developed by Statistics Research Associates Ltd and Opus International Consultants for the NZTA (Cenek et al 2012a; 2012b). The model used a database that included linked road condition, road geometry, traffic and injury crash data (fatal, serious injury and minor injury) from the NZTA's road assessment and maintenance management (RAMM) data tables, but did not contain any information on the roadsides.

The information that is available on roadsides is contained in the RAMM database and in KiwiRAP. KiwiRAP is the New Zealand Road Assessment Programme. It falls under the umbrella of the International Road Assessment Programme, otherwise known as iRAP. Similar road assessment programmes have been implemented in over 70 countries and include Europe (EuroRAP), Australia (AusRAP) the US (usRAP), South Africa and Malaysia. Road assessment programmes internationally consist of three 'protocols':

1. Risk mapping – uses historical traffic and crash data to produce colour-coded maps which illustrate the relative level of risk on sections of the road network.
2. Performance tracking – involves a comparison of crash rates over time to establish whether fewer – or more – people are being killed or injured and to determine if measures to improve safety have been effective.
3. Star rating – road inspections look at the engineering features of a road. Between one and five stars are awarded to road links depending on the level of safety 'built-in' to the road.

The first set of KiwiRAP risk maps for New Zealand was published in January 2008. This was followed by the publication of KiwiRAP star ratings in June 2010.

Accordingly, for this project the statistical modelling database was updated to include the most up-to-date RAMM, crash and KiwiRAP data available. The following sections describe the data extraction and validation carried out by MWH New Zealand Ltd (MWH).

3.2 Barrier/railings data

Barrier or railings data was sourced from the NZTA's RAMM database as of 30 January 2012. The data for the entire state highway network, with the exception of divided (multi-lane) roads, was extracted from RAMM. This included all the NZTA required fields, which are listed in table 3.1.

This data was one of the key elements underpinning the study of the effects of clear zones and barriers on crash risk. As such it was important that the data be as robust as possible. However, it was known that there were quality issues with some of the RAMM data and that the barrier and railings data in particular could have significant errors. Accordingly, a number of validation and manual video checks were undertaken. These are described in section 3.2.2.

Table 3.1 NZTA required RAMM railings fields

Required fields
road_id
start_m
end_m
length_m
offset
side
railing_type
install_date
ground_height
railing_make
shape
railing_material
railing_attach
rail_start_style
rail_end_style
railing_ground_fix
risk_likelihood
risk_consequence

3.2.1 Classification of barrier type

For the purposes of this study, railing types were assigned a broad classification representing the barrier type as one of the following:

- wire rope, which represents flexible barriers
- semi-rigid, which represents guard rail and w-section type barriers
- rigid, which represents concrete and other rigid types of barriers
- low effectiveness, which includes sight rails, hand rails and other railing types that are unlikely to be effective in restraining out-of-control vehicles (low effectiveness railings were excluded from the analyses as railings, and the KiwiRAP roadside condition used in their place)
- excluded, which represents railing types, such as crash cushions that were specifically excluded from the analysis.

In determining the barrier classification the following approaches were taken where assumptions or manual checks were required:

- Where the railing type was not clear, ie barrier or other, a manual check was performed. Those with a material type recorded as concrete were coded as rigid and those recorded as galvanised or steel were coded as semi-rigid unless the notes fields in the record indicated otherwise. This resulted in the inclusion of an additional 138 railing records.

- Wooden railings, non-standard steel rails, flexi-posts etc. were coded as 'low effectiveness'.
- Crash cushions, rock catch fences, mesh fences etc were excluded.
- Sea walls were included as rigid barrier types.
- Breakaway cable terminal units, steel wire rope end anchor blocks, and trailing end anchor units were included where their length was 10m+ as these were likely to have been incorrectly coded. This resulted in the inclusion of an additional 42 railing records.

In total, of all railings records including ramps and divided roads, 341 railings records were flagged as requiring a manual check or adjustment of the railing type, and 36 of these were excluded. Table 3.2 lists the classification of barrier types that was used.

Table 3.2 Classification of barrier types from RAMM railing type

RAMM railing type	RAMM railing type description	Barrier type classification	Notes
BARR	Barrier	Classified manually	As 'barrier' could be any type of railing, the record was checked to manually classify the railing type.
BCT	Breakaway cable terminal unit	Semi-rigid	BCTs were only included where longer lengths were recorded (indicating that the railing type had been incorrectly coded). Short lengths were excluded.
CABLE	Cable barrier	Wire rope	
FTYPE	F-type concrete	Rigid	
GR	Guard rail	Semi-rigid	
GREAT	GREAT system crash units	Excluded	
HR	Hand rail	Low effectiveness	
NJ	New Jersey barrier	Rigid	
OTHER	Other	Classified manually	As 'other' could be any type of railing, the record was checked to manually classify the railing type.
SDCC	Steel drum crash cushion	Excluded	
SIBC	Steel medium barrier – IBC	Rigid	
SR	Sight rail	Low effectiveness	
STP	Steel tube and post barrier	Low effectiveness	
SWR	Steel wire rope barrier	Wire rope	
SWRA	Steel wire rope end anchor block	Wire rope	Only included where longer lengths were recorded (indicating that the railing type had been incorrectly coded). Short lengths were excluded.
TBGR	THRIE beam steel guard rail	Semi-rigid	
TEA	Trailing end anchor units	Semi-rigid	TEAs were only included where longer lengths were recorded (indicating that the railing type had been incorrectly coded). Short lengths were excluded.
TRIC	TRIC block concrete barrier	Rigid	
WGR	W-section guard rail	Semi-rigid	

3.2.2 Validation and manual checking

Validation checks were undertaken using the state highway video to check that the attributes of interest were correct. For efficiency, these checks were generally performed on whole route stations, with an emphasis on route stations that had a number of flagged or overlapping records.

3.2.2.1 Flagged records

Validation checks were developed to highlight potential issues with the railings data. These focused on tests that would highlight issues with the railing type, offset and location (start, end and side) as the attributes used in this study. The following validation checks were used to flag questionable records:

- wooden barriers with terminal ends
- wooden barriers with X350 ends
- Armco cable railings
- cable railing with Texas twist ends
- cable railing with bull nose ends
- concrete guardrail
- mesh guardrail
- wooden guardrail
- Armco new jersey barrier
- wooden New Jersey barrier
- New Jersey barrier with bull nose ends
- New Jersey barrier with fishtail/butterfly ends
- Armco sight rail
- galvanised steel sight rail
- steel sight rail
- sight rail with Texas twist ends
- sight rail with FL350 ends
- steel tube barrier with SK350 ends
- steel tube barrier with bull nose ends
- mesh steel wire rope railings
- steel wire rope railing with bull nose ends
- steel wire rope railing with TEA ends
- steel wire rope railing with BCT ends

- steel wire rope railing with Texas twist ends
- wooden THRIE beam
- THRIE beam with cable ends
- galvanised steel TRIC block
- concrete WGR
- mesh WGR
- wooden WGR
- WGR with cable ends
- WGR with cable safety ends
- WGR with SWRA ends
- railings in the centre of an increasing/decreasing split carriageway
- railings in the centre with an offset
- railing on left/right with a 0 off-set
- railings that exceed the road end
- railings outside the road extents
- offsets > 20m.

It should be noted that while these records were flagged, this does not necessarily mean that any of the attributes of interest (railing location and type) were incorrect. For example, incorrect material or end terminal types (75 occurrences) were not an issue in themselves as this field was not used in the analysis, but they could be an indicator of an incorrectly recorded railing type.

In total, 611 railings records were checked using the state highway video, including both flagged and un-flagged records. They were either corrected, if the error was apparent (seven records), or excluded from the analysis (26 records). In conducting these checks of both flagged and un-flagged records it was possible to gain an appreciation of the error rate, with 95% of records found to be correct for the attributes of interest. As such, it was decided to include the remaining 126 unchecked flagged records on undivided roads.

3.2.2.2 Overlaps

During the data processing, 433 instances of overlapping railings records were also identified. These included overlapping ends, overlaps where one barrier overlapped a number of others, and overlaps where the start and end points of both barriers were the same. While overlaps can be legitimate, particularly in the case of wire rope barriers where the start and end of consecutive barriers will overlap, the occurrence of an overlap can be an indication of an incorrectly recorded barrier location. Similarly, duplicate records (38 suspected occurrences) were not an issue as the higher railing ID was simply taken when incorporating the railing data into the statistical model. Checks were undertaken using the state highway video to correct or exclude a number of these records, with a focus on long railings. For efficiency, the checks undertaken were often performed on whole route stations, with an emphasis on route stations that had a number of questionable or overlapping records. While further checking would have been ideal, there was a limit to the checks that could be done and significant effort was put into checking the data within the time available.

3.2.2.3 Installation date and offset

For the purposes of the statistical analysis, barrier installation dates and offset distance from the edgeline were required. However, only 48% of the 7868 railing records included in the analysis had a populated installation date. As the statistical analysis discussed later used only the last four to five years of data it was the more recent railings, installed in the last four to five years where the installation date was of concern. As such, it was possible to use the 'added on' or 'changed on' fields, which indicated when the record was added to the RAMM database and when it was last changed, to identify whether a railing had been installed for a time. For example, of the 3707 railings records that did not have an installation date, 65% of these had an 'added on' date older than five years.

In RAMM the railing offset is measured from the centreline, yet for the purposes of this study the offset from the edge of seal was required. To overcome this issue, the carriageway (not lane) width was used to approximate the offset to give an 'adjusted railing offset'. However, this did result in some error. For example, this method would not account for variation in shoulder width between the left and right side of the road.

3.2.2.4 Summary of barrier/railings dataset used

Table 3.3 summarises the barrier data provided for the statistical analysis.

Table 3.3 Summary of barrier/railings data (number of records)

Barrier type	Offset (m)				Total
	0m to 4m	4m to 9m	9m to 15m	15m+	
Wire rope	31	211	5	0	**247**
Semi-rigid	862	6457	226	21	**7566**
Rigid	9	51	0	1	**60**
Total	**902**	**6719**	**231**	**22**	**7873**

Of these railings:

- 611 were verified using the state highway video
- 7 were corrected
- 26 were excluded
- 126 were not checked and were marked as questionable from the validation checks.

3.3 KiwiRAP

The KiwiRAP star rating model is based on 18 infrastructure features that are rated or coded in order to produce the star ratings. This model has been applied to 10,002km of the rural state highway network to produce star rating results published in 2010. As such the KiwiRAP data provides a rich source of data on the state highway network. The 18 infrastructure features that feed into the model are coded based on where they sit within specified bands or ranges. For example, lane width is coded as either <2.8m, 2.8m to <3.1m, 3.1 to 3.4m, or >3.4m. Each feature is either rated manually from video, or assessed using automated data routines utilising the NZ Transport Agency's high-speed road geometry data. The current published KiwiRAP star ratings were released in June 2010 and were based on video footage and SCRIM surveys undertaken over the 2008–09 summer period.

3.3.1 KiwiRAP data

The KiwiRAP attributes utilised for this project included 1) the roadside hazard risk, 2) the horizontal alignment and 3) the terrain. These are discussed below.

3.3.1.1 Roadside hazard risk

When a vehicle runs off the road, the likelihood of a crash and the severity of the outcome is related to the presence of roadside hazards, the type of hazard and the distance any hazards are offset from the carriageway. On this basis, KiwiRAP uses a matrix approach to assess roadside hazard risk. The hazard type is recorded against one of five categories (see table 3.4) and the offset between the edgeline and the hazard is assigned to one of four offset categories (0m–4m, 4m–9m, 9m–15m, 15m+). The head-on severity outcome is coded where the median is such that an errant vehicle could completely cross it into oncoming traffic. The combination of hazard type and offset is then used to determine the run-off-road hazard risk or condition by assigning four categories of negligible, minor, moderate or severe as shown in table 3.5. Each of these run-off-road risk categories is also given a risk score/factor.

Table 3.4 KiwiRAP hazard condition (severity outcome) descriptions

Severity outcome	Description
Negligible	Minor property damage only, eg kerb, wire-rope barrier, level slope with no hazards
Rigid barriers	Rigid barriers, steel beam guard fence, including guardrail and other semi-rigid barriers
Moderate	Intermittent hazard likely to cause moderate damage or injury, eg shallow embankment, cut, longitudinal bridge or wall, mid-size culvert
Severe	Likely to cause fatality or serious injury, eg trees greater than 300mm diameter, rollover – greater than 4:1 fill, transverse wall / bridge pylon
Head-on*	On divided carriageway roads where the median is such that an errant vehicle could completely cross the median into oncoming traffic the 'head-on' severity category is used for the right side hazard condition (severity outcome), eg lack of barriers or other obstacles in the median. The offset is taken as the distance between the nearest travelled lanes in each direction.

* Applicable only to right side hazard condition (severity outcome) where run-off onto the opposing carriageway is possible.

Table 3.5 KiwiRAP run-off-road hazard risk/condition codes and risk factors vs offset

Severity outcome	Offset from edge of sealed carriageway[a]			
	0m to 4m	4m to 9m	9m to 15m	15m+
Negligible (including wire rope barriers)	1 – Negligible (0.40)[b]	1 – Negligible (0.40)	1 – Negligible (0.40)	1 – Negligible (0.40)
Rigid barriers	2 – Minor (0.67)	1 – Negligible (0.40)	1 – Negligible (0.40)	1 – Negligible (0.40)
Moderate	3 – Moderate (1.43)	2 – Minor (0.67)	1 – Negligible (0.40)	1 –Negligible (0.40)
Severe	4 – Severe (2.80)	3 – Moderate (1.43)	2 – Minor (0.67)	1 – Negligible (0.40)
Head-on	4 – Severe (2.80)	3 – Moderate (1.43)	2 – Minor (0.67)	1 – Negligible (0.40)

[a] For head-on category the distance relates to the width of any median that does not include a barrier

[b] Risk factor

During the rating process, the hazard scoring was done by identifying the worst hazard every 100m using the matrix as explained above. The left and right sides of the road were scored separately.

3.3.1.2 Horizontal alignment

The horizontal alignment score is based on a crash risk model, developed for New Zealand state highways by Cenek and Davies (2004). The model takes into account both the alignment characteristics of the road section and the relationship between this and the preceding alignment. The crash risk model uses the 10m high-speed road geometry data collected as part of the annual state highway SCRIM surveys. The model outputs are converted to a risk score which ranges from 1 to 6, as shown in table 3.6, and averaged for both directions over each 100m section to determine the horizontal alignment risk score.

Table 3.6 KiwiRAP horizontal alignment risk scores

Model output[a]	Code and risk score	Horizontal alignment description
<2.5	1	Consistently straight road (typically radii >3500m)
2.5 – <3.75	2	Easy curves (typically radii 1400m–3500m) with alignment/advisory speeds >100km/h
3.75 – <5.25	3	Easy-moderate curves (typically radii 750m–1400m) with alignment/advisory speeds 90–100km/h, which may be slightly out of context
5.25 – <7.25	4	Moderate curves (typically radii 470m–750m) with alignment/advisory speeds of 85–90km/h and/or curves that are moderately out of context
7.25 – <9.5	5	Tight curves (typically radii 330m–470m) with alignment/advisory speeds of 75–85km/h and/or curves that are highly out of context
9.5+	6	Very tight curves (typically radii <330m) with alignment/advisory speeds <75km/h and/or curves that are severely out of context

[a] Note that in new version of KiwiRAP these output bands have since been adjusted due to corrections made.

3.3.1.3 Terrain

In KiwiRAP, the terrain is rated as either level, rolling or mountainous, and is determined using high-speed geometry data as defined in table 3.7 below for every 10m section of road and then taking the 500m rolling average. The terrain score is assigned to every 100m section by taking the mode of the 10m codes from both directions. The rating and risk scores were derived from the crash rates reported in the EEM volume 1 and previous research by McLarin (1995). The descriptions/notes are compatible with those used in the EEM volume 1, but the assessment criteria may differ (refer section A7.3).

Table 3.7 Terrain codes and risk scores

Terrain	Code	Risk score	Assessment criteria	Descriptions/notes
Level	1	1	Average absolute gradient[(a)] ≤ 1.5%, and max. gradient – min. gradient ≤ 6%, and max. 1000/horizontal curvature[(b)] – min. 1000/horizontal curvature ≤ 5rad/km	Level of gently rolling country, with gradients generally from flat up to 3%, which offers few obstacles to an unrestricted horizontal and vertical alignment
Rolling[1]	2	1.5	1.5% < average absolute gradient ≤ 4.5%, or 6% < max. gradient – min. gradient ≤ 12%, or 5rad/km < max. 1000/horizontal curvature – min. 1000/horizontal curvature ≤ 15rad/km	Rolling, hill, or foothill country with moderate grades generally from 3% to 6% in the main, but where occasional steep slopes may be encountered.
Mountainous	3	2.0	Average absolute gradient > 4.5%, or max. 1000/horizontal curvature – min. 1000/horizontal curvature > 15rad/km	Rugged, hilly, and mountainous country (and river gorges) often involving long, steep grades over 6%, and considerable proportions of the road with limited sight distance.

(a) The average absolute gradient is the average of the absolute gradients within the 500m rolling average that is calculated for every 10m length, where the gradient is the % of longitudinal gradient

(b) Horizontal curvature is the radius of curvature, and 1000/horizontal curvature is used purely for practicality in calculations as it means that straight roads with large curvatures are represented by numbers approaching zero.

3.3.1.4 KiwiRAP rating bias

The KiwiRAP data was coded from a four-way camera that was driven along the state highway network in the increasing direction. It is not known whether any correction was made for the camera position when rating attributes presented on the decreasing direction, such as a hazard risk on the right side of the road when facing in the increasing direction. A number of road attributes, such as lane width and shoulder width were rated using on-screen measurement tools. However, it is not known whether roadside hazard offsets were measured or rated based on visual judgement. It is suspected that visual judgement alone was used when rating the hazard risk on both the right and left sides of the road. A count of left and right offsets for undivided rural roads (refer table 3.8) seems to confirm this, showing that the right-hand offset

[1] For the June 2010 release of KiwiRAP the assessment criteria for rolling terrain incorrectly had an 'and' instead of an 'or' for the second logic statement, ie 6% < max. gradient – min. gradient ≤ 12%, and 5rad/km < max. 1000/horizontal curvature – min. 1000/horizontal curvature ≤ 15rad/km.

tends to be smaller than the left-hand offset, when over the whole network you would expect them to be similar.

