Improved multi-lane roundabout designs for urban areas

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Executive summary

Introduction

The type of control to install at an intersection is one of the most important decisions to be made by road planners and traffic engineers, usually having major safety and capacity implications for the sustainability of a road network. The main objectives of this project, undertaken 2008–2010, were to evaluate the difference in safety performance between multi-lane roundabouts and traffic signals, and to research design options for roundabouts to improve their safety and operation. Most of the material is specifically relevant to urban speed environments (a ≤50km/h speed limit), but many of the findings also apply to higher-speed rural or highway situations.

The research on this project, undertaken 2008–2010, was divided into five main tasks:

- Compare the safety between traffic signals and multi-lane roundabouts for all road users.
- Research and evaluate the current guidelines for visibility at roundabouts. Sightlines to the right can affect the speed of approaching vehicles, so the relationship of sightlines to safety at roundabouts was investigated.
- Research and evaluate options for pedestrian facilities at multi-lane roundabouts. Safety and amenities for pedestrians at multi-lane roundabouts can be a concern, so existing New Zealand and overseas facilities was undertaken were evaluated.
- Research and evaluate the use of vertical deflection devices at main road roundabouts. These can be an effective means of speed control for addressing the safety of pedestrians and cyclists especially.
- Evaluate the turbo-roundabout for feasibility in New Zealand. This is a low-speed design developed in The Netherlands which apparently offers improved safety and capacity compared to conventional multi-lane roundabouts.

Comparing the safety of roundabouts and traffic signals

Evidence from overseas and New Zealand demonstrates that a well-designed roundabout should have significantly fewer injury crashes (especially serious and fatal) than if the intersection was signalised. This statement is applicable for all types of urban roads, including main road multi-lane intersections. Results for a given location will depend on traffic volumes, the number of arms and other features particular to that site. However, an analysis of 40 intersections in the Auckland region demonstrated a 47% reduction in vehicle occupant injuries and some overseas studies demonstrated even larger savings. It has been concluded that in order to reduce nationwide injury crash statistics at urban intersections, roundabouts should be the preferred choice over traffic signals, particularly for intersections with four arms or more.

Crash model work undertaken in New Zealand seems to be contrary to overseas research, which shows an appreciable reduction in vehicle user injury crashes for roundabouts compared to traffic signals for all types of intersection. These crash prediction models (which are based on nationwide data) appear to demonstrate that although roundabouts at four-arm intersections in New Zealand are safer than traffic signals, the difference is somewhat less than many overseas studies indicate; at three-arm intersections, traffic signals are marginally safer. These results may be influenced by a lack of adequate speed control at roundabouts in New Zealand, which affects their safety performance. The New Zealand *Economic evaluation manual* (EEM) also overestimates crash rates for roundabouts on this basis.

For pedestrians, this research did not conclusively find a significant difference in safety performance between multi-lane roundabouts and traffic signals, but evidence suggests that roundabout controls may be safer. Further research would be required to confirm whether or not a multi-lane roundabout with well-designed crossing facilities would be safer for pedestrians than a signalised intersection.

However, the safety and amenity of cyclists at multi-lane roundabouts does justify more attention, as evidence indicates these vulnerable users in particular can be adversely affected by the current design standards for roundabouts used in New Zealand. Measures to reduce roundabout vehicle entry speed or to physically separate cyclists from vehicle traffic are expected to address this substantially (most cyclist crashes at roundabouts involve the circulating cyclist being hit by a driver entering the roundabout). A new type of low-speed multi-lane roundabout called the C-roundabout has been developed in New Zealand specifically to improve safety for cyclists; several of these have been constructed in Waitakere City. The results so far indicate safety benefits. Signalised roundabouts in the United Kingdom (UK) have also been shown to improve cyclist safety. ‘Cyclist priority’ crossings are also used at roundabouts in The Netherlands, although they can experience higher crash rates.

For comparing the expected safety performance of various countermeasures at a particular intersection, the field of crash modelling appears to offer potential in this regard. Such models need to use proven inputs and to be able to take into account the full range of traffic engineering safety countermeasures for roundabout and traffic signal options. Beca Ltd has produced material that can be used for traffic signals as well as roundabouts, but this material requires further development to make it easier for practitioners to apply. Other currently available crash models for roundabouts include ARCADY and ARNDT.

Key recommendations are:

- The NZ Transport Agency (NZTA) should consider adopting a ‘Roundabouts First’ type policy. The primary motivator for this policy is traffic safety, and vehicle delay and environmental reasons. In practice, such a policy could require road controlling authorities (RCAs) to justify the use of alternative intersection controls, if installing a roundabout is viable.
- Engineers and safety auditors who are responsible for considering the design details of roundabouts must implement best current design practice, particularly in relation to adequate speed control. This is a critical design factor which is not always being appropriately adhered to in New Zealand.
- Current crash rates for roundabouts in the EEM should be revised to better represent current best design practice, including adequate speed control. The crash rates are based on nationwide data that includes many roundabouts designed with inadequate deflection and other shortcomings, thereby reducing the economic viability of installing roundabouts.
- Pedestrian crash rates at roundabouts and traffic signals should be better determined, as evidence suggests that well-designed roundabouts may be a safer form of intersection control for these users than traffic signals. This applies particularly to fatal and serious pedestrian injury crashes.
- The legal use of cyclist priority crossings at roundabouts should be considered for a trial in New Zealand, as they can offer greater mobility for these users. Speed platforms may be required to mitigate any safety concerns.
- The field of crash modelling should be further developed so practitioners can better compare the safety performance between roundabouts and traffic signals for a particular site.

Sightlines to the right at roundabouts

Sightlines to the right can influence speed through a roundabout more significantly than roundabout geometry. Understanding the effects of sightline restrictions to approach speeds can be valuable for the safer design of roundabouts and preventing crashes, particularly for cyclists and motorcyclists.

Excessive sightlines to the right can encourage higher than desirable driver entry speeds at a roundabout, which can subsequently increase crash types including loss-of-control, rear-end and entering v circulating (particularly two-wheeled users, who are less visible). In the UK, visibility barriers have been successfully used to address loss-of-control and rear-end crashes at higher-speed rural locations, and British design guidelines recommend this measure as an optional treatment.

However, one significant finding from this research is that if sightlines to the right are too restrictive when the speed of opposing vehicles is high, entering v circulating crashes can be expected to increase. A safety analysis of a roundabout in Otahuhu, Auckland, amply demonstrated this finding.

Key recommendations are:

- Practical applications of the findings about sightline restrictions to improve safety at roundabouts have been developed. These guidelines are recommended to RCAs to design safer roundabouts at locations where geometric means of speed control are difficult to achieve (ie are costly), or where it is necessary to address a crash pattern (eg via the use of sight screens).
- For existing roundabouts with loss-of-control or rear-end type crash patterns, consideration should be given to restricting sightlines for entering drivers as per the UK guidelines. However, if opposing vehicle speeds are high, this needs to be taken into account if an increase in entering v circulating vehicle crashes is to be avoided.
- Predicting driver approach speed relative to visibility to the right at a roundabout (restricted by either sight screens or obstructions) should to be further researched, as this concept offers a viable economic alternative to geometric means of speed control at roundabouts. This would require some 'in the field' experimentation.

Pedestrian facilities at multi-lane roundabouts

Multi-lane roundabouts, if well-designed, are able to accommodate pedestrians safely, and hence are a viable alternative to a signalised intersection. t is particularly relevant that no pedestrian fatality has been recorded at any roundabout in New Zealand during 2005–2008, compared to 11 at traffic signal intersections. Zebra crossing facilities offer the greatest mobility to able-bodied pedestrians, although they can have some disadvantages to visually impaired users.

A review of zebra crossings at multi-lane crossing points in Auckland demonstrated they can be relatively safe if located less than 20m from the roundabout, mainly because of the lower vehicle speeds near circulating lanes. However, zebra crossings at multi-lane locations where vehicle speeds are higher (eg more than 20m from the roundabout) often experience safety issues, so additional measures or even alternative crossing facilities may be desirable. Appropriate speed control at the roundabout is a significant consideration, and advance warning devices such as flashing road studs or raised pedestrian platforms will also improve pedestrian safety at these facilities. Some practical advice for safer zebra crossings at roundabouts has been included.

Pedestrian signals near roundabouts are a viable alternative to zebra crossings, but pedestrian wait times need to be set low enough to reduce the jaywalking that may otherwise occur, which, in turn, can compromise pedestrian safety. Staggered crossings, although sometimes not popular with pedestrians, can reduce disruption to vehicle movement, as crossing times are shorter for each direction.

'Hawk' and 'Pelican' crossings as used overseas are appropriate signalised crossing alternatives near roundabouts that can reduce disruption to traffic flow with no apparent compromise to pedestrian safety. However, as they have flashing displays, they are not legal to use in New Zealand. Pedestrian detection technology as used with 'Puffin' crossings in the UK could feasibly achieve a similar objective (their reliability does need to be better proven).

Signalised roundabouts can also satisfactorily incorporate pedestrian facilities and have demonstrable safety benefits for cyclists. However, compared to an unsignalised roundabout, vehicle delays may be substantially higher during off-peak periods and would need to be taken into account. Part-time signal operation as used overseas, which may address this, is not currently legal in New Zealand.

Key recommendations are:

- The practical application document should be referred to for the design of pedestrian facilities at roundabouts.
- The legal use of flashing signal displays such as used at 'Pelican' and 'Hawk' signal crossings should be considered for adoption in New Zealand. These types of facilities can reduce the disruptive effects of signalised crossings to traffic flow, including at roundabouts.
- The legal use of part-time signals should be considered for adoption by the NZTA. This is particularly relevant for signalised roundabouts or metered signals on roundabout approaches, whereby signals could feasibly be switched off as a means of reducing driver delay during off-peak periods.
- Current design guidelines in New Zealand require the use of lane arrows at multi-lane approaches for roundabouts but not at traffic signals. These lane arrows can potentially have adverse effects for pedestrian safety at multi-lane crossing points, and it is recommended that this requirement be amended to an optional measure as per UK practice.
- The current New Zealand standard diameter for Belisha discs used at zebra crossings is only 400mm. The *Manual of traffic signs and markings* standard should be amended to include a 750mm diameter option or similar, which would make the Belisha discs of similar visibility to those used overseas.

The use of vertical deflection devices at roundabouts

Given that vertical deflection devices at roundabouts are beneficial for pedestrian and cyclist safety, some justification should be given as to why they are not used more often on main road roundabouts in New Zealand. In some overseas cities such as Malmö, Sweden, they are often being used for this purpose.

This research has identified that the most likely adverse effect of any significance would be some additional noise generated from some heavy vehicles as they traverse the device, eg lightly laden trucks with three axles or more and mechanical leaf-spring suspension, or two-axle trucks if driven at excessive speed. Any acceleration/deceleration noise from heavy vehicles would depend upon the particular device and proximity to the roundabout. Some other potential adverse effects are possible, including delays to emergency vehicles, vehicle occupant discomfort (particularly bus passengers), fatigue damage to heavy vehicles, traffic diversion, and vibration damage to adjacent buildings or structures. However, all of these effects were usually found to be of minor nature and significance. Hence for any proposed installation, the safety benefits of a vertical deflection device should be objectively weighed up against the potential adverse effects. For example, the noise effects could feasibly be assessed by a review of truck volumes by type, time of day and proximity to sensitive land use activities.

It is concluded that RCAs could more seriously consider the application of vertical deflection devices at roundabouts on main roads outside the context of central business districts (CBDs) or shopping areas, which is currently the case in New Zealand. In addition, the use of vertical deflection devices at roundabouts should not be limited to pedestrian and cyclist safety considerations only in urban areas. They do offer an economic alternative to geometric means of vehicle speed control at roundabouts, which can otherwise be costly in terms of land-take. Options include raised speed platforms (eg up to 100mm high), speed humps and speed cushions. In general, the higher profile the vertical deflection device has, the greater the speed reduction effect.

Key recommendations are:

- RCA should consider the use of vertical deflection devices on main roads as a means of speed control at roundabouts, and not just in the context of CBDs or shopping centres. However, their application does require careful consideration of potential adverse effects, and a practical application of how to use these findings when installing vertical deflection devices has been drafted.
- If vertical deflection devices are to be used more commonly on main roads, the possibility of introducing legislation to require or encourage the more widespread use of less noisy alternatives to mechanical suspension (such as air suspension) on larger heavy vehicles should be explored.

The Dutch turbo-roundabout

The turbo-roundabout is a series of designs developed in The Netherlands. Their main design element is a spiralling lane arrangement with mountable lane dividers on the circulating carriageway and approaches, which produces a tendency to slower vehicle speeds and fewer sideswipe crashes. Evidence suggests they have better safety and capacity performance compared to conventional multi-lane roundabouts with similar lane numbers, although they are likely to be more expensive to install

The turbo-roundabout is a viable form of intersection control for use in New Zealand, the advantages in both safety and capacity being reasonably well documented. When evaluating a turbo-roundabout against other intersection options, a design engineer will need to take the following factors into account:

- A turbo-roundabout will generally be a more expensive option than a conventional multi-lane roundabout in terms of land area and additional costs such as lane dividers, delineation and signage.
- The largest New Zealand design truck requires more room for tracking than the equivalent Dutch design vehicle. Although it is expected that the Dutch standard configuration for a turbo-roundabout may operate satisfactorily, this should be taken into account for the particular location being considered in terms of expected truck volumes and type. The largest vehicles in New Zealand would be classified as over-dimension vehicles in The Netherlands, and would have to traverse mountable sections and lane dividers.
- If raised lane dividers were to be used in New Zealand, appropriate advance warning signage and delineation would be required, particularly for the safety of motorcyclists.

The key recommendation is:

- The turbo-roundabout is a viable low-speed design concept that has been used successfully in The Netherlands, and it is recommended that an example be built and evaluated in New Zealand, including a comparison of safety and capacity with and without the mountable lane dividers.

Abstract

This research, undertaken 2008–2010, investigated the comparative safety of multi-lane roundabouts versus signalised intersections, pedestrian facilities, vertical deflection devices and visibility to the right. Guidance for practical application of the relevant measures to enhance roundabout safety has been developed and is included in this document. The Dutch turbo-roundabout was reviewed and considered to be feasible for application in New Zealand.

For intersections with four arms or more, a well-designed multi-lane roundabout should be significantly safer for vehicle users than traffic signals. Several means of adequately catering for pedestrians and cyclists at multi-lane roundabouts are feasible to implement in many cases.

In the interest of road safety, a 'Roundabouts First' policy is recommended for adoption by the NZTA. The legal use of flashing signal displays and part-time signal operation are also recommended for consideration, which would potentially allow for 'Pelican' type pedestrian crossing installations, and also for signalised roundabouts to operate with less vehicle delay during off-peak periods.

1 Introduction

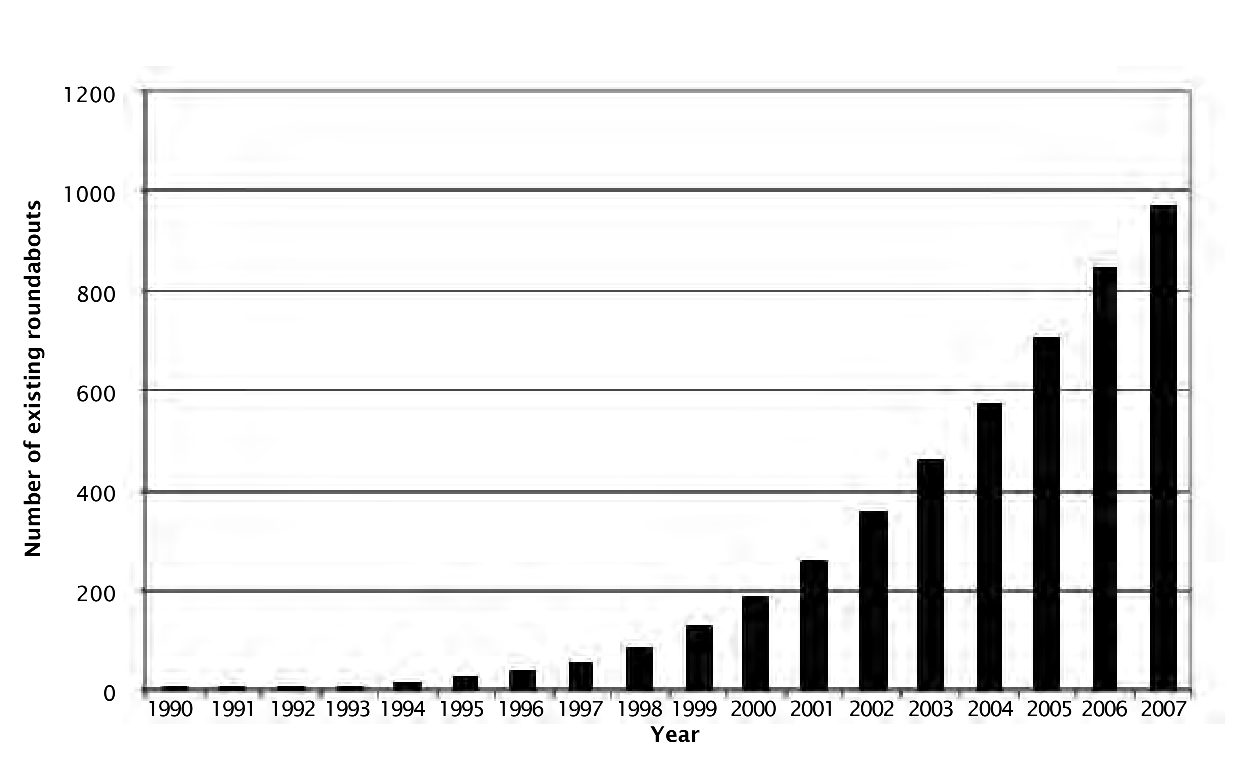
1.1 Background

Until recent decades, large roundabouts have largely been ignored as a design option in mainland Europe and the United States (US). However, they are now being increasingly used there (see figure 1.1 below), largely because of the growing recognition that roundabouts can experience fewer serious injury and fatal crashes than traffic signals (Persaud et al 2000). In the United Kingdom (UK), they have historically been a default design option, and are sometimes fully or partially signalised for capacity reasons. However, in New Zealand, their installation in many larger cities is declining, and a major factor is the perceived safety concerns that road planners have with regard to cyclists and pedestrians (particularly where pedestrians are required to cross two or more lanes in each direction).

The provision of a safe environment for cyclists and pedestrians at multi-lane roundabouts can be a challenge for many traffic engineers. In New Zealand, this problem is often averted (in urban areas at least) by the installation of traffic signals at an intersection, even though this may result in additional driver delays and a greater overall number of injury crashes. This trend is likely to continue unless road planners are clearly presented with better alternatives.

It is apparent that if the safety and amenity of cyclists and pedestrians can be adequately addressed, then well-designed roundabouts would appear to offer the most promising form of traffic control in terms of safety and delays, and their adoption could then be more encouraged in New Zealand. Recent research undertaken by the NZ Transport Agency (NZTA) investigated the needs of cyclists and a new design option for multi-lane roundabouts was developed, the C-roundabout (Campbell et al 2006). This current project, carried out during 2008–2010, was intended as an extension of that research, including a review of the relative safety performance between roundabouts and traffic signals, as well as addressing the issue of catering for pedestrians. Most of the material is specifically relevant to urban speed environments (ie a 50km/h speed limit or less), but many of the findings will also apply to higher-speed rural or highway situations.

Figure 1.1 Cumulative number of roundabouts in the United States in recent years (adapted from Rodegerdts 2008)



1.2 Project objectives

The objectives of this project are as follows:

- Compare safety between traffic signals and multi-lane roundabouts for all road users (chapters 2 and 3). Injury crash rates and severity are purportedly lower at roundabouts, and this could potentially be a greater motivator to install them in New Zealand. This section included some crash modelling work.
- Research and evaluate the current guidelines for visibility at roundabouts (chapter 4). Guidelines in the UK differ from those of Austroads in relation to sightlines to the right in particular. Because of the safety implications, this topic deserved fuller attention. The results of this research were used to create a method for their practical application (appendix D).
- Research and evaluate options for pedestrian facilities at multi-lane roundabouts (chapter 5 and 6). Safety and amenity for pedestrians at multi-lane roundabouts can be a concern for road planners, so an evaluation of potential measures was undertaken that included those not yet used in New Zealand. A practical application of the findings was drafted (appendix F). This section included an evaluation of zebra crossing facilities from a psychologist's perspective.
- Research and evaluate the use of vertical deflection devices at main road roundabouts (chapter 7). These can be an effective means of speed control, but for several reasons, many Road Controlling Authorities (RCAs) are reluctant to use them more often on main roads. A practical application of the findings was produced (appendix H).

- Research and evaluate the turbo-roundabout (chapter 8). This is a special low-speed design developed in The Netherlands that supposedly offers improved safety and capacity compared to conventional multi-lane roundabouts.

Although these are quite separate topics in their own right, it is expected that they will provide excellent background material to assist New Zealand road planners and traffic engineers decide upon appropriate forms of intersection control, and also enable them to design safer roundabouts for all road users.

2 Comparative safety of roundabouts and signalised intersections: literature review

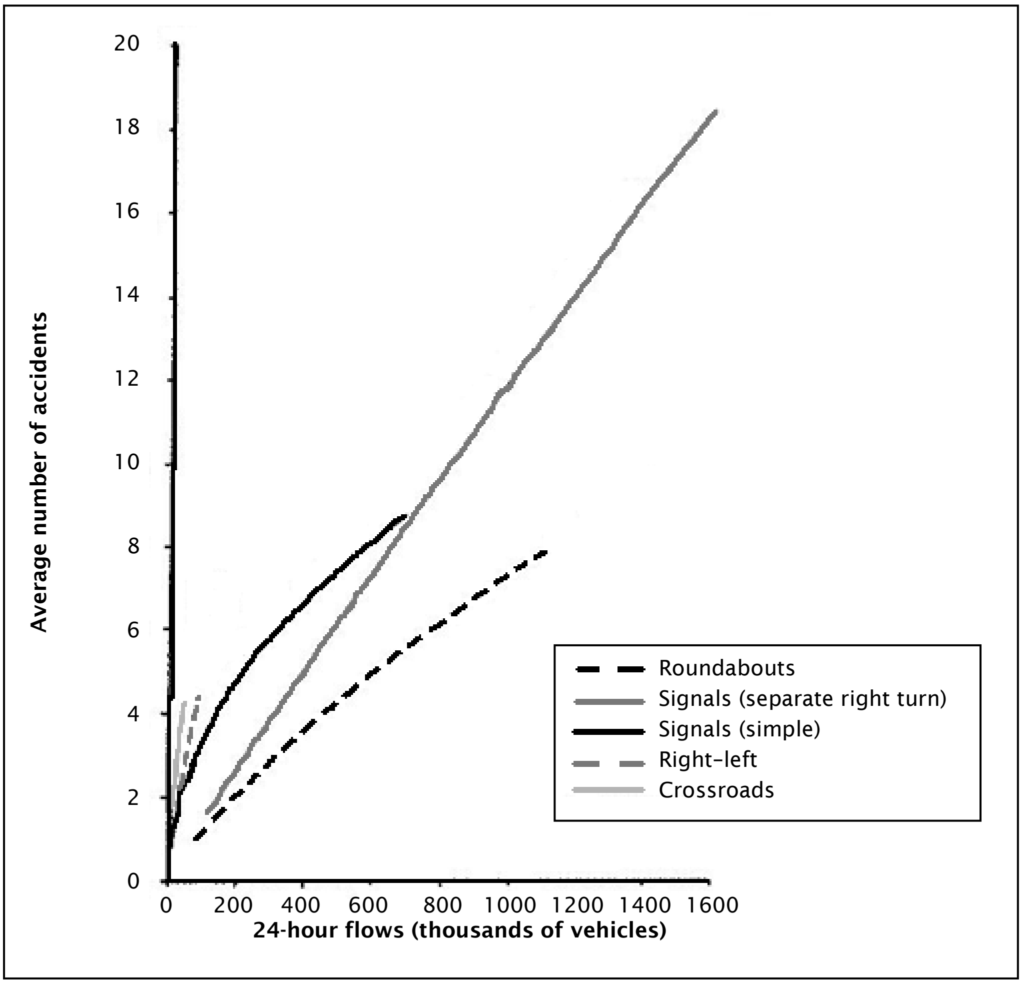
2.1 Injury and non-injury crashes

Most of the studies reviewed indicate that injury crashes have been found to be fewer in number and less severe for a roundabout junction than traffic signals in Australia, Britain, Belgium, the US, The Netherlands and Norway. Estimated savings range between 25% and 74% for injury crashes, but this can depend upon traffic volumes, the speed limit and the number of approach roads. Non-injury crashes may possibly be higher at roundabouts, but this is not well proven.

Some of the relevant studies are as follows:

- An Australian study (Corben 1989) from a review of literature claims a reduction in injury crashes of 25% can be assumed when converting a signalised junction to a roundabout. This study goes so far as to recommend the introduction of 'program[me] based traffic safety guidelines for replacing intersection signals with roundabouts at appropriate locations'.
- The Austroads guideline for roundabouts (Austroads 1993) included a review of comparative studies carried out in Australia. Typical injury crash rates for high volume roundabouts was found to be 0.6–1.1 crashes per year, compared to 1.2–1.6 and 1.6–1.8 for signalised T-intersections and crossroads respectively. This represents at least 30–39% fewer injury crashes at roundabouts compared to traffic signals.
- A study from the UK (Hall and Surl 1981) indicates that roundabouts could expect to experience significantly fewer injury crashes than traffic signals, depending upon traffic exposure. A relationship between injury crashes and traffic flow for four-arm dual carriageway intersections (ie two traffic lanes in each direction) is illustrated in figure 2.1.

Figure 2.1 Regression lines for injury crashes at dual-carriageway junctions (adapted from Hall and Surl 1981)



- A Belgian study (Wallonne Ministry of Equipment and Transports 2005) of 273 priority junctions converted to either roundabouts or traffic signals found that injury crash numbers for the traffic signal sites were 21% greater than roundabouts for urban situations, 52% greater for suburban and 116% greater for open country.
- A US study (Nambisahn and Parimi 2007) compared three major road junctions (defined as greater than 20,000 vehicles per day) controlled by roundabouts to three signalised sites with similar traffic volumes. It was found that roundabouts experienced fewer injury crashes and were a little safer in terms of crash severity, although overall crash rates were significantly higher for the roundabout sites. The high rate of non-injury crashes was partly attributed by the authors to inadequate roundabout design and the fact that most US drivers were unfamiliar with roundabout controls at the time of writing.
- A more comprehensive US study of 23 intersection conversions to roundabouts (Persaud et al 2000) concluded that converting intersections from traffic signal controls to modern roundabouts can produce substantial reductions in motor vehicle crashes, and that multi-lane roundabouts seem to be effective in eliminating most serious injury crashes. For a set of four roundabouts converted from traffic signals (three of which were multi-lane roundabout designs), the estimated reductions were 35% for all crashes combined and 74% for injury crashes.

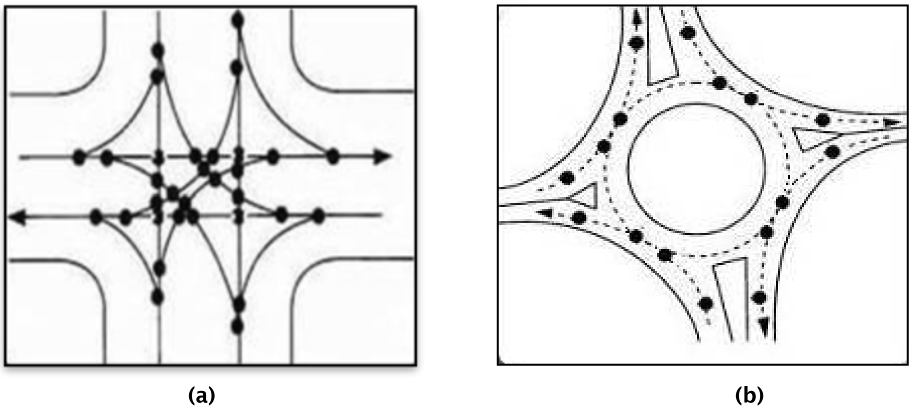
- A study from The Netherlands investigated the effect of converting nine signalised junctions to roundabouts, and found a 27% reduction in total crashes with a 33% reduction in casualties (Schoon and van Minnen 1994).
- A Norwegian study that compared the crash statistics of 59 roundabouts and 124 signalised intersections found injury crash rates to be 40–50% lower at the roundabout sites (Giaever 1992).
- With regard to non-injury crashes, it seems to be indicated that roundabouts may experience more of these than traffic signals, but this is not well proven, mainly because of under-reporting of these types of incidents (Persaud et al 2000; Elvik 2003; Elvik and Vaa 2004). Three-arm intersections in particular may experience higher non-injury crash rates at roundabouts compared to signals (Elvik 2003).

2.2 Crash severity

The difference in safety performance between traffic signals and roundabouts appears to be mainly attributable to the higher potential relative speeds of vehicles that are possible at a signalised intersection. A well-designed roundabout will achieve lower potential relative speeds by geometric means and should therefore experience less severe injuries when crashes do occur. In addition, the number of conflict points is greatly reduced, as shown in figure 2.2.

The evidence from New Zealand and overseas affirms that roundabouts can be expected to experience less severe crashes compared to traffic signals. Studies from the UK, the US and Belgium demonstrated savings of 25–66% in fatal and serious crashes, depending upon the number of arms at the intersection and the speed environment. New Zealand crash data does not demonstrate such substantial savings in serious crashes, but fatal crashes were still substantially less – the authors believe these lesser savings may have been influenced by inadequate speed control at many roundabouts in New Zealand, which is discussed further in section 3.4.4.

Figure 2.2 Diagram showing the difference in intersection vehicle–vehicle conflict points: traffic signals (a) have 32 potential collision points, while multi-lane roundabouts (b) have just 16



(a) (b)

A study from the UK (Hall and Surl 1981) compared four-arm intersections controlled by either a roundabout or traffic signals in 30–40mph areas. Thirteen of these junctions were roundabouts, 11 were controlled by traffic signals with no separate right-turn phases and 12 were controlled by traffic signals with separate right-turn phasing. The results (table 2.1) demonstrated a significant reduction in crash severity for the roundabout sites, which experienced 40% fewer serious or fatal crashes, and this result was significant at the 1% level. Although the signalised sites apparently experienced approximately 65%

more pedestrian traffic than the roundabouts, less than 17% of the crashes involved these users in all categories of intersection.

Table 2.1 Crash severity for four-arm dual-carriageway junctions in the UK (Hall and Surl 1981)

Junction type	% fatal crashes*	% serious injury crashes*	Total % serious or fatal crashes*
Roundabouts	0.5	11.3	11.8
Traffic signals (no separate right-turn phase)	1.8	17.8	19.6
Traffic signals (separate right-turn phase)	1.5	17.8	19.3

* Figures represent percentages of all injury crashes only

A US study of four-arm junctions (Elvik 2003) also noted that a 59% reduction in fatal and 46% reduction in serious injury crashes might be expected from converting a signalised junction to roundabout. However, this result was not significant at the 5% level.

A Belgian study of 273 priority junctions converted to either roundabouts or traffic signals (Wallonne Ministry of Equipment and Transports 2005) found that serious accidents for the traffic signal sites were 25% greater than roundabouts for urban situations, 24% greater for suburban locations and 66% greater for open country locations.

As a comparison, a review of 2003–2007 crash statistics available from the Crash Analysis System (CAS) for all roundabouts and traffic signals in 50km/h areas in New Zealand gave the results shown in table 2.2. The proportions of fatal and serious injury crashes are marginally less for roundabouts than for traffic signals, though the roundabout sites include a higher proportion of minor road junctions.

Table 2.2 Crash severity for New Zealand intersections 2003–2007

Junction type	% fatal crashes*	% serious injury crashes*	Total % serious or fatal crashes*
Roundabouts	0.4	13.0	13.4
All traffic signals	0.8	13.7	14.5
Traffic signals: crossroads	0.7	14.2	14.9
Traffic signals: T-junction	0.6	9.8	10.4

* Figures represent percentages of all injury crashes only

2.3 Number of arms on the roundabout

Several studies have demonstrated that although the difference in safety performance between roundabouts and traffic signals is still distinct for a three-arm intersection, it is more so for a junction with four arms or more. Injury crash savings for roundabouts are 11–40% for three-arm and 17–50% for four-arm intersections.

A Norwegian study (Seim 1991) compared crash statistics between 59 roundabouts and 124 signalised intersections between 1985 and 1988, and the results are shown in table 2.3. Roundabouts were found to be the safer form of control, with 40% fewer injury crashes per million vehicles at the three-arm junctions and 50% fewer at the four-arm junctions.

Table 2.3 Expected injury crash statistics from Norway (Seim 1991)

No. arms	Injury accident rate per million vehicles	
	Roundabouts	Traffic signals
3	0.03	0.05
4	0.05	0.10

The *Handbook of road safety measures* (Elvik and Vaa 2004) estimated crash savings for a roundabout on the basis of a review of several international studies (table 2.4); note that although injury crashes are reduced, non-injury crashes are estimated to increase by substantial margins. Injury crashes were still expected to reduce, but again less significantly for the three-arm junctions.

Table 2.4 Percentage change of the number of crashes at roundabouts compared to signalised intersections (from Elvik and Vaa 2004)

Junction type	Accident severity	Best estimate
Three-arm junction (previously a signalised intersection)	Injury	–11
	Non-injury	+32
Four-arm junction (previously a signalised intersection)	Injury	–17
	Non-injury	+42

Another US study (Elvik 2003) reviewed international evidence and estimated the effects, as shown in table 2.5, which affirms the previous studies in finding that a four-arm roundabout will be substantially safer compared to traffic signals. Again, injury crashes are predicted to decrease, but with an increase in non-injury type. However, the study did note that these results were not statistically significant at the 5% level.

Table 2.5 Expected crash statistics for a roundabout previously controlled by traffic signals (Elvik 2003)

Number of arms	Percentage change of the number of crashes	
	Accident severity	Best estimate
Three	Fatal	–42
	Serious injury	–24
	Minor injury	–22
	Non-injury	+55
Four	Fatal	–59
	Serious injury	–46
	Minor injury	–45
	Non-injury	+10

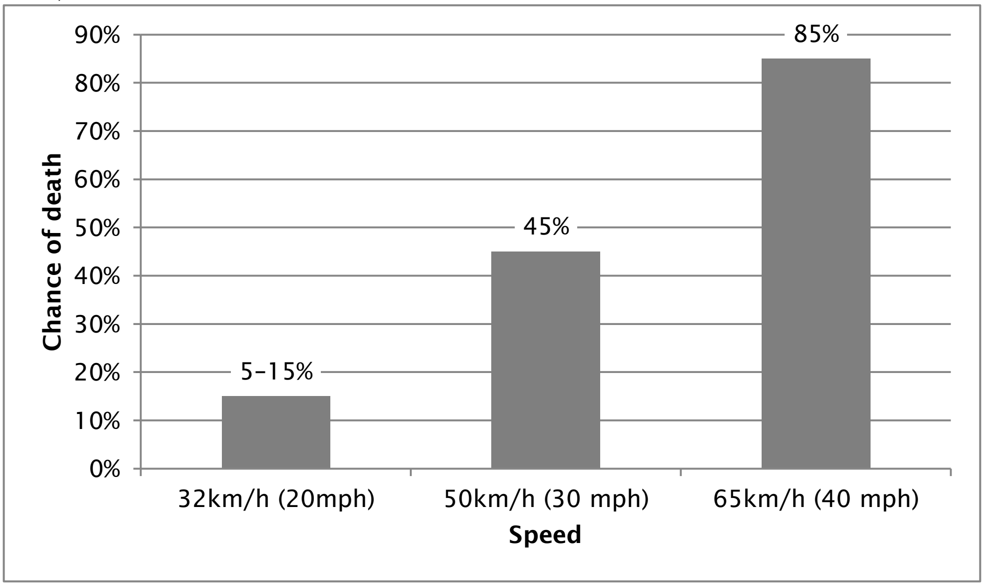
2.4 Pedestrians

2.4.1 International findings

Research that directly compares crash rates for pedestrians at roundabouts and traffic signals is relatively sparse, but what is available either does not show a significant difference or suggests that a roundabout control is safer. Chapters 5 and 6 show that although historical exceptions can be found in Auckland (mostly because of poor design), pedestrian crossing facilities at multi-lane roundabouts can be designed to operate relatively safely. Further research is required to determine whether a multi-lane roundabout with well-designed crossing facilities would be safer for pedestrians than an intersection controlled by traffic signals.

Previous well-known research has demonstrated the relationship between collision speed and the risk of fatality (Ashton and Mackay 1979), and this is shown in figure 2.3. At a collision speed of 32km/h, 5–15% of pedestrians will be killed compared to 45% if the speed is 50km/h. Although this relationship does not directly infer that roundabouts will be safer overall for pedestrians than traffic signals, the reduced speed environment at a well-designed roundabout should mean that collisions might be less severe than at traffic signals which permit higher vehicle speeds through the junction.

Figure 2.3 Pedestrians' chance of death if hit by a vehicle (adapted from Federal Highway Administration 2000)



Studies from the UK (Maycock and Hall 1984; Hall 1986) that took pedestrian crossing volumes into account give an indication of relative crash rates at four-arm intersections, and these are shown in table 2.6. These researchers concluded that small and conventional roundabouts are safer for pedestrians than traffic signals. Pedestrian crash rates at single-carriageway traffic signals (ie with no separating median between opposing traffic lanes) are substantially higher than for small roundabouts, but are not too dissimilar to larger roundabouts. At less than one reported injury per million pedestrians, the chances of an incident at either control type would appear to be relatively small in any case.

