Optimising expenditure on roadside safety barriers

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NJ Jamieson, Opus International Consultants, Lower Hutt
Dr S Richardson, Delta-V Experts, Victoria

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NZ Transport Agency
Private Bag 6995, Wellington 6141, New Zealand
Telephone 64 4 894 5400; facsimile 64 4 894 6100
research@nzta.govt.nz
www.nzta.govt.nz

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Abbreviations and acronyms

Delta-V	change in vehicle velocity pre and post collision
EEM	Economic Evaluation Manual
FSI	fatal or serious injury
MASH	Manual for Assessing Safety Hardware
OIV	occupant impact velocity
ORA	occupant ridedown acceleration
SHGDM	State Highway Geometric Design Manual
SUV	sports utility vehicle

Contents

Executive summary

This research was undertaken in 2013 to identify if and when it is more appropriate to rectify or replace existing roadside crash barriers that do not conform to the installation specifications, particularly in terms of height and condition, or to install new roadside crash barriers at locations with significant hazards where there are currently no barriers. This was to provide road controlling authorities with information that would assist them to establish spending options and priorities.

This research used computer simulation modelling to quantify the effects of barrier height and condition on crash severity for selected barrier types (W-beam and wire rope), vehicles (including types, speeds and travel paths), and physical contexts (straights and corners). Crash severity costs were derived for:

- existing deficient roadside barriers
- rectified and reinstalled barriers, or new barriers in the same locations
- new barriers at previously untreated different locations that have significant hazards.

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

Conclusions

Literature review

- Only limited information was available on the magnitude of the perceived problem of barrier heights that were too low for whatever reason (eg pavement overlays). There was a relative lack of knowledge of the lengths of barriers that were too low, the amounts by which they were too low, and how both of these factors varied with barrier type. Some of the data indicated that around 14% of barriers in the Wellington region were 30mm or more (too high or too low) from the specified height, but did not provide maximum differences.
- Similarly, there was little information in the literature on how a variation in barrier height could affect crash severity. One study comparing both full-scale barrier crash tests and computer simulation modelling of barrier crashes suggested that a height deficiency of as little 40–60mm could affect the ability of a W-beam barrier to contain and redirect pickups and large sports utility vehicles (SUVs). However, the same study also found little difference in crash severity for this level of height deficiency.
- The literature described a variety of different metrics to measure crash severity, one of which was the Occupant Impact Velocity (OIV), which is often reported in full-scale crash testing, and another being Delta-V, which is the change in the pre-collision and post-collision vehicle velocity. Delta-V was the metric originally proposed as the basis for this research project. One study suggested there was little statistical advantage in using the more complex OIV as opposed to the computationally simpler Delta-V.
- Very little information was found on the effect of corrosion on barrier strength or performance, and none of it was quantitative. Discussions with a corrosion expert suggested there could potentially be considerable differences in the ‘ribbon-like’ performance of a barrier, particularly W-beam and similar barriers, depending on the location and extent of the corrosion.

Computer simulation modelling

- Comparison of full-scale barrier crash deflection and crash severity (OIV) data with corresponding data from computer simulation modelling (deflection and Delta-V) indicated that the simulation modelling would be adequate for the purposes of this study.
- Simulations of drift-off low-angle impacts into a W-beam barrier in wet conditions showed low crash severities, as measured using the Delta-V values, no significant variation with barrier height, and only a small increase with vehicle speed.
- For the lighter car that was investigated, simulations of maximum-rate turn crashes into a W-beam barrier in wet conditions showed a small increase in crash severity with a lower barrier height, but there were minimal difference for the heavier car and SUV that were investigated.
- Straight-line impacts into both W-beam and wire-rope barriers at a 25° angle showed increases in the probability of serious injury of around 0.038 and 0.006, respectively, for a representative 50mm reduction in barrier height.
- Simulation of impacts into both W-beam and wire-rope barriers on a small radius of curvature corner showed increases in the probability of serious injury of around 0.026 and 0.013, respectively, for a representative 50mm reduction in barrier height.

Barrier and crash costs

- There was wide regional and contractor variation in the costs/m, both to erect new barriers and to fix or raise them.
- Generally, wire-rope barriers were significantly cheaper to erect and fix than W-beam barriers.
- Combining the effects of barrier height on crash severity with the various cost factors associated with barrier construction or remediation, the results of the simulation modelling suggested that in many cases, and particularly with wire-rope barriers, it was much more cost effective to install new barriers in previously untreated locations than to raise existing ones to the correct heights.

Recommendations for further research

The recommendations arising from this study for further work on the effects of safety barrier height and condition on crash severity on New Zealand roadsides are as follows:

- A more detailed understanding of the size and extent of the perceived problem of barrier heights being lower than specified is needed. This may require some representative sampling during barrier inspections, or there may be existing data in the information systems of the Transport Agency or its consultants and contractors.
- A limited programme of full-scale testing of the effects of barrier corrosion would be useful, both by potentially leading to a better understanding of its effects on barrier strength and performance, and also by refining visual condition assessment.
- Although the sample sizes may be small, it may be useful, where possible, to develop more detail on the relationship between barrier height and the crash outcomes/severity in actual barrier crashes.
- A more detailed analysis of the cost/benefits associated with erecting new barriers in previously untreated locations or remediating existing barriers is needed before consideration is given to

changing current Transport Agency policies and procedures. In particular, further analysis is needed on all of the costs involved in rectifying existing substandard barriers. This should consider all of the significant potential failings that existing roadside barriers may exhibit, as it is probable that substandard height would not be the sole or even the predominant trigger for remediation.

Abstract

This research, which was carried out in New Zealand in 2013, used computer simulation modelling to identify whether it is better to rectify or replace existing roadside crash barriers that are of substandard height or are corroded, or to install new roadside crash barriers at locations with significant hazards where there are currently no barriers. This information would assist road controlling authorities in establishing spending options and priorities.

The computer simulation modelling quantified the effects of barrier height on crash severity for a selected range of barrier types (W-beam/wooden post and wire rope), vehicles (models, speeds and paths) and physical contexts. Crash severity costs were also derived for a limited selection of rectified and reinstalled barriers, new barriers in the same locations; and new barriers at untreated locations that have significant hazards.

The key finding was that for both barrier types there was an effect on increasing crash severity with barrier heights that were lower than specifications. However, this was not generally found to be severe, even for height differences thought to exceed those expected to occur on the New Zealand state highway network. The research results suggested that in many cases (especially for wire-rope barriers) it would be much more cost effective to install new barriers at previously untreated locations than to raise existing barriers to the correct heights.

1 Introduction

1.1 Objectives

The purpose of this research project, which was carried out in 2013, was to understand and quantify the effects on crash severity, and hence on crash severity costs, of:

1 differences in roadside barrier height from the specified installation heights

2 the condition of the barrier material.

This would allow road controlling authorities to establish the most cost-effective spending options and priorities.

The principal objectives of the research were to:

1 quantify the effects of barrier height and condition on crash severity, using computer simulation modelling for:
   - two selected barrier types (W-beam/wooden post and wire rope)
   - selected vehicle models, speeds and paths
   - road/roadside configurations (straight and curved road sections)
   - different roadside slopes

2 provide a limited assessment of costs, including:
   - the crash severity costs associated with existing deficient roadside barriers, compared with the costs of rectifying them or replacing them with new barriers in the same location, or of installing new barriers in different locations that have a significant hazard
   - the remediation/replacement and maintenance costs for existing deficient barriers, and the construction and maintenance costs for new barriers installed in different locations

3 develop recommendations for asset managers regarding prioritisation of investment into existing or new roadside barriers.

1.2 Background

In New Zealand, run-off-road crashes constitute a very significant proportion of the total number of road crashes on the state highway network. There is a need to provide appropriate roadside treatments that will help to reduce the numbers of crashes, or at least mitigate their effects so as to avoid deaths and serious injuries. This is referred to as a 'Safe System' approach to road safety, and is one of the objectives of Safer Journeys, the New Zealand government's strategy to guide improvements in road safety over the decade 2010-2020.

Roadside barriers (rigid, semi-rigid or flexible) and 'clear zones' are currently among the most widely used treatments for roadsides on the state highway network, and are intended to reduce the consequences for vehicles that run off the road. The ‘clear zone’ is defined as an area extending from the lane edgeline that is free of hazards and obstacles, which vehicles can cross with minimum damage to the vehicle and its occupants. Roadside barriers are often used where clear zones are not practical, or to shield significant hazards – eg cliffs, embankments or bridge approaches.

Roadside barriers are known to be an effective means of reducing the severity of crash outcomes through the containment and redirection of vehicles and shielding of greater hazards (eg trees and poles). However, to ensure that these barriers perform as they were designed and intended, they need to be installed and maintained correctly (ie in the right locations, at the correct heights) and kept in good condition. An internal review by the NZ Transport Agency showed that for a variety of reasons, some of the roadside barriers installed on the New Zealand state highway network did not conform to the specifications, either because of incorrect heights or poor condition. Incorrect heights could be caused by a variety of factors, including ground subsidence and additional seal layers. The condition of barriers could be affected by environmental conditions, with corrosion of the barrier material (steel) or deterioration of the supporting elements (eg wooden posts).

1.3 The need for research

The need for this research was driven by a combination of:

1. an awareness that a proportion of roadside barriers installed on New Zealand state highways are not up to the installation specifications, because of their height and/or condition
2. a lack of knowledge about how these deficiencies might affect crash severity and crash costs
3. a need to understand the relative costs of remediating or replacing deficient barriers, as opposed to building new barriers in other locations
4. the need to target the limited amount of funding available for road safety improvements.

In the Wellington region, a limited review of around 135km of roadside barriers showed that:

- ~19km (~14%) were more than 30mm higher or lower than the specified height
- ~44km (~33%) were between 10mm and 30mm higher or lower than the specified height
- ~70.5km (~52%) were within 10mm of the specified height.

The height of the remainder was undetermined. (Note that the installation height tolerance for roadside barriers is ±20mm for W-beam and wire-rope barriers.)

These findings suggested that up to ~85% of roadside barriers in the Wellington region were within their installation tolerance. It is also important to note that there are still many older barrier installations that were installed at, and are currently at, much lower heights than the current specified barrier installation heights.

1.4 Research process

The primary goal of this research was to quantify the effects of roadside barrier height and condition on crash severity, so that practitioners can judge whether it is most appropriate and cost effective to remedy or replace deficient barriers, or to erect new barriers in different locations that have a significant hazard.

The research began with a literature review to:

- gather information on the effects of roadside crash barriers on crash severity
- identify whether there is any evidence of safety or crash severity issues being affected by roadside barriers being either too low or too high, or in poor condition
- provide full-scale barrier crash data for calibrating the computer simulation modelling of barrier crashes.

The next stage was to use computer simulation modelling to investigate and quantify the effects of barrier height and condition on crash severity for:

- W-beam/wooden post barriers and flexible wire-rope barriers
- selected vehicle models, speeds and travel paths, and road geometry (straight and curved road sections).

This was followed by a limited assessment of the costs of remediating existing deficient roadside barriers, compared with the costs of replacing them with new barriers in the same location, or installing new roadside barriers in different locations that have a significant hazard.

1.5 Structure of the report

- Chapter 2 presents the results of the literature review.
- Chapter 3 describes the computer simulation modelling and calibration against full-scale crash data.
- The computer simulation modelling of selected road configurations, barriers, vehicle models and vehicle behaviours is described in chapter 4.
- In chapter 5, limited comparisons of barrier remediation, maintenance and construction costs are made.
- Chapter 6 contains a discussion of the findings of the literature review, the results of the computer simulation modelling, and the various costs that were investigated.
- 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 the current international research and best practice regarding roadside barriers in relation to crash severity, barrier height and barrier condition. This identified a considerable body of literature on the effects of run-off-road crashes into barriers and the results of full-scale crash testing, a lesser amount on computer simulation modelling, and a very limited amount on the effects on crash severity of barrier height and condition. The review was not intended to be a comprehensive review of this body of literature, or a description of current practice. Rather, it was targeted according to the objectives of the project described earlier - ie the effects of barriers, and variations in their height and condition, on crash severity, and to gather full-scale crash test data.

2.2 Roadside barriers – general

A wide range of safety hardware elements can be installed in roadside areas. Some of these are designed to provide a visual guide aimed at keeping vehicles on the road. Others, such as roadside barriers, are intended to mitigate the effects of vehicles leaving the road, usually by shielding a significant hazard. In New Zealand, a wide variety of roadside barriers have been installed over many years. Those currently considered appropriate for installation on the New Zealand state highway network are generally one of the following three types:

1. flexible – eg wire-rope barriers, consisting of tensioned wire ropes supported by closely spaced lightweight steel posts
2. semi-rigid – eg W-beam or Thrie-beam barriers, consisting of steel rails attached to closely spaced steel or timber posts
3. rigid – eg segmental concrete barrier, consisting of either pre-cast or cast-in-situ rigid blocks that are keyed, pinned or back-stopped, or are cast in situ or slip-formed and embedded below the pavement surface.

Figure 2.1 presents photos of some of the roadside barrier types currently used in New Zealand.

Figure 2.1 Examples of roadside barriers used in New Zealand

a) Wire-rope barrier (© CSP Pacific)

b) Semi-rigid W-beam barrier

c) Rigid concrete barrier (segmental system)

2.3 Roadside barriers - current practice

Both the New Zealand *State highway geometric design manual* SHGDM (NZ Transport Agency 2002, 2005) and the Australian *Rural road design: a guide to the geometric design of rural roads* (Austroads 2003) consider roadside barriers to be hazards, in the same way poles and trees are considered hazards. In general terms, their use is supposed to be avoided unless warranted by geometric circumstances or by shielding a greater hazard. The 2002 SHGDM established the need for either a clear zone or a barrier in a given situation.

2.3.1 New Zealand

In New Zealand, the specific requirements for the installation and maintenance of road safety barriers have been covered in past years by the joint Australian and New Zealand Standard *AS/NZS 3845: 1999 Road safety barrier systems*. This has recently been released as a revised draft (DR AS/NZS 3845.1 (2012)) for public comment and includes a number of changes, of which the most relevant to this study are changes to the allowed test procedures on the acceptable performance of roadside safety barriers.

The Transport Agency's *M23A: 2012 Specification for road safety barrier systems* sets out the approval process, design layout and installation requirements for permanent barrier systems on state highways. Only the barriers listed in this specification, or for which an interim acceptance has been issued, are approved for use in New Zealand as safety barrier systems.

The 2010 *Guide to road design: part 6: roadside design, safety and barriers* (Austroads 2010a), which has effectively superseded the Transport Agency's 2005 SHGDM, covers barrier location and layout factors such as:

- the offset from the edge of the traffic lane
- deflection requirements
- any terrain effects
- flare rate (the rate of change of offset from the road)
- the length of need.

Under the Transport Agency's M23A: 2012 specification, the minimum requirement for road safety barrier systems on state highways was based on Test Level 3 (TL3) in *Recommended procedures for the safety performance evaluation of highway features* (NCHRP 350) (NCHRP 1999). This test required that such a barrier had to be able to perform adequately in crash tests with an 820kg car travelling at 100km/h impacting at an angle of 20°, or a 2000kg pick-up travelling at 100km/h impacting at an angle of 25°. However, this has been superseded by the American *Manual for assessing safety hardware* (MASH) (AASHTO 2009). This contains changes to the procedures and criteria that are 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). Table 2.1 summarises the relevant differences for TL3 between NCHRP 350 (1999) and MASH (AASHTO 2009).

Table 2.1 Differences in Test Level 3 (TL3) – NCHRP 350 (1999) and MASH (2009)

Item	NCHRP 350	MASH
Small-car test vehicle	820kg	1100kg
Small-car impact angle	20°	25°
Pickup/utility test vehicle	2000kg	2270kg

In November 2012, the Transport Agency adopted MASH (AASHTO 2009) as the nominal testing protocol for new road safety hardware systems installed on the state highway network, and they are currently reviewing the M23A specification and other relevant documentation. Accordingly, unless otherwise stated in M23A, all barrier hardware that has been tested and is currently accepted under the NCHRP 350 (1999) criteria does not need to be retested to MASH, but may remain in place and continue to be manufactured and installed. However, all new barrier hardware that is developed, or significant variants of existing systems, must be tested and evaluated according to MASH.

In New Zealand, the use of median and roadside barriers, particularly wire-rope barriers, has increased 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.

2.3.2 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 requirements of the joint Australian and New Zealand Standard *AS/NZS 3845: 1999 – Road safety barrier systems*, which is based on the testing standards of NCHRP 350 (1999). As in New Zealand, NCHRP 350 is to be replaced by MASH (AASHTO 2009). Flexible, semi-rigid or rigid barriers similar to those used in New Zealand are selected in accordance with *Guide to road design: part 6 - roadside design, safety and barriers* (Austroads 2010a).

2.4 Roadside barrier crashes – general

Numerous studies on run-off-road crashes into roadside barriers have been conducted around the world - eg Shaw-Pin and Miaou (2001), ASSHTO (2006) and Levett (2007). Some of these have been listed in the bibliography at the end of this report. Several of these studies have led to, or fed into, the geometric design guides used in different countries, including the US, New Zealand and Australia. The development of roadside design standards in the US was well covered in McLean (2002), which also included an assessment of the implications for Australian practice. Like Australia, New Zealand has typically tended to follow design methodologies similar to those used in the US. The multiyear Austroads research project *Improving roadside safety* (Austroads 2010b, 2011a, 2011b and 2012) also reviewed run-off-road crashes in Australia and New Zealand, and current barrier research and practice.

Jamieson et al (2013) reported on a study to quantify, through statistical and computer simulation modelling, 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. This showed that the roadside condition, whether it consisted of 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. With specific reference to barrier types, the study showed that flexible barriers performed somewhat better than semi-rigid and rigid barriers.

2.5 Roadside barriers - crash severity

2.5.1 Barrier crash severity - general

When vehicles leave the road (for whatever reason) and crash into a roadside barrier, the consequences can range from vehicle/barrier damage only through to minor injuries, major injuries or fatalities. The actual crash outcome will depend on a wide variety of factors relating to the vehicle, the driver, and the road environment (which includes the roadside).

There are four ways to assess the effects of different roadside barriers on crash severity:

1 assessment of individual crash outcomes

2 statistical analysis of all of the available and relevant crash data - eg as reported by Jamieson et al (2013)

3 full-scale crash testing

4 computer simulation modelling.