Table 3.8 Disparity between KiwiRAP left and right offsets

Offset category	Left count	Right count	Ratio of right count to left count
1 (≤4m)	75,748	82,107	1.08
2 (4-9m)	18,121	12,480	0.69
3 (9-15m)	2500	1846	0.74
4 (15+m)	582	518	0.89

Part of this difference could be legitimate and part of it could be due to the subjective nature of the rating and some skew due to the position of the video. However, as there is no robust way to separate the two or to correct for this no adjustment has been made. It should, however, be noted that there appears to be some difference in left and right offset categorisation, and this is likely, at least in part, to be due to bias introduced during the rating process.

3.4 Geometry, road condition and crash data

Geometry (gradient, curvature and crossfall) data and road condition (roughness, rutting and skid resistance) data for the entire state highway network was extracted from the RAMM database for the 2010 and 2011 state highway surveys. Crash data for 2011 was also extracted. The data included the following information for each 10m or 20m segment from the RAMM tables:

- geometry – geometry data including gradient, curvature, crossfall etc
- roughness – roughness data including IRI, NAASRA etc
- rutting – rutting and shoving data
- SCRIM – skid resistance data
- texture – macro texture data
- CAS crash – crash details including the crash movement code and weather conditions etc
- CAS crash cause – the cause codes for factors identified as probably contributing to the crash
- CAS object – object(s) hit in the crash
- CAS vehicle – vehicle types involved in the crash

This data, together with the barrier and KiwiRAP data, was provided to Robert Davies of Statistics Research Associates Ltd in specific formats intended to be compatible with his existing crash risk database, which already contains crash data up to 2010.

4 Statistical modelling

4.1 Background

This project built on previous work done on crash risk relationships by Robert Davies of Statistics Research Associates Ltd for New Zealand's state highway network which successfully related vehicle crash rates to road surface characteristics and geometry. The crash risk models have found application in two high-profile NZTA road safety initiatives: KiwiRAP, where the models have been used to automatically assign crash risk scores for horizontal alignment, and skid resistance management of curves where model derived personal and collective crash risk values have been used to set skid resistance levels and prioritise curves for treatment (Cenek et al 2012a; 2012b).

The statistical modelling for this project was also undertaken by Robert Davies. It essentially represents an extension of his earlier crash risk modelling work, using updated data, and with the inclusion of the railing and KiwiRAP data. The following sections provide a brief description of the statistical modelling and a fuller presentation of the results.

4.2 Creation of combined dataset

The first step involved updating the existing dataset used in Cenek et al (2012a; 2012b), with the latest data, including the 2011 crash data, and the integration of the KiwiRAP and railing data. Initial preparation and processing of the data was carried out using the MySQL database software program. C++ routines were created to set up the data structures needed for carrying out the analyses, read in the data generated by MySQL, carry out data checking and generate the transformed data where required. In particular, these routines linked in the 10m or 20m geometry, skid resistance, roughness, crash and road data and calculated the adjusted skid site, adjusted IRI, and the OOCC variables. They also checked for isolated missing values in the predictor variables and attempted to estimate these from neighbouring variables.

The result was a combined dataset for the entire state highway network, with the exception of divided roads and the region around Christchurch for 2010 and 2011. The latter were omitted because of the disruption caused by the earthquakes. Accordingly, our analysis was restricted to rural undivided roads. Following creation of the combined dataset, a number of validation and sanity checks were carried out, including checks using the state highway video record. These were to ensure that the data had been loaded and integrated correctly.

It is important to note here that the data extracted from RAMM is based on either 10m or 20m road segments, and the KiwiRAP data is based on 100m segments. The combined dataset uses 10m as a base, and the 20m or 100m data is mapped onto this 10m base. For example, this means that each of 10 consecutive 10m sections has the same data from one of the 100m KiwiRAP sections.

4.3 Statistical modelling - analysis

The statistical analysis used a modified Poisson regression, and was based on the assumption that each side of each 10m length of road can generate crashes at the rate (per year) described in the following formula:

Crash rate (injury/fatal crashes per 10m per year) =

$$a \exp(\boldsymbol{L}) \qquad \text{(Equation 4.1)}$$

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

- a constant term
- gradient (in the second approach described below)
- curvature
- out of context curve effect (OOCC)
- skid-site classification
- skid resistance
- roughness (IRI)
- log(ADT)
- year
- region
- road-side and railing types.

Note that the ADT appears in the model in two places, a in equation 4.1 and as a component of ***L***. These could have been combined into a single term in ***L***. However, by using the formulation in equation 4.1 the component in ***L*** is present only if the crash risk (expected number of crashes per 100 million vehicle kilometres) depends on ADT. When there is dependence, this dependence is modelled by the size of the coefficient of log(ADT) in ***L***.

The model supposes that the rate that crashes are reported in a 10m length of road is the average of generating rates over the 10m lengths within 100m of the length being considered and summed over the two sides of the road. This averaging allows for error in reporting the location and the possibility that a crash ends at a location some distance from the piece of road involved in generating the crash. Because we are combining the sides of the road we do not have to know the directions of vehicles involved in the crash.

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

The model fitting was done by maximum likelihood and used C++ libraries for matrix manipulation and automatic differentiation and a prototype array and statistical modelling package.

The model assumes that roadside condition and the geometry and road surface conditions are relevant only to the side a vehicle is travelling on. In the case of a head-on crash we can suppose this applies to the vehicle at fault. However, this is an approximation to the actual situation, particularly when one considers roadside condition, since a vehicle may cross the road before leaving the road. Hence, we might expect the size of the effects of the roadside conditions to be exaggerated since the effect for both sides of the road will be assigned to one side. However, predictions of the total effect on the combined crash rate for both sides of the road should be realistic since this is what the model is fitting. One could imagine having terms in the model for the roadside condition for each side of the road but there are technical reasons why this is difficult to do.

Two approaches were used in the analysis:

1 The roadside condition, as determined by the KiwiRAP rating or railing type, was included in the model. Two different formulations of the roadside condition were investigated. It was supposed that the roadside condition was relevant only to vehicles travelling on its side of the road. It used the 2008–11 (four years) crash data.

2 The model was fitted to the crash data for 2004–11 (eight years) without any roadside terms. The road section was then categorised by the roadside condition, and the number of crashes predicted by the model, without the roadside terms for 2008–11, was compared with the actual crash numbers for each of the roadside conditions.

Note that for these analyses, three barrier classifications were used, these being 1) wire rope, 2) semi-rigid and 3) short rail. The short railing lengths (< 100m) were separated out because they are often associated with another hazard, such as a bridge approach. There were only a small number of rigid barriers in this study as most of these were on divided roads, which were excluded. In the first analysis they were combined with the short rails. In the following analyses they were assigned to the KiwiRAP rigid barrier category since this was possibly a more natural classification. Either way they had little influence on the overall results.

4.4 Statistical modelling – results

4.4.1 Regression analysis including roadside condition

The results of fitting two versions of the Poisson regression model are presented here. Note, that in this section all casualty crashes are considered. That is, all reported crashes that involve at least one fatality, serious or minor injury. Intersection crashes are allowed for by including an adjusted skid-site term in the model which identifies intersections.

In the first version of the Poisson regression, we wanted to fit the model using the railing group and railing offset if a railing was present, and the KiwiRAP roadside severity and roadside offset if no railing was present. That is, we used the railing data and ignored the KiwiRAP data if a railing was present. If there was no railing we used the KiwiRAP data.

The railing offset and the KiwiRAP offset are measured differently and should not be represented by the same term. The following method was used for setting up the model. A pair of variables, is_rail and not_rail, indicated whether or not a railing was present. That is, they were given the values 1 and 0 respectively if a railing was present, otherwise 0 and 1. These variables then determined whether the KiwiRAP severity and offset variables (denoted in the analyses by rs_severity and rs_offset) were fitted or the railing variables railing group (wire rope, semi-rigid, and short rail) and the adjusted railing offset. Because the railing offset was measured from the centre-line, one third of the carriageway (not lane) width was subtracted to give an approximate distance from the lane edge (this assumed each lane occupied about a third of the carriageway width). The adjusted railing offset was bounded by 0 and 4 and then fitted as a linear regression term. This initial analysis was applied to the model to see whether the different roadside conditions had a statistically significant effect on the crash rate. Table 4.1 shows the analysis of variance for this model. Note that comments made on the statistical significance of variables or data are derived from the full statistical analysis report. In particular, because there are sources of random error apart from the Poisson variability in the number of crashes, a substantial margin should be allowed between the 5% point and the chi-squared value before declaring significance. In this case, we suggest a factor of 3.

Two versions of the chi-squared values are shown: type III which is appropriate when the variable is the last one fitted and type I when the variables are added sequentially. The former is commonly employed by SAS users and the latter by R and S-plus users. The type III version will show if a variable can be removed from the regression and the type I version will indicate the importance of each new term as it is included. The individual terms are described in more detail in the full statistical analysis report that will be available on http://robertnz.net/crashrisk).

Table 4.1 Analysis of variance – severity, offset and barrier/rail

Predictor variable	Degrees of freedom	5% pt.	Chi-squared	
			Type III	Type I
year	3	7.82	14.4	72.9
region	13	22.4	45.8	144.1
adj_skid_site	2	5.99	1506.3	1771.7
poly3_bound_OOCC	3	7.82	230.2	3326.9
poly2_bound_log10_abs_curvature	2	5.99	17.8	27.6
poly2_log10_ADT	2	5.99	142.4	123.6
poly2_scrim-0.5000	2	5.99	63.2	78.8
poly3_bound_adj_log10_iri	3	7.82	10.8	37.8
poly2_bound_log10_abs_curvature × poly2_bound_adj_log10_iri	4	9.49	30.2	31.9
is_rail	1	3.84	18.6	10.0
not_rail*rs_severity	3	7.82	24.1	26.1
not_rail*rs_offset	3	7.82	15.5	15.6
is_rail*railing_group	2	5.99	13.6	13.6
is_rail*bound_rail_adj_offset	1	3.84	0.0	0.0

Table 4.1 shows that individually the roadside condition variables relating to severity and offset (the last five rows of the table), are marginally significant. However, if they are considered collectively the roadside condition is statistically significant with a collective chi-squared value of 65.3 for a type I distribution, compared with a 5% chi-squared value with 10 degrees of freedom of 18.3. In order to show the effects of the individual roadside condition variables we selected a set of parameter values and then calculated the predicted crash rates while varying one parameter and holding the others at the selected values. The values chosen for this exercise are listed in table 4.2

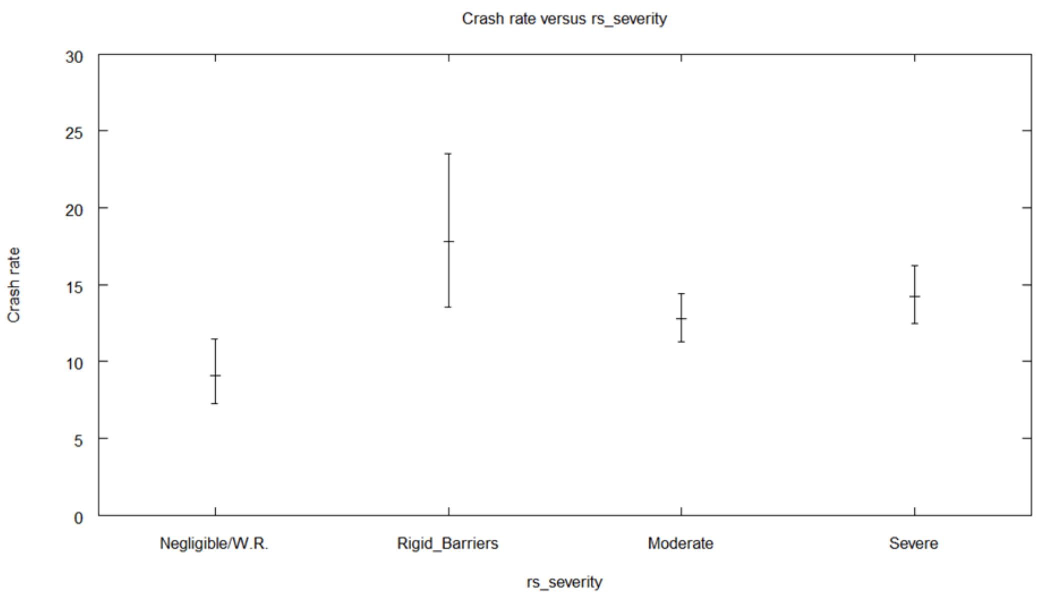
Table 4.2 Chosen model variable values

Variable	Value
year	2008
region	R03
adj_skid_site	4
OOCC	0
curvature	5000
ADT	1000
scrim	0.5
adj_log10_iri	0.3
rs_severity	Moderate
rs_offset	<4m
rs_risk	Moderate
railing_group	Semi-rigid
rail_adj_offset	1
rail_rs_cat	Moderate

4.4.1.1 Analysis of KiwiRAP data

Figure 4.1 shows a plot of the results for the KiwiRAP **severity** ranking including 95% confidence limits. (In this and the following graphs, crash rates are shown in crashes per 100 million vehicle kilometres).

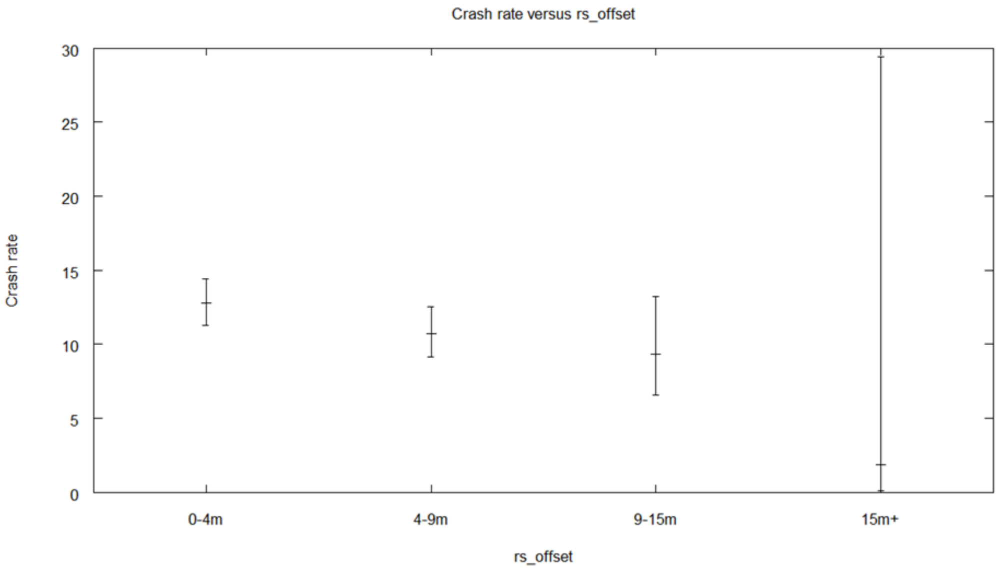
Figure 4.1 Variation of crash rate with KiwiRAP severity



The analysis in the full report indicates that, in terms of statistical significance, negligible/wire rope performs better that everything else, and that moderate is possibly better than severe or rigid barriers. However, the data suggests an increase of crash rate as we go from negligible/wire rope to moderate and then to severe. The rigid barrier category does not seem to fit into this trend.

Figure 4.2 shows a plot of the results for the offset categories. It includes the 95% confidence limits. Note that the confidence interval for the 15m+ value is very large because there is very little data in this category.

Figure 4.2 Variation of crash rate with KiwiRAP offset category



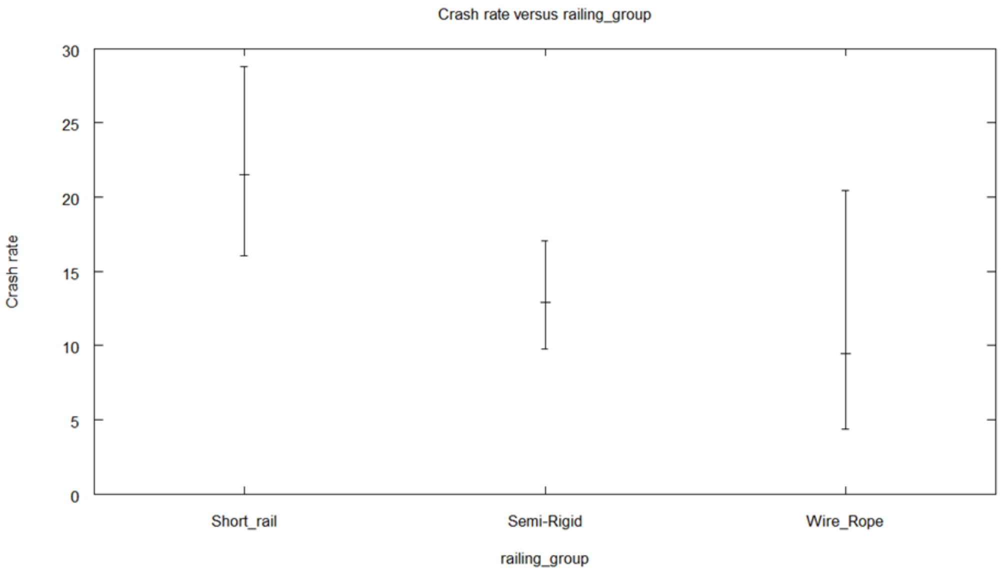
This plot suggests that the <4m category is worse than the others, and that the crash rate generally decreases with increasing offset (width of clear zone).

4.4.1.2 Analysis of barrier data

An analysis was also carried out to assess whether there was any significant effect on crash rate due to the barrier/railing offset. This showed there was no significant difference in crash rate with offset, as could be expected given that the greater proportion of barriers are placed at offsets of between 2m and 4m from the edge of the travelled lane.

Figure 4.3 shows the variation of crash rate between the different barrier categories. It includes the 95% confidence limits.

Figure 4.3 Variation of crash rate with barrier category



The full analysis suggests that short rail is worse than semi-rigid and may be worse than wire rope. The long confidence interval for wire rope is due to the limited amount of data available for wire rope.

4.4.2 Combined KiwiRAP and barrier data

It would be convenient to summarise the KiwiRAP severity and offset codes with a single code. KiwiRAP does this as shown in table 3.5, and this has been reproduced in table 4.3, with the cells shaded to show the different descriptors.

