Roundabout crash prediction models
June 2009

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NZ Transport Agency research report 386

ISBN 978-0-478-35220-7 (PDF)
ISBN 978-0-478-35221-4 (paperback)
ISSN 1173-3764 (PDF)
ISSN 1173-3756 (paperback)

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Turner, SA, AP Roozenburg and AW Smith. 2009. Roundabout crash prediction models. *NZ Transport Agency Research Report 386.* 102 pp.

Keywords: accident, accident prediction models, crash, cyclists, modelling, New Zealand, pedestrians, prediction, roundabouts, sight distance, speed, visibility

An important note for the reader

Acknowledgments

Firstly, we would like to thank Professor Graham Wood of Macquarie University in Sydney for his assistance in resolving the statistical problems associated with crash prediction modelling. Graham's ongoing development of the crash prediction modelling process is very much appreciated.

To Professor Bhagwant Persaud of Ryerson University in Canada, we express our gratitude for his advice throughout this study and his in-depth knowledge of North American and international safety analysis research.

We would also like to thank the Beca staff that worked on this project and who assisted in data collection, surveyor coordination, data analysis and project management. We would also like to thank the project steering group and peer reviewers who provided valuable input into the direction of this research.

Outside of the team working on this project, we would like to thank Glenn Connelly of Palmerston North City Council and Bruce Kelly of Christchurch City Council for providing the count data used in this study.

Abbreviations

AADT: Annual Average Daily Traffic

BIC: Bayesian Information Criterion

CAS: Crash Analysis System

NZTA: NZ Transport Agency

S_E: Entering speed

V_{10}: Visibility from 10 metres back from the limit line to vehicles turning right or travelling through the roundabout from their right.

Contents

Executive summary

Roundabouts are a popular choice for intersection control around New Zealand, particularly for replacing priority controlled intersections where traffic volumes are high and safety has deteriorated. However, safety problems can occur at poorly designed roundabouts, particularly where speed is not managed well and where cycle volumes are high.

Despite their generally good record, safety deficient roundabout designs have received considerable attention from safety auditors over the last 10 or so years. This culminated in the publication of the guide *The ins and outs of roundabouts*. This guide lists problems encountered in 50 safety audit reports. The guide lists visibility and geometric design features, particularly inadequate deflection and marking, as problem areas. The guide states that 'the safe and efficient movement of traffic relies on good unobstructed lines of sight'. The provision of good visibility at roundabouts follows the guidance in the Austroads *Guide to* t*raffic engineering practice part 6: roundabouts.* This practice, which occurs in New Zealand and Australia, differs to practice in other parts of the world, particularly Europe, where visibility is often restricted to reduce speeds and improve safety. This discrepancy was a major motivator for this research project.

While roundabouts often have better safety records overall when compared with other forms of control, they have a poor safety record with respect to cyclist crashes, particularly at large roundabouts with multiple lanes. This higher cycle crash risk at larger and medium roundabouts is probably caused by higher motor vehicle speeds, resulting in a larger speed differential between cyclists and motor vehicles. In addition, the increased complexity of negotiating multi-lane and high-speed roundabouts could be a reason why some drivers do not see cyclists.

This study, undertaken in 2006, aimed to investigate these issues by focusing on the relationship between crashes, speed, traffic volume and sight distance for various approach and circulating movements at roundabouts. This research extends on previous work into flow-only crash prediction models developed in New Zealand by including key non-flow variables. Given the impact vehicle speed is expected to have on the 'active' modes (walking and cycling) as opposed to the impact on motorised modes, separate models have been developed for crashes involving these modes. Future research will examine the impact that geometry has on various crash types.

The research team had access to existing sample sets of roundabouts that were collected in previous studies into crash prediction models for roundabouts. The majority of the sites in this dataset were in Christchurch and were single-lane, four-arm intersections. The researchers and steering group wanted a more geographically diverse dataset that would produce models that could be applied nationally, so a number of additional roundabouts were added from Auckland and Palmerston North. These roundabouts had a more diverse range of features, including three-, four- and five-arm junctions, and single and double circulating and approach lanes.

While a wide variety of roundabout features were included in the sample set, sites that had been constructed within the last five years or had undergone significant modification during this period were excluded, as their crash history over the last five years would not be representative. The broader selection criteria were:

- at least five years since installation
- all approaches two-way

- located in one of three centres (Auckland, Christchurch and Palmerston North)
- urban speed limits only (70km/h or less).

Data on each of the 104 roundabouts were collected on site. This included:

- manual motor vehicle, pedestrian and cyclist counts for each movement
- negotiation speeds of free vehicles travelling through the roundabout as they entered and circulated through the roundabout for each approach
- the sight distance between drivers entering the intersection to vehicles approaching from their right, measured from three locations:
  - at the limit line
  - 10m back from the limit line
  - 40m back from the limit line
- diameter
- number of lanes for each approach
- road markings
- super-elevation direction of circulating lanes (whether inwards or outwards)
- direction of the gradient of approaches
- location of lighting
- pedestrian and cycle facilities, where relevant
- surrounding land use
- features that obstruct the visibility.

Injury crash data associated with each approach for the period from 2001–2005 was obtained from the Ministry of Transport's Crash Analysis System database. Where roundabouts had been installed for 10 years, cyclist and pedestrian crash data were obtained for the period 1996–2001.

An additional dataset of crashes and link volumes at 17 high-speed roundabouts with speed limits of 80km/h or more was also collected to investigate the effect of higher speed limits. Given the limited number of sites that meet these criteria, all high-speed roundabouts for which data were readily available were included in the sample set.

We first analysed the relationships between key flow and non-flow variables, and explored the possibility of constructing predictive speed models based on these variables. The models developed initially did not have significantly high measures of fit, but results using statistical relationships among variables provided good methodological bases for crash prediction modelling, and will lead to further work on developing speed models.

Generalised linear models were then developed using either a negative binomial or Poisson distribution error structure, following an analysis of the appropriate functional forms. Using the Bayesian Information Criterion and grouped goodness of fit methodology, a preferred model for each crash type was determined. This preferred model has a parsimonious variable set and a good fit to the data, and comes from a large number of possible models.

Multiplicative factors were also produced for the difference in crash rate for low-speed roundabouts (70km/h and less) and high-speed (80km/h and more) roundabouts, as shown in the following model for the total number of crashes per roundabout approach:

$$A_{AAAR\,0} = 3.21 \times 10^{-4} \times Q_a^{0.66} \times \phi_{HS}$$

where:

A_{AAAR0} = annual number of all crashes occurring at an approach

Q_a = approach flow (sum of entering and exiting motor vehicle flows)

Φ_{MEL} = factor to multiply the crash prediction by if the speed limit on the approach is greater than 70km/h. This factor is: ϕ_{HS} = 1.35.

This model indicates that roundabouts with speed limits greater than 70km/h have a 35% higher crash rate than their counterparts in the urban environment.

For urban roundabouts, the most important non-flow variable was found to be vehicle speed. This is illustrated by the model for entering versus circulating crashes that did not involve cyclists, as shown below:

$$A_{UMAR\,1} = 6.12 \times 10^{-8} \times Q_e^{0.47} \times Q_c^{0.26} \times S_C^{2.13}$$

where:

A_{UMAR1} = annual number of entering versus circulating crashes involving motor vehicles only

Q_e = entering flow on the approach

Q_c = circulating flow perpendicular to the entering flow

S_C = free mean speed of circulating vehicles as they pass the approach being modelled.

This model illustrates that as the free mean speed of circulating vehicles increases, so does the number of crashes. The relationship between increasing speeds and increasing crashes is similar for other crash types, and is supported by international studies of roundabout safety. Another important variable is the visibility of vehicles approaching from the right, particularly for loss of control type crashes. Interestingly, this indicates that crashes increase with increasing visibility.

It was found that higher visibility is directly correlated to higher vehicle speeds, indicating that the increase in crashes may be more to do with higher speeds, which are a result of greater visibility. Crashes therefore increase because as visibility increases, so does the speed. Another important finding is that roundabouts with multiple entry lanes have a much higher number of crashes (66% more) than single-lane roundabouts, even when the increased volume at the former is taken into account.

The authors recommend that:

- further research is undertaken to determine how negotiation speed through the roundabout is affected by roundabout geometry and visibility, and in turn how this influences safety
- the models for total roundabout crashes per approach for urban and high-speed roundabouts be included in the NZ Transport Agency's *Economic evaluation manual vol. 1*, replacing the existing product of link models.

Abstract

The management of speed is considered an important safety issue at roundabouts. The approach speed and negotiating speed through roundabouts depends on the geometric design of the roundabout and sight distance. In New Zealand and in Australia, the design standards recommend long approach sight distances and provision of relatively high design speeds. This is in contrast to European roundabouts, where visibility is normally restricted and the geometric design encourages slow approach and negotiation speeds. This work, undertaken in 2006, extends previous research by the authors developing crash prediction models at roundabouts to include sight distance, intersection layout and observed speed variables.

Models have been produced for the major motor vehicles only, pedestrians versus motor vehicles and cyclists versus motor vehicle crash types. Flow-only models have also been produced for roundabouts on roads with high speed limits. The models produced indicate that roundabouts with lower speeds (observed and speed limit), fewer approach lanes and reduced visibilities have lower crash rates.

1. Introduction

1.1 Background

Roundabouts are a popular choice for intersection control around New Zealand, particularly to replace priority controlled intersections where traffic volumes are high and safety has deteriorated. However, safety problems can occur at poorly designed roundabouts, particularly where speed is not managed well and where cycle volumes are high.

Safety deficiencies in existing and proposed roundabouts have received considerable attention from safety auditors over the last 10 years or more. The reoccurrence of common deficiencies in the design of new roundabouts in New Zealand culminated in the publication of the guide *The ins and outs of roundabouts,* which was published by Transfund New Zealand (2000). This guide provides a list of problems that have been encountered in 50 safety audit reports. Visibility and geometric design features, particularly inadequate deflection and marking, feature as problems in many of the safety audit reports. While not specifically mentioned in this report, approach and negotiating speed have the potential to exacerbate any geometric and other deficiencies present at a roundabout.

Roundabouts, particularly large and two-lane roundabouts, have a poor safety record with respect to cyclists. This is illustrated in the proportion of injury crashes involving cyclists at roundabouts (25%), compared with signalised crossroads (8%) and priority crossroads (11%). Many cycle advocates have strong opinions on this matter and strongly oppose the use of roundabouts, particularly larger roundabouts, on cycle routes. Two main reasons are given for this increased crash risk to cyclists:

- As roundabouts become larger, with more lanes and often higher speeds, they become more complex to negotiate by motor vehicle drivers, and motorists are less likely to see cyclists because of the relatively small size of cyclists.
- As motor vehicle speeds increase, the relative speed between cyclists and motor vehicles increases and drivers are more likely to overtake cyclists in an unsafe manner, while cyclists are more likely to misjudge the gap/space required for various manoeuvres.

It is expected that reduced vehicle speeds and complexity (single-lane circulating) should improve safety for cyclists.

The research presented in this report, which was carried out in 2006, focuses on the relationship between crashes, speed, traffic volume and sight distance for various approach and circulating movements at roundabouts. The flow-only models developed by Turner (2000) are extended in this study to include observed speed, sight distance and intersection layout variables in various forms. Given the impact vehicle speed is expected to have on ‘active’ mode (walking and cycling) crashes, compared with motor vehicle only crashes, separate models have been developed for the major crash type for each mode.

1.2 Objectives

The purpose of this research is to extend the current flow-only motor vehicle crash prediction models developed by Turner (2000) and the flow-only cyclist crash prediction models developed by Turner et al (2006) for roundabouts to include design (eg number of through-lanes), visibility, and approach and negotiation speed variables.

The research objectives are:

- **to develop crash prediction models for motor vehicle only crashes at roundabouts that include significant flow and non-flow variables:** this may include turning traffic volumes, inter-vehicle visibility, approach and negotiating vehicle speed, and geometric variables such as approach alignment, inscribed circle diameter, number of lanes and deflection
- **to develop crash prediction models for cycle versus motor vehicle crashes at roundabouts that include significant flow and non-flow variables:** this includes turning motor vehicle and cycle volumes, how visible circulating cyclists are to approaching motorists, approach and negotiating vehicle speed, and geometric variables such as approach alignment, number of lanes and inscribed circle diameter
- **to develop crash prediction models for pedestrian versus motor vehicle crashes at roundabouts that include significant flow and non-flow variables:** this may include turning motor vehicle flows, crossing pedestrian flows, approach and negotiating vehicle speeds, pedestrian crossing time, and geometric variables such as pedestrian crossing facilities, number of lanes and deflection
- **to provide guidance to traffic engineers (particularly safety auditors) and geometric designs on the key design elements that influence the safety of motor vehicle occupants, cyclists and pedestrians at roundabouts**, which will enable safety auditors to prioritise design elements that need to be fixed at existing roundabouts
- **to address the lack of research on the impact that visibility and negotiating speed have on crash occurrence at roundabouts.** While competent safety auditors have opinions on the influence of such factors on the safety of road users and identify such factors in their safety audit reports, they are unable to quantify the effect on safety of each factor.
- **to explore the possibility of developing predictive models for entering and circulating speeds based on other key variables,** both as an end in itself and also for integration with crash prediction models where speed data is not available.

1.3 Report structure

This report has been divided into five sections (chapters 2–6), excluding the introduction, conclusions references and appendices:

- Chapter 2 introduces the topic of crash types and user involvement in roundabout crashes in New Zealand, and reviews other studies that have investigated the effect of visibility and speed on crash occurrence at roundabouts.
- Chapter 3 details the site selection criteria and the data that was collected, while chapter 4 analyses the relationships between speed, visibility and traffic volume obtained from this data. Chapter 4 also gives an analysis of the relationships among variables that potentially contribute to crash rates.
- Chapter 5 outlines the crash prediction modelling process, the analysis of goodness of fit, selection of the preferred models and the interpretation of the modelled relationships.
- Chapter 6 presents the preferred models for each crash type and other statistically significant relationships uncovered.
- Chapter 7 develops predictive models for speed, based on key variables.

These chapters are followed by conclusions and recommendations, and four appendices:

- Appendix A contains all the crash prediction models developed in the study
- Appendix B presents the Crash Analysis System (CAS) codes used by the NZ Transport Agency (NZTA).
- Appendix C explains the model subscripts.
- Appendix D presents the aerial photos for a selection of the roundabouts studied; these photos were used to measure the roundabouts' geometrics (see section 3.11).

2. Roundabout crash trends and previous studies

2.1 General

The first task was to examine the crashes that occur at urban roundabouts and to investigate which roundabout features should be included in the models as possible predictor variables.

This involved:

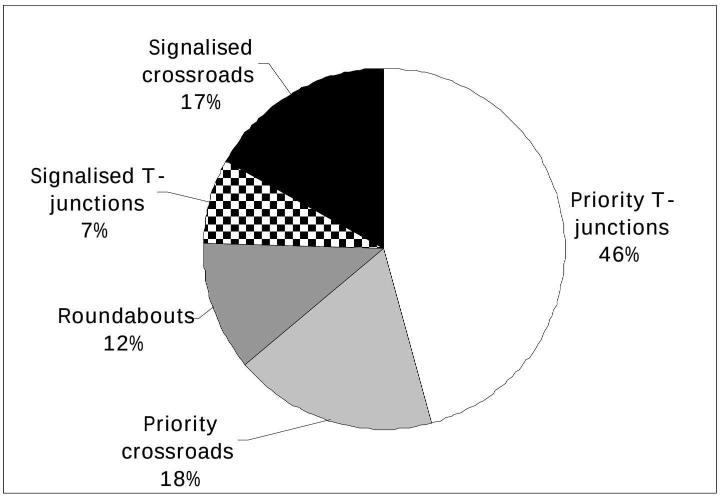
- examining the involvement of pedestrians and cyclists in crashes at roundabouts
- determining the major crash types occurring at roundabouts for the various modes
- reviewing other studies on roundabouts to check that we include all important prediction variables and to check how visibility and speed have been introduced in the crash predictions.

2.2 New Zealand crash data

The Ministry of Transport's CAS contains details of all crashes reported by the police to the NZTA. National crash data was extracted from CAS for all urban roundabouts and other forms of intersection control between 2001 and 2005. Urban intersections have a speed limit of 70km/h or less on all approaches. Most roundabouts have a 50km/h speed limit on all approaches.

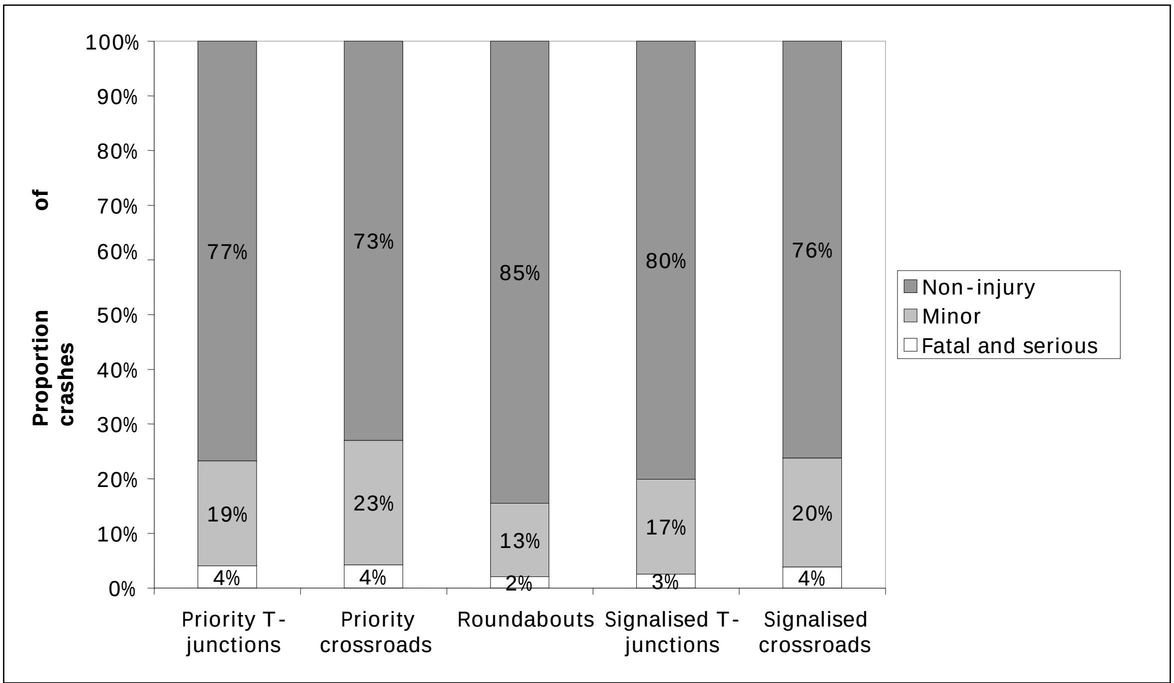
Figure 2.1 shows the location of injury and non-injury combined urban intersection crashes during 2001–2005. This shows that 12% of intersection crashes occur at roundabouts.

Figure 2.1 Intersection control of urban intersection crashes (2001–2005)



The proportion of crashes at each form of intersection control is related to the number of intersections of each type and the number of crashes occurring at each, which is a function of the form of control and the traffic volume. The form of control also influences the severity of crashes. Figure 2.2 illustrates the severity of crashes at each form of control and shows that roundabouts have the lowest severity of all intersection types examined. The intersection types with the highest severity are crossroads, particularly priority crossroads. This is because at crossroads, crashes can occur where vehicles are travelling perpendicular to each other at speed, resulting in an impact to the side of the vehicle, where occupants have less protection than when hit at an acute angle or from behind.

Figure2.2 Severity of crashes by form of control (2001–2005)



The roundabout crash data was disaggregated at several levels in order to produce useful statistics for analysis. The first step in disaggregating the crash data was to categorise reported crashes by severity. Non-injury crashes are generally excluded from any analysis because of their generally low – and at times highly variable – reporting rates.

The crash types within the NZTA's crash coding system (see appendix B) were then analysed. Figure 2.3 shows that the majority of injury and fatal crash types are entering v circulating crashes, followed by loss of control crashes.

Figure 2.3 Crash type of injury crashes at urban roundabouts (2000–2004)

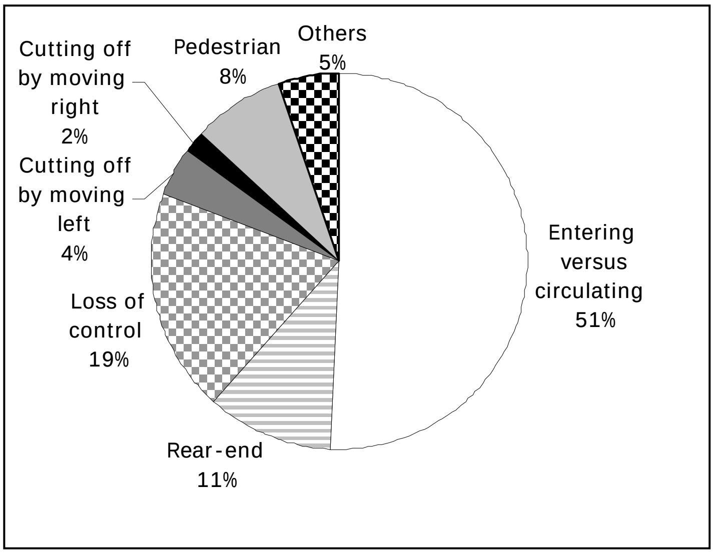
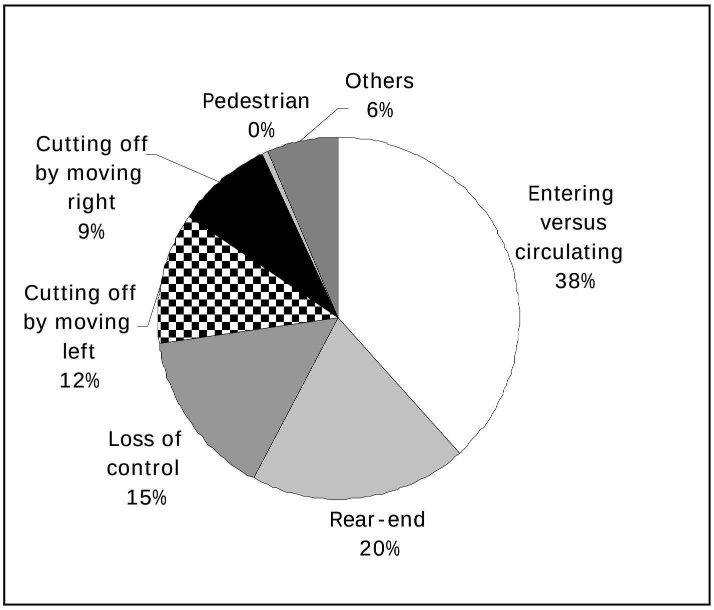


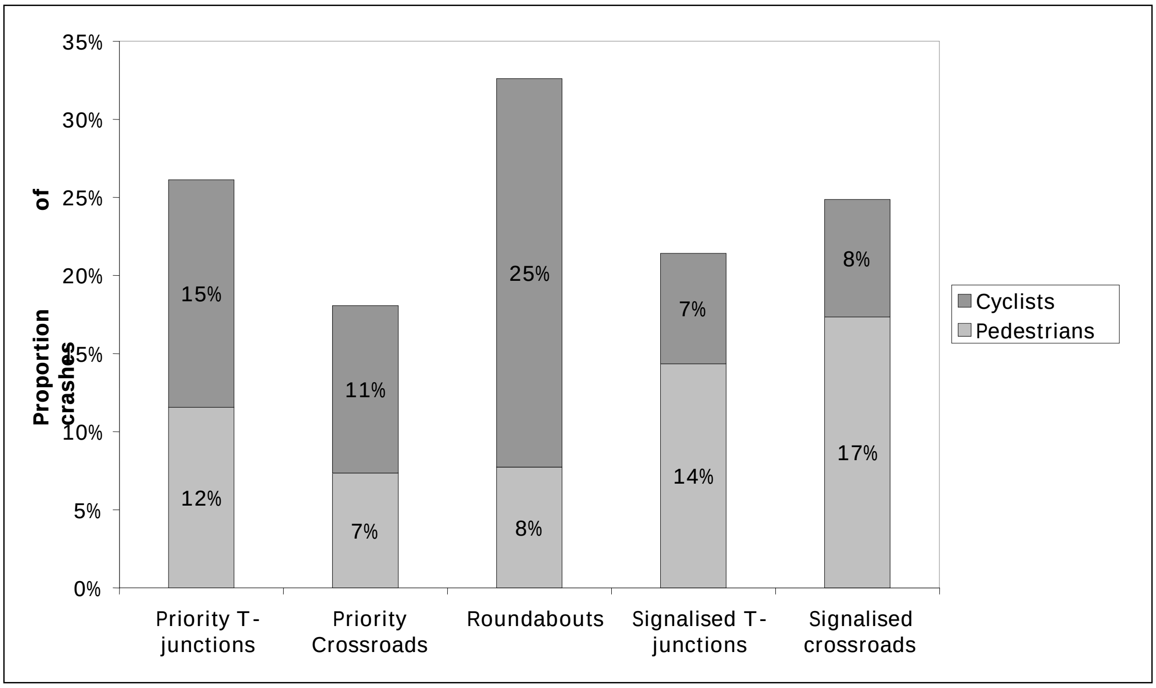
Figure 2.4 shows the proportion of each crash type for non-injury crashes. This figure shows that entering v circulating crashes are less common in non-injury crashes. The proportion of entering v circulating crashes drops from 51% of all injury crashes to 38% of non-injury crashes, indicating that this crash type has a higher severity than other crash types. This would be because crashes where the side of the vehicle is struck are more severe than crashes to the rear and front of the vehicles where the occupants have more protection.