These are discussed below.

2.5.2 Barrier crash severity – individual crash outcomes

In terms of crash severity, an analysis of the outcomes of individual crashes on the state highway network will often provide good information in relation to the specific circumstances associated with a particular crash into a particular type of barrier. However, there is usually a good deal of uncertainty associated with assessing or identifying the vehicle’s trajectory and speed, and the actions of the driver. For this research project, an analysis of actual records of crashes into barriers was not considered useful.

2.5.3 Barrier crash severity – statistical analysis

Collating the available barrier crash data does provide a larger dataset for analysis, and can provide valuable information on the crash rates and crash severity for different barrier types. In Australia and New Zealand, which have similar standards and practices for roadside barriers, there have been several studies investigating both barrier crash rates and crash severity.

In Australia, an Austroads multiyear study on improving roadside safety (Austroads 2010b, 2011a, 2011b and 2012) included detailed analysis of crashes into safety barriers. This study focused on defining two severity indices:

1 the risk of a fatal or serious injury (FSI)

2 the risk of a fatal outcome (F).

These are described in the following equations:

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

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

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

An alternative definition of the FSI ratio was to use the final Austroads report (Austroads 2012), where:

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

The analysis of urban and rural crashes for a 10-year period across Victoria in Australia (Austroads 2011a and 2011b) was used to develop severity indices for different types of barriers (rigid, semi-rigid and flexible), as well as a range of other roadside hazards. These are shown in table 2.2. Included in this table is the corresponding FSI_{2012} data from the Austroads 2012 report.

Table 2.2 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
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

The relatively high severity levels for semi-rigid barriers were likely to be due to the situations to which they were applied, compared with the other barrier types. However, the data suggested that flexible barriers perform better than the other barrier types in terms of crash severity, and that barriers are generally associated with a lower crash severity than some other objects that are commonly hit in roadside crashes.

Jamieson et al (2013) carried out a study based on statistical analysis of New Zealand crash data to quantify the effects of barriers and clear zones on the mitigation of crash numbers and crash severity. This study extended an existing crash risk model database covering road condition, road geometry and crash data, to also include the relevant available information on roadside clear zones and barriers. Statistical analyses were carried out on this database to identify the effects of different roadside treatments. Table 2.3 shows the predicted crash rates associated with different barrier types (classified into four broad classes), together with the predicted crash rates associated with different roadside conditions.

Table 2.3 Crash rates associated with different barrier/rail types and roadside conditions (from Jamieson et al 2013)

	Barrier/rail type or roadside condition	Predicted crash rate (per 100 million vehicle.km)
Barrier	Rigid	17
	Short-rail[a]	23
	Semi-rigid	13
	Flexible (wire rope)	10
Roadside condition	High (moderate hazard)	13
	Extra high (severe hazard eg large tree)	14

a) Short rails are those short lengths usually associated with other structures (eg bridges).

Note that the differences in crash rates between barrier types were probably due to a combination of the types of situations in which different barriers had typically been used and the possible reduction in severity associated with wire rope barriers, which translated into a lower crash reporting rate. In similar crash prediction modelling that did not consider the roadside environment, Davies (2004) and Cenek et al (2012a) predicted crash rates between ~10 and 15 per 100 million vehicle.km.

An analysis was also carried out on crash severity. This showed that across the different roadside barrier/railing types - rigid, short-rail, semi-rigid or flexible (wire rope) - there was very little significant variation. The proportions of fatal to serious crashes were around 0.3 for all of the barrier types. This may have been due to the relatively small datasets available, and/or that some barriers were only used in certain road environments. Similarly, apart from roadsides with wide clear zones and negligible hazards, the proportions of fatal to serious crashes for different roadside conditions were also around 0.3.

2.5.4 Barrier crash severity – full-scale crash testing

Full-scale crash testing of roadside barriers is the accepted method in many countries (including New Zealand) for carrying out uniform testing of proprietary roadside barrier systems for certification for use on roading networks. Both NCHRP 350 (NCHRP 1999) and MASH (AASHTO 2009) have provided a uniform series of guidelines for crash testing of barriers designed to provide:

- a basis for researchers and users to compare the impact performance of different systems
- guidance for developers of new or improved systems
- a basis for the formulation of performance specifications.

Both of these sets of guidelines also provide a series of criteria for the assessment of full-scale crash tests. These criteria, which are designed to minimise crash severity, are based on a combination of physical measures relating to the vehicle, such as:

- containment and redirection of the vehicle
- the vehicle remaining upright (ie not rolling over)
- whether detached elements (debris) or deformation of the vehicle causes intrusion into passenger spaces, and measures of aspects such as the maximum velocities and accelerations that would be experienced by the vehicle's occupants in a crash.

There are a number of issues with full-scale testing in relation to the performance of roadside barrier systems. Of necessity, the relatively high costs and amount of time involved in full-scale testing limit the numbers and types of vehicles and crash scenarios that can be investigated. While the test configurations in NCHRP 350 (1999) and MASH (2009) were chosen with the intention of covering some of what are considered the worst-case situations, some questions remained over whether the testing adequately reflected the range of vehicles and the road geometries at which crashes can occur.

Full-scale crash testing of roadside barriers typically involves the evaluation of the barrier system's performance in terms of the:

- risk of injury to occupants
- structural adequacy of the system
- risk to people behind the barrier
- post-impact vehicle behaviour.

This generally requires careful instrumentation of the test vehicle (eg accelerometers and gyros), and often includes instrumented dummies that simulate vehicle occupants. The testing usually involves the recording of data from the instrumentation, as well as photographic and video recording prior to, during, and after the crash.

As part of the literature review for this project, a search was carried out for readily available data from full-scale crash testing that could be used to validate and adjust the computer simulation modelling that formed the basis of this project – particularly data on the physical motion of the vehicle (direction, speed, acceleration, pitch, roll and yaw), and parameters relating to measures of crash severity. The data used for the calibration of the computer simulation modelling is discussed in a later section of this report.

2.5.5 Barrier crash severity – computer simulation modelling

Computer simulation modelling is increasingly being used in the modelling and reconstruction of vehicle crashes. Programs such as LS-DYNA, HVE (Human Vehicle Environment) and PC-Crash have been widely used for years to reconstruct and simulate vehicle crashes, including those into roadside barriers. It is important to realise that in all computer simulation modelling projects, calibration or validation against full-scale data is critical to ensure that any results are relevant and useful.

2.5.6 Barrier crash severity – metrics

Of necessity, measures of crash severity differ between analysis of individual crashes, multiple crash records and statistical crash data (eg Candappa et al 2009; Jamieson et al 2013), and information from either full-scale crash testing or computer simulation modelling. The analysis of crash data generally relies on information about the numbers of minor injuries, serious injuries and fatalities, compared to the numbers of vehicle occupants, or the amount of traffic, as well as the degree of physical damage to vehicles and the roading infrastructure. Analysis of full-scale crash testing generally relies on measurements taken from on-board vehicle sensors, such as accelerometers, or sensors connected to 'crash-test dummies' that are designed to simulate the vehicle occupants. Analysis of computer simulation models generally relies on calculated values of various crash severity measures, based either on the response of the vehicle or the response of simulated vehicle occupants. The accuracy of computer simulation models depends not only on the ability of the models to match the complex interactions that can occur during a barrier crash, but also on the calibration of the computer models against full-scale test data.

While computer simulation modelling is also used in crash reconstruction, there are usually larger uncertainties or unknowns – this means full-scale crash testing under controlled and known conditions represents the best source of comparative data.

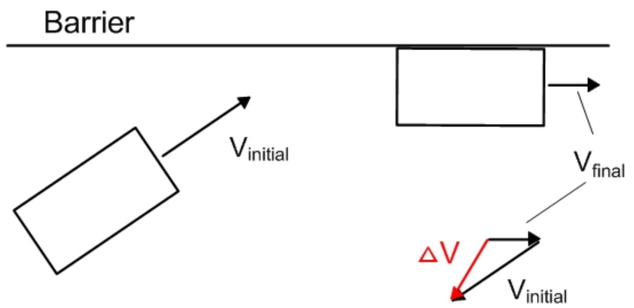
A number of different crash severity metrics are used by road safety researchers and practitioners. The more commonly used ones, and those considered relevant to this study, are described below.

2.5.6.1 Delta-V

Delta-V (ΔV) is defined as the change in velocity between pre-collision and post-collision vehicle trajectories and is described by the following equation, and shown simplistically in figure 2.2:

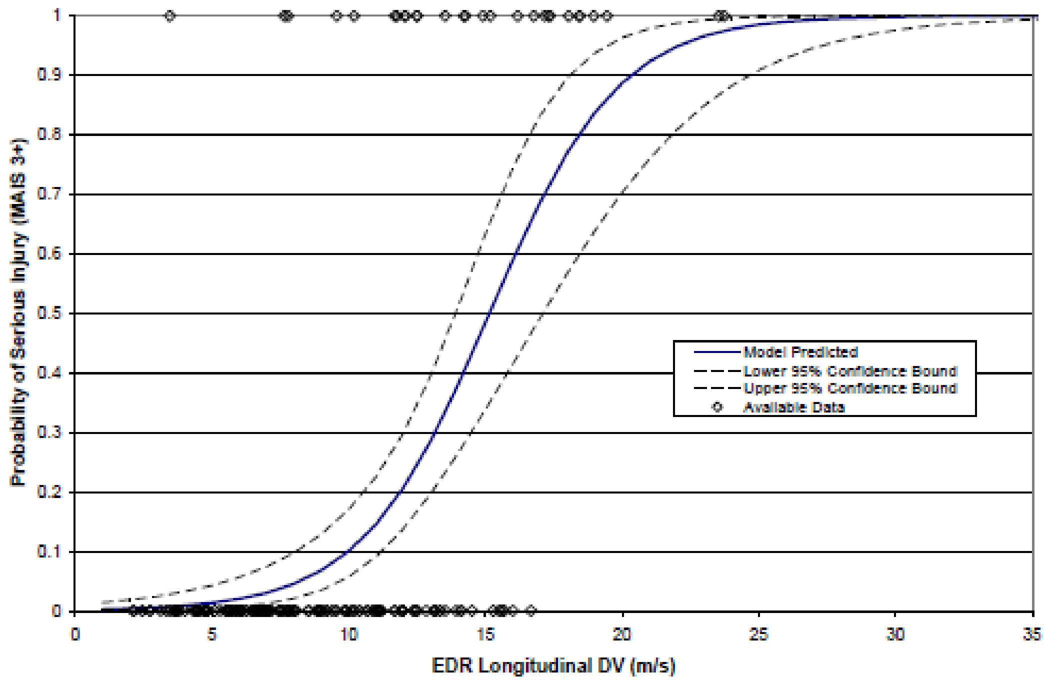
$$\Delta V = V_{final} - V_{initial} \quad \text{(Equation 2.5)}$$

Figure 2.2 Representation of Delta-V for a simple barrier crash



Delta-V emerged in the 1970s during the development of crash reconstruction analysis. It is considered by many researchers to be the best single predictor of crash severity (Shelby 2011). A study by Joksch (1993) reported that the percentage of collisions resulting in a fatality is proportional to ΔV^4, and similar studies confirmed that this provides a good approximate fit. Figure 2.3 shows a plot of the injury risk against Delta-V from Gabauer and Gabler (2006), who reported on a study of injury data for frontal collisions.

Figure 2.3 Comparison of Delta-V (DV) and injury risk (Gabauer and Gabler 2006)



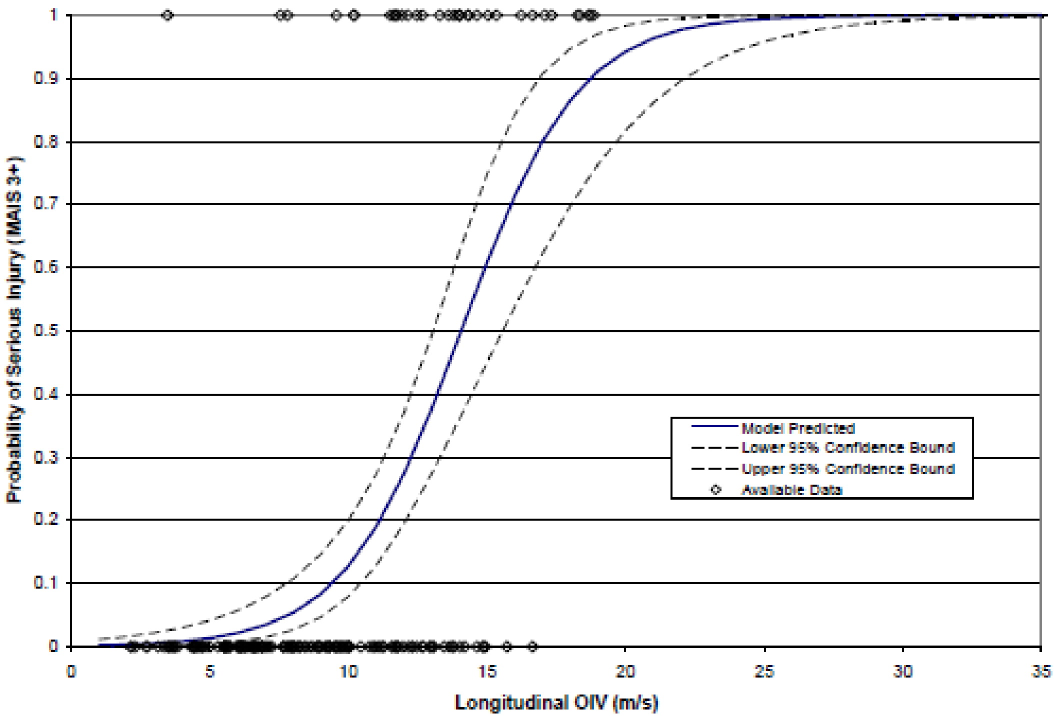
2.5.6.2 Acceleration Severity Index (ASI)

The Acceleration Severity Index, ASI, is a measure of the vehicle acceleration during impact, which is evaluated over a moving interval of 50ms and normalised with allowable accelerations in the three axes. In some cases an ASI value exceeding 1 to 1.4 is considered dangerous or lethal (Vesenjak et al 2007).

2.5.6.3 Occupant Impact Velocity (OIV)

This metric assumes that the crash severity for a vehicle occupant is related to the velocity with which the occupant strikes the vehicle interior, and the subsequent acceleration forces. It is based on a ‘flail-space’ model that allows the occupant to ‘flail’ 0.6m horizontally and 0.3m laterally, and measures the space between the occupant and the occupant compartment. According to NCHRP 350 (NCHRP 1999) and MASH (AASHTO 2009), the preferred limit for OIV is 9m/s and the maximum limit is 12m/s. Figure 2.4 shows a plot of the injury risk against OIV from Gabauer and Gabler (2006).

Figure 2.4 Comparison of OIV and injury risk (Gabauer and Gabler 2006)



Gabauer and Gabler (2006) concluded that 'the more computationally intensive OIV offers no statistically significant advantage over the simpler Delta-V crash severity metric'.

2.5.6.4 Occupant Ridedown Acceleration (ORA)

This is defined as the maximum 10ms moving average acceleration after the occupant has impacted the interior of the vehicle. The lateral and longitudinal accelerations are often treated separately to produce two separate ridedown accelerations. According to NCHRP 350 (NCHRP 1999) and MASH (AASHTO 2009), the preferred limit for ridedown acceleration, either lateral or longitudinal, is 15g and the maximum limit is 20g, where g is the acceleration due to gravity ($g = 9.81 m/s^2$).

2.5.6.5 Theoretical Head Impact Velocity (THIV)

The Theoretical Head Impact Velocity (THIV) is determined by assuming that the head of a vehicle occupant is a freely moving object, and then determining the velocity with which it strikes an interior surface of the vehicle.

2.5.6.6 Post-Impact Head Deceleration (PHD)

This is related to the THIV metric in that it is the maximum acceleration of the theoretical head after impact with the vehicle interior.

2.6 Roadside barriers – variation of height

The survey of the available literature on roadside barriers revealed very little information on the variation in barrier performance and crash severity with changes in barrier height. The most detailed information was contained in a study reported by Marzougui et al (2007b), which investigated the effect of height on the safety performance of W-beam guardrail barriers. There were three stages to the research. The first stage involved the creation of a detailed finite element model of the W-beam guardrail system. Simulations were then run to validate the computer model by comparing the results of the simulations with the full-scale crash data for the same W-beam system. In the second stage, the validated computer model was used to generate additional simulation models with guardrails of different heights. Two of these models used guardrail heights raised by 40mm and 75mm, and a further two used rail heights lowered by 40mm and 75mm. Simulations were then run using these models, and the results were compared with the original simulation model. In the third stage of the research, two full-scale crash tests were performed, one with the guardrail at the standard height, and one with the guardrail lowered by 60mm. The focus of the analysis and evaluation of the barrier performance concentrated on the physical response of the vehicle – ie whether it under-rode or over-road the barrier, and whether it remained upright through the collision. However, various crash severity metrics, including OIV and ORA, were also calculated or measured.

According to Marzougui et al (2007b) the main findings of the simulation modelling and full-scale testing were as follows:

1 There was reasonable agreement between the model simulation data and the full-scale crash test data for the standard-height guardrails in terms of the barrier deflection, OIV, ORA, vehicle roll and yaw.

2 For the standard-height and two raised-height simulation configurations, the vehicle was redirected and would be likely to meet all of the NCHRP 350 (NCHRP 1999) recommendations.

3 For the reduced-height computer simulations, the vehicle over-rode the barrier and consequently did not meet the NCHRP 350 criteria.

4 The simulation modelling suggested that guardrails that were lower than the standard height by a little as 40mm could reduce the ability of the barrier to redirect pickups and large sports utility vehicles (SUVs).

5 The full-scale crash testing largely replicated the simulation modelling, with the standard-height barrier redirecting the vehicle, but the vehicle over-rode the 60mm lower barrier and rolled upon impact.

6 The OIVs and ORAs measured during the full-scale testing were very similar for the standard-height barrier and the barrier that was 60mm lower, and in both cases these were below the preferred limits of 9m/s and 15m/s respectively, and well below the maximum limits of 12g and 20g respectively prescribed by NCHRP 350 (NCHRP 1999) and MASH (AASHTO 2009).