Table 2.6 Pedestrian crash statistics at four-arm intersections in the UK (Maycock and Hall 1984; Hall 1986)

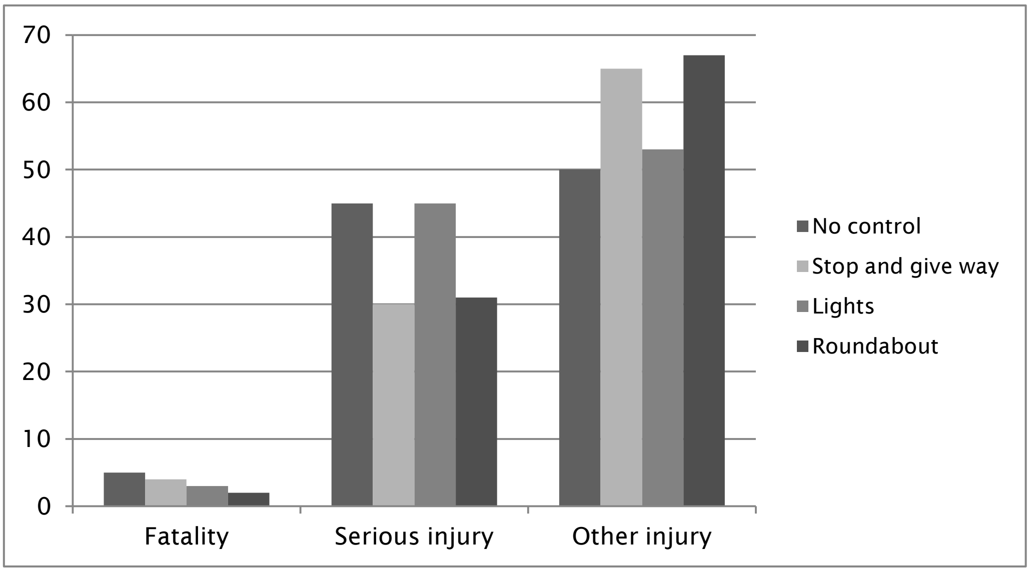
Intersection type	Pedestrian injuries per million pedestrians
Small roundabouts	0.33
Conventional roundabout	0.45
Dual carriageway roundabout	0.72
Signals at single carriageway junctions	0.67

A Swedish study found that for two-lane roundabouts, the pedestrian crash risk was comparable to signalised intersections (Brude and Larsson 2000). This was based on empirical data for 72 roundabouts compared with expected values for comparable signalised intersections.

France has over 25,000 roundabouts, but in 2003, these only experienced two pedestrian fatalities (Guichet 2005). Although the significant majority of these are single-lane roundabouts, many are multi-lane.

An Australian study (Tumber 1997) investigated pedestrian crash statistics from 400 arterial roundabouts in the Melbourne metropolitan area. Over an eight-year period between 1987 and 1994, 64 reported pedestrian injury crashes occurred at 38 roundabout locations, representing an average crash rate of just 0.02 pedestrian injury crashes per roundabout per annum. The majority of these 38 sites were in shopping precincts, which experience higher volumes of pedestrians. Elderly pedestrians were slightly over-represented, and the majority of pedestrian crashes were hit on the approach side of the roundabout. Citywide, the severity of crashes was found to be lower than at other intersection types (figure 2.4). Although a comparison between traffic signals and roundabouts was attempted, because of the low numbers of crashes, a meaningful comparison was not able to be made. However, the study did at least conclude that pedestrian safety at roundabouts in Melbourne was not a significant concern.

Figure 2.4 Injury severity of pedestrian accidents by intersection control type in Melbourne 1987–1995 (adapted from Tumber 1997)



2.4.2 New Zealand crash statistics

A search of the New Zealand CAS showed that nationwide, no pedestrian fatality has occurred at any urban roundabout in 2004–2008, compared to 11 fatalities at urban signalised intersections. These 11 fatalities at signals included five pedestrian jaywalking incidents, and four where vehicles were making left or right turns during pedestrian green phases but did not give way. These figures do not include all jaywalking incidents or crashes at nearby pedestrian facilities, which might be entered into the CAS system as mid-block locations instead of as being associated with an intersection; for example, only half of the zebra crossing pedestrian crashes at the 11 multi-lane roundabout sites studied in chapter 6 were classified as a roundabout control under CAS. It is also the authors' experience that pedestrian crashes at traffic signals usually occur a distance away from the intersection.

Further research on this subject would be desirable to confirm if pedestrian crash rates in New Zealand at traffic signals are significantly different from those occurring at roundabouts.

2.5 Cyclists

Roundabouts are safer than a comparable priority junction for all road users including cyclists, but larger multi-lane types are more hazardous and have higher cyclist crash rates than traffic signals (Campbell et al 2006). Options to improve safety for cyclists are either to provide separate off-road facilities, which are usually very expensive, or to reduce vehicle speeds (particularly when entering the roundabout) by way of geometric design or other means (Campbell et al 2006). Signalised roundabouts can also give safety benefits for cyclists and this is discussed further in section 2.7.

Roundabouts have been proven to have a high casualty rate for cyclists relative to motorists, both in New Zealand as well as overseas. New Zealand studies have shown that cyclists account for 6% of accidents at roundabouts compared to just 1% at traffic signals and 4% at priority junctions (Transfund NZ 2000), and cyclists are also 20 times more likely to be injured than other road users at a roundabout (Wood 1999).

Cyclists also comprise 24% of all injury crashes at roundabouts in New Zealand, and multi-lane roundabouts have generally been found to have a significantly higher crash rate for all road users than single-lane roundabouts (Harper and Dunn 2003). A search of the CAS database also showed that in 2004–2008, 387 cyclist injury crashes happened at 1097 urban roundabouts, compared to 337 cyclist injuries at 1461 urban signalised intersections. This represents a 50% higher incident rate at the roundabouts even though these roundabouts include a large proportion of small single-lane type with minor volumes of traffic.

In the UK, cycle accident rates at roundabouts are 15 times higher than those involving cars, and two to three times greater than bicycle accident rates at signalised intersections (Allott and Lomax 1991).

The predominant crash pattern for cyclists at roundabouts in New Zealand as well as overseas involves entering vehicles hitting circulating cyclists already on the roundabout. Generally, 50–60% of all cyclist crashes at roundabouts have been attributed to this one crash type. In New Zealand, this is about 50% (Harper and Dunn 2003). A more recent evaluation of multi-lane roundabouts in Auckland found that 69% of cyclist injury crashes involved this manoeuvre (Campbell et al 2006).

A new type of multi-lane roundabout design called the C-roundabout was developed in New Zealand specifically to improve safety for cyclists (Campbell et al 2006). To date, several of these have been constructed in Waitakere City, Auckland (an example is shown in figures 2.5 and 2.6). Justification for the works were to improve cyclist and pedestrian safety, and to address a history of high-speed single-vehicle crashes at that location. The C-roundabout uses confined geometry as a means of reducing vehicle speed to around 30km/h or lower, and consequently requires large trucks to straddle traffic lanes as they negotiate the roundabout. On-road cyclists are expected to benefit both from the reduced speed environment and also the narrow traffic lanes, which dissuade car drivers from overtaking them. Currently, the C-roundabout is being comprehensively evaluated as part of an NZTA research project; the results to date indicate that it is successful in reducing driver speeds and has been favourably received by cyclists.

Figure 2.5 Aerial photo of the Palomino Drive–Sturges Road roundabout in Waitakere City, Auckland, prior to reconstruction

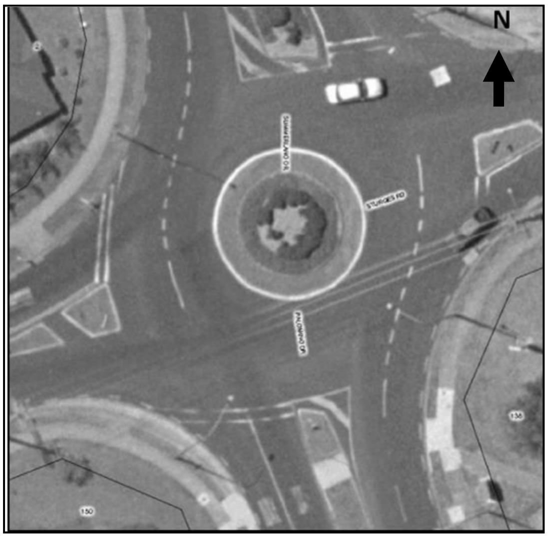


Figure 2.6 Aerial photo of the Palomino Drive–Sturges Road roundabout in Waitakere City, Auckland, after a C-roundabout configuration was installed in 2009

In The Netherlands, it is legal to install 'cyclist priority' crossings, and these are discussed further in section 8.3.3. 'Cyclist priority' crossings are not currently legal to install in New Zealand (NZ Government 2004), but it is suggested this could be reviewed in light of experience from The Netherlands. Although such crossings seem to be susceptible to higher numbers of cyclist injuries, well-staggered median islands that force cyclists to slow down and/or raised platform treatments on the roadway could mitigate these safety concerns. Greater mobility for cyclists would be the overall benefit.

2.6 Design elements that can affect safety at roundabouts and traffic signals

2.6.1 Summary

A shortcoming with studies comparing intersection types such as roundabouts and traffic signals is that they do not demonstrably identify whether or not critical safety design criteria are being adhered to for the traffic signal or roundabout installations. For example, on a one-to-one basis, it may be unfair to compare a poorly designed roundabout with inadequate speed control to a traffic signal junction operating with protected right turns and red light cameras. It can also only be assumed that similar due care has been taken on the behalf of the respective designers for each of the intersection types.

For the purpose of comparing the expected safety performance of a particular intersection for roundabout or traffic signal scenarios, it would be useful to be able to take all of the critical design elements and traffic engineering tools available into account, but this is currently difficult to do on a basis that is widely accepted by practitioners. However, modelling crash rates as developed by Beca Ltd in New Zealand does offer some potential in this regard. It is recommended this be further developed to take the effects of both good and deficient design practice into account, as well as the multitude of traffic engineering measures available.

2.6.2 Safety elements for roundabouts

Key elements of roundabout design that have been found to affect safety include deflection, entry width and visibility to the right for loss-of-control crashes (Maycock and Hall 1984). Maycock and Hall also found that roundabouts with no deflection had crash rates about 8.5 times those with maximum deflection, a result which affected future roundabout design (Kennedy et al 2005). A New Zealand review of a sample of 349 roundabouts from 33 RCAs found that 17% had inadequate deflection on roundabout approaches (NZTA 2000). Given the aforementioned finding, this minority could be creating a disproportionately adverse effect to the overall safety performance for roundabouts in New Zealand if speed control is not being properly applied (this is further discussed in section 3.4.4).

One measure that has demonstrably improved safety at roundabouts is full signalisation, and this is also discussed further in section 2.7.

In addition, New Zealand research has found a relationship between excessive visibility to the right for entering vehicles and crash rates (Turner and Roozenburg 2007), and this is explored further in chapter 4.

2.6.3 Safety elements for traffic signals

Key elements of traffic signal design that have been found to affect safety include:

- approaches on an upgrade
- median islands and protected right turns
- the width of traffic lanes
- lack of driver awareness regarding the presence of an intersection, such as on a bend or over a crest (Ogden 1994).

Several measures can be applied to signalised intersections junctions that can improve their safety performance:

- Prohibition of filtered right turns can reduce right-turning against crashes (Ogden 1994; Institute of Transportation Engineers (ITE) 2004) and potentially reduce total intersection crashes by 23–48% (ITE 2004).
- Red light camera installation and enforcement can reportedly reduce injury crashes by around 25% or more according to some studies (Retting and Ferguson 2003; Aeron-Thomas and Hess 2005). The *Handbook of road safety measures* (Elvik and Vaa 2004) suggests that a 12% reduction in injury crashes will result. In addition, red light camera technology has been suggested to extend all-red times automatically upon detection of late running vehicles (Wainwright 2004).
- The use of flashing yellow rather than an all-green display to clarify driver expectations that a filter is operating has been suggested in the US (Wainwright 2004).
- The use of larger signal displays, particularly the red display, can reduce red light running (ITE 2004).
- Use of raised speed platforms at the intersection can reduce vehicle speeds through the intersection. This has been done in the Province of South Holland in The Netherlands, with apparently substantial reductions in injury crashes (Fortuijn 2009c).

Note that some of these measures may adversely affect intersection capacity, and a decision to implement them in practice will also depend upon operational demands.

2.7 Signalised roundabouts

Traffic signal control of a roundabout, either part-time or full-time, is reasonably common in the UK but New Zealand drivers have little experience of their use. Signal control at a roundabout is usually installed in the UK to improve capacity by balancing a junction with high flows and some guidelines for their applications have recently been published (Department for Transport (DfT) 2009). In summary, full signalisation of roundabouts would appear to offer some overall safety benefits, especially for cyclists. Figures 2.7 and 2.8 show examples of signalised roundabouts.

Figure 2.7 A signalised roundabout installed in Tauranga (Chard et al 2008)

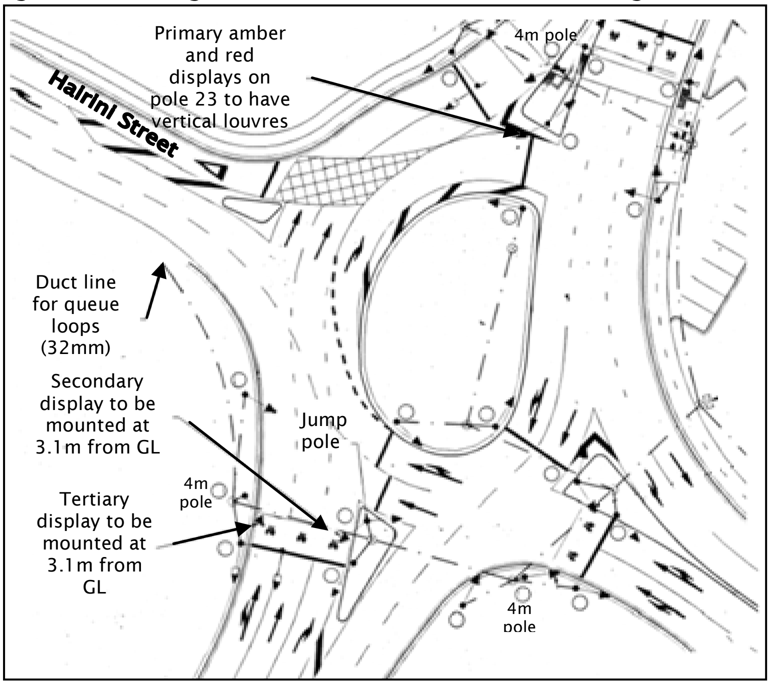


Figure 2.8 A signalised roundabout in Villeurbanne, France (aerial photo courtesy of Google maps)

Full-time signals (on all or some arms) in the UK have displayed considerable reductions in cyclist crashes at roundabout entries (Lines 1995). The safety benefit for cyclists is considered by the authors of this report to be created by the time separation of entering vehicles from circulating roundabout traffic by signal control – the majority of cyclist crashes at roundabouts involve them being struck by entering vehicles as they are circulating past (Campbell et al 2006).

A more recent study (Institute of Highways and Transportation (IHT) 2005) found some substantial crash reductions (to a significance level of 10% or better) when 10 existing at-grade roundabouts were fully signalised, as shown in table 2.7. Pedestrian crashes were reduced from 30 to 24 but this was not significant at the 10% level. However, given that signalised intersections can be provided more readily, amenities for blind or elderly pedestrians are likely to be improved. It should be noted that signalised roundabouts in the UK are often very large in diameter and have quite high operating speeds, and these crash savings could, in a large part, be attributed to this. Safety implications for New Zealand roundabouts could thus be much less significant. In addition, speed-related crashes (ie loss-of-control) increased after the roundabouts were signalised but the UK study did apparently not attempt to identify reasons for this.

Table 2.7 Crash reductions following signalisation of 10 roundabouts in the UK (IHT 2005)

Collision type	Collisions before	Collisions after	Change (%)
Total collisions	384	277	–28%
Involving a motorbike	85	63	–26%
Involving a cyclist	70	14	–80%
On a wet road surface	79	49	–38%
During hours of darkness	101	73	–28%
Entering a roundabout	71	30	–58%
Speed-related crashes	26	44	+69%

2.8 Roundabouts First policies in North America

Several jurisdictions in the US and Canada have introduced 'Roundabouts First' policies which strongly favour a roundabout over other forms of intersection control. The main ones identified are New York State (New York State Department of Transportation 2006), British Columbia (British Colombia Ministry of Transportation and Infrastructure 2007) and Virginia (Virginia Department of Transportation 2010), and these policies are soon to be adopted in Alaska (Alaska Department of Transportation and Public Facilities 2010). Minnesota, Washington and Wisconsin have also apparently introduced similar legislation (Weber 2008).

The main reason for these policies is traffic safety, but other reasons include reductions in vehicle delay and pollutant emissions.

The *British Columbia supplement to TAC*[1] *geometric design guide* (British Colombia Ministry of Transportation and Infrastructure 2007) states that:

> *British Columbia's Roundabout First Policy: Roundabouts shall be considered as the first option for intersection designs where 4-way stop control or traffic signals are supported by traffic analysis. If an intersection treatment other than a roundabout is recommended, the project documentation should include a reason why a roundabout solution was not selected for that location. This roundabouts 'first' policy supports the province's Climate Action Program of 2007.*
>
> *Roundabouts shall be considered on all roadways including intersections at interchange ramps.*

The *New York highway design manual* (New York State Department of Transportation 2006) says:

> *NYSDOT's Roundabout First Policy: When a project includes reconstructing or constructing new intersections, a roundabout alternative is to be analyzed to determine if it is a feasible solution based on site constraints, including [right of way], environmental factors, and other design constraints.*
>
> *Exceptions to this requirement are where the intersection:*
>
> - *has no current or anticipated safety, capacity, or other operational problems*
> - *is within a well working coordinated signal system in a low-speed (<80km/h) urban environment with acceptable accident histories*
> - *is where signals will be installed solely for emergency vehicle pre-emption*
> - *has steep terrain that makes providing an area, graded at 5% or less for the circulating roadways, infeasible*
> - *has been deemed unsuitable for a roundabout by the Roundabout Design Unit.*
>
> *When the analysis shows that a roundabout is a feasible alternative, it should be considered the Department's preferred alternative due to the proven substantial safety benefits and other operational benefits*

1 Transportation Association of Canada; the title of the cited work uses the acronym.

2.9 Summary of literature review

Based on the literature review, the following conclusions have been made:

- It is clearly indicated that for most intersections, a roundabout will experience substantially fewer injury crashes than traffic signals by around 25–74%, and especially the more serious type that may involve fatality or hospitalisation. This difference in safety performance will be greater for intersections with four arms or more.
- In terms of non-injury crashes, some evidence suggests that multi-lane roundabouts may experience a greater number of these crashes compared to traffic signals, particularly at three-arm intersections.
- For pedestrians, the relative safety performance between roundabouts and traffic signals is not well proven to be significant, and the chances of injury are relatively small for both control types in any case. However, the lower-speed environment of a well-designed roundabout means that any collisions with a pedestrian would be expected to be less severe than at traffic signals, and nationwide New Zealand statistics seem to affirm this. Further research is required to confirm whether a multi-lane roundabout with well-designed crossing facilities would be safer for pedestrians than an intersection controlled by traffic signals.
- Traffic signals are significantly safer for cyclists than multi-lane roundabouts at present in New Zealand. However, measures at roundabouts to reduce driver entry speed or to physically separate cyclists from vehicle traffic are expected to address this substantially. A new type of low-speed multi-lane roundabout specifically to improve safety for cyclists called the C-roundabout is currently being evaluated as part of an NZTA research project. ‘Cyclist priority’ crossings are also used at roundabouts in The Netherlands, although they can experience higher cyclist crash rates.
- Crash rates at roundabouts can be influenced by design elements such as deflection, entry width and visibility to the right for loss-of-control crashes.
- Crash rates at signals can be influenced by design elements such as size of displays, red light cameras and banning of filtered turns.
- Crash modelling analysis appears to offer potential for making direct comparisons between intersection controls for a particular location, and is recommended for further development.
- Installing full-time traffic signals on a multi-lane roundabout may potentially further improve traffic safety for cyclists in particular, and should also address amenity issues for visually impaired or elderly pedestrians. To date, only a few signalised roundabouts have been installed in New Zealand.
- Several jurisdictions in North America have introduced ‘Roundabouts First’ policies, based foremost on traffic safety, but also for vehicle delay and environmental reasons.

3 Comparison of roundabouts and traffic signals

3.1 Introduction

3.1.1 Background

The main objective of this section was to identify differences in safety performance between roundabouts and traffic signals at main intersections for all categories of road user. Many overseas studies show roundabouts to be the safer alternative and some North American jurisdictions, including New York and British Columbia, have even introduced 'Roundabouts First' polices on that basis. A qualitative assessment based on New Zealand experience is desirable before following suit.

3.1.2 Methodology

In order to provide an assessment of the relative safety performance of roundabouts and traffic signals, this section of research included the following tasks:

- a literature review of available material from New Zealand and overseas (chapter 2)
- a statistical comparison of crash histories between 20 matched arterial road roundabout and traffic signal sites in Auckland, matched on the basis of having similar geometry and traffic volumes
- a statistical comparison of crash histories between any identified sites that were converted from multi-lane roundabouts to traffic signals, or vice versa
- crash model analysis comparing expected crash rates between roundabout and traffic signal control for some typical arterial road intersection scenarios based on New Zealand experience.

3.2 Comparison between 20 matched multi-lane roundabout and traffic signal sites in Auckland

3.2.1 Summary

The purpose of this section is to make a local comparison of arterial road multi-lane sites in Auckland, and compare the results with the conclusions of the literature review in chapter 2, which found that roundabouts are, overall, a safer junction control.

The results from the 40 Auckland sites studied demonstrated a statistically significant difference between the roundabout and traffic signal sites. The roundabouts experienced 47% fewer vehicle injury crashes, with 67% fewer serious and fatal injury crashes.

3.2.2 Methodology

Two sets of 20 matched urban sites were selected relatively randomly on the basis of:

- junction geometry, ie number of approach arms
- daily traffic volumes through each site.

Appendix A contains aerial photos of these locations and a table showing crash data, while appendix B contains a covering letter by the reviewer statistician and some sample output. Traffic volume data was sourced from either publically available traffic count data in proximity to the site, intersection count data or from Sydney Coordinated Adaptive Traffic System data provided from the Auckland Traffic Management Unit (TMU).

Crash data for each site is based on reported crashes in 2003–2007 within a 50m radius of the junction. Crash reports were reviewed and any non-intersection crashes were excluded (such as turning manoeuvres into driveways etc).

3.2.3 Results and statistical analysis

Using a simple binomial test, the total number of crashes for each set of 20 sites was compared. Daily traffic volumes for the traffic signals were, overall, 2% higher than that of the roundabouts, which is considered a negligible difference for the purpose of this exercise.

The important statistically significant results, as shown below in table 3.1, are in relation to vehicle crashes only, since pedestrian and cyclist volumes were not counted. Total vehicle injury crash savings of 47% were demonstrated for the roundabout sites, and a 67% saving for serious and fatal injury types.

Note that of the four serious injury vehicle crashes at the roundabout sites (no fatalities occurred), two of these involved motorbikes, which could be considered another vulnerable user group. A statistically significant saving of 9% was achieved in the total number of vehicle crashes (injury and non-injury combined), although no statistical difference could be found for non-injury crashes.

All of the 12 vehicle serious injury and fatal crashes at signals involved speed as a major factor (two involved deaths). Five crashes were right-angle crossing incidents involving red light running. Four crashes involved loss-of-control or head-on collisions, and three involved right-turn against crashes at a green light filter. Only one of these 12 crashes involved a motorbike.

In addition, a Wilcoxon signed rank test was applied in order to examine the differences between the two groups of paired data. This test depends on the hypothesis that if no significant difference exists between two sets of paired measurements, any chance differences which are present ought to consist of roughly equal numbers of plus and minus differences. This test takes into account not only the direction of the differences, but also the size of the differences between matched pairs. The results shown in table 3.1 indicate statistically fewer vehicle injury crashes (at the 0.01 level) and also a lower total number of crashes at the roundabouts compared to traffic signals. In figure 3.1, the prevalence of traffic signal sites (squares) to the right of the roundabout sites (circles) visibly demonstrates the significant difference in crash numbers that was identified.

Table 3.1 Comparison of crashes at signals and multi-lane roundabouts at 20 matched sites in Auckland for the period 2003–2007

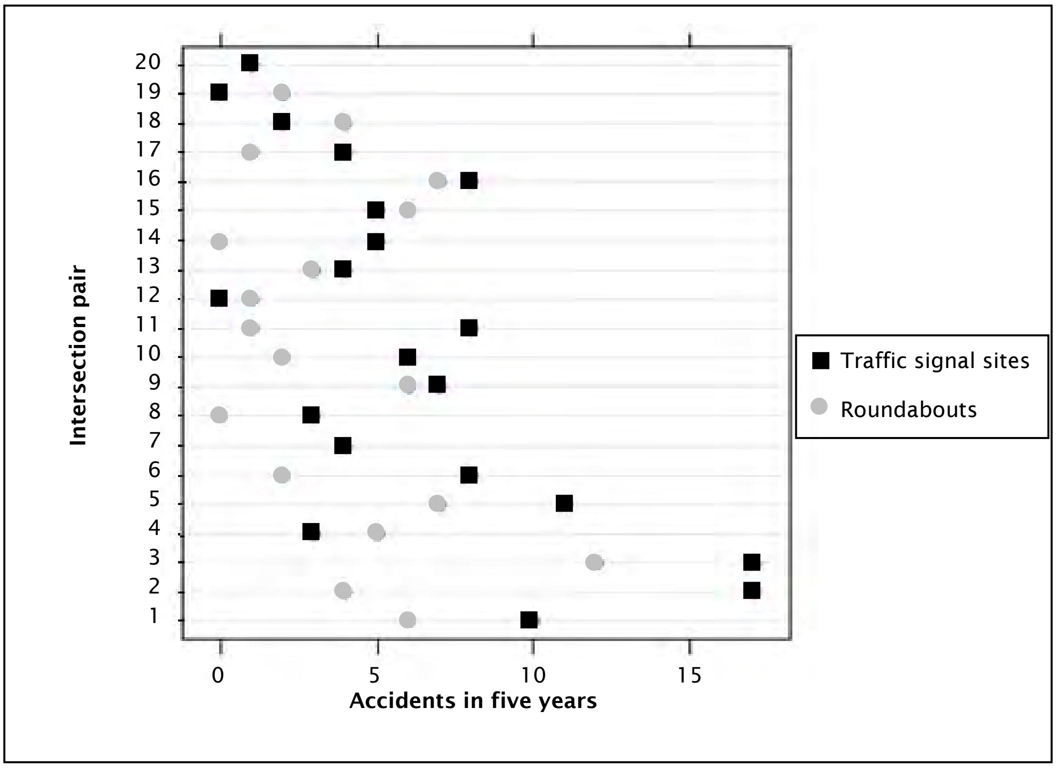
	Total injury[a,b]	Total serious	Total minor	Vehicle injury	Total vehicle serious + fatal	Total vehicle crashes
Roundabout sites	74	6	68	49	4	642
Traffic signal sites	123	17	104	92	12	706
Degree of significance	0.0006	0.0371	0.0076	0.0004	0.0800	0.0860
% crash saving at roundabouts	40%	65%	35%	47%	67%	9%

Notes to table 3.1:

a Only the significant results of binomial test comparisons are shown.

b Note that the total injury figures include pedestrian and cyclist casualties.

Figure 3.1 Results of a Wilcoxon signed ranked test with regard to reported injury crashes



3.2.4 Discussion

The New Zealand Transport Strategy (Ministry of Transport 2008) had a target of reducing nationwide road fatalities to less than 200 per annum, and serious injuries on roads to less than 1500 per annum by the year 2040. This compares to the reported 421 fatal and 2140 serious casualties in the 2007 calendar year, of which four of the fatal and 103 of the serious casualties involving vehicle occupants happened at traffic signals in urban areas. If these signalised intersections were roundabouts, on the basis that the Auckland experience of 67% savings in fatal and serious injury crashes could be replicated elsewhere, then these nationwide figures could feasibly have been reduced by 3 fatal and 69 serious casualties. In terms of nationwide injury statistics, 3429 reported injury crashes happened at signalised urban intersections in 2004–2008. Assuming the 47% injury savings experienced at the Auckland sites could be replicated nationwide, roundabouts could potentially have saved around 1611 injury crashes in this period, or 322 injury crashes per annum.

It could therefore be inferred that in order to reduce vehicle occupant injury crash statistics at urban intersections nationwide, roundabouts should be preferable to traffic signals.

3.3 Comparison between sites converted from multi-lane roundabouts to traffic signals

The purpose of this section of the research is to investigate the safety record of any sites in New Zealand that have been converted from multi-lane roundabouts to traffic signals or vice versa. Data from the CAS database for the jurisdictions of Auckland City, Waitakere City, North Shore, Manukau City, Tauranga and Christchurch were scanned for indications of these conversions within the past 15 years.

Only a few sites were identified that had been converted within the past 15 years and that have substantial 'after' periods - just four in the Auckland region (three of them in Manukau City and one on the North Shore) and one in Christchurch. All are four-way intersections. This small number did not provide results that were statistically significant, apart from one location at Ti Rakau Drive–Te Irirangi Drive, which had zero vehicle injury crashes as a roundabout and five after the signals were installed. However, the results shown in figures 3.2 and 3.3 still appear to indicate that injury crashes are somewhat higher for the traffic signal sites, especially as traffic volumes should have increased after the signals were installed. Total vehicle crashes (injury and non-injury combined) were somewhat greater for the roundabouts, which had experienced a total of four cyclist injury crashes compared to only one for the period after signals were installed. Note that the results are for crashes occurring within a 50m radius of the intersection, and any that were not directly related to the intersection (such as turning into a driveway) have been excluded. Note that in figure 3.2, the results are somewhat variable but tend to indicate a higher crash rate at the roundabouts, given that traffic volumes will have increased since the signals were installed. However, in figure 3.3, the results are still variable, but seem to show higher injury crash rates at the signals.

In Christchurch, an unusually high number of sites (15) have been converted from roundabouts (mostly single-lane) to traffic signals in the past 15 years, which is greater than the total number of conversions identified in the other five urban areas combined. This appears to reflect the prevailing support in Christchurch for cyclists, and the perceived safety disadvantages of roundabouts for these road users.

Figure 3.2 Total vehicle crashes for the five sites converted from multi-lane roundabouts to traffic signals for the five years before and after conversion (injury and non-injury combined)

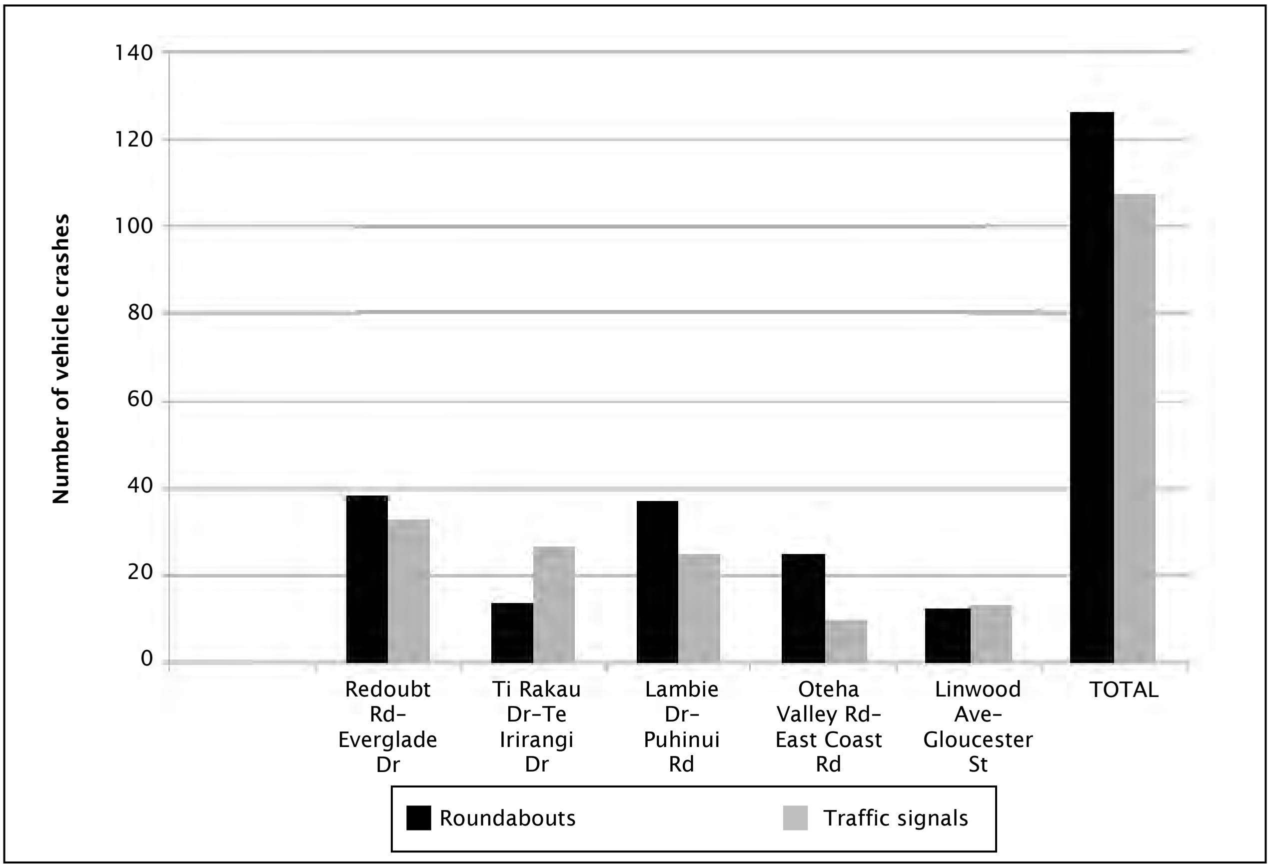
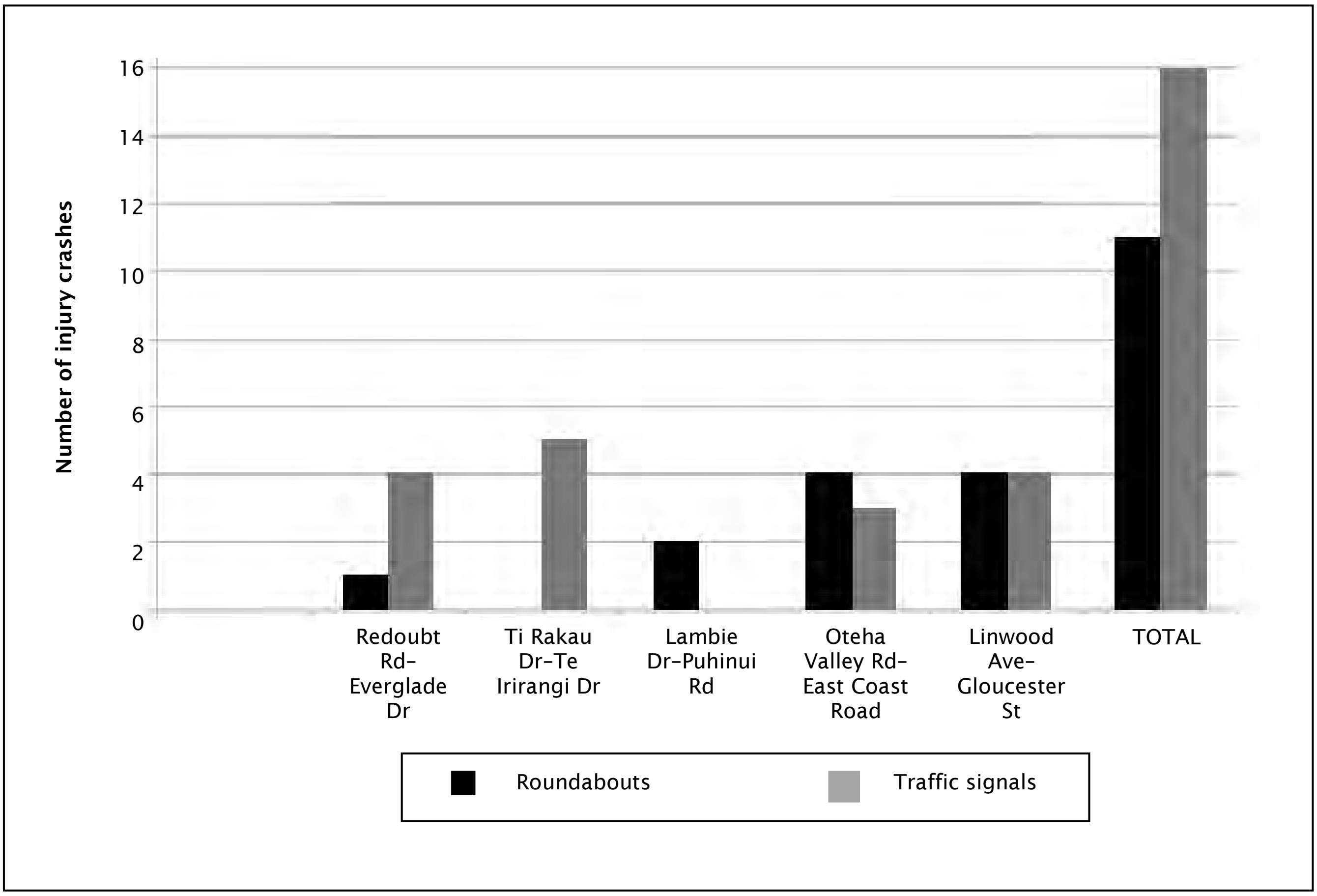


Figure 3.3 Total vehicle injury crashes for the five sites converted from multi-lane roundabouts to traffic signals for the five years before and after conversion



3.4 Comparison between simulated multi-lane roundabout and traffic signal junctions using crash prediction models

3.4.1 Introduction

For this section of the research, Beca Ltd in New Zealand was engaged to model a number of main road intersection scenarios were modelled using the Beca Accident Prediction Model Toolkit (henceforth APM) for a comparison of the expected injury rates for roundabouts and traffic signals[2]. These models are based on accumulated crash data from large numbers of intersections in main cities nationwide. For examples of how this crash modelling methodology can be applied, the reader is directed to Beca Carter Hollings & Ferner Ltd (2000), Turner et al (2006) and Turner et al (2009). Some other available crash simulations for roundabouts also include ARCADY from the UK and ARNDT from Australia.