Figure2.4 Crash type of non-injury crashes at urban roundabouts (2000–2004)



When stating the proportion of crashes involving pedestrians and cyclists at roundabouts, the proportion of all reported crashes is often stated. This is misleading because of the generally higher injury severity of crashes involving these modes when compared to motor vehicle only crashes, meaning that cyclists and pedestrians are involved in a greater proportion of injury crashes. Figure 2.5 shows the relative proportions of injury crashes involving cyclists and pedestrians for different forms of intersection control. Cyclists are involved in a much greater proportion of injury crashes at roundabouts compared to other intersection types. The large difference in the proportion of pedestrian crashes between these two intersection types is likely to be because signalised intersections are prevalent in areas of high pedestrian demand.

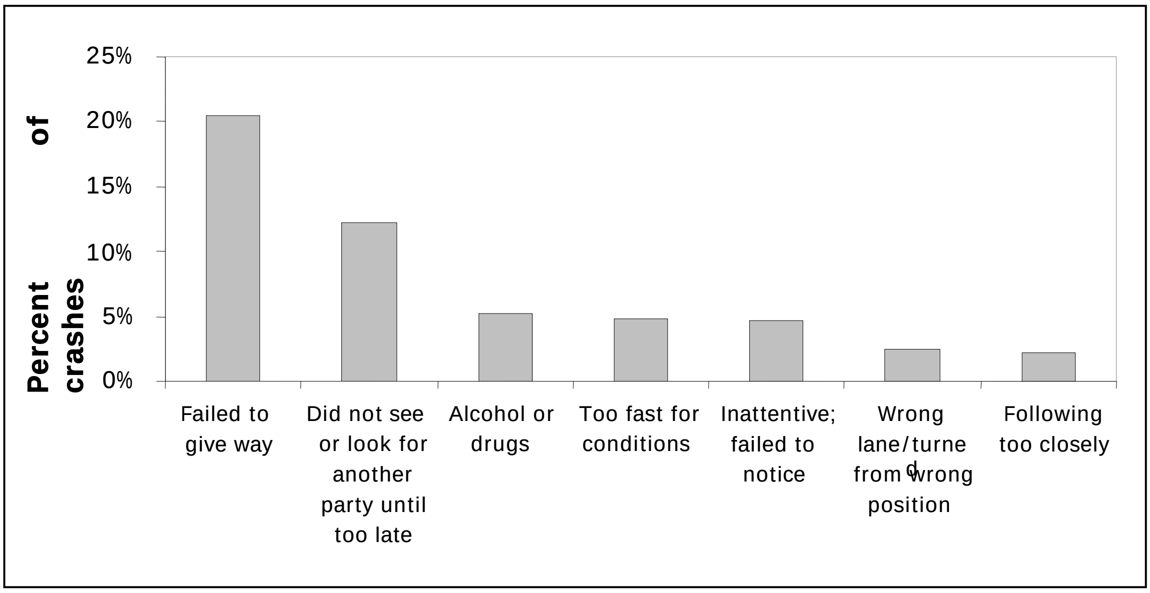
Figure2.5 Pedestrian and cyclist involvement in injury crashes for different intersection control types (2000–2004)



The majority of pedestrian crashes at roundabouts involved pedestrians crossing perpendicular to the vehicle direction of travel. Because of the crash coding process, it is not clear nationally whether these occur on the exit or entering lanes. Of the cycle crashes at roundabouts, 82% of are entering v circulating crashes, 74% of which occur when the cyclist is circulating and the motor vehicle is entering (approximately 60% of cycle crashes).

Figure 2.6 shows the frequently listed crash causes for injury crashes at roundabouts. The high proportion of crashes where a road user failed to give way reflects the high proportion of entering v circulating crashes.

Figure 2.6 Percent of crashes where a particular cause is reported



2.3 Influence of speed, visibility and design

2.3.1 Previous roundabout crash prediction model studies

A small number of studies internationally have examined the influence of roundabout design on crash occurrence. The majority of studies on roundabout safety focus on the conversion of priority and signal controlled intersections to roundabout control.

This section summarises the results of four studies investigating the effect of roundabout design. These include studies undertaken in New Zealand, Australia, the United Kingdom and Sweden. The New Zealand and Australian studies are investigated in detail, as designers in both countries generally follow the design advice in the Austroads *Guide for roundabout design* (Austroads 1993). The final section summaries the key variable relationships pertaining to the objectives of this study.

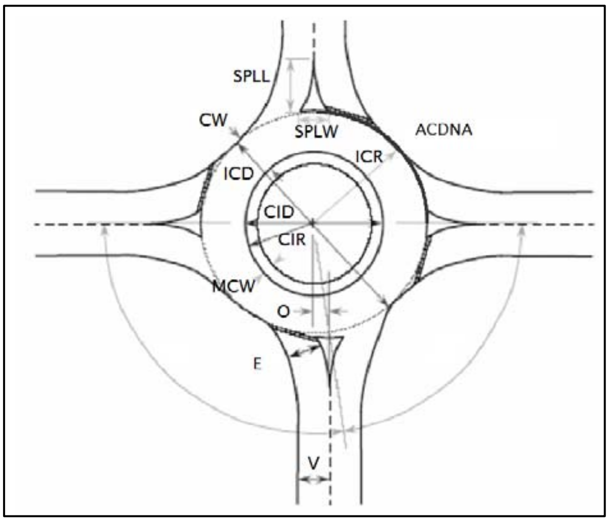
2.3.2 Harper and Dunn (2005) – New Zealand

Harper and Dunn (2005) detail research on the development of crash prediction models for roundabouts, including geometric variables. Their models were developed using a dataset of 95 urban roundabouts throughout New Zealand. A number of the roundabouts used in this study were common to the study undertaken by Turner (2000) and this study.

Harper and Dunn (2005) developed models for individual crash types and product of link crashes using similar crash types to those used by Turner (2000). They found that in most cases, the inclusion of geometric variables improved the predictive accuracy of the models.

Scaled aerials were used to measure a number of geometric variables. The measurements were taken in respect to each approach. Harper and Dunn (2005) noted that sight distance could not be accurately calculated from aerial photos and therefore excluded this from their analysis. Also, deflection was excluded from the analysis, as no apparent standard had been established for defining the deflection path. The geometric characteristics used in the study are illustrated in figure 2.7.

Figure 2.7 Basic geometric measurement definition plan (from Harper and Dunn 2005)



Notes to figure 2.7:
CW = circulating width
SPLL = splitter island length
SPLW = splitter island width
ACDNA = alternative chord distance to next approach
ICR = inscribed circle radius
ICD = inscribed circle diameter
CID = central island diameter
CIR = central island radius
MCW = median circulating width
O = offset
E = entry width
V = approach half width

Harper and Dunn (2005) outlined the methodology used in developing the models. Models were developed using generalised linear modelling techniques with Poisson and negative binomial error structures. It was stated that model accuracy and fit were measured using the χ^2, R^2 and $1 - Pr(>|z|)$ statistical measures. A 'bottom up' process was employed to construct the models to avoid overcomplicating the relationships and to minimise the number of explanatory variables. The model form used for the conflicting flow models is specified in equation 2.1.

$$A = b_0 \times Q_e^{b_1} \times Q_c^{b_2} \times e^{\sum G_i b_i} \qquad \text{(Equation 2.1)}$$

where:

A = accidents (crashes) per year

Q_e = entering flow on the approach

Q_c = circulating flow perpendicular to the entering flow

G_i = geometric variables

b_i = model parameters.

It was found that the entering v circulating, rear-end and pedestrian flow-only crash prediction models had relationships to flow that were similar to those developed in Turner (2000). It was reported that models for loss of control and rear-end crashes could not be enhanced by the addition of any of the 28 geometric variables tested. Harper and Dunn (2005) stated that this is not surprising, as the traffic volume variables make many of the geometric variables redundant for the purposes of crash prediction, as a number of the variables were correlated with flow.

The model for the total number of crashes included only one non-flow variable. Equation 2.2 shows this model.

$$A_{Total} = 5.31 \times 10^{-4} \times Q_e^{0.47} \times Q_c^{0.29} \times e^{ACWL \times 0.057} \quad \text{(Equation 2.2)}$$

where:

$ACWL$ = adjacent circulating width left: The circulating width between the current approach and the next approach in a clockwise direction (see 'CW' (circulating width) in figure 2.7)

Q_e = entering flow on the approach

Q_c = circulating flow perpendicular to the entering flow.

Harper and Dunn stated that the significance of the *ACWL* variable seemed to be a strange result and argue that the circulating width at this point constricts all vehicles entering and circulating the roundabout, and therefore has a significant influence on the crash frequency. The parameter of this variable indicates that as *ACWL* increases, so does the number of crashes.

Two geometric variables were significant in models for entering v circulating crashes. Equation 2.3 shows this model.

$$A_{EvC} = 2.93 \times 10^{-5} \times Q_e^{0.59} \times Q_c^{0.73} \times e^{(ACDNA \times -0.057)+(EL \times -0.52)} \quad \text{(Equation 2.3)}$$

where:

A_{EvC} entering v circulating accidents per year

$ACDNA$ = alternative chord distance to next approach: the distance between the tip of the splitter island of the current approach and that of the next approach in a clockwise direction, based on the average inscribed circle radius of both approaches (see figure 2.7)

EL = number of entry lanes (ie the number of entry lanes in the current approach)

Q_e = entering flow on the approach

Q_c = circulating flow perpendicular to the entering flow.

Harper and Dunn state that the entering v circulating model is possibly the most logical, with the number of entry lanes and distance to the next approach having strong significance. Their model indicates that the number of crashes of this type decrease with increasing numbers of entry lanes and greater circulating radius.

Harper and Dunn also developed models for pedestrian crashes. Equation 2.4 shows this model. The model includes all crossing locations, which included some geometric variables and specific ones for crossings with kerb cut-downs only, zebra crossings and signalised crossings. The number of approaches with each facility type is not clarified in this paper. It should be noted that the numbers of pedestrians crossing each roundabout approach are not included in the model. The model indicates that as the distance of the crossing from the intersection increases, so does the number of crashes. This may be caused by a reduction in intervisibility between drivers exiting the roundabout and pedestrians crossing at the crossing point, and an increase in vehicle speeds (as drivers accelerate out of the roundabout).

$$A_{Ped} = 4.10 \times 10^{-4} \times Q_c^{0.63} \times e^{(PDG \times 0.058)} \qquad \text{(Equation 2.4)}$$

where:

A_{Ped} = pedestrian crashes per year

PDG = pedestrian crossing distance to the give way line: the distance from the give way line of the current approach to the closest point of the pedestrian crossing

Q_c = circulating flow perpendicular to the entering flow.

2.3.3 Arndt (1994, 1998) – Australia

Ardnt developed models using multiple linear regression with independent variables related to flow, 85th percentile speed, vehicle path radius and changes in 85th percentile speed (as a vehicle progresses through the roundabout) for roundabouts in Queensland, Australia. The first study (Arndt 1994) included the first set of models, while the second (Arndt 1998) included models for additional crash types, and was refined to include variables such as the number of approach lanes, the vehicle path radius (the curve radius of different elements for vehicles travelling through the roundabout) and the length of each vehicle path (distance travelled by vehicles through the roundabout).

Both rural and urban roundabouts were included in the study, with a total sample size of 100 roundabouts. Seventy-two percenthad four arms and 61% had at least one approach with multiple entering and circulating lanes.

To determine 85th percentile speeds through a roundabout, Arndt calculated theoretical speeds based on curve radii using a modified version of a method to calculate speeds for various curve radii on rural roads. To do this, curve radii through the roundabout from each approach had to be measured. Curve radii were measured assuming a vehicle path that would allow the highest possible speed and therefore the largest radius. The process of calculating the approach, circulating and departure curve radii is described in the *Road planning and design manual* (Department of Main Roads 2005) and is summarised for roundabouts with single and multiple lanes in figure 2.8 and figure 2.9 respectively.

Figure2.8 Vehicle path construction through a single-lane roundabout (Department of Main Roads 2005)

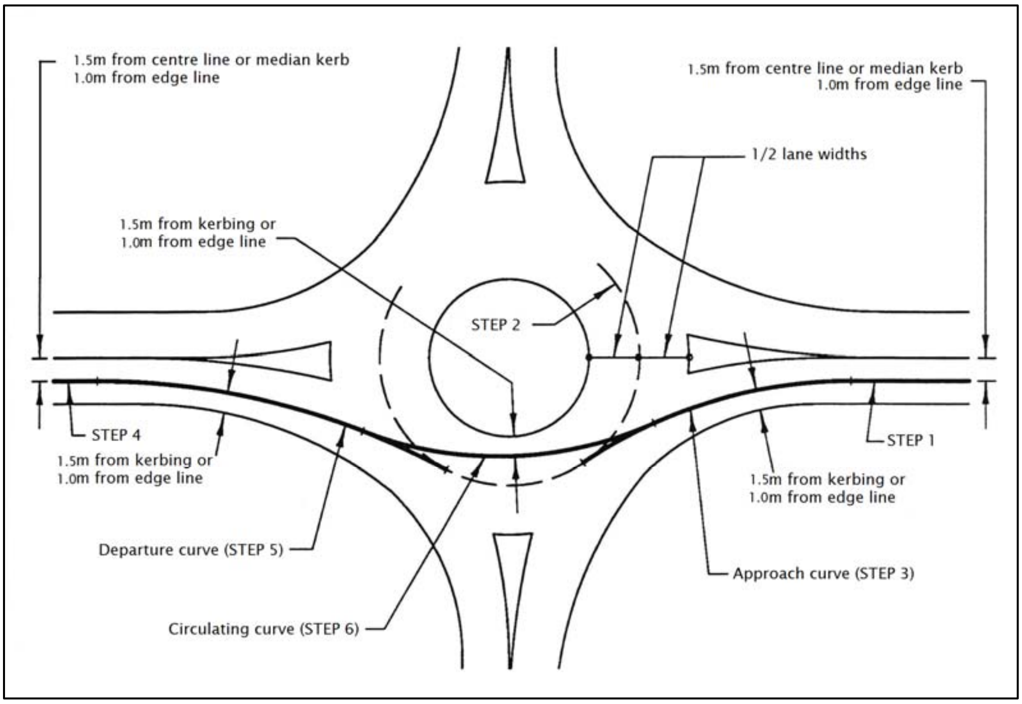
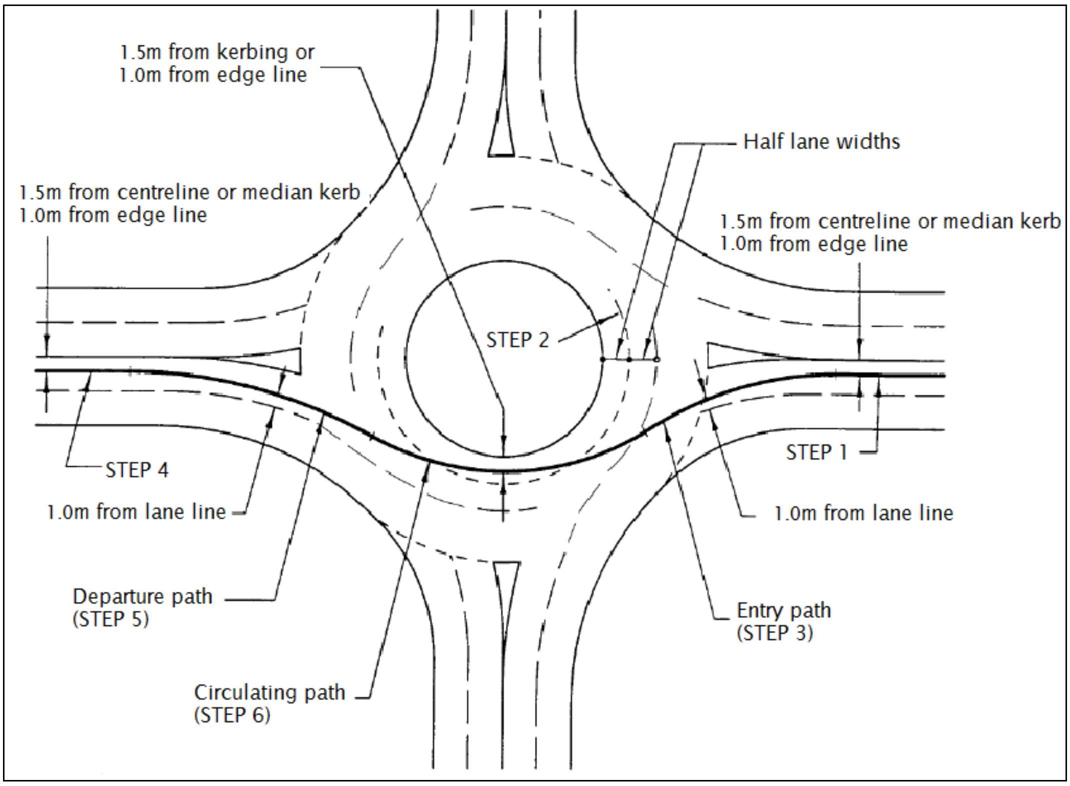


Figure2.9 Vehicle path construction through a double-lane roundabout (Department of Main Roads 2005)



Arndt developed linear and non-linear regression models with a Poisson error structure. Models for the main six crash types were developed. These were:

- single vehicle crash model
- rear-end vehicle crash model
- entering v circulating vehicle crash model
- exiting v circulating vehicle crash model
- sideswipe vehicle crash model
- other vehicle crash model.

Two models for single vehicle crashes are presented. The models do not apply to vehicles turning left. The models are for crashes prior to (equation 2.5) and after (equation 2.6) the give way line. Eighteen percent of the 492 crashes in Arndt's dataset are single vehicle crashes.

$$A_{sp} = 1.64\times10^{-12}\times Q^{1.17}\times L\times(S+\Delta S)^{4.12}\times R^{-1.91} \quad \text{(Equation 2.5)}$$

$$A_{sa} = 1.79\times10^{-9}\times Q^{0.91}\times L\times(S+\Delta S)^{1.93}\times R^{-0.65} \quad \text{(Equation 2.6)}$$

where:

A_{sp} = number of single vehicle crashes per year per approach *prior* to the give way line

A_{sa} = number of single vehicle crashes per year per approach *after* the give way line

Q = flow in direction considered (Q_e for A_{sp}, Q_c for approach to left for A_{sa})

L = length of vehicle path on the horizontal geometric element (length prior to or after the give way line)

S = 85th percentile speed on the horizontal geometric element (85th percentile speed prior to or after the give way line)

ΔS = decrease in 85th percentile speed at the start of the horizontal geometric element (decrease in 85th percentile speed prior to or after the give way line)

R = vehicle path radius on the horizontal geometric element (radius of vehicle path prior to or after the give way line).

Equations 2.5 and 2.6 indicate that crashes increase with increased 85th percentile speeds and change in 85th percentile speeds. Interestingly, the models predict that as radii increase, the number of crashes decreases. This is obviously contradictory with the first finding, as speeds will be directly correlated to radii, as would radii and segment length.

Eighteen percent of the total crashes in Arndt's dataset are rear-end crashes that occur when vehicles approach a roundabout. Equation 2.7 shows the model for this crash type.

$$A_r = 1.81 \times 10^{-18} \times Q_e^{1.39} \times Q_c^{0.65} \times S_a^{4.77} \times N_e^{2.31} \quad \text{(Equation 2.7)}$$

where:

A_r = number of approaching rear-end vehicle crashes per year per approach

Q_e = entering flow on the approach

Q_c = circulating flow perpendicular to the entering flow

S_a = 85th percentile speed on the approach curve

N_e = number of entry lanes on the approach.

Like the models for single vehicle crashes, higher 85th percentile speeds would result in higher numbers of crashes per year. The model also indicates that an approach with similar flows and speeds but with a single entry lane would have 80% fewer crashes than an approach with two entry lanes.

Fifty-one percent of crashes in Arndt's dataset are entering v circulating crashes, making it the dominant crash type. Equation 2.8 shows the model for this crash type.

$$A_{EvC} = 7.31 \times 10^{-7} \times Q_e^{0.47} \times N_c^{0.9} \times Q_c^{0.41} \times S_{ra}^{1.38} \times t_{Ga}^{-0.21} \quad \text{(Equation 2.8)}$$

where:

A_{EvC} = number of entering v circulating vehicle crashes per year per approach

Q_e = entering flow on the approach

Q_c = circulating flow perpendicular to the entering flow

N_c = number of circulating lanes adjacent to an approach

S_{ra} = the average relative 85th percentile speeds between vehicles on the approach curve and circulating vehicles from each direction (km/h)

t_{Ga} = the average time taken to travel from the give way lines of the preceding approaches to the intersection point between entering and circulating vehicles.

Equation 2.8 indicates that the number of crashes increases with increasing circulating vehicle lanes and average relative 85th percentile speeds, and decreases with increasing average travel times between approaches.

Arndt developed a model for exiting versus circulating crashes on multi-lane roundabouts. Equation 2.9 outlines the model for this crash type.

$$A_{EvX} = 1.33 \times 10^{-11} \times Q_c^{0.32} \times Q_x^{0.68} \times S_{ra}^{4.13}$$ (Equation 2.9)

where:

A_{EvX} = number of entering v exiting vehicle crashes per year per departure approach

Q_x = exiting flow on the approach

Q_c = circulating flow perpendicular to the departure approach being modelled

S_{ra} = average relative 85th percentile speeds between vehicles on exiting and vehicles circulating.

Equation 2.9 indicates that crashes will increase with greater relative exiting and circulating speeds.

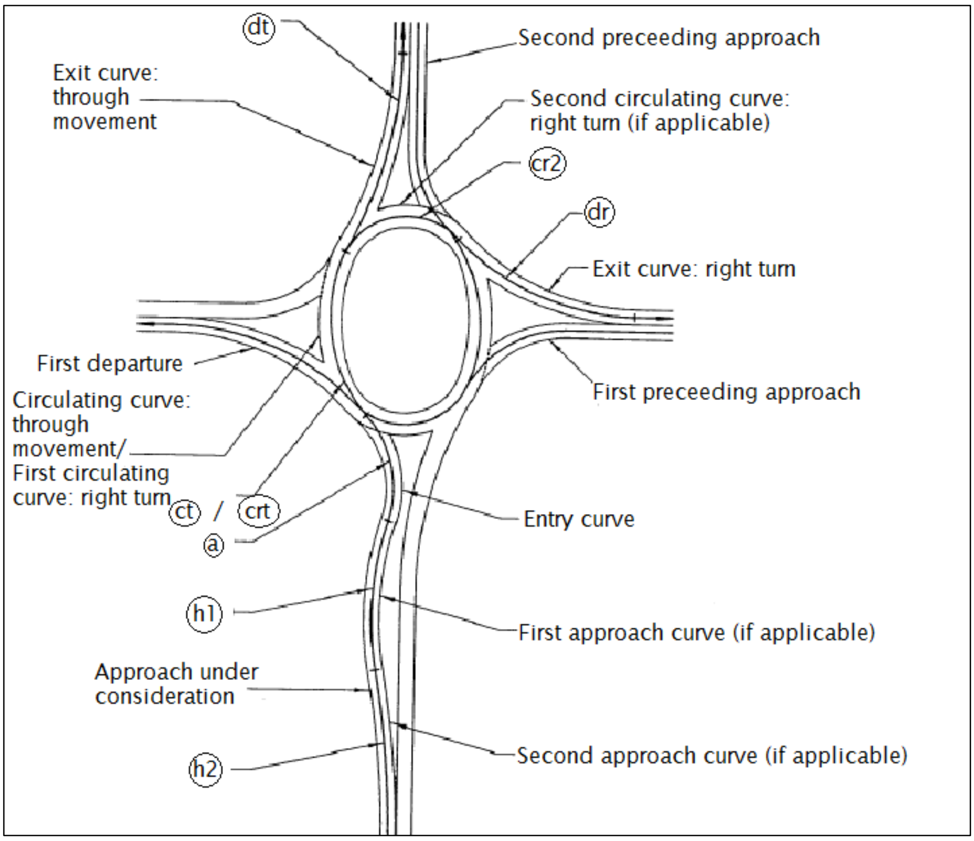
A model was developed for 'sideswipe' crashes on roundabouts with multiple lanes. The model was applied separately to:

- road segments prior to the approach curve and on the approach curve
- the circulating through-segment
- the circulating right-turn segment
- the departing through segment
- the departing right-turn segment.

Crashes occurring on these segments contribute 4% (18 crashes) to the total number of crashes. Given the small number of observed crashes, care should be applied when using such a model.

This model uses a product of the total flow (*Q*) on the particular geometric elements (see figure 2.10) and the flow of a particular movement (Q_t). The flows differ depending on which geometric element is being considered; these are outlined in table 2.1. Equation 2.10 outlines the model for this crash type.

Figure 2.10 Vehicle path segments used for modelling crash rates by Arndt (Department of Main Roads 2005)



Note to figure 2.10: the abbreviations in this diagram relate to computer coding and are not relevant to this report.

Table 2.1 Parameters used for modelling sideswipe traffic flows

Movement	Parameter	Applicable traffic flow
Approach	Q	Total approaching traffic flow
	Q_t	Total approaching traffic flow
Entering	Q	Total approaching traffic flow
	Q_t	Total approaching traffic flow
Circulating through	Q	Circulating through-traffic flow
	Q_t	Total circulating through-traffic flow
Circulating right-turn	Q	Circulating right traffic flow
	Q_t	Total circulating through-traffic flow
Exiting through	Q	Exiting through-traffic flow
	Q_t	Total departing traffic flow
Exiting right-turn	Q	Exiting right traffic flow
	Q_t	Total departing traffic flow

$$A_{ss} = 6.49 \times 10^{-8} \times (Q \times Q_t)\ 0.72 \times \Delta f_1\ 10.59 \quad \text{(Equation 2.10)}$$

where:

A_{SS} = number of sideswipe vehicle crashes per approach per vehicle path segment

Δf_1 = difference in potential side friction (km/h²/m).