Table 4.3 KiwiRAP Run-off road severity codes and risk descriptors[2]

Severity	Offset			
	<4m	4–9m	9–15m	15m+
Negligible/wire rope	Negligible	Negligible	Negligible	Negligible
Rigid barriers	Minor	Negligible	Negligible	Negligible
Moderate (including semi-rigid)	Moderate	Minor	Negligible	Negligible
Severe/head-on	Severe	Moderate	Minor	Negligible

Our analysis suggests that the following table 4.4 may be slightly more appropriate. Here, the risk levels have been given the names tiny, low, medium, high, extra high and rigid to avoid confusion with the KiwiRAP nomenclature. The numbers, which are measures of the predicted and actual crashes, and the ratio of the two, are described in section 4.4.3. The ratio of predicted and actual crashes in table 4.4 gives a measure of the roadside risk. Note that the numbers of crashes have been rounded to the nearest whole number.

Table 4.4 Proposed severity codes and risk descriptors

Severity outcome	Offset from edge of sealed carriageway			
	0–4 metres	4–9 metres	9–15 metres	15+ metres
Negligible	Medium (656, 601, 0.92)[1]	Low (112, 78, 0.70)	Tiny (14, 6, 0.4)	Tiny (6, 3, 0.5)
Moderate	High (6532, 6504, 1.00)	Medium (744, 674, 0.91)	Low (91, 73, 0.80)	Tiny (19, 10, 0.5)
Severe, head-on	Extra high (3142, 3288, 1.05)	High (1352, 1367, 1.01)	Medium (175, 157, 0.90)	Low (32, 18, 0.57)
Rigid barriers	Rigid (236, 299, 1.27)	Rigid (4, 4, 0.9)	Rigid (1, 1, 1.6)	Rigid (0, 0, 0.0)

1 – (656 = predicted crashes, 601 = actual crashes, 0.92 = actual/predicted)

In the KiwiRAP classification, rigid barriers include bridges, rigid and semi-rigid railings and possibly some low effectiveness railings. Rigid barriers have been separated from the other categories. We have separated out the railing/barrier types by using data from RAMM and used this data to override the KiwiRAP data where railings are present. Accordingly, the KiwiRAP rigid barriers category now only

[2] The 'head-on' category, shown in table 3.5 has been combined with the severe category.

includes barriers that have been omitted from the railing database and possibly some low-effectiveness railings. Where a KiwiRAP 100m segment includes a railing for some of its length, the part of that segment where the railing is present will be given the appropriate railing classification, but the rest may still be in the rigid barriers category.

There are a small number of KiwiRAP segments that have the head-on classification. These arise where there is a centre divider just before an intersection. KiwiRAP seems to associate these with the severe classification in table 3.5 so we did the same. There were very few of these so they did not have a material effect on the results.

We also included rigid railings in our rigid classification rather than having them as a separate category or combining them with the short railings as in the previous analysis.

Since the offset variable was not statistically significant for the railings data we did not need to include it in any further analysis. This meant we could classify the road-side risk with a single factor taking the values extra high, high, medium, low, tiny, rigid, short-rail, semi-rigid or wire rope. In this classification we included rigid railings in the rigid classification rather than in the short-rail classification.

We then repeated the Poisson regression analysis using the new road-side descriptor. The analysis of variance table is in table 4.5.

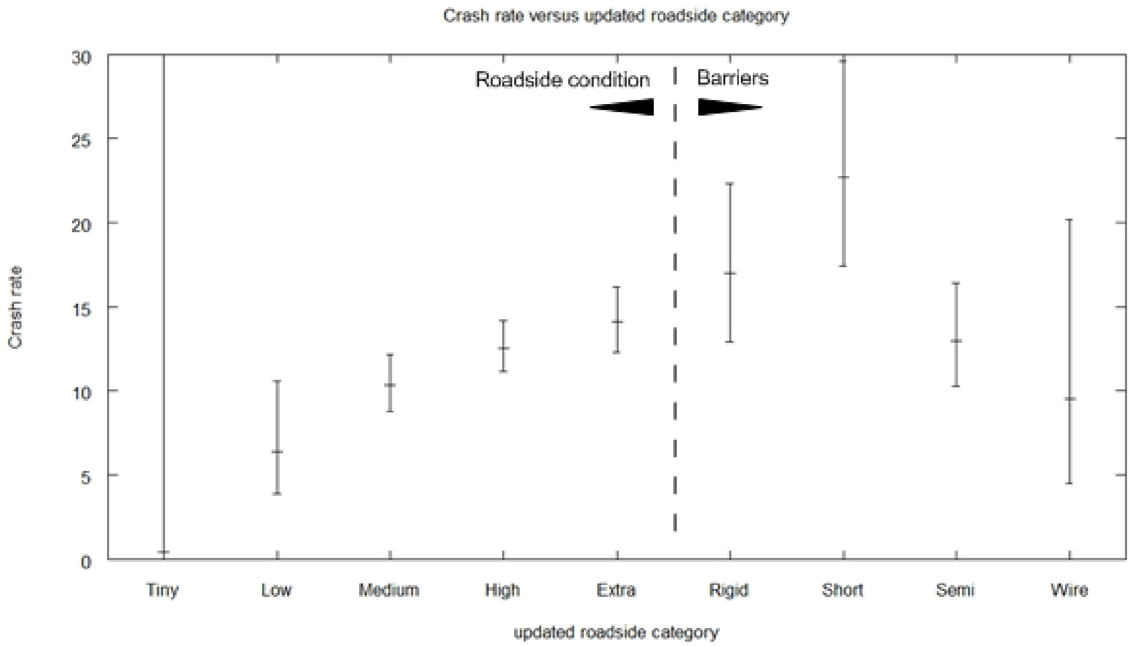
Table 4.5 Analysis of variance – updated roadside category

Predictor variable	Degrees of freedom	5% point	Chi-squared	
			Type III	Type I
year	3	7.82	14.5	72.6
region	13	22.4	47.0	143.1
adj_skid_site	2	5.99	1508.4	1765.4
poly3_bound_OOCC	3	7.82	229.1	3325.2
poly2_bound_log10_abs_curvature	2	5.99	18.8	27.6
poly2_log10_ADT	2	5.99	140.9	123.0
poly2_scrim-0.5000	2	5.99	62.9	78.6
poly3_bound_adj_log10_iri	3	7.82	10.5	38.5
poly2_bound_log10_abs_curvature × poly2_bound_adj_log10_iri	4	9.49	30.2	31.9
Updated roadside category	8	15.5	63.9	63.9

The last line replaces the last five lines of table 4.1 and has an almost identical total chi-squared value.

Figure 4.4 shows the resulting variation of crash rate and the values are also listed in table 4.6.

Figure 4.4 Variation of crash rate with barrier/rail or risk



In this graph, extra is an abbreviation for extra-high, semi an abbreviation for semi-rigid and wire and abbreviation for wire rope. The confidence interval for tiny is large because of the relatively limited amount of data.

Table 4.6 Variation of crash rate with barrier/rail or risk descriptor (from figure 4.4)

Classification type	Barrier/rail or road-side risk category	Predicted crash rate (per 100 million vehicle.km)
Derived from KiwiRAP	Tiny	0.4
	Low	6
	Medium	10
	High	13
	Extra high	14
Barrier/rail	Rigid	17
	Short rail	23
	Semi-rigid	13
	Flexible (wire rope)	10

From this graph and table, and the more detailed statistical analysis we can suggest the following:

- Low is better than extra high, rigid and short rail, and probably better than high and semi-rigid.
- Flexible (wire rope) is probably better than short rail.
- Medium is probably better than high, and better than extra high, rigid and short rail.
- High is probably worse than low and medium, and probably better than extra high and rigid and better than short rail.

- Semi-rigid is probably worse than low and better than short rail.
- Extra high is worse than low and medium, probably worse than high, and better than short rail.
- Short rail is worse than low, medium, high, semi-rigid and extra high, and probably worse than wire rope.

The overall trend is that the crash rate increases as we go through the categories derived from KiwiRAP, that is tiny to extra high. Rigid and short rail seem higher, semi-rigid seems to slot in around high in the KiwiRAP progression, and while flexible (wire rope) seems lower there is not enough data to reach a firm conclusion.

The updated roadside categories we have introduced here do seem to provide an effective simplification of the model with virtually the same explanatory power as the more complex model considered in section 4.1.1.

The information shown in these plots and tables, and in previous plots, indicates that while the offset to the hazard, ie the clear zone, is significant, it is the combination of the offset and the severity of the hazard that a vehicle would encounter after crossing the offset/clear zone that is more important. For example, with reference to table 3.4, it is probably worse to cross a clear zone and strike a severe hazard such as a large tree than to cross the same clear zone and strike a more moderate hazard such as a shallow embankment.

4.4.3 Comparison method – all casualty crashes

The modelling approach described in section 4.4.1 became unsatisfactory when we tried to restrict attention to a subset of the crashes or introduce interactions between the roadside conditions and curvature. This was due to a combination of the small amount of data available for the wire-rope and tiny categories and the assumption in the model that the roadside condition affected only vehicles on its side of the road.

The comparison method provided an alternative approach. As described in section 4.3, this method involved fitting the model described by equation 4.1 in section 4.3 to the crash data for 2004–11 inclusive without any roadside terms, using this to predict the number of crashes for the 2008–11 inclusive period for the various roadside conditions and then comparing this with the actual crash numbers.

Applying this method to all casualty crashes for both sides of the road for the 2008–11 inclusive period and the same roadside categories as in the second regression analysis we get the following table of results.

Table 4.7 Comparison of predicted and actual crash numbers – all casualty crashes for 2008–11

Roadside category	Length (km)	Traffic[1]	Predicted crashes	Actual crashes	Predicted crash-rate[1]	Actual crash-rate[(a)]	Risk ratio (actual/predicted)
Tiny	228	342	38.2	19	11.1	5.6	0.50
Low	1334	1865	234.7	169	12.6	9.1	0.72
Medium	8474	11104	1575.4	1432	14.2	12.9	0.91
High	42376	45891	7883.6	7871	17.2	17.2	1.00
Extra high	15376	18297	3141.8	3288	17.2	18.0	1.05
Rigid	735	1592	248.0	308	15.6	19.3	1.24
Short_rail	729	1053	245.8	348	23.3	33.0	1.42
Semi-rigid	1362	2520	509.3	522	20.2	20.7	1.03
Wire rope	233	338	49.4	43	14.6	12.7	0.87

[(a)] 100 million vehicles per 10m segment.

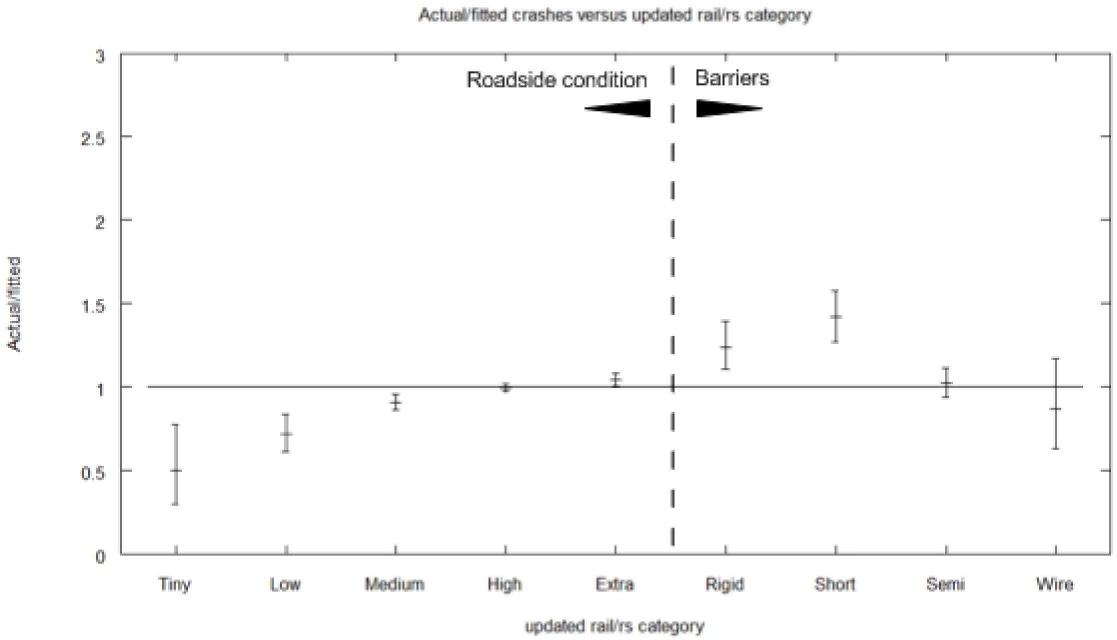
The columns show the combined length for both sides of the road involved (counted each year and summed to provide a four-year total); the total traffic (100 million of cars per 10m segment); the predicted number of crashes using the model that does not allow for roadside condition; the actual number of crashes; the predicted crash rate; the actual crash rate calculated from the number of crashes; and the ratio of actual to predicted crashes. Note that the high and extra high categories dominate in terms of length, traffic and crashes.

The table is derived by calculating the length, traffic and crash columns separately for the increasing and decreasing sides of the road separately and then adding the results. Since the crashes are for the whole road, in some instances, when there is the same roadside category on each side of the road, crashes will be included in the calculation twice.

The predicted crash-rate column gives an estimate of the danger of the type of location, before we include the road-side condition in the model, and is based only on the parameters used in the model. So, for example, semi-rigid barriers tend to be in more dangerous places than wire-rope barriers. That is, the predicted crash rate (20.2) for the semi-rigid barriers, before we include them in the model, is higher than that (14.6) for the wire-rope barriers.

The ratio of actual to predicted crashes is of most interest. This gives an estimate of the effect of each road-side condition on the crash-risk. This can also be presented as a graph, as shown in figure 4.5.

Figure 4.5 Ratio of actual to predicted crashes – all casualty crashes



The confidence intervals are 95% confidence intervals based on the Poisson distribution. The horizontal line is for a ratio equal to 1 and represents a kind of average for the network after allowing for the traffic, geometry and road surface effects and might be considered as a benchmark. Since the 'high' risk category dominates the road-side conditions this has a ratio very close to 1. Values above 1 indicate crash rate values greater than typical, lower less than typical.

There needs to be some caveats about this graph and the following ones. Each condition on each side of the road is considered separately but the number of crashes is for both sides of the road. So where the same type of condition is present on both sides of the road, crashes will be included in the calculation twice, once for each side of the road. This means the Poisson distribution will under-estimate the randomness. This is particularly the case for the rigid category which includes most bridges. It also means that the actual size of the effect in the case of the rigid category, may be exaggerated in comparison with the other categories, since the analysis implicitly assumes no correlation between the conditions on the opposite sides of the road.

Also we are not taking into account the error in the predicted values or the unaccounted for randomness in the crash numbers. However, where the number of crashes is small, the Poisson variability will dominate. Unlike the Poisson regression model, this analysis does not allow for error in the location of the crashes. This may not be such a problem with the KiwiRAP data which is based on 100m lengths of road or the longer rails but could be a problem with the short rails. It is vaguely possible that there is a false effect with the rigid category. This includes bridges, which are sometimes associated with reference stations. It is possible that some crashes are preferentially assigned to locations near reference stations so apparently giving a higher risk to these locations.

The figure 4.5 is broadly similar to figure 4.4, as we would expect. However, what is being modelled is slightly different. The Poisson regression analysis attempts to assign the effect of the roadside condition to just one side of the road whereas the comparison method looks at the effect on crashes on both sides. For example, the Poisson regression analysis estimates a crash rate for the tiny category as nearly zero whereas the comparison method gives it a value near 0.5.

4.4.4 Comparison method – serious/fatal crashes and crash severity

We can repeat the analysis for all casualty crashes in the previous section looking only at the serious injury and fatal crashes. Applying this method we get the following table of results.

Table 4.8 Comparison of predicted and actual crash numbers – serious injury and fatal crashes

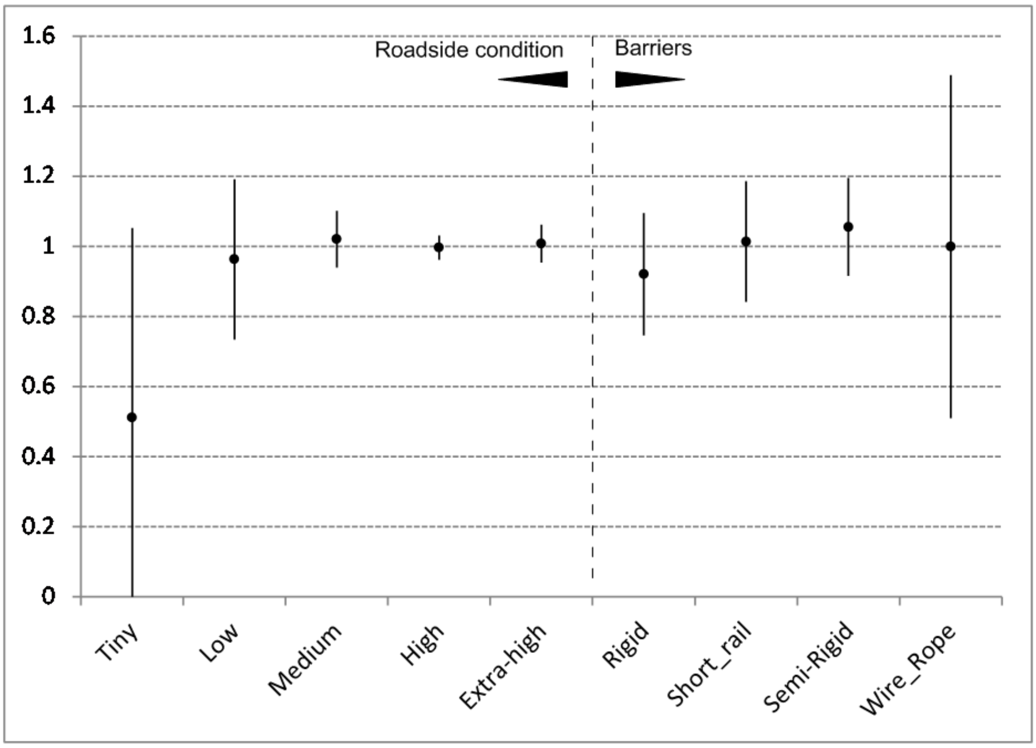
Roadside category	Length (km)	Traffic	Predicted crashes	Actual crashes	Predicted crash rate	Actual crash rate	Risk ratio (actual/predicted)
Tiny	228	342.3	11.8	3	3.5	0.9	0.25
Low	1334	1865.2	72.1	50	3.9	2.7	0.69
Medium	8474	11,104.9	475.3	441	4.3	4	0.93
High	42,376	45,891.7	2333.4	2321	5.1	5.1	0.99
Extra high	15,376	18,297.4	915.1	965	5	5.3	1.05
Rigid	735	1592.2	71.7	82	4.5	5.2	1.14
Short_rail	729	1053.8	69	99	6.5	9.4	1.43
Semi-rigid	1362	2520.7	147	159	5.8	6.3	1.08
Wire_rope	233	338.6	13.8	12	4.1	3.5	0.87

Accordingly, we can obtain a measure of change in crash severity for the different roadside categories by dividing the risk ratios for serious/fatal crashes from table 4.8 by the corresponding values for all casualty crashes from table 4.7. These crash severity ratios are listed in table 4.9 and plotted in figure 4.6, together with the 95% confidence limits.