2 We thank Shane Turner of Beca for kindly carrying out this analysis using the APM and for the material in appendix B.

3.4.2 Methodology

The APM was used to estimate injury crashes at a selection of existing roundabout sites in Auckland, as listed in table 3.2.

Table 3.2 Roundabout sites in Auckland chosen for APM estimation

Roundabout type	Location
Three-arm junction	Swanson Road–Metcalfe Road
Four-arm junction	Shore Road–Orakei Road
	Bader Drive–Robertson Road
	Swanson Road–Universal Drive
Five-arm junction	Great North Road–St Georges Road
	Blockhouse Bay Road–Donovan Street

Each of these sites was modelled as a roundabout and as a signalised intersection, with cyclist traffic volumes of 1200 cyclists per day. Pedestrian crashes were not evaluated, as the Beca APM Toolkit is not able to model these for roundabout scenarios.

3.4.3 Results

The APM results demonstrated that for junctions with four arms or more, roundabouts should result in a safer junction for vehicle drivers, although this may be at the expense of cyclist safety (based on the design standards currently used in New Zealand). For three-arm junctions, traffic signals were demonstrated to be the safer form of traffic control overall. Content from a supporting letter from Shane Turner of Beca Ltd and some sample output pages from the APM are shown in appendix B.

The main conclusions are as follows:

- For four- and five-arm intersections, roundabouts will generally experience fewer vehicle injury crashes than traffic signals, as shown in figure 3.4. The models indicate that the margin increases with increased traffic volumes, as shown in figure 3.5.
- For three-arm intersections, traffic signals will generally experience fewer vehicle injury crashes than roundabouts, though the models indicate that the difference may taper off with increased traffic volumes. This is demonstrated in figures 3.4 and 3.5. Increasing the proportion of turning movements to and from minor arms makes a negligible difference to this result.
- For cyclists, traffic signals are much the safer intersection control for all situations, as shown in figure 3.6. However, the proven effect of 'safety in numbers' (Turner et al 2006; Davies et al 1997; DfT 2003) is likely to mitigate this to a reasonable degree, especially in the case of roundabouts, so in reality, the difference is likely to be less exaggerated. Nonetheless, it is clear that cyclist safety can be a valid concern at roundabouts, particularly with respect to the design standards currently used in New Zealand.

Note that these models are general only and do not take particular site variations into account such as filtered right-turn movements at traffic signals, or roundabouts built with inadequate deflection. It would be valuable if the models could include these types of factors when a particular junction is analysed.

Figure 3.4 Expected vehicle injury crash rates in New Zealand by intersection type and daily traffic volumes as predicted by the APM

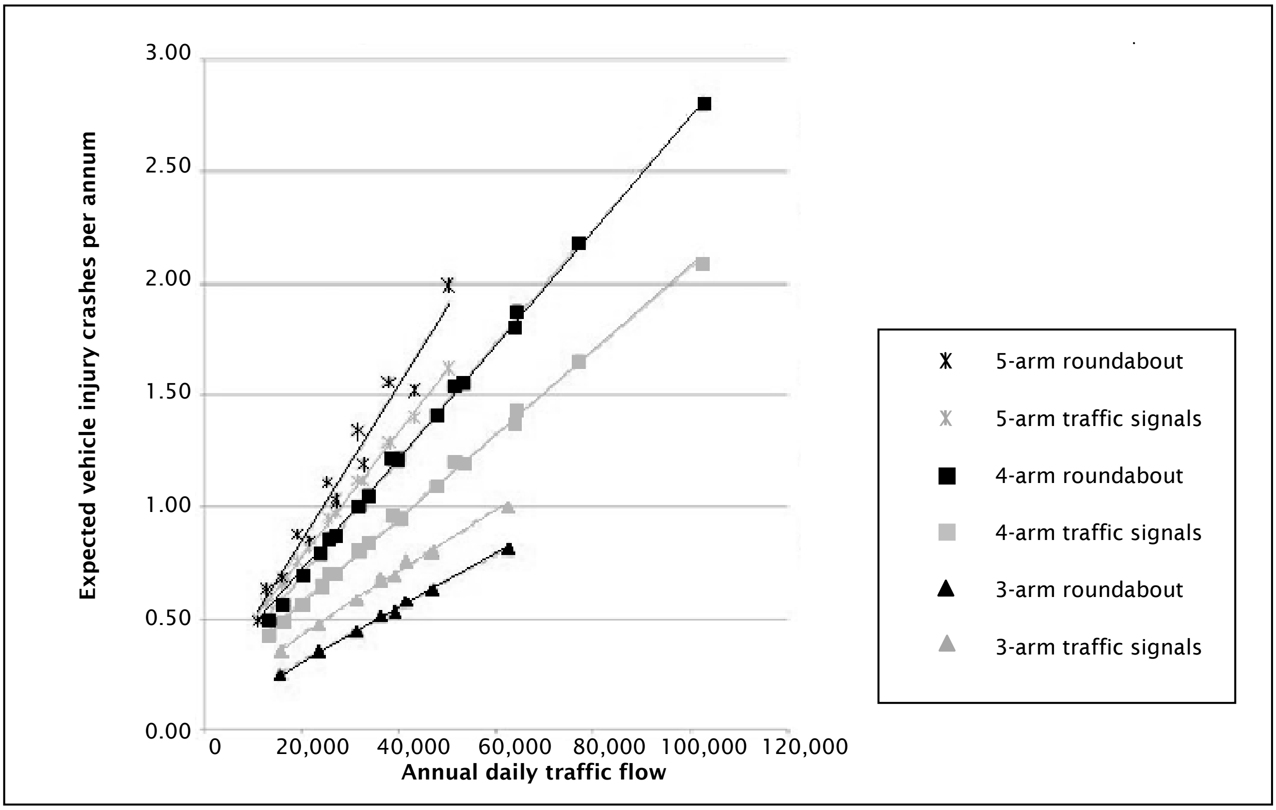
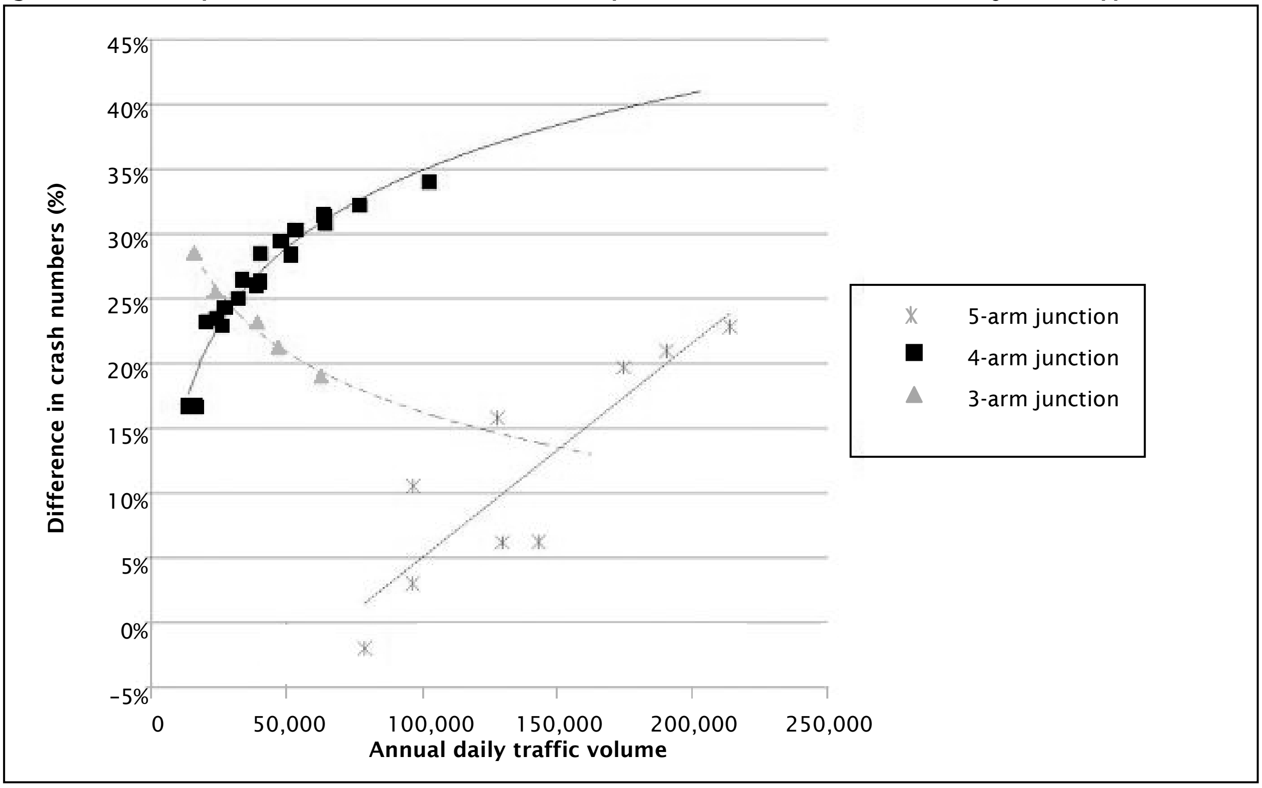
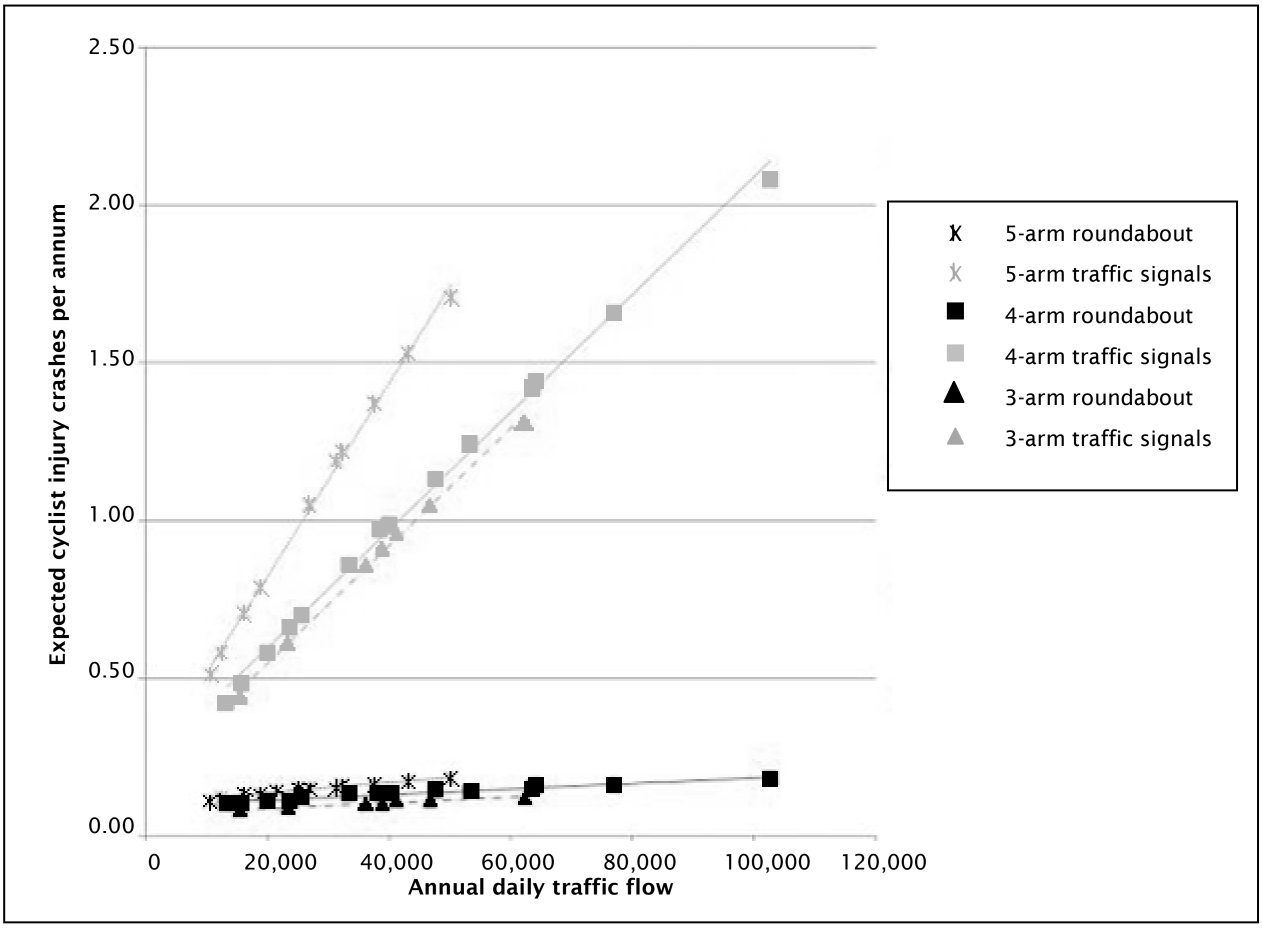


Figure 3.5 Extrapolated trends of the difference in expected vehicle crashes for the two junction types



Note: Solid lines indicate that roundabouts are safer for vehicle users; dashed lines indicate that signals are the safer form of control.

Figure 3.6 Expected cyclist injury crash rates by intersection type and daily traffic volumes as predicted by the APM, assuming 1200 cyclists per day use the junction (a very high number by New Zealand standards)



3.4.4 Discussion

The APM appears to indicate that although a difference in safety performance can be seen between traffic signals and roundabouts, it is much less significant than overseas studies have concluded (chapter 2). Indeed, for three-arm junctions in New Zealand, traffic signals would appear to be the safer form of control, which is the most contrary finding.

The authors would like to postulate that a major contributing factor in New Zealand is that speed control (ie deflection) for roundabouts is often deficient, even for recent installations. The authors have frequently seen evidence of this and some examples are shown in figure 3.7–3.11. A few of these roundabouts have significant crash histories that are much larger than the roundabouts studied in section 3.2. In addition, vehicle injury crashes at eight multi-lane roundabouts in Auckland which comply with the deflection criteria as per the Austroads *Guide to traffic engineering part 6* (Austroads 1993) were plotted to compare with the expected APM results, as shown in table 3.3 and figure 3.12.

The following points should be noted about the roundabouts shown in figures 3.7–3.11:

- A pre-construction safety audit had identified the issue shown in figure 3.7, but the local authority still proceeded with this design. This is just one example showing that the importance of good speed control at roundabouts is not widely appreciated in New Zealand.

- The example in figure 3.8 at the Glenfield Road–Coronation Road intersection has a substantial crash history, experiencing 37 crashes, including six injury crashes for the five-year period 2004–2008.
- The example in figure 3.11 at the intersection of Riccarton Road and Deans Avenue has a particularly significant crash history with 45 reported crashes during 2004–2008, including seven minor injury crashes.

Figure 3.7 A recently installed three-arm roundabout in urban Auckland with deficient deflection for through-vehicles (shown by the superimposed black arrows)

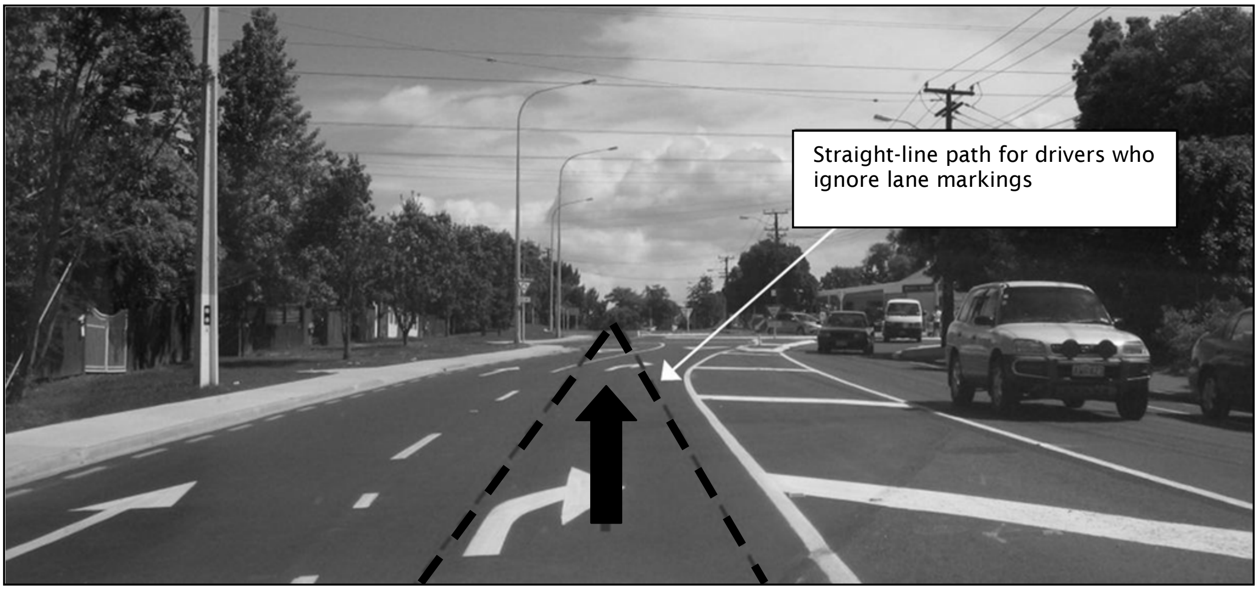


Figure 3.8 Example of a roundabout built with minimal regard for speed control: Glenfield Road and Coronation Road in the North Shore, Auckland (photo courtesy of Google Maps)

Figure 3.9 Example of a roundabout built with minimal regard for speed control: Lake Road and Taharoto Road in the North Shore, Auckland (photo courtesy of Google Maps)

Figure 3.10 Example of a roundabout built with minimal regard for speed control: Pages Road, New Brighton Road, Owles Terrace and Seaview Road in Christchurch (photos courtesy of Google Maps)

Figure 3.11 Example of a roundabout built with minimal regard for speed control: Riccarton Road and Deans Avenue in Christchurch (photos courtesy of Google Maps)

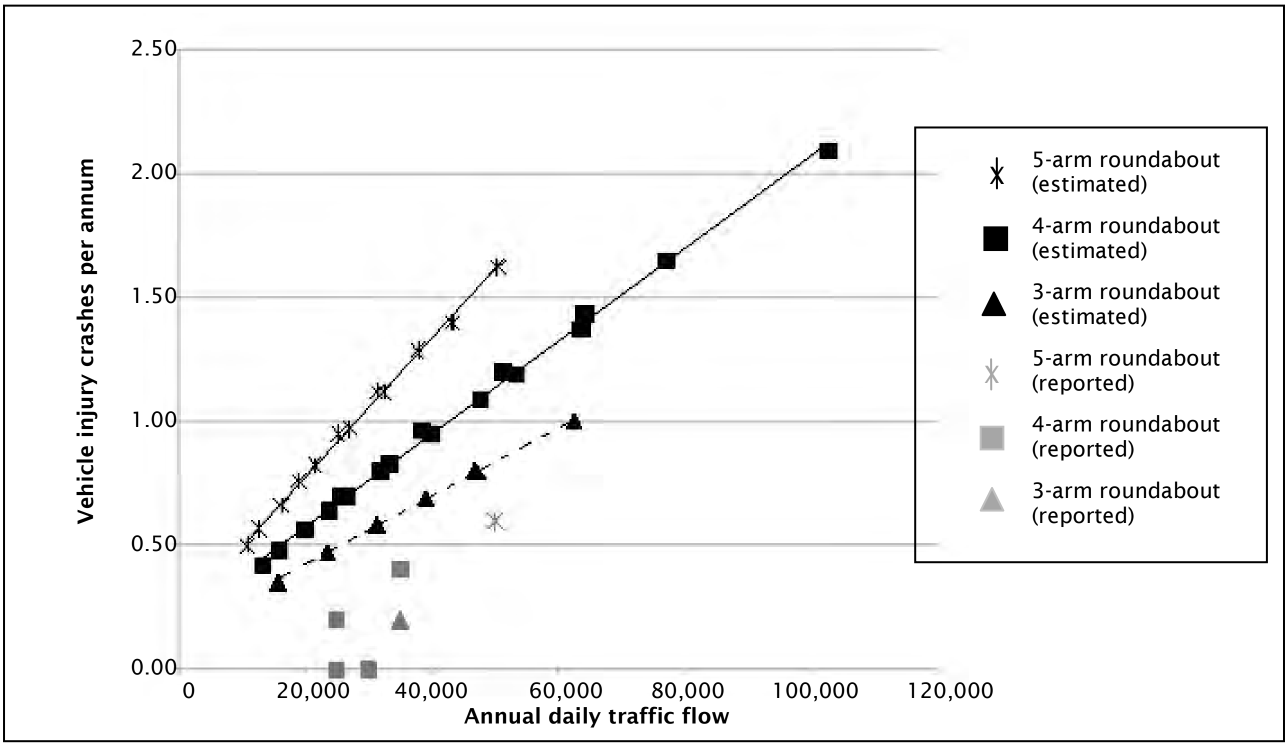
Table 3.3 Reported vehicle injury crash rates at seven selected multi-lane roundabout sites in Auckland that are designed with deflection as per Austroads (1993)

Intersecting roads		Daily traffic volumes	Annual reported vehicle injury crashes 2003–2007	Expected vehicle injury crashes*
Manukau Road	Mt Albert Road	50,000	0.60	1.14
Mt Wellington Highway	Vestey Drive	35,000	0.40	0.86
Shore Road	Orakei Road	30,000	0.00	0.76
Apirana Avenue	Merton Road	25,000	0.00	0.67
Pilkington Road	Tripoli Road	25,000	0.20	0.67
Ayr Road	Shore Road	25,000	0.00	0.67
Lunn Avenue	College Road	35,000	0.20	0.86

* Figures are as estimated by the APM.

As discussed in section 2.6, a study from the UK found that roundabouts with no deflection had crash rates about 8.5 times greater than those with maximum deflection (Maycock and Hall 1984). A New Zealand study undertaken in 2000 found that 17% of roundabouts surveyed had inadequate deflection on the approaches (NZTA 2000) and a further 18% had deflection that was described as 'adequate'. In addition, 7 of the 20 Auckland multi-lane roundabouts in this study had clearly inadequate deflection on at least one major road movement. It is therefore considered by the authors that the performance of a substantial minority of sites is likely to be disproportionately influencing roundabout crash statistics nationwide and, by default, the crash rates produced by the APM. These will also be affecting predicted crash rates as used in the *Economic evaluation manual* (EEM) (NZTA 2010a) which references this data, so roundabouts do not currently compare nearly as well as they could do with traffic signal options on safety grounds. It is recommended that these crash rates be revised on the basis of good design practice being adhered to, and that the critical nature of good speed control is more widely broadcast to road designers in New Zealand. Since the seven roundabouts analysed in figure 3.12 have adequate deflection, it appears to demonstrate that this critical design factor, where deficient, could be adversely influencing crash statistics nationwide.

Figure 3.12 Comparison of seven multi-lane roundabouts in Auckland City with the APM results



3.5 Conclusions

Based on the research described above and in chapter 2, the following conclusions have been made:

- International evidence suggests that for any given intersection, a well-designed roundabout will experience substantially fewer injury crashes than traffic signals (25–74%), with an additional reduction in crash severity. This difference in safety performance will be greater for intersections with four arms or more, and will also depend upon traffic volumes and the speed environment.
- Based on injury savings alone, RCAs in New Zealand should consider roundabouts as the first option for an intersection before traffic signals, particularly for intersections with four arms or more.
- A review of five four-arm intersections that were converted from multi-lane roundabouts to traffic signals did not demonstrate a significant difference in total crash numbers, although it did appear to indicate that the traffic signals were less safe in terms of vehicle injury crashes.
- A comparison was made in Auckland between 20 matched pairs of multi-lane roundabouts and traffic signal intersections based on traffic volume and layout. The statistically significant results were that the roundabouts experienced 47% fewer vehicle injury crashes, with 67% fewer serious and fatal injury crashes.
- An accident prediction model based on New Zealand crash data produced by the APM demonstrated that intersections with four arms or more will generally experience fewer vehicle injury crashes if controlled by roundabouts rather than traffic signals; for three-arm intersections, it was found that traffic signals would be marginally safer. The authors of this report believe these results are likely to have been influenced by inadequate speed control at a substantial minority of poorly designed roundabouts in New Zealand, and the EEM will consequently be overestimating crash rates for roundabouts. These crash rates should be revised to take good design practice into account, and

roundabout designers in New Zealand should be better informed as to the critical nature of good speed control.

- Research that compares pedestrian crash rates between roundabouts and traffic signals is relatively sparse, but what is available either does not show a significant difference or suggests that a roundabout is safer. Further research is required to confirm whether a multi-lane roundabout with well-designed crossing facilities would be safer for pedestrians than an intersection controlled by traffic signals.
- Traffic signals are substantially safer for cyclists than multi-lane roundabouts, although measures at roundabouts to reduce vehicle entry speed or physically separate cyclists from vehicle traffic are expected to address this substantially. The C-roundabout is a multi-lane roundabout developed in New Zealand to improve safety for cyclists and is currently being evaluated. Signalised roundabouts can also be substantially safer for these users. 'Cyclist priority' crossings as used in The Netherlands are also an option but may require raised platforms to address safety concerns.
- Crash modelling analysis using the APM offers good potential for comparing the safety performance of a particular intersection for various forms of intersection control. It is recommended that the APM be further developed to take the effects of both good and deficient design practice into account more effectively as well as the multitude of traffic engineering tools available.
- 'Roundabouts First' policies as introduced by several jurisdictions in North America appear to have a sound basis on the grounds of traffic safety.

3.6 Recommendations

Ample evidence suggests that, overall, well-designed roundabouts offer the safest form of intersection control by a substantial margin when compared to traffic signals. Although cyclists can be disadvantaged users at multi-lane roundabouts, means of addressing this via speed control at roundabout entries and/or separated path facilities are available, and every attempt should be made to do so if cyclists are present in any numbers.

Therefore, the following recommendations are made:

- The NZTA should consider adopting a 'Roundabouts First' type policy similar to several North American precedents. The primary motivator for these policies is traffic safety, but also vehicle delay and environmental reasons. In practice, such a policy could require RCAs to justify when an alternative intersection control is proposed if it is viable to install a roundabout.
- Current crash rates for roundabouts in the EEM should be revised to better represent current best design practice that includes adequate speed control. These crash rates are based on nationwide data that includes many roundabouts designed with inadequate deflection, which reduces the economic viability for installing roundabouts.
- The NZTA should consider funding the further development of crash modelling that will better enable direct safety comparisons to be made for particular locations.
- Improved education of the engineers and safety auditors responsible for designing roundabouts should be provided. Adequate speed control is a critical design factor that is too often overlooked in New Zealand.

- The legal use of cyclist priority crossings at roundabouts as used in The Netherlands should be considered for a trial in New Zealand, as they can potentially offer greater mobility for these users. A speed platform may be required to address safety concerns.

4 Sightlines to the right at roundabouts

4.1 Introduction

4.1.1 Background

Conventional traffic safety wisdom is that the greater visibility of oncoming vehicles a driver is provided with, the safer a junction will be. However, a relationship between excessive sightlines at higher-speed rural roundabouts and loss-of-control crashes was demonstrated in the UK in the 1980s (Maycock and Hall 1984). More recently, barrier screens are being successfully installed to restrict the visibility of circulating traffic in order to address the rear-end crash patterns associated with drivers entering the roundabout at excessive speeds. British guidelines for roundabouts (see section 4.2.2) emphasise that sightlines between intersecting arms on a roundabout should be restricted 'so as not to encourage high vehicle entry speeds on roundabout approaches' (DfT 2007a), which is contrary to the Austroads recommendations that are widely referenced in New Zealand.

The topic of sightlines at roundabouts is one that considers driver behaviour. That sightlines of opposing vehicles will influence speed of vehicles entering a roundabout is not difficult to appreciate at the driver's level. One only needs to drive up to a few roundabouts (or crossroads) where visibility is restricted by a building or hedge to appreciate how this factor can affect approach speed.

The principle objective of this study was to attain a better understanding of how driver sightlines can affect roundabout crash statistics, including the aforementioned loss-of-control and rear-end types. A preliminary practical application for road designers was the desired outcome.

4.1.2 Methodology

This section of research included the following tasks:

- Undertake a comprehensive literature review of any published New Zealand and overseas research on this topic. This exercise revealed some research that identified relevant cyclist crash patterns at several roundabouts in Christchurch that were influenced by sightlines (Hughes 1994).
- By studying some roundabouts in practice, determine the relationship between sightlines, approach vehicle speeds and driver behaviour. Originally, it was proposed to identify four roundabout approaches in Waitakere City and undertake a before/after study subsequent to sightlines being restricted. However, during this exercise, it was realised that the provision of greatly excessive sightlines in the urban context is more often the exception rather than the rule, and it was considered that detailed evaluation of a particular site in Auckland would yield more worthwhile results. This four-arm single-lane roundabout at the Church Street–Avenue Road intersection in Otahuhu, Auckland, comprises a scenario where one approach had almost unrestricted visibility (an open field on one corner), with the remaining three approaches having very restricted sightlines owing to boundary fences. A historical crash pattern here involving collisions with opposing vehicles from one particular roundabout approach appeared to be greatly influenced by this sightline environment.
- Prepare a practical application for practitioners.

4.2 Literature review

4.2.1 Introduction

The topic of the effect of sightlines at roundabouts (or even priority intersections) is not one that has received wide attention in terms of published material. However, practitioners in the UK have been using visibility barriers for some time to improve safety at roundabouts in high-speed environments (refer to section 4.2.5), and British roundabout guidelines give some basic advice on this subject.

The Austroads guidelines that New Zealand practitioners generally refer to does not offer much additional insight on this topic (refer to section 4.2.3). An example can be found on a state highway in New Zealand where visibility screening was used as a safety improvement by reducing approach driver speeds at a priority junction. Previous New Zealand research has also inferred that reducing sightlines could potentially be used as a means of speed control to improve safety at roundabouts (Turner and Roozenburg 2007).

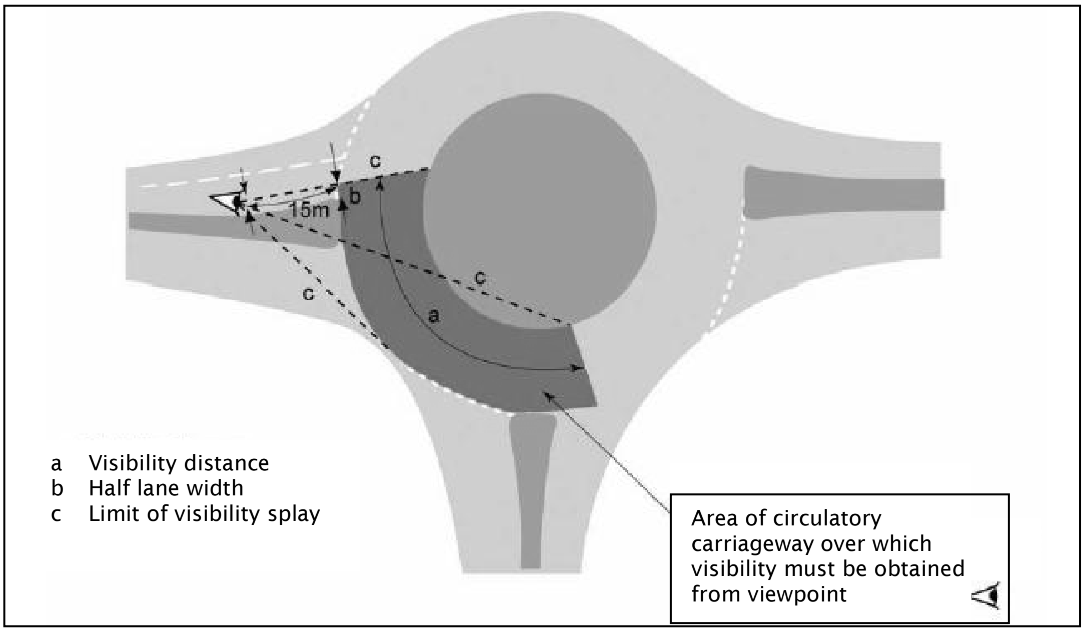
4.2.2 UK design guidelines

Recently published updates for UK standards for roundabouts and mini-roundabouts have some guidance for visibility at roundabouts (DfT 2007a & b). Criteria are given for forward visibility on approach (stopping sight distance), forward visibility at entry, visibility to the right, circulatory visibility, pedestrian crossing visibility and exit visibility. As discussed previously, the main focus of this report is to study the effects of differing visibility to the right, and the relevant sections are discussed below:

4.2.2.1 TD 16/07 Geometric design of roundabouts (DfT 2007a)

The recommended practice is for vehicles at the limit line to have clear sightlines of approaching vehicles to the right for 40–70m, depending upon inscribed circle diameter of the roundabout. These sightlines should also be available at a point 15m back from the limit line (figure 4.1). This is a minimum requirement for roundabouts in general, but also is a suggested maximum for roads with speed limits over 40 mph that might be experiencing excessive approach speeds. Explicit mention is made of the fact that ‘excessive visibility to the right can result in high entry speeds, potentially leading to accidents.’ The guide goes on to suggest the potential use of visibility screens at least 2m high to reduce excessive approach speeds, but has limited the scope of this suggestion to only dual carriageway approaches where the speed limit is greater than 40mph.

Figure 4.1 Visibility to right along circulating carriageway required at 15m in advance of limit lines (DfT 2007a)



4.2.2.2 TD 54/07 *Design of mini-roundabouts* (DfT 2007b))

The design philosophy for mini-roundabouts is subtly different from standard roundabouts and is based on a gap acceptance distance from the potential conflict point, using an assumed gap acceptance time and the approach speeds of vehicles from the arm to the right. The minimum distance from the limit line where these sightlines are available is given as 9m, although an exception is given for approaches with less than 300 vehicles per hour, which can be reduced to just 2.4m as an absolute minimum (ie vehicles would have to come to a virtual stop in order to see opposing traffic before proceeding past the limit line).

As a means of speed control on mini-roundabout approaches, this guide suggests limiting visibility to the right of adjacent entries to a maximum distance of 15m back from the limit line.

4.2.2.3 TD 42/95 *Geometric design of major/minor priority junctions* (DfT 1995b)

This publication also makes reference to limiting the sightlines of main road vehicles to no more than 9m back from the limit line, in the interest of not inducing high approach speeds to the junction on minor roads.

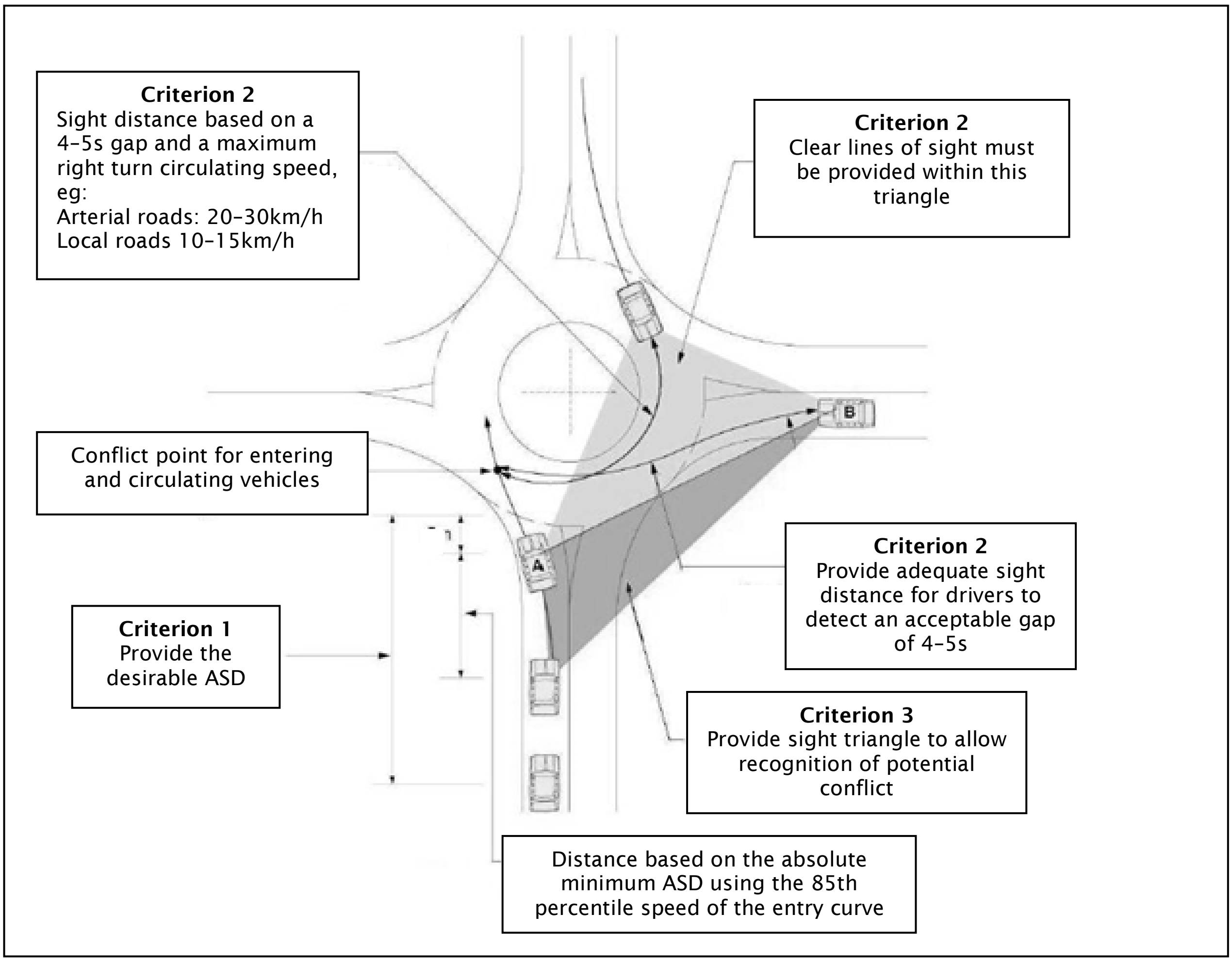
4.2.3 The Austroads Design Guideline

The *Guide to road design part 4b – roundabouts* (Austroads 2009), like Austroads (1993), recommends three sight distance criteria for roundabouts and these are shown in figure 4.2 below:

- The Approach Sight Distance (ASD) on roundabout approaches must allow drivers to identify the junction ahead and slow down appropriately. This is an essential requirement.
- At the limit line, drivers should have a clear line of sight of approaching vehicles from the right. This sight distance depends upon assumed parameters of vehicle speed and a gap acceptance value of 4–5 seconds. This is also an essential requirement.
- This final criterion comprises a sight triangle in order to allow comfortable recognition of potential conflict for both circulating and approaching drivers, and is dependent upon assumed vehicle speeds.