The difference in potential side friction is calculated with equation 2.11.

$$\Delta f_1 \left| \frac{(S_C + \Delta S_C)^2}{127 \times R} - \frac{(S_{C+\Delta S_C})^2}{127 \times R_C} \right| \quad \text{(Equation 2.11)}$$

where:

S_c = 85th percentile speed on the horizontal geometric element for the particular movement for vehicles cutting lanes

ΔS_c = decrease in 85th percentile speed at the start of the horizontal geometric element for the particular movement for vehicles cutting lanes

R_c radius of vehicle path for vehicles cutting lanes

R radius of vehicle path for vehicles not cutting lanes.

For completeness, Arndt developed a model for the crashes types not included in any of the other model categories. The model is simply the total remaining crashes divided by the total number of vehicles entering all the roundabouts in one day. Equation 2.12 presents this model.

$$A_0 = 4.29 \times 10^{-6} \times \Sigma Q_e \quad \text{(Equation 2.12)}$$

where:

A_0 = number of ‘other’ crashes per year

ΣQ_e = sum of all flows entering the roundabout.

2.3.4 Maycock and Hall (1984) – United Kingdom

Maycock and Hall studied 84 four-arm roundabouts in the United Kingdom using generalised linear modelling. Maycock and Hall used traffic flow variables and geometric variables describing the characteristics of each intersection. They also developed models for pedestrians and used pedestrian crossing volumes in their models. They found that the traffic flow variables explained a lot more of the variation in the crash occurrence than the geometric variables, and that, in many cases, the geometric variables were not statistically significant and could therefore be removed from the models.

Maycock and Hall divided the crashes that occurred at the roundabouts into five crash types which were associated with each approach of the intersection. The crash types were:

- entering v circulating crashes
- approaching crashes
- single-vehicle crashes
- other crashes (all crashes not included in other categories
- pedestrian crashes (any crash involving a pedestrian).

Three different types of model were developed with varying levels of complexity. The lowest level of complexity was the product of links model, which calculated the total number of injury crashes as a function of vehicle and pedestrian flows. The second level models are similar to the first, but predict crashes by crash type and use specific turning movements that are conflicting flows. The third and highest level models are the same as the second but include non-flow variables such as geometry. It is these third level models which are of primary interest here.

In developing the level 1 models, it was found that the numbers of crashes were higher at roundabouts with small central islands than roundabouts with 'normal' central islands. In general, roundabouts with higher speed limits on the approaches also had higher crash rates.

For entering v circulating crashes, Maycock and Hall found that crashes increased with increasing entry width, percentage of motorcycles and increasing uphill gradient on the approach to the roundabout. It was also found that crashes decreased with increasing angle between the approach and the approach to the left, and increasing entry path curvature.

Maycock and Hall found that approaching crashes increased with increasing sight distances, decreasing entry path curvature (higher radius), decreasing entry width and decreasing uphill gradient.

For single-vehicle crashes, the number of crashes increased with increasing approach width, decreasing entry path curvature and increasing sight distances.

For 'other' and pedestrian crashes, no non-flow variables included in the analysis were significant.

2.3.5 Brude and Larsson (2000) – Sweden

Brude and Larsson (2000) surveyed 650 of Sweden's approximately 700 roundabouts and classified them with respect to geometric design, speed and a number of other factors. Crash data was then collected as well as the number of vehicles, cyclists and pedestrians passing through the roundabouts for a number of sites. Three studies were then undertaken into speed at 536 roundabouts, cyclist and pedestrian safety at 72 roundabouts, and motor vehicle safety at 182 roundabouts.

Speed surveys were conducted by driving through each roundabout and measuring the entering, circulating and exiting speeds through the roundabouts. A non-linear regression was then carried out and a speed prediction model was developed. These steps revealed the following:

- Speeds are higher when the general speed limit is higher than the local limit.
- Speeds were higher on multi-lane roundabouts than on single-lane roundabouts.
- Speed is lower if the radius of the central island is 10–20m than if it is smaller or larger.
- Flaring the approach to the left reduces speeds into and through the roundabout (Sweden drives on the right-hand side of the road).
- Provision of additional trafficable area around the central island has no effect on speed.

The study investigating pedestrian and cyclist crashes included roundabouts where cyclist volumes were assessed to be at least 100 cyclists per day. The factor that had the greatest effect on crashes involving cyclists, apart from cyclist and motor vehicle volume, was the number of lanes. Brude and Larsson also found that fewer cyclist crashes occurred if the radius of the central island was greater than 10m. They found that it was safer for cyclists to travel on cycle bypasses than on the roadway. They found that single-lane roundabouts were much safer for pedestrians than multi-lane roundabouts.

Brude and Larsson also studied motor vehicle crashes at 182 roundabouts from 1994–1997. Crash prediction models were developed and made several interesting findings:

- The number of crashes is directly proportional to speed.
- The number of injuries has approximately a quadratic relationship with speed.
- The lower the speed limit, the lower the crash risk and the lower the number of injuries per crash.
- Crash and injury rates are higher if the radius is large (>25m) or small (<10m). Brude and Larsson suggest that roundabouts with large radii result in higher speeds. Where radii are small, vehicles can travel straight through the roundabout, resulting in higher speeds and more crashes.

2.3.6 Summary of key relationships

This section summarises the key relationships that pertain to this study.

Number of entry and circulating lanes

Arndt (1998) found that multiple entry lanes increased the number of rear-end crashes, and multiple circulating lanes increased the number of entering v circulating crashes. This is consistent with Brude and Larsson (2000), who found that multi-lane roundabouts had higher crash rates for motorists, cyclists and pedestrians. The only study where the opposite relationship was observed was that of Harper (2005), who found that approaches with multiple entry lanes had lower entering v circulating crash rates. This seems contradictory with Harper's model for total crashes, which indicated that crashes increased with increasing circulating width for vehicles that travel straight through the intersection.

Vehicle speed

Arndt (1998) used a theoretical relationship with radii of path of travel to determine 85th percentile speeds. He found that increasing 85th percentile speeds resulted in more crashes for nearly all crash types and also that a change in 85th percentile speed between geometric elements resulted in more single-vehicle crashes. Brude and Larsson (2000) found that speed was directly proportional to crashes and that speeds were higher when the general speed limit was higher than the local limit, where the roundabout had multiple lanes and where the radius of the central island was 10–20m. They also found that where the radius of the central island was smaller than 10m, speeds were higher. This is consistent with Maycock and Hall's observation (1984) that more crashes occurred at roundabouts with higher speed limits.

Sight distance

The only study to include sight distance as an explanatory variable in the analysis was that of Maycock and Hall (1984). The variable was found to be significant in the approaching and single-vehicle crash models. Both of these models indicated that crashes increased with increasing sight distance. This may be because large sight distances are correlated to higher speeds.

3. Data collection

3.1 Introduction

This section discusses the site selection process; the location and types of roundabouts included in the sample set; and the collection of motor vehicle, cyclist and pedestrian counts, speed and visibility measurements, and crash data.

3.2 Site selection

The research team had access to an existing sample set of roundabouts that was collected in two previous studies by Turner (2000) and Turner et al (2006). The majority of the sites in the latter study were in Christchurch, and were single-lane four-arm intersections. A number of additional sites were added from Auckland and New Plymouth to increase the sample size and to include other roundabout types.

3.3 Selection criteria

A roundabout is made up of a series of 'give way' controlled T-junctions, where the through (or circulating) route is one-way. Roundabouts can be large or small, and can have one or more circulating and entry lanes. New Zealand has a significantly diverse variety of roundabouts because of changes in design practices over many years.

The most common roundabout type in New Zealand has four arms and one circulating lane. Previous studies on roundabouts by Turner (2000) and Turner et al (2006) concentrated on this common roundabout type. Even this common roundabout type has a lot of variety in terms of central island diameter, approach design and overall roundabout shape.

The research steering group and research team decided that a broader sample of roundabouts should be included in this study, so that the effects of speed, visibility and layout on crash occurrence could be examined. The sample set for this study includes three-, four- and five-arm roundabouts with both single and dual entering and circulating lanes. As in the population of roundabouts, the sample set has considerably more roundabouts with single entering and circulating lanes.

While a wide variety of roundabout features were included in the sample set, sites that had been constructed within the last five years or had undergone significant modification during this period were excluded, as their crash history over the last five years would not be representative. The broader selection criteria were:

- at least five years since installation
- all approaches two-way
- located in one of three centres (Auckland, Christchurch and Palmerston North)
- urban speed limits only (70km/h or less).

3.4 Sample size

Experience in other studies of this type indicates that a sample set of at least 100 sites is generally necessary to develop crash prediction models for the major crash types. A large sample size is particularly important in this study, as it considers a variety of intersection types and uses a lot of non-flow variables as predictor variables, and because the study develops models for less common modes, such as cyclists and pedestrians.

In total, a sample set of 104 roundabouts were selected in Auckland, Christchurch and Palmerston North. Table 3.1 shows a breakdown of the sites by location and roundabout type.

Table 3.1 Roundabout locations and types

Type	**Location**			
	Christchurch	**Auckland**	**Palmerston North**	**Total**
Single-lane circulating				
three-arm	–	2	2	4
four-arm	35	22	8	65
Two-lane circulating				
three-arm	–	4	–	4
four-arm	4	21	3	28
five-arm	–	3	–	3
TOTAL	**39**	**52**	**13**	**104**

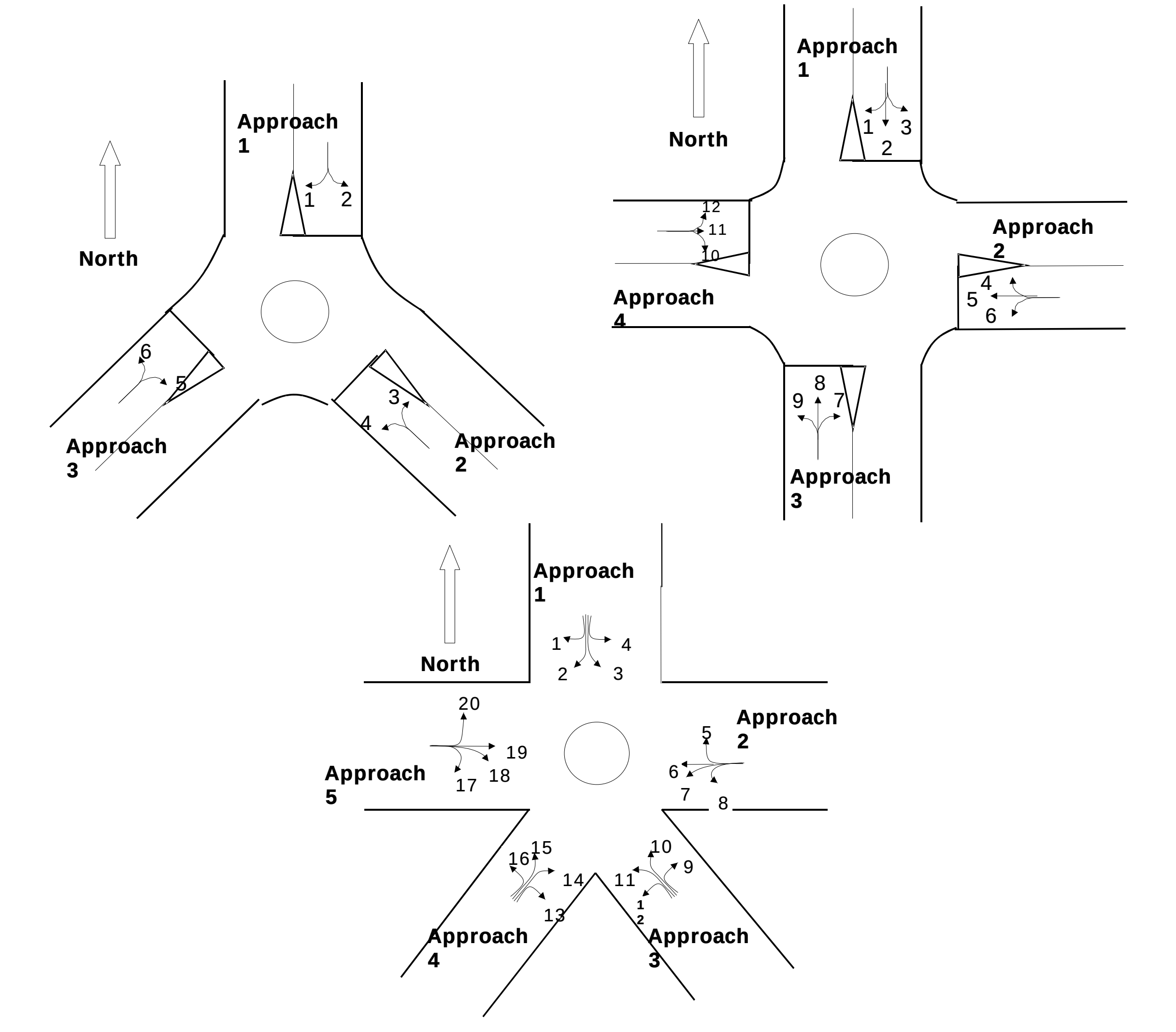
No database lists all the roundabouts in New Zealand, so it was not possible to use a formal sampling procedure to select a sample of sites that meet the criteria. Instead, the sites were selected so that a variety of different layouts and sizes were included in the sample from around the country.

A smaller sample set of 17 high-speed roundabouts was also selected from around the country. This included sites in Christchurch, Auckland, Hamilton and Tauranga. A high-speed roundabout must have one through-road that has a speed limit of 80km/h or more. Given the limited number of sites that meet these criteria, all high-speed roundabouts for which data was readily available were included in the sample set.

3.5 Motor vehicle counts

The flow variables used in the urban roundabout intersection models were first defined for four-arm intersection in Turner (1995). Each vehicle movement is numbered in a clockwise direction starting at the northernmost approach. Approaches are also numbered using the same technique and are numbered in a clockwise direction (see figure 3.1).

Figure 3.1 Numbering convention for movements and approaches



Individual movements are denoted as a lower case character for the user type (eg q_i). Totals of various movements are denoted with an upper case character (eg Q_j). Models are developed for each approach and are defined using the totals of various movements. These are:

Q_e entering volume for each approach

Q_c circulating flow perpendicular to the entering flow

Q_a approach flow (the sum of the entering and exiting flows for each approach).

Bruce Kelly of the Christchurch City Council and Glenn Connelly of Palmerston North City Council provided manual turning movement data for these two cities. In Auckland, turning movement counts had to be collected. Three one-hour manual turning volume counts were either provided or collected at each site, in the morning, evening and at mid-day.

All volume counts were factored up to the annual average daily traffic using the weekly, daily and hourly correction factors given in the *Guide to estimation and monitoring of traffic counting and traffic growth* (Traffic Design Group 2001). The hourly factors were calculated from flow profiles for the different road types.

For the analysis of high-speed roundabouts, approach volumes (Q_a) have been used. The volumes for the high-speed intersections have been estimated from the link volumes collected through tube counting programmes.

3.6 Cyclist counts

Manual cyclist movement counts were collected at each site for the morning and evening peaks, and at mid-day. Like motor vehicle counts, daily and hourly correction factors were used to estimate annual averaged daily volumes. Seasonal factors were also applied. These took into account the secondary school terms and holidays. Three separate profiles were used. These were applied based on the location of the roundabout and the vicinity of schools. The three profiles were 'commuter', 'school/off-road' and a combination of both. The commuter profile was always used for dual-lane roundabouts, as it was not expected that many school cyclists would travel through these. These factors are updated versions of those found in the *Cycle network and route planning guide* (Land Transport New Zealand 2004).

The cyclist flow variables are defined by movement in the same way that motor vehicle movements are defined: they are numbered in a clockwise direction at intersections, starting at the northernmost approach. Individual cyclist movements are denoted as a lower case character for the user type (eg c_i). Totals of various movements are denoted with an upper case character (eg C_i).

3.7 Pedestrian counts

Manual pedestrian counts were collected at each site in conjunction with cyclist counts. Pedestrians were counted as they crossed each arm of the intersection. These counts were also factored to average annual daily flows. Three profiles were used: 'suburban', 'CBD' and 'combined'. In most cases, the 'suburban' profile was used, with the exception being roundabouts in a commercial area. These factors were developed using data collected in a previous study (Turner et al 2006). The total crossing volume for each approach is denoted as an upper case *P.* The approaches are numbered from the northernmost approach for consistency with cyclist and motor vehicle movements.

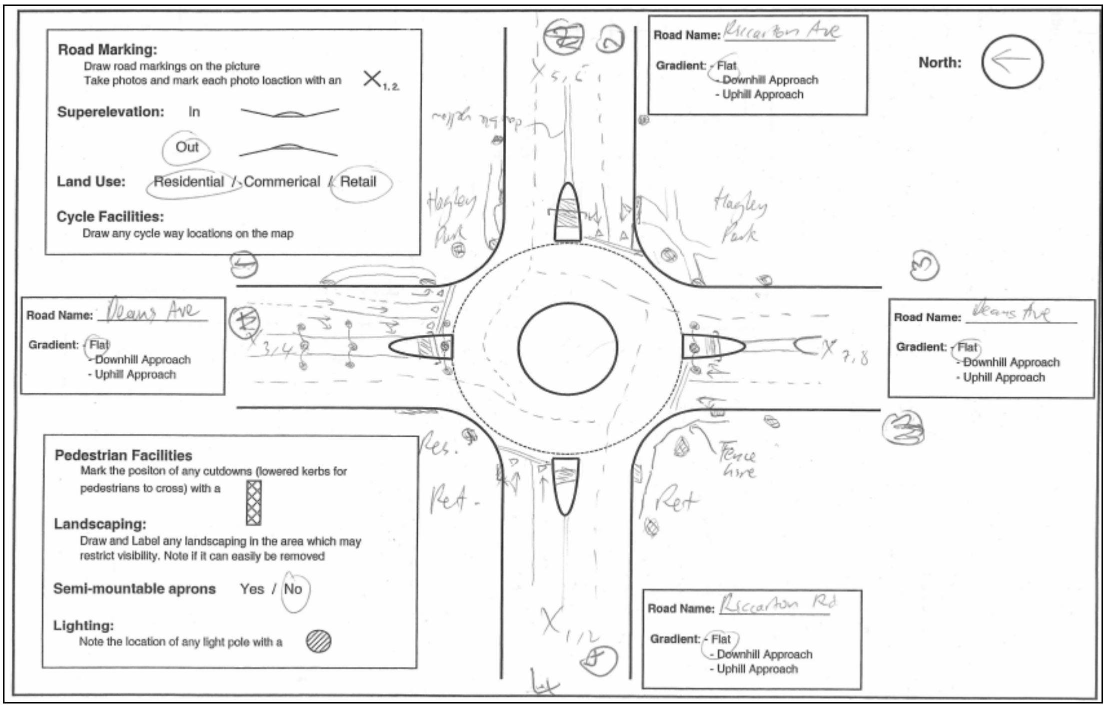
3.8 Intersection layout

Data on the layout of each roundabout was collected on site. This included such items as:

- road markings
- diameter
- superelevation direction of circulating lanes (whether inward or outward)
- direction of the gradient of approaches
- location of lighting
- pedestrian and cycle facilities provided
- surrounding land use
- features that obstruct visibility.

An example of the data collection form is shown in figure 3.2.

Figure 3.2 Example of intersection layout information collected on site (in this case, the Riccarton Road/Deans Ave roundabout in Christchurch)



From the information collected, variables were developed to represent different roundabout features where a large number of roundabouts had the feature present. These variables were discrete, unlike vehicle flows, which are continuous, and were incorporated into the crash prediction models as covariates. The covariates are represented by multiplicative factors that are used to adjust the prediction if the feature is present. The covariates used in the modelling process and their definitions are listed in table 3.2.

Table3.2 Intersection layout covariates incorporated into crash prediction models

Variable	Description
Φ_{MEL}	Multiple entering lanes
Φ_{MCL}	Multiple circulating lanes
Φ_{TJUN}	Intersections with three arms
Φ_{GRADD}	Downhill gradient on approach to intersection

3.9 Visibility

The visibility between drivers entering the intersection to vehicles approaching from their right was collected on-site for all approaches. The visibility was measured from three locations:

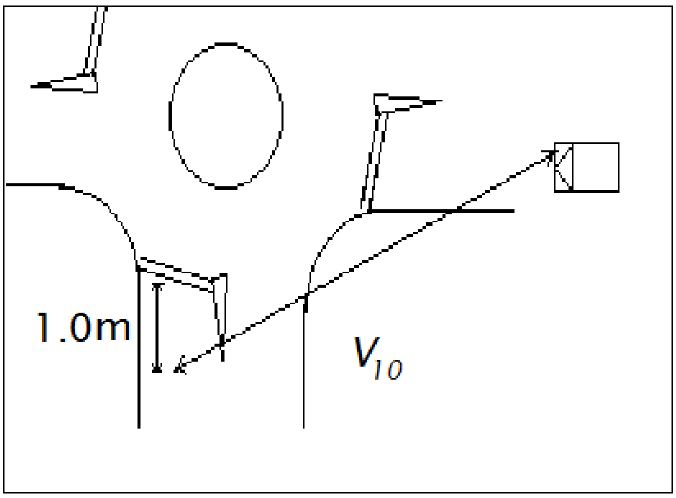
- at the limit line
- 10m back from the limit line
- 40m back from the limit line.

Table 3.3 contains definitions of these three visibilities and figure 3.3 shows an example for the measurement of the visibility from 10m back from the limit line.

Table 3.3 Visibility variables used for crash prediction models

Variable	Description
V_{LL}	Visibility from the limit line to vehicles turning right or travelling through the roundabout from their right
V_{10}	Visibility from 10m back from the limit line to vehicles turning right or travelling through the roundabout from their right
V_{40}	Visibility from 40m back from the limit line to vehicles turning right or travelling through the roundabout from their right

Figure3.3 Measurement of V_{10} (visibility for drivers 10m from limit line to vehicles on their right)



3.10 Roundabout negotiation speed

The average free speed of vehicles entering and circulating on all approaches was calculated using observed data. The entry speeds were the speeds measured as vehicles crossed the limit line and the circulating speeds were taken from circulating vehicles adjacent to the approach's splitter island. Only the free speeds of vehicles travelling straight through (not turning) were collected, as these vehicles are involved in the major crash type (entering v circulating). Collecting speeds at the two locations (entry and circulating) provided speed data for each conflicting vehicle stream in the entering v circulating crash type.

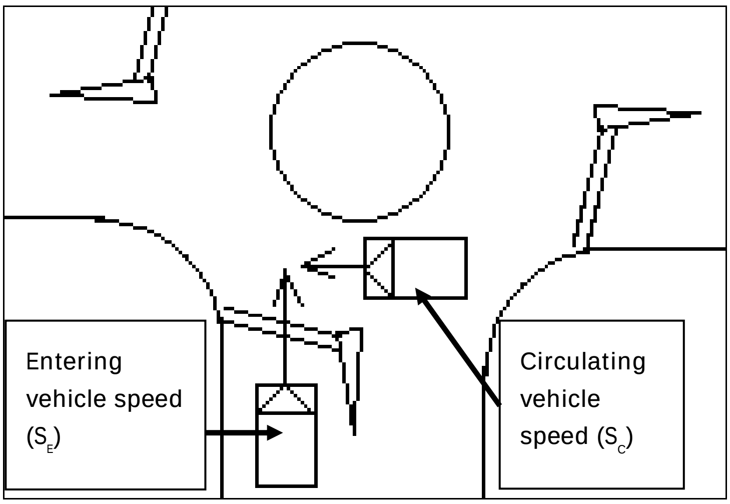
A target of 30 speed observations was collected at each location on each approach using a radar gun. Only the free speeds of vehicles (where vehicles did not have to give way) were recorded, so that speeds could be related to the design of the roundabout and not to the traffic conditions at the time of the survey.

Table 3.4 contains definitions of the speed variables used in the modelling exercise. Figure 3.4 illustrates the location (entry and circulating) where speeds were collected.