The AASHTO 2011 *Roadside design guide* does provide some general discussion with respect to the heights of W-beam barriers, which are the most common roadside barrier system found on the New Zealand state highway network. This states:

> *It should be recognized that overall impact performance of longitudinal barriers cannot be solely measured by a series of controlled crash tests. Many real world factors affect the in-field performance abilities of any longitudinal barrier system. Whereas new installations of strong post W-Beam guardrail should be installed according to this guidance, it is recognised that many transportation agencies have installed miles of barrier at 686mm [27in], based on previous guidance. This has resulted in barrier systems being installed at a height lower than the currently recommended heights found under the current controlled crash conditions.*

> *Many of these existing systems have and should continue to have acceptable real world performance. It is not cost-effective or practical to raise all existing guardrail to the current criteria on a highway agency's entire roadway system. However, guardrail should be upgraded as part of a reconstruction or new highway construction project. For TL-3 applications on 3R projects located on the National Highway System (NHS), highway agencies should consider raising W-beam barrier systems having an existing top rail height less than 673mm [26 ½ in].*

AASHTO 2011 also suggests that 'for TL-3 applications, agencies may elect to raise the top of the traditional strong post W-beam to 737mm [29in] ± 25mm [1in] to the top of the rail to accommodate modest pavement overlays adjacent to the rail'.

2.7 Roadside barriers – corrosion

This research project aimed to compare differences in crash severity associated with:

- existing roadside crash barriers that were too low or corroded
- new roadside crash barriers at previously untreated locations.

While the barrier height was a parameter that could be changed in the simulation modelling, the situation regarding corrosion was less clear. Our review of the available literature provided no specific information on the assessment or measurement of the effect of corrosion on barrier strength.

Discussions were held with Willie Mandeno (Technical Principal, Corrosion Engineering and Protective Coatings, Opus International Consultants) regarding corrosion of roadside barriers. These discussions suggested it is extremely difficult to assess the likely effects of corrosion on the physical strength and performance of roadside barriers, including W-beam and wire-rope barriers. In particular, it was suggested that the location (eg at posts or mid-span) and extent of any corrosion (eg perforations or general loss of cross-section) could have significantly different effects on the 'ribbon-like' behaviour expected of roadside barriers, especially the W-beam and wire-rope barriers that were the primary focus of this project.

Current barrier repair and maintenance practices in New Zealand also typically only suggest that barrier elements should be in good condition, and not weakened by damage or corrosion. Accordingly, it was not considered appropriate to try to address the corrosion issue through the computer simulation modelling part of this project. However, several recommendations regarding corrosion have been included later in the report, both in terms or current practice and for further research.

3 Computer simulation modelling – validation

This research was based on using computer simulation modelling to quantify the effects of barrier height on crash severity for selected barrier types (W-beam and wire rope), vehicles (including types, speeds and travel paths), and physical contexts (curvature, roadside slope). This modelling used PC-Crash (Version 9) modelling software. A description of PC-Crash and a list 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).

However, for this project it was also necessary to validate the modelling of roadside barriers and barrier crashes using PC-Crash against full-scale crash data. Accordingly, the literature search was used to obtain full-scale data that provided information that could be compared with outputs from PC-Crash. This is described in the following sections.

3.1 Full-scale crash data

Our search for full-scale crash data showed that while crash tests were often carried out according to the requirements of NCHRP 350 (NCHRP 1999), the information reported in the literature varied considerably. However, we considered that there was sufficient data available to assess the agreement of PC-Crash with the full-scale data. The most commonly reported metrics were: the physical response of the vehicle (eg contained and redirected); the deflection of the barrier; and the OIV. Table 3.1 lists the selected full-scale data.

It can be seen from table 3.1 that the OIV values listed are generally highest for the rigid concrete barriers, lower for the semi-rigid W-beam barriers, and lower still for the flexible wire-rope barriers. This is in general agreement with the injury ratios in table 2.2 and the crash rates in table 2.3.

Table 3.1 Full-scale barrier crash data

Variable	Barrier type													
	Concrete double-sided F			W-beam						Wire rope				
	Hammonds & Troutbeck 2012			Hammonds & Troutbeck 2012			Marzougui et al 2007b		Faller et al 2007	Hammonds & Troutbeck 2012			MIROS 2012	
Height (mm)	810			730			700	650	706	720			720	720
Post spacing (m)	N/A			2.0			1.9	1.9	1.9	2.5			1.0	2.4
Vehicle[a]	(a)	(b)	(c)	(a)	(b)	(c)	(d)	(d)	(e)	(a)	(b)	(c)	Small car	Medium car
Vehicle weight (kg)	1100	1800	2500	1100	1800	2500	2000	2000	2270	1100	1800	2500	753	1500
Speed (km/h)	100	100	100	100	100	100	100	100	100	100	100	100	113	113
Angle (°)	20	20	20	20	20	20	25	25	26	20	20	20	20	20
Physical response[b]	C/R	C/R	C/R roll	C/R	C/R	C/R roll	C/R	Rode over & rolled	C/R	C/R	C/R	C/R P/Y	C/R	C/R
Deflection (m)	0	0	0	0.45	0.7	0.8	0.7	Rupture	0.845	1.0	1.9	2.0	0.86	1.7
Contact length (m)	-	-	-	6.1	9.1	10	-	-	-	12.5	27.2	24.1	-	-
OIV lateral (m/s)	7.1	6.5	7	5.7	3.6	3.9	-	-	3.99	4.6	3.2	3.5	-	-
OIV longitudinal (m/s)	3.3	3.1	3.4	3.4	4.8	4.1	-	-	5.38	2.8	2.5	2.1	-	-
OIV, net (m/s)	7.83	7.20	7.78	6.64	6.0	5.66	7.1	7.5	6.7	5.39	4.06	4.08	-	-
Maximum lateral ORA (m/s^2)	11.9	10.8	11.3	11.4	12.6	7.7	-	-	6.61	11.5	4.3	3.8	-	-
Maximum longitudinal ORA (m/s^2)	5.7	2.5	6.6	16.1	10.3	7.3	-	-	6.92	5.5	2.8	2.9	-	-
ORA, net (m/s^2)	-	-	-	-	-	-	9.16	10.05	9.57	-	-	-	-	-
Maximum roll angle (°)	-	-	-	-	-	-	13.5	40.1	-	-	-	-	-	-
Maximum yaw angle (°)	-	-	-	-	-	-	23.4	42.8	-	-	-	-	-	-
Test label for comparisons with simulation data	A	B	C	D	E	F	G	H	I	J	K	L	M	N

a) Vehicles: (a) Daihatsu Charade, (b) Holden Commodore, (c) Toyota Landcruiser, (d) Chevrolet 2500, (e) Dodge Ram 1500

b) Physical response: C = Contained, R = Redirected, P = Pitch, Y = Yaw, - = not given

3.2 Computer simulation modelling – background

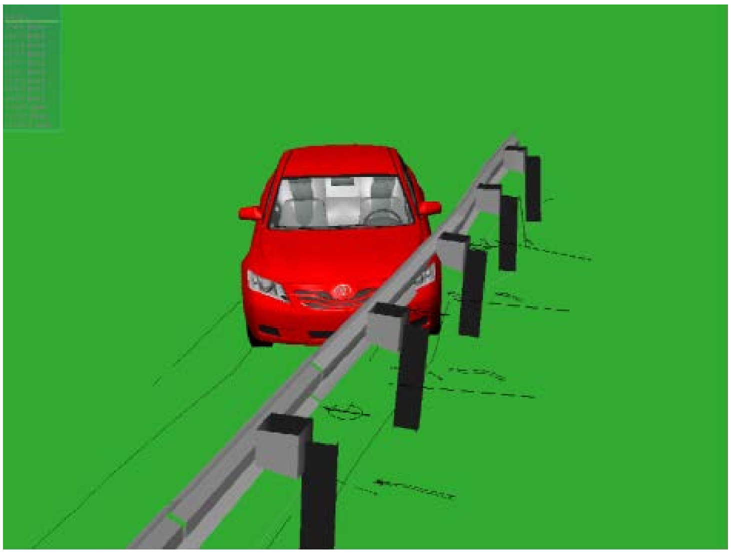
The full-scale crash data listed in table 3.1 is the end result of real-world simulations under more or less controlled conditions. In computer simulation modelling, the initial parameters used to set up the crash simulation will define the outcome of the crash. If these parameters are kept the same, the simulation will be repeatable and the results will be the same every time the same simulation is run. When the simulation modelling is being used for crash reconstruction, as was intended here, the outcome is known and so some of the input parameters can be varied until the simulation matches the real-world outcome reasonably well. This was the aim of this validation process.

3.3 Computer simulation modelling – PC-Crash

The software package used for the modelling was PC-Crash, Version 9 (3D). This is an internationally recognised 3-dimensional vehicle crash and trajectory simulation package widely used by police, civilian crash investigators and analysts. A description of PC-Crash and its features is given in appendix A.

For each of the full-scale crash tests listed in table 3.1, separate simulation models were created in PC-Crash. Flat test surfaces were created and assigned a surface friction value consistent with a dry surface. The specific vehicles were imported from the PC-Crash vehicle databases, and centre of gravity heights were assigned to them. These vehicle models accurately model: the vehicle dimensions; mass; mass distribution; moments of inertia in pitch, roll and yaw; steering response; tyre properties; location and mass of passengers; suspension properties; and brake forces. Models of the different barriers were then created as interlinked elements, which modelled the barrier dimensions and physical properties as accurately as practical within the software system. These models for the W-beam and wire-rope barriers were initially developed by Dr Shane Richardson of Delta-V Experts in Australia. The vehicles were positioned at the appropriate angle to the barriers and assigned the appropriate test speed, and the simulations were run. Figure 3.1 shows an image from a barrier simulation setup. Simulations were repeated, with some changes to the barrier modelling to provide a reasonable match to the measured full-scale deflections. Output data from the simulation models was tabulated, including the Delta-V values.

Figure 3.1 PC-Crash – barrier simulation model



3.4 Simulation results and comparison with full-scale data

Table 3.2 lists the corresponding and relevant data from the PC-Crash simulations. Figure 3.2 compares the full-scale barrier deflections with the corresponding simulation barrier deflections. Figure 3.3 compares the full-scale net OIVs with the Delta-V values from the simulation modelling.

These results show that with a correlation coefficient (R^2) of 0.98, the simulation deflections agreed reasonably well with the measured crash test data. They also show that the simulation crash severity metric, Delta-V also correlated reasonably well (R^2 = 0.84) with the OIV measured in the actual crash tests. This was considered to be a good enough agreement to proceed with the simulation programme. It also meant that the relationship between Delta-V and the probability of serious injury shown in figure 2.2 could provide an approximate assessment of the probability of serious injury in a barrier crash.

Table 3.2 PC-Crash simulation data

Variable	Barrier type													
	Concrete double-sided F			W-beam						Wire rope				
	Hammonds & Troutbeck 2012			Hammonds & Troutbeck 2012			Marzougui et al 2007b		Faller et al 2007	Hammonds & Troutbeck 2012			MIROS 2012	
Height (mm)	810			730			700	650	706	720			720	720
Post spacing (m)	N/A			2.0			1.9	1.9	1.9	2.5			1.0	2.4
Vehicle[a]	(a)	(b)	(c)	(a)	(b)	(c)	(d)	(d)	(e)	(a)	(b)	(c)	Small car	Medium car
Vehicle weight (kg)	1100	1800	2500	1100	1800	2500	2000	2000	2270	1100	1800	2500	753	1500
Speed (km/h)	100	100	100	100	100	100	100	100	100	100	100	100	113	113
Angle (°)	20	20	20	20	20	20	25	25	26	20	20	20	20	20
Physical response[b]	C/R	C/R	C/R roll	C/R	C/R	C/R	C/R	C/R	C/R	C/R	C/R	C/R	C/R	C/R
Deflection (m)	0.04	0.06	0.1	0.55	0.8	1.0	1.0	0.9	0.86	1.2	2.2	2.6	0.9	2.0
Contact length (m)	-	-	-	8	11	12.5	-	-	-	17	30	25	-	-
Delta-V (km/h)	29.4	30.6	27.5	26.4	25.5	25.0	30.1	31.2	21.6	14.4	9.5	7.8	12.9	11.6
Maximum yaw rate (rad/s)	3.7	2.3	2.5	4.2	3.3	3.2	-	-	3.7	4.1	2.6	2.5	3.6	3.0
Maximum roll rate (rad/s)	0.80	0.52	2.90	0.50	0.27	0.50	-	-	0.45	0.46	0.35	0.37	0.53	0.28
Maximum pitch rate (rad/s)	0.26	0.16	2.0	0.03	0.02	0.02	-	-	0.015	0.02	0.02	0.02	0.01	0.01
Maximum roll angle (°)	-	-	-	-	-	-	11	12	-	-	-	-	-	-
Maximum yaw angle (°)	-	-	-	-	-	-	26.1	26.2	-	-	-	-	-	-
Test label	A	B	C	D	E	F	G	H	I	J	K	L	M	N

a) Vehicles: (a) Daihatsu Charade, (b) Holden Commodore, (c) Toyota Landcruiser, (d) Chevrolet 2500, (e) Dodge Ram 1500

b) Physical response: C = Contained, R = Redirected, P = Pitch, Y = Yaw, - = not given

Figure 3.2 Comparison of full-scale and PC-Crash simulation deflections

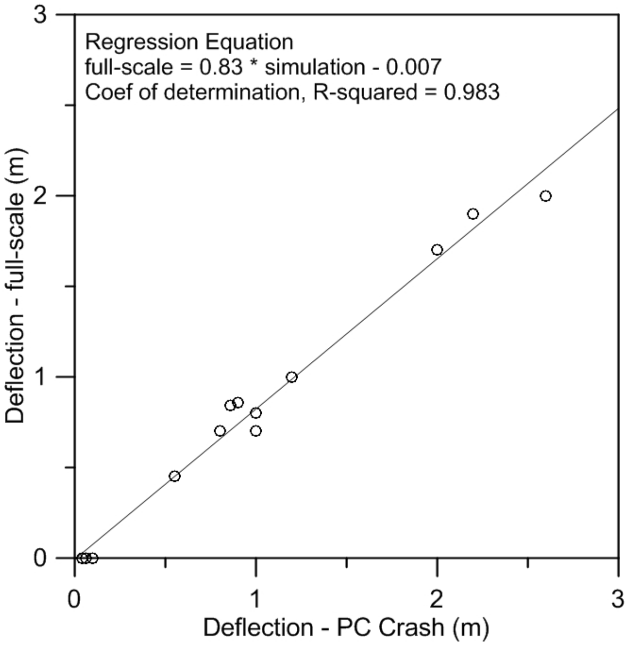
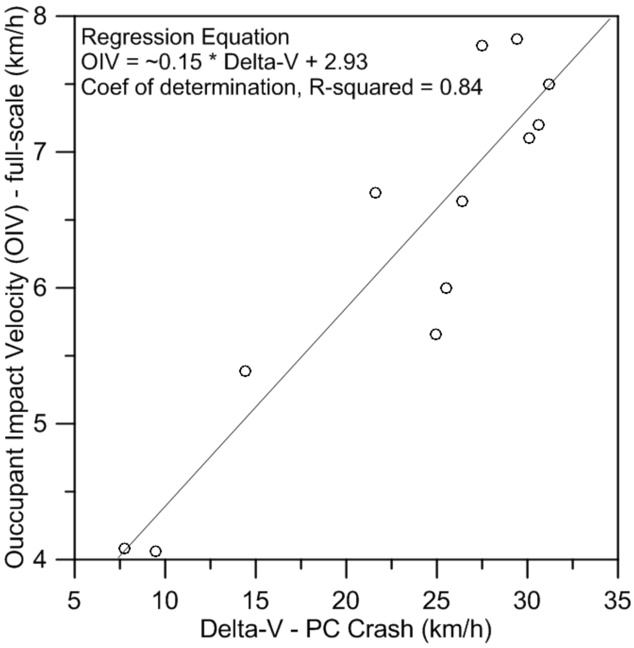


Figure 3.3 Comparison of full-scale OIV and PC-Crash Delta-V crash severity metrics



4 Computer simulation modelling programme

The computer simulation modelling programme was developed to cover a reasonable variety of crash scenarios. Rather than carrying out a full matrix of simulations covering all combinations of variables, the programme was based on an evolutionary process, with decisions being made on the basis of results from earlier simulations.

The following two different barrier types were chosen:

- A standard W-beam (strong wooden post with wooden blockouts) barrier, similar to that shown in figure 2.1(b), 710mm to the top of the rail, with a rail 310mm high, with four different variations:
  - the standard height barrier described
  - a barrier 50mm higher than the standard base height
  - a barrier 100mm lower than the standard base height
  - a barrier 200mm lower than the standard base height.
- A wire-rope barrier similar to that shown in figure 2.1(a), ~690mm to the top wires and ~590mm to the bottom wires, with four different variations:
  - the standard height barrier described
  - a barrier 50mm higher than the standard base height
  - a barrier 90mm lower than the standard base height
  - a barrier 190mm lower than the standard base height.

These height differences were chosen as being more extreme than the barrier-height deficiencies reported in section 1.3.

Three vehicles were chosen as covering a range of vehicle types. These were three of the vehicles for which full-scale test results were reported earlier:

- Daihatsu Charade (1100kg)
- Holden Commodore (1800kg)
- Toyota Landcruiser (2500kg).

Two road sections were chosen - a straight section and a low-radius corner section, to cover two significantly different extremes of curvature. Two types of collision scenario were then chosen for modelling:

- a low-angle ‘grazing’ approach, which represented the maximum likely longitudinal velocity impact with the barrier
- a maximum-rate turning scenario, which represented the maximum likely lateral velocity impact with the barrier.

The simulation modelling, which focused initially on the W-beam barrier configurations, is discussed in the following sections.

4.1 Simulation modelling – straight-road section

A 3D road section 100m long, with flat (0%) gradient and lanes 3.75m wide, sealed shoulders 0.25m wide, a crossfall of 4%, and flat shoulders, was 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. Each of the three vehicles was imported and placed pointing directly along the road. The different barrier-height combinations were then positioned parallel to the road 0.75m from the edge of the seal. This barrier offset was used for all of the straight-road simulations. This gave a total of 12 separate simulation files.