The guide acknowledges that in urban areas, this criterion might not be achievable and is therefore desirable only. This recommendation is not found in UK guidelines.

Figure 4.2 Sightline criteria as recommended by Austroads guidelines (adapted from Austroads 2009b)



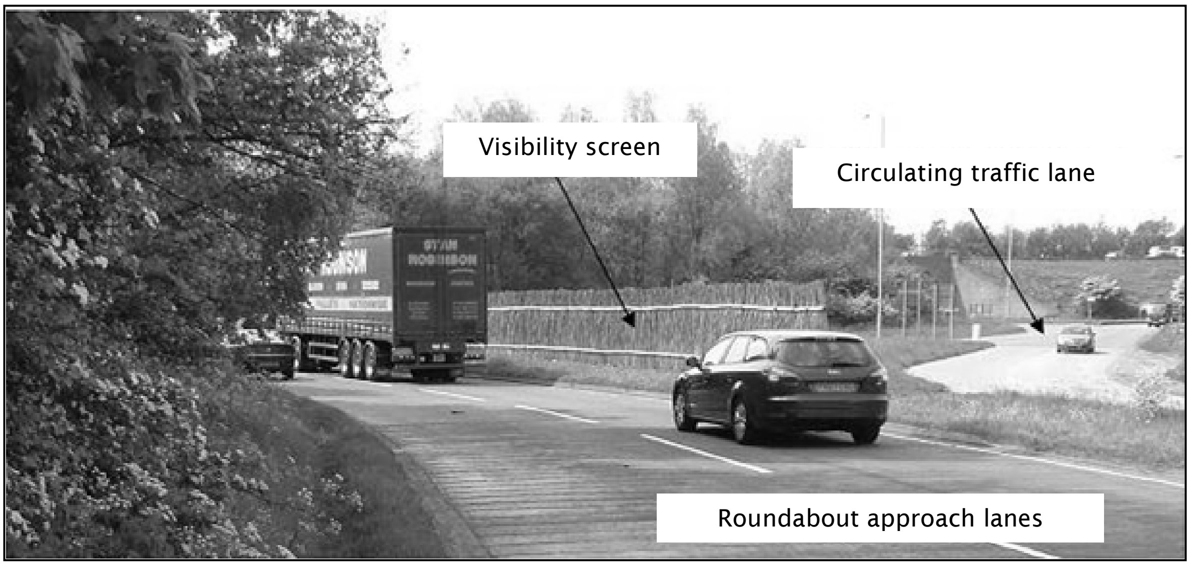
4.2.4 The United States Department of Transportation design guidelines

A guideline from the US (United States Department of Transportation (USDOT) 2009a) has extrapolated on the recommendations from British guidelines (section 4.2.2), and specifically advises that the sight distance of approaching vehicles (to the left for US drivers) should be limited by landscaping to no more than 15m from the limit line for all roundabouts. Similar to Austroads (section 4.2.3), the criteria for the sight distance of conflicting vehicles is based on assumed vehicle speed and gap acceptance values.

4.2.5 Use of visibility barriers at roundabouts in the UK

A search of the internet revealed some evidence of the recent use of visibility barriers at roundabouts as a means of crash treatment. Leicestershire County Council has used them at roundabout locations where open visibility combined with fast approach speeds were apparently resulting in rear-end crash patterns (R Wightman, Transport Schemes Development LCC, pers. comm. January 2009). The drivers' attention was perceived to be on traffic circulating the roundabout rather than on the vehicle in front, and the barriers were installed around 15m from the limit line as per TD 16/07 (DfT 2007a) and appear to have been successful in reducing these crash types. Sample plans of an installation in Leicestershire County Council are contained in appendix C and an example is shown in figure 4.3. Injury crash reductions of 46% apparently resulted from this treatment at one roundabout location in the UK after the first 16 months of operation compared with the previous three years (4.3/yr before; 2.3/yr after) (Thompson 2009). However, anecdotal evidence has provided at least one example where roundabout screens were removed at the request of local cyclists who felt they could not engage approaching drivers in a timely manner and subsequently had an increased perception of vulnerability.

Figure 4.3 A 2.5m high visibility screen installed on the approach to a roundabout at the intersection of the A50/A511 and Junction 22 of the M1 motorway in Markfield, Leicestershire County Council, UK (photo taken in 2008)



4.2.6 Use of visibility barriers in New Zealand

At the Paeroa-Tahuna Road–State Highway 27 intersection between Rotorua and Auckland, a visibility barrier was installed for safety reasons in 2001 (Charlton 2002). This was a significant crash location with some 24 reported crashes between 1995 and 1999 including seven serious injury and nine minor injury crashes. Ninety-one percent of the 23 crossing or turning crashes apparently involved vehicles from the eastbound minor road approach colliding with highway road vehicles.

A human factors team from Waikato University was engaged by Transit New Zealand to investigate potential solutions. It was identified that the primary difference between eastbound and westbound minor road approaches was a very large broad sightline triangle associated with the eastbound approach. It was perceived that this factor might be encouraging anticipatory decision making by eastbound drivers, who then approached the junction at higher speeds than desirable.

In February 2001, a large (~100m) hessian screen was installed on the eastbound approach (figure 4.4), and was still there until a roundabout was installed in 2010. The screen terminated 25m prior to the limit line and disrupted the previously open view of oncoming vehicles to the left. A before/after study was undertaken that compared approaching vehicle speeds and also made an assessment of driver recognition of main road vehicles. It was determined that the hessian screen conclusively resulted in a substantial, immediate and long-term reduction of approach speeds, and also increased the rate at which drivers on the minor road identified traffic on the main road. A conclusion of the researchers was that visibility screens tend to focus the drivers' attention on the key area where they are more likely to identify approaching vehicles (Charlton 2002).

At that time, the screen was not envisaged as a long-term solution, but rather as an interim measure until a more permanent solution could be installed. The crash history for the eight years since installation (2001–2008) shows a total of eight reported crashes including two fatality, two serious injury and three minor injury crashes involving eastbound vehicles colliding with main highway traffic. This would appear to indicate that although the visibility screening may have led to a reduction in driver approach speeds and be an improved situation compared to previously, the junction was still a significant crash location.

Figure 4.4 The minor road eastbound approach showing the hessian screen at the Paeroa-Tahuna Road–State Highway 27 intersection (photo taken in 2008)

The second local example of a visibility restriction is the State Highway 29–Takitimu Drive roundabout in Tauranga where, along with other measures, landscaping was installed on the central island to address a pattern of high-speed truck rollover crashes following the roundabout's opening in July 2003 (Charlton et al 2004). The landscaping was intended to increase the visual conspicuousness of the central island, which previously had a low profile and was construed by the investigating safety team as having the visual effect of minimising the perceived lateral deviation required for negotiating the roundabout. However, no post-construction review is understood to have been undertaken.

4.2.7 Other references to effects of reducing sightlines at intersections

York et al (2007) examined the effects of reducing sightlines at urban junctions in 30mph areas, and found a positive correlation with speed reduction and predicted an improvement in safety on this basis, although the study did identify that sight distances of less than 40m may comprise an unacceptable margin of safety. Reducing lines of sight distances from 120m to 20m reduced vehicle approach speeds by approximately 11mph.

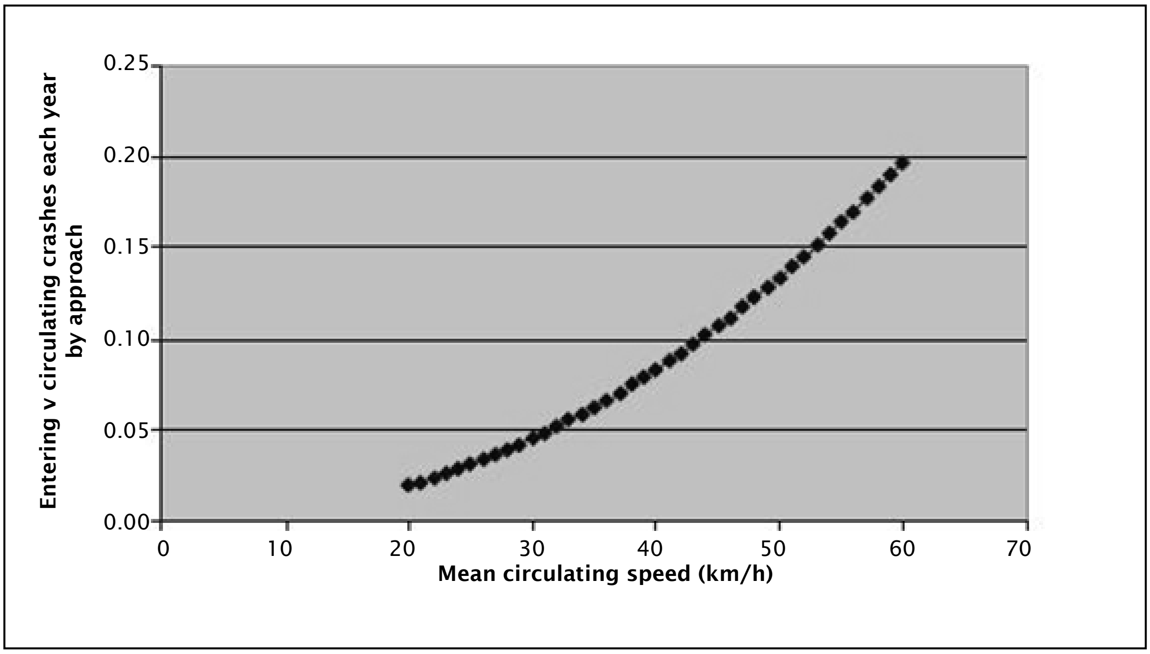
A significant UK study of roundabouts identified a statistical relationship between visibility to the right and loss-of-control crashes (Maycock and Hall 1984), and this research apparently led to the British guidelines that suggest sightlines can be restricted for roundabouts in high-speed areas (see section 4.2.2).

A US study that evaluated the effects of central island landscaping for single-lane roundabouts (Schurr and Abos-Sanchez 2005) found that the installation of objects that block the sight distance of oncoming traffic can achieve lower vehicle speeds on roundabout approaches. The study also found that more uniform speeds were achieved, and concluded that this would result in safer conditions for drivers, pedestrians and cyclists.

Another study undertaken in 1993 in the US evaluated passive railway crossings with restricted sightlines of approaching trains (Ward and Wilde 1995). This study concluded that although slower driver speeds may result after advance warning signage is installed, the safety benefits of these signs is questionable, as detailed analysis did not demonstrate any quantifiable improvement in terms of safe driver behaviour (as measured by observations of head movement and brake light activation). The inference of this finding was that slower vehicle approach speeds do not necessarily equal a reduction in the probability of a crash.

Crash analysis work undertaken in New Zealand led to a correlation being drawn between the sightlines of vehicles to the right and crashes at roundabouts, specifically loss-of-control and rear-end approach types (Turner and Roozenburg 2007; Turner and Wood 2009). It was reported that the potential benefits of reducing sightlines to other crash types (including entering v circulating vehicle) would be mainly caused by any reductions in vehicle circulating speed that might occur (see figure 4.5 below). It was then questioned whether or not New Zealand adherence to Austroads' guidelines (see section 4.2.3) achieved the optimum safety performance at roundabouts.

Figure 4.5 The relationship between mean circulating speeds and entering v circulating crashes at roundabouts (Turner and Roozenburg 2007)



4.2.8 Summary of literature review

In summary, the main points from the literature review are as follows:

- Roundabout design guidelines from the UK make reference to the slowing effect of visibility restrictions, which have been used to address loss-of-control or rear-end crash patterns. US roundabout guidelines have followed the example of recommending that the sightlines of opposing vehicles should be limited to a point approximately 15m ahead of the limit lines.
- Austroads guidelines, which are widely referenced in New Zealand, do not take sightline restrictions into account, or at least do not identify them as a desirable safety feature.

4.3 Christchurch experience with cyclist crashes at three roundabouts

4.3.1 Summary

Hughes (1994) has already presented material on the subject of intersection visibility and its observed relationship to cyclist crashes. At three single-lane roundabouts in Christchurch where visibility had been changed, an observable difference in the crash patterns involving entering vehicles versus circulating cyclists and motorbike users (and, to some extent, circulating vehicles) had occurred. It was inferred that visibility at roundabouts was potentially a major safety factor to be considered at single-lane roundabouts, and further research was recommended on this topic. CAS plots of these junctions were reviewed by the authors of this current report for confirmation of the reported crash patterns.

Hughes found that for two roundabout approaches with well above optimum visibility of oncoming traffic, circulating cyclists or motorbikes were more likely to be struck. It was surmised that drivers are anticipating opposing vehicles further back along adjoining roads and, and are thus less likely to identify users who have a less visible profile. These sites are described in more detail in sections 4.3.2 and 4.3.3.

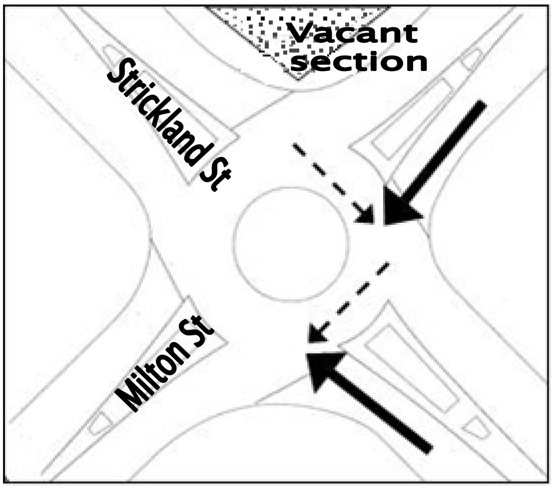
For the third roundabout approach, which had very restricted visibility of oncoming traffic, it was found that circulating cyclists and motorbikes were also more likely to be struck. It was surmised that although drivers enter the roundabout at a lower speeds because of this sightline restriction, they were still travelling too fast to identify and stop in time for less visible two-wheeled users who might still be circulating at reasonably high speeds (especially the motorbikes). This site is described in more detail in section 4.3.4.

4.3.2 Milton Street–Strickland Street single-lane roundabout

The Milton Street westbound approach, for a period of about two years following the roundabout being installed in July 1989, showed a significant pattern of crashes involving entering drivers from the westbound Milton Street approach colliding with cyclists circulating on the roundabout (four crashes including one serious injury and two minor injury crashes (figure 4.6). In addition, the adjacent northbound Strickland Street approach had a pattern of crashes involving collisions between entering vehicles and through-traffic from the aforementioned approach (six vehicle crashes including two minor injuries to circulating motorcyclists).

The vacant section on the right-hand side of this Milton Street westbound approach was occupied around late 1991. Up to this time, it was perceived that this factor was encouraging higher vehicle speeds, which contributed to these crash patterns. From 1992 to 1999, after which when traffic signals were installed, this crash pattern largely disappeared, with just one motorbike and three cyclist crashes being reported on both these approaches for the eight-year period of 1992–1999.

Figure 4.6 Diagram showing the prevalent crashes at the Milton Street–Strickland Street roundabout that largely disappeared after the vacant section was occupied in late 1991 (the dashed arrows depict two-wheeled users)

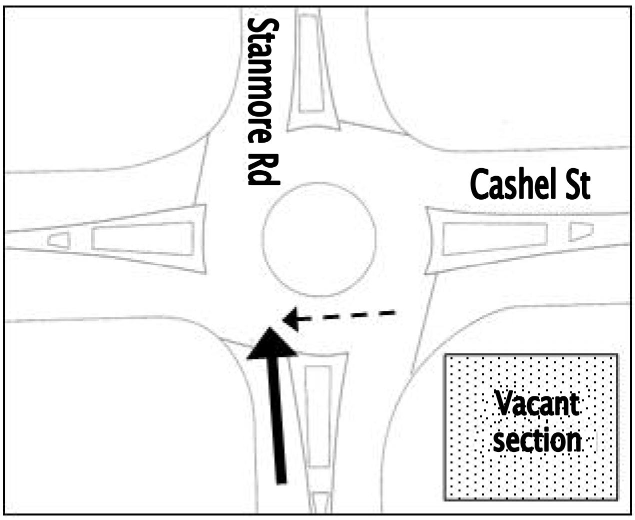


4.3.3 Cashel Street–Stanmore Road single-lane roundabout

The southeast corner of this junction was a large vacant section when the roundabout was installed in late 1988, and was subsequently occupied in approximately late 1995. During this period, the roundabout experienced 13 reported crashes involving cyclists or motorcyclists, including one serious and 11 minor injury (figure 4.7). Seven of these crashes involved collisions between circulating cyclists or motorbike users and northbound vehicles from Stanmore Road, the approach with clear visibility across the vacant section (four reported crashes involving entering v circulating vehicles occurred on this approach). After 1996, when residential housing was constructed on the southeast corner, which substantially reduced visibility of vehicles to the right for the northbound approach, the crash pattern there largely disappeared with just four reported crashes (three cyclist and one vehicle) being reported since.

As with the previous location at Milton Street–Strickland Street, the high vehicle speeds of the northbound approach prior to 1995 were perceived to be the main causal factor of the crashes.

Figure 4.7 Diagram showing the prevalent crashes at the Stanmore Road–Cashel Street roundabout that largely disappeared after the vacant section was occupied (dashed arrow depicts two-wheeled users)

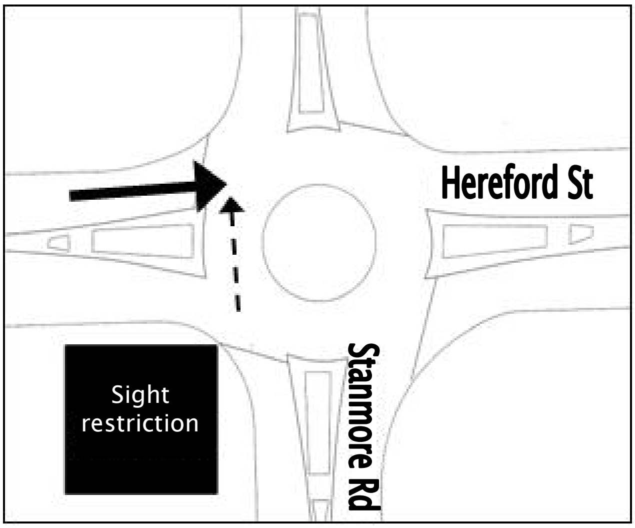


4.3.4 Hereford Street–Stanmore Road single-lane roundabout

In the case of this roundabout, a severe visibility restriction on the southwest corner created by street furniture was thought to be a factor in the pattern of cyclist and motorbike crashes between 1988, when the roundabout was installed, and 1991, when these impediments to visibility were removed (figure 4.8). In this short period, six minor injury crashes had occurred, involving collisions with vehicles entering from this approach and circulating cyclists (four incidents) or motorbikes (two incidents). Although adequate visibility of oncoming vehicles to the right was still obtainable at the limit line, it was thought that drivers were not slowing down enough to adequately identify and stop for the less visible two-wheeled users circulating the roundabout.

During 1991–2008, only two incidents involving two-wheeled users have been reported, just one of which involved injury. It is surmised that the sightlines of opposing traffic were improved to an extent that approaching drivers could then react and comfortably stop in time.

Figure 4.8 Diagram showing the prevalent crashes at the Hereford Street–Stanmore Road roundabout that largely disappeared after the sight restrictions were removed (dashed arrow depicts two-wheeled users)



4.4 Trial site in Otahuhu, Auckland

4.4.1 Summary

Speed data from the Church Street–Avenue Road roundabout in Otahuhu, Auckland, was analysed for the purpose of assessing differences in driver behaviour caused by sightlines. The results demonstrated that sightline restrictions to the right can certainly reduce driver approach speeds to a roundabout, but may not necessarily result in an improved situation with regard to traffic safety. A proportion of drivers will continue to travel at speeds that are inappropriate for the road environment. If circulating vehicle speeds remain high enough, then an increase in entering v circulating crashes may result.

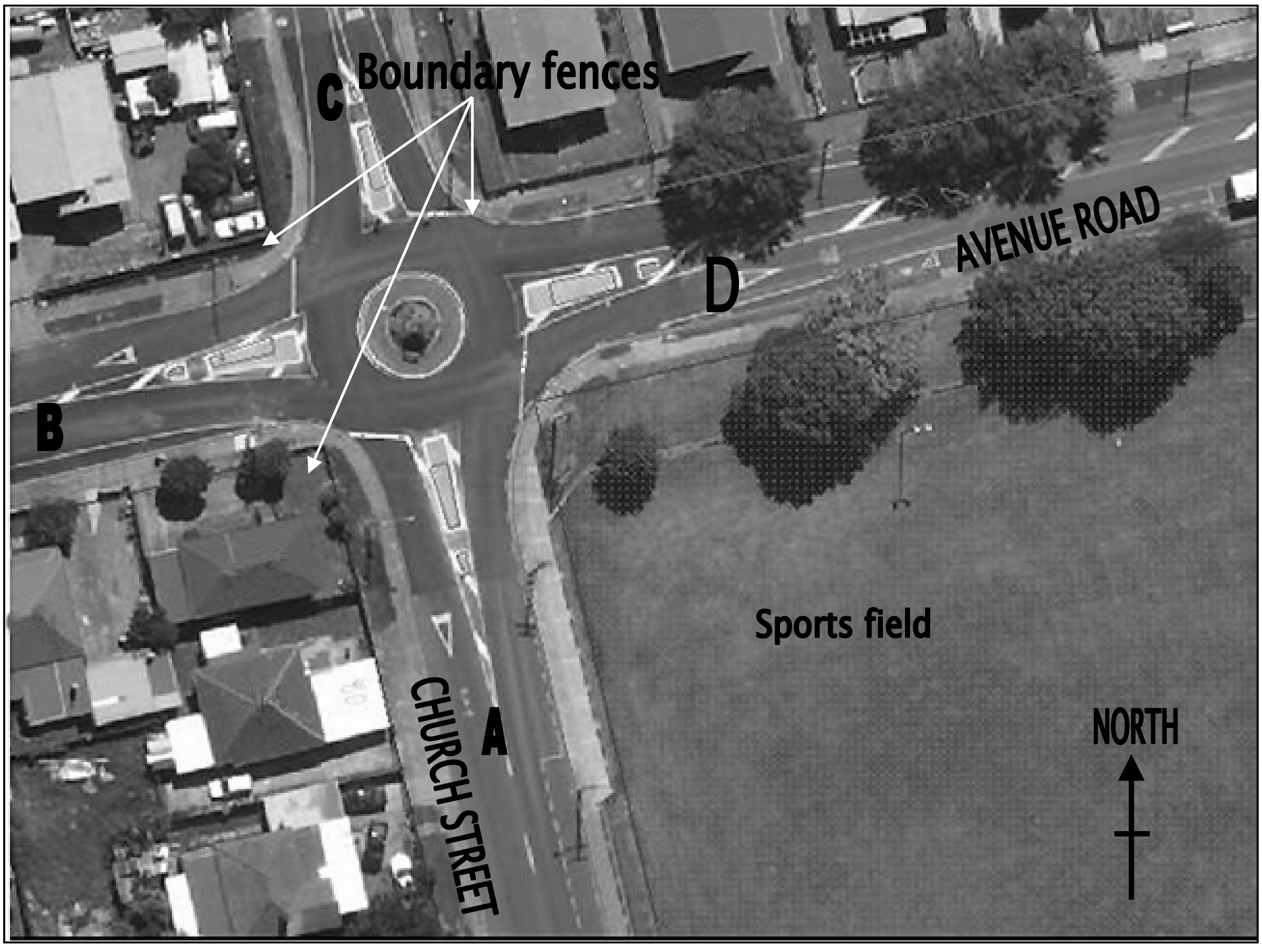
Further research is recommended to better understand the effects of sightline restrictions on driver approach speeds to a roundabout. This would potentially be very useful for roundabout design and crash reduction.

4.4.2 Church Street–Avenue Road

The Church Street–Avenue Road roundabout in Otahuhu is in a 50km/h residential area and was selected for evaluation as part of this research project for the following reasons:

- It has an unusual combination of sightline constraints, with three of the four approaches being restricted by corner boundary fences, and the fourth having almost unimpeded visibility across a sports field (figures 4.9 and 4.11–4.14). This layout would meet UK TD 54/07 guidelines for mini-roundabouts (DfT 2007b) (when approach arms have <300 vehicles per hour), and also Austroads guidelines for roundabouts (Austroads 2009b) as described in section 4.2.3.
- It has previously been identified as a site with an unusual crash pattern which appeared to be related to these visibility factors, even though the sightlines of approaching vehicles are satisfactory at the limit line (figure 4.10).
- Higher vehicle speeds through the roundabout from the Church Street southern approach (labelled approach A in figure 4.9) appeared to be the major factor in the crash pattern here.

Figure 4.9 Aerial photo showing the Church Street–Avenue Road roundabout in Otahuhu, Auckland



Notes to figure 4.9:

A Church Street southern approach

B Avenue Road western approach

C Church Street northern approach

D Avenue Road eastern approach

Figure 4.10 Driver sightline distances at the limit line for approaches B–D, which are more than adequate for drivers to see a safe gap to proceed in approaching traffic streams

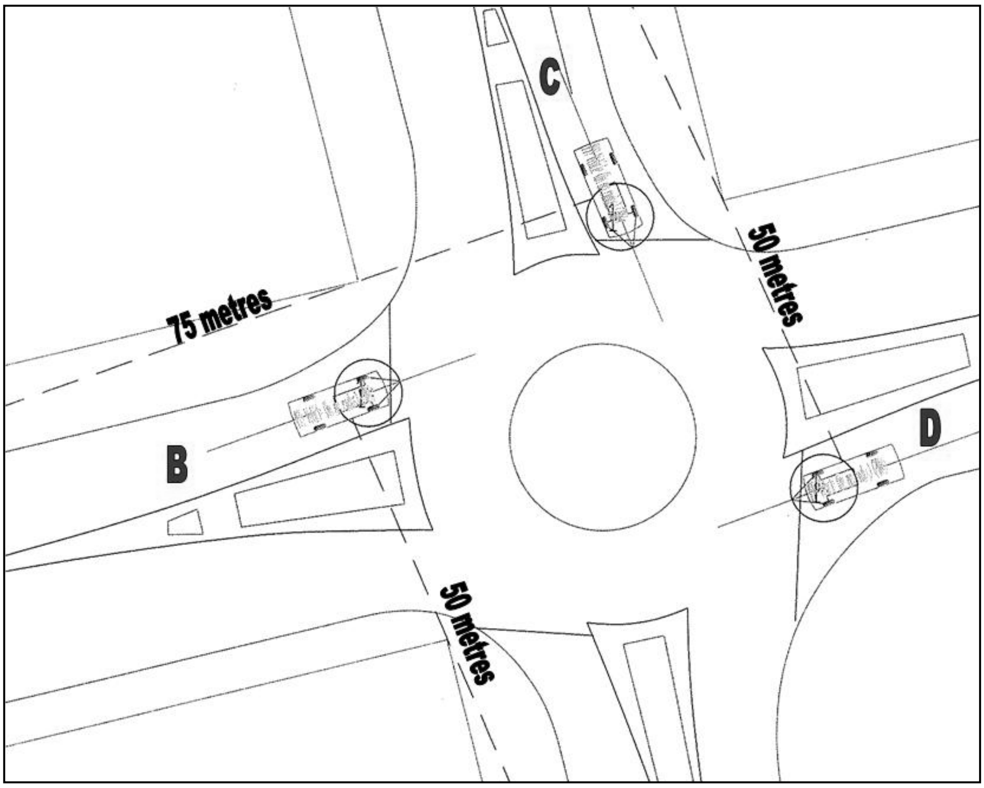


Figure 4.11 View taken on approach A at a point 25m from the roundabout limit line, showing the almost unimpeded visibility of opposing vehicles coming from approach D to the right

Figure 4.12 View taken on approach B at a point 10 m from the roundabout limit line, showing the corner boundary fence which severely restricts visibility of vehicles coming from approach A to the right

Figure 4.13 View taken on approach C at a point 10m from the roundabout limit line, showing the corner boundary fence which severely restricts visibility of opposing vehicles coming from approach B to the right

Figure 4.14 View taken on approach D at a point 10m from the roundabout limit line, showing the corner boundary fence which severely restricts visibility of opposing vehicles coming from approach C to the right

4.4.3 Crash history

A crash history for the nine-year period 2000–2008 is shown in table 4.1. Note that all crashes involved straight-through versus straight-through vehicles, and 13 of these 16 crashes (81%) involved vehicles from approach A. Six occurred at night, six during wet road conditions and three during peak traffic hour periods. The only other crashes at this location in this period were four loss-of-control crashes in no significant pattern, all non-injury. Off-peak traffic volumes, as shown in figure 4.15, demonstrate that the chances of conflicting straight-through versus straight-through movements are reasonably comparable for each of the four approaches, and are certainly not reflective of this crash pattern.

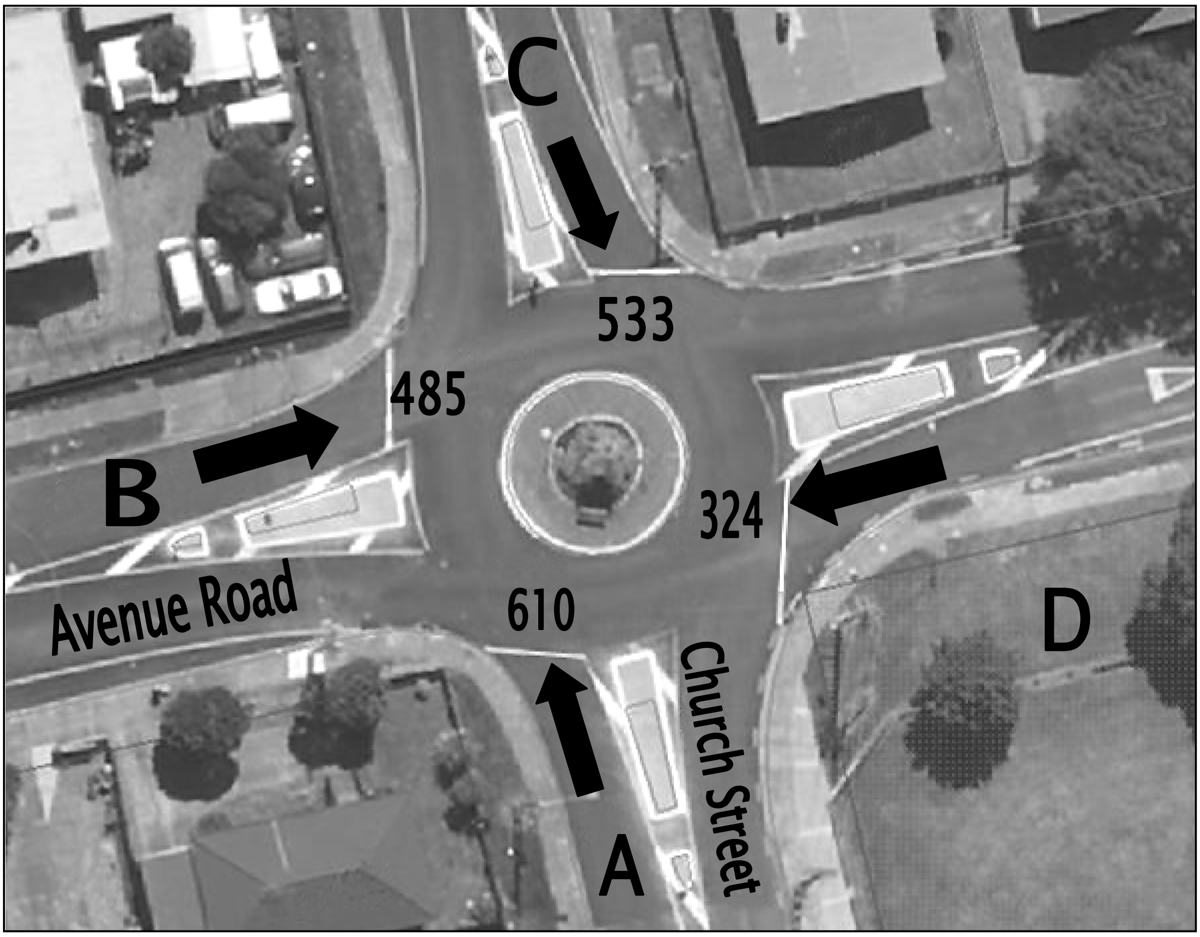
The significant crash pattern at approach B was perceived by the authors to relate directly to the higher speeds of through-vehicles from approach A, which would also contribute to the crash pattern between vehicles from approaches A and D.

Table 4.1 Reported entering v circulating crashes for the nine-year period 2000–2008 at the Church Street–Avenue Road roundabout

Approach*	Crashes	
	Number	Type
A	4	Non-injury
B	3	Minor injury
	6	Non-injury
C	1	Non-injury
D	2	Non-injury

*see figure 4.9 for approach locations

Figure 4.15 Diagram showing counted total traffic volumes between 9:30am and 3:00pm on one sample weekday



4.4.4 Straight-through circulating vehicle speed survey

A video survey was undertaken at the intersection on Wednesday 18 February 2009. Unimpeded straight-through-vehicle speeds were measured by timing the travel distances approximately 20m past each of the four limit lines. Videos were closely examined to determine as much as possible that each vehicle had at least four seconds of headway from traffic ahead, and that no other factors could have influenced driver behaviour. Over 100 samples were taken for each approach, which, based on equation 4.1 (taken from ITE 2000), was determined to be around 90% accurate ±1km/h for 85% speeds and 95% accurate ±2km/h for 95% speeds.

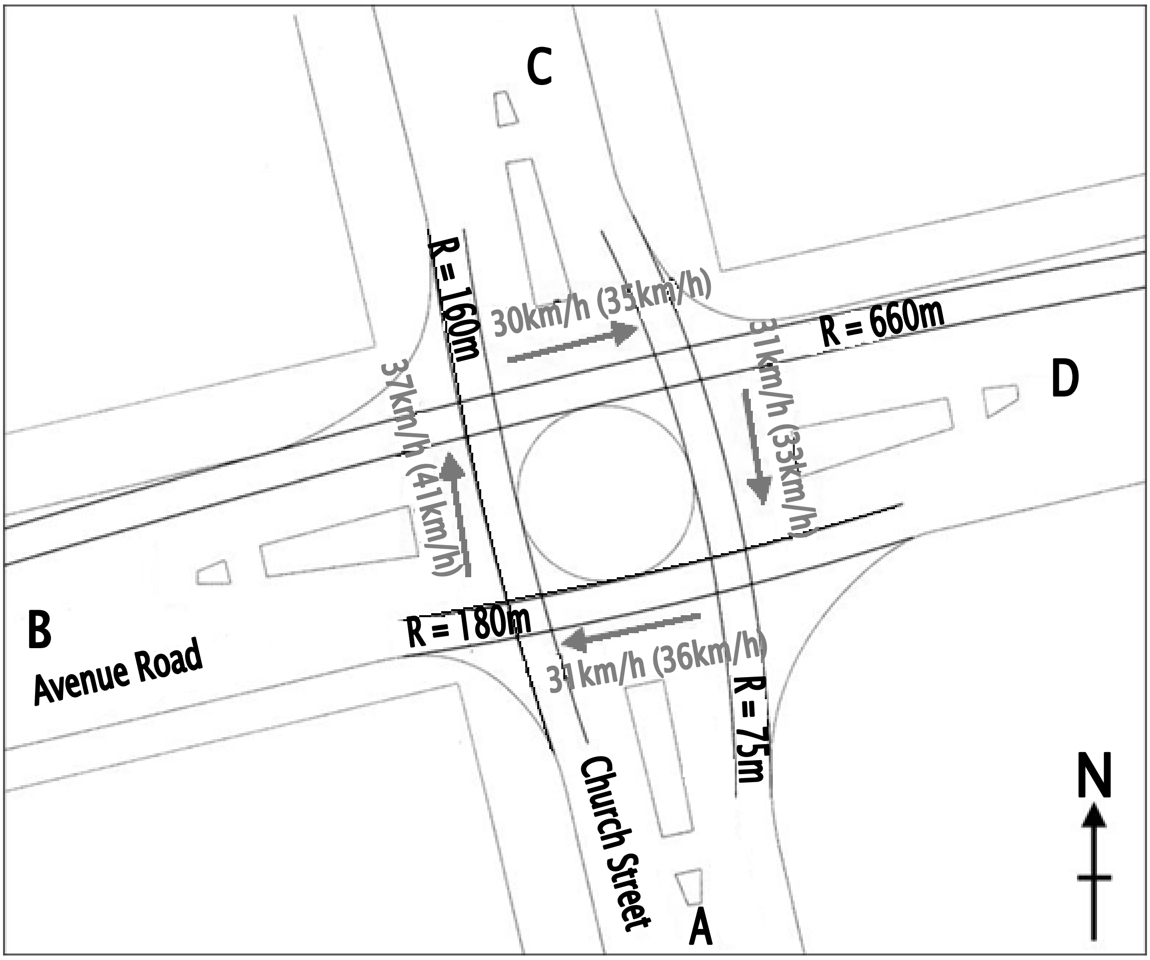
(Equation 4.1)

Where:

- *N* = minimum sample size
- *S* = estimated sample standard deviation (km/h)
- *K* = constant corresponding to desired confidence level (for 90% confidence, this is 1.64)
- *E* = permitted error in the speed estimate (km/h)
- *U* = constant corresponding to desired speed statistic (for 85% speeds, this is 1.04).