Table 4.9 Crash severity factors

Roadside category	Risk ratio (serious injury and fatal crashes)	Risk ratio (all casualty crashes)	Crash severity factor
Tiny	0.25	0.50	0.51
Low	0.69	0.72	0.96
Medium	0.93	0.91	1.02
High	0.99	1.00	1.00
Extra high	1.05	1.05	1.01
Rigid	1.14	1.24	0.92
Short_rail	1.43	1.42	1.01
Semi-rigid	1.08	1.03	1.06
Wire_rope	0.87	0.87	1.00

Figure 4.6 Crash severity factors for roadside categories



This table and plotted data shows that, apart from the tiny category, there is very little significant variation in the crash severity factors between the different roadside categories; however, even in this category the confidence interval is long.

We can also look at the simple ratios of serious and fatal crash numbers divided by the numbers of all casualty crashes. The results are in figure 4.7 and table 4.10.

Figure 4.7 Crash severity ratios

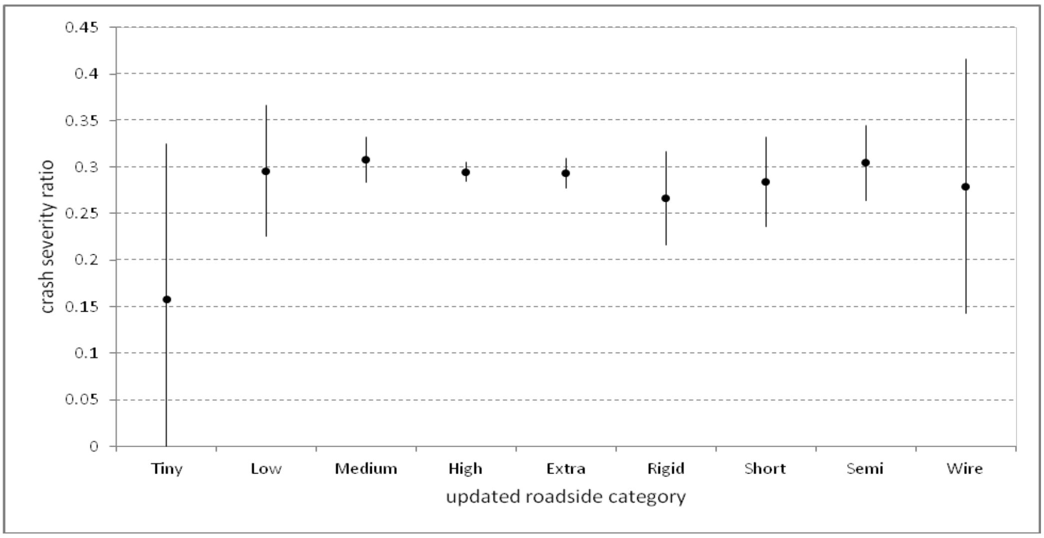


Table 4.10 Crash severity ratios

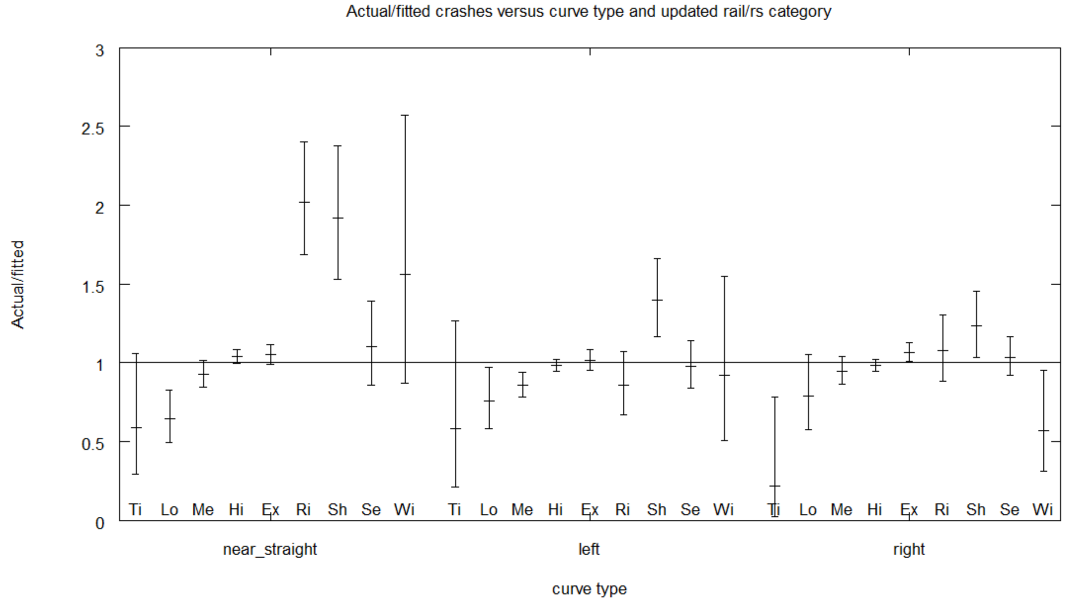
Roadside category	**Crash severity ratio** (proportion of all casualty crashes that are fatal or serious)
Tiny	0.16
Low	0.29
Medium	0.31
High	0.29
Extra high	0.29
Rigid	0.27
Short_rail	0.28
Semi-rigid	0.30
Wire_rope	0.28

Similar caveats to those for the previous graphs apply to this graph. It has the same general appearance to the information in figure 4.6. All the confidence intervals cross the 0.3 level and most of the centre values hover around this line. These ratios differ from the Austroads FSI and FSI_{2012} ratios reported in tables 2.4 above and 4.13 below. There may be a number of reasons for this including sample sizes and the respective road environments that the barriers are within. As with figure 4.6 the confidence intervals for tiny and wire rope are very long. In principle, one cannot separate the effect of the roadside category on crash severity from the effect of the road geometry and road properties. In fact, there is very little effect of the road geometry and other road properties and so we get the same general appearance as figure 4.6.

4.4.5 Comparison method – curvature

After subdividing the road type by curve type: near straight, where the radius of curvature is greater than 5000 metres, and left and right curves where the radius of curvature is less than or equal to 5000 metres, we can repeat the analysis. Figure 4.8 shows a graph of the results of this analysis. Note that the names of roadside condition categories have been abbreviated by their first two letters, eg Ti = tiny.

Figure 4.8 Ratio of actual to predicted crashes subdivided by curve type – all casualty crashes



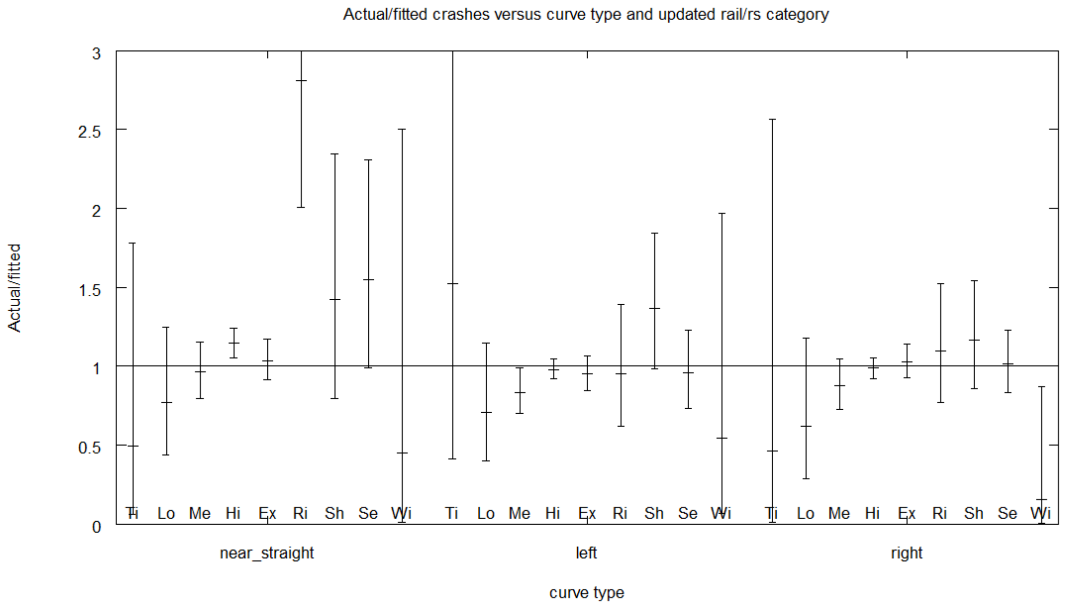
The values for the right-hand curves are roughly similar to those for when we did not subdivide by curve-type, except the wire rope is now just significantly different from the benchmark. Note the high values for rigid and short rails for the near straight roads. This is probably due to associated risk, for example due to a bridge.

The general pattern is as in figure 4.6. Note the high value for the rigid category for straight roads.

4.4.6 Comparison method – various crash types

We can do the same kind of analysis for various crash types and these are shown in the following figures. Figure 4.9 is for casualty crashes where the road has been reported as being wet.

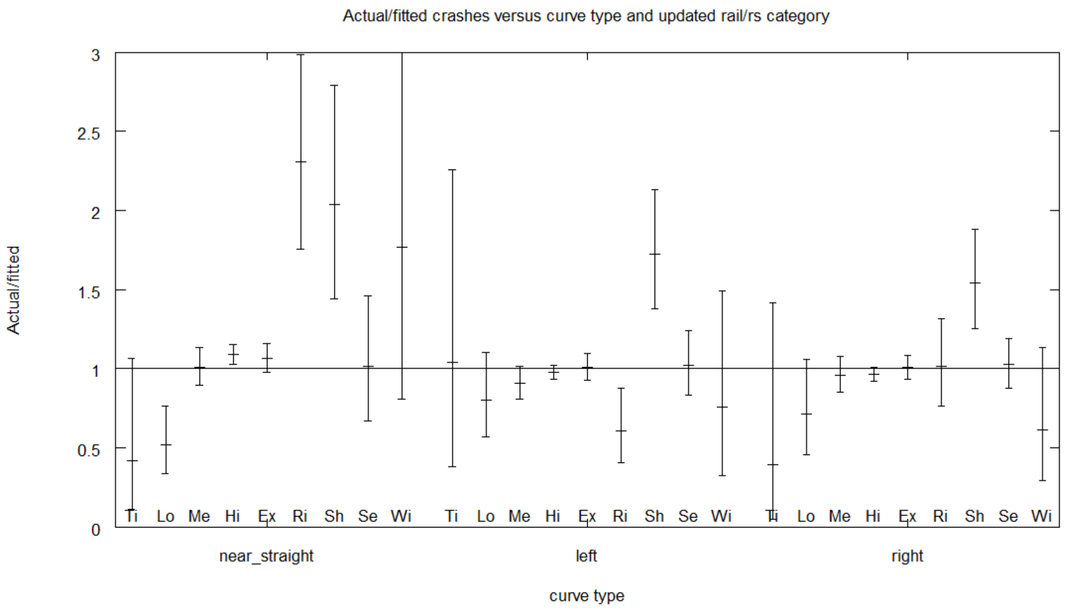
Figure 4.9 Ratio of actual to predicted crashes subdivided by curve type – wet road crashes



The general pattern is as in figure 4.6. Note the high value for the rigid category for straight roads.

Figure 4.9 is for run-off-road crashes. These are crashes with movement codes C, DA, DB, DO, AD or AF.

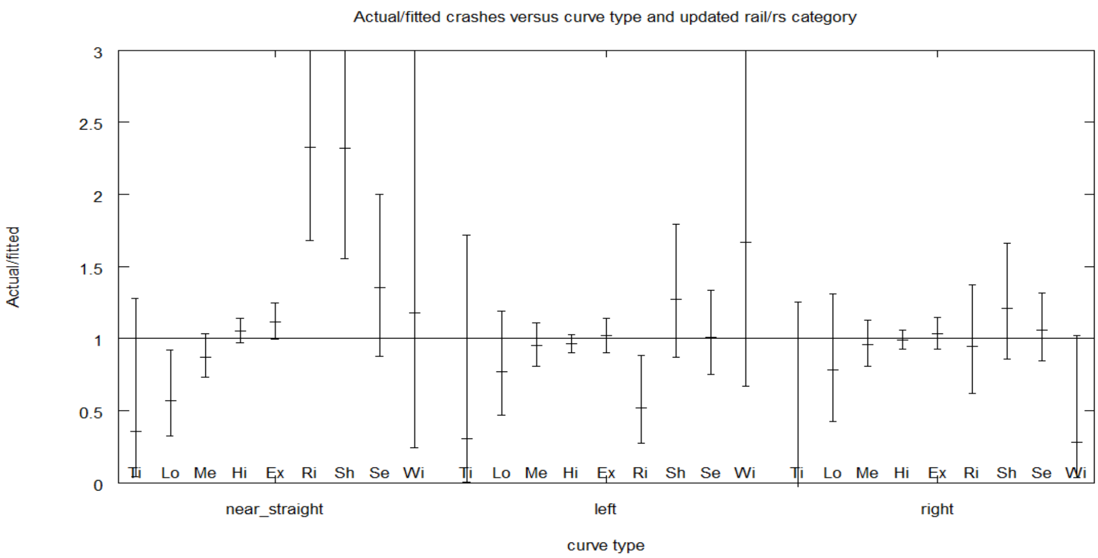
Figure 4.10 Ratio of actual to predicted crashes subdivided by curve type – run-off-road crashes



Again the pattern is similar. Rigid and short rail are high for straight roads, but short rail is also high for the other two categories. Wire rope is not quite significant for right-hand curves.

Figure 4.11 is for serious and fatal crashes, ie crashes in which there was at least one fatality or serious injury.

Figure 4.11 Ratio of actual to predicted crashes subdivided by curve type – serious/fatal crashes



All the graphs show a similar pattern: The values on the right-hand bends are roughly similar to those in figure 4.8 but with a stronger wire-rope effect which sometimes is statistically significantly below the benchmark. Rigid and short-rail are substantially raised on the near-straight roads.

4.4.7 Terrain and horizontal alignment score

We can carry out the same kind of analysis subdividing by terrain (refer table 3.7) or horizontal alignment score (refer table 3.6), as defined by KiwiRAP. Figures 4.12 and 4.13 show the results.

Figure 4.12 Ratio of actual to predicted crashes subdivided by terrain – all crashes

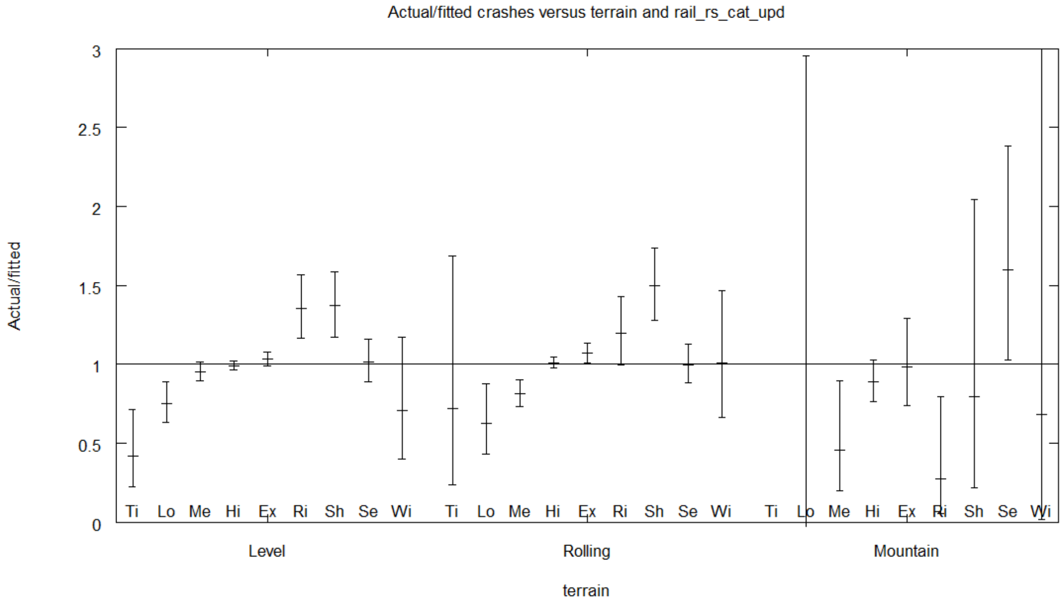
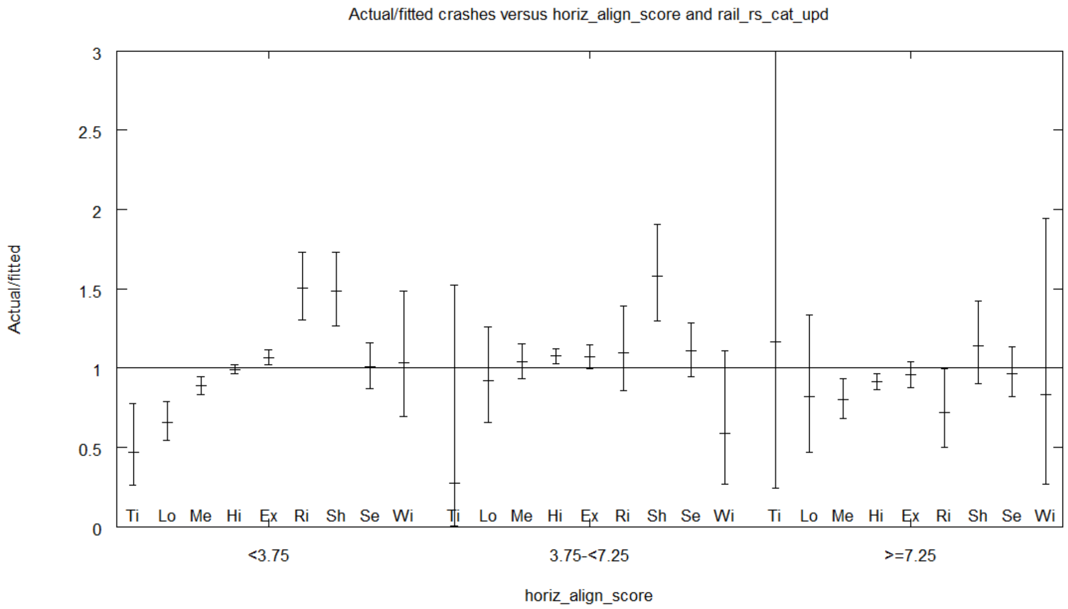


Figure 4.13 Ratio of actual to predicted crashes subdivided by horizontal alignment – all crashes



These graphs show up very little that is new. For the level and rolling terrains the results are similar to figure 4.8; for the mountain terrain there is insufficient information. For the horizontal alignment scores the results are similar to figure 4.8 except that the effects of rigid and short-rail are lower for the more curvy roads. We might expect this since the high risks of these two roadside conditions seem to be associated with straighter roads.