Table3.4 Speed variables used for modelling

Variable	Description
S_E	Average free mean speed of entering vehicles travelling through the roundabout at the limit line
S_C	Average free mean speed of circulating vehicles travelling through the roundabout as they pass each approach (adjacent to splitter island)
SSD_E	Standard deviation of free speeds of entering vehicles at the limit line
SSD_C	Standard deviation of free speeds of circulating vehicles as they pass the approach being modelled

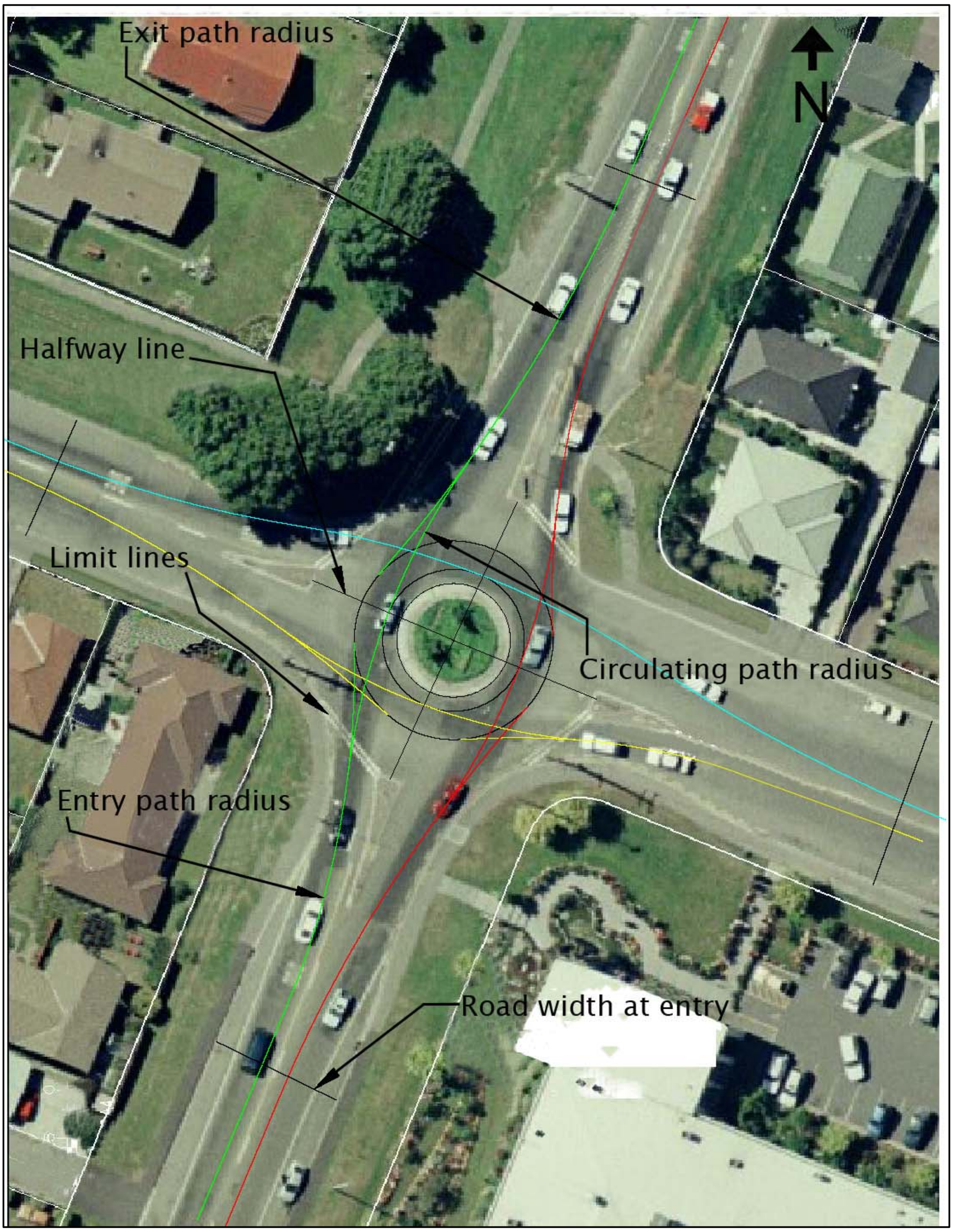
Figure3.4 Entering and circulating vehicle speeds



3.11 Geometric data

A Computer Aided Design program was used to measure geometrics for each roundabout from aerial photographs. Figure 3.5 shows one example of these photographs; a sample of other photographs used for this study is shown in appendix D. The aerial photographs were obtained from either local councils or Google Earth.

Figure 3.5 Aerial photo of the Buchanans Road/Carmen Road roundabout in Christchurch with overlaid measurement lines



The aspects of each roundabout that were measured included:

- average diameter of central island
- difference between the maximum and minimum diameter
- entry path radius
- exist path radius
- circulating path radius
- total width of approach traffic lanes
- distance to the upstream approach.

The surveyed roundabouts were found to have circular and oval central islands. An average of and the difference between the maximum and minimum diameters was recorded for oval central islands.

The entry path radius is the radius of an arc that is:

- tangent to a line 1.5m offset from and parallel to the approach centreline,
- tangent to an arc 1.5m offset from and concentric to the kerb line to the left of an approach
- tangent to a circle passing halfway between the central island and splitter islands and concentric to the central island.

The exit path radius is measured similar to the entry path radius, but for the roundabout exit directly across from the corresponding approach.

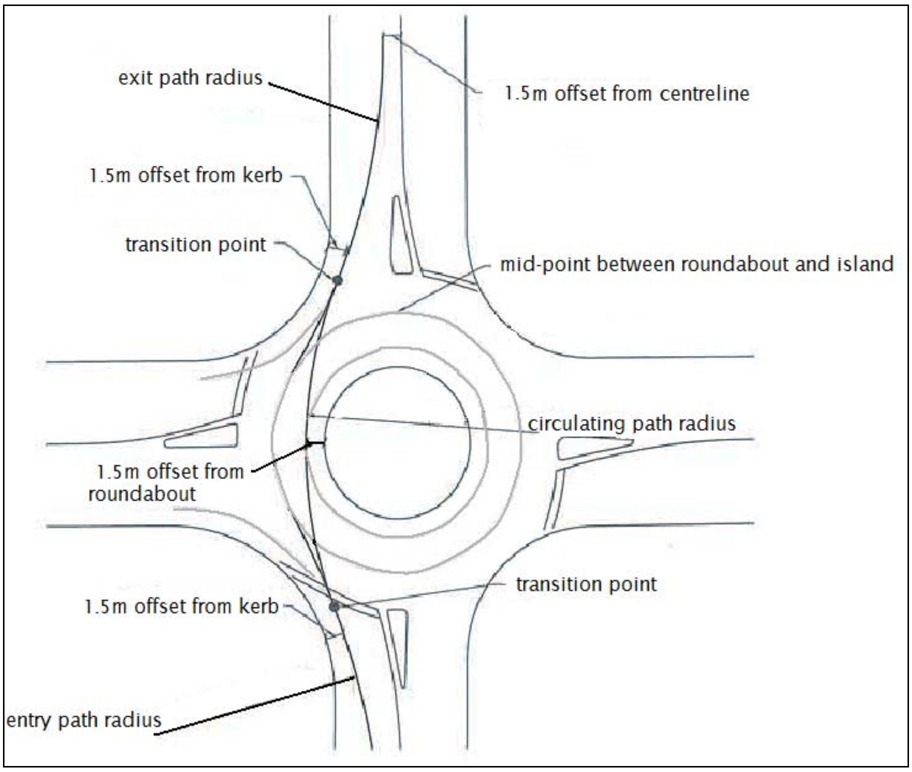
The circulating path radius is the radius of an arc that is tangent to the entry path radius, the exit path radius, and a circle 1.5m offset from and concentric to the central island.

The total width of the approach traffic lanes was measured and divided by the number of traffic lanes to find the approach lane width.

The path travelled through roundabout (following the entry, circulating and exit path radii) between the limit line to the right of the approach and the approach splitter island was measured to find the distance to the upstream approach.

Figure 3.6 below illustrates the roundabout geometric measurements.

Figure 3.6 Entry, circulating, and exit path radii



3.12 Crash data

Crash data for each roundabout was extracted from the Ministry of Transport's CAS for 1 January 2001 to 31 December 2005. The sample set crash data was compared with national crash data to assess whether similar crash trends were evident. During this period, 1202 injury crashes were reported at urban roundabouts, including 7 fatal and 154 serious crashes (13% of injury crashes). This compares to 365 reported injury crashes, including 2 fatal and 44 serious crashes (13% of injury crashes) at the 104 urban roundabouts included in the sample set.

Models were developed from the major crash types, with the remaining crashes being grouped as 'other'. The crash types used in the modelling exercise are as follows:

- entering v circulating (motor vehicle only)
- rear-end (motor vehicle only)
- loss of control (motor vehicle only)
- other (motor vehicle only)
- pedestrian
- entering v circulating cyclist
- other motor vehicle v cyclist.

4. Data analysis

4.1 Introduction

To understand the relationships between crashes and explanatory variables observed in the crash prediction models, it is necessary to know how these variables are related to each other. This section analyses the relationships between the key non-flow variable, speed, and the other explanatory variables in the dataset.

The relationships examined in this section include:

- traffic volume and speed
- visibility and speed
- diameter and speed.

It is important to note that the speed is free speed and not that of all entering vehicles, which would depend on the traffic volumes at the time of the speed survey, where speeds would be lower in periods of high traffic flows.

4.2 Correlation among variables

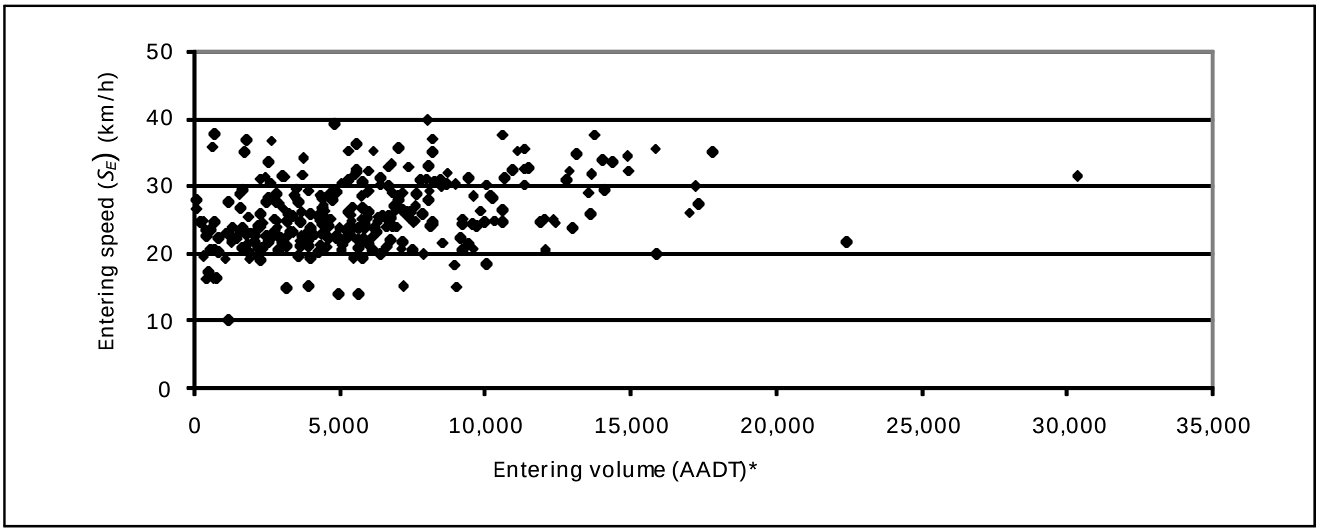
Correlation coefficients between two variables measure the linear dependence between them. Zero indicates independence; -1 and 1 indicate complete negative and positive dependence respectively. Coefficients for relevant variables are listed in table 4.1.

Table 4.1 Coefficients for the variables used in the modelling

Variable 1	Variable 2	Correlation coefficient
Entering volume	Entering speed (S_E)	0.30
Circulating volume	Circulating speed (S_C)	0.23
Sight distance – V_{LL}	Entering speed (S_E)	0.33
Sight distance – V_{10}	Entering speed (S_E)	0.40
Sight distance – V_{40}	Entering speed (S_E)	0.37
Diameter	Entering speed (S_E)	0.49

These results show that speed is positively correlated with flow volume, though not strongly. This is probably a result of roundabouts with high traffic volumes being designed to have higher speeds to improve capacity. Of the sight distance variables, speed is most strongly correlated with the sight distance from 10m behind the limit lines. Speed is even more strongly correlated with diameter. Plots of these relationships are shown in figures 4.1 to 4.6.

Figure 4.1 Relationship between entering volume and entering speed (S_E)



* AADT: Annual Average Daily Traffic

Figure 4.2 Relationship between circulating volume and circulating speed (S_C)

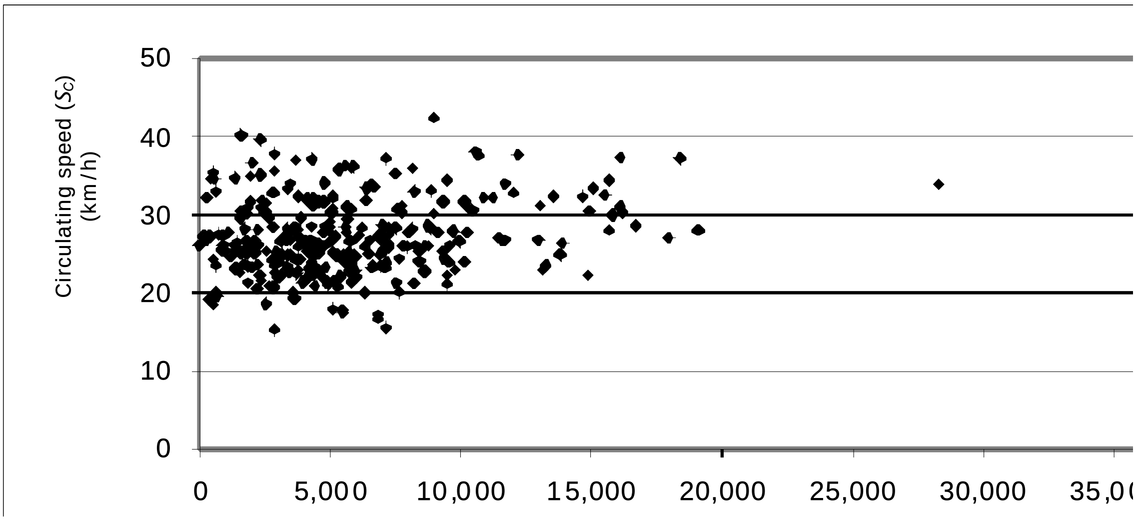


Figure 4.3 Relationship between sight distance (V_{LL}) and entering speed (S_E)

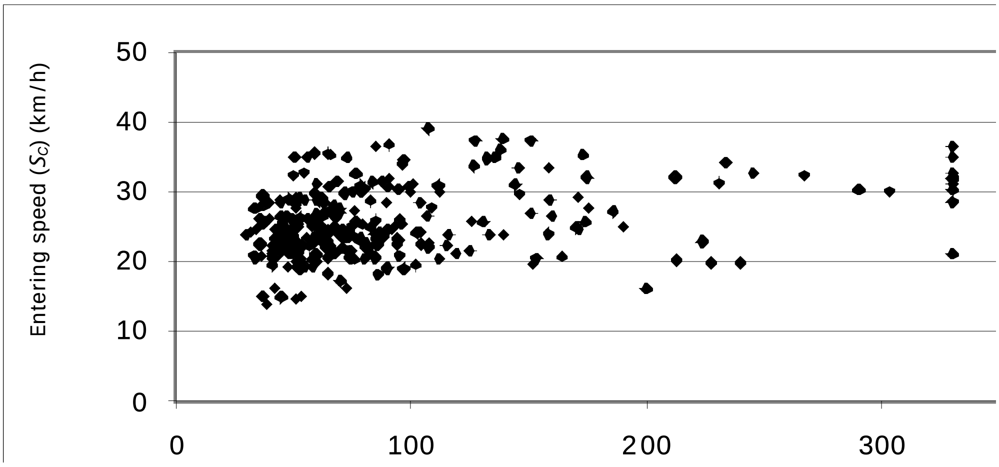


Figure 4.4 Relationship between sight distance (V_{10}) and entering speed (S_E)

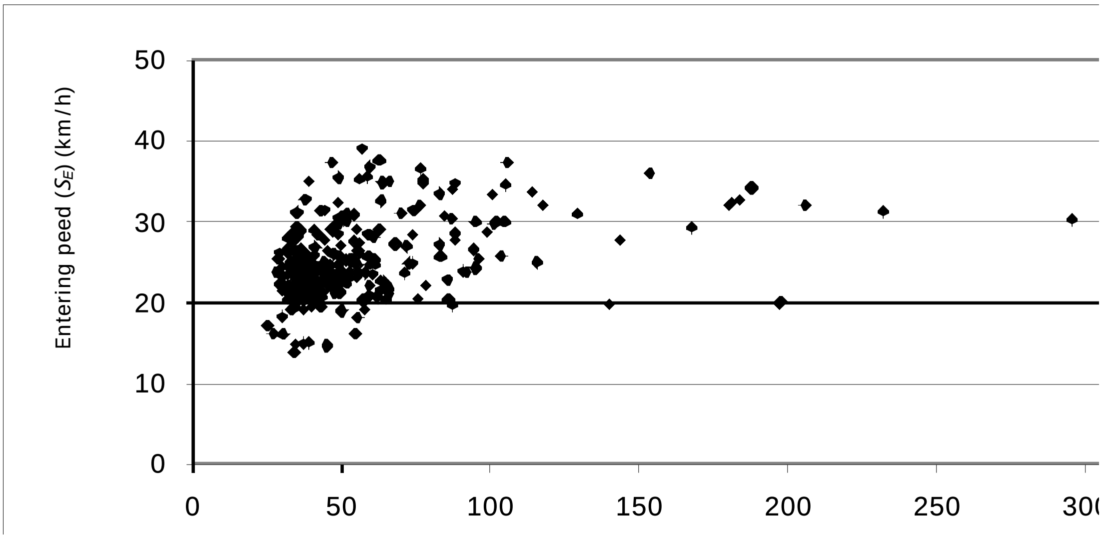


Figure 4.5 Relationship between sight distance (V_{40}) and entering speed (S_E)

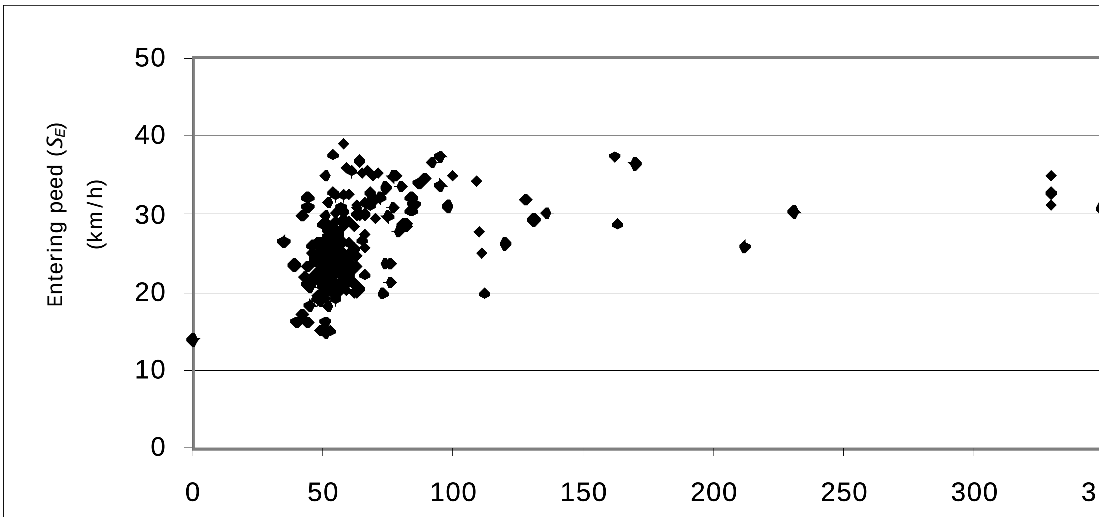
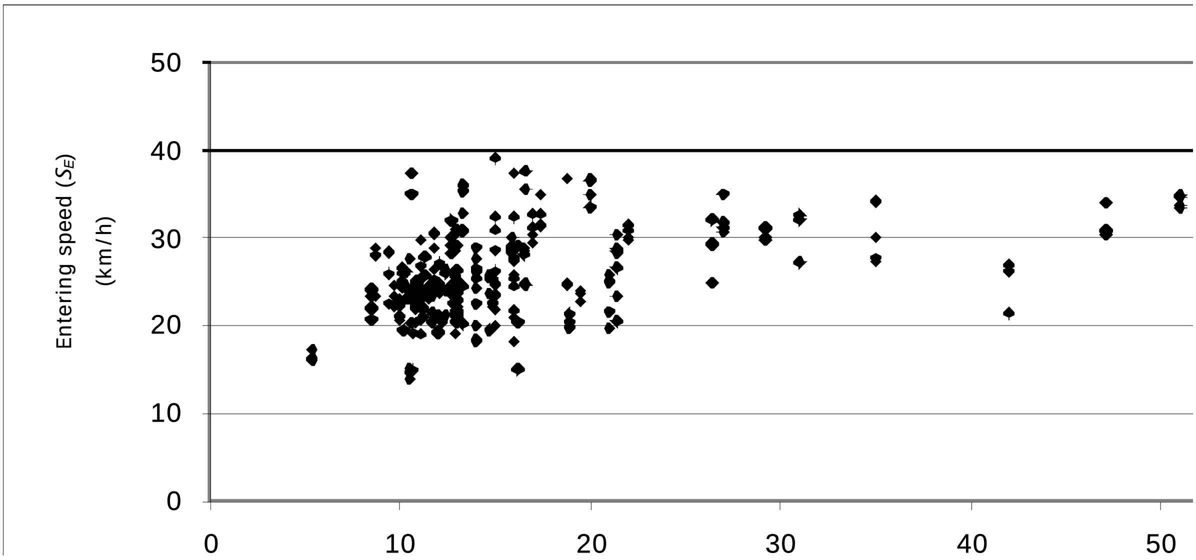


Figure 4.6 Relationship between diameter and entering speed (S_E)



5. Crash prediction modelling

5.1 Introduction

The aim of crash prediction modelling in this case is to develop relationships between the flow variables (mean number of crashes, and traffic, cycle and pedestrian flows) and the non-flow predictor variables such as visibility and speed. The models are called generalised linear models and typically have a negative binomial or Poisson error structure. Generalised linear models were first introduced to modern road crash studies by Maycock and Hall (1984) and extensively developed in Hauer et al (1989). These models were further developed and fitted using crash data and traffic counts in the New Zealand context for motor vehicle only crashes by Turner (1995).

Over recent years, the process has been refined to allow for incorporating non-flow variables, which allow different functional forms, improved goodness of fit statistics and the selection of 'preferred' models. This chapter outlines the current modelling process used, which is:

1. selecting the correct functional form for model parameters
2. fitting crash prediction models
3. selecting models for goodness of fit testing
4. testing goodness of fit and selecting preferred models
5. interpreting crash relationships and significance.

5.2 Selecting correct functional form

When crash prediction models were developed for conflicting flow-only variables, only one model was generally developed for each crash type. The form of the functional form of the crash model was assumed to be a power function as shown in equation 5.1.

$$A = b_0 x_1^{b_1} x_2^{b_2} \qquad \text{(Equation 5.1)}$$

However, with the inclusion of non-flow variables and the realisation that a power function may not always be appropriate, a tool was needed to determine potential functional forms for all predictor variables being included in the model. Also, if the functional form does not match the relationship between the predictor variable and crashes then the fit of the model is likely to be poor and the model may be misleading, particularly over certain ranges of the variable. Hauer and Bamfo's (1997) integrate-differentiate method is such a tool that assists in identifying possible functional forms.

The integrate-differentiate method has been used in this study with three different functional forms; these were: power functions (equation 5.2), exponential functions (equation 5.3) and Hoerl's functions (equation 5.4).

$$A = b_0 x_1^{b_1} \qquad \text{(Equation 5.2)}$$

$$A = b_0 e^{x_1 b_1} \qquad \text{(Equation 5.3)}$$

$$A = b_0 x_1^{b_1} e^{x_1 b_2} \quad \text{(Equation 5.4)}$$

where:

A = annual mean number of crashes

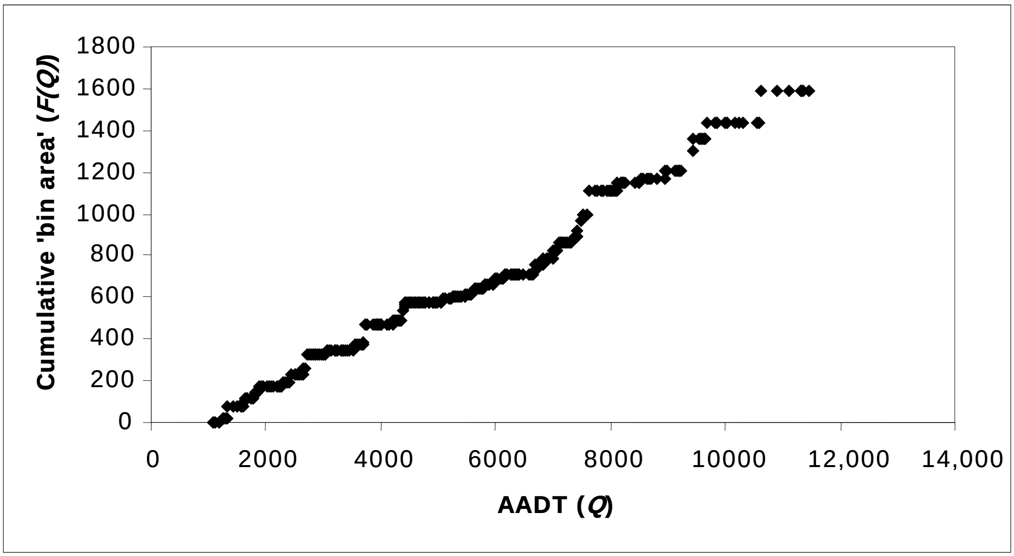
x_1 = continuous flow or non-flow variable

b_0, b_1 and b_2 = model parameters.

The first step in the integrate-differentiate method consists of determining the empirical integral function. The method for determining the empirical integral function is calculated as follows (Hauer and Bamfo 1997):

1. Sort the crash and predictor variable data by the predictor variable of interest, eg the data could be sorted by flow (*Q*).
2. Determine the 'bin width' of each data point. If this were flow, then it would be the difference in flow between the next higher and next lower flow divided by two.
3. Calculate the 'bin area' by multiplying the bin width by the crash count for each data point. Continuing the example, the bin area for each approach would be the number of crashes at the approach multiplied by the bin width.
4. Calculate the sum of all bin areas from the lowest value of the predictor variable up and plot this against the predictor variable as shown in figure 5.1.