The survey results are shown in figure 4.16 below.

Figure 4.16 Approximate vehicle deflections through Church Street–Avenue Road roundabout as defined by Austroads (1993), plus 85% speeds of unopposed straight-through-vehicles are shown for each approach*



*95% speeds are shown in brackets

Figure 4.16 also shows the vehicle path deflections that were determined using on-site measurements, and did not take into account any on-street parked vehicles (very few of which were observed during the survey period). Most do not meet the Austroads recommended criterion for a maximum radius of 100m, but in any case, observed circulating speeds did not appear to relate significantly to these deflections as indicated by the grey figures showing the measured 85% speeds of unimpeded straight-through vehicles (95% speeds are shown in brackets). Note that an Australian study has previously demonstrated that a 100m maximum path radius for roundabouts generally correlates with 85% unimpeded through-vehicle speeds of 50km/h or less (Hosseen and Barker 1988).

The 95% speeds were lowest for approach C, which has the better speed control. It was perceived that this is perhaps a result of the better deflection there.

Results from the speed survey illustrate that vehicle speeds through this roundabout were better related to sightline constraints rather than roundabout geometry, which confirmed the intuition of the authors after driving through numerous times from each approach.

4.4.5 Approach speed survey

4.4.5.1 Introduction

The survey of vehicle speeds through the roundabout as described in section 4.4.4 confirmed that sightlines affect driver behaviour, and that the sports field on the southeastern corner was encouraging higher vehicle speeds from approach A. However, as figure 4.10 demonstrates, if drivers from approach B were cautious enough to slow down and adequately look for oncoming vehicles from approach A, the historical crash pattern between these vehicles should not occur. It was therefore supposed that although sightline restrictions were still reducing vehicle speeds on approach B, these drivers were still not slowing sufficiently to react and stop if a vehicle suddenly appeared from approach A.

As a means of evaluating this assertion, it was decided to measure vehicle speeds at a point around 10m back from each limit line for each approach (figures 4.17 and 4.18). At this point, it was estimated that if vehicle speeds are in excess of around 30km/h then the chances of a collision is greatly increased, as the driver will be less able to stop in time if an opposing vehicle suddenly comes into view. This is based upon the following assumptions:

- The deceleration rate was 3.5m/s^2, which is considered by the authors to be a desirable maximum for average drivers. Relying upon deceleration rates higher than this figure (such as for emergency stopping) are not considered to be conducive to satisfactory operation.
- The reaction time was 0.7–1.0 seconds, which previous research into human behaviour (Green 2000) indicates is the best estimate if a driver is alert and aware of the possibility that braking will be necessary, such as when approaching a roundabout where one might be expected to give priority to opposing vehicles.
- A driver travelling at 30km/h requires around 10m to stop if decelerating at 3.5m/s^2 excluding reaction time. Thus even if already decelerating in preparation to stop for opposing vehicles on the roundabout, drivers travelling in excess of 30km/h will have to decelerate uncomfortably hard in order to prevent a collision, or to at least avoid over-running the roundabout limit lines.

As a comparison, a driver travelling at 35km/h requires 14m to stop if decelerating at 3.5 m/s^2, which would bring them well within the conflict area with opposing vehicles. For this same driver to stop within 10m, they would have to decelerate at around 4.7m/s^2, which is equivalent to an emergency stop under Austroads (1993) guidelines for roundabouts.

Pneumatic tube counters[3] were considered to be the most practical method of gathering a large quantity of spot speed data. Although it is impossible to distinguish speed data for those vehicles that are travelling straight through and unimpeded by opposing traffic, it is considered a reasonable assumption that the significant majority of vehicle speeds over 30km/h should be in this category. The tube counters were in place for the week of 3–9 May 2009, a week which experienced only a few days without recurrent rain showers. During the week that the tube counters were in place, one of the authors drove numerous straight-through passes from the southern approach and confirmed that vehicle speeds of 30km/h or more at the tube counter (discernable by an audible thud as the tubes are driven over) made it uncomfortable to stop adequately before the limit line; at 35km/h, it felt like something in the order of an emergency stop.

3 Tube counters comprise of two separate air filled tubes set apart 1m, and vehicle speeds are determined by measured travel times between these.

Figure 4.17 Aerial photo showing locations of the tube counters installed on the roundabout approaches

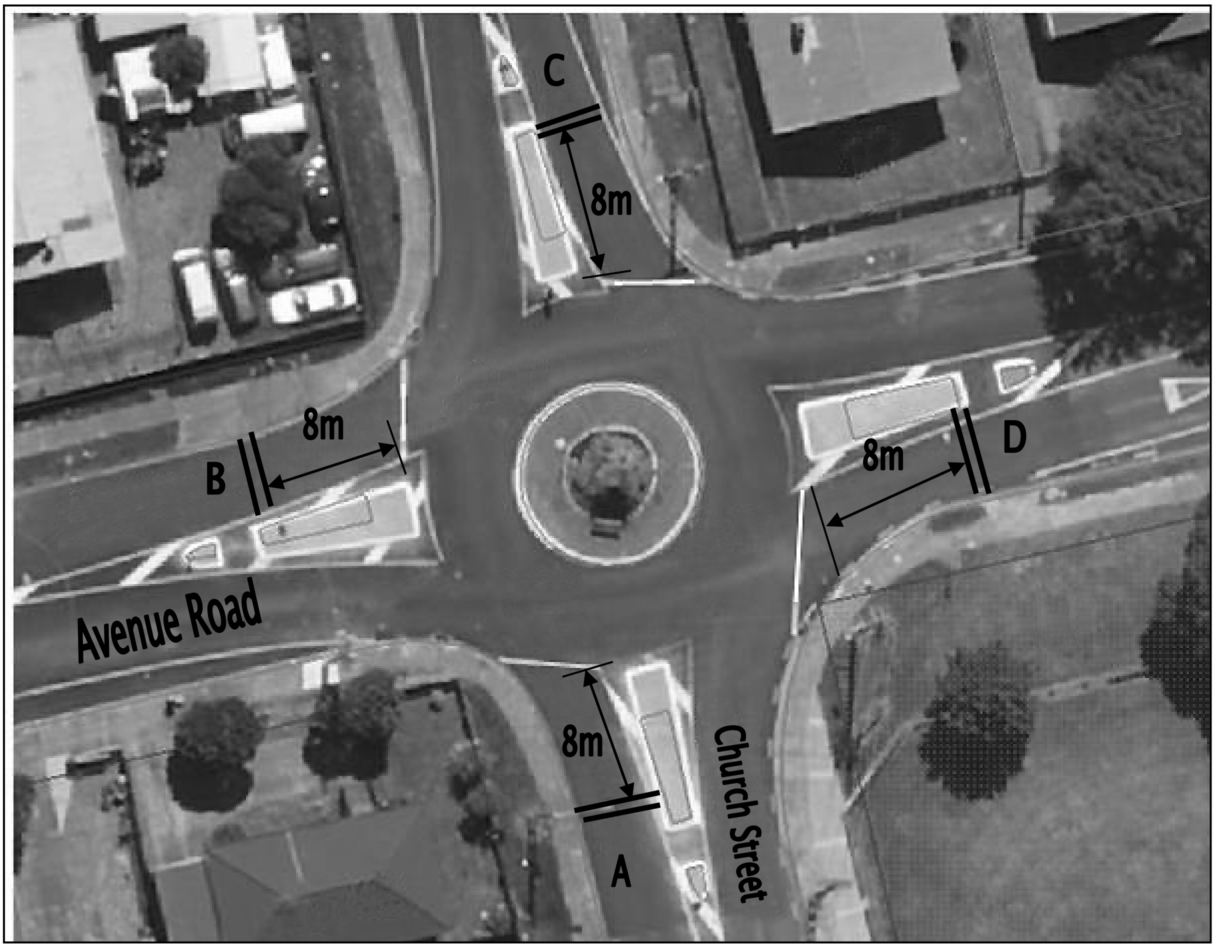


Figure 4.18 One of the tube counters around 10m from the limit line on approach C

4.4.5.2 Results of tube counter surveys

The results of the tube counter surveys are shown in table 4.2. Some maximum speeds estimated by geometric factors are also shown to demonstrate that they bear little resemblance to actual measured speeds.

Table 4.2 Measured vehicle speeds at around 10m in advance of roundabout limit lines from one week of tube count data (3–9 May 2009)

	Roundabout approach			
	A	B	C	D
Total seven-day vehicle count (N)	16,615	19,146	16,032	14,118
Daily 85% speeds	30–32km/h	26–27km/h	25–27km/h	27–28km/h
Vehicles travelling at 30–35km/h (n)	2216	593	542	643
Vehicles travelling at 35–40km/h (n)	716	88	71	126
Vehicles travelling at >40km/h (n)	213	26	13	22
Deflection curve radii through roundabout (m)	160m	660m	75m	180m
Estimated maximum speed due to geometry (f = 0.2, e = –0.02)	60km/h	123km/h	41km/h	64km/h
Maximum measured vehicle speed	58km/h	53km/h	51km/h	63km/h
% vehicles travelling at >30km/h	18.9%	3.7%	3.9%	5.6%

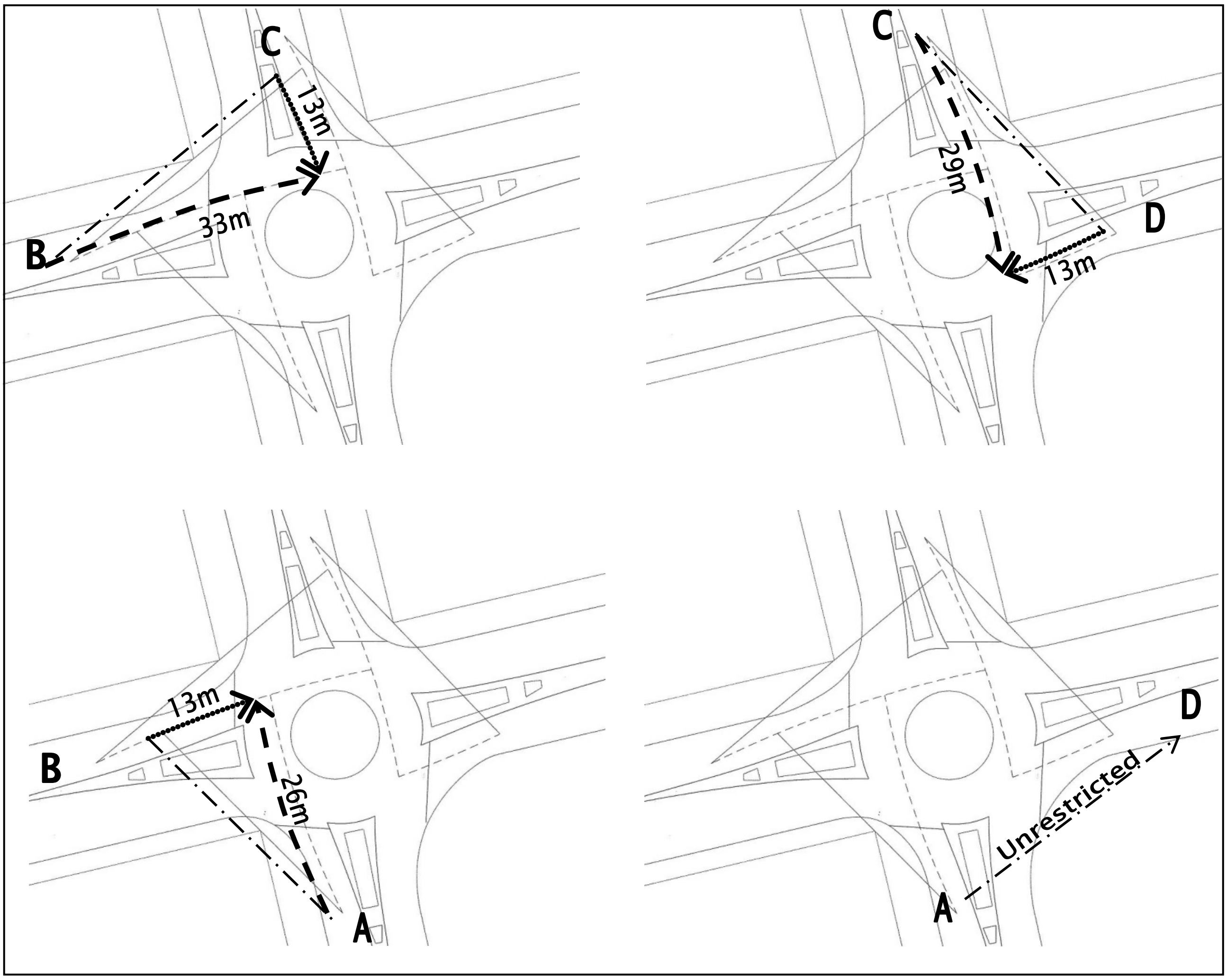
Some key findings from these results are as follows:

- Vehicle speeds from approach A, which has almost unrestricted sightlines, are significantly higher than for the other approaches, reiterating the results from section 4.4.4.
- Approach C experienced the lowest recorded maximum speed, and it is that believed this is most likely to be related to the fact that it has the best deflection by a substantial margin.
- A relatively high proportion of drivers on approaches B, C and D were driving up to the limit line at speeds faster than are desirable to stop in time for opposing traffic (ie greater than 30km/h), given the sightline restrictions for those approaches. If a vehicle were to suddenly appear from the approach to the right, depending upon the speed of this oncoming vehicle, a collision could ensue if evasive action is not taken by either or both parties (note that drivers entering a roundabout are less likely to be prepared to stop for vehicles suddenly appearing from their left, who could be assumed to be giving way). Figure 4.19 demonstrates the available sightline distances of a vehicle 10m from the limit line. Approach B represents the most critical combination of driver approach and circulating traffic speed, and the crash pattern appears to demonstrate this.
- The significant majority of reported crashes at the Church Street–Avenue Road roundabout involve entering vehicles from approach B colliding with through-vehicles from approach A. The most critical scenario is approach B, where sight distance is most restricted and through-vehicle speeds from adjacent approach A the highest. For example, if a vehicle from approach B entered the roundabout at 30km/h, it would only just clear the conflict point (taking into account the length of the vehicle) before a vehicle from approach A travelled past at 40km/h without slowing. The vehicle from approach A in this scenario also has marginal distance to react and come to an emergency stop. The historical crash pattern here confirms this is a safety problem, and would appear to demonstrate the

adverse effects of a particular roundabout layout which experiences driver approach speeds that are too high to stop in time for opposing vehicles should they suddenly appear in view

- The reason that approaches C and D experience much fewer significant reported crashes than approach B appears to be largely a result of the lower vehicle speeds of opposing through-vehicles coming from their right. Although approach speeds for C and D are similar to those of approach B, even if a vehicle does suddenly come into view, a collision is more likely to be averted here simply because the oncoming vehicle does not reach the conflict point in time.
- A higher proportion of drivers from approach D drive through at speeds in excess of 30km/h compared to approaches B and C, which have similar sightline constraints. Approach D recorded the highest maximum through-speed of all four approaches. It is speculated that the boundary fence here is not quite high enough to restrict sightlines completely for drivers with higher driving positions (eg in a four-wheel drive or truck) who might be more inclined to speed through (see figure 4.14). Three out of the six entering v circulating vehicle crashes in 2000–2008 that involved vehicles from approach D were taller vehicles such as vans or four-wheel drives from approach D, which seems to support this. A higher fence would thus appear to be desirable here.

Figure 4.19 Visibility triangles at a point 10m back from the limit line where vehicle speeds were measured by tube counters showing distances to conflict points are shown for entering (dotted lines) and opposing (dashed lines) vehicles



4.4.6 Discussion

The speed surveys as undertaken at the Church Street–Avenue Road roundabout in Otahuhu demonstrated that vehicle speeds can be significantly influenced by sightline restrictions, and also that a proportion of people will still approach a roundabout at speeds that are unacceptable for stopping in time for oncoming vehicles that they should be giving priority to. Therefore, although sightline restrictions can feasibly be a useful method of speed control at a roundabout, this consideration of driver behaviour does need to be taken into account.

Restricted sightlines do not necessarily comprise a significant safety problem if opposing vehicle speeds are low enough that the first vehicle is able to clear the conflict point before the second vehicle arrives. The absence of any substantial crash pattern at approaches C and D appears to demonstrate this. However, the substantial crash pattern at approach B clearly shows the result if opposing vehicle speeds are higher than a certain threshold.

As a result of this analysis of the Otahuhu roundabout and taking into account the findings of the rest of this chapter, some implications for roundabout design are as follows:

- Sightline restrictions have an effect on driver speeds at a roundabout and are an important consideration for traffic safety. Deflection elements of roundabout design, in some cases, may become of secondary importance, except perhaps in affecting absolute maximum speeds.
- The potential use of sightline barrier screens does have some merit in terms of crash reduction. Even though it has to be accepted that a minority of drivers will drive at inappropriately high speeds for the conditions, this does not necessarily correspond to a significant safety problem in terms of crash statistics. However, sight screens should be of sufficient height to restrict visibility of taller vehicles which otherwise might drive through at speed.
- The potential speed of vehicles approaching the conflict point on the roundabout is a critical consideration and will greatly determine whether or not a significant crash problem might ensue as a result of sightline restrictions. If vehicle speeds based on visibility constraints can be reliably estimated in advance of a roundabout being installed, safety implications can be predicted better. Crash models already developed for roundabouts in New Zealand (Turner et al 2009) have identified vehicle speed as a main factor for entering v circulating crashes. Inputs could potentially be used in these prediction models. This is a topic which justifies further research, as the implications for roundabout design are especially relevant for built-up urban areas where sightline restrictions are commonplace.
- Roundabout designs that rely solely upon speed control by the use of sight restrictions alone could conceivably operate relatively safely if the sight distances for each approach can allow for expected opposing vehicle speeds. This is more likely to be applicable for smaller diameter roundabouts in urban areas where very restricted sightlines are possible, although deflection islands that affect maximum possible speeds are certainly preferable. As a point of reference, the Church Street–Avenue Road roundabout in Otahuhu demonstrated an 85% speed of around 30km/h for unopposed through-vehicles with sight restrictions of around 30m at a point 10m back from the limit line.

4.4.7 Potential safety measures at the Church Street–Avenue Road roundabout

Several solutions could be implemented at the Church Street–Avenue Road roundabout to address the crashes being experienced there. Each of them would reduce through-vehicle speeds from approach A, which is expected to result in a decrease in crashes involving these vehicles. They are as follows:

- Install a visibility screen for the southern approach of Church Street (ie approach A), so that sightline restrictions are similar to approaches B–D.
- Significantly increase deflection for through-vehicles from approach A. Given that 85% vehicle speeds will need to be reduced to around 30km/h, this will probably only be achievable by substantially extending the central island of the roundabout. Buses which currently travel through the intersection in a south–north direction would have to drive over large sections of mountable kerb, as would any large trucks.
- Install a 100mm high speed table or hump on approach A. This would probably be the most effective measure of ensuring that vehicle speeds over 30km/h will not occur.

4.5 Conclusions

Based on the research in this chapter, the following conclusions have been made:

- Excessive sightlines to the right can contribute to higher than desirable driver speeds at a roundabout, which can potentially increase crash types including loss-of-control, rear-end and entering v circulating crashes (particularly crashes involving two-wheeled users who are less visible).
- The UK experience has been that excessive sightlines can contribute to loss-of-control and rear-end crash patterns, and sight-screens have successfully been installed for treatment of these problems at some rural roundabouts in higher-speed areas. UK design guidelines for roundabouts (DfT 2007a) recommend this measure as an optional treatment.
- The study site in Otahuhu, Auckland, clearly demonstrated that sightlines to the right can sometimes influence driver speed more than roundabout geometry.
- If sightlines to the right at a roundabout are restricted too much relative to the speed of opposing vehicles then entering v circulating crashes may increase. A proportion of entering drivers will not drive at speeds appropriate to the road environment, and may not have time to react if oncoming vehicles suddenly appear. Sightlines to the right appropriate to the speed environment are therefore important for traffic safety. For a four-arm roundabout, this implies that sightline restrictions might be similar for each approach.
- Better understanding of the effects of sightline restrictions on driver approach speeds to a roundabout could be valuable for the safe design of roundabouts, and for preventing crashes involving cyclists and motorbikes in particular. A practical application of these findings based on close analysis of a roundabout in Otahuhu, Auckland, is contained in appendix D.

The visibility of oncoming vehicles can influence driver speed at a roundabout, and visibility screens have been successfully used in the UK to improve safety and are an acknowledged practice (section 4.2.5). If a driver does not perceive any opposing vehicles while he/she is still at some distance from a roundabout, he/she may enter at a higher speed than desirable for the safety of themselves and other road users (particularly less visible cyclists and motorcyclists, who are more difficult to discern).

A positive safety improvement can result when the overall speed environment is reduced by means of visibility restrictions. However, from the analysis of the Otahuhu roundabout, it has been identified that entering v circulating crashes may potentially increase, and this effect is primarily dependent upon the speed of opposing traffic.

Based on the findings of this research, the following recommendations are made:

- A practical application of how to use sightline restrictions at roundabouts has been developed and is contained in appendix D. This application should be referred to by traffic engineers to design safer roundabouts at locations where geometric means of speed control might be difficult to achieve, or to address crash patterns at existing locations.
- For existing roundabouts with loss-of-control or rear-end type crash patterns, consideration should be given to restricting sightlines for entering drivers as per the UK guidelines (refer section 4.2.2). However, opposing vehicle speeds need to be taken into account if an increase in entering v circulating vehicle crashes is to be avoided. Speed reduction measures of any means could be used to address this.

Predicting driver approach speed relative to visibility to the right at a roundabout (restricted by either sight screens or obstructions) should be further researched, as this concept offers an economic alternative to geometric means of speed control at roundabouts. This would require some 'in the field' experimentation.

5 Pedestrian facilities at multi-lane roundabouts

5.1 Introduction

5.1.1 Background

In New Zealand, zebra crossings or refuge islands are the most commonly installed facilities for pedestrians at roundabouts, with mid-block pedestrian signals sometimes being installed on busier roundabout arms. Crossings that are amenable to pedestrians can sometimes be difficult to achieve for roundabouts in multi-lane situations, and anecdotal evidence suggests that many pedestrians are wary of crossing at large busy roundabouts. Partly because of this – in Auckland, at least – traffic signals have often been installed in recent years in preference to roundabouts at intersections with high volumes of pedestrians.

The main objective of this section is to research and evaluate the pedestrian crossing options available to traffic engineers for multi-lane roundabouts.

5.1.2 Methodology

This section of the research included the following tasks:

- Undertake a literature review of New Zealand and overseas research on this topic, and thoroughly evaluate any published material.
- Analyse crash records to compare the safety records of different types of pedestrian crossing facilities at arterial road roundabouts in Auckland (chapter 6). These included zebra crossings, refuge islands, raised platforms and pedestrian signals.
- Undertake a closer evaluation of pedestrian and driver behaviour at several different types of pedestrian crossing facilities at roundabouts. These include zebra crossings on entry and exit legs, and some signalised crossings.
- Contact representatives from the New Zealand Crippled Children Society (CCS Disability Action or CSS) and the Royal New Zealand Foundation for the Blind (RNZFB) regarding pedestrian facilities for disabled and visually impaired pedestrians.
- Prepare a practical application for practitioners based on this research.

5.2 Roundabout pedestrian facilities currently used in New Zealand

The standard installations in New Zealand include:

- pedestrian refuge islands
- zebra crossings
- pedestrian signals
- raised platforms

Pedestrian refuge islands (figure 5.1) are commonly installed at roundabouts where pedestrian volumes are low and do not justify installation of a zebra crossing or traffic signal facility. As the priority of way is with vehicle traffic it is assumed that pedestrians will use due caution before crossing, although at busy vehicle locations, refuge islands can be much less amenable than zebra crossings.

This type of facility will always serve a purpose at locations with relatively low pedestrian volumes, or where for safety or operational reasons the preference is to keep priority with vehicle traffic.

Figure 5.1 A pedestrian refuge island by the Sel Peacock Drive–Alderman Drive roundabout in Waitakere, Auckland

Zebra crossings (figures 5.2 and 5.3) are some of the most common facilities at roundabouts in New Zealand that cater for substantial volumes of pedestrians. Pedestrians have legal priority of way, although, according to the New Zealand *Road code* (NZTA 2010b), they are not supposed to step out if any vehicles are so close to the crossing that they cannot stop.

In New Zealand, zebra crossings are generally only installed where they meet warrant criteria based on traffic and pedestrian volumes. The reason for this is mainly safety-related, as crossings installed where few pedestrians are present mean that drivers might be expected to be less alert for potential stopping manoeuvres.

Staggered island layouts are sometimes installed, and the general consensus is that these can improve safety by breaking a roadway into two distinct shorter crossings where pedestrians are better able to discern safe opportunities to cross. However, they are not ideal to install near busy roundabouts, as they can push exiting vehicle queues into circulating traffic lanes.

Some zebra crossings near roundabouts can also be prone to pedestrian safety problems, and further analysis of a number of multi-lane facilities in Auckland is described in chapter 6.

Figure 5.2 Zebra crossing facility at a roundabout in Waitakere, Auckland

Note: Here, both the standard 300mm Belisha beacons as well as 400mm orange Belisha discs have been installed, but both are relatively small and inconspicuous.

Figure 5.3 Photo of a roundabout in the US with zebra crossing type facilities (where drivers are supposed to yield to pedestrians) with associated signage* and slightly raised red paver treatments

* In the US, these facilities are not required to be marked with white stripes as they are in New Zealand. Note the much larger signs used at the crossing compared to the Belisha discs and/or beacons used in New Zealand.

The conventional alternatives to zebra crossings in New Zealand are mid-block **pedestrian signals**, with either a full width or staggered island arrangement. Disruptive effects on traffic flow will depend upon signal timing, the volume of pedestrians, carriageway width and proximity of the crossing to the roundabout (queued vehicles can block circulating lanes if the crossing is too close to the circulating lane). Staggered crossings can reduce disruption to traffic, as crossing times are shorter for each direction.

Generally, delays for pedestrians will be greater than for a zebra crossing, and if wait times are set too long, pedestrian safety can potentially be compromised as people choose to ignore the displays and jaywalk. Since 2008, the TMU in Auckland has been reconfiguring staggered pedestrian signal arrangements to reduce pedestrian wait times. The key changes are anticipatory call-up of the opposite stage crossing (ie to minimise waiting time on the central island) and setting lower maximum green times for traffic phases. Detailed explanations of how to do this are expected to be incorporated into future versions of the TMU Traffic Signal Design Guidelines, which are available nationwide.

Raised platforms (figure 5.4) have occasionally been used to improve pedestrian safety at designated crossing points near roundabouts, and they do so by virtue of the fact that they provide a reduced traffic speed environment (provided that the platform is of sufficient height to have this effect). However, speed platforms potentially have some adverse effects on vehicle traffic and this subject is researched in more detail in chapter 7.

Figure 5.4 Whakahue Street–Tutanekai Street intersection in the Rotorua Central Business District (CBD), where the entire roundabout (single-lane) is constructed as a raised platform, giving a low-speed environment that is conducive to pedestrians

5.3 Literature review and evaluation of overseas practice

5.3.1 Summary

The aim of this section was to research overseas practice with respect to pedestrian crossing facilities and to evaluate them in the context of application at roundabouts. More vulnerable pedestrians at roundabouts include children, the elderly and mobility or visually impaired pedestrians, and most of the identified treatments should improve the situation for them.

It was found that ‘Hawk’, ‘Pelican’ and ‘Puffin’ crossings, which reduce pedestrian signal walk times, are feasible for use in New Zealand, although some law changes are required to allow the flashing signal operation which is used in these. Improvements to zebra crossings that have demonstrable benefits are activated flashing road studs or signs. The road studs in particular have already been successfully trialled in Auckland and Christchurch. Signalised roundabouts which have recently been installed in small numbers in New Zealand can also effectively provide for pedestrians, and their part-time operation (currently illegal in New Zealand) is also deemed worthy of consideration. Raised speed platforms, which are also an option, are more closely evaluated in chapter 7.

5.3.2 Pedestrian safety performance of roundabouts compared to traffic signals

As discussed in section 2.4, relatively little objective analysis has compared crash rates for pedestrians between multi-lane roundabouts and signalised junctions. The few studies that have attempted to do this did not identify any significant differences.

A search of the New Zealand CAS database showed that nationwide, 24 serious pedestrian crashes and no pedestrian fatalities occurred at any urban roundabout during the five-year period 2004–2008, compared to 11 fatal and 160 serious injury crashes at urban signalised intersections. These statistics imply that traffic signals may present considerably more safety problems for pedestrians than roundabouts. It was identified in section 2.4 that this topic justifies further research to confirm if this is actually the case.

5.3.3 Zebra crossings

A 1982 study from the UK (Marlow and Maycock 1982) developed a procedure for quantifying the effects of zebra crossings on entry capacity and also the 'blocking back' effect on the exit side of a roundabout. Some simulation packages, including aaSIDRA and VISSIM, are able to evaluate the disruptive effects of pedestrian facilities on traffic flow.

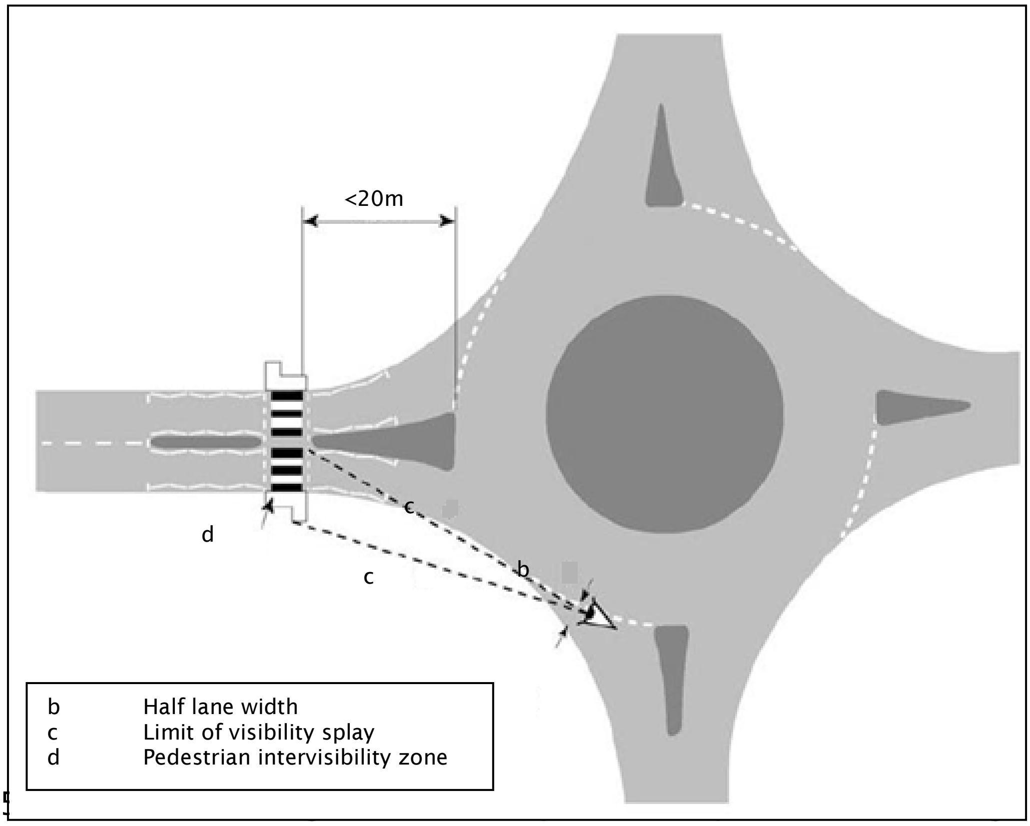
A report from the US (National Cooperative Highway Research Program 2007) undertook a comprehensive observational study of around 769 pedestrian crossing events at 10 arms of seven roundabouts (all had zebra crossing facilities). In summary, no substantial safety problems for pedestrians at roundabouts were found, as shown by the low numbers of reported crashes and a very small number of observed conflicts. However, the researchers also found the following:

- Exit lanes appear to place crossing pedestrians at a greater risk than entry lanes. Motorists were less likely to yield to pedestrians on the exit side (38% of the time) compared to the entry side (23% of the time).
- Two-lane arms are more difficult for pedestrians to cross than one-lane arms, primarily because of the non-yielding behaviour of motorists. On one-lane arms, 17% of the motorists did not yield to a crossing/waiting pedestrian. On two-lane arms, the non-yielding percentage was 43%.

Guidelines from the UK (DfT 2007a) recommend that zebra crossings should not be located between 20m and 60m from roundabout limit lines, and if zebra crossings are less than 20m away, sightlines between pedestrians and drivers should be kept clear, as shown in figure 5.4.

Standard signage for zebra crossings in New Zealand is illuminated Belisha beacons and/or reflective Belisha discs (refer to figure 5.2). It is the authors' opinion that for busy arterial road applications, these are relatively inconspicuous and should be increased in size from the current standard of 400mm diameter to 750mm, which would be comparable to some overseas practice (refer to figure 5.3). It is recommended that the *Manual of traffic signs and markings* (MOTSAM) (NZTA 2010c) be amended on this basis.

Figure 5.4 Visibility requirements for zebra crossings in the UK (DfT 2007a)



5.3.4.1 General remarks

Improving safety at zebra crossing facilities where pedestrians have priority over vehicle traffic has received some attention both overseas and in New Zealand. The intention has been to draw more driver attention to pedestrians using the crossing via flashing road studs or roadside flashing signs; both these systems have benefits. Although one study from the US demonstrated that flashing road studs are more effective (Malek 2001), it is considered that the more recent development of road signs with rapid flashing displays (rectangular rapid flashing beacons or RRFBs) may offer a more practical solution with lower ongoing maintenance costs. Automated detection rather than discretionary activation by pedestrians is the preferred means of operation.

The use of active warning devices is considered by the authors to be applicable for more than just zebra crossings. They could also be used at signalised pedestrian crossings to alert drivers of a red light ahead, and could be activated as the amber phase is brought up as a preventative safety measure in this context.

5.3.4.2 Flashing road studs

Since at least the 1990s, flashing road studs (or embedded pavement lights) have been used in the US at zebra crossings where drivers are expected to give priority to pedestrians. The lights flash only when pedestrians use a push-button or are detected as they begin to make the crossing, and are intended to alert approaching drivers of their presence. They have also been used in New Zealand with promising results.

Some studies undertaken in the US provide us with some interesting findings:

- A study from California (Whitlock & Weinberger Transportation Inc 1998) recommended amber as an appropriate colour for the flashing studs, based on drivers' visual capabilities and vehicle laws. This study also recommended automatic pedestrian detection rather than a push-button, as it would be less prone to confusion to a minority of people, who could perceive that the act of pushing a button will cause traffic to stop. For the benefit of visually impaired pedestrians, it was suggested that a voice box which says, ‘The warning flashers have been activated: cross with caution,’ or similar could conceivably be used.

- Several studies have found that after flashing road studs were installed at crossing locations, vehicle speeds during activation decreased substantially, observed conflicts between vehicles and pedestrians reduced, and pedestrian behaviour near the crossing improved (Huang et al 1999; Parevedouros 2001; Van Derlofske et al 2002; Hakkert et al 2002).
- A study from New York (Van Derlofske et al 2002) which evaluated the difference between striping and striping with flashing road studs at two locations found that the number of conflicts per crossing event (defined as an occasion when a driver moves over the crossing while a pedestrian is on the carriageway) increased after the road flashers were installed. The microwave detection system used was blamed for this effect, as it had a very high incorrect activation rate (ie missed a crossing pedestrian or falsely activated when no pedestrians were present) of 27% and 40% for the two sites. It was concluded that a reliable pedestrian detection system is important to ensure good rates of driver compliance.

Recent trials of flashing road stud devices at three zebra crossings in Christchurch and Auckland have demonstrated some improvements in driver and pedestrian behaviour, and a reduction in observed conflicts compared to the situation prior to installation (Smith et al 2008). One of these zebra crossings is close to a busy multi-lane roundabout in Royal Oak, Auckland, as shown in figure 5.5. The Christchurch installation, which is a mid-block installation atop a raised platform with a single lane in each direction, cost in the order of $30,000, including road studs, power source equipment and photoelectric detection units.

Figure 5.5 Driver view when exiting the Royal Oak roundabout of the Mt Albert Road zebra crossing fitted with amber flashing road studs

Note: the approximate stud locations have been added for additonal emphasis, as they are less discernible in sunny conditions, such as when this photo was taken. The studs were installed in 2006, and it is entirely likely that with improved light-emitting diode (LED) technology, their visibility in daytime conditions would improve.

5.3.4.3 Flashing signs

Flashing sign arrangements at pedestrian crossing facilities are also common in the US, and often use push-button call-up (figure 5.6). A potential advantage of signs over the flashing road stud system is reduced maintenance costs (for example, road reseals will be an issue for road studs), although installation costs, including detection equipment, are likely to be reasonably comparable for both systems. Anecdotal evidence from a few practitioners in the US suggests that some agencies are having trouble maintaining the flashing road stud installations and are replacing them with flashing sign arrangements.

Figure 5.6 An example of an active warning sign with push-button call-up installed at a pedestrian crossing site in the US

A US study (Department of Transportation Minnesota 2009) was not absolutely definitive as to the benefits of flashing sign devices at sites where they are activated by a push-button, and recommended that if flashing signals were installed, an automated detection system of pedestrians be used because a proportion of users do not bother to activate the warning signs, which was considered to be a shortcoming.

A 2001 study from California (Malek 2001) compared effectiveness of flashing road studs (figure 4.7) and overhead yellow flashing lights (figure 4.8), both using identical infra-red systems for detecting pedestrians. The pavement lights were found to be substantially more effective in alerting drivers to the presence of pedestrians in both daytime and night conditions. It was acknowledged that road studs may be liable to additional maintenance costs. However, more recently, RRFBs have been used at pedestrian crossing facilities with some success and have also been measured as having superior performance to overhead yellow flashing light systems (Federal Highway Administration 2010). It is considered by the authors of this present report that RRFBs might be a more practical solution.