4.1.1 'Drift-off' simulations and results – W-beam

The first series of simulations were based on what we have called a 'drift-off' scenario, where a driver may become unconscious or fall asleep, drift off the road as the vehicle is affected by the road geometry (in this case the crossfall), and eventually strike the barrier in a grazing fashion. The simulations were run with initial vehicle speeds of 100km/h, 120km/h and 140km/h, giving a total of 36 simulation runs. The simulations were initially run for the W-beam barrier. Barrier deflection and maximum Delta-V values were recorded for each simulation, together with the angle at which the barrier was struck and the physical response of the vehicle. This data is listed in table 4.1.

Table 4.1 Results – drift off scenario into W-beam barrier

Vehicle	Barrier height (mm)	Height variation (mm)	Initial speed (km/h)	Physical response	Impact angle (°)	Deflection (m)	Delta-V (km/h)
Daihatsu	710	Standard	100	Slides along barrier	0.8	0.06	0.8
			120	Slides along barrier	0.8	0.06	0.9
			140	Slides along barrier	0.8	0.05	1.7
	760	50mm higher	100	Slides along barrier	0.8	0.06	0.8
			120	Slides along barrier	0.8	0.06	0.9
			140	Slides along barrier	0.8	0.06	1.3
	610	100mm lower	100	Slides along barrier	0.8	0.06	0.8
			120	Slides along barrier	0.8	0.06	0.9
			140	Slides along barrier	0.8	0.06	1.2
	510	200mm lower	100	Slides along barrier	0.8	0.06	0.8
			120	Slides along barrier	0.8	0.06	0.9
			140	Slides along barrier	0.8	0.06	1.2

Vehicle	Barrier height (mm)	Height variation (mm)	Initial speed (km/h)	Physical response	Impact angle (°)	Deflection (m)	Delta-V (km/h)
Commodore	710	Standard	100	Slides along barrier	0.75	0.06	0.7
			120	Slides along barrier	0.75	0.05	0.8
			140	Slides along barrier	0.75	0.05	1.2
	760	50mm higher	100	Slides along barrier	0.75	0.05	0.7
			120	Slides along barrier	0.75	0.05	0.8
			140	Slides along barrier	0.75	0.05	1.2
	610	100mm lower	100	Slides along barrier	0.75	0.05	0.7
			120	Slides along barrier	0.75	0.05	0.8
			140	Slides along barrier	0.75	0.05	1.2
	510	200mm lower	100	Slides along barrier	0.75	0.06	0.7
			120	Slides along barrier	0.75	0.06	0.8
			140	Slides along barrier	0.75	0.06	1.2
Landcruiser	710	Standard	100	Slides along barrier	0.75	0.06	0.7
			120	Slides along barrier	0.75	0.06	0.9
			140	Slides along barrier	0.75	0.06	0.9
	760	50mm higher	100	Slides along barrier	0.75	0.05	0.7
			120	Slides along barrier	0.75	0.05	0.9
			140	Slides along barrier	0.75	0.05	0.9
	610	100mm lower	100	Slides along barrier	0.75	0.06	0.7
			120	Slides along barrier	0.75	0.06	0.9
			140	Slides along barrier	0.75	0.06	0.9
	510	200mm lower	100	Slides along barrier	0.75	0.06	0.7
			120	Slides along barrier	0.75	0.06	0.9
			140	Slides along barrier	0.75	0.06	0.9

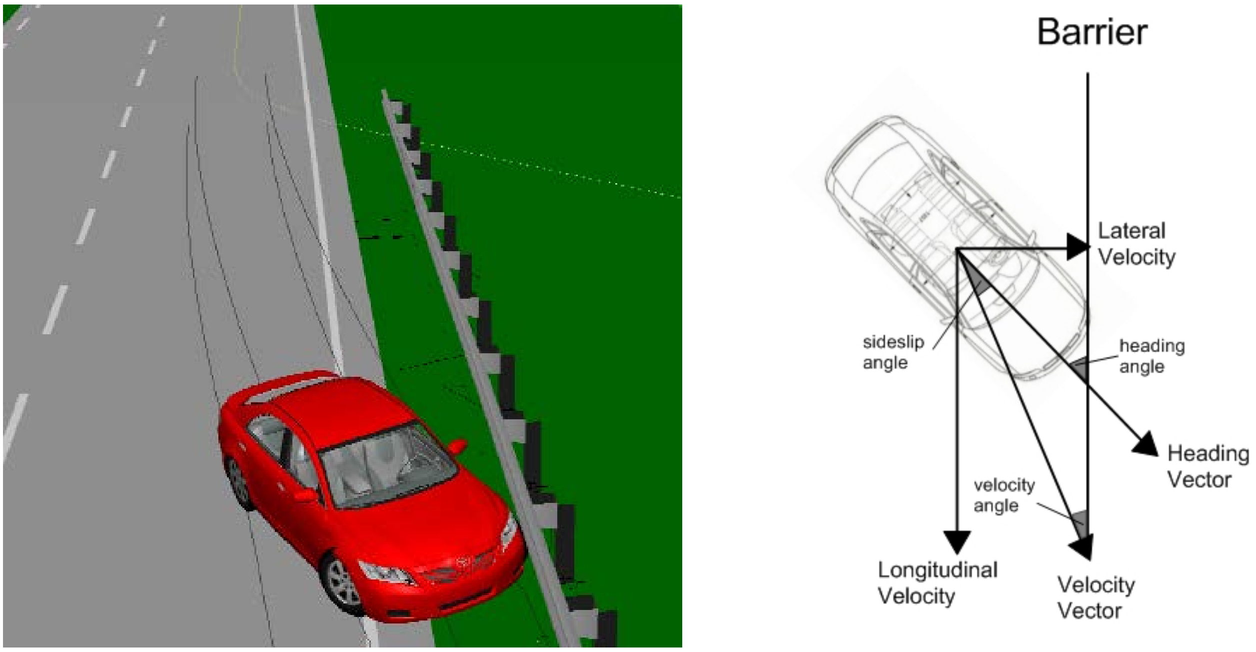
The results show that, as expected for grazing into the W-beam barrier, the impact angles were very low, as were the deflections and the Delta-V values. There was a very marginal reduction in Delta-V for the heavier Toyota Landcruiser, but no significant difference in the Delta-V values between the different barrier heights. This is perhaps to be expected given the low impact angles and the consequently low lateral impact forces. Given the low Delta-V values, it was considered that performing the drift-off simulations for the wire-rope barriers would not show anything significantly different, and that efforts should be concentrated on simulation configurations for more extreme impacts.

4.1.2 Maximum-rate turn simulations – W-beam barrier

The second series of simulations used what we have called a ‘maximum-turn’ scenario into a W-beam barrier using a ‘follow point path’. 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 path, it will slide or roll depending on 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 (CoG), or any of the four wheels.

In this case the same flat road sections, barrier models and barrier offsets that were used for the drift-off scenario were employed. Again, wet surface friction values were applied. Each of the test vehicles was then 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 sharp 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. The turn path was chosen so that in the turn, the vehicle would begin to slide both laterally and longitudinally before hitting the barrier. Figure 4.1 shows an example of this, with the vehicle trying to track the follow point path (the dotted yellow line veering off the side of the road) but sliding, as the wheel tracks show.

Figure 4.1 Vehicle dynamics – maximum-rate turn



As for the drift-off scenario, the simulations were then run with initial vehicle speeds of 100km/h, 120km/h and 140km/h for the four different height barriers, again giving a total of 36 simulation runs. Barrier deflection and maximum Delta-V values were recorded for each simulation, together with the angle at which the barrier was struck and the physical response of the vehicle. This data is listed in table 4.2 and the results are presented in figure 4.2, together with the range of Delta-V values for straight no-sliding impacts from the validation tests listed in table 3.2 for the same vehicles.

Table 4.2 Results – maximum-turn scenario into W-beam barrier

Vehicle	Barrier height (mm)	Height variation (mm)	Initial speed (km/h)	Physical response	Impact angle (°)	Deflection (m)	Delta-V (km/h)
Daihatsu	710	Standard	100	Slides along barrier	17.1	0.11	10.1
			120	Slides along barrier	16.2	0.14	9.5
			140	Slides along barrier	17.3	0.14	9.9
	760	50mm higher	100	Slides along barrier	17.3	0.12	10.3
			120	Slides along barrier	16.5	0.16	9.4
			140	Slides along barrier	17.0	0.16	10.2
	610	100mm lower	100	Slides along barrier	17.1	0.12	10.1
			120	Slides along barrier	16.9	0.12	10.3
			140	Slides along barrier	16.9	0.14	10.0
	510	200mm lower	100	Slides along barrier	17.1	0.12	10.0
			120	Slides along barrier	16.9	0.12	10.4
			140	Slides along barrier	16.9	0.14	9.9
Commodore	710	Standard	100	Slides along barrier	14.2	0.20	8.4
			120	Slides along barrier	14.2	0.18	8.8
			140	Slides along barrier	14.6	0.16	8.6
	760	50mm higher	100	Slides along barrier	14.4	0.20	8.9
			120	Slides along barrier	14.2	0.16	8.7
			140	Slides along barrier	14.4	0.16	8.4
	610	100mm lower	100	Slides along barrier	14.0	0.20	8.3
			120	Slides along barrier	14.2	0.17	8.6
			140	Slides along barrier	14.2	0.16	8.5
	510	200mm lower	100	Slides along barrier	14.4	0.19	8.7
			120	Slides along barrier	14.4	0.17	9.0
			140	Slides along barrier	14.5	0.15	8.5
Landcruiser	710	Standard	100	Slides along barrier	15.2	0.25	8.9
			120	Slides along barrier	14.5	0.23	8.6
			140	Slides along barrier	15	0.20	8.4
	760	50mm higher	100	Slides along barrier	14.8	0.25	8.6
			120	Slides along barrier	14.7	0.20	8.8
			140	Slides along barrier	15.1	0.20	8.3
	610	100mm lower	100	Slides along barrier	15.2	0.25	8.9
			120	Slides along barrier	14.5	0.20	8.6
			140	Slides along barrier	15.0	0.18	8.4
	510	200mm lower	100	Slides along barrier	14.8	0.25	8.7
			120	Slides along barrier	14.7	0.19	8.9
			140	Slides along barrier	15.0	0.17	8.3

Figure 4.2 Delta-V data for maximum turn

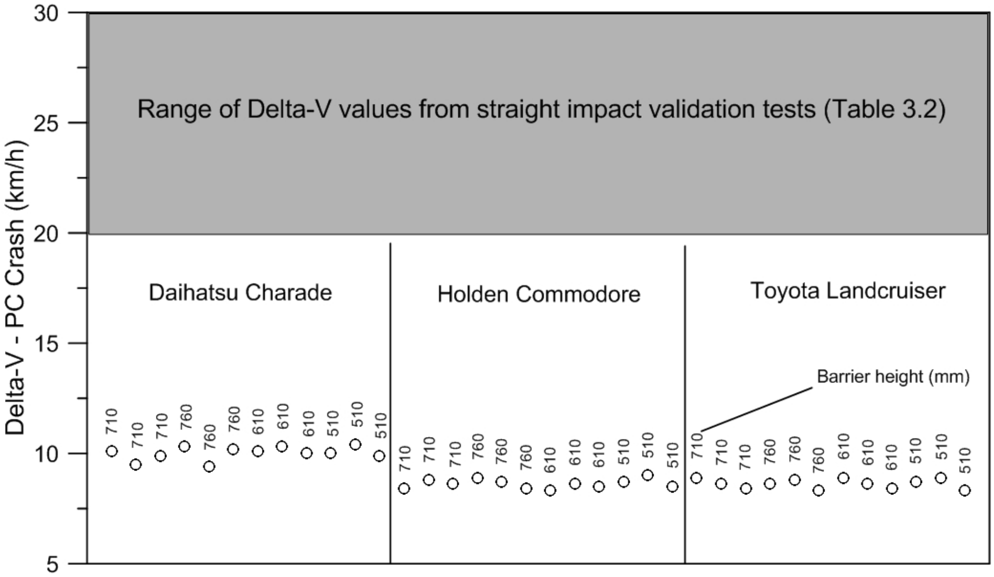


Table 4.2 and figure 4.2 show that the Delta-V values and barrier deflections for what are essentially sliding impacts into the W-beam barriers were, as expected, significantly lower than those found during the straight-line no-sliding impacts in the validation simulations (refer to table 3.2). This was partly because of the somewhat lower impact angles, 14°-17.3° compared with 20°-26°, and partly because the vehicle was sliding both laterally and longitudinally. The values were also slightly higher for the lighter car than for the two heavier vehicles. Analysis of the variation of Delta-V with the barrier height showed a small average increase as the barrier height reduced for the lighter car (Daihatsu Charade), but minimal differences for the two heavier vehicles.

4.1.3 Straight non-sliding impacts – W-beam barrier

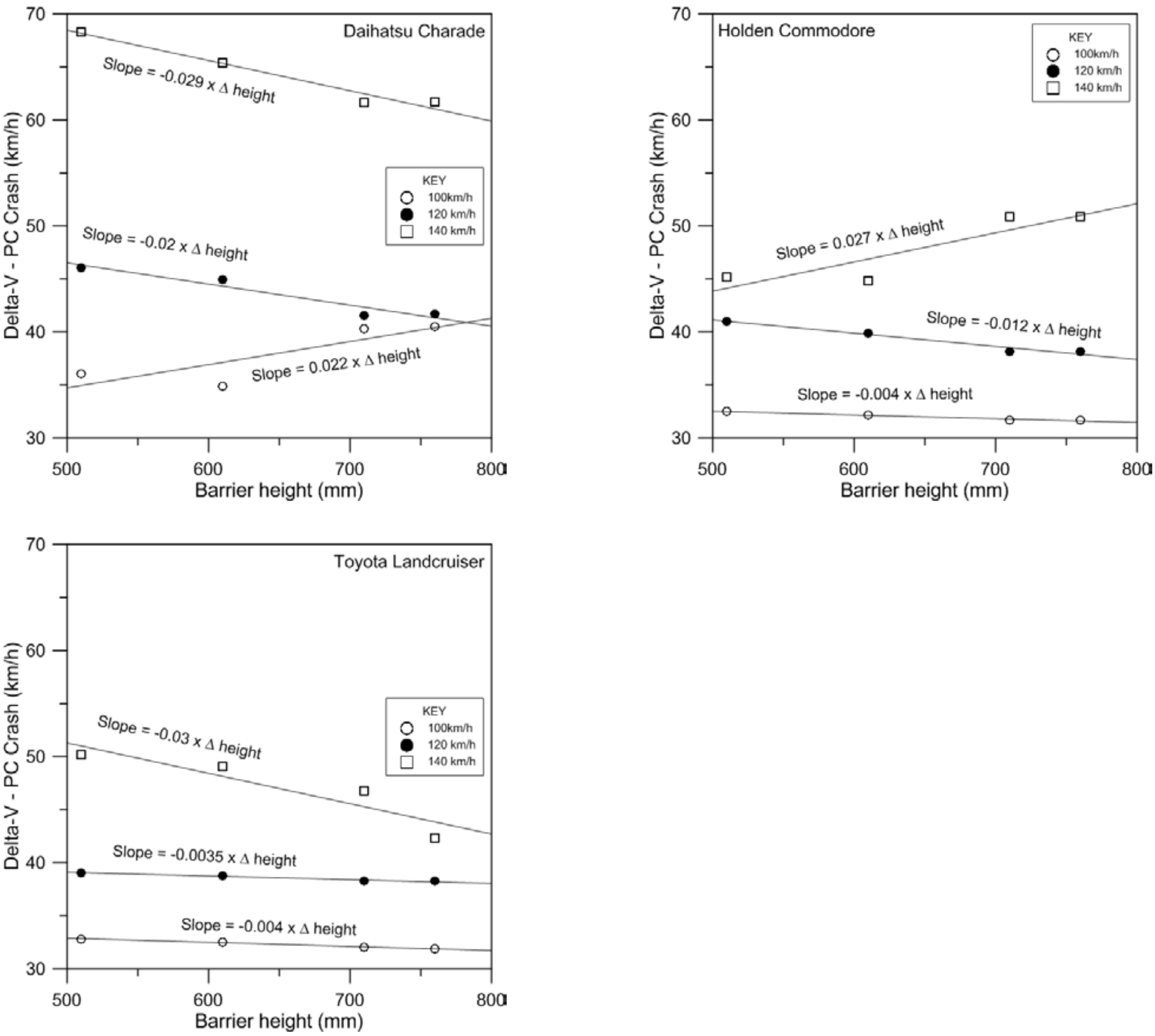
Having found only small differences in Delta-V between the different vehicles and different barrier heights for vehicles sliding both laterally and longitudinally, it was decided to essentially repeat the straight-line non-sliding impact tests from the validation exercise for the three test speeds of 100km/h, 120km/h and 140 km/h, but for the higher impact angle of 25°. Again, these simulations were run for wet road conditions. Table 4.3 lists the measured barrier deflections and the Delta-V values for these tests.