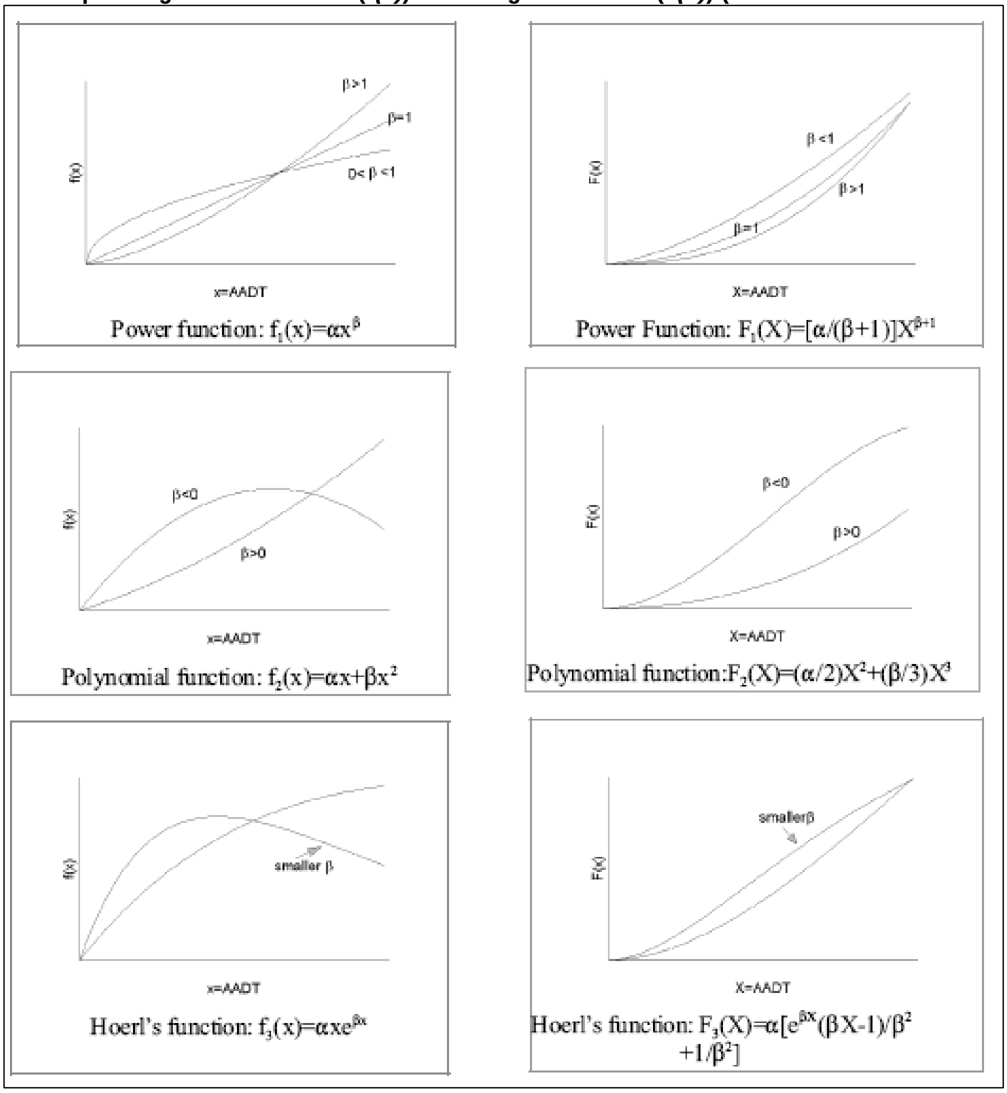
Figure5.1 Example showing the estimate of the empirical integral function



Assuming that a function *f(Q)* exists for the relationship between the predictor variable (*Q*) and crashes (*A*), the definite integral of *f(Q)* from *Q*=0 to *Q*=x (ie the area under the curve *f(Q)*) will be the integral function, *F(Q)*. The summing of the bin areas to determine the empirical integral function is therefore an estimate of the integral function.

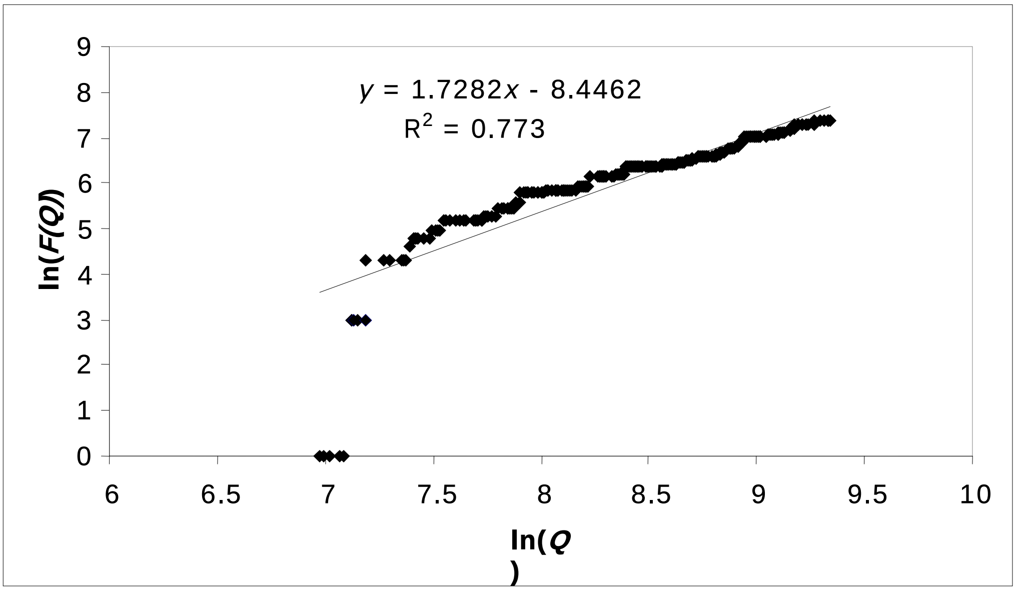
By inspecting the empirical integral function (as shown in figure 5.1), the relationship can be inferred by comparing it with the graphs in figure 5.2 for (from Hauer and Bamfo 1997). In the case of figure 5.1, the relationship is unclear.

Figure 2.2 Corresponding functional form (*f(x)*) and integral function (*F(X)*) (from Hauer and Bamfo 1997)



To determine which functional form may be suitable, the empirical integral function can be transformed. In the case of the power function, this can be done by plotting the natural log of flow against the natural log of the integral function. Figure 5.3shows this transformation has a linear trend. This indicates that the power function is the appropriate functional form. If a linear trend is not observed then the functional form is inappropriate.

Figure 5.3 Transformed *F(Q)* indicating that a power function is the appropriate relationship



5.3 Fitting crash prediction model parameters

Once the functional form for each variable has been determined, generalised linear models can then be developed using either a negative binomial or Poisson distribution error structure. Generalised linear models were first introduced to road crash studies by Maycock and Hall (1984) and extensively developed by others (eg Hauer et al 1989). These modelling techniques were further developed in the New Zealand context for motor vehicle only crashes by Turner (1995).

Software has been developed in Minitab in order to fit such models (ie to estimate the model coefficients); this can be readily done, however, in many commercial packages, eg GENSTAT, LIMDEP or SAS.

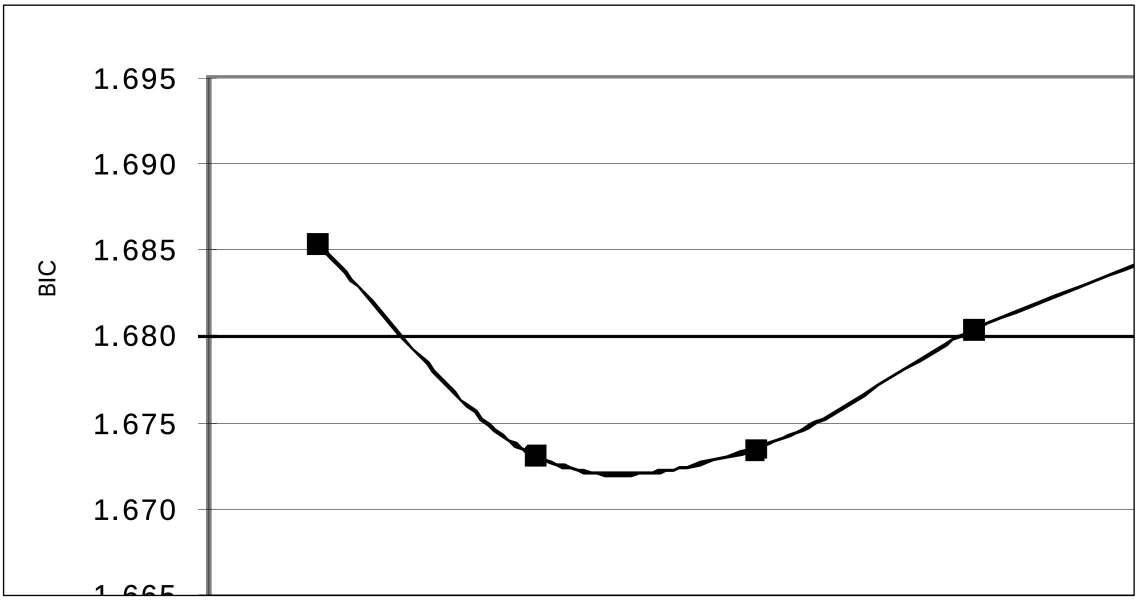
5.4 Adding variables to the models

Given the large number of possible variables for inclusion in the models for a particular crash type, a criterion is needed to decide when the addition of a new variable is worthwhile; this balances the inevitable increase in the maximum likelihood (*ML)* of the data against the addition of a new variable (where *p* is the number of variables included in the model and *n* is the total number of observations in the sample set). We chose to use the popular Bayesian Information Criterion (BIC). We stop adding variables when the BIC reaches its lowest point. The BIC is given by equation 5.5.

$$BIC = (-2ln(ML) + pln(n))/n \qquad \text{(Equation 5.5)}$$

The model with the lowest BIC is typically the preferred model. Addition of a new variable to a model generally provides an improved fit, though this may be slight and may therefore not reduce the BIC. In figure 5.4, the BIC values indicate that the parsimonious number of parameters is two. However, if the analyst considers that model with three parameters includes an important variable that the model with two parameters does not then he/she could justifiably select the model with three parameters, depending on the outcome of goodness of fit testing (see section 5.5).

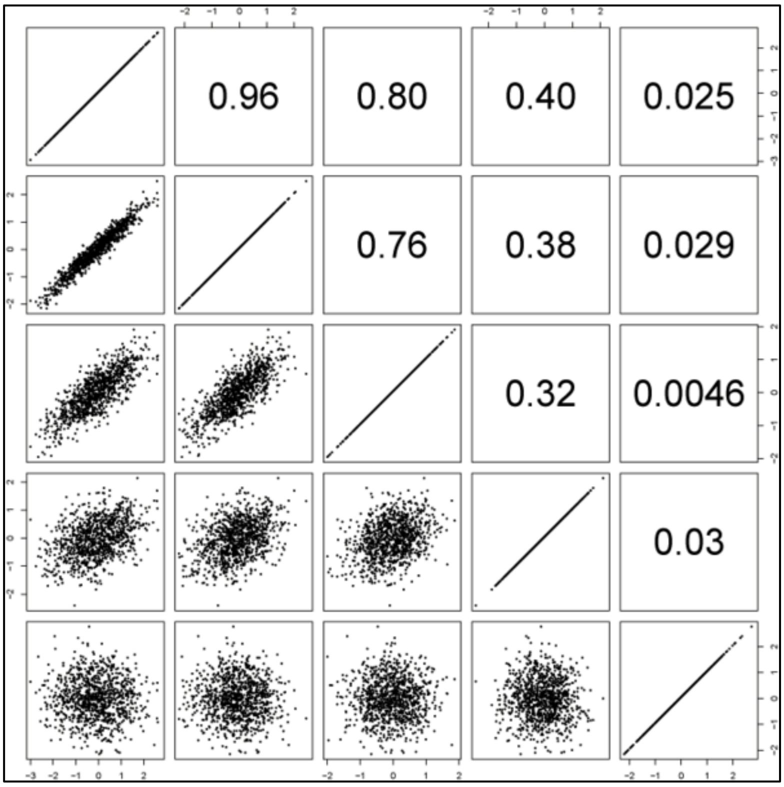
Figure5.4 Graph used to determine the number of parameters yielding the optimal BIC



Modelling every possible combination of variables to determine which has the lowest BIC would be time-consuming and inefficient. The process used in this study is to introduce each non-flow variable to a model with the main flow variables. Many studies have shown that flow variables are generally more important predictor variables than non-flow variables. The variables that maximise the log-likelihood (and therefore minimise the BIC) are then added to the flow-only model in a forward substitution process and the BIC is calculated. This process is repeated for a number of variable combinations (but not all combinations), taking into account that some variables may be correlated, as this is fairly common, particularly for layout/design variables.

Where variables are correlated, the 'best' two variables may not result in a better model. The correlation between different variables can be determined by examining the correlation matrix. The correlation matrix is a matrix of correlation coefficients between the variables used for modelling. Correlation coefficients indicate the strength and direction of a linear relationship between two random variables, where a value of one indicates a perfect positive correlation between two variables and a value of zero indicates statistical independence. Figure 5.5 illustrates an example of different values of linear correlation

Figure 5.5 Examples of linear correlation



5.5 Testing goodness of fit and preferred models

After the model with the lowest BIC has been obtained, the models are ranked in order of lowest (best) to highest (worst) BIC. A number of models are then selected for goodness of fit testing, because although the BIC provides us with models based on a parsimonious variable set and maximum likelihood, the models may still not fit the data well. Additionally, likelihood and goodness of fit are not directly related, meaning that the model with the best likelihood or BIC may not be the model with the best goodness of fit.

The models that are selected for goodness of fit testing are those that have a low BIC and have the variables that professional knowledge deems necessary. These 'necessary' variables are usually limited to the conflicting flow variables, such as entering and circulating flows in predicting entering v circulating crashes.

The usual methods for testing goodness of fit for generalised linear models involve using the test statistics: scaled deviance G^2 (twice the logarithm of the ratio of the likelihood of the data under the larger model to that of the data under the smaller model) or Pearson's χ^2 (the sum of squares of the standardised observations). These statistical tests are not accurate for testing goodness of fit for crash prediction models, except at an aggregate level (total crashes) at higher flow intersections where crash rates are relatively light. In most cases, the models are fitted to data with very low crash means, and this results in the 'low mean value' problems. This problem was first pointed out by Maycock and Hall (1984).

In Wood (2002), a grouping method has been developed which overcomes the 'low mean value' problem. The central idea is that sites are clustered and then aggregate data from the clusters is used to ensure that a grouped scaled deviance follows a χ^2 distribution if the model fits well. Evidence of goodness of fit is provided by a p-value. If this value is less than 0.05, say, this is evidence at the 5% level that the model does not fit well. Software has been written in the form of Minitab macros in order to run this procedure.

Once the goodness of fit has been calculated for the models selected for testing, the 'preferred' model is identified. This is the model that maximises the goodness of fit.

If the model fits poorly over a certain range of predictor variables (for example high or low volumes), this can be identified using the grouping technique by plotting predicted crashes against reported crashes. A poor fit is illustrated by a group that has a different predicted and reported number of crashes (where the plotted point is furthest from the 45 degree line). The site features of approaches in any outlier groups can then be examined to determine where the model relationship may not apply.

5.6 Model interpretation

5.6.1 Determining significance

Once models have been developed, the relationship between crashes and predictor variables can be interpreted from the parameter values in most cases. However, caution should always be exercised when interpreting such relationships when multiple predictor variables are used because two or more variables can be correlated (see section 5.4). Where variables are correlated or where a variable appears twice in the model (Hoerl's function), it is advisable to plot the model to understand the relationship between the predictor variables and crashes.

When examining the relationships with non-flow variables, it is important to determine whether they are significant. The significance of the model parameters is determined by examining the 95% confidence interval for the model parameter to identify if the relationship changes in trend over the range of the confidence interval. For example, a relationship may be significant if the both the upper and lower limits of the confidence interval indicate crashes increase with increases in the value of the predictor variable.

In the following sections, guidance is given on interpreting crash relationships for:

- power functions
- exponential functions
- covariates.

5.6.2 Power functions

Equation 5.6 presents a model with a single variable (such as a flow or speed) with a power function form. This section examines interpretation of the relationship between crashes and a predictor variable in a model of this type. The method can also be used to examine a single variable with a power function form in a multiple variable model.

$$A = b_0 x_1^{b_1} \quad \text{(Equation 5.6)}$$

where:

A	=	annual mean number of crashes
x_1	=	continuous flow or non-flow variable
b_0 and b_1	=	model parameters.

In this model form, the parameter b_0 acts as a constant multiplicative value. If the number of reported injury crashes is not dependent on the value of predictor variable (x_1), then the model parameter b_1 would be zero. In this situation, the value of b_0 is equal to the mean number of crashes. The value of the parameter b_1 indicates the relationship that the predictor variable has (over its range) with crash occurrence. Five types of relationship exist for this model form, as presented in figure 5.6 and discussed in table 5.1.

Figure 5.6 Relationship between crashes (*A*) and predictor variable *x* for different values of model exponents (b_1)

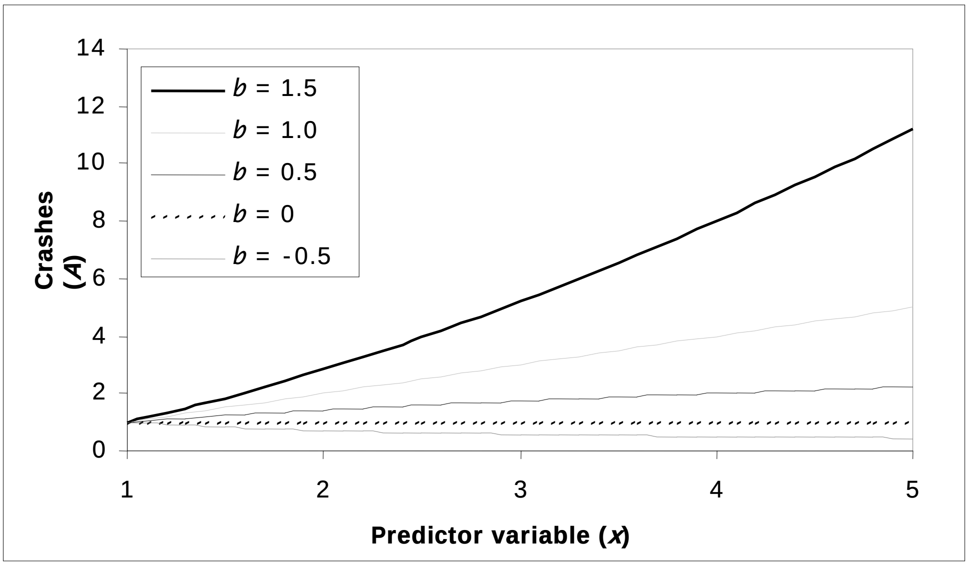


Table 5.1 Relationship between predictor variable and crash rate

Value of exponent	Relationship with crash rate
$b_i > 1$	For increasing values of the variable, the number of crashes will increase at an increasing rate
$b_i = 1$	For increasing values of the variable, the number of crashes will increase at a constant (or linear) rate
$0 < b_i < 1$	For increasing values of the variable, the number of crashes will increase at a decreasing rate
$b_i = 0$	The number of crashes will not change with changes in the predictor variable
$b_i < 0$	For increasing values of the variable, the number of crashes will decrease

Generally, models of this form have exponents between $b_i = 0$ and $b_i = 1$, with most flow variables having an exponent close to 0.5, ie the square root of flow. In some situations, however, parameters have a value outside this range.

5.6.3 Exponential functions

Equation 5.7 presents a model with a single variable (such as a flow or speed) with an exponential function form. As with power functions, the interpretation can also be used to examine a single variable in a multiple variable model.

$$A = b_0 e^{x_1 b_1} \quad \text{(Equation 5.7)}$$

where:

A	=	annual mean number of crashes;
x_1	=	continuous flow or non-flow variable; and
b_0 and b_1	=	model parameters.

The value of the parameter b_1 indicates the relationship that the predictor variable has (over its range) with crash occurrence. Three types of relationship can be seen for this model form, as presented in figure 5.7 and discussed in table 5.2.

Figure 5.7 Relationship between crashes (*A*) and a predictor variable *x* for different values of model parameter (b_1)

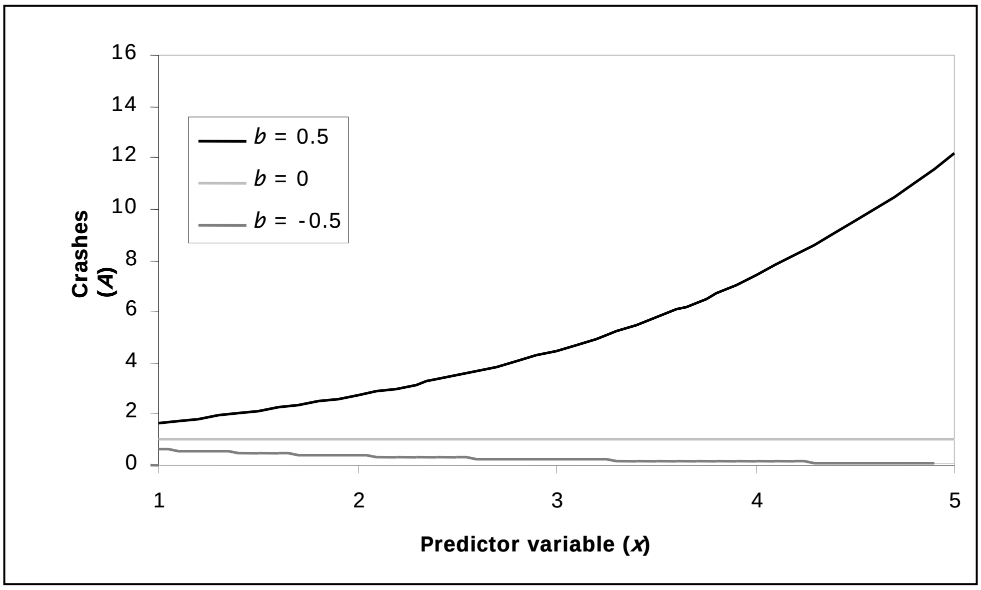


Table5.2 Relationship between predictor variable and crash rate

Value of parameter	Relationship with crash rate
$b_i > 0$	For increasing values of the variable, the number of crashes will increase at a increasing rate
$b_i = 0$	The number of crashes will not change with changes in the predictor variable
$b_i < 0$	For increasing values of the variable, the number of crashes will decrease at a decreasing rate

5.6.4 Covariates

In the modeling exercise, covariates are different b_0 parameters for various features which, in this study, are discrete variables with a small number of alternatives such as the number of entry lanes. As all crash prediction models include multiplicative b_0 parameters regardless of the functional form of the predictor variables (section 5.2), covariates can be applied to all models.

In this report, instead of having multiple b_0 values, a b_0 value is presented for the most common case (eg single entry lanes) and a multiplier for other situations (eg multiple entry lanes). This multiplier factor indicates how much higher (or lower) the number of crashes is for sites with a particular value of the covariate. For example, for a specific crash type, a covariate analysis may indicate that irrespective of traffic volume and other key predictor variables, roundabouts with multiple entry lanes have 66% more crashes than roundabouts with single entry lanes.

6. Roundabout crash models

6.1 Introduction

The following sections present the crash prediction models developed for the following major crash types at urban roundabouts:

- entering v circulating (motor vehicle only)
- rear-end (motor vehicle only)
- loss of control (motor vehicle only)
- other (motor vehicle only)
- pedestrian
- entering v circulating cyclist
- other cyclist.

A model for all crashes is also presented in section 6.9. This ‘all crash’ model type has been developed so that it is possible to predict the total number of crashes at a roundabout where only link volumes are available. We strongly recommend that analysts collect turning volume count data for at least motor vehicles at roundabouts and that they use the models by crash type, as this will give more accurate predictions.

6.2 Entering v circulating (motor vehicle only)

Models were developed for entering versus circulating crashes involving all motor vehicle classes but excluding crashes with cyclists. The NZTA crash types included in this dataset are crash codes H, J, K and L[1].

The models were developed in accordance with the process outlined in chapter 5. In this analysis, 22 models were developed for this crash type before setting in a preferred model. Appendix A outlines the full set of predictor variables and model parameters that were calculated for each of the 22 models. Equation 6.1 presents the preferred model form, which includes the entering and circulating volumes and the mean speed of the circulating traffic.

$$A_{UMAR\,1} = 6.12 \times 10^{-8} \times Q_e^{0.47} \times Q_c^{0.26} \times S_C^{2.13} \qquad \text{(Equation 6.1)}$$

where:

A_{UMAR1} = annual number of entering versus circulating crashes involving motor vehicles only (subscript denotes model type – see appendix C)

Q_e = entering flow on the approach

Q_c = circulating flow perpendicular to the entering flow

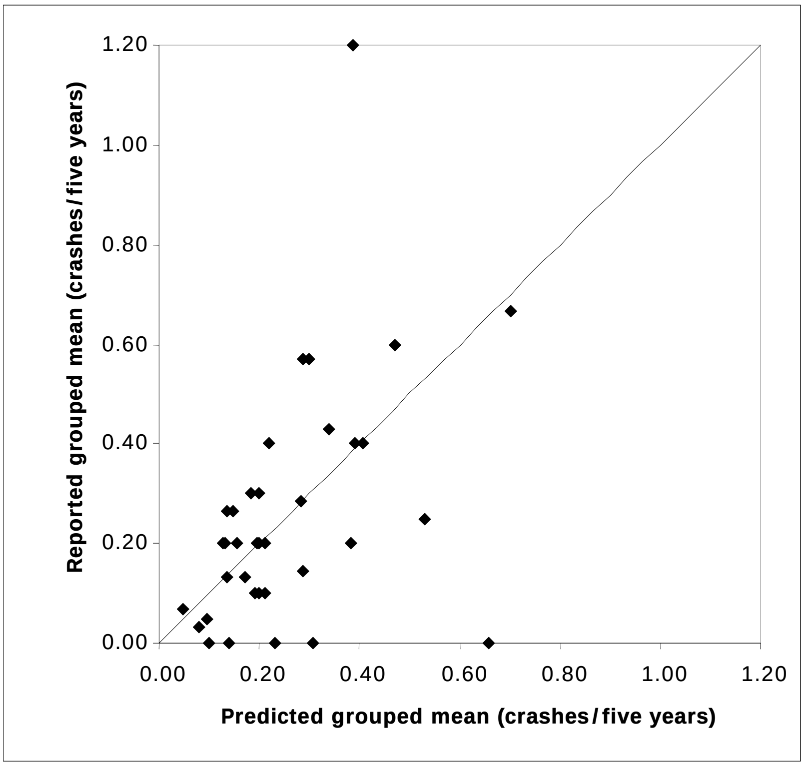
S_C = free mean speed of circulating vehicles as they pass the approach being modelled.