4.4.8 Predicted and actual crash numbers for KiwiRAP roadside conditions

The comparison method was used for deriving the values in table 4.4. The railing data was separated out and predicted and actual crash numbers were found for the various roadside offset, and severity values for both sides of the road. The results are given in table 4.11.

Table 4.11 Comparison of predicted and actual crash numbers for KiwiRAP roadside conditions

Roadside_ offset	Length (km)	Traffic (ADT)	Predicted crashes	Actual crashes	Predicted crash risk	Actual crash risk	Crash ratio (actual/predicted)
rs_severity = negligible/WR							
<4m	4073	4766	656	601	13.8	12.6	0.92
4-9m	659	884	112	78	12.7	8.8	0.70
9-15m	87	130	14	6	10.8	4.6	0.43
15m+	45	53	5.6	3	10.6	5.6	0.53
rs_severity = moderate							
<4m	35,914	37,279	6532	6504	17.5	17.4	1.00
4-9m	3495	5115	744	674	14.5	13.2	0.91
9-15m	493	727	91	73	12.5	10.0	0.80
15m+	96	160	19	10	11.6	6.3	0.54
rs_severity = severe							
<4m	15,376	18,297	3142	3288	17.2	18.0	1.05
4-9m	6462	8613	1352	1367	15.7	15.9	1.01
9-15m	906	1224	175	157	14.3	12.8	0.90
15m+	183	254	32	18	12.5	7.1	0.57
rs_severity = rigid barriers							
<4m	702	1503	236	299	15.7	19.9	1.27
4-9m	18	28	4.4	4	15.4	14.2	0.92
9-15m	3	4	0.6	1	14.7	23.9	1.63
15m+	0	2	0.1	0	8.5	0.0	0.00

Table 4.4 shows the predicted and actual number of crashes and their ratio from the relevant columns in table 4.11. Note that for the 9m–15m and 15m+ offsets the number of crashes is small so values of the ratio can be considered only as indications. In fact, the risk assignments given in table 4.4 do seem to be leading to an effective combination of roadside severity and offset with both the Poisson regression analysis and the comparison method showing an increase in risk as we go from the tiny category to the extra high category. While it might be argued that this is slightly self-fulfilling since these assignments are based on the observations on which the final analysis was done, the fact that the assignments are in a logical arrangement means they were not too arbitrary and should have some credibility.

4.5 Comparison with Australian data

We can make a very approximate comparison between the results of the statistical analysis, as shown in figure 4.4, with the data from the Austroads study presented as FSI ratios in tables 2.4 and 2.5. This is very approximate because of the somewhat different classifications used between the different countries and the inclusion in the Australian data of information from multi-lane roads. Table 4.12 lists the values shown in figure 4.4 and table 4.6, including the values normalised against the rate for semi-rigid barriers. Table 4.13 repeats this for the Australian data. Figure 4.14 compares the New Zealand and Australian data (FSI and FSI_{2012}) graphically.

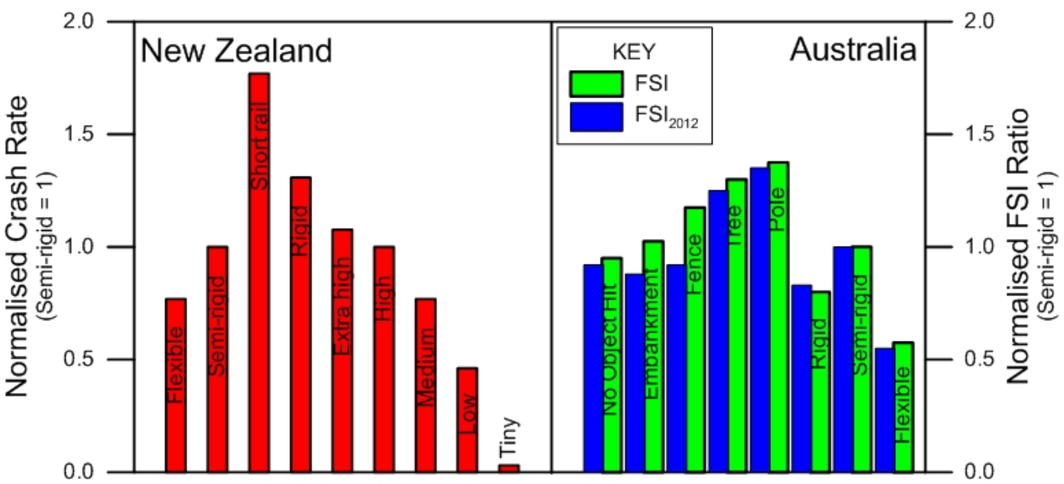
Table 4.12 Variation of crash rate (New Zealand) with barrier/rail or risk (from figure 4.4)

Barrier/rail or risk category	Predicted crash rate (per 100 million vehicle/km)	Predicted crash rate (relative to semi-rigid barriers)
Tiny	0.4	0.03
Low	6	0.46
Medium	10	0.77
High	13	1.00
Extra high	14	1.08
Rigid	17	1.31
Short rail	23	1.77
Semi-rigid	13	1.00
Flexible (wire rope)	10	0.77

Table 4.13 Variation of FSI (Australia) with barrier/hazard type (from tables 2.4 and 2.5)

Barrier/hazard type	FSI ratio	FSI_{2012} ratio	Normalised FSI ratio (relative to semi-rigid barriers)	Normalised FSI_{2012} ratio (relative to semi-rigid barriers)
No object hit	0.38	0.55	0.95	0.92
Embankment	0.41	0.53	1.03	0.88
Fence/wall/gate	0.47	0.55	1.18	0.92
Tree/shrub/scrub	0.52	0.75	1.30	1.25
Pole (power/phone)	0.55	0.81	1.38	1.35
Rigid	0.32	0.50	0.80	0.83
Semi-rigid	0.40	0.60	1.00	1.00
Flexible	0.23	0.33	0.58	0.55

Figure 4.14 Comparison of New Zealand and Australian data



Given the very general comparison, there are only a few things that can be said here:

- Flexible barriers perform reasonably well in both countries.
- The overall spread is similar for both countries.
- The Australian FSI ratios generally show the same relativities when the numbers of fatalities and serious injuries are compared with either the total number of vehicle occupants, or the total number of casualties.

As a second comparison, table 4.1 in Austroads (2011a) gives estimates of clear-zone effects. This is reproduced in table 4.14.

Table 4.14 Comparison of relative risk results from data analysis and from modelling

Clear zone range (m)	ROR casualty crash relative risk	
	Descriptive analysis	Statistical model
0–2	2.4	1.7
2–4	1.6	1.3
4–8	1.1	1.1
> 8	1.0	1.0

We can derive a similar table from the first Poisson regression model using the data from figure 4.2. This needs to be rescaled to give a comparison with the last column in table 4.14. This is done in table 4.15.

Table 4.15 Effects of clear zone from KiwiRAP model – all casualty crashes

Clear-zone range (m)	Crash rate	Rescaled
0–4	12.8	1.4
4-9	10.7	1.1
9-15	9.3	1.0
15+	1.8	0.2

The first three rows of the table 4.15 (the New Zealand data) should be compared with the last three rows of table 4.14 (the Austroads data). The values are remarkably similar. In fact since we are looking at all crashes rather than run-off-road crashes possibly ours should be smaller.

5 Computer simulation modelling

It had been expected that there might be relatively small numbers of crashes for certain combinations of barrier and clear-zone variables. Accordingly, a limited programme of computer simulation modelling was developed to provide additional information towards estimates of crash severity in these cases and also to support and test the validity of the statistical analysis. This modelling used PC-Crash (version 9) software. A description of PC-Crash and a listing of the features of the software are given in appendix A. Appendix B reproduces the section on the assessment and verification of PC-Crash from Jamieson (2012).

The crash data used for the statistical analysis described earlier is essentially the end result of 'real world' simulations. With computer simulation modelling, the initial setup parameters will determine the outcome of the simulation. If these parameters are the same, the results will be the same every time. When the simulation modelling is being used for crash reconstruction, the outcome is known and the input parameters can be varied until the simulation matches the real-world outcome reasonably well. In this study we have tried to choose setup parameters that give results that are most appropriate for what is being investigated, ie the effect of clear zones and barriers.

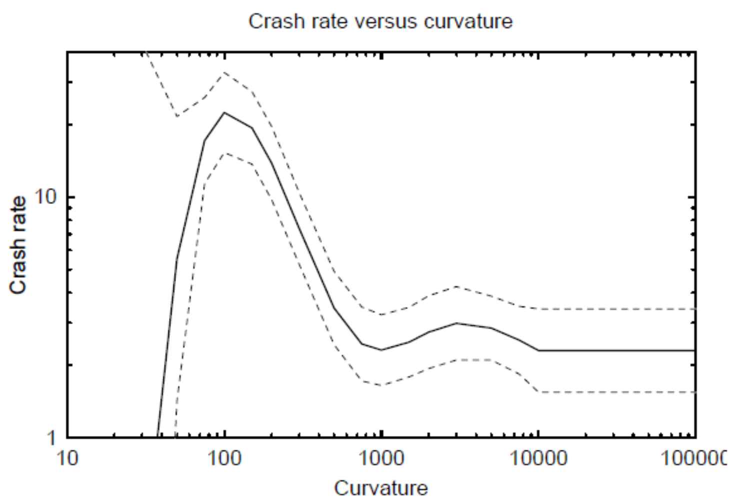
It was not intended or expected that PC-Crash would provide direct measures of the severity of the outcomes of the simulations. Rather, it was intended that the simulation modelling would provide information on the speeds and angles measured at distances from the road lane representative of either 1) where barriers would normally be located, or 2) typical clear-zone width ranges. It is generally accepted that the severity outcome of a crash into an object is proportional to the speed and angle of the vehicle when it strikes the object. This is covered in the discussion of the results of the simulation modelling.

5.1 3D road simulation modelling

5.1.1 Selected road simulation configurations

Selection of the road simulation configurations was based on consideration of the variation of crash data with curvature, as shown in figure 5.1, the statistical analysis described earlier, current clear zone and barrier practices and discussions between members of the project team and the project steering group.

Figure 5.1 Variation of crash rate with curvature – wet road crashes (Davies 2004)



Based on this, three simulation scenarios were chosen as follows:

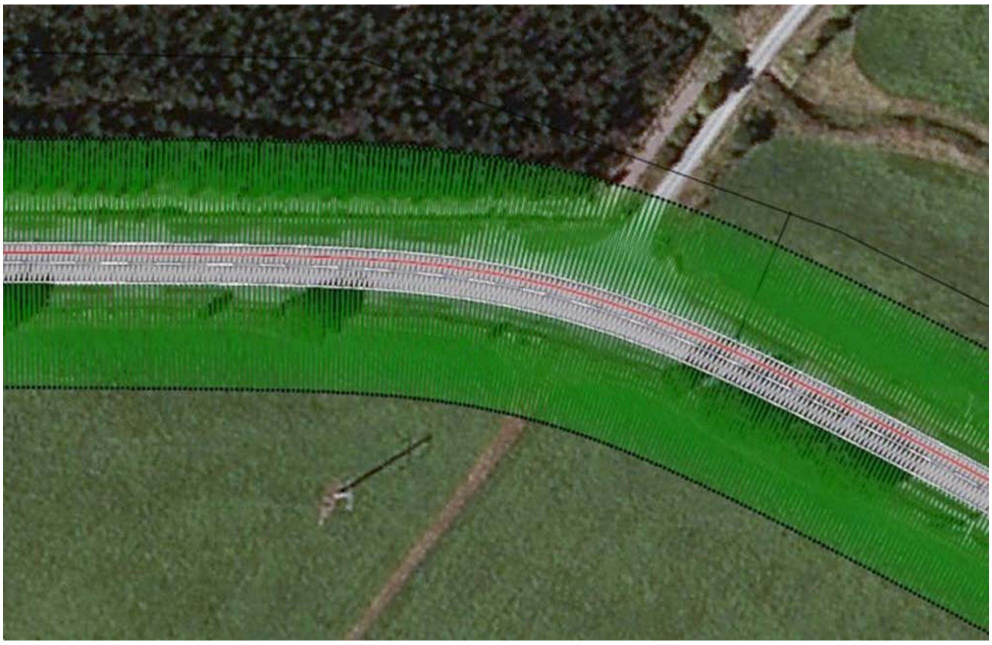
1. A straight road section with flat (0%) gradient with lane widths of 3.5m, 0.5m wide sealed shoulders, and crossfall of 4%, which is typical of such sections found on the state highway network
2. An isolated flat (0%) gradient corner with a radius of around 120m, with lane widths of 3.5m, 0.5m wide sealed shoulders, levels of crossfall typical of such sections found on the state highway network
3. An isolated flat (0%) gradient corner with a radius of around 170m, with lane widths of 3.5m, 0.5m wide sealed shoulders, and levels of crossfall typical of such sections found on the state highway network.

5.1.2 Simulation setup in PC-Crash

Model corners were generated in the PC-Crash simulation. Wet friction values for the road surfaces were assigned on the basis of the results of the annual state highway network survey. Wet friction values for the roadsides were assigned on the basis of the work of Cenek et al (2003) on the friction characteristics of roadside grasses. Additional friction polygon overlays for the roadsides were generated so that friction levels typical of the grass and vegetation on the roadside verges could also be modelled and varied accordingly. The roadsides were initially modelled as flat out to a minimum distance of 20m.

Follow point paths for two different driveline configurations were added, these being the 'mid-lane' and 'left in – right out' configurations from Jamieson (2012). Follow point paths are generated lines to which simulated vehicles can be anchored, and which the vehicle will follow as closely as the laws of physics will allow. When or if the vehicle can no longer maintain the follow point line, it will slide or roll according to the vehicle speed, road geometry and surface friction values. Vehicles can be anchored to the follow point path at selected points, including the centre of gravity, or any of the four wheels. Figure 5.2 shows a plan view of one of the modelled corners. It includes the follow path for the mid-lane driveline.

Figure 5.2 Plan view of 3D road corner model (red line – mid-lane follow path)



5.2 Vehicle selection and modelling

Three vehicles were selected from the wide variety of vehicle types, sizes, weights and shapes currently on New Zealand roads. They were: 1) a front wheel drive car – Toyota Corolla; 2) a rear wheel drive car – BMW 335i; and 3) a 4WD sport utility vehicle (SUV) – RAV 4 5 door 4WD. To represent a worst case scenario the ABS was turned off. The vehicles were also modelled as having a driver and a front seat passenger, with a combined weight of 200kg.

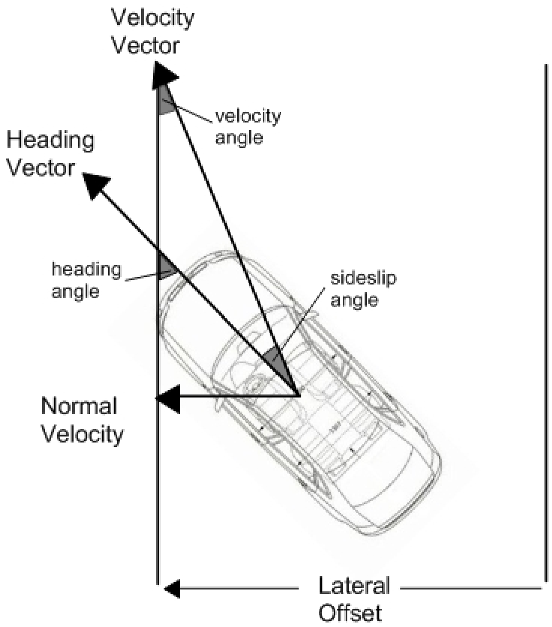
5.3 Simulation generation and results

For each of the three road configurations (straight, corner radius – 120m, corner radius – 170m) set up in PC-Crash, each of the three vehicles was added, to create nine baseline simulations. These were then used to create separate additional simulations for the straight road section and the two corners.

5.3.1 Straight road - simulation generation

The objectives of the straight road simulations were to identify how quickly departures from the lane might occur and to quantify the vehicle forward speeds, and the vehicle speeds normal to nominal barrier offsets of 2m, 4m and 9m. Figure 5.3 illustrates these parameters graphically. These definitions are the same for both straight and curved road sections.

Figure 5.3 Vehicle dynamics – speeds and angles



Two initial simulation scenarios were generated. The first of these was a 'drift off' situation, where the vehicle was placed in the centre of the lane, pointed straight down the road at constant speed, with no steering input, and allowed to drift off the road in response to the road geometry, ie the crossfall.

The second simulation was a 'maximum turn' scenario, where the vehicle was placed in the centre of the lane, pointed straight down the road, and using a follow point path, was instructed to try to follow a 90° turn at constant speed as closely as the laws of physics and the vehicle simulation (vehicle characteristics, road geometry, road and roadside friction) would allow. This should give the highest normal velocity for the road and geometry conditions. Constant speeds of 80km/h, 100km/h and 120km/h were used.

These simulations were run with essentially flat roads, ie very low gradient, with flat roadsides. Limited additional simulations were also run to investigate the effects of 1) having a 10° downhill gradient, 2) having a 10° downward sloping roadside and 3) initiating emergency braking as soon as the vehicle began to leave the lane. These were only conducted for the maximum turn scenarios.