Table 4.3 Results – straight-line non-sliding impacts into W-beam barrier

Vehicle	Barrier heigh (mm)	Height variation (mm)	Initial speed (km/h)	Physical response	Deflection (m)	Delta-V (km/h)
Daihatsu	710	Standard	100	Contained/redirected	0.4	40.3
			120	Contained/redirected	0.5	41.6
			140	Contained/redirected	0.55	61.6
	760	50mm higher	100	Contained/redirected	0.38	40.5
			120	Contained/redirected	0.5	41.7
			140	Contained/redirected	0.6	61.7
	610	100mm lower	100	Contained/redirected	0.45	34.9
			120	Contained/redirected	0.48	45.0
			140	Contained/redirected	0.54	65.4
	510	200mm lower	100	Contained/redirected	0.42	36.1
			120	Contained/redirected	0.5	46.1
			140	Contained/redirected	0.57	68.3
Commodore	710	Standard	100	Contained/redirected	0.57	31.7
			120	Contained/redirected	0.64	38.1
			140	Contained/redirected	0.8	50.8
	760	50mm higher	100	Contained/redirected	0.56	31.7
			120	Contained/redirected	0.7	38.2
			140	Contained/redirected	0.78	50.9
	610	100mm lower	100	Contained/redirected	0.63	32.2
			120	Contained/redirected	0.72	39.8
			140	Contained/redirected	0.78	44.8
	510	200mm lower	100	Contained/redirected	0.6	32.5
			120	Contained/redirected	0.74	41.0
			140	Contained/redirected	0.8	45.1
Landcruiser	710	Standard	100	Contained/redirected	0.74	32.0
			120	Contained/redirected/yaws	0.8	38.3
			140	Contained/redirected/yaws	1.1	46.8
	760	50mm higher	100	Contained/redirected	0.75	31.9
			120	Contained/redirected	0.9	38.3
			140	Contained/redirected	1.12	42.3
	610	100mm lower	100	Contained/redirected	0.8	32.6
			120	Contained/redirected	0.96	38.8
			140	Contained/redirected	1.06	49.0
	510	200mm lower	100	Contained/redirected	0.81	32.8
			120	Contained/redirected	0.95	39.1
			140	Contained/redirected	1.08	50.2

As expected, these Delta-V and barrier deflection values were more consistent with those for the W-beam barriers from the validation study listed in table 3.2. In addition, as for the maximum-turn tests, the Delta-V values were higher for the lighter Daihatsu Charade than for the heavier Holden Commodore and Toyota Landcruiser. To assess if there was any variation in the Delta-V data between the different barrier heights, figure 4.3 plots the Delta-V data against the barrier heights separately for each of the three vehicles.

Figure 4.3 Variation of Delta-V with barrier height – straight-line non-sliding into W-beam



The slopes on these graphs show that there did appear to be some consistent variations with change in barrier height, although these were not totally consistent between the different vehicles and speeds. This may have been due to differences in the vehicle shapes and how they interacted with the barrier. Table 4.4 lists the changes in Delta-V with barrier height and the corresponding changes in the probability of serious injury according to the relationship shown in figure 2.2 for a representative reduction in barrier height of 50mm. The changes in the probability of serious injury can effectively be considered to be related to the overall changes in crash severity.

Table 4.4 Variation of Delta-V with barrier height – straight-line non-sliding into W-beam

Vehicle	Change in Delta-V/ change in barrier height (Delta-V/mm)			Change in probability of serious injury for 50mm change in barrier height from the standard height of 710mm		
	100km/h	120km/h	140km/h	100km/h	120km/h	140km/h
Daihatsu Charade	0.022	-0.020	-0.029	-0.0165	0.0035	0.0112
Holden Commodore	-0.004	-0.012	0.027	0.0080	0.0081	0.0055
Toyota Landcruiser	-0.004	-0.0035	-0.03	0.0121	-0.0171	0.0384

Taking the greatest change in Delta-V with barrier height, this would suggest a maximum increase in the probability of serious injury of around 0.038 for each 50mm reduction in barrier height.

4.1.4 Straight non-sliding impacts – wire-rope barrier

Having found some differences in Delta-V between the different vehicles and different barrier heights for straight non-sliding impacts into the W-beam barrier, it was decided to repeat these tests for the wire-rope barrier. Accordingly, the three test vehicles were 'driven' into the wire-rope barrier models for the three test speeds of 100km/h, 120km/h and 140 km/h, but for the higher impact angle of 25°. Again, these simulations were run for wet road conditions. Table 4.5 lists the measured barrier deflections and the Delta-V values for these tests. Please note that while we are generally confident about the deflection and Delta-V values, and the initial physical response of the vehicle, we have some reservations about the motion of the vehicle once the barrier had reached maximum deflection. Full-scale barrier test videos often show the elasticity in the barrier system causing the vehicle to be redirected back off the barrier out toward the trafficked lane. The PC-Crash simulations do not show this happening to the same degree. Nevertheless, we believe that the PC-Crash simulations do offer a reasonable measure of the crash severity through the initial impact Delta-V data.

Table 4.5 Results – straight-line non-sliding impacts into wire-rope barrier

Vehicle	Barrier height (mm)	Height variation (mm)	Initial speed (km/h)	Physical response	Deflection (m)	Delta-V (km/h)
Daihatsu	690	Standard	100	Contained/redirected	1.6	14.7
			120	Contained/redirected	1.9	33.1
			140	Contained/redirected	2.3	38.9
	740	50mm higher	100	Contained/redirected	1.55	12.7
			120	Contained/redirected	1.8	32.4
			140	Contained/redirected	2.25	38.3
	600	90mm lower	100	Contained/redirected	1.6	15.2
			120	Contained/redirected	1.95	32.7
			140	Contained/redirected	2.4	40.5
	500	190mm lower	100	Contained/redirected	1.65	19.4
			120	Contained/redirected	2.0	35.1
			140	Contained/redirected	2.35	40.6

Vehicle	Barrier height (mm)	Height variation (mm)	Initial speed (km/h)	Physical response	Deflection (m)	Delta-V (km/h)
Commodore	690	Standard	100	Contained/redirected	2.3	18.3
			120	Contained/redirected	2.7	22.6
			140	Contained/redirected	3.2	31.3
	740	50mm higher	100	Contained/redirected	2.2	21.1
			120	Contained/redirected	2.5	19.8
			140	Contained/redirected	3.3	30.8
	600	90mm lower	100	Contained/redirected	2.2	19.5
			120	Contained/redirected	2.85	25.4
			140	Contained/redirected	3.3	32.5
	500	190mm lower	100	Contained/redirected	2.25	20.0
			120	Contained/redirected	2.9	25.5
			140	Contained/redirected	3.45	31.9
Landcruiser	690	Standard	100	Contained/redirected	2.7	11.2
			120	Contained/redirected	3.5	17.0
			140	Contained/redirected	3.9	26.6
	740	50mm higher	100	Contained/redirected	2.8	11.2
			120	Contained/redirected	3.4	16.8
			140	Contained/redirected	4.2	26.5
	600	90mm lower	100	Contained/redirected	3.0	12.8
			120	Contained/redirected	3.5	17.2
			140	Contained/redirected	4.3	26.1
	500	190mm lower	100	Contained/redirected	2.9	12.8
			120	Contained/redirected	3.4	20.8
			140	Contained/redirected	4.1	29.1

As expected, these Delta-V and barrier deflection values were more consistent with those for the wire-rope barriers from the validation study listed in table 3.2. Also, as for the maximum-turn simulation tests, the Delta-V values were higher for the lighter Daihatsu Charade than for the heavier Holden Commodore and Toyota Landcruiser. To identify any variation in the Delta-V data between the different barrier heights, figure 4.4 plots the Delta-V data against the barrier heights separately for each of the three vehicles.

Figure 4.4 Variation of Delta-V with barrier height – straight-line non-sliding into wire rope

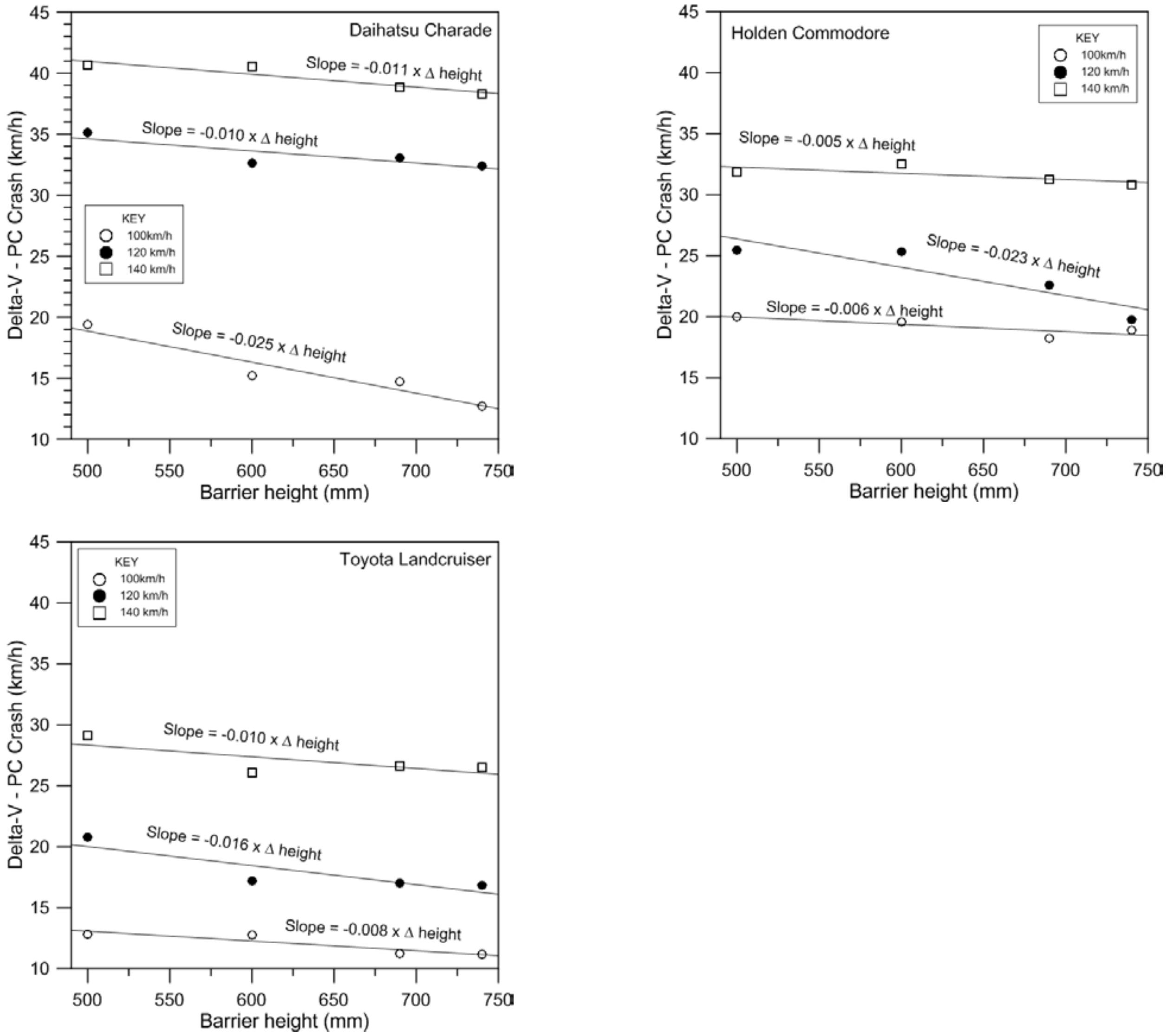


Figure 4.4 shows some consistent variations in the Delta-V data with change in barrier height, although as for the W-beam barrier, the effects differed somewhat between the different vehicles and speeds. Table 4.6 lists the changes in Delta-V with barrier height and the corresponding changes in the probability of serious injury according to the relationship shown in figure 2.2 for a representative reduction in barrier height of 50mm. The changes in the probability of serious injury can effectively be considered to be related to the overall changes in crash severity.

Table 4.6 Variation of Delta-V with barrier height – straight-line non-sliding into wire rope

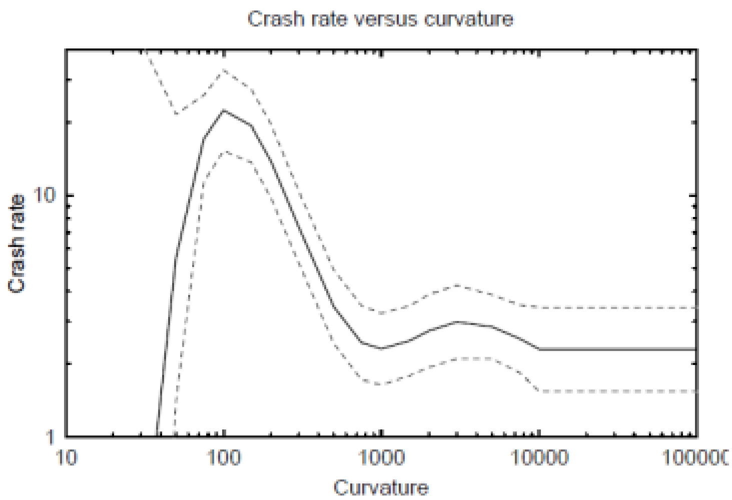
Vehicle	Change in Delta-V/ change in barrier height (Delta-V/mm)			Change in probability of serious injury for 50mm change in barrier height from the standard height of 690mm		
	100km/h	120km/h	140km/h	100km/h	120km/h	140km/h
Daihatsu Charade	-0.025	-0.010	-0.011	0.0011	0.0008	0.0002
Holden Commodore	-0.006	-0.023	-0.005	0.0026	0.0034	0.0003
Toyota Landcruiser	-0.008	-0.016	-0.010	0.0057	0.0061	0.0023

Taking the greatest change in Delta-V with barrier height, this would suggest a maximum increase in the probability of serious injury of around 0.006 for each 50mm reduction in barrier height.

4.2 Simulation modelling – curved road section

The previous section described the modelling, simulation testing and results for crashes into W-beam and wire-rope barriers. The next stage of the simulation modelling was to examine the effect of being on a curved road section, starting with the W-beam barriers. This firstly involved the choice of road geometry for the base simulation model, and this was made by looking at the variation of crash rate with curvature, as shown in figure 4.5.

Figure 4.5 Variation of crash rate with curvature – wet road crashes (Davies 2004)

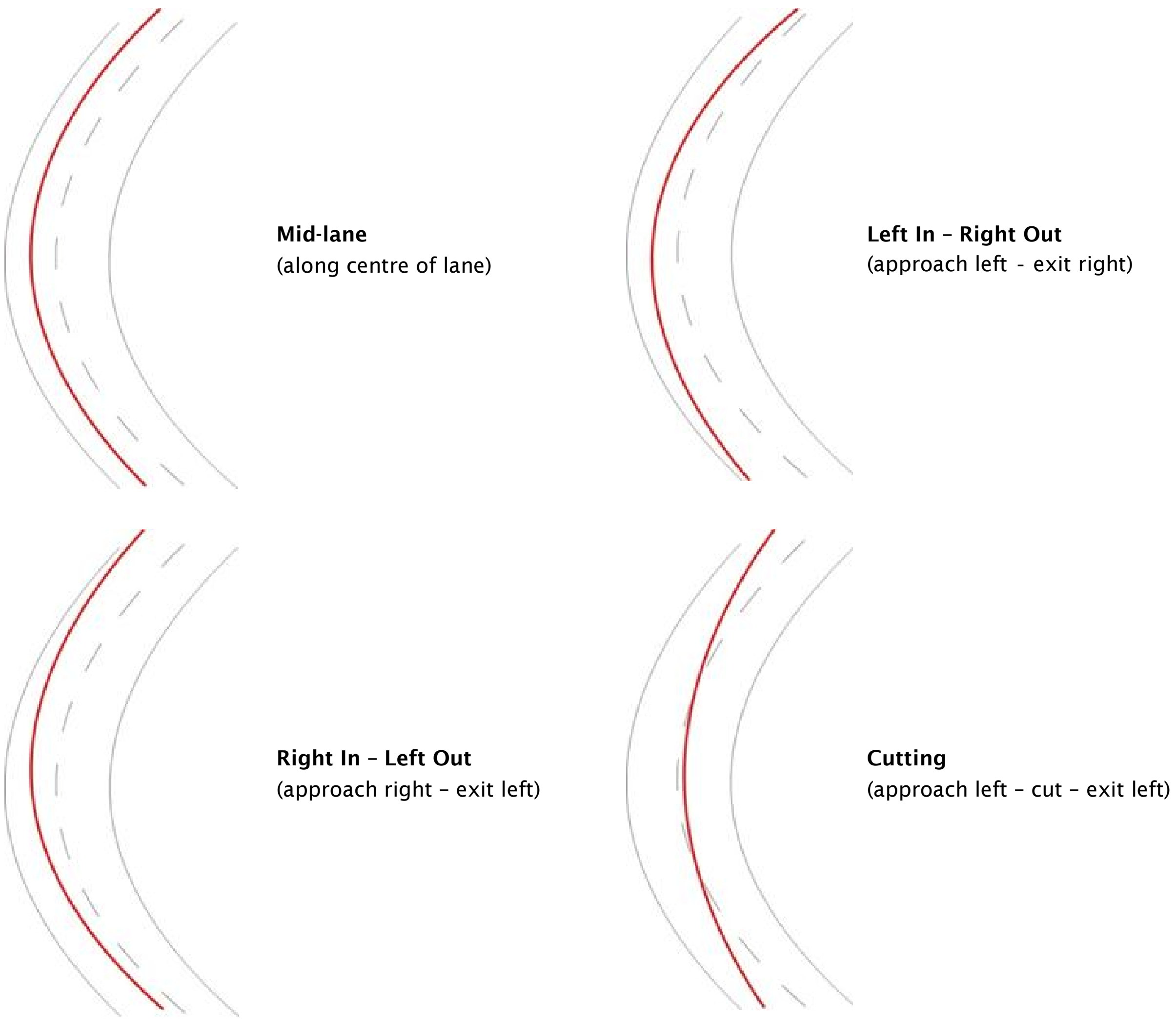


Based on the peak in the crash rate at around 100m curvature, it was decided that an isolated flat-gradient (0%) corner with a radius of around 100m, with lanes 3.75m wide, sealed shoulders 0.25m wide, and levels of crossfall typical of such sections found on the state highway network, would form the basis of the corner/barrier simulations.

A 3D corner road section 100m long was generated in the PC-Crash simulation. Wet friction values were assigned for the road surface. Each of the three vehicles was imported and placed pointing directly along the road. The different barrier-height combinations were then positioned parallel to the road 0.75m from the edge of the seal. This gave a total of 12 separate simulation files. The next step was to define the paths that the vehicle would take around the corners.

As part of a study on clear zones and barriers for the New Zealand Road Safety Trust, Jamieson (2012) examined the available literature on the variation of drivers' tracking behaviour around corners, and followed this with video recordings of vehicles traversing a range of corners of different radii. These video recordings were used to identify a number of representative driving lines. These four drivelines are shown in figure 4.6.