Equation 6.1 implies that the European approach to the design of roundabouts, where circulating speeds are reduced, has safety benefits. For example, the model suggests that if a mean circulating speed of 26km/h was reduced by 20% then the resulting reduction in crashes of this type would be 38%. Examination of the correlation matrix indicates that the speed of circulating vehicles is correlated to the flow of circulating vehicles. This may be a result of roundabouts at higher volumes being designed for higher speeds.

Equation 6.1 has a *p*-value of 0.26, indicating a model with good fit (values below 0.05 indicate a poor model). The goodness of fit can be illustrated by comparing the predicted mean number of crashes and the reported number of crashes for 'grouped' (approaches) data (as outlined in Wood 2002). Figure 6.1 presents this comparison between 'grouped' reported and predicted crashes for the preferred model. A poor fit is illustrated by a group that has a different predicted and reported number of crashes (where the plotted point is furthest from the 45 degree line). If we find no evidence of poor fit, this gives us valid grounds for increased confidence in the model. Figure 6.1 indicates a generally good fit for most approach groups.

[1] A copy of the NZTA's crash type coding matrix is included in appendix B.

Figure 6.1 Relationship between predicted and reported crashes for the A_{UMAR1} model



A number of other models were developed in the modelling process. Apart from circulating vehicle speed, the following crash relationships are significant:

- presence of multiple entering lanes
- entering vehicle speed (S_E)
- variation in entering vehicle speed
- presence of multiple circulating lanes.

The models showed that the number of crashes increased with increasing circulating and entering vehicle speeds, provision of multiple entering and circulating lanes, and greater variation in vehicle speeds and increasing visibilities (see appendix A). These results are consistent with those of Arndt (1998), and Brude and Larsson (2000).

6.3 Rear-end (motor vehicle only)

Models were developed for rear-end crashes involving motor vehicles only. The NZTA crash types that are included in this dataset are crash codes FA–FO, GA and GD (see appendix B).

The models were again developed in accordance with the process outlined in chapter 5. Fifteen models were developed in total. Appendix A outlines the predictor variables and the parameters for each of the models developed. Equation 6.2 presents the preferred model.

$$A_{UMAR2} = 9.63 \times 10^{-2} \times Q_e^{-0.38} \times e^{0.00024 Q_e} \quad \text{(Equation 6.2)}$$

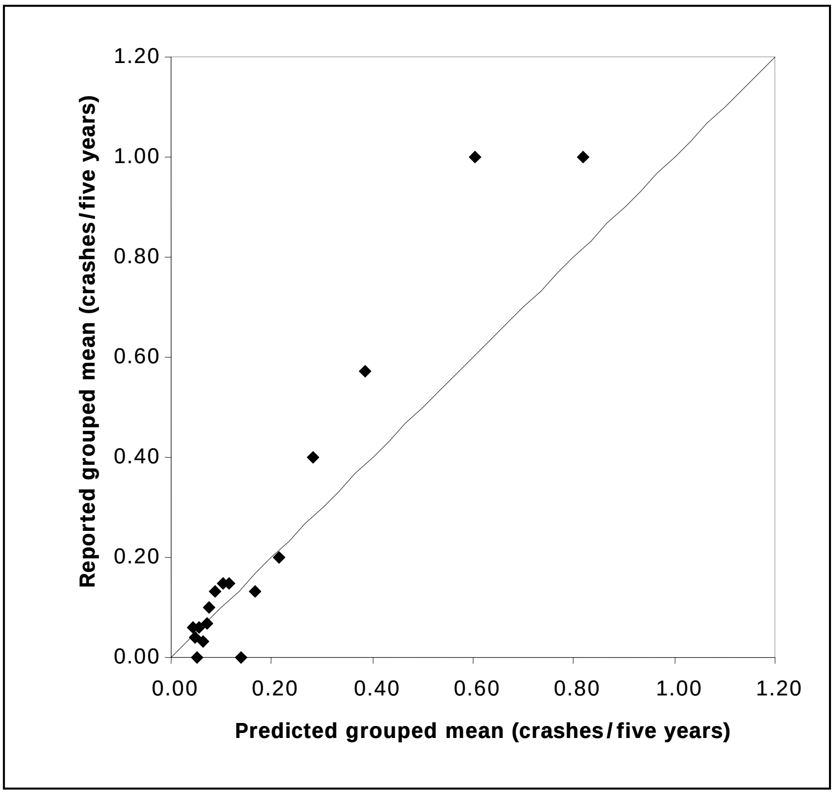
where:

A_{UMAR2} = annual number of rear-end entering crashes involving motor vehicles only

Q_e = entering flow on the approach.

Non-flow variables were included in a number of the crash prediction models developed. However, these did not feature in the preferred model. Equation 6.2 is also different from the typical power function crash prediction models developed in previous research studies: it has a Hoerl's function as its functional form. Given the functional form, this model should only be applied over the flow ranges for which data was available. At low and high volumes, the model forms will produce unreliable and deceptive crash predictions.

Figure 6.2 Relationship between predicted and reported crashes for the A_{UMAR2} model



The model has a p-value of 0.25, indicating a good fit. Figure 6.2 presents the comparison between the predicted and reported number of crashes for the preferred model. Figure 6.2 indicates a generally good fit. However, the model appears to underestimate crashes at sites with higher traffic volumes.

Although no non-flow variables were present in the preferred model, a number of models were developed to include non-flow variables with relationships that are significant. These are:

- variation in entering vehicle speed
- entering vehicle speed (S_E)
- presence of multiple entry lanes
- visibility measured from 10m back from the limit line (V_{10}).

The models showed that crashes increased with increasing entering volumes, increasing speeds and variation in speeds, presence of multiple entering lanes and visibilities (see appendix A). The only reviewed study to investigate visibility (Maycock and Hall 1984) found this to be an important variable in predicting crashes of this type (approaching) and produced a model that predicts more crashes with greater visibility.

6.4 Loss of control (motor vehicle only)

Models were developed for loss of control crashes involving motor vehicles entering and exiting the roundabout. The NZTA crash types that are included in this dataset are crash codes CA–CO, DA–DO, AD and AF (see appendix B).

Twelve models were developed in total. Appendix A outlines the predictor variables and the parameters of each of the models developed. Equation 6.3 presents the preferred model, which includes the approach flow and visibility.

$$A_{UMAR3} = 6.36 \times 10^{-6} \times Q_a^{0.59} \times V_{10}^{0.68} \quad \text{(Equation 6.3)}$$

where:

A_{UMAR3} = annual number of rear-end entering crashes involving motor vehicles only

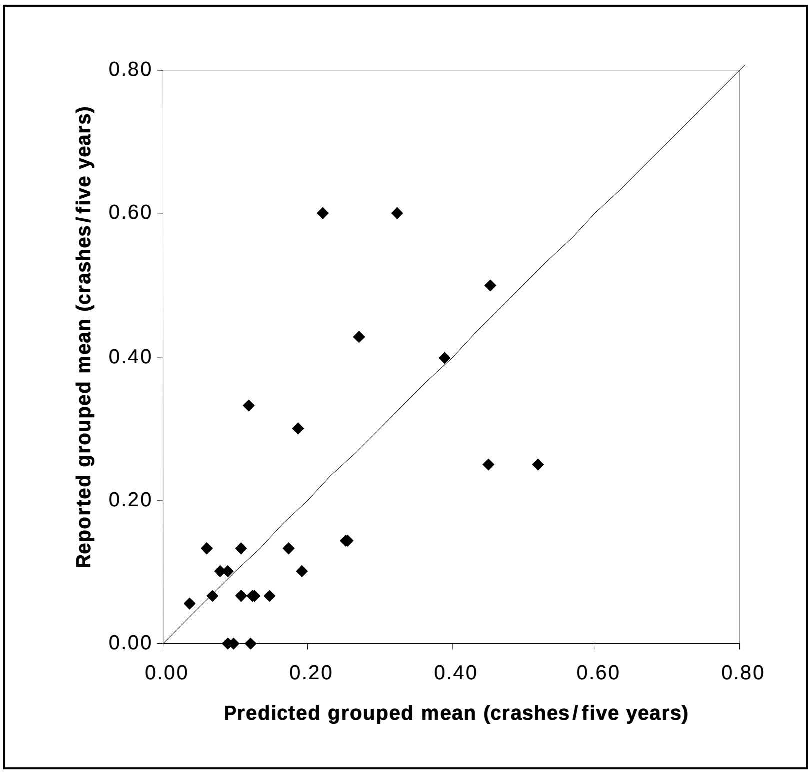
Q_a = approach flow (sum of entering and exiting flows

V_{10} = visibility 10m back from the limit line to vehicles turning right or travelling through the roundabout from the approach to the right.

The model indicates that as traffic volume or visibility increases, the number of loss of control crashes also increases. The model has a p-value of 0.25, indicating a good fit.

Figure 6.2 presents the comparison between the predicted and reported number of crashes for the preferred model. Figure 6.3 indicates a generally good fit.

Figure 6.3 Relationship between predicted and reported crashes for the *AUMAR3* model



A number of other models were developed in the modelling process. Apart from visibility (V_{10}), other significant non-flow relationships are:

- visibility measured from the limit line
- visibility measures from 40m back from the limit line (V_{40})
- entering vehicle speed.

Like rear-end crashes, where visibility has a significant relationship with crash rates, the models indicate that as visibility increases, so does the number of crashes. For this same crash type, Maycock and Hall (1984) found visibility to be an important predictor variable and observed a similar relationship. The models also show that the number of crashes increased with increasing entering vehicle speeds.

While the models show that reducing visibility on the roundabout approach (V_{10}) seems to reduce crash rates, design standards (and drivers) will have a minimum acceptable visibility. This is an area requiring further research.

6.5 Other (motor vehicle only)

Eleven models were developed for 'other' motor vehicle only crashes at roundabouts. The crash types include all those not covered by the three previous models that do not involve pedestrians or cyclists.

Appendix A outlines the predictor variables and the parameters of all the models developed for this crash type. Equation 6.4 presents the preferred model that includes the entering flow and number of entry lanes.

$$A_{UMAR4} = 1.34 \times 10^{-5} \times Q_a^{0.71} \times \phi_{MEL} \quad \text{(Equation 6.4)}$$

where:

A_{UMAR4} annual number of 'other' crashes involving motor vehicles only

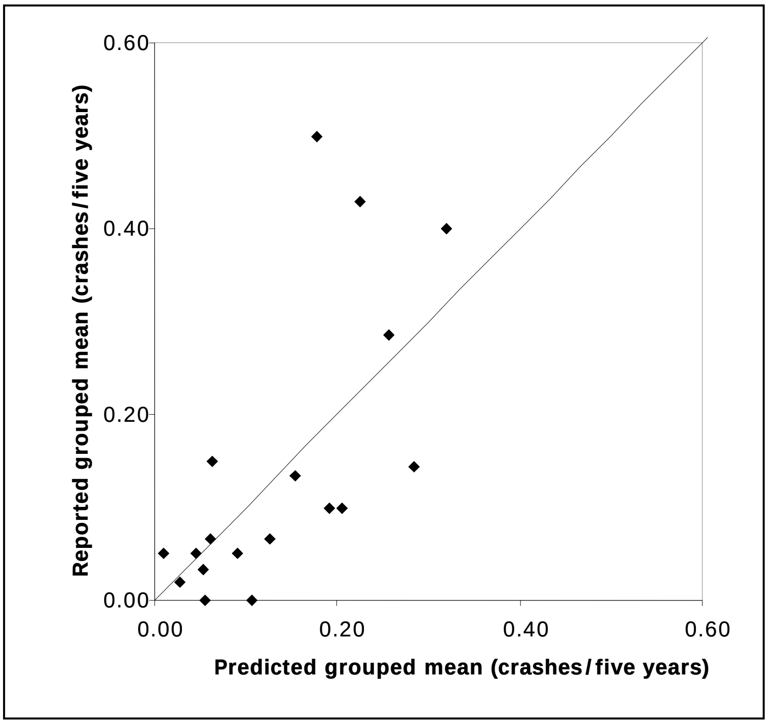
Q_a approach flow (sum of entering and exiting flows)

Φ_{MEL} factor to multiply the crash prediction by if multiple entry lanes are present. This factor is Φ_{MEL}.

The model indicates that as traffic volumes increase, the number of crashes also increases. It also indicates that intersection approaches with multiple entering lanes have an 'other' crash rate 2.66 times higher than those with single entry lanes. The model has a p-value of 0.17, indicating a good fit.

Figure 6.4 presents the comparison between the predicted and reported number of crashes for the preferred model. This indicates a generally good fit.

Figure 6.4 Relationship between predicted and reported crashes for the *A_{UMAR4}* model



Apart from presence of multiple entering lanes, this crash type had no other significant relationships between non-flow predictor variables and crashes.

6.6 Pedestrian

Models were developed for all crashes involving pedestrians and motor vehicles. The NZTA crash types that are included in this dataset are crash codes N and P (see appendix B).

The models were developed in accordance with the process outlined in chapter 5. Sixteen models were developed in total for this crash type. Appendix A outlines the predictor variables and the parameters of all the models developed. Equation 6.5 presents the preferred model form, which includes the approach volume and the number of pedestrians crossing each approach.

$$A_{UPAR1} = 3.45 \times 10^{-4} \times P^{0.60} \times e^{0.000067\,Q_a} \qquad \text{(Equation 6.5)}$$

where:

A_{UPAR1} = annual number of pedestrian crashes;

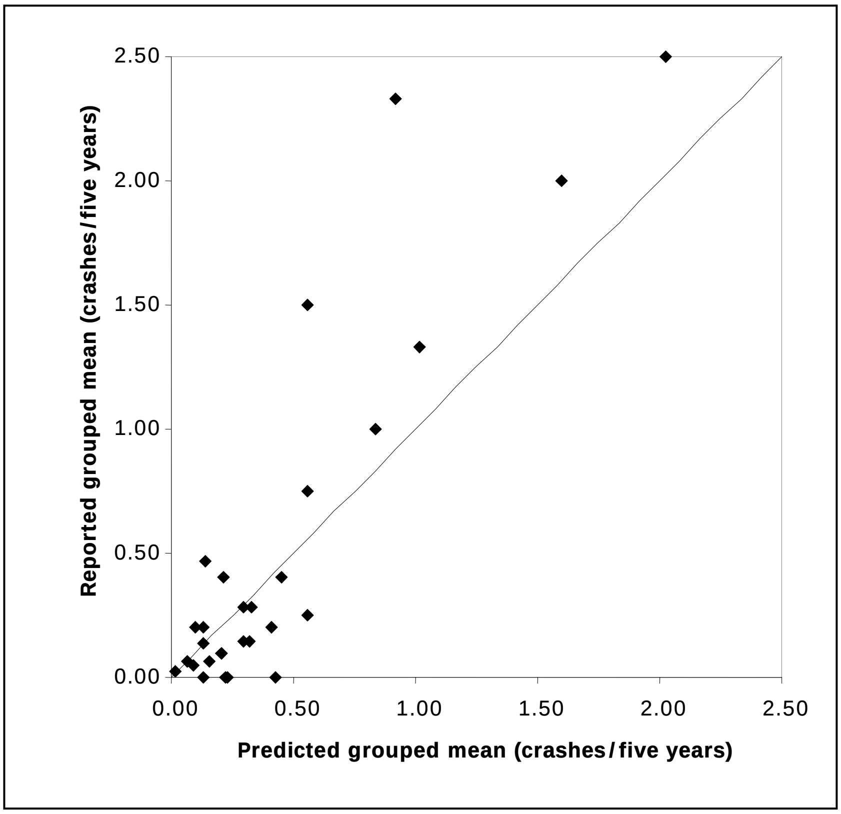
Q_a = approach flow (sum of entering and exiting flows)

P = pedestrians crossing the approach in either direction.

Non-flow variables were included in the crash prediction model development but did not feature in the preferred model. Equation 6.5 differs from the typical crash prediction models in that it includes both exponential and power functions (a Hoerl's function?). Given the functional form, this model should only be applied over the flow ranges for which data was available. At low and high volumes, the model form will produce unrealistic and deceptive crash predictions.

The model has a p-value of 0.17, indicating a good fit. Figure 6.5 presents the comparison between the predicted and reported number of crashes for the preferred model. This indicates a generally good fit. However, it appears to underestimate crashes at sites with a combination of high pedestrian and high traffic volumes.

Figure 6.5 Relationship between predicted and reported crashes for the A_{UPAR1} model



Although no non-flow variables were present in the preferred model, two variables have significant relationships. These are:

- presence of multiple entry lanes
- variation in entering vehicle speed.

The models show that the number of crashes increases with increasing vehicle and pedestrian flows, the presence of multiple entry lanes and greater variation in entry speeds (see appendix A).

6.7 Entering v circulating cyclist

Models were developed for entering v circulating crashes involving motor vehicles (entering) and cyclists (circulating). A much smaller percentage of crashes involve cyclists entering and motorists circulating. Therefore these crashes are included in the 'other cyclists' crash type. The NZTA crash types that are included in this dataset are crash codes H, J, K and L (see appendix B).

The models were developed in accordance with the process outlined in chapter 5. Twenty-two models were developed in total. Appendix A outlines the predictor variables and the parameters of the models developed. Equation 6.6 presents the preferred model form, which includes entering motor vehicle volumes, circulating cyclist volumes and the mean speed of the entering motor vehicles.

$$A_{UCAR\,1} = 3.88 \times 10^{-5} \times Q_e^{0.43} \times C_c^{0.38} \times S_E^{0.49} \qquad \text{(Equation 6.6)}$$

where:

A_{UCAR1} = annual number of entering v circulating cyclist crashes

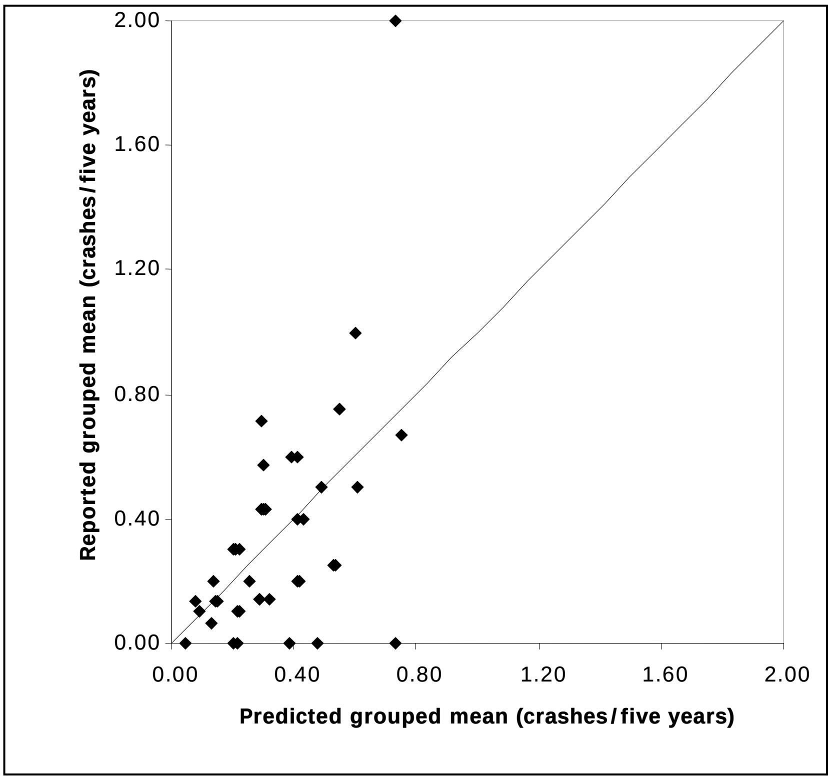
Q_e = entering flow on the approach

C_c = circulating cyclist flow perpendicular to the entering motor vehicle flow

S_E = free mean speed of vehicles as they enter the roundabout.

Equation 6.6 has a *p*-value of 0.61, indicating a good fit for the model. Figure 6.6 presents the comparison between reported and predicted crashes of the preferred model. Figure 6.6 indicates a generally good fit, except for an outlier with a reported grouped mean of 2.0 and a predicted grouped mean of 0.73. This outlier comprises of a group of three approaches with high entering motor vehicle volumes and high cyclist circulating volumes.

Figure6.6 Relationship between predicted and reported crashes for the *AUCAR1* model



Apart from entering vehicle speed, other significant relationships between non-flow variables and crashes are:

- presence of a downhill gradient on the approach to the roundabout
- circulating vehicle speed.

The models showed that the number of crashes increases with increasing circulating and entering vehicle speeds, and with the presence of a downhill gradient (see appendix A).

6.8 Other cyclist

Twelve models were developed for 'other' crashes involving cyclists entering and exiting the roundabout. The crash types that are included in the dataset are those involving both cyclists and motor vehicle but exclude crashes where the cyclist is circulating and the motor vehicle is entering, as this is covered by a separate model.

Appendix A outlines the predictor variables and the parameters of all the models. Equation 6.7 presents the preferred model, which includes both the motor vehicle and cyclist approach flows.

$$A_{UCAR\,2} = 2.07 \times 10^{-7} \times Q_a^{1.04} \times C_a^{0.23}$$ (Equation 6.7)

where:

A_{UCAR1} = annual number of 'other' crashes involving cyclists

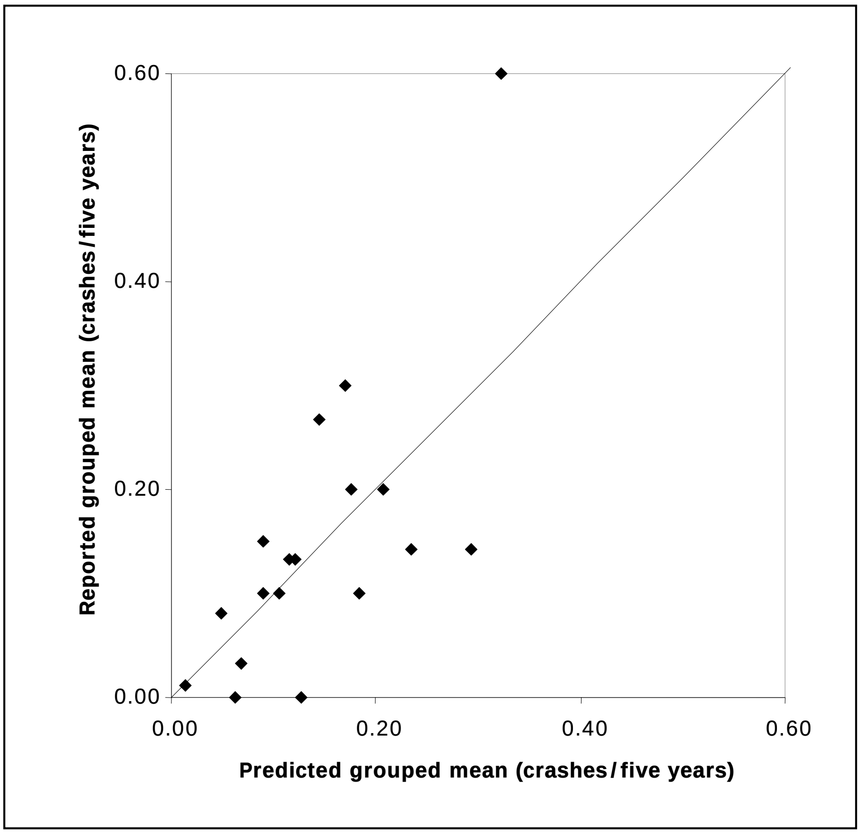
Q_a = approach flow (sum of entering and exiting motor vehicle flows)

C_a = cyclist approach flow (sum of entering and exiting cyclist flows).

The model indicates that as traffic volumes or cyclist volumes increase, the number of crashes also increases. The number of crashes is influenced more by an increase in the motor vehicle volume than an increase in the cyclist volume. Increasing the cyclist volume has a 'safety in numbers' effect, where the per-cyclist crash risk drops. More evidence of this effect can be found in Turner et al (2006).

The preferred model has a p-value of 0.50, indicating a good fit. Figure 6.7 presents the comparison between the predicted and reported number of crashes for the preferred model.

Figure 6.7 Relationship between predicted and reported crashes for the A_{UCAR2} model



No significant relationships were noted between non-flow variables and crashes for this crash type. However, the relationships observed are similar to the 'other' motor vehicle only models while being, at the same time, different from all other crash types for motor vehicles only, pedestrians and cyclists. For example, visibility variables in both 'other' crash types indicate that as visibility increases, the number of crashes decreases, while the opposite is true for other crash types. Also, only these 'other' crash types have a Poisson error structure, while all other crash types have a negative binomial error structure, indicating either over-dispersion or else more variability in the data.

6.9 All crashes

Typical crash prediction models for all crashes are normally 'product of link models'. These models use two-way link volumes collected by tube counts on the 'major' and 'minor' roads. Models have been developed for roundabouts in the past using these 'major' and 'minor' flows. However, unlike most traffic signals and priority intersections, 'major' and 'minor' roads are not easy to define and often, the main movement may be between two adjacent arms of the intersection. For this reason, models have been developed on an approach basis, using approach volumes (attainable from link counts), with the total number of crashes found by adding the crashes occurring on each intersection approach.