Figure 4.7 Flashing road studs used at a zebra crossing in the US (Malek 2001)

Figure 4.8 Overhead yellow flashing lights used at a zebra crossing in the US (Malek 2001)

Figure 5.8 RRFB signage used in the US (Malek 2001)

5.3.5 Signalised roundabouts

5.3.5.1 Full-time signalised roundabouts

Signalised roundabouts as commonly used in the UK can satisfactorily accommodate pedestrians via signalised crossing points either on roundabout approaches or using the central island as a walking route (see figures 5.9 to 5.11), and they have demonstrable safety benefits for cyclists as well (Lines 1995; DfT 2009).

However, compared to an unsignalised roundabout, vehicle delays will be substantially higher during off-peak periods. Alongside a relatively high installation cost, this would be one of their main drawbacks. Part-time operation, as sometimes done in the UK, could mitigate this to a degree.

Figure 5.9 A full-time signalised pedestrian crossing at a multi-lane roundabout using the central island as a walking route (DfT 2009) (pale grey indicates the pedestrians' paths)

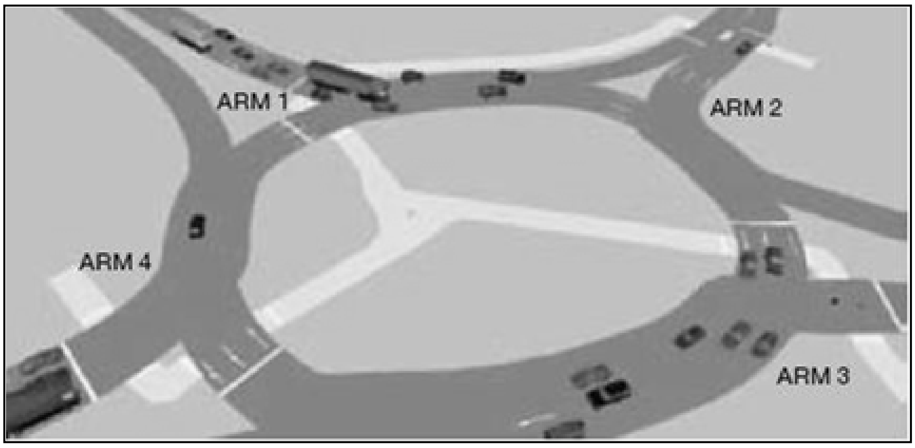


Figure 5.10 A full-time pedestrian crossing at a multi-lane roundabout using staggered crossing points on each approach road as walking routes (pale grey track)

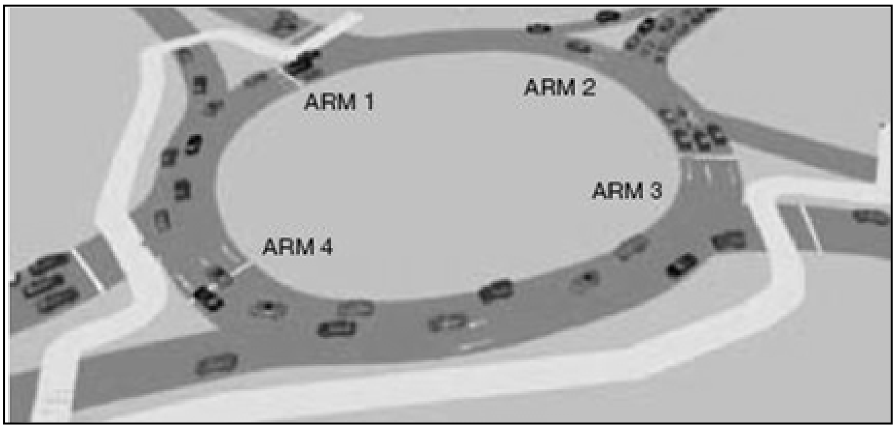


Figure 5.11 Model of a signalised turbo-roundabout (see chapter 8) currently operating in The Netherlands

5.3.5.2 Part-time signal operation

Currently, part-time signal operation is not legal in New Zealand, but the authors of this report recommend that the NZTA should reconsider this stance. Tauranga City Council has three multi-lane signalised roundabouts in its district (one installed by the council, the other two by the NZTA), and Tauranga City Council endorses this view not only for roundabouts but for all signalised intersections.

Part-time signals at roundabouts have been installed in the UK (figure 5.12), but the most recent guidelines from there are not encouraging their use. One reason for this is because pedestrian facilities may be difficult to provide for satisfactorily in all traffic conditions (DfT 2009). However, part-time operation of a signalised roundabout means driver delays in off-peak periods can be minimised when the signals are turned off, while the benefits of peak-hour signal operation can still be realised. As a minimum, pedestrian facilities could at least be located a distance from the roundabout where drivers would be unaffected. This situation is deemed worthy of further consideration by the NZTA.

Figure 5.12 Part-time signals in the UK at a motorway junction (DfT 2009)

5.3.6 'Hawk', 'Pelican' and 'Puffin' signalised crossing points

5.3.6.1 Benefits

It is recommended that 'Hawk', 'Pelican' and 'Puffin' signal crossings be considered for widespread application in New Zealand. All these offer improved performance compared to conventional pedestrian signals, primarily because they can reduce pedestrian clearance times that would otherwise be required for conservatively low walking speeds. In the context of roundabouts, one main implication is that traffic queues on exit-arm crossings would disrupt circulating lanes less frequently.

Currently, part-time and flashing signal arrangements as used by the Hawk and Pelican crossings are not legal to use in New Zealand, so use of the Puffin crossing would appear to offer the most expedient way forward. However, the other two systems are technically simpler and do not rely upon advanced pedestrian detection technology, which has apparently not yet developed to a reliable standard.

5.3.6.2 The Hawk and Pelican

The Hawk hybrid pedestrian signal system is currently being put forward in the US as the optimum signal facility for multi-lane roundabouts that can provide for pedestrian accessibility (particularly for visually impaired users, as discussed further in section 5.3.7) as well as minimise disruptions to roundabout traffic operations. It is based on the Pelican crossing (figure 5.13), which has been used since 1968 in the UK (Kennedy and Sexton 2009) and is also a standard configuration used in Australia.

Figure 5.13 A British Pelican crossing, which is a full-time signal arrangement using three-aspect displays facing drivers. This particular example is fitted with nearside displays for pedestrians similar to those used by Puffin crossings (photo from Dudley Metropolitan Borough Council)

Pelican crossings have a short period of displaying a fixed green walking figure for 4–9 seconds, during which vehicles are shown a red signal. This is followed by a clearance period with a flashing green figure for pedestrians and flashing amber lights to drivers, who may proceed if the crossing is clear (DfT 1995a). Australian studies have shown that vehicle delays at Pelican crossings are approximately half those at conventional pedestrian-activated crossings (Austroads 2009a).

The Hawk system, as used in the US (see figure 5.14 and table 5.3), is very similar in practice to the Pelican. However, at roundabouts, it offers an option of blanking out the displays unless the Hawk is activated, so pedestrians confident enough to cross without using the lights can choose not to use the push-button at all. This is the main difference between the Hawk and the British Pelican – the Hawk has the flexibility to function as a regular zebra crossing facility when not activated by pedestrians, while the Pelican is a full-time signal arrangement. In addition, the Hawk uses only amber and red displays facing vehicles, but the Pelican also uses a green display.

Figure 5.14 Hawk hybrid pedestrian signal in the United States (photo from Ada County Highways Department)

An analysis of operational effects using VISSIM software undertaken in the US (Schroeder et al 2008) demonstrated that compared to zebra crossings, Hawk signals and staged crossings can significantly reduce vehicle delay once pedestrian volumes exceed a certain threshold. It was suggested that signalisation as a means of controlling 'pedestrian interference' to vehicular operations could be the appropriate philosophy to follow – which is apparently the general approach taken in the UK.

The Hawk has recently been incorporated in the latest revision of the Manual on Uniform Traffic Control Devices, which is referred to in the US (USDOT 2009b). It is currently being deliberated by the US Accessibility Board as to whether Hawk signals will be mandatory for all multi-lane roundabouts where pedestrian facilities are being provided. The Insurance Institute for Highway Safety is a US-based non-profit organisation funded by vehicle insurance firms, and has opposed such a requirement on the basis that it would increase vehicle crashes at roundabouts (primarily rear-end crashes) and would discourage installation of roundabouts because of the increased maintenance costs of signal hardware (Baranowski 2005).

Table 5.3 Symbols displayed by the US Hawk signalised crossing (adapted from an Ada County Highway Department brochure)

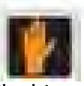
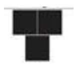
What drivers see	What pedestrians see
 Dark	 Push the button
 Flashing	
 Steady	
 Steady	 Start crossing
 Alternating (like a railway crossing). Stop, then go if clear	 Flashing Continue crossing
 Dark	

Figure 5.15 A Hawk signal at a two-lane entry to a roundabout in Michigan in the US

5.3.6.3 Puffin crossings

Puffin crossings, as used in the UK, are pedestrian signals with standard green, amber and red phases (no flashing periods); nearside pedestrian displays; and the ability to have pedestrian calls either cancelled or extended via video detection of pedestrians. This detection technology could feasibly be used in

New Zealand at either conventional pedestrian signals or Puffin crossings to reduce disruptions to traffic flow.

A study from the UK which compared mid-block Puffin with Pelican crossings found no observable difference in safety between the two (Walker et al 2005). However, mainly because pedestrian calls were, in practice, rarely cancelled at the Puffin sites, vehicle delays at the signals were shorter at the Pelican sites because drivers were able to move as soon as the flashing amber phase began. Reliable detection of pedestrians has been an issue with traffic engineers for some time, but recent research from the US using stereo camera detection has apparently made considerable progress in this field (Gibson et al 2009). The performance of Puffin crossings thus appears likely to improve in the future.

Puffin crossings have recently been trialled by Lower Hutt City Council in New Zealand (King 2010; see figure 5.16), although pedestrian detection equipment was not used to reduce pedestrian walk time. The nearside displays associated with Puffin crossings apparently improved pedestrian compliance by around 60% compared to the previous standard signal arrangement, and this was considered by Lower Hutt City Council to be a worthwhile improvement for the roughly $6,000 it cost to upgrade.

Figure 5.16 The nearside pedestrian displays that are a feature of the Puffin crossing recently trialled in Lower Hutt (King 2010)

5.3.7 Challenges for visually impaired and other disadvantaged pedestrians

5.3.7.1 Motivation for improvement

Non-signalised pedestrian facilities at busy roundabouts can often present difficulties to people who have difficulty judging gaps in the traffic stream, particularly visually impaired pedestrians and young children. For crossing points close to the roundabout, discerning whether a vehicle is exiting or continuing to circulate can present problems for visually impaired pedestrians, and, in general, these users will prefer signalised crossing points at busy multi-lane locations. Elderly pedestrians are also over-represented in crash statistics at the Auckland zebra crossing sites investigated in chapter 6.

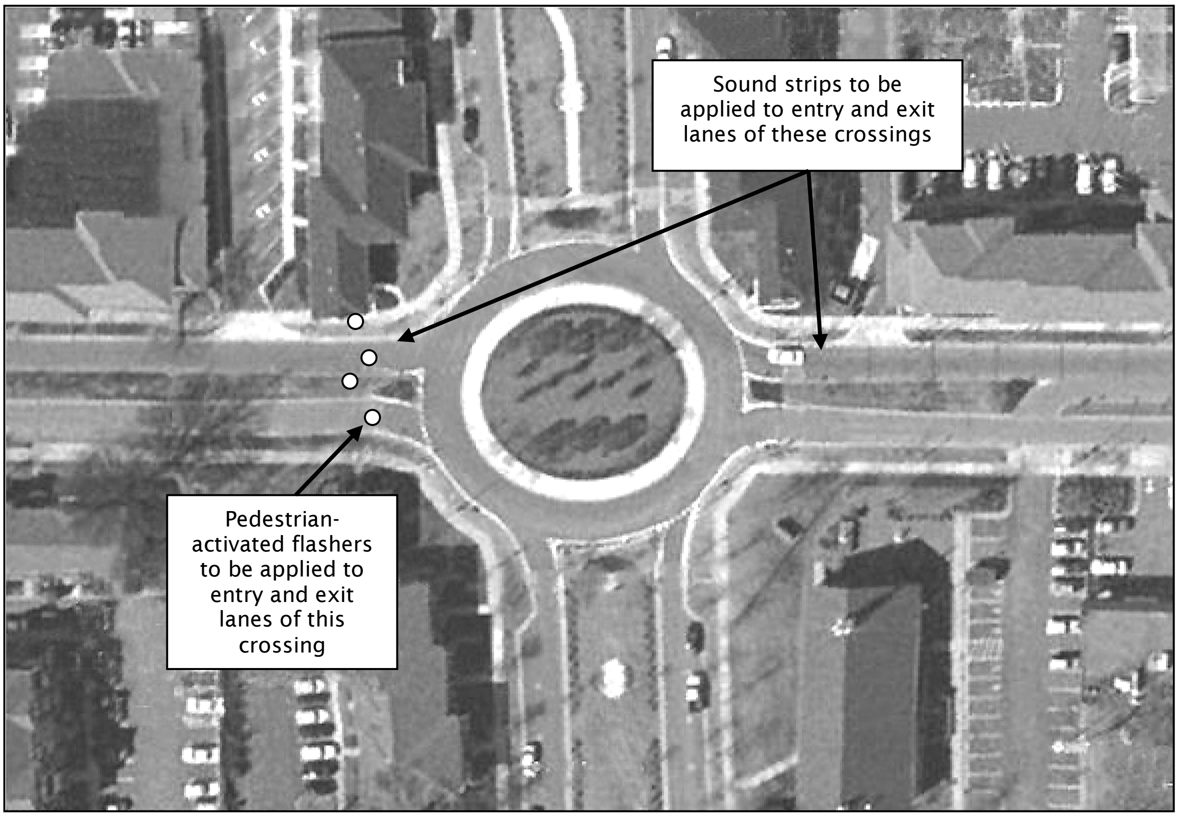
5.3.7.2 The United States

As a result of public lobbying, the subject of accessibility at roundabouts for visually impaired pedestrians has recently received some prominence in the US. Funding for researching this topic has therefore been readily available.

The United States Access Board is a federal agency that develops accessibility guidelines. In 1999, this organisation established a committee to make recommendations on accessibility guidelines for public rights of way. A document entitled *Guidelines for accessible public rights-of-way* was in its draft stages at the time of writing, and its final recommendations may possibly require mandatory adherence. This has, in part, motivated a large research project from the National Cooperative Highways Research Program entitled *Crossing solutions at roundabouts and channelized turn lanes for pedestrians with vision disabilities* (2011), which includes evaluation of Hawk signals as discussed in section 5.3.6.

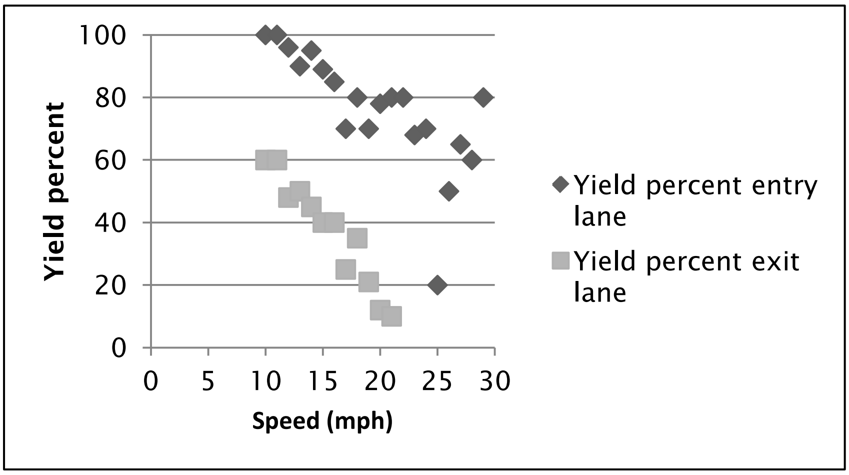
Another US study was undertaken to evaluate a system whereby visually impaired pedestrians might be able to detect vehicles stopping for them at priority crossing points at double-lane roundabouts (Inman et al 2006; see figure 5.17). The pavement treatment comprises of a series of sound strips (in practice, 3.8cm diameter polyvinyl chloride pipe was used) laid across the carriageway of a closed roadway course. The behaviour of seven visually impaired pedestrians was observed after this treatment was installed. Unfortunately, the number of false positive detections was problematic in the double-lane situation and, for this reason, was considered to be a reasonably insurmountable hurdle to the application of this treatment. However, the study did conclude that pavement treatments similar to that used in these studies could be effective at single-lane roundabouts.

Figure 5.17 Diagram showing sound strips applied at a single-lane roundabout in the US as part of a trial for assisting visually impaired pedestrians to detect if oncoming vehicles are stopping to let them cross the road (adapted from Inman et al 2006)



Another study undertaken by the Maryland School for the Blind (Geruschat and Hassan 2005; figure 5.18) found that driver yielding rates for zebra crossings at two multi-lane roundabouts were substantially related to vehicle speed, and also to whether or not the crossing was on the entry or exit side. Yield rates at roundabout entries were substantially higher for similar vehicle speeds on approach to the crossing point, but the difference was concluded to be that drivers will be decelerating on entry and accelerating for exits. Although this might not always correlate to pedestrian crash statistics at all roundabout exits (refer to chapter 6), for visually impaired users who are seeking a gap to cross in the traffic stream, this is clearly an important consideration.

Figure 5.18 The difference in driver yield rates for exit and entry arms of a roundabout (based on data from the Maryland School for the Blind Project (Geruschat and Hassan 2005))



5.3.7.3 New Zealand

Feedback on this subject was sought from the RNZFB and CCS. The current membership of the RNZFB is around 11,700, although from the 2006 Disability Survey (pers. comm. from Andrew McLaren, Statistics New Zealand, 17 February 2010), it has been estimated that around 71,000 people nationwide have a level of long-term vision impairment that at least requires glasses or contact lenses for reading (or around 1.8 % of the population).

Carina Duke, Practice Advisor and Instructor Adult Orientation and Mobility for the RNZFB, highlighted that the main difficulty at multi-lane roundabouts for visually impaired (and also for children and mobility impaired users) is identifying when it is safe to cross the road (pers. comm. July 2009). Roundabout designs where speed is not adequately reduced exacerbate these difficulties, as do locations with high traffic noise that hinder the ability of a person to identify a safe gap. Ms Duke considered that the majority of visually impaired persons would not be able to cross a busy roundabout safely for these reasons. Signalised crossings are therefore the preferred treatment for multi-lane situations near roundabouts, and consultation with Orientation and Mobility instructors is recommended as a mandatory measure for new intersection installations, particularly for intersections near shopping centres and on accessible routes to schools. Mention was also made of a particular roundabout crossing example in Christchurch (figure 5.19) where a red splitter island had been installed between two approach lanes, which effectively requires the pedestrian to cross two separate single-lane roadways rather than one double-lane roadway, which would otherwise be the case. However, Ms Duke comments that visually impaired users still find it difficult to listen for a sufficient gap to cross (because of the proximity of the roundabout and the associated traffic noise), and also find it impossible to differentiate which lane an oncoming vehicle is in.

Figure 5.19 Harewood Road eastbound approach to a double-lane roundabout at its intersection with Highsted Road in Christchurch.

Mike Hamill from CCS Disability Action (Southland branch) made the following comments (pers. comm. July 2009):

- Zebra crossings such as at roundabouts are preferable for mobility impaired users compared to signalised intersections. At signals, the main safety concern is that crossing times are usually shorter than necessary for mobility impaired users to clear the road before the green traffic phase begins. Left-turning drivers in particular can become agitated when mobility impaired users do not clear the intersection in time before the vehicle green phase begins.
- The higher speeds of vehicles as they are exiting a roundabout can be of particular concern for multi-lane situations, which take longer for mobility impaired users to clear.
- Support is offered for speed bump treatments to slow vehicle speeds, and also for separating pedestrian facilities from roundabouts by a distance of at least 50m.
- In general, CCS supports roundabouts, provided vehicle speeds are low enough to enable safe passage for mobility impaired users.

Cecilia De Souza, also from CCS Disability Action, made several further comments (pers. comm. July 2009):

- In general, large urban roundabouts can present a significant barrier to mobility impaired and elderly pedestrians.
- When pedestrian crossing points (including zebra crossings) are located very close to roundabout exits, this can be problematic, as drivers are less likely to see pedestrians step onto the road. For this reason, it is suggested that crossing points be located further from the roundabout where possible.
- Central islands should be installed at grade to allow for quick exit from the road (for wheelchair and mobility scooter users), and pram crossings also need to be satisfactory for this purpose.

6 Safety performance of some pedestrian facilities at multi-lane roundabouts in Auckland

6.1 Summary

As a means of assessing the safety performance of pedestrian facilities at multi-lane roundabouts in New Zealand, crash histories were reviewed at 11 busy arterial road junctions in Auckland and Waitakere City. Pedestrian and rear-end crashes associated with pedestrian crossing facilities were evaluated, and several sites were chosen for closer evaluation via video observation of pedestrian and driver behaviour[4].

In summary, it was identified that multi-lane zebra crossings can potentially present the most safety problems for pedestrians, but are only of some significance if situated where vehicle speeds are higher, ie at locations greater than 20m from the roundabout (assuming the geometry at the roundabout effectively reduces vehicle speeds). Engineering improvements where problems are occurring can include the active warning devices discussed in section 5.3.4, pedestrian signals or raised speed platforms (which are evaluated in some detail in chapter 7). Zebra crossings closer than 20m to the roundabout are much less likely to experience pedestrian safety problems, but good speed control at the roundabout is still important.

6.2 Introduction

Tables and diagrams showing the reported pedestrian crashes for the 10-year period 1999–2008 and rear-end crashes associated with pedestrian crossings (zebra or signalised) for 2004–2008 are shown for each of the 11 selected roundabout locations. These are generally the two types of crashes that are associated with pedestrian facilities. Traffic crash reports were reviewed to confirm crash circumstances. Potential aggravating factors for crashes have been identified for some sites.

A summary of potential improvement measures is also given in most cases, and video observation of pedestrian and driver behaviour was undertaken for several sites.

4 Dr Samuel Charlton, Associate Professor, Psychology, Traffic and Road Safety Research Group, Waikato University, was engaged for comment on the research presented in this chapter, as he has considerable experience in the field of human factors with regard to road projects and is an acknowledged expert in the field of traffic studies. His comments relating to the zebra crossings in particular are presented in appendix E.

6.3 Site 1: Alderman Drive–Sel Peacock Drive, Waitakere

6.3.1 Crash history at site 1

Figure 6.1 Aerial view of Alderman Drive–Sel Peacock Drive, showing crash locations

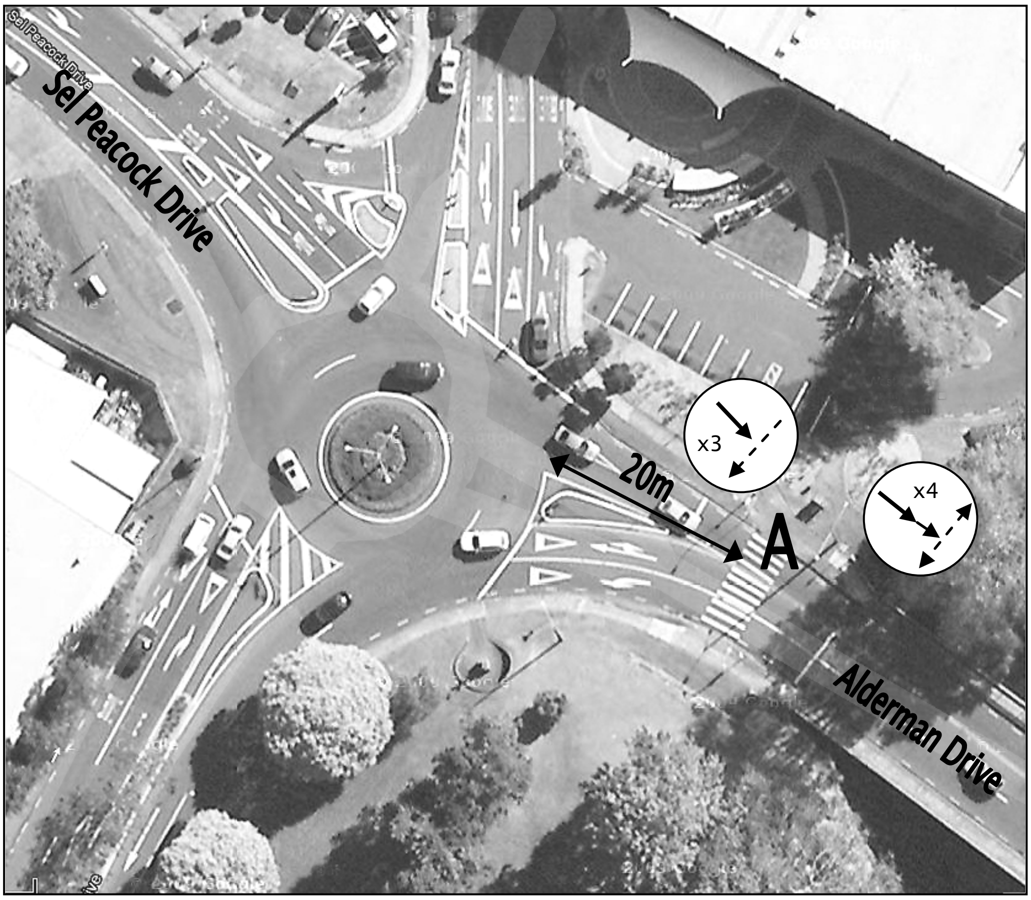


Table 6.1 Pedestrian and rear-end crash history for the Alderman Drive–Sel Peacock Drive intersection in Waitakere.

Crash number	Location	Type[a]	Injury level	Time of accident	Other details
2436948	A	Rear-end	Non-injury	1630h	–
2703353	A	Rear-end	Minor injury	1420h	Raining
2746317	A	Rear-end	Non-injury	1701h	–
2835780	A	Rear-end	Non-injury	0900h	–
2503000	A	Pedestrian	Serious injury	–	Raining; pedestrian aged 40(?) years
2735284	A	Cyclist[b]	Non-injury	1630h	Raining; cyclist was a child
2806342	A	Pedestrian	Minor injury	0648h	Pedestrian aged 40 years

Notes to table 6.1:

a Pedestrian crashes occurred in 1999–2008; rear-end crashes in 2004–2008.

b This cycle crash was classed in CAS as a pedestrian crash, as the cyclist was using the crossing.

The single-lane exit on the eastbound Alderman Drive arm of the roundabout site has a history of pedestrian and rear-end crashes (table 6.1) associated with the zebra crossing, which is approximately 20m from the roundabout (figure 6.1). The dual-lane zebra crossing on the approach side of this same arm had no reported crashes. According to Waitakere City Council, some local residents have historically reported that near-miss incidents involving pedestrians occur regularly at this crossing.

The principal potential aggravating factor for crashes at this location is that the eastbound Alderman Drive leg has virtually no vehicle deflection coming from Sel Peacock Drive (ie vehicle approach speeds to the crossing can be expected to be higher), and the crash history at the zebra crossing might be partly attributable to this.

6.3.2 Video observation of the zebra crossing on Alderman Drive

Two hours of video observation of the zebra crossing was undertaken during a weekday off-peak period during fine weather in September 2009 (figure 6.2). The only observation of note was that virtually all pedestrians crossing from the south side (24 out of 25) had exiting drivers from the roundabout stopping for them when they were still on the other side of the road. Only one pedestrian had a vehicle exiting the roundabout drive past them whilst they were on the crossing, which is captured in figure 6.2. No pedestrian–vehicle conflicts or near-conflicts were observed.

Figure 6.2 Photo showing the full width of the zebra crossing on the Alderman Drive arm of the roundabout. This shows the only time a vehicle was observed driving past when a pedestrian coming from the south side was on the crossing

6.3.3 Potential improvements

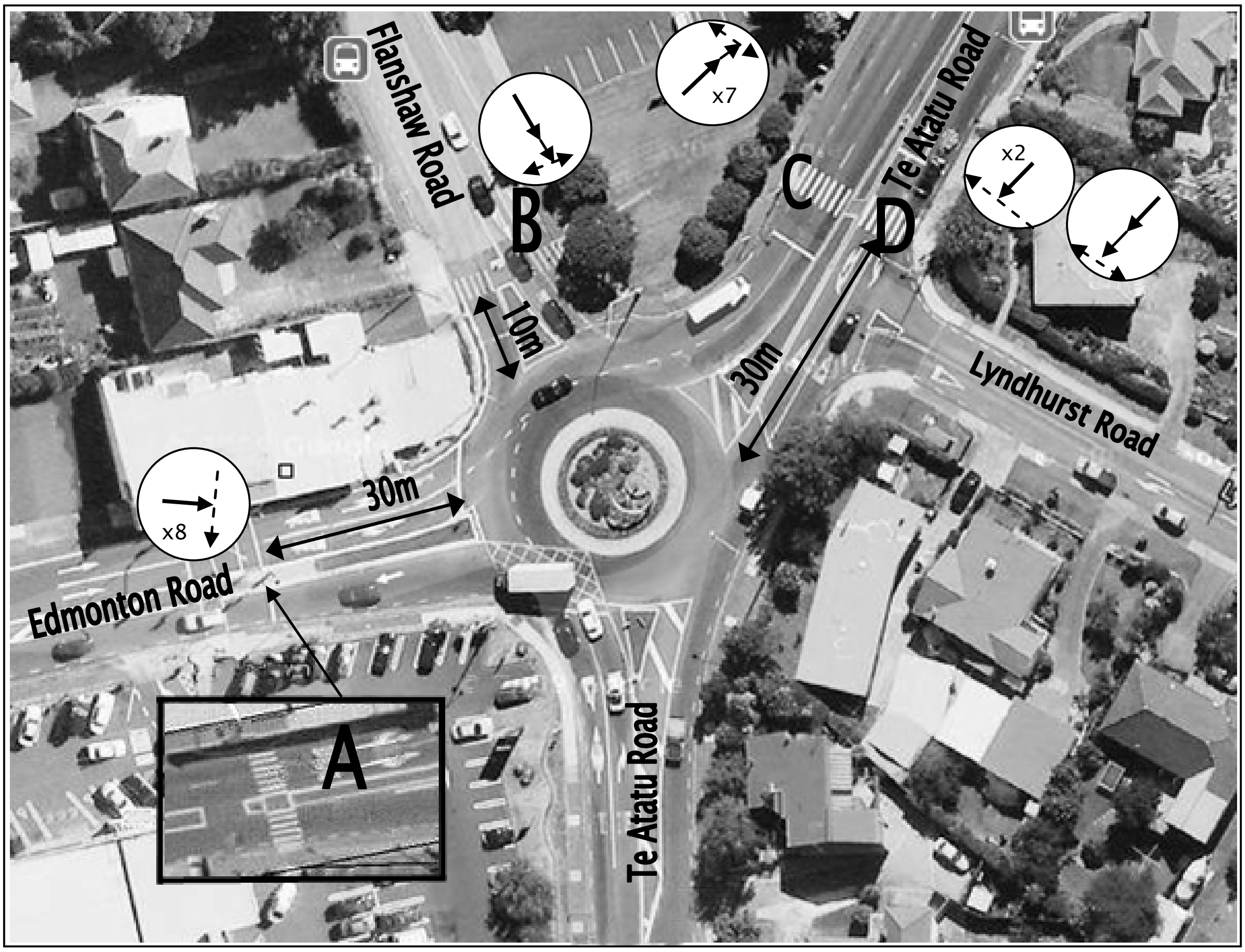
In order to address the pedestrian and rear-end crash patterns identified at the zebra crossing on Alderman Drive, the following measures are deemed worthy of consideration, either separately or in combination:

- relocating the zebra crossing closer to the roundabout
- installing a speed platform at the zebra crossing point
- installing flashing road studs or flashing signs at the crossing
- redesigning the roundabout so that the through-vehicles from the Sel Peacock Drive approach have improved deflection before exiting at the zebra crossing on Alderman Drive.

6.4 Site 2: Te Atatu Road–Edmonton Road, Waitakere

6.4.1 Crash history at site 2

Figure 6.3 Aerial view (2011) of Te Atatu Road–Edmonton Road, showing crash locations (insert shows the pedestrian crossing prior to the staggered pedestrian signals being installed in 2005)



All crashes at location A took place prior to 2005 when the new layout was installed.

Table 6.2 Pedestrian and rear-end crash history for the Te Atatu Road–Edmonton Road intersection in Waitakere

Crash number	Location	Type[a]	Injury level	Time of accident	Other details
9901970	A	Pedestrian	Minor injury	1215h	Pedestrian aged 13 years; vehicle was overtaking a queue and the pedestrian was concealed
2002995	A	Pedestrian	Serious injury	1010h	Pedestrian aged 79 years
2040082	A	Pedestrian	Non-injury	2015h	Night-time
2140320	A	Cyclist[b]	Non-injury	1310h	–
2239319	A	Pedestrian	Minor injury	1600h	Vehicle was overtaking a queue and the pedestrian was concealed
2303388	A	Pedestrian	Minor injury	1030h	Pedestrian aged 65 years; vehicle was overtaking a queue and the pedestrian was concealed
2401494	A	Pedestrian	Minor injury	0815h	Pedestrian aged 11 years; vehicle was overtaking a queue and the pedestrian was concealed
25456052	B	Rear-end	Non-injury	1645h	–
2443029	C	Rear-end	Non-injury	1520h	–
2503427	C	Rear-end	Minor injury	1630h	Raining
2503477	C	Rear-end	Minor injury	0740h	Raining
2836100	C	Rear-end	Non-injury	0818h	–
2732627	C	Rear-end	Non-injury	1530h	–
2837522	C	Rear-end	Non-injury	0940h	–
2840583	C	Rear-end	Non-injury	1853h	–
2003321	D	Pedestrian	Minor injury	1510h	Pedestrian aged 5 years; vehicle was overtaking a queue and the pedestrian was concealed
2302776	D	Pedestrian	Minor injury	0702h	Pedestrian aged 64 years

Notes to table 6.2:

a Pedestrian crashes occurred in 1999–2008; rear-end crashes in 2004–2008.

b This cycle crash was classed as a pedestrian crash as the cyclist was using the crossing.

The dual-lane entry on the eastbound approach of Edmonton Road (location A) had a substantial pedestrian crash history associated with the zebra crossing (table 6.2), until a staggered signalised crossing was installed in 2005 (see inset in figure 6.3) and no incidents have been reported since.

The majority of these pedestrian crashes involved drivers overtaking stopped vehicles on the kerbside lane. The crossings are 30m from the roundabout, meaning that vehicle speeds could still be expected to be reasonably high, which would have exacerbated injury severity. Since the signals were installed, no further pedestrian crashes have been reported.

The dual-lane zebra crossing on the Te Atatu Road southbound approach (location D) also experienced two reported pedestrian crashes, one of these during queued periods, as stated in table 6.2.

The 30m distance from the roundabout may be a factor in these crashes, as this is a location where vehicle speeds can be higher.

The dual-lane exit on the Te Atatu Road northbound approach (location C) has experienced a significant crash history with regard to rear-end crashes, mostly occurring during peak hour periods. Speed control from the Edmonton Road approach is minimal, which could be a factor in this rear-end crash pattern.

The Flanshaw Road zebra crossing (location B) experienced one reported rear-end collision, but traffic flow on this road is relatively minor compared to Edmonton Road and Te Atatu Road.

6.4.2 Video observation of the signalised crossing on Edmonton Road

This location was videoed for two hours on a fine weekday during the off-peak period in October 2009 (see figure 6.4), and a total of 70 pedestrians were observed crossing Edmonton Road in the vicinity of the signalised crossing point. Forty-four pedestrians used the signals to cross either the full width or one stage of the crossing, with 37 using it to cross the two stages (52% of total pedestrians). Eighteen pedestrians (26%) did not use the signals at all to cross, and 33 (47%) crossed the road for one stage or more without using the signals. No pedestrian–vehicle conflicts or near-conflicts were observed.

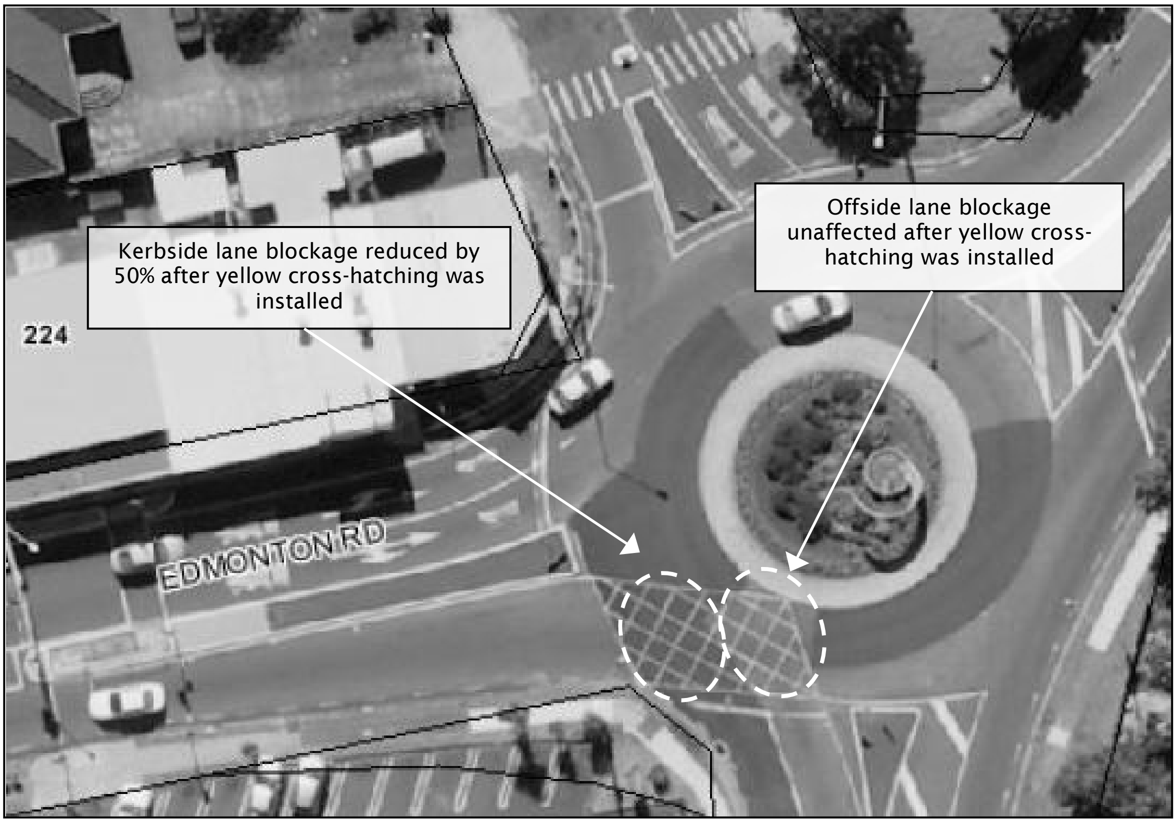
This location has just a single-lane crossing for the westbound direction, and many pedestrians crossed this stage without using the push-button. The total crossing time is not much over 30 seconds for those who choose to use the signals, comprising approximately 20 seconds total waiting time for both staged crossings combined, the remainder being walking time. In figure 6.4, the pedestrians standing on the staggered island had been waiting around 10 seconds before the crossing phase was called up for them to walk across to the shops on the far side. These relatively short waiting times mean that people appear to be much more inclined to use the signals compared to those installed at site 4. According to the Auckland TMU, this location has been configured with these lower pedestrian wait times for at least two years.