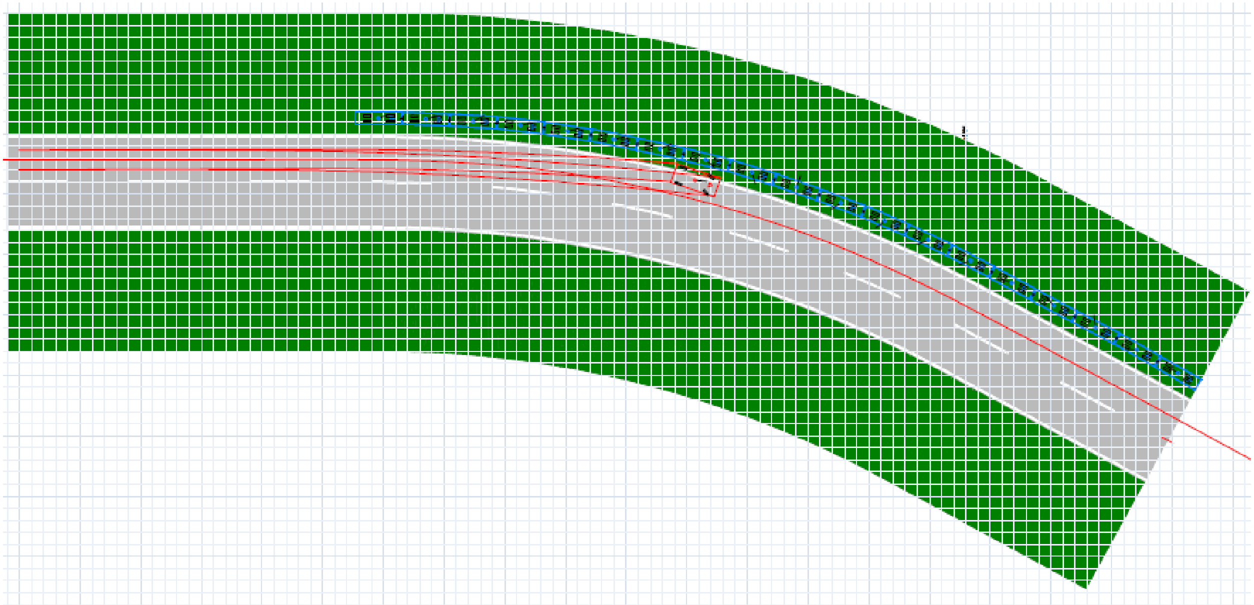
Figure 4.6 Representative corner drivelines (Jamieson (2012)



4.2.1 Corner simulations and results – W-beam barrier

Simulations for each of the vehicle, driveline and barrier-height combinations were run with initial vehicle speeds of 100km/h, 120km/h and 140km/h, giving a total of 144 simulation runs. The simulations were initially run for the W-beam barrier. Figure 4.7 shows a vehicle attempting to follow a mid-lane follow point path, and sliding when the road surface friction is too low to maintain this path. In each case the vehicle strikes the barrier. However, the speed, weight and driveline significantly affect where and at what angle the different vehicles strike the barrier - eg nose first or tail first - and hence potentially the crash severity and physical response after the crash.

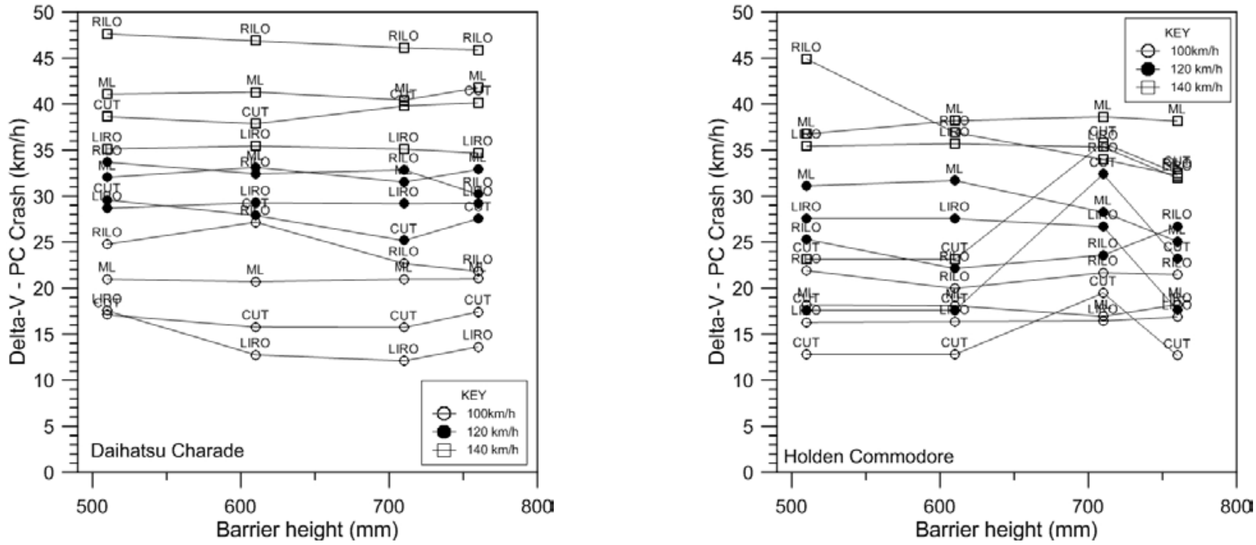
Figure 4.7 Vehicle attempting mid-lane follow point path



Barrier deflection and maximum Delta-V values were recorded for each simulation, together with the maximum yaw and roll rates and the physical response of the vehicle. This data has been plotted in figure 4.8 for the three different vehicles.

There is a considerable amount of information shown in these diagrams. There is also a considerable amount of variation in the Delta-V data. This variation came through differences between the vehicles, their characteristics, their speeds and driving lines. These affected where and how they interacted with the different height barriers. However, for this cornering scenario we were really concerned with identifying whether there was a significant effect with height across the different vehicles and speeds. Generally speaking, these diagrams show that for all three vehicles the highest Delta-V (greatest crash severity) and greatest change in Delta-V with change in barrier height occurred for the **Right In** approach **Left Out** exit driving line at 140km/h.

Figure 4.8 Delta-V values - curved corner section – W-beam (ML = mid-lane, RILO = right in, left out, LIRO = left in, right out, CUT = cutting)



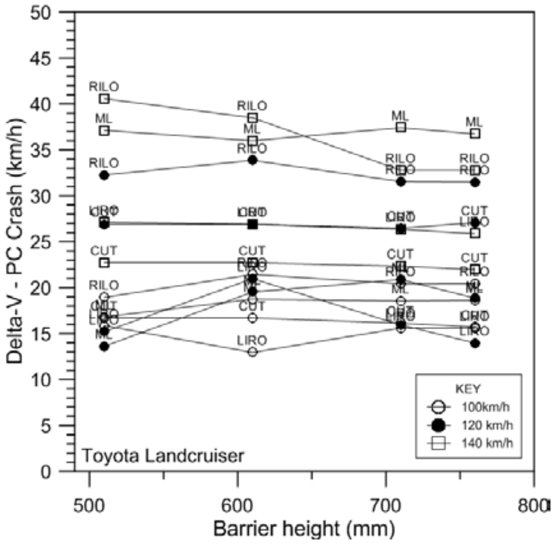


Table 4.7 lists the changes in Delta-V with barrier height for this speed and driving line for each of the three vehicles, and the corresponding changes in the probability of serious injury according to the relationship shown in figure 2.2 for a representative reduction in barrier height of 50mm.

Table 4.7 Variation of Delta-V with barrier height – W-beam on corner (140km/h)

Vehicle	Change in Delta-V/ change in barrier height (Delta-V/mm)	Change in probability of serious injury for 50mm change in barrier height from the standard height of 710mm
Daihatsu Charade	-0.007	0.0083
Holden Commodore	-0.049	0.0255
Toyota Landcruiser	-0.035	0.0159

Taking the greatest change in Delta-V with barrier height, this would suggest a maximum increase in the probability of serious injury of around 0.026 for each 50mm reduction in barrier height.

4.2.2 Corner simulations and results – wire-rope barrier

Given these results, it was not considered useful to entirely repeat the computer simulation corner modelling exercise for all of the combinations used for the W-beam barrier. Rather, it was decided to carry out the testing for the drive line showing generally the largest Delta-V values and the greatest variation in Delta-V with barrier height, this being the Right In – Left Out (RILO) drive line. Figure 4.9 shows the variation of the Delta-V data for this drive line with the change in barrier height.

Figure 4.9 Delta-V values - curved corner section – wire rope (RILO drive line)

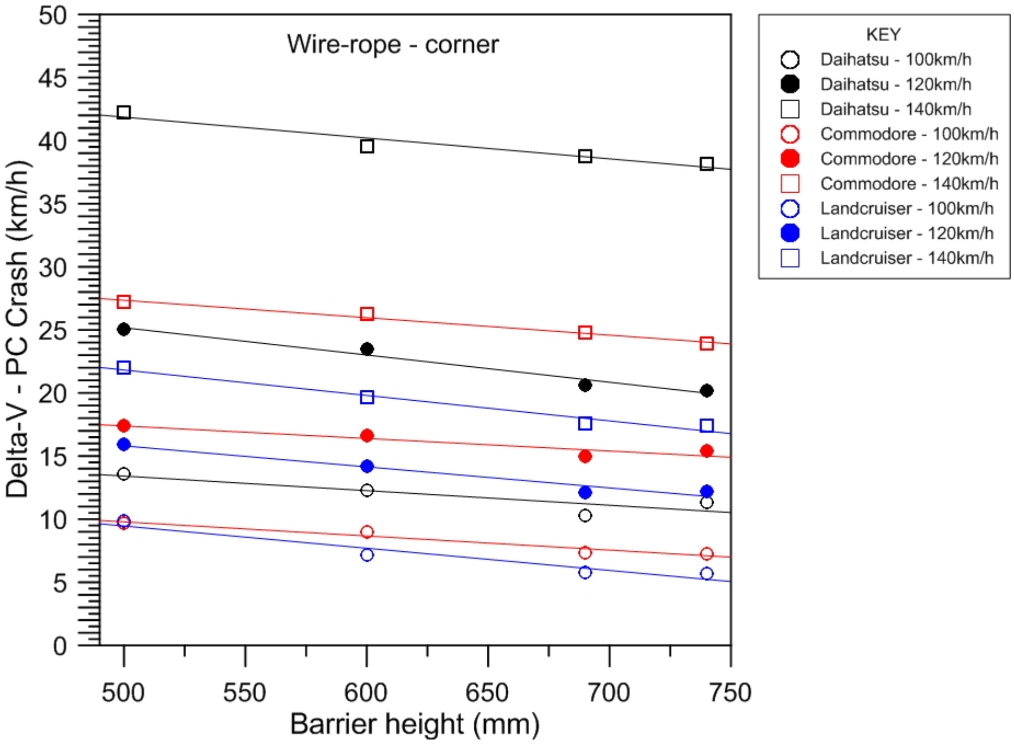


Figure 4.9 shows generally consistent variations of Delta-V with changes in barrier height. The values generally increase with increasing speeds, and also increase as the vehicle mass reduces. Table 4.8 lists the changes in Delta-V with barrier height for the Right In – Left Out drive line for each of the three vehicles impacting the wire-rope barrier, and the corresponding changes in the probability of serious injury according to the relationship shown in figure 2.2 for a representative reduction in barrier height of 50mm.

Table 4.8 Variation of Delta-V with barrier height – wire rope (RILO drive line)

Vehicle	Change in Delta-V/ change in barrier height (Delta-V/mm)			Change in probability of serious injury for 50mm change in barrier height from the standard height of 690mm		
	100km/h	120km/h	140km/h	100km/h	120km/h	140km/h
Daihatsu Charade	-0.012	-0.022	-0.017	0.0002	0.0012	0.0129
Holden Commodore	-0.011	-0.010	-0.014	0.0001	0.0004	0.0033
Toyota Landcruiser	-0.018	-0.017	-0.020	0.0001	0.0003	0.0014

Taking the greatest change in Delta-V with barrier height, this would suggest a maximum increase in the probability of serious injury of around 0.013 for each 50mm reduction in barrier height.

5 Barrier and crash costs

This project was intended to provide the Transport Agency, network consultants and contractors with information to assist them in making decisions about whether to rectify or remediate deficient existing barriers or to erect new ones in different, previously untreated locations that have significant hazards. This required an assessment of the costs and benefits involved. These included:

1. the costs associated with remediating, replacing or installing barriers
2. the costs associated with crashes, both into existing barriers and at untreated locations
3. the benefits of reducing the crash rates or crash severity in places where there are existing barriers or at untreated locations that have significant hazards.

The following sections describe a limited assessment of these costs. It was intended to identify if there were large differences in costs between treating existing barriers and constructing new ones.

5.1 Barrier costs

There are two areas of barrier-related costs:

1. the costs to rectify or remediate barriers that are found to be lower than the specified installation height
2. the costs of new barriers.

Inquiries were made through the Opus International Consultants Practice Interest Network (PIN) Groups to try to identify some of these costs on network contracts around New Zealand. Table 5.1 lists the ranges of prices/m and the median price/m for rectifying/maintaining W-beam and wire-rope barriers, and for installing new ones.

Table 5.1 Costs for new roadside barrier construction and maintenance (including raising height)

Barrier type	New construction cost - range ($/m)	New construction cost - median ($/m)	Raising barrier cost range ($/m)	Raising barrier cost median ($/m)
W-beam	85–185	135	~44–85	73
Wire rope	75–128	95	~40–60	NA[a]

a) Only one source of pricing.

These costs show that there was considerable variation in the costs for new barrier construction and in the costs for raising the height of existing barriers. Some of this variation was regional, and some was probably based on economies of scale, although we tried to remove costs for short lengths, which can be much higher. For example, the cost/m for new wire-rope barrier around 1400m long was ~$97/m, while for around 170m long it was $158/m.

5.2 Crash costs

The Transport Agency's *Economic Evaluation Manual (EEM) vol 1* (2010) ascribes costs to crashes depending on their severity. It provides cost breakdowns for different crash causes (eg run-off-road crashes) and for different degrees of severity – fatal, serious-injury, minor-injury and non-injury. Table 5.2 lists the different costs from the EEM for run-off-road crashes for specific vehicles and all vehicles.

Table 5.2 EEM crash severity costs ($,100km/h posted speed limit) – lost control off road

Vehicle type	Crash severity type			
	Fatal	Serious injury	Minor injury	Non-injury
Push cycle	3,100,000	320,000	18,000	1200
Motorcycle	3,550,000	375,000	19,000	1300
Bus	3,100,000	335,000	16,000	1100
Truck	3,350,000	375,000	34,000	6300
Car, van & other	3,600,000	385,000	22,000	1300
All vehicles	3,550,000	375,000	22,000	1600

5.3 Barrier crash and crash severity costs

This project was aimed at providing information to assist with the decision about whether it is more cost effective to:

- restore W-beam and wire-rope barriers that are too low, or too high, to the correct height
- construct new barriers in different untreated locations that have significant hazards.

This required understanding the likely crash rates and crash severities, and the differences in costs associated with these.

We approached this by looking at three representative sections 1km long that included a 100m radius corner and were of approximately identical geometry – one with a barrier at the correct height, one with the same type of barrier but was 50mm lower, and one with no barrier but had significant hazards on the roadside. We then:

1. assigned a nominal predicted crash rate to these sites of 13 (per 100 million vehicle.km), based on the prediction models of Davies (2004) and Cenek et al (2012a)
2. used the relative proportions of fatal, serious-injury, minor-injury and non-injury crash severities from table 2.2
3. combined these predicted crash rate and crash severity proportions with the EEM crash costs in table 5.2 to derive a cost for the predicted crash rate
4. applied the effects to these costs of barrier-height variation on the probability of serious injury, and calculated the differences in costs between barriers at the correct height and those 50mm lower – for the purpose of this exercise we assumed that:
   - the proportion of fatalities would be a maximum of 0.07, which is consistent with table 2.2

- the effect of barrier height on the probability of serious and minor injuries would be the same as that determined from the simulation modelling for serious injury
- the non-injury proportion would go down accordingly

5 compared these cost differences with the barrier construction and remediation costs from table 5.1. (the calculations are listed in table 5.3 below).

Table 5.3 Comparison of crash and barrier costs (1km barrier length)

Element	Barrier comparison scenario					
	W-beam comparison			Wire rope comparison		
	Correct height	50mm lower	New location (no current barrier)	Correct height	50mm lower	New location (no current barrier)
Predicted crash rate (per 100 million vehicle.km)[a]	13(x)	13	13	13	13	13
Crash severity proportions:[b]						
- Fatal	0.07(y)	0.07	0.07	0.01	0.01	0.07
- Serious-injury	0.33	0.33	0.45	0.22	0.22	0.45
- Minor-injury	0.41	0.41	0.37	0.36	0.36	0.37
- Non-injury	0.19	0.19	0.11	0.41	0.41	0.11
Crash severity costs ($):[c]						
- Fatal	3,550,000(z)	3,550,000	3,550,000	3,550,000	3,550,000	3,550,000
- Serious-injury	375,000	375,000	375,000	375,000	375,000	375,000
- Minor-injury	22,000	22,000	22,000	22,000	22,000	22,000
- Non-injury	1600	1600	1600	1600	1600	1600
Cost for predicted crash rate ($):						
- Fatal (x) x (y) x (z)	3,230,500	3,230,500	3,230,500	461,500	461,500	3,230,500
- Serious-injury	1,608,750	1,608,750	2,193,750	1,072,500	1,072,500	2,193,750
- Minor-injury	117,260	117,260	105,820	102,960	102,960	105,820
- Non-injury	3952	3952	2288	8528	8528	2288
Total	*4,960,462*	*4,960,462*	*5,532,358*	*1,645,488*	*1,645,488*	*5,532,358*
Effect of barrier height on probability of serious injury[d]	0.0	0.026	0.0	0.0	0.013	0.0
Modified crash severity proportions – height:						
- Fatal	0.07	0.07	0.07	0.01	0.01	0.07
- Serious-injury	0.33	0.33+0.026	0.45	0.22	0.22+0.013	0.45
- Minor-injury	0.41	0.41+0.026	0.37	0.36	0.36+0.013	0.37
- Non-injury	0.19	0.19-0.052	0.11	0.41	0.41-0.026	0.11
Modified crash severity cost ($) total	4,960,462	5,093,566	5,532,358	1,645,488	1,712,040	5,532,358
Cost difference from correct height barrier ($)	N/A	133,104	571,896	N/A	66,552	3,886,870
Construction or remediation cost ($)						
- Low	N/A	44,000	85,000	N/A	40,000	75,000
- High	N/A	85,000	185,000	N/A	60,000	128,000
- Median	N/A	73,000	135,000	N/A	N/A	95,000

(a) From Davies (2004) and Cenek et al (2012a).
(b) From table 2.2.
(c) From table 5.2 (for all vehicles).
(d) From crash simulation modelling.