The models were developed in accordance with the process outlined in chapter 5. Eleven models were developed in total. Appendix A outlines the predictor variables and the parameters of the models developed. Equation 6.8 presents the preferred model form, which includes the approach volume and the presence of multiple entry lanes.

$$A_{UAAR\,0} = 6.11 \times 10^{-4} \times Q_a^{0.58} \times \phi_{MEL} \qquad \text{(Equation 6.8)}$$

where:

A_{UAAR1} = annual number of all crashes occurring at an approach

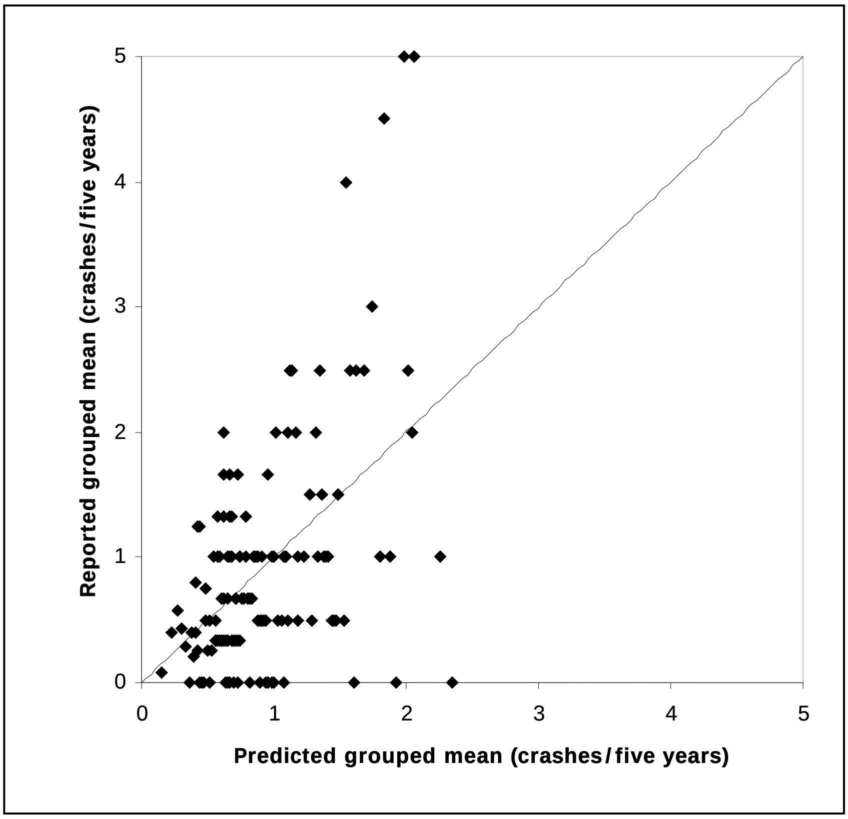
Q_a = approach flow (sum of entering and exiting motor vehicle flows)

Φ_{MEL} = factor to multiply the crash prediction by if multiple entry lanes present are. This factor is: ϕ_{MEL} = 1.66.

This model indicates that approaches with multiple entering lanes will have 66% more crashes than approaches with single entering lanes. No matter which crash type was being modelled, every time this variable was included, the covariate was always greater than 1.0. This strong result indicates the reduced safety of multi-lane roundabouts compared to single-lane roundabouts, irrespective of the traffic volumes.

Equation 6.8 has a p-value of 0.28, indicating a good fitting model. This fit can be illustrated by comparing the predicted mean number of crashes and the reported number of crashes, as shown in figure 6.8. Figure 6.8 differs from previous graphs of this type because the higher number of crashes results in smaller group sizes and a larger number of groups, using the Wood (2002) method. The median group size is three and 40% of the groups include only two approaches.

Figure 5.1 Relationship between predicted and reported crashes for the A_{UAAR0} model



Other variables were included in the modelling process. Apart from the number of entry lanes, the only other significant relationship was entering vehicle speed (S_E), with the model indicating that as entry vehicle speed increases, so does the crash rate (see appendix A).

6.10 High versus low speed limits

Using the smaller sample set of 17 high-speed roundabouts (with speed limits on at least two approaches being greater than 70km/h), the influence of high speed limits was investigated. As this data consisted only of the approach volume and number of crashes, no non-flow variables could be examined for this dataset other than the speed limit.

Using the link flow data, a covariate analysis of the effect of higher speed limits on crashes was carried out. Equation 6.9 presents the model that contains approach flows and approaches with a speed limit above 70km/h.

$$A_{AAAR0} = 3.21 \times 10^{-4} \times Q_a^{0.66} \times \phi_{HS} \qquad \text{(Equation 6.9)}$$

where:

A_{AAAR1} = annual number of all crashes occurring at an approach

Q_a = approach flow (sum of entering and exiting motor vehicle flows); and

Φ_{HS} = factor to multiply the crash prediction by if a speed limit on the approach is greater than 70km/h. This factor is ϕ_{HS} = 1.35.

The model has a good fit, with a p-value of 0.16. The covariate for the higher speed sites indicates that at speed limits of 80km/h or greater, 35% more injury crashes are reported than at a roundabout with an urban speed limit, for a given traffic volume.

6.11 Summary

This section summarises the models for each crash type. The typical mean annual numbers of reported injury crashes at an urban roundabout can be calculated using turning movement counts; data for various non-flow variables such as visibility, speed and geometry; and the crash prediction models in table 6.1. The total number of crashes can be predicted by summing the individual predictions for each crash group which are calculated for each approach. Where turning movement counts and/or non-flow variable data are unavailable, the total number of crashes can be estimated using the model outlined in section 6.9. However, we strongly recommend the use of the crash models by type, particularly where volumes of cyclists and pedestrians are likely to be high.

Table 6.1 Urban roundabout crash prediction models

Crash type	Equation (crashes per approach)	Error structure	GoF[a]
Entering v circulating (motor vehicle only)	$A_{UCAR\,1} \times 6.12 \times 10^{-8} \times Q_e^{0.47} \times Q_c^{0.26} \times S_C^{2.13}$	NB[b] (k=1.3)[c]	0.26
Rear-end (motor vehicle only)	$A_{UMAR\,2} = 9.63 \times 10^{-2} \times Q_e^{-0.38} \times e^{0.00024 Q_e}$	NB (k=0.7)*	0.25
Loss of control (motor vehicle only)	$A_{UMAR\,3} = 6.36 \times 10^{-6} \times Q_a^{0.59} \times V_{10}^{0.68}$	NB (k=3.9)*	0.25
Other (motor vehicle only)	$A_{UMAR\,4} = 1.34 \times 10^{-5} \times Q_a^{0.71} \times \phi_{MEL}$ $\phi_{MEL} = 2.66$	Poisson	0.17
Pedestrian	$A_{UPAR\,1} = 3.45 \times 10^{-4} \times P^{0.60} \times e^{0.000067\, Q_a}$	NB (k=1.0)*	0.17
Entering v circulating cyclist	$A_{UCAR\,1} = 3.88 \times 10^{-5} \times Q_e^{0.43} \times C_c^{0.38} \times S_e^{0}$	NB (k=1.2)*	0.61
Other (cyclist)	$A_{UCAR\,2} = 2.07 \times 10^{-7} \times Q_a^{1.04} \times C_a^{0.23}$	Poisson	0.50

Notes to table 6.1

a GoF (Goodness of Fit statistic) indicates the fit of the model to the data. A value of less than 0.05 indicates a poor fit, whereas a high value indicates a good fit.

b NB = negative binomial

c k is the gamma distribution shape parameter for the negative binomial distribution.

The models in table 6.1 can be compared with those developed in previous studies to determine whether crash rates per vehicle have changed or whether the importance of particular variables has changed for the entering v circulating crash models developed in Turner (2000), Turner et al (2006) and this study. The 'flow-only' models developed for this study are shown in table 6.2 along with the model for circulating cyclist crashes from Turner et al (2006) and the model for crashes involving all wheeled road users (cyclists and motor vehicles) in Turner (2000).

Table 6.2 Entering-versus-circulating crash prediction models

Flow only models	Study	Equation (crashes per approach)
Motor vehicle only crashes	This study	$A_{UMAR\,1} = 2.49 \times 10^{-5} \times Q_e^{0.48} \times Q_c^{0.37}$
Motor vehicle and cyclist Crashes	Turner 2000	$A_{UWXR\,1} = 1.14 \times 10^{-4} \times Q_e^{0.42} \times Q_c^{0.41}$
Circulating cyclist crashes	This study	$A_{UCAR\,1} = 1.51 \times 10^{-4} \times Q_e^{0.46} \times C_c^{0.38}$
Circulating cyclist crashes	Turner et al 2006	$A_{UCXR\,1} = 2.40 \times 10^{-5} \times Q_e^{0.79} \times C_c^{0.32}$

A comparison between the preferred models (motor vehicle only) in table 6.1 and the flow-only models in table 6.2 illustrates the effect of the correlation between circulating flow and mean circulating speed. The lower exponent for the circulating flow (Q_c) in table 6.1 (enters v circulating), when compared with the Q_c in the first model in table 6.2, shows the correlation between circulating flow and circulating speed.

Table 6.2 shows that the relationships between the flow variables and motor vehicle crashes appears in this current study and the Turner (2000) study. The higher *b* coefficient for the earlier study (1.14×10^{-4}) compared with this study (2.49×10^{-5}) is likely to be the result of a downward trend in crashes in New Zealand over recent years, and the inclusion of cyclist crashes in the Turner (2000) study. It is interesting that the models for cyclist crashes have similar exponents on the circulating flow variable to the models for motor vehicle only crashes. This indicates that similar relationships between flows and crashes may exist for both road user groups.

7. Speed models

7.1 Terminology

Chapter 4 showed that speed is most strongly correlated with sight distance from 10m behind limit lines (V_{10}; for the remainder of this chapter, this variable will be denoted as visibility) and diameter. We will explore speed models where the independent variables consist of these two quantities.

7.2 Methodological considerations

7.2.1 Functional form

In ascertaining the most appropriate functional form for diameter (taking the average of the speed over the site) and visibility, a power curve produced the best relationship by the methodology outlined earlier in this report. Therefore we present results considering power relationships.

7.2.2 Error structure

It is not clear which error structure should be assumed in the development of a speed model. The frequency distribution of speed has a skewness of 0.33 and a kurtosis of 3.16, which are not outside expected ranges for skewness and kurtosis of Normal datasets of this size (n = 309). Therefore, in the absence of any indication to the contrary, we have assumed a Normal error structure for speed.

7.2.3 Data grouping

Data exists for all approaches to surveyed roundabouts. Diameter, however, is a property of the roundabout site, not of the approach; it is therefore necessary to consider a second dataset: the original set grouped by site.

7.3 Predictive models

Here we construct predictive equations for entering speed, S_E, considering diameter, D and visibility, V_{10}.

Figure 7.1 Regression curve between diameter and speed (S_E) for approaches

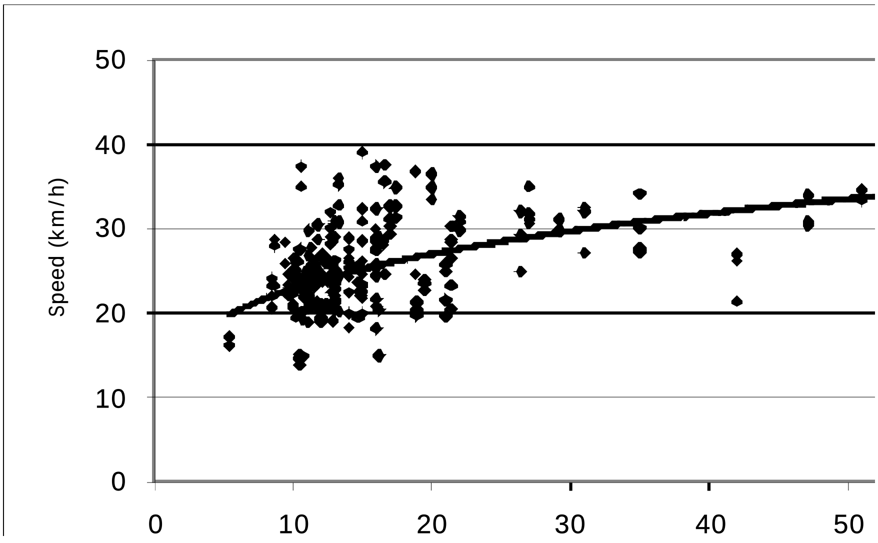


Figure 7.2 Regression curve between visibility and speed (S_E) for approaches

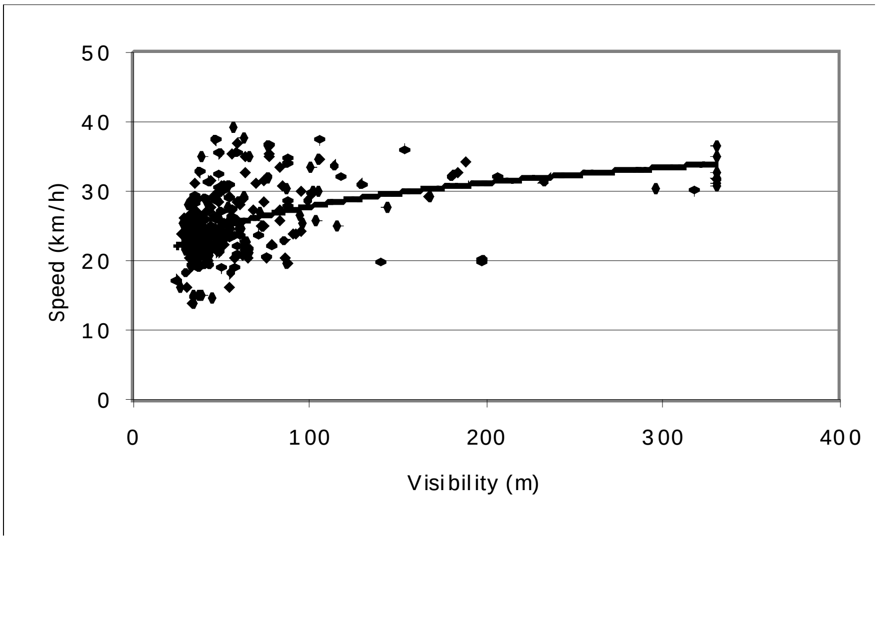


Figure 7.3 Regression curve between diameter and speed (*S_E*) for sites

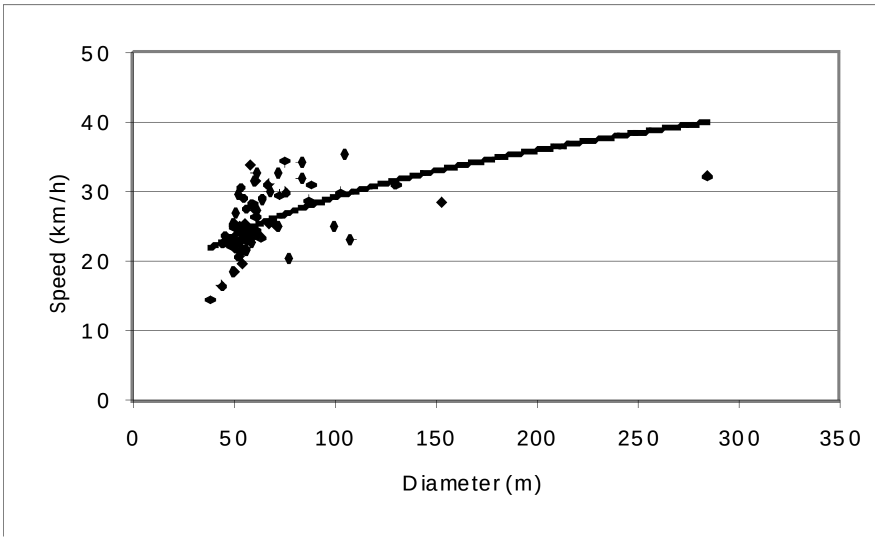
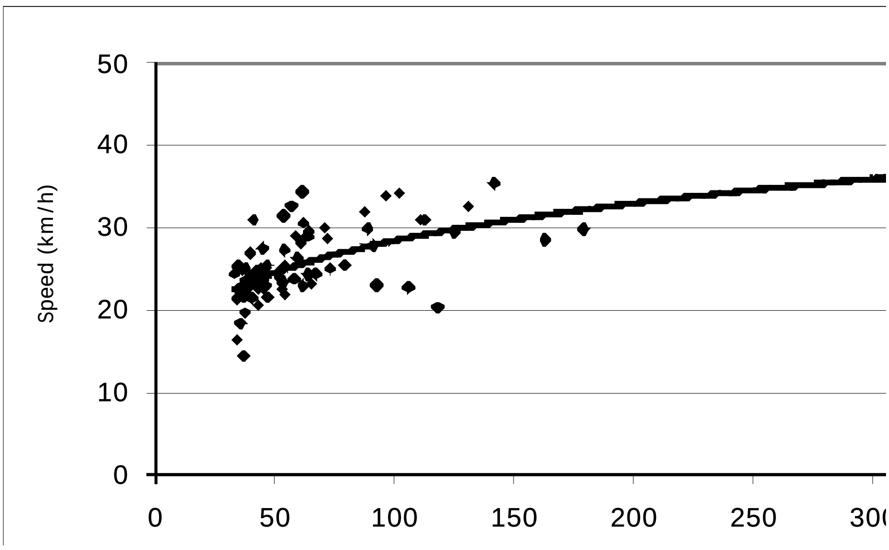


Figure 7.4 Regression curve between visibility (*V_{10}*) and speed (*S_E*) for sites



7.4 Analysis

R^2 is a statistical measure of the predictive power of a deterministic model. It can be considered as the proportion of the variance in the dependent variable that can be accounted for by the variance in its predictors. Here we will use an adjusted R^2 value, so that by-approach and by-site formulations, which have a different number of data points, can be compared meaningfully. Equation 7.1 is used to calculate the R^2 value, while equation 7.2 is used to adjust the R^2 value discovered via equation 7.1.

$$R^2 = 1 - \frac{VAR(S_{MOD} - S_{OBS})}{VAR(S_{OBS})} \quad \text{(Equation 7.1)}$$

$$R^2{}_{ADJ} = 1 - (1 - R^2)\frac{n-1}{n-p-1} \quad \text{(Equation 7.2)}$$

where:

S_{MOD} = modelled speed

S_{OBS} = observed speed

n = number of data points (309 approaches and 79 sites)

p = number of predictors (1 or 2).

Table 7.1 Regression and adjusted R^2 for formulations considering roundabouts by approach

Variable	Regression equation	R^2 adj.
Diameter (*D*)	$S = 12.9\ D^{0.247}$	27.2%
Visibility (*V*)	$S = 13.3\ V^{0.159}$	17.2%
Diameter and visibility	$S = 10.8\ D^{0.198}\ V^{0.079}$	30.1%

Table 7.2 Regression and adjusted R^2 for formulations considering roundabouts by site

Variable	Regression equation	R^2 Adj.
Diameter (*D*)	$S = 13.2\ D^{0.243}$	36.8%
Visibility (*V*)	$S = 10.7\ V^{0.213}$	33.3%
Diameter and visibility	$S = 9.9\ D^{0.163}\ V^{0.123}$	43.6%

In both by-approach and by-site formulations, approach speed generally increases with increasing diameter as well as with increasing visibility; these results were indicated by the positive values in the table of correlation coefficients, and confirm expectations from intuition.

The comparisons of modelled speeds against observed speeds (considering both diameter and visibility) are shown in figures 7.5 and 7.6, which report data relevant to approaches and sites respectively.

Figure 7.5 Modelled v observed approach speeds

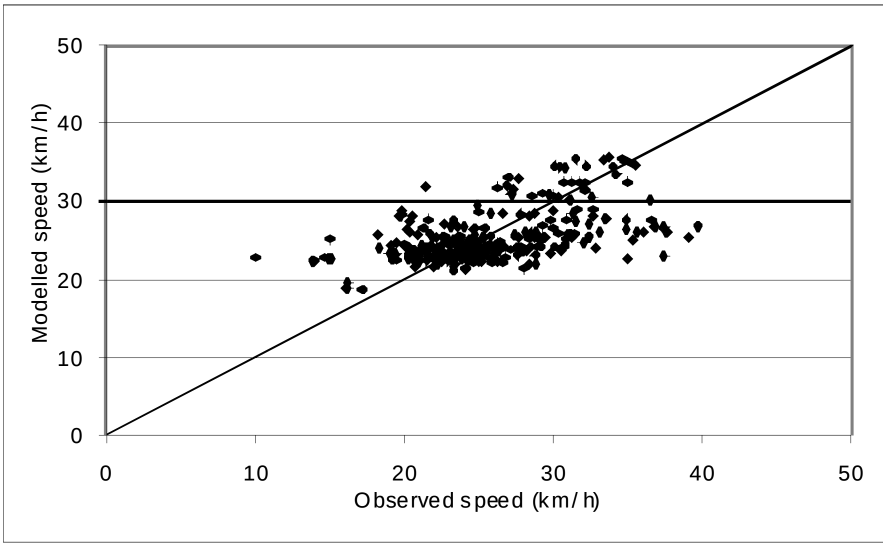
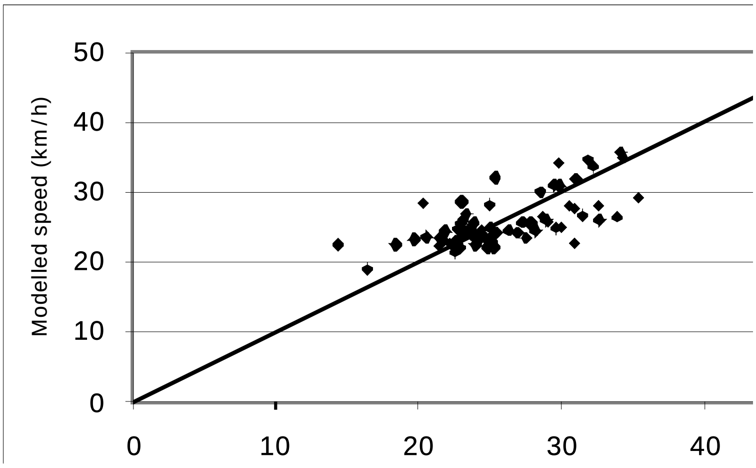


Figure 7.6 Modelled v observed site speeds



These figures show that low (observed) speeds are being over-predicted and that high speeds are being under-predicted. That is, the variation in diameter and visibility does not adequately account for the variation in approach speed, which is indicated by the low adjusted R^2 values.

Finally, we can analyse the distribution of the differences (errors) between modelled and observed speeds to assess the assumption of a Normal error structure retrospectively. Approach speed errors have a skewness of –0.32 and a kurtosis of 4.14; site speed errors have a skewness of 0.04 and a kurtosis of 3.54. Again, these are within expected values for Normal distributions of these sizes, so that the Normal error structure assumption is considered acceptable in hindsight. Distribution plots of the errors are given in figures 7.7 and 7.8.

Figure 7.7 Distribution of approach speed errors

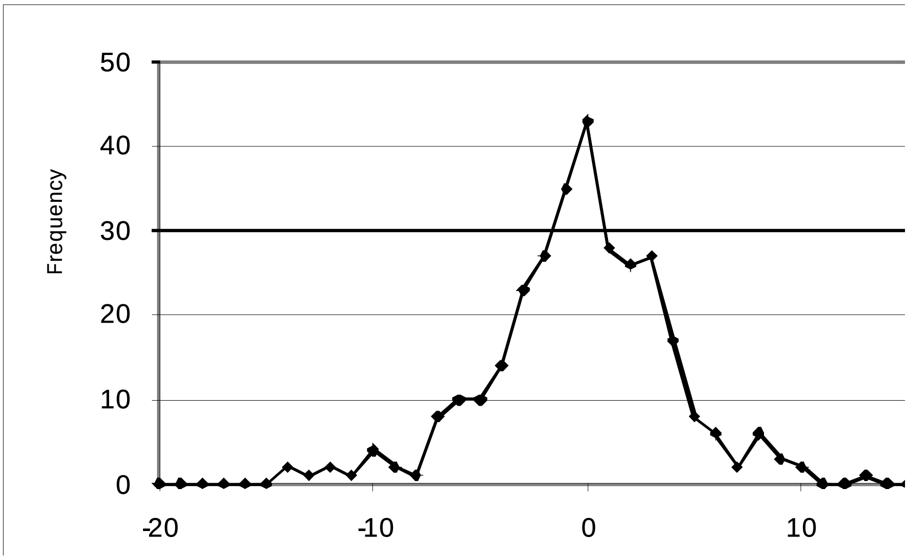
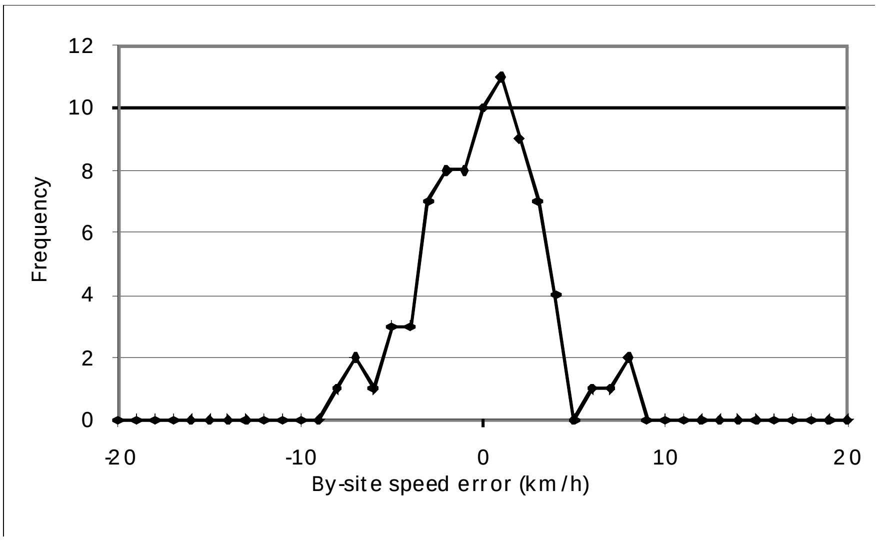


Figure 7.8 Distribution of site speed errors



7.5 Discussion

We have identified diameter and visibility (V_{10} – sight distance from 10m behind the limit lines) as the variables that contribute most effectively to a prediction model for entering speed, and generated regression equations exhibiting power relationships for a Normal error structure for speed.