5.3.2 Straight road – simulation results

Table 5.2 lists the longitudinal distances taken for each of the vehicles to drift to the left and start leaving the sealed road surface.

Table 5.2 Longitudinal drift-off distances

BMW		Corolla		RAV 4	
Speed (km/h)	Distance (m)	Speed (km/h)	Distance (m)	Speed (km/h)	Distance (m)
80	179	80	182	80	178
100	185	100	189	100	183
120	192	120	195	120	191

These results show that in a simple drift-off situation, with no steering input and no braking, it takes a considerable distance for a vehicle to begin to move out of the sealed lane, let alone reach lateral distances of 2m, 4m, or 9m. In this situation the forward speed of the vehicle is high, but the normal velocity is very low, being less than 1km/h.

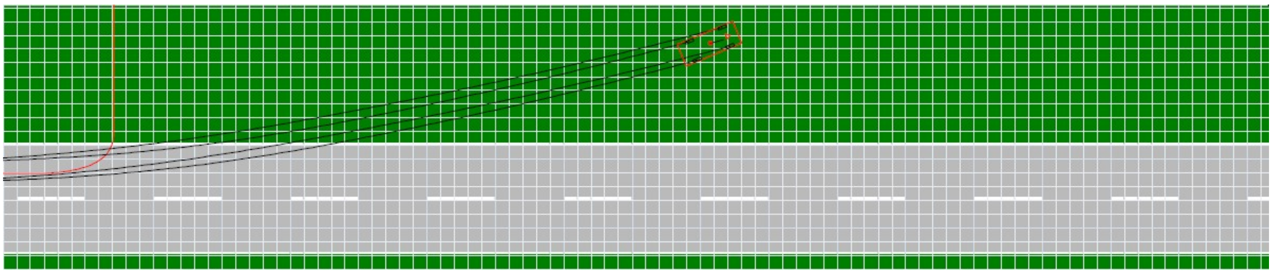
The situations for the maximum curve simulations were much different. Essentially, they represent the worst run-off-road scenario likely, with the highest normal velocities that might be expected at the 2m and 4m lateral offsets spanning the range where barriers would normally be placed, and at a 9m lateral offset for a clear zone. The results for all three vehicles were very similar. Accordingly, table 5.3 lists the results for one of the vehicles (Toyota Corolla) for the combinations of speeds and geometries. Figure 5.5 compares the vehicle trajectories for several of these scenarios for the Toyota Corolla at 100km/h. In this figure, all the simulations have been stopped when the vehicle reaches a lateral distance of 9m. Note that as previously, the red line indicates the trajectory it is trying to follow.

Table 5.3 Straight road results for Toyota Corolla – angle and velocity (100km/h initial speed)

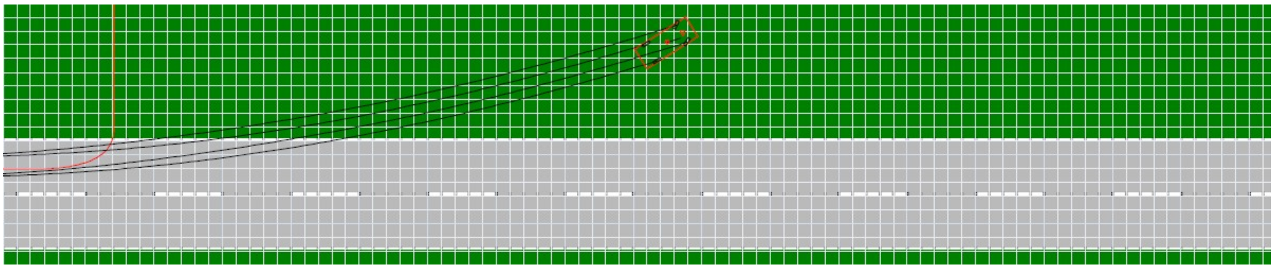
Vehicle	Road slope	Roadside slope	Braking	Lateral distance offset (m)	Heading angle (°)	Normal speed at offset (km/h)	Forward speed at offset (km/h)
Corolla	Flat	Flat	No	2	23.1	16	~100
				4	25.0	19	~100
				9	23.0	24	~100
	Flat	10°	No	2	23.1	16	~100
				4	26.7	21	~100
				9	32.3	29	~100
	Flat	Flat	Yes	2	23.4	11	91
				4	19.0	9	85

Vehicle	Road slope	Roadside slope	Braking	Lateral distance offset (m)	Heading angle (º)	Normal speed at offset (km/h)	Forward speed at offset (km/h)
				9	2.4	7	68
	10˚ downhill	Flat	No	2	22.6	15	~100
				4	19.6	16	~100
				9	12.2	20	~100

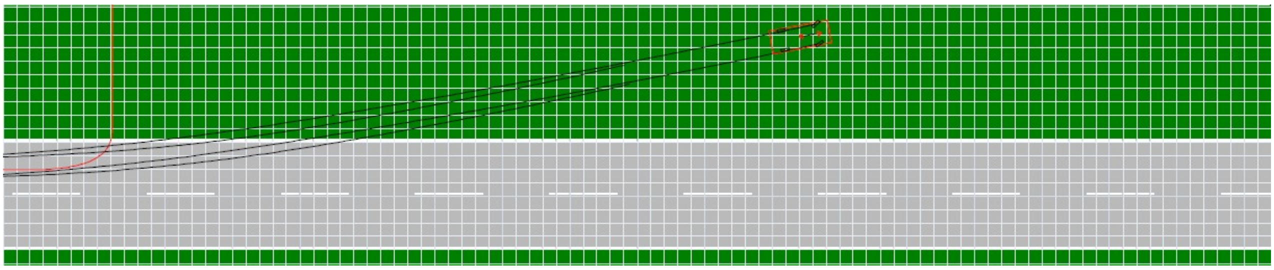
Figure 5.5 Selected straight road simulation trajectories – Toyota Corolla (100km/h)



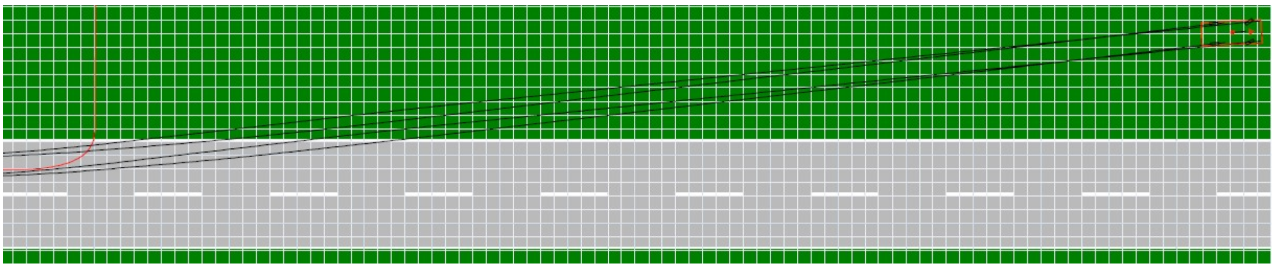
a) Flat road – flat roadside



b) Flat road – 10º down roadside slop



c) 10º down road slope – flat roadside



d) Flat road – flat roadside – emergency braking

It can be seen that in attempting to track the assigned follow path the vehicles have departed the road at different angles. Compared with the flat road, on the downward sloping roadside the vehicle reaches the 9m offset several metres sooner at a slightly greater angle. On the downward sloping road, the trajectory is, as expected, somewhat elongated, and the angle at 9m slightly shallower. Under emergency braking the longitudinal distance travelled before the vehicle reaches the 9m offset is much greater and the angle is the shallowest.

Table 5.3 shows that in the wet conditions modelled and for an initial speed of 100km/h, the Toyota Corolla reaches the offset distances of 2m, 4m and 9m with normal speeds mostly of around 30km/h or less, and angles of less than 30º. The importance of these normal speeds and angles is covered in the discussion of results for both the straight and corner road sections.

With simulation modelling there are only a limited number of individual simulations that can be reasonably run within a timeframe and budget. There will always be 'what if …' or 'what about…' questions, and suggestions that 'you should have done…'. One of the inevitable comments on these straight road simulations is that they should have been done in dry conditions, rather than wet, as vehicles should be able to turn more quickly before sliding so normal velocities would be higher. Accordingly, wet and dry simulations were run for the Corolla at 100km/h on a flat road. Table 5.4 lists the data for wet conditions from table 5.3, and the additional data from the dry simulation.

Table 5.4 Comparison of wet and dry vehicle speeds, angles and normal speeds (100km/h)

Vehicle	Road/ condition	Roadside	Braking	Lateral distance offset (m)	Heading angle (º)	Normal speed at offset (km/h)	Forward speed (km/h
Corolla	Flat/wet	Flat	No	2	23.1	16	~100
				4	25.0	19	~100
				9	23.0	24	~100
	Flat/wet	Flat	Yes	2	23.4	11	91
				4	19.0	9	85
				9	2.4	7	68
	Flat/dry	Flat	No	2	28.9	26	~100
				4	32.0	26	~100
				9	30.8	28	~100
	Flat/dry	Flat	Yes	2	25.4	12	92
				4	19.4	13	83
				9	1 [a]	12	64

[a] - indicates tail first incidence

These results show that for the likely differences in dry and wet friction levels that could be expected on grassy roadsides, there were not huge differences in the angles, normal speeds, or forward speeds at the different offsets. The forward speed is lower by the time the vehicle reaches a 9m lateral offset, but not substantially.

5.3.3 Corners – simulation generation

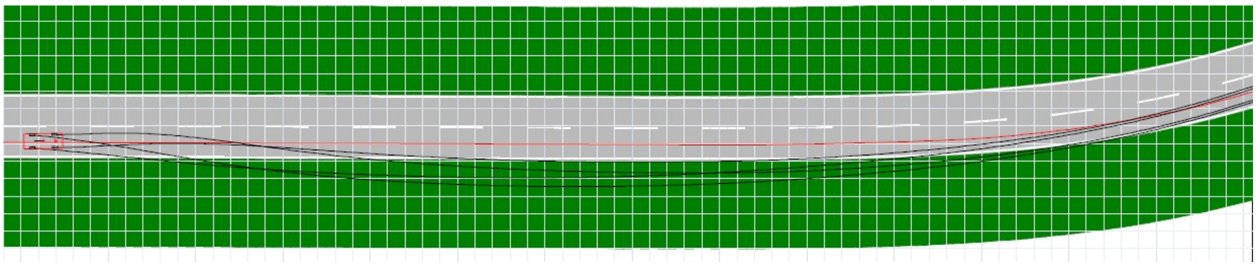
The same simulation types were generated for both the 120m and 170m radius corners. The following describes the simulation generation for one of the corners.

For each of the three corner/vehicle simulations two separate derivatives of each of these were generated using different follow paths. These were the 'mid-lane' path, and the 'left in – right out' path. The simulations were run with the vehicles directed to travel at constant speed around the corner. Steering inputs were automatically generated to follow the designated path as closely as possible. The speed was then varied from 80km/h to 120km/h in 10km/h increments. The vehicles will obey the laws of physics and 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. If the friction is too low, the vehicle will slide, drift or spin, depending on the trajectory of the vehicle when this first occurs. At lower speeds the vehicles will track the designated follow paths very closely. At higher speed this will become more difficult, and the vehicle will begin to deviate, but it may be able to recover and return to the follow path within the lane. Finally, when the speed becomes too great, the vehicle will lose control either through sliding or rollover.

The intentions of this first stage of corner simulations were to identify whether the vehicle ran off the road, and if so, to quantify the maximum lateral extent of the encroachment onto the roadside. The vehicle's forward speed was determined together with the vehicle's normal speed (as shown in figure 5.3) at lateral offsets of 2m, 4m and 9m.

Figure 5.6 shows an example of a vehicle initially on a mid-lane follow path, which has then left the road, and managed to return to it. By moving the vehicle along the trajectory, vehicle speeds and angles can be determined at any point, including the 2m, 4m and 9m offsets, if the encroachment onto the roadside extends that far laterally.

Figure 5.6 Example of vehicle encroachment and return to road



The initial simulation results showed that, in general, there were only limited differences between the results for the two different follow paths, and so the ongoing simulations were limited to the mid-lane follow path.

The above simulations were run with essentially flat roads, ie very low gradient, with flat roadsides. Next, the simulations were repeated to investigate the effects of having either a 10° downhill gradient or a 10° downward sloping roadside.

Having identified the speed at which encroachment began, the next stage assumed that the simulation 'driver', having realised they were in trouble when they began to leave the lane, would initiate emergency braking while still trying to remain on the road, ie maintaining the mid-lane follow path. These simulations were only run for the higher speeds where encroachment onto the roadside or loss of control occurred. A limited number of additional braking simulations were also run with the follow path removed so the vehicle would essentially brake as it left the road, but would be influenced only by the vehicle speed and motion at that point and the effects of the road and roadside (friction and geometry).

5.3.4 Corners - simulation results

Rather than presenting the data for all three vehicles here, this has been included in appendix C, and only data for the BMW335i for the 120m radius corner is shown in table 5.5. Note that for the corner simulations, the vehicle reached the lateral offsets of 2m, 4m and 9m with the rear left corner first in most cases.

Table 5.5 Corner simulation results – 120m radius (BMW 335i)

Road slope	Roadside slope	Braking	Speed (kmh)	Outcome	Lateral distance offset (m)	Heading angle (°)	Normal speed at offset (km/h)	Forward speed at offset (km/h)
Flat	Flat	No	80	Stays on road	-	-	-	-
			90	Stays on road	-	-	-	-
			100	Stays on road	-	-	-	-
			110	5m encroachment	2	9.6	13.9	109
					4	28.2	7.4	108
			120	Loss of control	2	5.3	26.5	118
					4	9.3	23.7	118
					9	22.9	17.9	116
		Yes	110	Loss of control	2	7.4	13	98
					4	21.5	11	95
					9	90.0	9	82
			120	Loss of control	2	6.5	14	112
					4	9.2	19	110
					9	18.9	23	105
	10°	Yes	110	Loss of control	2	7.5	10	99
					4	14.3	20	97
					9	29.1	22	92
			120	Loss of control	2	6.2	13	113
					4	10.2	25	111
					9	18.5	29	108
10°	Flat	No	80	Stays on road	-	-	-	-
			90	Stays on road	-	-	-	-
			100	Stays on road	-	-	-	-
			110	8m encroachment	2	4.4	11	109
					4	9.3	10	109
		Yes	110	Loss of control	2	6.3	14	100
					4	13.1	21	99
					9	27.1	31	97
		No	120	Loss of control	2	8.6	19	119
					4	15.5	19	118
					9	32.4	24	118

Road slope	Roadside slope	Braking	Speed (kmh)	Outcome	Lateral distance offset (m)	Heading angle (°)	Normal speed at offset (km/h)	Forward speed at offset (km/h)
		Yes	120	Loss of control	2	9.7	17	113
					4	13.6	23	111
					9	25.4	30	109

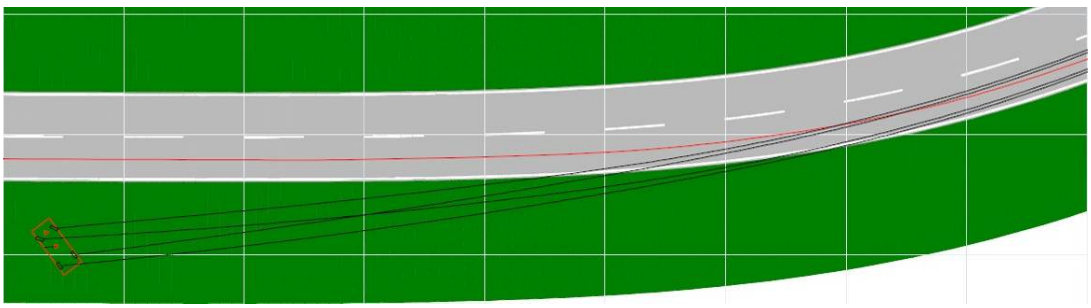
The results listed in table 5.5 and in appendix C show generally consistent results between the three vehicles, with similar angles and normal speeds at the lateral offset distances of 2m and 4m. At the 9m lateral offset, there was considerable variation in the angles, depending on the speed and the type of vehicle. Nevertheless, the normal speeds at the different offsets generally remained around 30km/h or less, except when the follow path was removed, and the vehicles essentially drove off the road, braking as they encroached onto the roadside. Here, the normal speeds were up to ~40km/h on the tighter radius corner.

5.3.5 Corners – effects of roadside friction

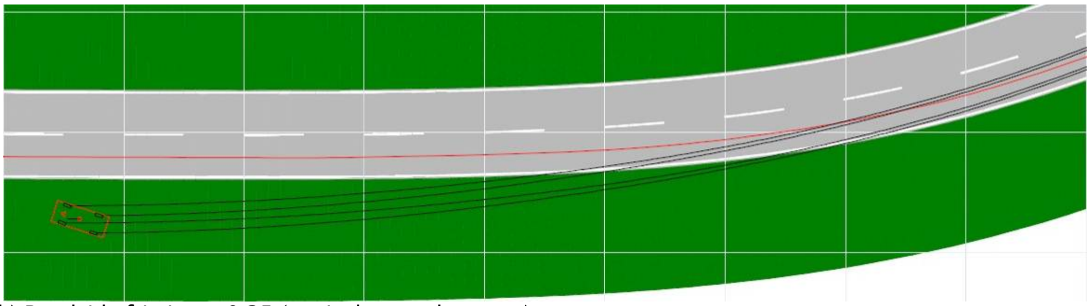
Cenek et al (2003) listed friction levels and stopping distances for locked wheel braking on some of the grass types found on New Zealand roadsides. These were the values used for assigning the most appropriate roadside friction levels in the simulation modelling described above. However, Jamieson (2012) identified that roadside friction levels have a significant impact on the lateral encroachment distances for cornering vehicles. The friction value of 0.2 used for the roadside in the simulation modelling represents a worst case scenario, where the normal speeds and angles and the forward speeds at various encroachment distances were expected to be highest. To visually illustrate the effects of roadside friction levels, one of the corner simulations, for a BMW 335i at 110km/h, was repeated with friction levels of 0.2 (wet grass), 0.35 (dry grass), and 0.5 (wet road surface). Figure 5.7 shows the three trajectories up to the same point in time (8s after initiation).