This suggests that if we have a 1km W-beam barrier that is 50mm too low, this would have a $133,104 crash severity penalty cost, and the median cost to rectify this would be $73,000. Putting that $73,000 toward a W-beam barrier in a new location would fund a new W-beam barrier 541m in length (at a median cost of construction of $135,000/km), which would generate $309,247 in crash severity savings, which is equivalent to $571,896/km.

For a 1km wire-rope barrier that is 50mm too low, this would have a $66,552 crash severity penalty cost, and the median cost to rectify this would be $50,000 (using a midrange figure in the only source of data). This $50,000 could fund around 526m of new wire-rope barrier at a previously untreated site (at a median cost of construction of $95,000). This new wire-rope barrier would be expected to generate $2,010984 in crash severity savings, which is equivalent to $3,820,870/km.

Tables 5.4 and 5.5 summarise this type of situation for W-beam and wire-rope barriers respectively by comparing the approximate relative costs/benefits for a situation where you could:

- do nothing
- raise an existing barrier that is deficient in height, but do nothing at a site that has significant hazards but no safety barrier
- do nothing with a barrier that is deficient in height, but erect a new barrier at a site that has significant hazards but no safety barrier.

Table 5.4 Barrier scenario cost comparison – W-beam barrier

Scenario	Deficient-height barrier crash severity cost penalty ($)	Untreated site potential crash severity cost saving ($)	Median construction cost ($)	Benefit/cost (B/C)
Do nothing	0	0	0	
Raise deficient-height barrier, leave untreated site	133,104	0	-73,000	1.8
Leave deficient-height barrier, install at untreated site	$0	309,247	-135,000	2.3

Table 5.5 Barrier scenario cost comparison – wire-rope barrier

Scenario	Deficient-height barrier crash severity cost penalty ($)	Untreated site potential crash severity cost saving ($)	Median construction cost ($)	Benefit/cost (B/C)
Do nothing	$0	$0	$0	
Raise deficient-height barrier, leave untreated site	+$66,552	$0	-$50,000	1.3
Leave deficient-height barrier, install at untreated site	-$66,552	+$3,886,870	-$95,000	40.2

Under these simple comparisons, the installation of new barriers at previously untreated locations would generally be more beneficial than raising existing barriers that were too low by the order of 50mm or less, particularly in the case of wire-rope barriers. Note that this supposes that the height deficiency is the primary trigger for any intervention.

The above scenarios compare a situation that includes a relatively small-radius curve. For a straight road section, the effects on the probability of serious injury for a 50mm reduction in barrier height were of a similar magnitude. Accordingly, the installation of new barriers on previously untreated straight road sections would also generally be more beneficial than raising existing barriers that were too low by the order of 50mm or less.

It is important to note that these calculations were based on comparative rather than absolute situations, and used certain assumptions for the crash severity proportions – ie the mix of fatal, serious-injury, minor-injury and non-injury crash victims. They also used the accident costs from the EEM (NZ Transport Agency 2010) for all vehicles, and the highest crash severity modification factors identified in the crash simulation modelling for the W-beam and wire-rope barriers for a low radius of curvature corner. We also did not separate barrier construction and remediation costs by region. For example, it is possible, but not necessarily likely, that one region may have a relatively expensive new-construction cost, but a relatively cheap remediation cost, or vice versa.

6 Summary of findings

6.1 Literature review

6.1.1 Barrier height

It was found during the initial investigation of the issue of barrier-height deficiencies that there was only a limited amount of information available about the actual extent of the problem on the New Zealand state highway network. The Transport Agency believed that the issue exists, but had only a small amount of actual numerical data on the magnitude and distribution of any height deficiencies, and no information on whether this occurs across all barrier types, or is limited to a particular type.

The review of the literature showed there was very little information available on the effects of the variation of barrier height on crash severity. One study by Marzougui et al (2007b), which combined computer simulation modelling and full-scale crash testing, suggested that W-beam guardrails that were as little as 40–60mm lower than the standard height could reduce the ability of the barrier to redirect pickups and large SUVs. However, they also noted that in the full-scale crash testing the OIVs and ORAs, which are commonly used crash severity metrics, were very similar for the standard-height barrier and a height barrier 60mm lower, and that in both cases these were below the preferred limits of 9m/s and 15m/s respectively, and well below the maximum limits of 12g and 20g respectively prescribed by NCHRP 350 (NCHRP 1999) and MASH-1 (AASHTO 2009).

In more general terms, the AASHTO *Roadside design guide* (2011) does provide comment with respect to the heights of W-beam barriers. Essentially, it states that many existing barrier systems that may be lower than current specifications, either because of changes to these specifications or pavement overlays, 'have or should continue to have acceptable real-world performance'. It also suggests that 'It is not cost-effective or practical to raise all existing guardrail to the current criteria on a highway agency's entire roadway system. However, guardrail should be upgraded as part of a reconstruction or new highway construction project'.

6.1.2 Crash severity metrics

The review of crash severity metrics showed that a variety of severity metrics are currently being used, with the most commonly used in reports on full-scale barrier crash tests being the OIV and the ORA. One study (Gabauer and Gabler 2006) suggested 'the more computationally intensive OIV offers no statistically significant advantage over the simpler Delta-V crash severity metric'. This would suggest that the choice of Delta-V as the crash severity metric for the computer simulation modelling would be reasonable, provided there was reasonable agreement between full-scale crash test data with the Delta-V data and other outputs for the particular software package used, in this case PC-Crash V9.0.

6.1.3 Corrosion

The literature showed even less information on the effects of corrosion on barrier condition, strength and performance. Discussions with corrosion expert Willie Mandeno suggested there could potentially be considerable differences in the 'ribbon-like' performance of a barrier, particularly W-beam and similar barriers, depending on the location and extent of the corrosion. He suggested that some full-scale tensile testing comparing barrier elements in good condition with corroded ones could provide some useful comparative information. He also tentatively suggested that replacing W-beam barrier elements as soon as perforations were found could be an appropriate treatment option.

6.2 Simulation modelling and crash severity

6.2.1 Validation

Computer simulation modelling was designed as the central pillar of this research project, as it offered the only realistic way to test a wider variety of situations than is practically or economically possible using full-scale testing. However, for the outputs of any computer simulation modelling to be considered useful in providing reasonably accurate data, including on crash severity through the Delta-V metric, it was necessary to compare data from full-scale crash tests with computer simulation data. Our comparison of barrier deflections for crashes into W-beam and wire-rope barriers showed reasonably good agreement between full-scale data and data from the PC-Crash simulation software, with a correlation coefficient of around 0.98. Similarly, our comparison of the full-scale crash severity metric of OIV and the computer simulation modelling metric Delta-V also showed acceptable agreement, with a correlation coefficient of around 0.84. These comparisons indicated that PC-Crash could provide a simulation of barrier crashes that was adequate for the purposes of this project.

6.2.2 Drift-off impacts – W-beam

The first stage of the simulation modelling was for three different vehicles (light car, heavier car and SUV) drifting off the road in wet conditions under the influence of the road geometry alone and impacting W-beam barriers of different heights. This showed, as expected given the shallow impact angles, very small values of Delta-V (the chosen crash severity metric) and very little variation between either the different vehicles or the different barrier heights. There was only a small increase with increasing vehicle speed.

6.2.3 Maximum-turn impacts – W-beam

In the next stage, a maximum-turn scenario into a W-beam barrier in wet conditions was investigated, which meant that the vehicles were sliding both laterally and longitudinally when they struck the barrier. This produced higher Delta-V values (~8–12km/h), although these were somewhat lower than those found during the validation exercise (~25–30km/h). Again, this was expected given the lower impact angles (~14°–18°) for the maximum-turn tests, and the vehicle's sliding both laterally and longitudinally. Analysis of the results showed that there was a small average increase in Delta-V as the barrier height was reduced for the lighter car investigated, but minimal differences for the heavier car and SUV. It also showed that the crash severity was higher for the lighter car than for the other two vehicles.

6.2.4 Straight-line impacts – W-beam

The next sequence of simulations was basically an extension of the validation exercise, where the three vehicles were driven in a straight-line path into W-beam barriers of various heights at various speeds, but at a higher impact angle of 25°. The Delta-V values identified (~30–60km/h) were much higher than for any of the previous tests, which was to be expected. However, they were generally consistent with the values found for the W-beam barriers in the validation exercise. Again, the crash severity was higher for the lighter car than the heavier vehicles.

The results showed some consistent variation of crash severity (Delta-V) with barrier height, although this was not totally consistent across the vehicles and speeds, which could have been due to the different vehicle shapes and how they interacted with the barrier. Analysis showed that the largest effect was for the lighter car, where a comparative reduction in barrier height of 50mm would represent an increase in the probability of serious injury of around 0.038.

6.2.5 Straight-line impacts – wire rope

This stage was essentially to repeat the straight-line impact tests into a wire-rope barrier instead of a W-beam barrier. The measured Delta-V values (~10–40km/h) were consistent with those measured in the validation exercise and were lower than for the same straight-line impact tests into the W-beam barrier. As with the others, they were higher for the lighter car than for the two heavier vehicles. The data showed an effect with barrier height, with an increase in the probability of serious injury of around 0.006 for a reduction in barrier height of 50mm.

6.2.6 Corner impacts – W-beam

While the straight-line impacts were generally expected to produce the highest crash severity, which is why this type of test forms the basis of the full-scale crash testing to MASH requirements, part of the research project was to investigate the effects of crashes into barriers on corners. This testing used the same vehicles, speeds and barrier models as the earlier tests, but on a relatively tight corner (minimum radius 100m). Different vehicle driving lines from Jamieson (2012) were used to assess whether there was any significant variation according to driver behaviour around corners. The first sequence looked at impacts into the W-beam barriers, under wet conditions as before. As with the maximum-turn tests described earlier, the vehicle would be sliding both laterally and longitudinally when striking the barrier. However, depending on the vehicle speed and the designated drive line, the vehicle could strike the barrier either nose first, tail first, or even approximately parallel.

As expected, there was considerable variation in the crash severity (as represented by the Delta-V values) and the probability of serious injury. Generally, the highest crash severity occurred for what is referred to as the ‘Right In approach – Left Out exit’ (RILO) drive line for the highest vehicle speed. While the Delta-V values were highest for the lighter car, as they had been in previous tests, the largest variation with barrier height occurred for the heavier car, with an increase in the probability of serious injury of around 0.026 for a 50mm reduction in barrier height, compared with an increase of around 0.016 for the SUV.

6.2.7 Corner impacts – wire rope

The corresponding tests for a wire-rope barrier were limited to the drive line generating the most severe results for the W-beam barrier – ie the Right In – Left Out vehicle path. These showed results for Delta-V (~10–40km/h) that were consistent with the results of the previous wire-rope barrier tests. Again, the Delta-V values were highest for the lighter car, as they were in previous tests. In this case, the largest variation in the probability of serious injury with a change in barrier height of 50mm was around 0.013.

6.3 Barrier and crash costs

Identifying the variation in crash severity with barrier height is only part of the information equation needed for decisions to be made about remedying substandard-height barriers or building new ones at previously untreated locations. The other part of the equation is the costs, in terms of both the barriers and the crashes into them. Information from around the country showed that:

- there was considerable variation in the barrier costs/m, both to fix or raise existing barriers and to erect new barriers at previously untreated locations
- generally speaking, wire-rope barriers were cheaper to erect and fix than W-beam barriers.

Part of the literature search for this project involved identifying the costs associated with crashes which, for the purposes of assessing safety measures and other roading changes, are defined by the Transport Agency's EEM (NZ Transport Agency 2010) for fatal, serious-injury, minor-injury and non-injury crashes. Another part of the literature search put numbers on the variation of the crash rates and crash severity distributions for different barrier types and roadside hazards.

We combined these costs with the changes in crash severity with barrier height found from the simulation modelling. This analysis suggested the following:

- Even with a crash severity penalty for a substandard-height barrier, installing new W-beam barriers instead of raising the height of existing substandard-height W-beam barriers to the correct height could be more cost effective on both straight and corner road sections, depending on the relative costs of doing so in the particular region of the country.
- Installing new wire-rope barriers at previously untreated locations instead of raising the height of existing substandard-height wire-rope barriers to the correct height would be likely to be quite cost effective. This is because of the:
  - lower crash rates resulting from shielding other hazardous areas
  - generally lower crash severity (mix of fatal, serious-injury, minor-injury and non-injury crashes)
  - relatively low cost of doing so, compared with the crash rate and crash severity cost savings.

It is important to note that existing barriers will often have other significant failings apart from the height – eg the condition, insufficient length of need and run-out length, and non-compliant end treatments. It is unlikely that substandard height would be the sole or even the main trigger for remediation. In practice, a substandard-height barrier may not be raised without addressing these other failings. In addition, any costing analysis used as a basis for comparison with new barriers needs to clearly state what is included in the cost for raising the height.

7 Conclusions and recommendations

The following conclusions were drawn from this study to investigate whether it is more appropriate to rectify or replace existing roadside crash barriers that do not conform to the installation specifications, particularly in terms of height and condition, or to install new roadside crash barriers at previously untreated locations. Recommendations for additional work are also made.

7.1 Conclusions – literature review

The review of the available literature revealed the following:

- There was only limited information available on the magnitude of the perceived problem of barrier heights that were too low for whatever reason (eg pavement overlays). There was a relative lack of knowledge of the lengths of barriers that were too low, the amounts by which they were too low, and how both of these factors varied with barrier type. Some of the data indicated that around 14% of barriers in the Wellington region were 30mm or more (too high or too low) from the specified height, but did not provide maximum differences.
- Similarly, there was little information in the literature on how a variation in barrier height could affect crash severity. One study comparing both full-scale barrier crash tests and computer simulation modelling of barrier crash tests suggested that a height deficiency of as little 40–60mm could affect the ability of a W-beam barrier to contain and redirect pickups and large SUVs. However, the same study also found little difference in the crash severity for this level of height deficiency.
- The literature described a variety of different crash severity metrics, one of which was the Occupant Impact Velocity (OIV), which is often reported in full-scale crash testing, and another being Delta-V (the metric originally proposed as the basis for this research project). One study suggested there was little statistical advantage in using the more complex OIV as opposed to the computationally simpler Delta-V.
- Very little information was found on the effect of corrosion on barrier strength or performance, and none of it was quantitative. Discussions with a corrosion expert suggested there could potentially be considerable differences in the 'ribbon-like' performance of a barrier, particularly W-beam and similar barriers, depending on the location and extent of the corrosion.

7.2 Conclusions – computer simulation modelling

The computer simulation modelling, which was the central pillar of this research project, led to the following conclusions regarding the likely effects of variations in barrier height on crash severity:

- Comparison of full-scale barrier crash deflection and crash severity (OIV) data with corresponding data from computer simulation modelling (deflection and Delta-V) indicated that the simulation modelling would be adequate for the purposes of this study.
- Simulations of drift-off low-angle impacts into a W-beam barrier in wet conditions showed low crash severities, as measured using the Delta-V values, no significant variation with barrier height, and only a small increase with vehicle speed.

- For the lighter car that was investigated, simulations of maximum-rate turn crashes into a W-beam barrier in wet conditions showed a small increase in crash severity with a lower barrier height, but there were minimal differences for the heavier car and SUV that were investigated.
- Straight-line impacts into both W-beam and wire-rope barriers at a 25° angle showed increases in the probability of serious injury of around 0.038 and 0.006, respectively, for a representative 50mm reduction in barrier height.
- Simulation of impacts into both W-beam and wire-rope barriers on a small radius of curvature corner showed increases in the probability of serious injury of around 0.026 and 0.013, respectively, for a representative 50mm reduction in barrier height.
- Note that these simulations included test speeds equal to, and significantly greater, than the posted open road speed limit of 100km/h.

7.3 Conclusions – barrier and crash costs

The review of barrier and crash costs revealed the following:

- There was wide regional and contractor variation in the costs/m, both to erect new barriers and to fix or raise them.
- Generally, wire-rope barriers were significantly cheaper to erect and fix than W-beam barriers.
- Considering the effects of barrier height on crash severity, and combining this with the various cost factors associated with barrier construction or remediation and crash severity, the results of the simulation modelling suggested that in many cases, and particularly with wire-rope barriers, it was much more cost effective to install new barriers at previously untreated locations than to raise existing ones to the correct heights.

7.4 Recommendations for further research

The recommendations arising from this study for further work on the effects of barrier height and condition on crash severity are as follows:

- A more detailed understanding of the size and extent of the perceived problem of barrier heights being lower than specified is needed. This may require some representative sampling during barrier inspections, or there may be existing data in the information systems of the Transport Agency or its consultants and contractors. Representative sampling would also identify other deficiencies (eg corrosion), thus ensuring that the actual triggers for remediation of substandard barriers are understood, and that the costs fully reflect a true retrofit scenario.
- A limited programme of full-scale testing of the effects of barrier corrosion would be useful, both by potentially leading to a better understanding of its effects on barrier strength and performance, and also by refining visual condition assessment.
- Although the sample sizes may be small, it may be useful, where possible, to develop more detail on the relationship between barrier height and the crash outcomes/severity in actual barrier crashes.

- A more detailed analysis of the costs/benefits associated with erecting new barriers at previously untreated locations or remediating existing barriers is needed before consideration is given to changing current Transport Agency policies and procedures. In particular, further analysis is needed on all of the costs involved in rectifying existing substandard barriers. This should consider all of the significant potential failings that existing roadside barriers may exhibit, including the height, condition, length of need and run-out length, and non-compliant end treatments. It is probable that substandard height would not be the sole or even the predominant trigger for remediation.

8 Bibliography

AASHTO (American Association of State Highway and Transportation Officials) (2006) *Roadside design guide*, 3rd ed. Washington DC: AASHTO.

AASHTO (American Association of State Highway and Transportation Officials) (2009) *Manual for assessing safety of hardware (MASH).* Washington DC: AASHTO.

AASHTO (American Association of State Highway and Transportation Officials) (2011) *Roadside design guide*, 4th ed. Washington DC: AASHTO.