Figure 6.4 View of the signalised crossing facility across Edmonton Road

6.4.3 Yellow cross hatching on circulating lanes

In 2006, yellow cross-hatching was installed on the roundabout to address the issue of vehicle queues extending into the roundabout from the pedestrian signals and disrupting traffic flow during evening peak periods (see figure 6.5). Waitakere City Council engaged a consultant to evaluate their effect, and found that the markings appeared to be effective in substantially reducing the proportion of time the kerbside lane was blocked from 18 minutes to 9 minutes over a seven-hour period. The offside lane was not significantly affected and experienced around six minutes' blockage over the same duration before and after the cross-hatching was installed.

Figure 6.5 Aerial photo showing the area of yellow cross-hatching used at the Edmonton Road–Te Atatu Road roundabout to address queuing that can occur when the pedestrian signals are activated on Edmonton Road



6.4.4 Potential improvements

In order to address the pedestrian and vehicle rear-end crash patterns identified at the zebra crossing on Te Atatu Road (location C), the following measures are deemed worthy of consideration, either alone or in combination:

- relocating the zebra crossing closer to the roundabout
- installing a speed platform at the zebra crossing point
- installing flashing road studs or flashing signs at the crossing
- redesigning the roundabout so that vehicles from Edmonton Road have improved deflection before exiting at the zebra crossing on Te Atatu Road

- installing high-friction surfacing on the exit approach to the zebra crossing to address the rear-end crashes.

Although the Edmonton Road signalised crossing is working safely enough, in the interest of improving roundabout vehicular operations in peak periods, it is considered that converting the departure side to a zebra crossing may be beneficial. A Hawk, Pelican or Puffin crossing would also give superior performance on the basis of reducing vehicle delays and thus queuing into the roundabout.

6.5 Site 3: Edsel Street–Vitasovich Avenue, Waitakere

6.5.1 Crash history at site 3

Table 6.3 Pedestrian and rear-end crash history for the Edsel Street–Vitasovich Avenue intersection in Waitakere

Crash number	Location	Type[a]	Injury level	Time of accident	Other details
2636972	A	Pedestrian	Non-injury	0830h	–
2705634	A	Rear-end	Minor injury	1650h	–
2104545	B	Pedestrian	Minor injury	1345h	Pedestrian aged 44 years; vehicle was overtaking a queue and the pedestrian was concealed; raining
270134	C	Pedestrian	Minor injury	1100h	Pedestrian aged 73 years
2140316	D	Pedestrian	Non-injury	1310h	–

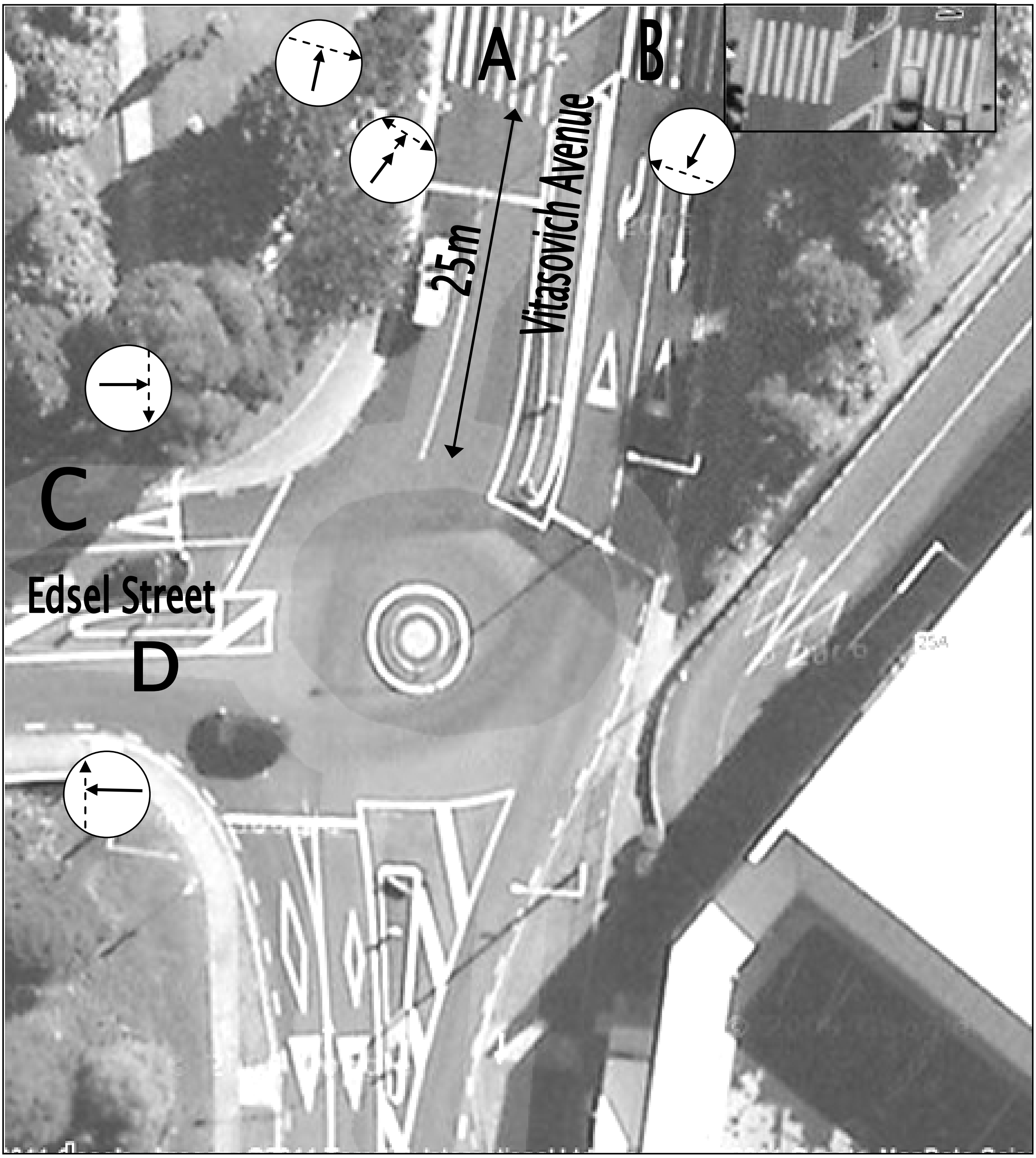
Note to table 6.3:

a Pedestrian crashes occurred in 1999–2008; rear-end crashes in 2004–2008.

The zebra crossing on the north arm of Vitasovich Avenue 25m from the roundabout has dual lanes in both directions. The entry side (location A in figure 6.6) had one reported pedestrian crash, which involved one vehicle overtaking another on the kerbside lane. The dual-lane exit (location B) has one pedestrian crash and one rear-end crash associated with it (table 6.3). As at site 2, the distance of the crossings from the roundabout limit line means that vehicle speeds on the approach to the roundabout might be reasonably high and could exacerbate the severity of any crashes that do occur.

In addition, two reported pedestrian crashes occurred on the Edsel Street arm (locations C and D) where no pedestrian facilities are provided.

Figure 6.6 Aerial view of Edsel Street–Vitasovich Avenue, showing crash locations (inset shows pedestrian crossing layout during the study period)



6.5.2 Potential improvements

Although no significant crash pattern is apparent at the zebra crossing on Vitasovich Avenue, the following measures are deemed worthy of consideration:

- relocating the zebra crossing closer to the roundabout
- installing a speed platform at the zebra crossing point.

6.6 Site 4:Te Atatu Road–Great North Road, Waitakere

6.6.1 Crash history at site 4

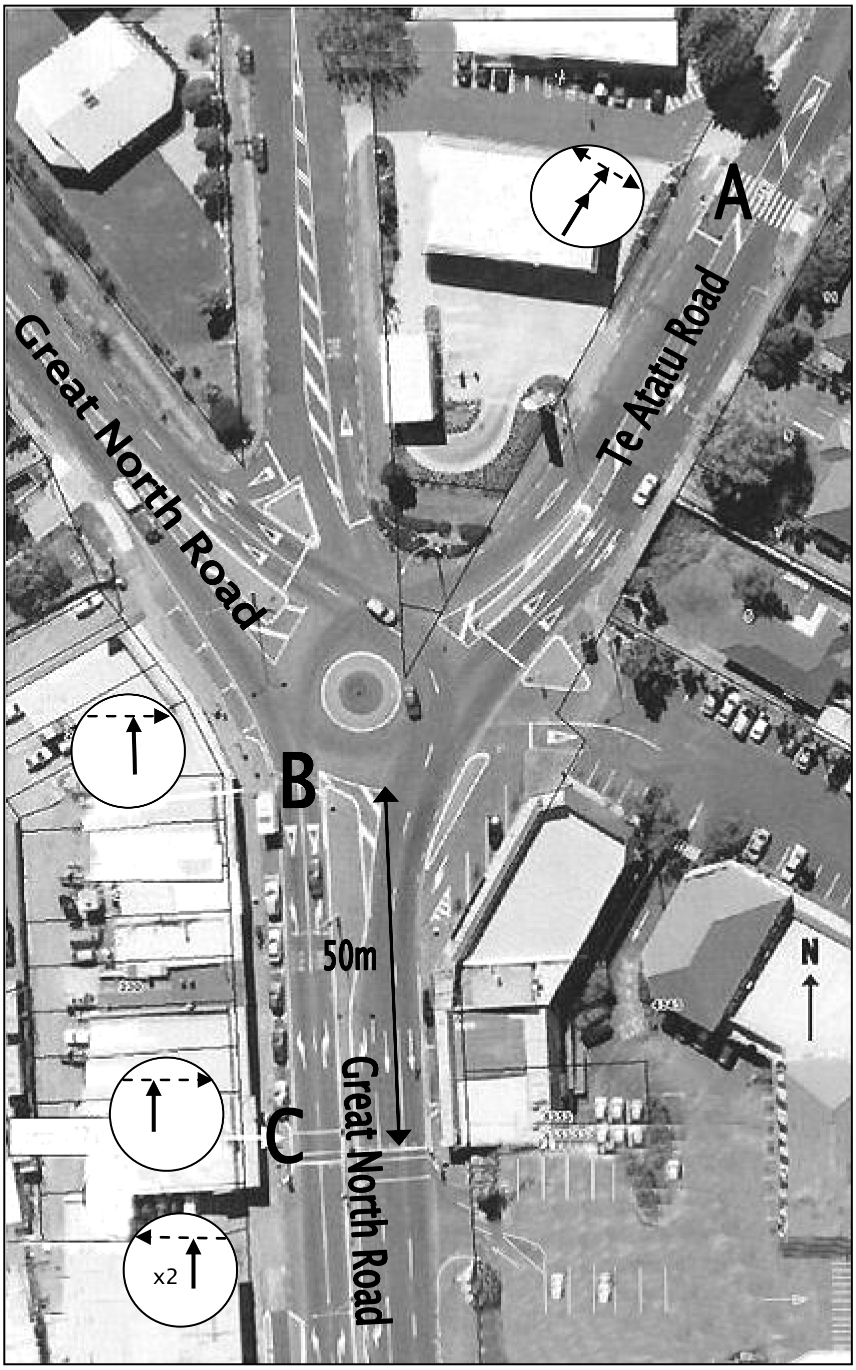
Table 6.4 Pedestrian and rear-end crash history for the Te Atatu Road–Great North Road intersection in Waitakere

Crash number	Location	Type[a]	Injury level	Time of accident	Other details
2501251	A	Rear-end	Minor injury	1459h	–
2244431	B	Pedestrian	Non-injury	0820	–
2132997	C	Pedestrian	Non-injury	1400h	Vehicle was overtaking a queue and the pedestrian was concealed
2204928	C	Pedestrian	Minor injury	1235h	Pedestrian aged 2 years
2405626	C	Pedestrian	Minor injury	1400h	–

Note to table 6.4:

a Pedestrian crashes occurred in 1999–2008; rear-end crashes in 2004–2008.

Figure 6.7 Aerial view of Te Atatu Road–Great North Road, showing crash locations



The dual-lane staggered pedestrian signals on Great North Road 50m to the south of the roundabout (location C) had three reported pedestrian crashes on the northbound approach (table 6.4). Two of these pedestrian crashes involved red light running. Overhead displays facing both approaches to the crossing were installed in 2008 for improved visibility of the signal heads, which are expected to improve the situation.

The single-lane zebra crossing on Te Atatu Road (location A) 70m to the north of the roundabout experienced one rear-end crash.

In addition, one non-injury incident involved a pedestrian attempting to cross the Great North Road south arm where no pedestrian facility is provided (location B).

6.6.2 Video observation of the signalised crossing on Great North Road

This location was videoed for two hours on a weekday off-peak period in October 2009 (see figure 6.8), and 77 pedestrians were observed crossing Great North Road in the vicinity of the signalised crossing point. Thirty-four pedestrians used the signals to cross either the full width or one stage of the crossing, with only 18 using it to cross the two stages (23% of total pedestrians). Twenty-nine pedestrians (38%) did not use the signals at all to cross, and 45 (58%) crossed the road for one stage or more without using the signals. No pedestrian–vehicle conflicts or near-conflicts were observed.

The substantial proportion of pedestrians crossing heedless of the pedestrian phase is probably because of the signal timing arrangement. Pedestrians wishing to use the staggered signals arrangement have a crossing time of around two minutes from first pressing the push-button to stepping off the kerb at the other side, comprising around one minute's wait from the first call-up to the pedestrian phase when crossing the first stage, 30 seconds' wait upon pressing the button on the central island for the second stage, and the remainder being walking time. Over the two-hour observation period, 10 false call-ups for the pedestrian phase were triggered by pedestrians that crossed before the pedestrian crossing phase was called up. Although the pedestrian wait times here are most probably set up to minimise delays to Great North Road traffic (ie to give more time to accumulate pedestrians on the footpath before crossing phases are called up), it is a compromise to pedestrian convenience and, consequently, a potentially adverse impact on pedestrian safety.

Figure 6.8 This photo at the Great North Road signalised crossing shows that while some pedestrians are prepared to wait up to a minute before the pedestrian cross phase is brought up, others are not so patient

6.6.3 Proposed improvements

Although no significant crash pattern involving jaywalking pedestrians is apparent at the signalised crossing on Te Atatu Road, pedestrian wait times should be reviewed. Reducing wait times is expected to improve pedestrian safety and amenity, and should have minimal adverse effects on traffic flow during off-peak periods especially. In February 2010, the Auckland TMU was requested by Waitakere City Council to improve the performance of this crossing.

6.7 Site 5: Alderman Drive–Edmonton Road, Waitakere

6.7.1 Crash history at site 5

Figure 6.9 Aerial view of Alderman Drive–Edmonton Road, showing crash locations

Table 6.5 Pedestrian and rear-end crash history for the Alderman Drive–Edmonton Road intersection in Waitakere

Crash number	Location	Type[a]	Injury level	Time of accident	Other details
2102077	A	Pedestrian	Minor injury	0650h	Pedestrian aged 40 years; vehicle was overtaking a queue and the pedestrian was concealed
2305706	A	Pedestrian	Minor injury	1210h	Pedestrian aged 11 years
2704551	A	Pedestrian	Minor injury	1600h	–

Note to table 6.5:

a Pedestrian crashes occurred in 1999–2008; rear-end crashes in 2004–2008.

The zebra crossing on the Edmonton Road arm (location A in figure 6.9) has dual lanes in both directions and is approximately 20m from the roundabout. The exit side has had three reported pedestrian crashes (table 6.5), one which involved one vehicle passing another in queued conditions.

The zebra crossing on the Alderman Drive arm experienced no reported crashes.

6.7.2 Video observation of the zebra crossing on Edmonton Road

During two hours of video observation undertaken during a weekday from approximately 9:00am to 11:00am, 4 (24%) out of the observed 17 pedestrians crossing from the south side had exiting vehicles from the roundabout drive through while they were stepping out onto the zebra crossing from the central island (figure 6.10). This demonstrates a similar circumstance to one of the reported pedestrian injuries at this crossing in 2001, where a van in the nearside lane had stopped to let an 11-year-old girl walk across from the east side, who was then struck by a vehicle in the adjacent lane that had failed to see her crossing in time. The remaining 13 pedestrians during the video period had exiting vehicles stop for them prior to their reaching the crossing on that side. This observation highlights that drivers are likely to be accelerating once they have left the roundabout and might be less prepared to stop for pedestrians. No pedestrian–vehicle conflicts or near-conflicts were observed.

Figure 6.10 Photo at the Edmonton Road crossing, showing vehicles driving through while a pedestrian is using the crossing

6.7.3 Potential improvements

In order to address the pedestrian crash pattern identified at the zebra crossing on Edmonton Road, the following measures are deemed worthy of consideration, either alone or in combination:

- relocating the zebra crossing closer to the roundabout
- installing a speed platform at the zebra crossing point
- installing flashing road studs or flashing signs at the crossing
- redesigning the roundabout so that the right-turning vehicles from Edmonton Road (south) have improved deflection before exiting at the zebra crossing on Edmonton Road (north).

6.8 Site 6: Rankin Avenue–Clark Street, Waitakere

6.8.1 Crash history at site 6

Figure 6.11 Aerial view of Rankin Avenue–Clark Street, showing crash locations

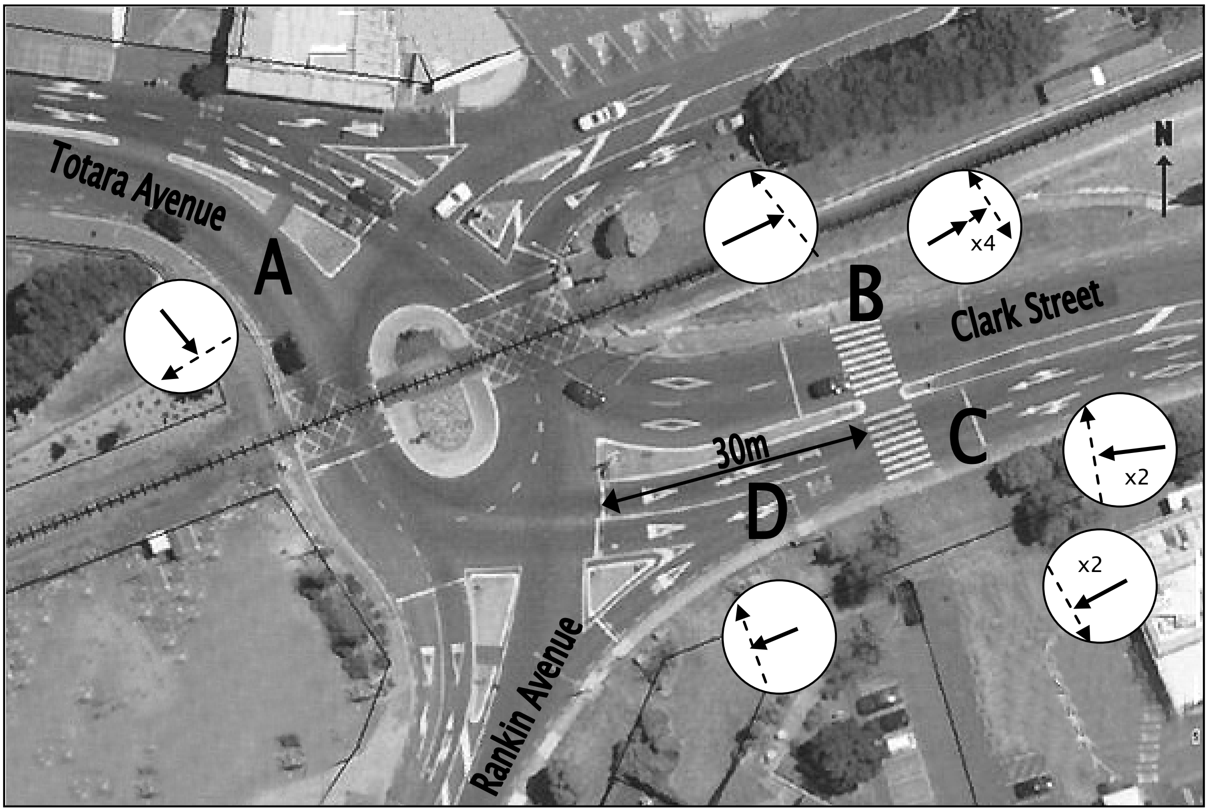


Table 6.6 Pedestrian and rear-end crash history for the Rankin Avenue–Clark Street intersection in Waitakere

Crash number	Location	Type[a]	Injury level	Time of accident	Other details
2504500	A	Pedestrian	Minor injury	1731h	Raining; pedestrian aged 37 years
2804927	B	Pedestrian	Minor injury	1040h	Raining; pedestrian aged 66 years
240454	B	Rear-end	Minor injury	1245h	–
244404	B	Rear-end	Non-injury	2240	Night-time
2635030	B	Rear-end	Non-injury	0700h	Raining
2639744	B	Rear-end	Non-injury	1600h	–
2201652	C	Pedestrian	Serious injury	1600h	Raining; pedestrian aged 23 years
2301614	C	Pedestrian	Minor injury	0855h	Pedestrian aged 66 years
9902842	C	Pedestrian	Minor injury	1445	Pedestrian aged 9 years; vehicle was overtaking a queue and the pedestrian was concealed

Crash number	Location	Type[a]	Injury level	Time of accident	Other details
2004305	C	Cyclist[b]	Minor injury	1240h	Cyclist aged 15 years; vehicle was overtaking a queue and the pedestrian was concealed
2002628	D	Pedestrian	Minor injury	?	Pedestrian aged 26 years

Notes to table 6.6:

a Pedestrian crashes occurred in 1999–2008; rear-end crashes in 2004–2008.

b This cycle crash was classed as a pedestrian crash, as the cyclist was using the crossing.

The zebra crossing on the Clark Street arm had, until recently, dual lanes in both directions (in September 2009, the roundabout was replaced with traffic signals and the zebra crossing was subsequently removed). The exit side (location B) experienced one pedestrian crash and four rear-end crashes (table 6.6). The entry side (location C) experienced four pedestrian crashes, two involving one vehicle passing another during queued conditions. As at site 2, the distance of the Clark Street crossing from the roundabout (approximately 30m) meant that vehicle speeds could be expected to still be reasonably high, which would exacerbate the severity of any crashes that occur.

In addition, two reported pedestrian crashes occurred on the Totara Avenue and Clark Street arms (locations A and D respectively) where no pedestrian facilities are provided.

6.8.2 Potential improvements

In order to address the pedestrian and rear-end crash patterns identified at the zebra crossing on Clark Street, the following measures are deemed worthy of consideration, either alone or in combination:

- relocating the zebra crossing closer to the roundabout
- installing a speed platform at the zebra crossing point
- installing flashing road studs or flashing signs at the crossing
- install high-friction surfacing on the exit approach to the zebra crossing to address rear-end crashes.

6.9 Site 7: Manukau Road–Mt Albert Road, Auckland City

6.9.1 Crash history at site 7

Table 6.7 Pedestrian and rear-end crash history for the Manukau Road–Mt Albert Road intersection in Auckland

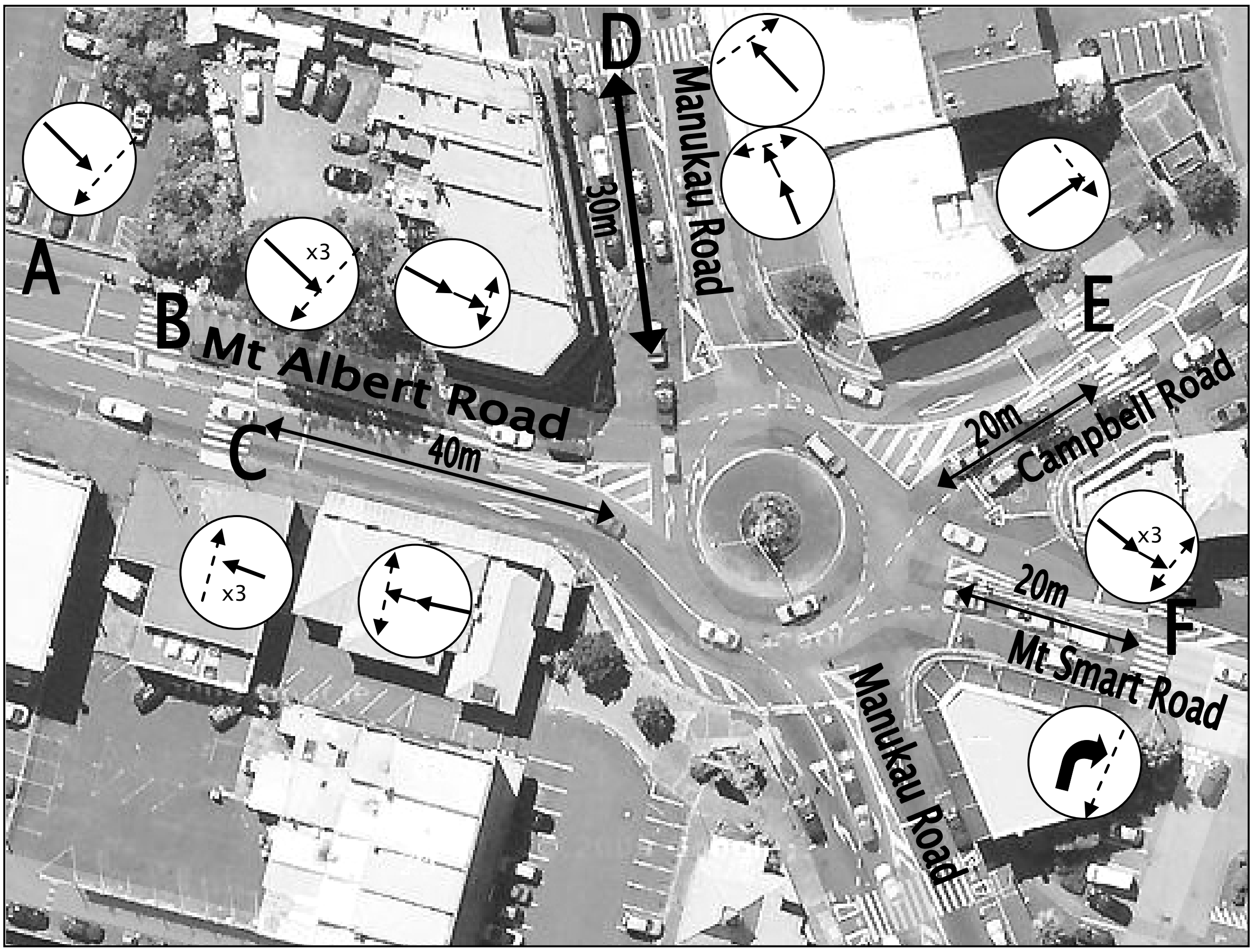
Crash number	Location	Type[a]	Injury level	Time of accident	Other details
2401143	A	Pedestrian	Minor injury	1630h	Raining; pedestrian aged 35 years
9943397	B	Pedestrian	Minor injury	1530h	Vehicle was overtaking a queue and the pedestrian was concealed
2104900	B	Pedestrian	Minor injury	?	Pedestrian aged 62 years; vehicle was overtaking a queue and the pedestrian was concealed
2500147	B	Pedestrian	Fatal	0900h	Pedestrian aged 91 years; vehicle was overtaking a queue and the pedestrian was concealed
2840558	B	Rear-end	Non-injury	0645h	Raining
2002655	C	Pedestrian	Minor injury	1130h	Pedestrian aged 20 years, vehicle was overtaking a queue and the pedestrian was concealed
2204281	C	Pedestrian	Minor injury	1530h	Pedestrian aged 29 years; vehicle was overtaking a queue and the pedestrian was concealed; raining
2801639	C	Pedestrian	Minor injury	1610h	Pedestrian aged 40 years; vehicle was overtaking a queue and the pedestrian was concealed
2103937	D	Pedestrian	Minor injury	1830h	Night-time; raining; pedestrian aged 71 years
2732918	D	Rear-end	Non-injury	1400h	–
2205448	E	Cyclist[b]	Minor injury	1710h	Cyclist aged 11 years
2542797	F	Rear-end	Non-injury	0800h	–
2646175	F	Rear-end	Non-injury	0945h	–
2739303	F	Rear-end	Non-injury	0807h	–
2204282	F	Pedestrian	Serious injury	1730h	Pedestrian aged 11 years; raining

Notes to table 6.7:

a Pedestrian crashes occurred in 1999–2008; rear-end crashes in 2004–2008.

b This cycle crash was classed as a pedestrian crash, as the cyclist was using the crossing.

Figure 6.12 Aerial view of Manukau Road–Mt Albert Road, showing crash locations



The zebra crossing on Mt Albert Road (dual lanes in both directions) has a substantial pedestrian crash history. The entry side (location B) has experienced three reported pedestrian crashes and a rear-end crash, and the exit side (location C) has experienced three pedestrian crashes and a rear-end crash (table 6.7). All of these pedestrian crashes involved vehicles passing others during queued conditions. The island layout for this crossing was changed from a straight-through to a staggered arrangement in 2000, and although this reduced the pedestrian crash rate somewhat, it did not seem to be adequately addressing the crashes occurring there. In February 2007, a flashing road stud arrangement was installed, whereby these studs are illuminated upon smart-pad detection of pedestrians waiting to cross the road (refer to section 5.3.4). Since then, one reported pedestrian injury and one rear-end crash have been associated with this crossing point, both occurring in 2008.

All of the pedestrian crashes at this crossing point involved a vehicle overtaking another already stopped on the kerbside lane. As at site 2, the crossing's distance from the roundabout limit line (approximately 40m) means that vehicle speeds can be expected to be reasonably high, which can exacerbate the severity of any crashes that occur.

The zebra crossing on Mt Smart Road (location F) has experienced three reported rear-end crashes at the single-lane exit, but no crashes on the dual lane entry. One serious injury pedestrian crash was recorded close to but not actually on the zebra crossing.

The zebra crossing on Campbell Road (location E) has experienced just one reported 'pedestrian' crash on the single-lane exit (actually a cyclist) but no crashes on the dual lane entry.

6.9.2 Staggered island layout installed on Mt Albert Road

Prior to 2000, the zebra crossing on Mt Albert Road was a straight-through island arrangement. For the six years prior (1994–1999), 11 reported pedestrian injury crashes had occurred, six involving serious injury and the remaining five incurring minor injury. For the next six years (2001–2006) until the flashing road studs were installed in 2007, four pedestrian injuries occurred (one fatality and three minor injury). Thus although it appears that the staggered island layout was a significant improvement, it still did not adequately address the safety problem of pedestrians crossing through stopped queues of traffic at this location.

Staggered crossing islands are also discussed further in section 6.15.2.

6.9.3 Video observation of the zebra crossing on Mt Albert Road

During the three hours of video recording during a weekday off-peak period, 32 (22%) out of 145 vehicles exiting the roundabout when a pedestrian was present stopped to let them cross while the pedestrian was still crossing from the opposite of the road and had not yet reached the traffic island. This compares to 42 out of 130 (32%) vehicles on the entry side of the roundabout. When pedestrians were walking on the staggered island, 61 out of 102 (60%) of drivers on the exit side and 65 out of 93 (70%) of drivers on the entry side stopped to let pedestrians cross. This would appear to indicate that drivers were more likely to yield early on the entry side of the roundabout compared to the exit, which concurs with findings from a US study (Geruschat and Hassan 2005).

Of the 272 pedestrians that used the islands during the observation period, 101 (37%) crossed during periods of potential conflict (either on the entry or exit side) where nearside vehicles had stopped at the zebra crossing limit line and restricted visibility to approaching vehicles in adjacent traffic lanes. This emphasises the need for additional measures to address such circumstances, particularly if vehicles speeds are higher and vehicle emergency stopping distances are greater (such as at locations further than around 20m from the roundabout).

It was observed that the road studs were often only activated a fraction of a second before pedestrians stepped out onto the zebra crossing, as a result of the pedestrian sensor pads being located immediately adjacent to kerb lines. It would be desirable if earlier detection could be achieved, although this would have been difficult at this particular site. A minority of pedestrians also cut across the smart-ped pads without triggering the road studs at all, so use of furniture on the footpath to guide people through the detection zone may also be beneficial.

Two pedestrian near-conflict situations were observed which, if either the pedestrian or driver had not taken evasive action, would have resulted in a collision (figures 6.13 and 6.14). In the first scenario (figure 6.13), a following vehicle (the light-coloured sedan) in the kerbside traffic lane decided to shift lanes after the vehicle ahead (the darker station-wagon) stopped to let two pedestrians cross. In this instance, the pedestrians were alert to the situation, and the vehicle managed to undertake an emergency stop before reaching the zebra crossing markings. The flashing road studs possibly contributed towards alerting the driver. In the second (figure 6.14), the pedestrian was not hidden by queued vehicles, but the kerbside vehicle (the light grey station-wagon) was approaching at speed and only just managed to perform an emergency stop prior to the pedestrian stepping out onto the zebra crossing. Again, it is possible that the flashing road studs contributed towards alerting the driver. Figure 6.15 also shows a scenario that illustrates a potential safety issue, especially for younger pedestrians, at multi-lane crossing points such as these. Thirty-seven percent of pedestrians observed during the survey crossed in circumstances where stopped vehicles in the nearside lane would be restricting how visible they are to drivers in the adjacent traffic lane. As a pedestrian injury occurred in 2008, this would seem to indicate that although the flashing road studs have improved the situation since 2007 when they were installed, mid-block staggered pedestrian signals might still possibly be a safer solution at this particular crossing.

Figure 6.13 The first near-conflict incident at the Mt Albert Road zebra crossing

Figure 6.14 The second near-conflict incident at the Mt Albert Road zebra crossing

Figure 6.15 A recorded incident demonstrating the particular vulnerability of younger pedestrians, who are even more likely to be hidden from view by queued vehicles

6.9.4 Potential improvements

In order to further improve pedestrian and driver safety at the zebra crossing on Mt Albert Road, the flashing road studs should be replaced as soon as practicable with newer brighter LEDs, which should be more visible in sunny conditions.

If pedestrian injuries continue to occur in the future, the following measures could be considered, singly or in combination:

- replacing the zebra crossing with staggered pedestrian signals
- relocating the zebra crossing closer to the roundabout
- installing a speed platform at the zebra crossing point.

6.10 Site 8: St Jude Street–Great North Road

6.10.1 Crash history at site 8

Figure 6.16 Aerial view of St Jude Street–Great North Road, showing crash locations (inset shows the straight-across arrangement in place until 2004)

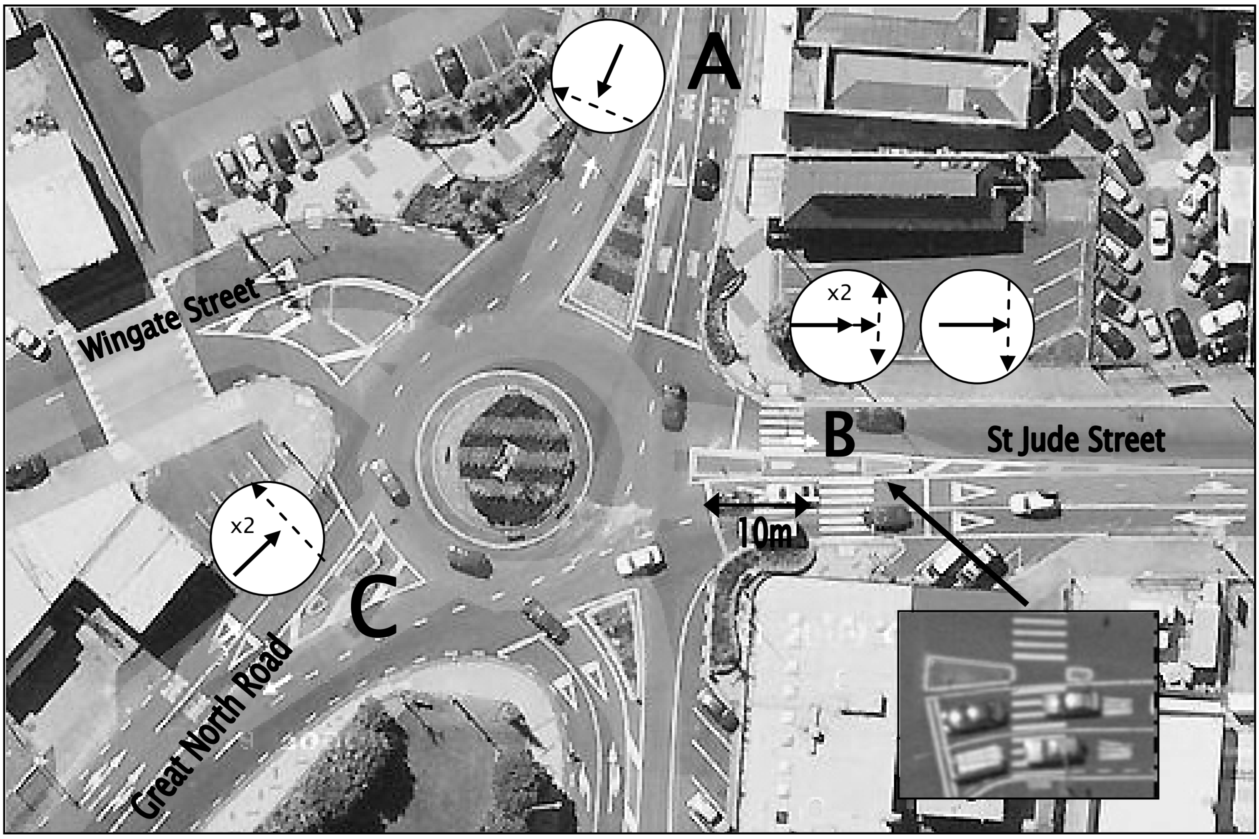


Table 6.8 Pedestrian and rear-end crash history for the St Jude Street–Great North Road intersection in Auckland City

Crash number	Location	Type[a]	Injury level	Time of accident	Other details
25058603	A	Pedestrian	Minor injury	1920h	Pedestrian aged 6 years
2542463	B	Rear-end	Non-injury	1000h	–
2738455	B	Rear-end	Non-injury	1025h	–
2342513	B	Pedestrian	Minor injury	0715h	Raining
9903854	C	Pedestrian	Minor injury	0755	Pedestrian aged 13 years
2234307	C	Pedestrian	Non-injury	1040	Pedestrian was a child

Note to table 6.8:

a Pedestrian crashes occurred in 1999–2008; rear-end crashes in 2004–2008.