It can be seen from figure 5.7 that the roadside friction has a considerable impact on the trajectory that the vehicle takes, and potentially a significant effect on the normal speed to any barrier, the stopping distance under emergency braking, or the forward speed when a vehicle strikes an obstacle.

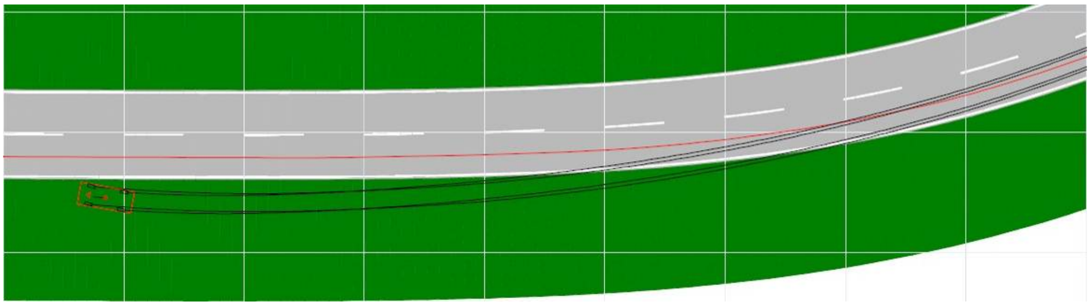
Figure 5.7 Effect of roadside friction on vehicle trajectory – BMW 335i at 110km/h



a) Roadside friction = 0.2 (equivalent to wet grass)



b) Roadside friction = 0.35 (equivalent to dry grass)



c) Roadside friction = 0.5 (equivalent to wet road)

6 Discussion of results

6.1 Statistical analysis

The statistical analysis examined the road condition and geometry data, together with the roadside risk and hazard information contained in KiwiRAP, and the latest crash data for a number of years, for the entire New Zealand state highway network. It extended the existing crash risk model (Cenek et al 2012a; 2012b) to include variables for the roadside condition.

This analysis showed that the roadside condition, ie types of barriers/railings and clear-zone/roadside hazard has an effect on the crash rate that is statistically significant. It also showed that while the width of clear zone, or the distance from the edge of the road to the nearest hazard is important, it is also the type of hazard encountered at the far side of this space that is important in determining the crash rate. For example, if a vehicle is going to pass through a 6m clear zone, with considerable remaining forward speed the consequences are likely to be worse if the hazard in the way is a severe one, such as a large tree, than if the hazard is a minor one, such as a shallow embankment.

During this analysis a range of barrier/rail or roadside risk categories were developed, these being the barrier/rail categories of rigid, short rail, semi-rigid, and flexible (wire rope), and the roadside risk categories of tiny, low, medium, high and extra high. Crash rates and crash severity ratios were determined for each of these categories. These were given in tables 4.6 and 4.10, and are reproduced in table 6.1.

Table 6.1 Crash rate and crash severity ratios with barrier/rail or roadside risk descriptor

Classification type	**Barrier/rail or road-side risk category**	**Predicted crash rate** (per 100 million vehicle/km)	**Crash severity ratios** (proportion of all casualty crashes that are fatal or serious)
Derived from KiwiRAP	Tiny[(a)]	0.4	0.16
	Low	6	0.29
	Medium	10	0.31
	High	13	0.29
	Extra high	14	0.29
Barrier/rail	Rigid	17	0.27
	Short rail	23	0.28
	Semi-rigid	13	0.30
	Flexible (wire rope)	10	0.28

[(a)] value should be treated with caution, given the size of the uncertainties in the data.

The barrier/rail categories are reasonably self-explanatory, but the tiny, low, medium, high and extra high descriptors do need more explanation to show how they relate to the physical nature of the roadside. To do this we need to show a modified version of table 4.4, as given in table 6.2. This shows these descriptors in relation to the KiwiRAP severity outcomes. We also need the KiwiRAP hazard condition descriptions given in table 3.4, which are reproduced in table 6.3.

Table 6.2 Proposed severity codes and risk descriptors (as in table 4.4)

Severity outcome	Offset from edge of sealed carriageway			
	0 – 4 metre	4 – 9 metre	9 – 15 metre	15+ metre
Negligible	Medium	Low	Tiny	Tiny
Moderate	High	Medium	Low	Tiny
Severe, head-on	Extra high	High	Medium	Low
Rigid barriers	Rigid	Rigid	Rigid	Rigid

Table 6.3 KiwiRAP hazard condition (severity outcome) descriptions (as in table 3.4)

Severity outcome	Description
Negligible	Minor property damage only, eg kerb, wire-rope barrier, level slope with no hazards
Rigid barriers	Rigid barriers, steel beam guard fence, including guardrail and other semi-rigid barriers
Moderate	Intermittent hazard likely to cause moderate damage or injury, eg shallow embankment, cut, longitudinal bridge or wall, mid-size culvert
Severe	Likely to cause fatality or serious injury, eg trees greater than 300mm diameter, rollover – greater than 4:1 fill, transverse wall/bridge pylon
Head-on	On divided carriageway roads where the median is such that an errant vehicle could completely cross the median into oncoming traffic the 'head-on' severity category is used for the right hand side hazard condition (severity outcome), eg lack of barriers or other obstacles in the median. The offset is taken as the distance between the nearest travelled lanes in each direction.

To realise the crash rate associated with the low descriptor given in table 6.1, we need to look at table 6.2 to see how we can achieve this. Table 6.2 shows that we can do this by having:

- a negligible severity outcome hazard, at 4m–9m, which from table 6.3 is, for example, a level slope with no hazards, or
- a moderate severity hazard at 9m–15m, which from table 6.3 is, for example, a shallow embankment, cut, longitudinal bridge or wall, or mid-size culvert, or
- a severe severity hazard at 15m+, which from table 6.3 is, for example, trees greater than 300mm diameter, rollover – greater than 4:1 fill, a transverse wall, or a bridge pylon.

To realise the crash rate associated with the extra high descriptor given in table 6.1, and looking at table 6.2, this can be achieved by having a severe outcome hazard at 0m–4m offset. For example, from table 6.3 this could be a tree greater than 300mm diameter, rollover – greater than 4:1 fill, a transverse wall, or a bridge pylon. The physical roadside conditions associated with the other descriptors, low, medium and high can be determined in a similar manner.

The statistical analysis also considered including the factors of crash severity, curvature, terrain and horizontal alignment, and wet road crashes but these did not add very much to the crash rate model. This is probably because these factors were either not critical for determining the effectiveness of the various roadside categories, or were better accounted for by factors already in the model, eg the horizontal alignment is strongly correlated with the OOCC factor, which was already included in the model.

Table 6.1 also shows that, in terms of crash rate, flexible (wire-rope) barriers seem to perform better than any of the other types of barriers currently used in New Zealand. The statistical analysis did show relatively high uncertainties in the crash rate for flexible barriers, which relates to their low frequency of use as roadside barriers compared with other types, and also their concentration largely in one NZTA region. Current Australian research by Austroads has also found that flexible barriers perform well, which supports the above finding.

However, recently reported Australian research involving limited full-scale barrier crash testing (Hammonds and Troutbeck 2012) also suggests that based on limited testing with crash dummies, there is little practical difference in crash severity reduction between wire-rope and W-beam semi-rigid barriers. This preliminary result is supported by the relatively small variations in the crash severity ratios shown in table 6.1 for the different roadside categories. Also, as a general comment within that research, the relative performance of some semi-rigid barriers might improve with further development and become closer to the performance of wire-rope barriers, but this would need to be confirmed through product development, testing and research.

6.2 Simulation modelling

The computer simulation modelling was intended to complement the statistical analysis. It was not intended to provide direct measures of the severity of the simulations, but information on the speeds and angles measured at distances from the road lane representative of either 1) where barriers would normally be located, or 2) typical clear-zone width ranges.

In computer simulation modelling, the initial setup parameters determine the outcome of the simulation. The chosen setup parameters were intended to model the most likely scenarios for run-off-road crashes on straights and corners, these being drift-off, speed and emergency braking.

It is generally accepted that the severity of the outcome of a crash into an object is proportional to the speed and angle of the vehicle when it strikes it. Doecke and Woolley (2011) state that ‘it is possible to infer from various barrier crash tests that barrier normal velocities of up to 57km/h should not produce serious injuries’. Furthermore, the Austroads guide (2006) states that a safe system speed for a vehicle having a side impact with a tree or pole is 30km/h to 40km/h.

The simulation modelling for the straight road section showed that, for a drift-off-road scenario, normal velocities were quite low (<5km/h) and it took a considerable longitudinal distance for the vehicle to start leaving the road surface. However, the forward speed remained quite high in wet conditions even under emergency braking; with potentially serious consequences should an object be struck.

For the far more radical run-off-road maximum turn manoeuvre on a straight road section, normal velocities at lateral distances of 2m, 4m and 9m, were generally 40km/h or less. The angles at these distances were also typically 30° or less. However, again the forward speeds remained quite high, even at 9m lateral displacement, being around 65km/h or higher, in both wet and dry conditions.

On both corners used in the simulations the three vehicles showed similar angles and similar normal speeds at the lateral offset distances of 2m and 4m, but considerable variation in the angles at 9m lateral offset. However, the normal speeds at the different offsets generally remained around 30km/h or less, except when the follow path was removed, and the vehicles essentially drove off the road, braking as they encroached onto the roadside. Here, the normal speeds ranged up to around 40km/h on the tighter radius corner. As for the straight road section, on relatively tight corners the forward speeds remained high, even under emergency braking, either when vehicles tried to stay on the road, or when they simply braked on beginning to depart from the road.

The range of normal speeds and low incident angles at lateral offset distances of 2m and 4m on both straights and corners suggest that for run-off-road crashes, barriers placed at these distances should not cause serious injuries or fatalities. While there is currently no intention to place barriers at distances that are significantly different from this 2m to 4m range, the normal speeds and angles at 9m offset would suggest there is no significant disadvantage to placing barriers further from the road.

All of the computer simulations, both straight and corners, showed relatively high forward speeds, even as far as 9m laterally from the road. This tends to support the finding of the statistical analysis that not only is the lateral distance to the hazard important, but the type of hazard is also important.

Limited additional simulation modelling showed that the lateral encroachment distances, forward and normal speeds, and incident angles, are all significantly dependent on the friction levels of the roadside. This tended to support the view that for a Safe System approach, the overall safety within the road reserve should be considered, starting with the road itself and carrying on to the roadside, including all of the roadside conditions, eg friction, slope, gradient, offset to hazard and type of hazard.

6.3 Implications for current practice

One of the objectives of this research was to provide information on the reduction rates for the numbers and severity of run-off-road crashes from different roadside treatments, including barrier types and clear-zone widths for inclusion in the EEM. Tables 6.1 through 6.3 provide information on the different crash rates and crash severity for different roadside treatments; however, to be able to include this information in the EEM will require an assessment of economic factors and costs.

These economic factors would include an assessment of the costs of each of the different roadside treatments against the potential costs associated with the relative differences in the crash rates.

The results of this study suggest that:

- Unless there are significant cost factors, or other strong non-cost factors, flexible (wire-rope) barriers should be considered for use before other barrier types.
- Application of a clear zone, of whatever depth, should not be considered without also considering the severity of the hazards that lie beyond it.

7 Conclusions and recommendations

The following conclusions have been drawn from this study to quantify the effects of roadside barriers and clear zones on the mitigation of run-off-road crash numbers and crash severity for New Zealand road and roadside characteristics. Recommendations for additional work are also made.

7.1 Conclusions – literature review

The review of the available literature, including current design practices and research tells us that:

- Current barrier and clear-zone practices do not necessarily reflect recent developments, in general geometric design, skid resistance, vehicle mechanical reliability, safety features (eg airbags, ABS, ESC), performance and road delineation.
- For a 100km/h speed environment, up to 70% of vehicles leaving the road are accommodated within the first 6m of lateral distance. However, a significant proportion of vehicles (up to 20%) that run off the road will encroach further than 9m laterally, and still have a high forward speed, even under emergency braking.
- The severity outcome of a run-off-road crash into an object is proportional to the speed and angle of the vehicle when it strikes the object, with barrier normal speeds of less than around 30km/h to 40km/h not expected to cause serious injuries.
- The treatment of roadsides using either clear zones or barriers is being revisited because of the adoption of the Safe System approach and the need to better target limited funding.

7.2 Conclusions – analysis dataset

The development of the analysis dataset led to the following conclusions regarding the quality of the data in the RAMM and crash databases, and in KiwiRAP:

- In the RAMM data there are some issues with the accuracy of the locations of infrastructure elements, in this case barriers and railings, and in their installation dates.
- The crash data and KiwiRAP data also have issues regarding specific locations, particularly with respect to the standard NZTA position referencing system.
- There is some evidence in the KiwiRAP data of differences in the subjective evaluation of the roadside hazards between the left and right sides of the road due to the video recording being taken only in one direction of travel. This may have caused bias in the data.

7.3 Conclusions – statistical analysis

The following conclusions have been drawn from the statistical analysis of the combined RAMM/crash/ KiwiRAP dataset:

- The roadside condition, which can comprise a combination of clear zones and barriers or other hazards, as defined in KiwiRAP, was found to have a statistically significant effect on the crash rate.
- Crash rates were predicted for different roadside conditions, where these are described in terms of either the barrier/rail risk categories of rigid, short rail, semi-rigid and flexible (wire rope), or roadside risk categories of tiny, low, medium, high and extra high. These roadside risk categories relate to the physical makeup of the roadside through the KiwiRAP severity outcomes and severity outcome descriptions. They essentially progress through increasing severity of the hazard and increasing proximity to the road. The predicted crash rates are listed in table 4.6.
- The best performing roadside conditions were the tiny and low-risk categories, followed by flexible (wire-rope) barriers and the medium category. However, the crash rate for the tiny category should be treated with some caution given the relatively low frequency of occurrence.
- Flexible (wire-rope) barriers performed reasonably well, and were the best performing of the barrier types. This performance seemed more important on right-hand bends. The relatively good performance of this type of barrier is also supported by recent Australian research. However, other Australian research suggests that based on limited testing with crash dummies, there is little practical difference in crash severity reduction between wire-rope and W-beam semi-rigid barriers. This preliminary result is supported by the relatively small variations in the crash severity ratios shown in tables 4.10 and 6.1 for the different roadside categories, except for tiny.
- There was high risk associated with short railings and rigid barriers. We suspect this was because of associated hazards and possibly their shorter offset distances rather than the railings themselves.
- While the lateral offset distance of the hazard from the road is important, ie the width of the clear zone, it is also the type of hazard that is encountered at the far side of this offset distance that is important in determining the crash rate.
- Consideration of crash severity showed there was little significant variation across the barrier/rail risk categories of rigid, short rail, semi-rigid, and flexible (wire rope), or the roadside risk categories of tiny, low, medium, high, extra high. The proportions of fatal and serious crashes to all casualty crashes were around 0.3 with only the tiny category showing significantly lower crash severity. This may be due to the lack of data, particularly for some roadside categories and/or some barriers are only used in certain roadside conditions.
- Consideration of additional factors including curvature, terrain and horizontal alignment, as well as wet road crashes did not add anything significant to the statistical model that was not already there. These factors were largely accounted for in other model variables, eg the horizontal alignment is strongly correlated with the OOCC factor, which was already included in the model.

7.4 Conclusions – computer simulation modelling

The following conclusions have been drawn from the limited computer simulation modelling that complemented the statistical analysis:

- For straight road, drift-off and maximum turn scenarios, simulations, including under emergency braking, showed that normal speeds at distances of 2m, 4m and 9m were generally 40km/h or less. The angles at these distances were also typically 30° or less. However, the forward speeds could remain quite high, even at 9m lateral displacement, in both wet and dry conditions.

- Simulations of two low radius corners showed very similar normal speeds and angles at 2m and 4m lateral offsets for the three vehicles used, but much more variation at 9m. However, the normal speeds at each of these offsets were still 40km/h or less, even under emergency braking where no attempt to return to the road was modelled.
- For the straight road sections, the forward speeds on these relatively tight corners remained high, even under emergency braking, irrespective of whether the vehicle was trying to stay on the road or not. This supports the view from the statistical analysis that not only is the lateral distance to the hazard important, so is the type of hazard.
- The normal speeds and relatively low incident angles at the 2m and 4m offsets on both straights and corners suggest that for run-off-road crashes, barriers placed in this range should not cause serious injuries or fatalities. There does not appear to be any disadvantage to placing barriers further from the road than this, although the literature does suggest a greater chance of rollover crashes.
- The corner simulations suggest that placing the barriers further out, for example at 4m offset, would accommodate a greater proportion of encroaching vehicles without a significant increase in the risk of serious injury because of high normal speeds and incident angles. However, placing barriers at much greater distances raises the possibility of increased risk of rollover crashes and also removes the potential route delineation that barriers can provide, particularly at night.
- Additional simulations showed that forward and normal speeds, and incident angles, are significantly affected by the surface friction of the roadside.

7.5 Conclusions – effects of clear zones and barriers

- The findings of this project support the view that for a Safe System approach, it is necessary to consider the overall safety within the road reserve, starting with the road itself, eg in terms of geometry and friction, and carrying on to the roadside, including all of the roadside conditions, eg friction, slope, gradient, offset to hazard and type of hazard.

7.6 Recommendations

The recommendations for further work arising from this study of the effects of clear zones and barriers on the run-off-road crash rates in New Zealand are as follows:

- An economic evaluation should be carried out on the cost implications of the different roadside barrier/rail risk categories of rigid, short rail, semi-rigid, and flexible (wire rope), or roadside risk categories of tiny, low, medium, high and extra high, given the calculated crash rates. This would allow the variations in crash rate and crash severity for different roadside conditions to be incorporated in the EEM.
- The uncertainties in the crash rates need to be reduced. This requires either more crash data, which would mean waiting for a number of years, or using the lesser applied roadside treatments more frequently. The relatively good performance of the flexible (wire-rope) barriers would suggest that their use should be expanded, particularly in areas where barriers are contemplated.
- The findings of the recently completed Austroads (2012) study should be reviewed, and the results of their statistical analysis compared with the crash rate predictions from this study.

- A limited selection of KiwiRAP data, including the video records if possible, should be assessed to investigate the effects due to mapping the 100m data onto 10m increments as was done for this statistical analysis. If this suggests that refinement of the KiwiRAP data would improve the confidence limits of the statistical analysis, further options should be considered.
- The apparent bias between the left and right roadside KiwiRAP data should be investigated further to determine the magnitude of the effect, and identify whether there are regional or other causes for the differences.
- Additional work is needed to identify the effective frictional values for New Zealand roadsides, including grasses and other vegetation, beyond the limited amount of data that is currently available.