Austroads (2002) *Urban road design: a guide to the geometric design of rural roads*. Austroads Road Design Series. Sydney: Austroads.

Austroads (2003) *Rural road design: a guide to the geometric design of rural roads*. Austroads Road Design Series. Sydney: Austroads.

Austroads (2006) *Guide to road safety part 3: speeds limits and speed management*. Austroads Design Series. Sydney: Austroads.

Austroads (2010a) *Guide to road design: part 6: roadside design, safety and barriers*. Austroads Road Design Series. Sydney: Austroads.

Austroads (2010b) *Improving roadside safety*. Austroads publication no. AP-T142/10. Sydney: Austroads.

Austroads (2011a) *Improving roadside safety – stage 2: interim report*. Austroads publication no. AP-R387/11. Sydney: Austroads.

Austroads (2011b) *Improving roadside safety – stage 3 interim report*. Austroads publication no. AP-R419-12. Sydney: Austroads.

Austroads (2012) Improving roadside safety: final report. Austroads draft publication. Sydney: Austroads.

Burbery, SL (2006) Single vehicle crashes on curves: a New Zealand perspective. *ASPACI Bi-Annual Conference 2006*, Brisbane, Queensland: 1–19.

Candappa, N, A D'Elia, B Corben and S Newstead (2009) Evaluation of the effectiveness of flexible barriers along Victorian roads. *Monash University Accident Research Centre report 291*. 33pp.

Cenek, PD and RB Davies (2004) Crash risk relationships for improved safety management of roads. *Towards Sustainable Land Transport Proceedings 2004*, Wellington.

Cenek, PD, RB Davies and RJ Henderson (2012a) Crash risk relationships for improved road safety management. *NZ Transport Agency research report 488*. 45pp.

Cenek, PD, RB Davies and RJ Henderson (2012b) Modelling crash risk on the New Zealand state highway network. *NZ Transport Agency research report 477*. 100pp.

Chalmers University of Technology (2005) *D06: European best practice for roadside design: guidelines for roadside infrastructure on new and existing roads*. Report for Riser Consortium. 142pp.

Crowther, S and R Swears (2010) Longswamp to Rangiriri wire rope barrier: increased crash numbers and improved safety. *24th ARRB Conference*, Melbourne, 2010.

Davies, RB (2004) *Crash-risk relationships*. Accessed May 2013. www.robertnz.net/pdf/crashrisk8.pdf

Davies, RB (2009) *Crash-risk model for curves*. Accessed May 2013. www.robertnz.net/pdf/report_curves3.pdf

Doecke, S and J Woolley (2010) Effective use of clear zone and barriers in a safe system's context. *Australasian Road Safety Research, Policing and Education Conference*, Canberra, 2010.

Doecke, S and J Woolley (2011) Further investigation into the effective use of clear zone and barriers in a safe system's context on rural roads. *Australasian Road Safety Research, Policing and Education Conference*, Perth, 2011.

Faller, RK, DL Sicking, RW Bielenberg, JR Rohde, KA Polivka and JD Reid (2007) Performance of steel-post, W-beam guardrail system, paper no. 07-2642. *TRB 86th Annual Meeting*, Washington DC, 21–25 January 2007. 30pp.

Felipe, E and F Navin (1998) Automobiles on horizontal curves: experiments and observations. *Transport Research Record 1628*: 50–56.

Gabauer, DJ and HC Gabler (2005) Evaluation of threshold values of acceleration severity index by using event data recorder technology. *Transportation Research Record: Journal of the Transportation Research Board 1904*: 37–45.

Gabauer, DJ and HC Gabler (2006) Comparison of Delta-V and Occupant Impact Velocity crash severity metrics using event data recorders. *Annual Proceedings of the Association for the Advancement of Automotive Medicine 50*: 57–71.

Gabler, HC, C Hampton and TA Roston (2003) Estimating crash severity: can event data recorders replace crash reconstruction? *Proceedings of the 18th International Technical Conference on the Enhanced Safety of Vehicles*, Nagoya, Japan, 2003.

Godthelp, H (1986) Vehicle control during curve driving. *Human Factors 28*, no.2: 211–221.

Gunay, B and D Woodward (2006) Lateral position of traffic negotiating horizontal bends. *Proceedings of the ICE – Transport160,* issue 1: 1–11.

Hammonds, BR and R Troutbeck (2012) Crash test outcomes for three generic barrier types. *25th ARRB Conference*, Perth, Australia.

Jamieson, NJ (2012) Clear zones, barriers and driving lines – mitigating the effects of crashes on corners (horizontal curves). *Central Laboratories report 12-529B33.00* for the Road Safety Trust. 79pp.

Jamieson, NJ, G Waibl and R Davies (2013) Use of roadside barriers versus clear zones. *NZ Transport Agency research report 517*. 92pp.

Joksch, H (1993) Velocity change and fatality risk in a crash – rule of thumb. *Accident Analysis and Prevention 25*, no.1: 103–104.

Jurewicz, C and V Pyta (2010) Effect of clear zone widths on run-off-road crash outcomes. *2010 Australasian Road Safety Research, Policing and Education Conference*, Canberra.

Knapp, KK (2008) Crash and safety surrogate impacts of horizontal curve delineation. *ITE (Institute of Transportation Engineers) 2008 Technical Conference and Exhibit*, Miami.

Koorey, G, F Tate and I Melsom (1998) The effect of curves and speed on crash rates and severity. *Road Engineering Association of Asia and Australasia (REAAA) Conference, vol 1*, 9 May 1998, Wellington.

Levett, S (2007) Retro-fitting incremental clearzone widths to existing rural roads. *Australasian Road Safety Research Policing Conference*, Melbourne.

MacLean, J (2002) Review of the development of US roadside design standards. *Road and Transport Research Journal 11*, no.2: 29–41.

Miaou, SP (2001) Estimating roadside encroachment rates with the combined strengths of accident- and encroachment-based approaches. *Federal Highway Administration report FHWA-RD-01-124*. 93pp.

Marzougui, D, P Mohan, U Mahadeviah and S Kan (2007a) Performance evaluation of low tension, three-strand cable median barriers on sloping terrains. *NCAC (National Crash Analysis Centre) document 2007-R-005.*

Marzougui, D, P Mohan, U Mahadeviah and S Kan (2007b) Evaluation of rail height effects on the safety performance of W-beam barriers. *NCAC National Crash Analysis Centre Working Paper, NCAC 2007-W-002*.

MIROS (Malaysian Institute of Road Safety Research) (2012) Stability of high-deck buses in a rollover and contact-impact with traffic barriers. *MIROS Research Report 01/2012*.

Mohan, P, D Marzougui and N Bedewi (2004) Finite element modelling and validation of a 3-strand cable guardrail system. *NCAC (National Crash Analysis Centre) Working Paper NCAC 2004-W-002*.

Navin, F, R Klymchuk, D Romilly and R Thomson (1993) Reconstruction of accidents involving highway barriers. *SAE Technical Paper Series 930656*.

NCAC (National Crash Analysis Centre) (2007) Effects of shoulder drop-off on W-beam guardrail performance. *National Crash Analysis Centre Technical Summary NCAC 2007-T-002*.

NCHRP (National Cooperative Highway Research Program) (1999) Recommended procedures for the safety performance evaluation of highway features. *NCHRP report 350*. 74pp.

NCHRP (National Cooperative Highway Research Program) (2010a) Evaluation of existing roadside safety hardware using Manual For Assessing Safety Hardware (MASH) criteria. *TRB Research Results Digest 349*.

NCHRP (National Cooperative Highway Research Program) (2010b) Volume 1: Evaluation of existing roadside safety hardware using updated criteria – technical report. *TRB Web-only document 157*.

NZ Transport Agency (2002) *State highway geometric design manual (SHGDM): section 6 – cross section*. Wellington: NZ Transport Agency. 22pp.

NZ Transport Agency (2005) *State highway geometric design manual (SHGDM): section 7 – roadside features*. Wellington: NZ Transport Agency. 36pp.

NZ Transport Agency (2010) *Economic evaluation manual (EEM) (vol 1)*. Wellington: NZ Transport Agency. 685pp.

NZ Transport Agency (2012a) NZTA M/23A – Road safety barrier systems. *NZTA Spec M23A: 2012* (includes specification and notes). Wellington: NZ Transport Agency.

NZ Transport Agency (2012b) *NZTA M/23: Appendix A – approved road safety barrier systems*. Wellington: NZ Transport Agency. 11pp.

Ross Jr, HE, DL Sicking and RA Zimmer (1993) Recommended procedures for the safety performance evaluation of highway features. *National Cooperative Highway Research Program (NCHRP) report 350*. 74pp.

Said, DG, Y Hassan and AO Abd El Halim (2007) Quantification and utilization of driver path in improving the design of highway horizontal curves. In *Proceedings 86th Annual Meeting of the Transportation Research Board*, Washington DC, 21–25 January 2007. 17pp.

Sheikh, NM, RP Bligh and JM Holt (2012) Minimum rail height and design impact load for longitudinal barriers that meet test level 4 of 'Manual for assessing safety hardware'. *TRB Annual Meeting 2012.*

Shelby, G (2011) Delta-V as a measure of traffic conflict severity. *3rd International Conference on Road Safety and Simulation*, Indianapolis, 14–16 September 2011. 20pp.

Standards Australia (1999) *AS/NZS 3845 Road safety barrier systems* (released in 2012 as DR AS/NZS 3845.1, a revised draft for public comment). Melbourne: Standards Australia.

Vesenjak, M, M Borovinsek and Z Ren (2007) *Computational simulations of road safety barriers using LS-DYNA*. Slovenia: University of Maribor, Faculty of Mechanical Engineering. 8pp.

Wach, W (2012) *Simulation of vehicle accidents using PC-Crash*. Cracow: Institute of Forensic Research. 789pp.

Williams, GL (2007) Whole life cost–benefit analysis for median safety barriers. *TRL Published Project Report PPR 279*. 57pp.

Williams, WF and WL Menges (2012) MASH test 3-11 of the W-beam guardrail on low-fill box culvert. *Texas Transportation Institute Test Report No. 405160-23-2*.57.

Wong, YD and A Nicholson (1993) Speed and lateral placement on horizontal curves. *ARRB Road and Transport Research 2*, no.1: 74–87.

Appendix A Features of PC-Crash V9.0

A.1 Background

The software package used for the computer simulation modelling was PC-Crash, Version 9 (3D). This is an internationally recognised 3-dimensional vehicle crash and trajectory simulation package widely used by police and civilian crash investigators and analysts. Road models can be created in three dimensions by the following methods:

- using CAD packages to create them from surveyed data and importing them into the simulation
- drawing topographic and road contours and generating a surface over them in the simulation
- creating a 3D road element by inputting length, elevation, radius, crossfall and width parameters.

Surface friction can be defined either as a standard value for the entire surface, or as friction polygons with specific defined dimensions and values. A wide range of vehicles from different manufacturers is available, including cars, trucks, buses, vans, motorcycles and trailers. These can be imported from a number of different databases and the vehicle parameters can be modified if required. Vehicle paths and speeds, including sequences of acceleration, steering or braking, can 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 or initial conditions unless the speed becomes too great for the simulation conditions – eg if the friction is too low, or if rollover occurs.

The modelling of the vehicles includes all of 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 (anti-lock braking) and ESP (electronic stability program).

A.2 Standard features

- Simultaneous simulation of up to 2 vehicles (PC-Crash 2D) or 32 vehicles (PC-Crash3D)
- 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 position and/or up to five intermediate vehicle positions
- Crash backwards calculation, using post-impact velocities
- Automatic kinematic calculation of accident avoidance
- Forwards automatic avoidance simulation (velocity decrease, brake increase)
- Various diagrams for wheel forces, etc
- Kinematic and kinetic (default mode) specification of vehicle paths
- Backtracking tyre marks with a kinematic skidding calculation to determine post-impact velocities, based on up to six post-impact positions and braking levels for each vehicle
- Automatic kinematic calculation of 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 downforce 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

A.2.1 Additional features of PC-Crash 3D

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

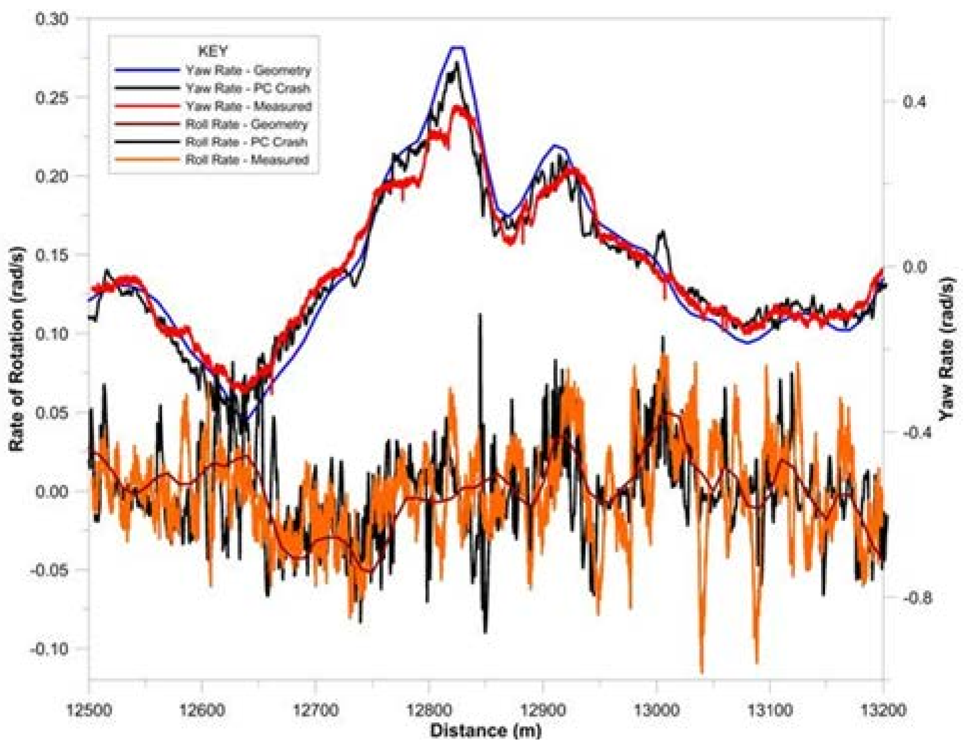
- 2D and 3D vehicle DXF automatic deformation model
- 3D window dynamic viewing
- Direct X 3D graphics, for improved rendering
- New stiffness-based crash simulation model
- New stiffness database with real crash test to be used in stiffness-based crash simulation
- Improved occupant simulation in PC-CRASH, including 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 tyre 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 multibody simulation model (faster calculation, new joint types)
- Sort function within Crash3 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 multibody calculations (further optimisation in progress)
- Preview for vehicle DXF dialogue

Appendix B Assessment and verification of PC Crash

The following section on the assessment and verification of PC-Crash has been reproduced from Jamieson (2012), with minor editing to reflect the current research objectives and report format.

PC-Crash is an internationally recognised 3-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), 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) (Jamieson 2012)



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 considered appropriate to also 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 2002a, Jamieson et al 2002b, 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 tests 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 (°)	Braking distance (m)	Yaw angle (°)
Chipseal	Dry	52	No	0.60	16.5	N/A	17.0	N/A
Chipseal	Wet	50	No	0.51	19.2	N/A	20.2	N/A
Chipseal	Wet	69	No	0.53	33.0	N/A	34.2	N/A
AC[a]	Dry	50	No	0.73	12.6	N/A	13.0	N/A
AC	Wet	73	No	0.59	36.6	N/A	35.8	N/A
AC	Wet	52	No	0.64	16.9	N/A	16.0	N/A
Clover	Dry	40	No	0.21	30	N/A	31.1	N/A
Clover	Wet	40	No	0.17	37	N/A	38.8	N/A
Ryegrass	Dry	40	No	0.38	17	N/A	17.3	N/A
Ryegrass	Wet	40	No	0.24	26	N/A	27.1	N/A
AC	Dry	50	No[a]	0.73	13.0	N/A	13.0	N/A
AC	Dry & wet	48	Yes[a]	0.65	13.5	23.4	14.3	22.0
AC	Dry & wet	58	Yes[a]	0.59	19.8	43.9	20.5	42.0
AC	Dry & wet	68	Yes[b]	0.64	28.0	22.2	27.1	21.5

a) Asphaltic concrete

b) Differential friction Site 1.

c) Differential friction Site 2.

These results showed 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 was good agreement between the measured and computer-derived yaw angles. These findings indicated that PC-Crash provided 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 was particularly important, given the objective of investigating encroachment of vehicles from the sealed lane onto the roadside, where the friction values would 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 in Jamieson 2012) 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 that was travelling in the decreasing direction around a right-hand curve that had 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 photo 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 suggested that the vehicle's speed was at least 75km/h, possibly as high as 90km/h, and it 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 gave 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 B References

Batista, M, T Magister, and L Bogdanovic (2005) Computer based road accident reconstruction experiences. *Promet – Traffic – Traffico 17*, no.2: 65–75.

Cenek, PD and NJ Jamieson (2005) Friction-speed relationships for low textured road surfaces. Central Laboratories Report 05-529716.01 for Transit New Zealand.

Cenek, PD, NJ Jamieson and RJ Henderson (2011) Improved rate-of-rotation design limits. *NZ Transport Agency research report 456*. 62pp.

Gopal, M, K Baron and M Shah (2004) Simulation and testing of a suite of field relevant rollovers. *SAE Technical Paper Series 2004-01-0335*. 12pp.

Jamieson, NJ and PD Cenek (2002a) Differential friction – Investigation of vehicle yaw and cross-lane movement. Central Laboratories Report 02-529707.00 for Transit New Zealand.

Jamieson, NJ and PD Cenek (2002b) Investigation of the effects of texture on locked-wheel braking performance. Central Laboratories Report 02-529700.00 for Transit New Zealand.

Kunz, S (2007) Accident simulation and analysis using Vehicle Infrastructure Interaction Simulation (VIIS). *Young Researchers Seminar*, Brno, Czech Republic.

Moser, A and H Steffan (1996) The collision and trajectory models of PC-CRASH. *SAE Technical Paper Series no. 960886*.

Spit, HH (2000) Evaluation of PC Crash: as tool for professional traffic accident research and reconstruction). *TNO report 2000.*