Measures of fit are 30.1% and 43.6% for the by-approach and the by-site formulations respectively, which are too low for their associated equations to be used for speed prediction purposes; ideally, for models of this type to be useful in a predictive sense, values of 60% or over are required. However, the lack of strong correlations and curve fits among these variables is helpful contextual knowledge for the crash prediction models documented in this report, considering that the likelihood of highly covariant and confounding variables affecting the power of those models is significantly reduced.

Future work in this area may entail the collection of more data with which to explore the idea of speed models further and/or the development of an overall methodology for combined speed and accident prediction models, where covariances among speed, flow and other key variables can be accommodated.

8. Conclusions and recommendations

8.1 Conclusions

This report presents a number of crash prediction models that have been developed for roundabouts. Models have been developed for the major crash types for motor vehicles only, motor vehicles versus cyclists, and motor vehicles versus pedestrians. The models include the principal flow variables and a number of non-flow variables, including approach speed and visibility. Multiplicative factors have also been produced to show the difference in crash rate for low speeds (70km/h and less) and high speeds (80km/h and more) at roundabouts.

The model forms specified by Hauer and Bamfo (1997) have been found to represent some crash relationships better than the standard power function model forms used in previous studies. The Hauer and Bamfo model forms allow greater flexibility in the nature of the relationship modelled.

Most of the 'preferred' models that were developed include 'non-flow' variables that were collected in addition to the flow variables, including visibility, speed and multiple entry lanes. While they did not occur in all preferred models, strong relationships were observed between crashes and both visibility and number of entry lanes. It is these relationships that are the key outcomes of this study, as they indicate which non-flow variables influence safety at roundabouts. The modelling has indicated that a major and important non-flow variable is vehicle speed. The models indicate that as speed increases, so does the number of crashes. This result is supported by other international studies on roundabout safety.

Another important variable is the visibility to vehicles approaching from the right, particularly in loss of control type crashes. The models indicate that crashes increase with increasing visibility. This result is supported by Maycock and Hall (1984) in the U.K. It is suggested that as visibility increases, so do speeds.

Another important result is that roundabouts with multiple entry lanes have a much higher number of crashes (66% more) than single-lane roundabouts, even when the relationship with volume is taken into account.

We have developed some speed models based on diameter and visibility. These were not found, however, to be accurate enough to be useful as predictive tools.

8.2 Recommendations

Based on our findings, we have several recommendations:

- Further analysis should be undertaken to determine how negotiation speed through the roundabout is affected by roundabout geometry and visibility, and how this influences safety.
- The models for total roundabout crashes per approach should be included in the NZTA's *Economic evaluation manual volume 1* (NZTA 2008), replacing the existing product of link models. Factors should also be included for the approach speed limit. The factor of 1.35 should be applied when speed limits are greater than 70km/h. A factor can also be included for multiple lanes (1.66).

9. References

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Appendix A Crash prediction model parameters

A1 Introduction

This appendix outlines all the crash prediction models developed using the modelling procedure in chapter 5. The model parameters are included in tables in the section A3 by crash type and have been sorted by their BIC. The preferred model, which is the model that maximises the goodness of fit while having a parsimonious number of variables, is highlighted in bold and pale grey shading.

To illustrate how the models can be reconstructed from their parameters, the parameters in Table A.1 will be reconstructed to form a model for predicting pedestrian crashes.

Table A.1 Example parameters for model reconstruction

Predictor variables	Parameters					Multiplier	Error structure	BIC
	b_0	b_1	b_2	b_3	b_4	Φ		
P, $e^{(Qa/100)}$ Φ_{MEL}	3.84×10^{-4}	0.55	0.003			3.67	k = 1.8	0.889

The first stage is to write out the functional form of the model. Models always start with the b_0 parameter and then the multiplicative variables are added. If the variables listed are not exponents or multipliers (Φ) (for example, P), they are in a power function form and have a model parameter as an exponent. If the variable is an exponent such as $Q_a/100$ then the model parameter is a multiplier in the exponent. Finally, the multipliers (Φ) are added without any parameters, and the value in the table is the multiplier if the feature is present. The parameters are numbered by the corresponding location in the list of predictor variables. Using this process, the functional form of the predictor variables in table A.1 is shown in equation A.1.

$$A = b_0 \times P^{b_1} \times e^{b_2 \times (Qa/100)} \times \phi_{MEL} \qquad \text{(Equation A.1)}$$

The next step is to add in the model parameters to the functional form as illustrated in equation A.2.

$$A = 3.84 \times 10^{-4} \times P^{0.55} \times e^{0.003 \times (Q_q/100)} \times \phi_{MEL} \qquad \text{(Equation A.2)}$$

A2 Model parameters

The predictor variables are explained in table A.2. The following section outlines the model parameters for the seven crash types and total crashes in tables A.3–A.10.

Table A.2 Definitions of the predictor variables used in the models

Abbreviation	Definition
Q_e	Entering volume for each approach
Q_c	Circulating flow perpendicular to the entering flow
Q_a	Approach flow (the sum of the entering and exiting flow for each approach)
Φ_{MEL}	Multiple entering lanes
Φ_{MCL}	Multiple circulating lanes
Φ_{TJUN}	Intersections with three arms
Φ_{GRADD}	Downhill gradient on approach to intersection
V_{LL}	Visibility from the limit line to vehicles turning right or travelling through the roundabout from their right
V_{10}	Visibility from 10 metres back from the limit line to vehicles turning right or travelling through the roundabout from their right
V_{40}	Visibility from 40 metres back from the limit line to vehicles turning right or travelling through the roundabout from their right
S_E	Average free mean speed of entering vehicles travelling through the roundabout at the limit line
S_C	Average free mean speed of circulating vehicles travelling through the roundabout as they pass each approach (adjacent to splitter island)
SSD_E	Standard deviation of free speeds of entering vehicles at the limit line
SSD_C	Standard deviation of free speeds of circulating vehicles as they pass the approach being modelled
P	Pedestrians crossing the approach in either direction

Table A.3 Entering v circulating (motor vehicle only) model parameters

Predictor variables	Parameters					Multiplier Φ	Error structure	BIC
	b_0	b_1	b_2	b_3	b_4			
Q_e, S_c	1.94×10^{-7}	0.52	2.33				k = 1.2	1.020
Q_e, $e^{(Sc)}$	4.75×10^{-5}	0.52	0.08				k = 1.2	1.020
Q_e, S_c, Φ_{MEL}	1.79×10^{-6}	0.36	2.00			1.91	k = 1.4	1.021
Q_e, Φ_{MEL}	1.20×10^{-3}	0.37				2.16	k = 1.2	1.026
Q_e, Q_c, S_c	**6.12×10^{-8}**	**0.47**	**0.26**	**2.13**			**k = 1.3**	**1.029**
Q_e, S_e	4.46×10^{-6}	0.42	1.66				k = 1.1	1.031
Q_e	3.20×10^{-4}	0.55					k = 1.0	1.031
Q_e, Q_c, S_c, Φ_{MEL}	6.73×10^{-7}	0.34	0.17	1.91		1.79	k = 1.5	1.034
Q_e, S_c, S_e, Φ_{MEL}	1.05×10^{-6}	0.32	1.68	0.58		1.87	k = 1.5	1.035
Q_e, Q_c	2.49×10^{-5}	0.48	0.37				k = 1.1	1.035
Q_e, Φ_{MCL}	6.36×10^{-4}	0.45				1.67	k = 1.1	1.037
Q_c	8.79×10^{-4}	0.44					k = 1.9	1.039
Q_e, V_{10}	1.35×10^{-4}	0.50	0.31				k = 1.0	1.040
Q_e, SSD_e	2.19×10^{-4}	0.53	0.44				k = 1.0	1.041
Q_e, SSD_c	1.64×10^{-4}	0.58	0.38				k = 1.0	1.042
Q_e, V_{LL}	1.77×10^{-4}	0.54	0.16				k = 1.0	1.044
Q_e, V_{40}	1.70×10^{-4}	0.54	0.19				k = 1.0	1.044
Q_e, Φ_{GRADD}	3.25×10^{-4}	0.55				0.85	k = 1.0	1.045
Q_e, Φ_{TJUN}	3.20×10^{-4}	0.55				1.12	k = 1.0	1.045

Table A.4 Rear end (motor vehicle only) model parameters

Predictor variables	Parameters					Multiplier Φ	Error structure	BIC
	b_0	b_1	b_2	b_3	b_4			
Q_e, $e^{(Qe/100)}$, SSD_e	3.92×10^{-2}	-0.53	0.03	1.50			k = 1.8	0.657
Q_e, $e^{(Qe/100)}$, SSD_e, S_e	2.96×10^{-4}	-0.53	0.02	1.32	1.59		k = 1.8	0.664
Q_e, SSD_e	2.86×10^{-7}	1.07	1.35				k = 1.9	0.669
Q_e, SSD_e, S_e	3.47×10^{-9}	0.89	1.13	1.92			k = 1.0	0.672
Q_e, $e^{(Qe/100)}$	**9.63×10^{-2}**	**-0.38**	**0.02**				**k = 1.7**	**0.672**
Q_e, S_e	1.73×10^{-9}	0.83	2.76				k = 1.9	0.674
Q_e, SSD_e, Φ_{MEL}	1.25×10^{-6}	0.91	1.16			1.78	k = 1.0	0.678
Q_e, $e^{(SSDe)}$	6.56×10^{-7}	1.08	0.22				k = 1.9	0.678
Q_e, Φ_{MEL}	8.99×10^{-6}	0.85				2.41	k = 1.8	0.682
Q_e	1.44×10^{-6}	1.10					k = 1.7	0.682
Q_e, V_{10}	4.87×10^{-7}	0.99	0.50				k = 1.8	0.688
Q_e, V_{40}	2.20×10^{-7}	1.03	0.60				k = 1.8	0.690
Q_e, Φ_{GRADD}	1.02×10^{-6}	1.13				2.22	k = 1.7	0.690
Q_e, V_{LL}	4.44×10^{-7}	1.05	0.38				k = 1.8	0.692
Q_e, Φ_{TJUN}	1.45×10^{-6}	1.10				1.14	k = 1.7	0.696

Table A.5 Loss of control (motor vehicle only) model parameters

Predictor variables	Parameters					Multiplier Φ	Error structure	BIC
	b_0	b_1	b_2	b_3	b_4			
Q_a, V_{10}	**6.36×10^{-6}**	**0.59**	**0.68**				**k = 3.9**	**0.786**
Q_a, $e^{(V10)}$	3.86×10^{-5}	0.65	0.01				k = 3.4	0.786
Q_a, V_{LL}	3.31×10^{-6}	0.65	0.65				k = 3.3	0.790
Q_a, V_{40}	3.05×10^{-6}	0.60	0.81				k = 3.9	0.791
Q_a	3.41×10^{-5}	0.71					k = 2.1	0.796
Q_a, V_{10}, S_e	7.72×10^{-7}	0.51	0.58	1.00			k = 3.9	0.797
Q_e, S_e	5.08×10^{-7}	0.54	1.77				k = 2.2	0.797
Q_a, Φ_{GRADD}	3.35×10^{-5}	0.72				0.39	k = 2.4	0.805
Q_a, Φ_{TJUN}	3.52×10^{-5}	0.70				2.01	k = 2.1	0.805
Q_e	3.60×10^{-4}	0.50					k = 1.6	0.806
Q_e, SSD_e	2.63×10^{-5}	0.70	0.27				k = 2.0	0.809
Q_a, Φ_{MEL}	5.60×10^{-5}	0.65				1.24	k = 2.2	0.809

Table A.6 Other (motor vehicle only) model parameters

Predictor variables	Parameters					Multiplier Φ	Error structure	BIC
	b_0	b_1	b_2	b_3	b_4			
Q_a, Φ_{MEL}	**1.34×10^{-5}**	**0.71**				**2.66**	**Poisson**	**0.568**
Q_a	9.68×10^{-7}	1.04					Poisson	0.569
Q_a, V_{LL}	2.30×10^{-6}	1.10	-0.34				Poisson	0.581
Q_e, SSD_e	1.46×10^{-6}	1.05	-0.43				Poisson	0.582
Q_a, $e^{(Qa/100)}$, Φ_{MEL}	1.61×10^{-4}	0.41	0.002			2.60	Poisson	0.582
Q_a, $e^{(Qa/100)}$	1.68×10^{-4}	0.42	0.005				Poisson	0.582
Q_a, Φ_{TJUN}	9.10×10^{-7}	1.05				0.45	Poisson	0.582
Q_a, V_{40}	2.18×10^{-6}	1.08	-0.31				Poisson	0.582
Q_a, V_{10}	1.14×10^{-6}	1.06	-0.10				Poisson	0.584
Q_a, Φ_{GRADD}	9.67×10^{-7}	1.04				0.97	Poisson	0.584
Q_e, S_e	1.02×10^{-6}	1.04	-0.03				Poisson	0.584

Table A.7 Pedestrian crossing model parameters

Predictor variables	Parameters					Multiplier Φ	Error structure	BIC
	b_0	b_1	b_2	b_3	b_4			
P, Φ_{MEL}	5.60×10^{-4}	0.55				4.66	k = 1.4	0.882
P, $e^{(Qa/100)}$ Φ_{MEL}	3.84×10^{-4}	0.55	0.003			3.67	k = 1.8	0.889
Q_a, P, Φ_{MEL}	3.10×10^{-5}	0.32	0.55			3.93	k = 1.6	0.891
P, $e^{(Qa/100)}$	**3.45×10^{-4}**	**0.60**	**0.01**				**k = 1.0**	**0.919**
Q_a, P	1.58×10^{-6}	0.68	0.59				k = 1.9	0.929
P, Q_a, $e^{(Qa/100)}$	7.88×10^{-4}	0.60	-0.10	0.007			k = 1.0	0.935
P	8.41×10^{-4}	0.61					k = 1.6	0.940
P, SSD_e	2.92×10^{-4}	0.61	0.79				k = 1.6	0.945
P, V_{10}	1.38×10^{-4}	0.64	0.40				k = 1.6	0.950
P, V_{40}	1.15×10^{-4}	0.63	0.45				k = 1.6	0.950
P, S_e	3.64×10^{-3}	0.58	-0.41				k = 1.5	0.955
P, Φ_{GRADD}	8.58×10^{-4}	0.60				1.14	k = 1.6	0.955
P, Φ_{TJUN}	8.23×10^{-4}	0.61				1.17	k = 1.6	0.955
P, V_{LL}	1.05×10^{-3}	0.60	-0.05				k = 1.6	0.955
Q_a	2.46×10^{-5}	0.71					k = 1.3	1.007
Q_a, $e^{(Qa/100)}$	6.08×10^{-3}	0.02	0.01				k = 1.3	1.016

Table A.8 Motorist entering versus circulating cyclist model parameters

Predictor variables	Parameters					Multiplier	Error structure	BIC
	b_0	b_1	b_2	b_3	b_4	Φ		
Q_e, C_c	1.51×10^{-4}	0.46	0.38				k = 1.2	1.230
C_c	7.45×10^{-3}	0.39					k = 1.0	1.236
C_c, $e^{(Qe/100)}$	5.41×10^{-3}	0.38	0.01				k = 1.1	1.243
Q_e, C_c, S_e	**3.88×10^{-5}**	**0.43**	**0.38**	**0.49**			**k = 1.2**	**1.245**
C_c, $e^{(Cc/100)}$	5.06×10^{-3}	0.58	-0.46				k = 1.1	1.245
C_c, S_e	2.59×10^{-4}	0.39	1.01				k = 1.0	1.247
C_c, Φ_{GRADD}	8.23×10^{-3}	0.37				0.50	k = 1.0	1.247
C_c, V_{40}	1.41×10^{-3}	0.40	0.39				k = 1.0	1.248
C_c, S_c	6.63×10^{-4}	0.38	0.74				k = 1.0	1.249
C_c, V_{LL}	1.69×10^{-2}	0.38	-0.19				k = 1.0	1.250
C_c, SSD_e	1.08×10^{-2}	0.37	-0.26				k = 1.0	1.250
C_c, SSD_c	5.32×10^{-3}	0.40	0.27				k = 1.0	1.250
C_c, Φ_{TJUN}	7.75×10^{-3}	0.38				0.63	k = 1.0	1.251
C_c, V_{10}	5.33×10^{-3}	0.39	0.08				k = 1.0	1.252
C_c, Φ_{MCL}	7.49×10^{-3}	0.39				0.99	k = 1.0	1.252
C_c, Φ_{MEL}	7.43×10^{-3}	0.39				1.00	k = 1.0	1.252
Q_e	3.27×10^{-4}	0.51					k = 1.8	1.262
Q_e, $e^{(Cc/100)}$	2.66×10^{-4}	0.51	0.43				k = 1.8	1.264
Q_c	4.20×10^{-4}	0.48					k = 1.8	1.264
Q_e, $e^{(Qe/100)}$	1.28×10^{-6}	1.26	-0.01				k = 1.8	1.268

Table A.9 Other cyclist model parameters

Predictor variables	Parameters					Multiplier Φ	Error structure	BIC
	b_0	b_1	b_2	b_3	b_4			
Q_a	2.33×10^{-7}	1.13					Poisson	0.611
Q_a, C_a	**2.07×10^{-7}**	**1.04**	**0.23**				**Poisson**	**0.621**
Q_a, V_{LL}	5.76×10^{-7}	1.22	-0.42				Poisson	0.622
Q_a, V_{10}	3.84×10^{-7}	1.22	-0.34				Poisson	0.624
Q_a, V_{40}	8.25×10^{-7}	1.19	-0.46				Poisson	0.625
Q_a, Φ_{TJUN}	2.13×10^{-7}	1.14				0.52	Poisson	0.626
Q_a, S_e	7.27×10^{-7}	1.17	-0.49				Poisson	0.626
Q_a, Φ_{MEL}	4.42×10^{-7}	1.05				1.24	Poisson	0.626
Q_a, SSD_e	2.75×10^{-7}	1.14	-0.22				Poisson	0.626
Q_a, Φ_{GRADD}	2.36×10^{-7}	1.13				0.89	Poisson	0.627
Q_a, C_a, V_{LL}	4.96×10^{-7}	1.12	0.21	-0.36			Poisson	0.633
C_a	2.27×10^{-3}	0.35					Poisson	0.639

Table A.10 Total crashes model parameters

Predictor variables	Parameters					Multiplier Φ	Error structure	BIC
	b_0	b_1	b_2	b_3	b_4			
Q_a, Φ_{MEL}	**6.11×10^{-4}**	**0.58**				**1.66**	**k = 2.2**	**2.611**
Q_a, $e^{(Qa/100)}$, Φ_{MEL}	1.36×10^{-2}	0.19	0.004			1.55	k = 2.3	2.617
Q_a, $e^{(Qa/100)}$	1.85×10^{-2}	0.15	0.005				k = 2.1	2.624
Q_a	2.18×10^{-4}	0.71					k = 1.9	2.627
Q_a, S_e	3.70×10^{-5}	0.64	0.72				k = 2.0	2.632
Q_a, SSD_e	1.56×10^{-4}	0.70	0.31				k = 2.0	2.634
Q_a, V_{10}	1.36×10^{-4}	0.68	0.19				k = 1.9	2.636
Q_a, V_{40}	1.63×10^{-4}	0.70	0.09				k = 1.9	2.642
Q_a, Φ_{TJUN}	2.17×10^{-4}	0.71				1.17	k = 1.9	2.642
Q_a, V_{LL}	1.81×10^{-4}	0.70	0.05				k = 1.9	2.642
Q_a, Φ_{GRADD}	2.17×10^{-4}	0.71				1.08	k = 1.9	2.643

Appendix B CAS coding sheet

Figure B.1 Matrix for CAS codes for crash types

	TYPE	A	B	C	D	E	F	G	O
A	Overtaking and lane change	Pulling out or changing lane to right	Head on	Cutting in or changing lane to left	Lost control (overtaking vehicle)	Side road	Lost control (overtaken vehicle)	Weaving in heavy traffic	Other
B	Head on	On straight	Cutting corner	Swinging wide	Both or unknown	Lost control on straight	Lost control on curve		Other
C	Lost control or off road (straight roads)	Out of control on roadway	Off roadway to left	Off roadway to right					Other
D	Cornering	Lost control turning right	Lost control turning left	Missed intersection or end of road					Other
E	Collision with obstruction	Parked vehicle	Crash or broken down	Non-vehicle obstructions including animals	Trade vehicle	Opening door			Other
F	Rear end	Slow vehicle	Cross-traffic	Pedestrian	Queue	Signals	Other		Other
G	Turning v same direction	Rear of left turning vehicle	Left turn side swipe	Stopped or turning from left side	Near centre line	Overtaking vehicle	Two turning		Other
H	Crossing (no turns)	Right angle (70° to 110°)							Other
J	Crosssing (vehicle turning)	Right turn right side	Obsolete	Two turning					Other
K	Merging	Left turn in	Right turn in	Two turning					Other
L	Right turn against	Stopped waiting to turn	Making turn						Other
M	Manoeuvring	Parking or leaving	U-turn	U-turn	Driveway manoeuvre	Parking opposite	Angle parking	Reversing along road	Other
N	Pedestrians crossing road	Left side	Right side	Left turn left side	Right turn right side	Left turn right side	Right turn left side	Manoeuvring vehicle	Other
P	Pedestrians other	Walking with traffic	Walking facing traffic	Walking on footpath	Child playing (tricycle)	Attending to vehicle	Entering or leaving vehicle		Other
Q	Miscellaneous	Fell while boarding or alighting	Fell from moving vehicle	Train	Parked vehicle ran away	Equestrian	Fell inside vehicle	Trailer or load	Other

* Movement applies for left and right hand bends, curves or turns

Appendix C Model subscripts

UMAR1: entering v circulating (motor vehicle only) crashes

UMAR2: rear-end (motor vehicle only) crashes

UMAR3: loss of control (motor vehicle only) crashes

UMAR4: other motor vehicle only crashes

UPAR1: pedestrian crashes

UCAR1: entering v circulating cyclist crashes

UCAR2: other cyclist crashes

UAAR0: all crashes

AAAR0: crashes where posted approach speeds are above 70km/h

Appendix D Aerial photographs of selected roundabouts

Figure D1 Aerial photograph of Taounui Street / George Street / Cuba Street roundabout, Palmerston North

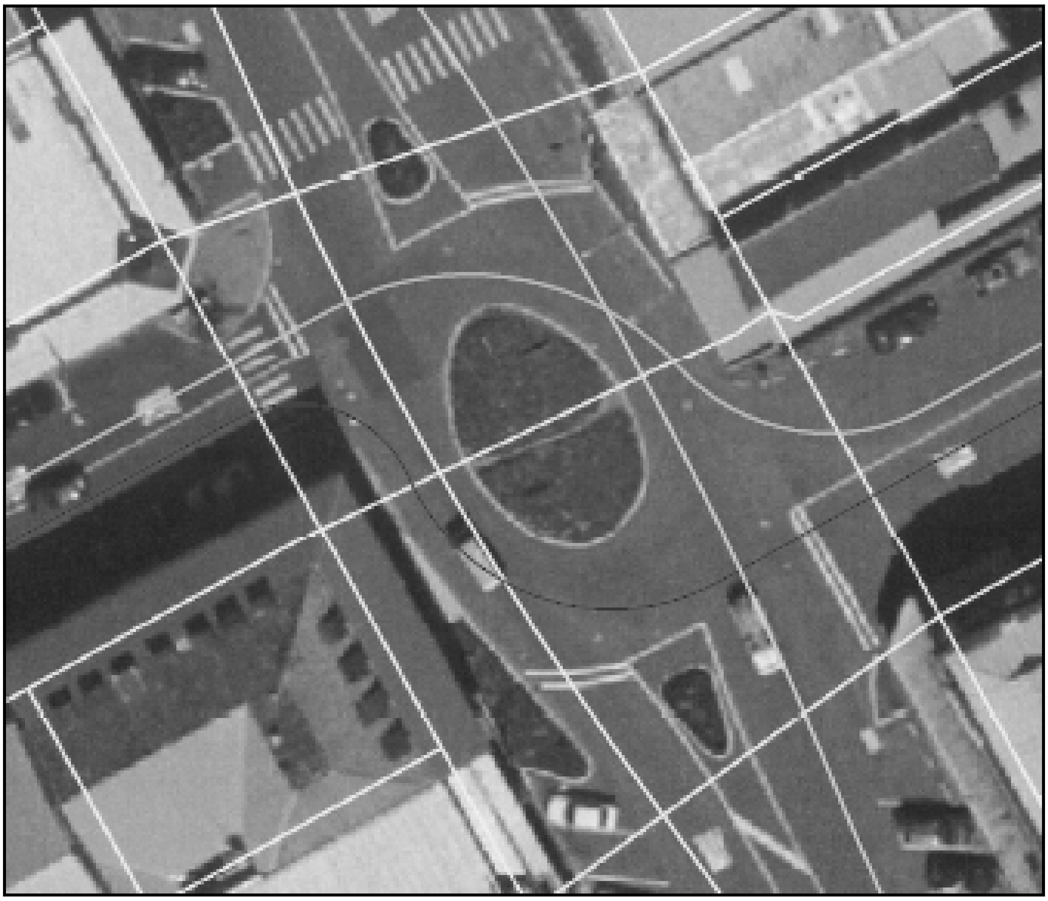

Figure D2 Aerial photograph of Blockhouse Bay Road / Donovan Street / Kinross Street roundabout, Auckland

Figure D3 Aerial photograph of Point England Road/Elstree Avenue/Erima Avenue roundabout, Auckland