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Appendix A: Features of PC-Crash V9.0

A1 Background

The computer software package used for the simulation modelling was PC-Crash, version 9 (3D). This is an internationally recognised three-dimensional vehicle crash and trajectory simulation package widely used by police and civilian crash investigators and analysts. Road models in three dimensions can be created by either 1) generating them in CAD packages from surveyed data and importing them into the simulation, 2) drawing contours then laying a surface over them in the simulation, or 3) 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, steering or braking can also 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.

PC-Crash uses a number of vehicle databases that provide access to a wide variety of vehicle makes and models, ranging from motorcycles, cars, SUVs, trucks and trailers. The modelling of the vehicles includes all the parameters required to simulate their motion in response to internal forces such as acceleration, braking and steering, and to external forces such as the road geometry and surface friction. The modelled parameters include:

- vehicle dimensions
- vehicle mass, mass distribution and moments of inertia in pitch, roll and yaw
- steering response
- tyre properties
- location and mass of passengers
- suspension properties
- brake forces
- ABS and ESP.

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
- ESP (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 tire 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 accident avoidance
- Automatic kinetic calculation of accident 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 modeller
- 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 (ESP)
- 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
- Mirror 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

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.
- Multi-body pedestrian model
- Multi-body motorcycle, bicycle and unrestrained occupant models
- Multiple multi-body 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

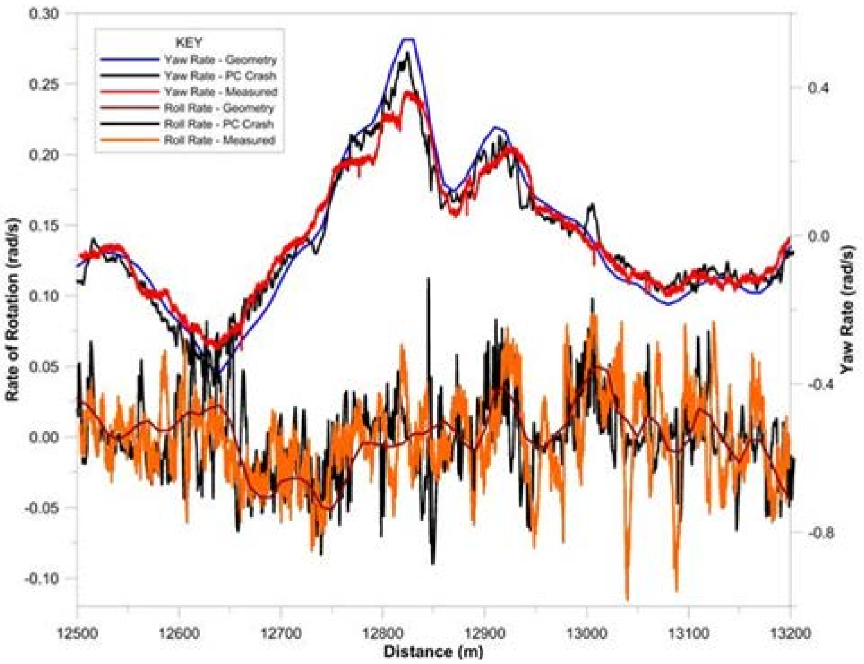
- Direct X 3D graphics, for improved rendering
- New stiffness based crash simulation model
- New stiffness database with real crash test to be used in stiffness based crash simulation
- Improved occupant simulation in PC-CRASH including seatbelts and car interior
- New mesh based impact model with improved 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 mirror 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 catalogue
- 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 B: Assessment and verification of PC-Crash

This appendix reproduces the section on the assessment and verification of PC-Crash from Jamieson (2012), with minor editing to reflect the current report format.

PC-Crash is an internationally recognised three-dimensional vehicle collision and trajectory simulation tool that is currently used by police and civilian crash investigators and analysts, with over 4000 licences worldwide. Since its initial development as a commercially available software package there have been a number of technical papers describing its use and agreement with real-life scenarios. These references include Moser and Steffan (1996), Spit (2000), Gopal et al (2004), Batista et al (2005), Tejera (2006) and Kunz (2007). They have found generally good agreement with real-life situations. PC-Crash was also used recently by Cenek et al (2011) to compare measured rates of yaw and rotation with values from the computer simulations. Figure B.1 shows an example comparison of the yaw and roll rates derived from geometry data in RAMM, on-road measurements, and the PC-Crash simulation.

Figure B.1 Comparison of geometry, on-road and computer simulation data – car (80km/h)



This suggests reasonably good agreement between measured and simulated vehicle response data for yaw and roll. However, for the purposes of this research project it was also considered appropriate to assess whether PC-Crash produced results that were in reasonable agreement with the braking and sliding conditions likely during real crash situations. Accordingly, a PC-Crash 3D model of a straight flat road section was constructed so that locked-wheel-braking tests carried out during other on-road testing programmes by Opus Central Laboratories (Jamieson et al 2002; Jamieson et al 2002; Cenek et al 2005) could be simulated. Friction and braking distance data was taken from a range of studies carried out on different surface types and conditions. The surface types included asphaltic concretes, chipseals and different grass types, and the conditions included dry and wet surfaces, as well as differential friction. Differential friction was achieved by wetting one wheelpath and leaving the other dry. PC-Crash simulations were then run using vehicles matching those used in the full-scale studies. Braking distances were measured for the same test speeds used in the full-scale testing, and yaw angles were also measured for the tests using differential friction. The results of these tests are listed in table B.1.

Table B.1 Locked-wheel-braking tests – comparison of full-scale and computer simulations

Surface	Condition (dry/wet)	Speed (km/h)	Differential friction	Coefficient of friction	Full-scale (m)		PC-Crash	
					Braking distance (m)	Yaw angle (º)	Braking distance (m)	Yaw angle (º)
Chipseal	Dry	52	No	0.60	16.5	NA	17.0	NA
Chipseal	Wet	50	No	0.51	19.2	NA	20.2	NA
Chipseal	Wet	69	No	0.53	33.0	NA	34.2	NA
Asphaltic concrete	Dry	50	No	0.73	12.6	NA	13.0	NA
Asphaltic concrete	Wet	73	No	0.59	36.6	NA	35.8	NA
Asphaltic concrete	Wet	52	No	0.64	16.9	NA	16.0	NA
Clover	Dry	40	No	0.21	30	NA	31.1	NA
Clover	Wet	40	No	0.17	37	NA	38.8	NA
Ryegrass	Dry	40	No	0.38	17	NA	17.3	NA
Ryegrass	Wet	40	No	0.24	26	NA	27.1	NA
Asphaltic concrete	Dry	50	No[a]	0.73	13.0	NA	13.0	NA
Asphaltic concrete	Dry & wet	48	Yes[a]	0.65	13.5	23.4	14.3	22.0
Asphaltic concrete	Dry & wet	58	Yes[a]	0.59	19.8	43.9	20.5	42.0
Asphaltic concrete	Dry & wet	68	Yes[b]	0.64	28.0	22.2	27.1	21.5

[a] Differential friction site 1. [b] Differential friction site 2.

This shows good agreement between the full-scale measured braking distances and those derived from the computer simulation, not only in straight line braking, but also under conditions of differential friction. In addition, there is good agreement between the measured and computer derived yaw angles. These findings indicate that PC-Crash provides a reasonably accurate simulation of vehicle movement in both the longitudinal and lateral directions across a broad range of friction values. The agreement between the yaw angles is particularly important given the objective of investigating encroachment of vehicles from the sealed lane onto the roadside where the friction values will generally be significantly different.

At this stage it was also considered appropriate to assess how well the PC-Crash simulation would replicate an actual crash situation. Given the good agreement shown above between real braking/sliding performance, it was not considered necessary to investigate more than one run-off-road crash situation. As described earlier, the corners selected for this study were chosen as having a history of one or more run-off-road vehicle crashes. The crash records for the corners were examined, and one of the crashes for corner F (see appendix A) was chosen as having sufficiently detailed information about the crash to give some confidence about choosing the simulation parameters. Figure B.2 shows a view of the corner.

Figure B.2 Corner F (SH53 RP0/0 13990–14080 (decreasing direction is from bottom to top)

This 2008 crash involved a 4WD Mitsubishi Pajero, which was travelling in the decreasing direction around a right-hand curve with a curve advisory speed of 75km/h. According to the driver it was raining heavily after a spell of dry weather and the vehicle was travelling at around 70km/h. The driver lost control of the vehicle and skidded off the road, just missing the power pole and advertising hoarding (see above), and eventually coming to a stop a short distance past this point.

The 3D model for this corner was imported into PC-Crash, and the appropriate vehicle was loaded. Friction values for the road surface and the roadside were chosen as for a very wet surface ($\mu = 0.3$). Vehicle tracks based on the four identified driving lines were used to run simulations at speeds around 70km/h and higher. The simulations suggest that the vehicle speed was at least 75km/h, possibly as high as 90km/h, and was cutting towards the middle of the corner, then beginning to encroach out of the lane past the apex of the corner. Figure B.3 shows a plot of the simulated vehicle path. This shows reasonably good agreement with the identified encroachment location, and the path of the vehicle past the pole and hoarding. Together with the locked wheel braking comparisons described in table B.1, this gives us confidence that PC-Crash provides an acceptable simulation of the sliding behaviour expected during run-off-road encroachments.

Figure B.3 Simulated vehicle path – PC-Crash

Appendix C: Computer simulation results

The following tables list the result for the computer simulations for the 120m radius and 170m radius corners. They list the vehicle speeds, angles and normal speeds for lateral offsets of 2m, 4m and 9m from the road edge.

Table C.1 Corner simulation results – 120m radius (– front left corner leading)

Vehicle	Road slope	Roadside slope	Braking	Speed (kmh)	Outcome	Lateral distance offset (m)	Angle to offset (°)	Normal speed at offset (km/h)	Forward speed at offset (km/h)
BMW	Flat	Flat	No	80	Stays on Road	-	-	-	-
				90	Stays on Road	-	-	-	-
				100	Stays on Road	-	-	-	-
				110	5m encroachment	2	9.6	13.9	109
				110	5m encroachment	4	28.2	7.4	108
				120	Loss of Control	2	5.3	26.5	118
					Loss of Control	4	9.3	23.7	118
					Loss of Control	9	22.9	17.9	116
			Yes	110	Loss of Control	2	7.4	13	98
					Loss of Control	4	21.5	11	95
					Loss of Control	9	90.0	9	82
				120	Loss of Control	2	6.5	14	112
					Loss of Control	4	9.2	19	110
					Loss of Control	9	18.9	23	105
		10deg	Yes	110	Loss of Control	2	7.5	10	99
					Loss of Control	4	14.3	20	97
					Loss of Control	9	29.1	22	92
				120	Loss of Control	2	6.2	13	113
					Loss of Control	4	10.2	25	111
					Loss of Control	9	18.5	29	108
	10deg	Flat	No	80	Stays on Road	-	-	-	-
				90	Stays on Road	-	-	-	-
				100	Stays on Road	-	-	-	-
				110	8m encroachment	2	4.4	11	109
				110	8m encroachment	4	9.3	10	109
			Yes	110	Loss of Control	2	6.3	14	100
					Loss of Control	4	13.1	21	99
					Loss of Control	9	27.1	31	97
			No	120	Loss of Control	2	8.6	19	119
					Loss of Control	4	15.5	19	118
					Loss of Control	9	32.4	24	118
			Yes	120	Loss of Control	2	9.7	17	113
					Loss of Control	4	13.6	23	111
					Loss of Control	9	25.4	30	109
Corolla	Flat	Flat	No	80	Stays on Road	-	-	-	-
				90	Stays on Road	-	-	-	-
				100	Stays on Road	-	-	-	-
				110	3m encroachment	2	2.0	13	106
			Yes	110	Loss of Control	2	7.7	11	97
					Loss of Control	4	10.3	12	94
					Loss of Control	9	1.5	5	79
				120	Loss of Control	2	5.8	16	112
					Loss of Control	4	9.6	20	110
					Loss of Control	9	19.8	24	104
		10deg	Yes	110	Loss of Control	2	6.7	11	98
					Loss of Control	4	16.0	17	96
					Loss of Control	9	36.6	23	91
				120	Loss of Control	2	6.1	16	112
					Loss of Control	4	8.0	21	111
					Loss of Control	9	12.1	29	108
	10deg	Flat	No	80	Stays on Road	-	-	-	-
				90	Stays on Road	-	-	-	-
				100	Stays on Road	-	-	-	-
				110	5.6m encroachment	2	23.6	11	108
					5.6m encroachment	4	57.0	6	107
			Yes	110	Loss of Control	2	21.3	17	103
					Loss of Control	4	43.9	17	102
					Loss of Control	9	121.8	14	98
			No	120	Loss of Control	2	13.4	14	119
					Loss of Control	4	20.6	24	118
					Loss of Control	9	44.2	21	118
			Yes	120	Loss of Control	2	13.5	17	116
					Loss of Control	4	20.1	24	115
					Loss of Control	9	40.3	25	113
RAV4	Flat	Flat	No	80	Stays on Road	-	-	-	-
				90	Stays on Road	-	-	-	-
				100	Stays on Road	-	-	-	-
				110	3.4m encroachment	2	11.9	8	107
			Yes	110	Loss of Control	2	2.0	13	97
					Loss of Control	4	2.0	19	94
					Loss of Control	9	11.2	22	89
			No	120	Loss of Control	2	7.2	16	119
					Loss of Control	4	8.2	21	119
					Loss of Control	9	19.8	21	116
			Yes	120	Loss of Control	2	1.0	18	111
					Loss of Control	4	3.0	25	109
					Loss of Control	9	10.5	29	104
		10deg	Yes	110	Loss of Control	2	1.3	15	98
					Loss of Control	4	1.7	24	96
					Loss of Control	9	9.2	33	93
				120	Loss of Control	2	2.0	18	111
					Loss of Control	4	4.0	26	110
					Loss of Control	9	9.2	35	107
	10deg	Flat	No	80	Stays on Road	-	-	-	-
				90	Stays on Road	-	-	-	-
				100	Stays on Road	-	-	-	-
				110	Loss of Control	2	24.9	14	109
					Loss of Control	4	45.2	15	108
					Loss of Control	9	116.0	15	104
			Yes	110	Loss of Control	2	9.1	14	101
					Loss of Control	4	14.8	25	100
					Loss of Control	9	31.3	26	98
			No	120	Loss of Control	2	15.1	18	119
					Loss of Control	4	25.8	20	119
					Loss of Control	9	54.1	22	117
			Yes	120	Loss of Control	2	10.6	17	114
					Loss of Control	4	18.2	29	113
					Loss of Control	9	33.5	29	111
	10deg	Flat (no follow path)	Yes	120	Loss of Control	2	10.6	22	114
					Loss of Control	4	7.4	34	113
					Loss of Control	9	6.3	41	111

Table C2 Corner simulation results – 170m radius

Vehicle	Road slope	Roadside slope	Braking	Speed (kmh)	Outcome	Lateral distance offset (m)	Angle to offset (˚)	Normal speed at offset (km/h)	Forward speed at offset (km/h)
BMW	Flat	Flat	No	80	Stays on Road	-	-	-	-
				90	Stays on Road	-	-	-	-
				100	Stays on Road	-	-	-	-
				110	Stays on Road	-	-	-	-
				120	0.6m encroachment	-	-	-	-
			Yes	120	Loss of Control	2	21.1	15	109
					Loss of Control	4	44.47	12	105
					Loss of Control	9	102	14	96
		10deg	Yes	120	Loss of Control	2	17.95	13	110
					Loss of Control	4	37	16	107
					Loss of Control	9	68.45	22	102
	10deg	Flat	No	80	Stays on Road	-	-	-	-
				90	Stays on Road	-	-	-	-
				100	Stays on Road	-	-	-	-
				110	Stays on Road	-	-	-	-
				120	3.6m encroachment	2	18.7	7.8	111
			Yes	120	Loss of Control	2	12.6	14	111
					Loss of Control	4	27.1	19	110
					Loss of Control	9	49.6	21	106
Corolla	Flat	Flat	No	80	Stays on Road	-	-	-	-
				90	Stays on Road	-	-	-	-
				100	Stays on Road	-	-	-	-
				110	Stays on Road	-	-	-	-
				120	0.7m encroachment	-	-	-	-
			Yes	120	Loss of Control	2	9.4	19	108
					Loss of Control	4	15.8	22	106
					Loss of Control	9	36.7	23	101
		10deg	Yes	120	Loss of Control	2	9.2	20	109
					Loss of Control	4	15.4	24	107
					Loss of Control	9	29.8	28	104
	10deg	Flat	No	80	Stays on Road	-	-	-	-
				90	Stays on Road	-	-	-	-
				100	Stays on Road	-	-	-	-
				110	Stays on Road	-	-	-	-
				120	4.4m encroachment	2	22.3	10	118
				120	4.4m encroachment	4	26.9	4	118
			Yes	120	Loss of Control	2	9.1	18	110
					Loss of Control	4	17.8	18	109
					Loss of Control	9	44.9	17	107
RAV4	Flat	Flat	No	80	Stays on Road	-	-	-	-
				90	Stays on Road	-	-	-	-
				100	Stays on Road	-	-	-	-
				110	Stays on Road	-	-	-	-
				120	0.8m encroachment	-	-	-	-
			Yes	120	Loss of Control	2	6.9	17	109
					Loss of Control	4	14.7	20	106
					Loss of Control	9	35.2	21	101
		10deg	Yes	120	Loss of Control	2	6.5	19	109
					Loss of Control	4	12.7	23	108
					Loss of Control	9	27	31	105
	10deg	Flat	No	80	Stays on Road	-	-	-	-
				90	Stays on Road	-	-	-	-
				100	Stays on Road	-	-	-	-
				110	Stays on Road	-	-	-	-
				120	4.3m encroachment	2	22.5	11	118
				120	4.3m encroachment	4	26.6	7	118
			Yes	120	Loss of Control	2	12.8	18	110
					Loss of Control	4	23.9	22	109
					Loss of Control	9	49.1	23	106
		Flat (no follow path)	Yes	120	Loss of Control	2	0.6	9	117
					Loss of Control	4	0	20	116
					Loss of Control	9	0.4	28	116