The zebra crossing on St Jude Street for the exit arm (location B) is located just 5m from the roundabout, and has experienced one reported pedestrian and two associated rear-end crashes (table 6.8). A staggered island arrangement was installed in 2004 in an attempt to address rear-end incidents from the roundabout, but crash numbers are too small to confirm whether or not it improved the situation. No reported crashes have occurred at the dual-lane entry.

In addition, three pedestrian crashes have been reported on the Great North Road arms (locations C and A) where no pedestrian facilities are provided.

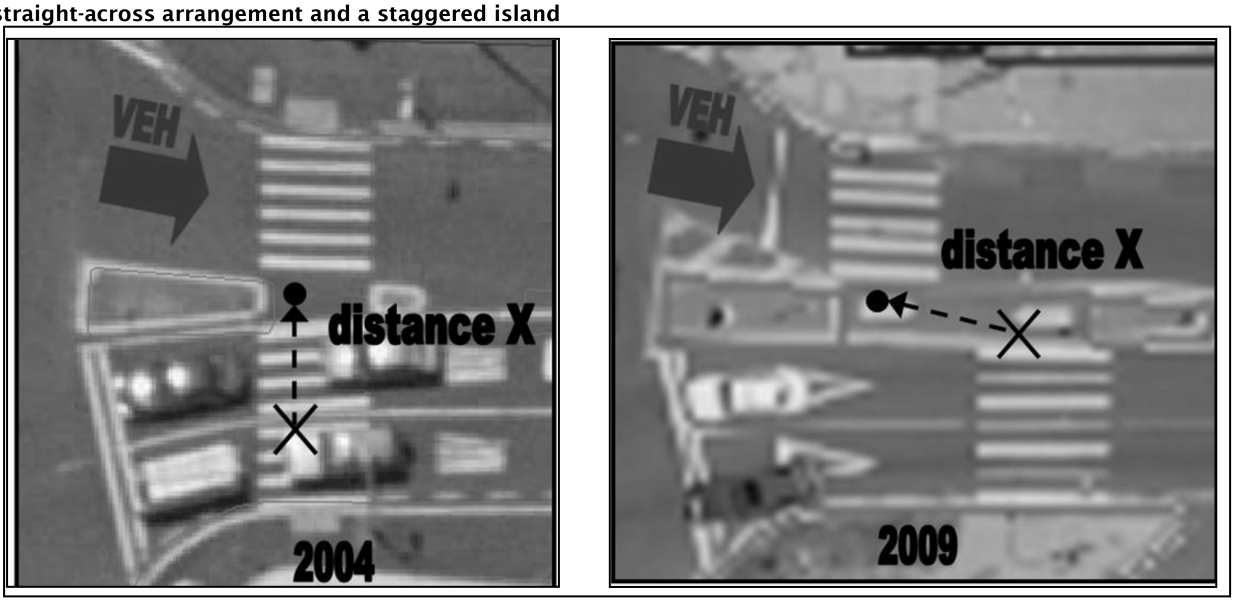
6.10.2 Video observation of the zebra crossing on St Jude Street

This crossing has good speed control from both Great North Road approaches to the single-lane exit of the zebra crossing, and no pedestrian–vehicle conflicts or near-conflicts were observed for two hours of video footage on a fine weekday morning in October 2009 that included an hour of peak hour traffic.

It was observed that around 40% (10 out of 26) of drivers exiting the roundabout stopped for pedestrians who were within the walking area of the staggered island. A similar video survey was undertaken in 2004 when it was a straight-across arrangement. This video showed that around 84% (26 out of 31) of drivers exiting the roundabout stopped for pedestrians who were within a similar distance from the waiting point on the central island (see figure 6.17). With the staggered island arrangement, roughly double the number of drivers exiting the roundabout drove through the crossing when pedestrians were a similar distance (distance X in figure 6.17) from the waiting point in the central island. This appears to demonstrate that the staggered island arrangement is, to some extent, addressing rear-end crashes by reducing the number of stopping vehicles, as originally intended. As no pedestrian incidents have been reported since installation, pedestrian safety does not seem to have been compromised. However, this arrangement is clearly not ideal, as queued vehicles would obstruct circulating traffic on the roundabout relatively regularly.

Staggered island crossings are discussed further in section 6.15.4.

Figure 6.17 Video observations in 2004 and 2009 showed the difference in driver behaviour between a straight-across arrangement and a staggered island



6.11 Site 9: Blockhouse Bay Road–Kinross Street

6.11.1 Crash history at site 9

Figure 6.18 Aerial view of Blockhouse Bay Road–Kinross Street, showing crash locations

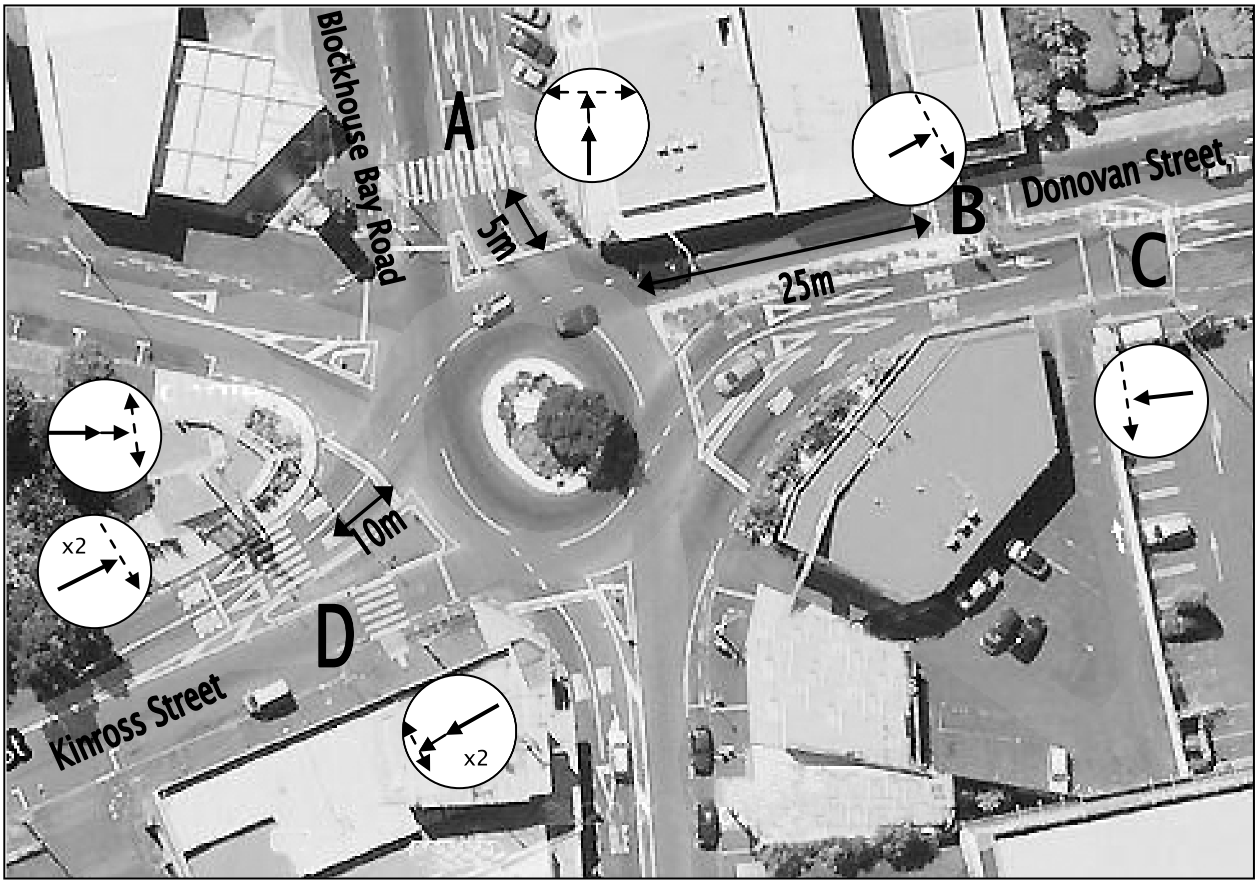


Table 6.9 Pedestrian and rear-end crash history for the Blockhouse Bay Road–Kinross Street intersection in Auckland City

Crash number	Location	Type[a]	Injury level	Time of accident	Other details
253374	A	Rear-end	Non-injury	0830h	–
2803123	B	Pedestrian	Minor injury	1900	Raining; night-time; pedestrian aged 25 years
2003313	C	Pedestrian	Minor injury	0830h	Pedestrian aged 8 years
9902622	D	Pedestrian	Serious injury	0900h	Pedestrian aged 80 years
2004486	D	Pedestrian	Minor injury	1415h	Pedestrian aged 81 years
2538990	D	Rear-end	Non-injury	1730h	–
2630181	D	Rear-end	Non-injury	1630h	–

Note to table 6.9:

a Pedestrian crashes occurred in 1999–2008; rear-end crashes in 2004–2008.

At the zebra crossing on Kinross Street (location D), which is located approximately 10m from the roundabout with a staggered island arrangement (see figure 6.19), two pedestrian crashes and one rear-end crash have been reported (table 6.9). Both pedestrians were quite elderly (80 and 81 years old). The single-lane exit has experienced two rear-end crashes.

The zebra crossing on Blockhouse Bay Road's north arm (location A) has experienced two rear-end crashes at the single-lane exit, with no reported crashes at the dual-lane entry.

The staggered pedestrian signals on Donovan Street (figure 6.20) approximately 25m from the roundabout (locations B and C) have experienced two pedestrian crashes, both involving pedestrians crossing heedless of a vehicle green light display.

Figure 6.19 Photo of the staggered pedestrian zebra crossing on the Kinross Street approach to the Blockhouse Bay roundabout

Figure 6.20 Photo of the staggered pedestrian signal arrangement on Donovan Street at the Blockhouse Bay roundabout

6.11.2 Potential improvements

The two pedestrian injuries that involved jaywalking pedestrians suggest that wait times might have been higher than desirable in the past, which would have encouraged such behaviour. However, in January 2010, the Auckland TMU reprogrammed the signal timing. On-site observations confirm that pedestrian wait times are minimal, with maximum kerb wait times being in the order of 30 seconds, and opposite side crossings being concurrently called up so that wait times on the staggered island are minimal.

6.12 Site 10: Dominion Road–Richardson Road

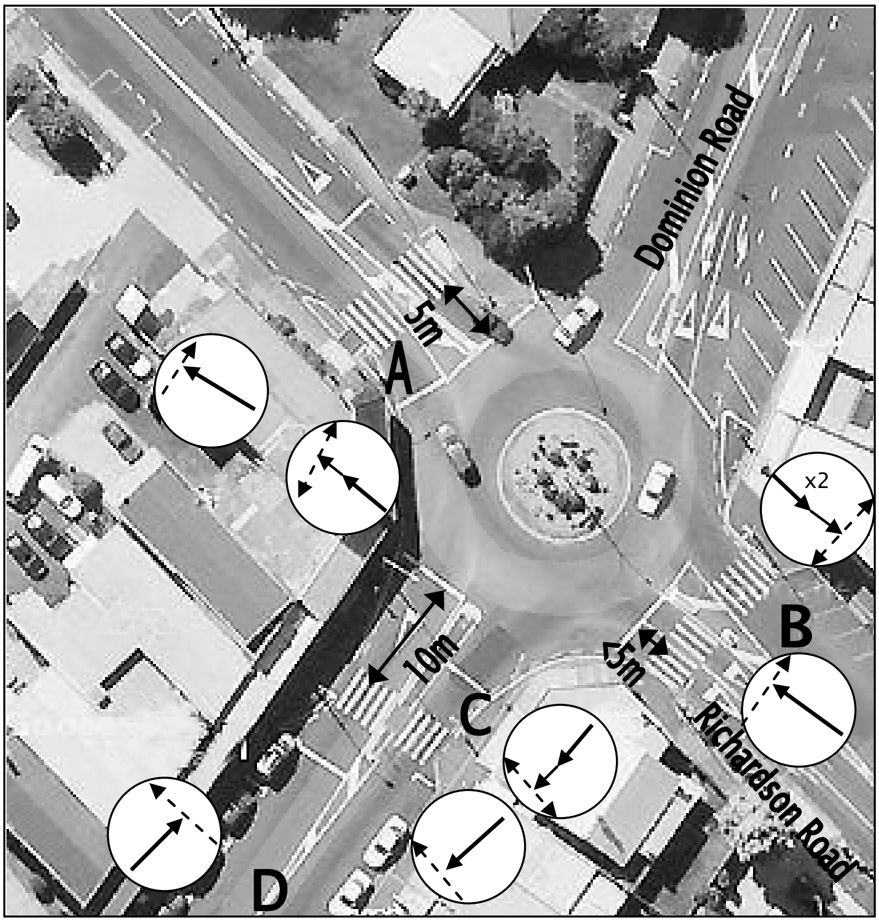
Table 6.10 Pedestrian and rear-end crash history for the Dominion Road–Richardson Road intersection in Auckland City

Crash number	Location	Type[a]	Injury level	Time of accident	Other details
2003029	A	Pedestrian	Minor injury	1600h	Pedestrian aged 6 years
2705618	A	Rear-end	Minor injury	1758h	–
243278	B	Rear-end	Non-injury	0800h	–
2640274	B	Rear-end	Non-injury	1115h	–
2504782	B	Pedestrian	Minor injury	1745	Pedestrian aged 30 years
2713519	C	Rear-end	Minor injury	2235h	Night-time
2804217	C	Pedestrian	Serious injury	1515h	Pedestrian aged 75 years
2201696	D	Pedestrian	Minor injury	1335h	Pedestrian aged 55 years

Note to table 6.10:

a Pedestrian crashes occurred in 1999–2008; rear-end crashes in 2004–2008.

Figure 6.21 Aerial view of Dominion Road–Richardson Road, showing crash locations



The zebra crossing on the Richardson Road south approach (location B), which is less than 5m from the roundabout, experienced one pedestrian crash on the dual-lane approach there, and two rear-end crashes at its single-lane exit.

The zebra crossing on Richardson Road north (location A) has experienced one pedestrian crash and one rear-end crash at its single-lane exit, with no crashes for its dual-lane entry.

In addition, the single-lane zebra crossing on the Dominion Road south approach (location C) has experienced one pedestrian crash and one rear-end crash on the roundabout exit, and none on the roundabout entry.

6.13 Site 11: Ellerslie Panmure Highway–Lagoon Drive

6.13.1 Crash history at site 11

Figure 6.22 Aerial view of Ellerslie Panmure Highway–Lagoon Drive, showing crash locations

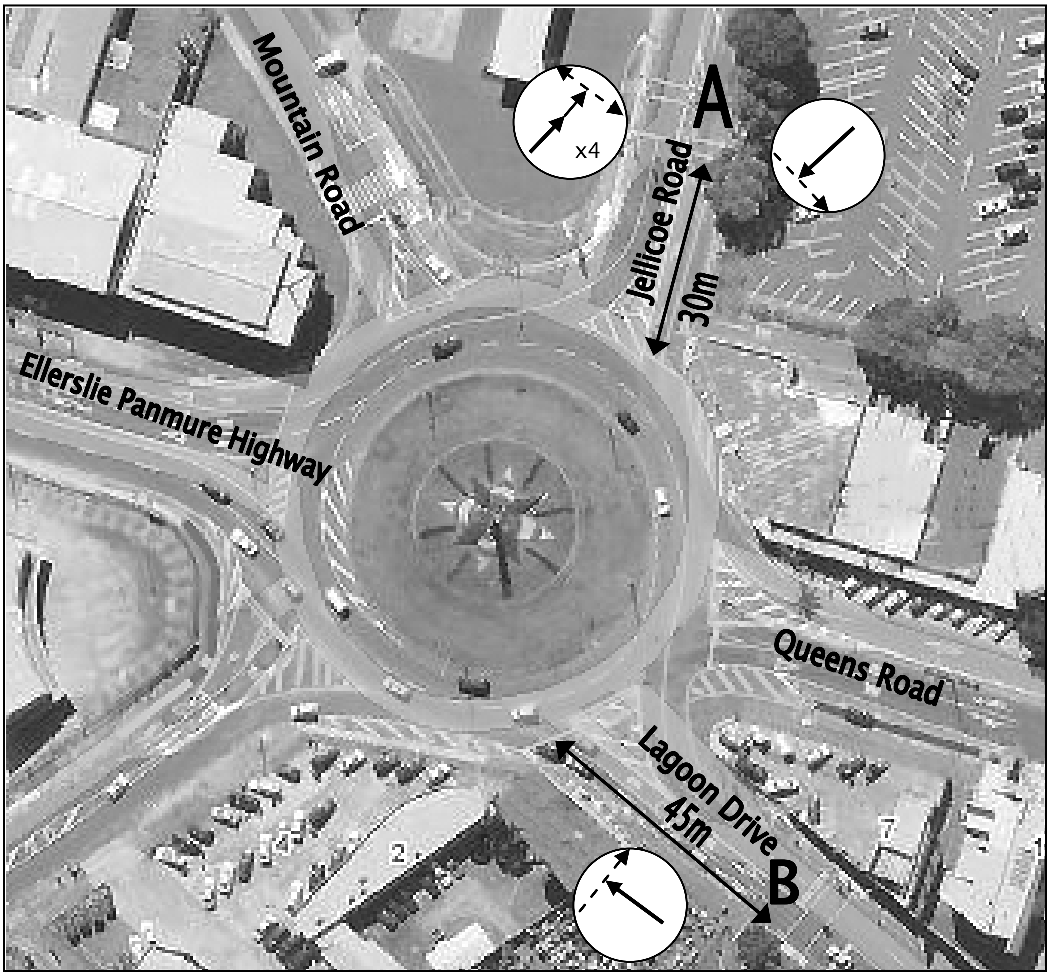


Table 6.11 Pedestrian and rear-end crash history for the Ellerslie Panmure Highway–Lagoon Drive intersection in Auckland City

Crash number	Location	Type[a]	Injury level	Time of accident	Other details
2631252	A	Rear-end	Non-injury	0930h	–
2646184	A	Rear-end	Non-injury	1300h	Raining
2704522	A	Rear-end	Minor injury	0119	Night-time
2833869	A	Rear-end	Non-injury	1753	–
2700105	A	Pedestrian	Fatal	1015h	Pedestrian aged 69 years
9904738	A	Pedestrian	Minor injury	1940	Pedestrian aged 12 years; raining; night-time

Note to table 6.11:

a Pedestrian crashes occurred in 1999–2008; rear-end crashes in 2004–2008.

The staggered pedestrian signals on Jellicoe Road (location A) have experienced one pedestrian fatality on its dual lane roundabout approach, and four rear-end crashes on its dual lane exit. The fatality involved an elderly pedestrian crossing against the vehicle green phase through queues who was then struck by a kerbside lane vehicle travelling at speed.

The zebra crossing on Mountain Road experienced no reported crashes, apart from an irrelevant incident whereby a driver reversed into a pedestrian (not shown in table 6.11).

The full-width signal crossing on Lagoon Drive (location B) experienced one pedestrian crash, which involved a driver running a red light.

6.13.2 Potential improvements

It is understood that the Auckland TMU reprogrammed the signal timing here at some time after 2009, with maximum kerbside waiting times set at 10 seconds for improved pedestrian safety and amenity. However, if pedestrian volumes become substantial, it is considered that this arrangement might need to be revisited in light of the rear-end crash pattern here. A mitigating measure to address these crashes would be to install high-friction surfacing on the exit approach to the zebra crossing and/or to re-evaluate pedestrian wait times.

6.14 Evaluation of selected Auckland zebra crossings

A more detailed evaluation of several of the zebra crossing locations is provided in appendix E. The following general conclusions[5] summarise this evaluation:

- Placement of the crossing relative to the roundabout appears to be very important. Too far a distance results in higher vehicle speeds and decreased visibility of pedestrians owing to drivers' focus of attention past the crossing point. A location too close to the roundabout, particularly relative to the exiting traffic, can result in stopped vehicles blocking other traffic on the circulating lanes and can decrease the visibility of pedestrians. Crossings too far back from the roundabout can also be incompatible with pedestrian desire lines, leading to jaywalking. A distance of approximately one car length between the crossing and the roundabout appears to be about optimal, particularly as regards traffic exiting the roundabout.
- Straight-through crossings may provide superior visibility of pedestrians owing to their direction of movement through the drivers' visual field. When a straight-through crossing is used, however, a pedestrian refuge (non-staggered/not off-set) should be included to reduce exposure times and improve safety.
- Although the off-set staggered configuration can provide some benefits by providing a refuge and discouraging high-speed crossings by joggers and cyclists, the direction and degree of the off-set could be improved at some sites. For example, figure 6.23 shows a staggered/off-set configuration as used at the Avondale site (site 8). Figure 6.24 shows a configuration with the direction of off-set reversed and the degree of stagger reduced. The probable effects of this alternative configuration are:
  - improved visibility of pedestrians by virtue of the placement of the crossings relative to where the drivers are looking as they exit or approach the roundabout, as well as the reduction in the off-set making crossing pedestrians more conspicuous

5 This summary and the evaluation in appendix E have been kindly provided by Dr Samuel Charlton of the University of Waikato.

- some reduction in the blockage of circulating lanes by exiting traffic stopped for pedestrians
- crossing locations that are more congruent with pedestrian desire lines.

Figure 6.23 Staggered island layouts near a roundabout: forward off-set configuration

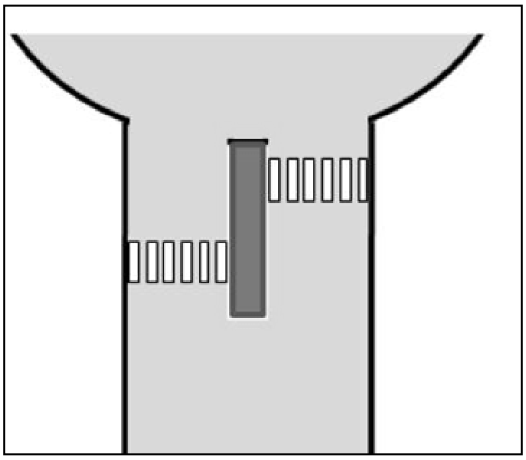
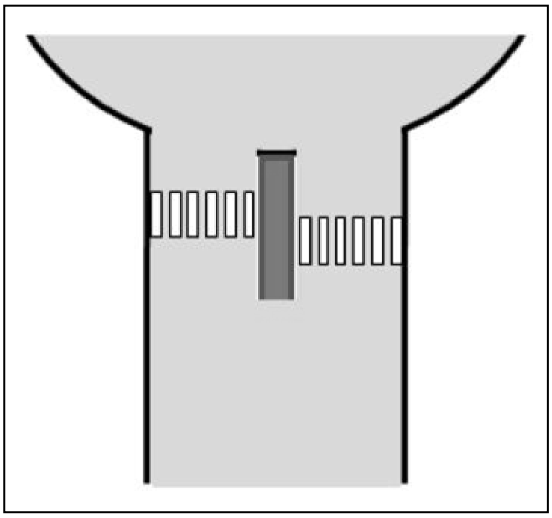


Figure 6.24 Staggered island layouts near a roundabout: reverse off-set configuration with the degree of stagger reduced



- The use of raised pedestrian platforms or speed tables, as suggested in chapter 7, would be compatible with and enhance any of the pedestrian crossing options described above.

6.15 Discussion

6.15.1 Zebra crossings

In general, the zebra crossing sites did not demonstrate any significant pedestrian safety problems that cannot be addressed.

Based on the analysis, (see table 6.12 for a crash summary), the following observations were made:

- Zebra crossings on dual-lane roundabout entries located 20m or closer to circulating lanes experience far fewer pedestrian crashes than those further away, with a total of just three reported pedestrian injury crashes at 11 crossings over a period of five years. A separation of around one to two vehicles from circulating lanes appears to be the optimum location. Note this finding is affirmed by design guidelines in the UK which recommend that zebra crossings should not be located between 20m and 60m from roundabout limit lines (DfT 2007a).

- Sixteen (84%) of the 19 reported crashes on dual-lane entries occurred at five zebra crossings located 25m or further from roundabout circulating lanes. This corresponds to an average pedestrian crash rate of 3.2 crashes per site every five years, which is considerably higher than for crossings located closer to the roundabout. Twelve of these 16 crashes involved collisions with pedestrians crossing in traffic queues, highlighting that this is the main safety issue experienced by pedestrians at multi-lane crossings.
- Single-lane crossings appear to operate reasonably safely, but inadequate speed control through the roundabout may still have an adverse effect on pedestrian safety.
- Dual-lane exits are not necessarily a significant safety problem for pedestrians if the exits are located close to the roundabout, even though the same potential safety problem exists when stopped vehicles restrict other drivers from seeing crossing pedestrians. It is surmised that for roundabout approaches, drivers may mistakenly associate stopped vehicles in the adjacent lane with queues from the roundabout, whereas for roundabout exits, this is perhaps less likely.
- Of the 29 pedestrian incidents at zebra crossings where age of the pedestrian was recorded, 11 (38%) involved pedestrians over 60 years old. Compared to nationwide figures from 2005 (Land Transport New Zealand 2006), which indicate that pedestrians aged over 60 comprise 19% of reported pedestrian casualties, it appears that aged pedestrians are over-represented in our sample sites. As a comparison, just 15% of pedestrian injuries at urban traffic signals in Auckland City in 2004–2008 involved pedestrians aged over 60.
- The time of day for reported pedestrian crashes occurred roughly in proportion with traffic volumes, with 7 (20%) of the 35 incidents occurring during 7:00am–9:00am and 8 (23%) during 4:00pm–6:00pm where the time of day was recorded.

Table 6.12 Reported pedestrian injury crashes at zebra crossing facilities for the 11 sites studied in Auckland

Lane arrangement	Pedestrian injury* crash statistics	Pedestrian injury crashes caused by overtaking in traffic queues	Comments
Single-lane exit	(SI × 2(+ (MI × 5) = total 7 pedestrian injury crashes at 15 locations = **0.46/site/5 years**	N/A	One site had two injury crashes; the remaining 14 sites had four injury crashes combined.
Dual-lane exit	MI × 7 = total 7 pedestrian injury crashes at 5 locations = **1.5/site/5 years**	MI × 4 or **57% of total**. Three occurred at Mt Albert Road crossing	Two sites had three injury crashes each; the remaining three sites had just one injury crash combined.
Dual-lane entry	(F × 1) + (SI × 3) + (MI × 15) = total 19 pedestrian injury crashes at 16 crossing locations = **1.19/site/5 years** Sixteen of the 19 pedestrian injury crashes occurred at five zebra crossings, all located 25m or more from the roundabout = **3.2/site/5 years** Just three pedestrian injury occurred for the 11 zebra crossings located 20m or less from roundabout = **0.27/site/5 years**	12 ((11 × MI) + (1 × F)) or **63% of total.** All 12 occurred at crossings >25m from the roundabout	Of the 11 crossings 20m or less from the roundabout, one had two injury crashes and the remaining 10 crossings had just one injury crash combined.

* F, fatality; SI, serious injury; MI, minor injury; NI, non-injury

6.15.2 Staggered islands at zebra crossings

Staggered island layouts for zebra crossings are not ideal at busy roundabouts, given that they will push exiting vehicle queues closer to circulating lanes. However, they are considered by the authors to offer the following benefits in terms of pedestrian safety:

- They discourage high-speed crossings by runners or cyclists.
- Compared to a straight-through crossing, they increase the time for a pedestrian to observe and make judgements of approaching traffic speed and driver intentions in order to determine an appropriate opportunity to cross.
- It increases the time a driver has to perceive a pedestrian walking in the middle of the road. However, in some cases, this might be negated by the fact that a pedestrian's direction of travel could be towards (or away from), rather than across the driver's visual field, as with a straight-through crossing (see section 6.14).

The experience at the Manukau Road–Mt Albert Road roundabout in Royal Oak, Auckland (site 7, section 6.9), where a staggered island layout substantially reduced the numbers of pedestrian injuries occurring at a multi-lane zebra crossing, appears to vindicate such a view. Notice, however, that this crossing is some distance from the roundabout so exiting vehicle queues will not impede circulating traffic often.

In addition, the before/after observations at the St Jude Street zebra crossing (site 8; refer to section 6.10) seems to indicate that staggered island arrangements might also be expected to reduce rear-end vehicle crashes with no apparent compromise to pedestrian safety (ie fewer vehicles are stopping for pedestrians). However, such an arrangement clearly is not ideal for vehicular operations here, as queues will obstruct circulating traffic on the roundabout relatively often.

It is not clear if large off-set distances (say, greater than one or two metres) are of significant safety benefit. Slight reverse off-sets may be desirable at roundabout exits for clearance of vehicle queues from roundabout circulating lanes. Pedestrians would, however, be walking away from rather than towards oncoming traffic, so such an arrangement should be trialled to confirm that pedestrian safety is not compromised..

6.15.3 Arrow markings at roundabouts

In 2006, it was made a mandatory requirement in New Zealand that multi-lane roundabouts be provided with directional lane arrows. Subclause 10.4(5) of the Land Transport Rule: Traffic Control Devices 2004 (Land Transport New Zealand 2005) states:

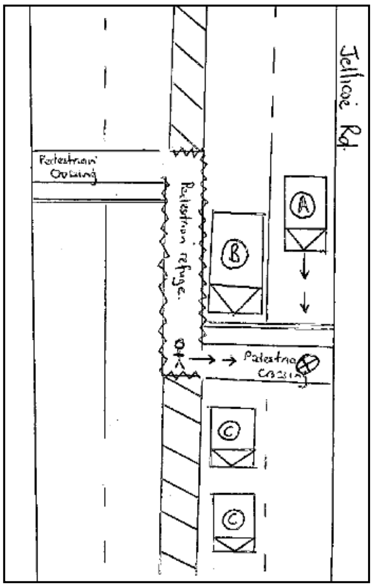
> *If a section of the roadway around a roundabout, or an exit from that section of roadway, has more than one lane for motor vehicles, a road controlling authority must, by 30 June 2006, mark lanes to direct the flow of traffic.*

Unfortunately, this requirement can increase vehicle queue lengths in some situations, which can potentially affect the safety of multi-lane pedestrian crossings, particularly if crossings are located further than 20m from a roundabout, where vehicle speeds can be higher. Peak hour flows can be tidal in many cases, which mean that lane use requirements might vary substantially at different times of the day. The pedestrian fatality at the Panmure roundabout (site 11, refer table 6.11 and figure 6.25), which involved jaywalking at a signalised crossing through queued vehicles, could have been an indirect result of this policy. Figure 6.25 illustrates the potentially hazardous situation for jaywalking pedestrians from the central island, where sightlines between themselves and kerbside vehicles (that might be travelling at speed) are restricted by queued traffic. Figure 6.26 shows the crash diagram from a 2008 fatality at this crossing that involved a jaywalking pedestrian. The authors are familiar with this roundabout and are aware that prior to some lane marking changes imposed around early 2007 (which included a spiral lane configuration), vehicle queues in both southbound approach lanes of Jellicoe Road were more comparable and the disparity of speeds of vehicles in the adjacent lane would have been much less acute. Since then, pedestrian waiting times have been much reduced at this crossing so jaywalking is less likely to occur.

Although it appears that lane arrow marking can probably reduce the chances of inappropriate lane changing behaviour on the roundabout and even reduce sideswipe vehicle crashes (which are likely to merely cause vehicle damage), they can potentially have implications for pedestrian safety at multi-lane crossings upstream. In light of this, it is recommended this requirement be instead amended to an optional measure, which is in line with roundabout design practice in the UK (DfT 2007a).

Figure 6.25 Photo showing southbound queues on Jellicoe Road past the signalised pedestrian crossing

Figure 6.26 Crash diagram of the pedestrian fatality at the Jellicoe Road crossing that occurred in 2008



6.15.4 Pedestrian signals

In general, the sites with pedestrian signals did not demonstrate any significant pedestrian safety issues that cannot be addressed.

Of the seven reported pedestrian incidents at the signal sites, three involved red light running, with the remaining four involving pedestrians who crossed heedless of the traffic signal. Therefore, in order to improve safety at these locations, the following measures could be taken:

- Visibility of signal displays to approaching drivers is an important consideration for reducing red light running incidents, and overhead signal displays are recommended in multi-lane situations.

- Preferably, pedestrian wait times should be set at not greater than around 30 seconds for each crossing stage, as previous research has shown that this can be the maximum amount of time people willing to wait a signalised crossing (Martin 2006). This should reduce the jaywalking that otherwise would inevitably occur and which could also adversely affect safety statistics. Anticipatory call-up of opposite cross phases is also recommended practice at staggered island arrangements.
- All-red times could be increased to reduce the chance of late-runners hitting pedestrians. This is more viable for staggered island crossings.
- Active advance warning measures such as flashing road studs or signs could potentially assist drivers perceiving a red light ahead.

6.15.5 Rear-end crashes at zebra crossings and pedestrian signals

Rear-end crashes are, in general, much more likely to occur at roundabout exits, with 34 (91%) out of the total 37 reported crashes for all zebra crossing and signal crossing locations occurring there. Higher driver speeds as vehicles are exiting the roundabout are probably the major factor in this. Mitigatory measures could potentially include high-friction surfacing and/or driver advance warning measures such as flashing road studs or signs.

6.15.6 Locations without formal pedestrian facilities

Five (11%) of the 44 total pedestrian injury crashes involved collisions between vehicles and pedestrians that were crossing where no formal pedestrian facility was provided (including at pedestrian refuge islands). This highlights that even where pedestrian numbers are so low as to not justify formal crossing points, incidents will still occur.

In the context of a lower speed environment near a well-designed roundabout, some relaxation of the warrant criteria for zebra crossings appears to be justifiable if road planners wish to give pedestrians greater mobility.

6.16 Conclusions

Based on the research in this chapter and chapter 5, the following conclusions have been made with respect to pedestrians and multi-lane roundabouts:

- Although no widespread data is available, we have no evidence to suggest a significant difference in pedestrian safety performance between traffic signals and multi-lane roundabouts. National statistics do not demonstrate that roundabouts are a significant pedestrian safety concern in New Zealand, with no fatalities and 24 serious injury crashes at urban roundabouts being reported from 2004–2008 according to CAS. This compares to 11 fatal and 160 serious injuries at urban traffic signal intersections in the same period. Additional research is required to confirm whether or not roundabouts (including multi-lane) are the safer form of control for pedestrians.
- Elderly pedestrians, those who are vision and mobility impaired, and young children are more vulnerable user groups who, if present in substantial numbers, may need to be given particular attention with respect to provision of safe crossing points.
- In general, good speed control at roundabouts is important with respect to pedestrian safety, particularly for roundabout exits where vehicle speeds are higher and drivers may be less likely to yield for pedestrians at crossing points. Ideally, vehicle speeds could be kept to 30km/h or less, which would minimise the chance of serious injury or fatality.

- Zebra crossings at dual-lane crossings can operate relatively safely if vehicle speed control is satisfactory and they are located less than 20m from circulating lanes. The major problem with multi-lane crossings is that pedestrians can be blocked from view by queued vehicles, but if vehicle speeds are low enough then pedestrian safety is not necessarily compromised to a significant degree.
- Flashing road studs or signs called up by pedestrian detection can improve driver yield rates and improve safety at zebra crossing facilities. In general, the flashing road studs are more discernable to drivers, but roadside or median signs may possibly be more visible in some cases. Signs may also be applicable for signalised crossing points, to be triggered as the amber phase is displayed to drivers.
- The visibility of busy arterial road zebra crossings would be improved if Belisha discs were increased in size from the standard 400mm diameter to 750mm or similar.
- Staggered island arrangements can be a desirable safety feature at zebra crossings, primarily as they give drivers and pedestrians more time to discern each other's intentions. However, they are not ideal for zebra crossings near busy roundabouts as they will push exiting vehicle queues into circulating traffic. Reverse stagger arrangements may be beneficial for vehicular operations but would need to be road-trialled first to confirm that pedestrian safety is not compromised.
- Signalised pedestrian crossings on roundabout approaches can be an effective solution for multi-lane crossings, but jaywalking will be exacerbated if pedestrian waiting times are much over 30 seconds, which, in turn, may affect safety statistics.
- Hawk, Pelican or Puffin signal crossings can reduce disruptive effects to roundabout traffic flow by reducing pedestrian clearance times. Flashing signals as used by Hawk and Pelican crossings are not currently legal to use in New Zealand; this situation is deemed worthy of review by the NZTA. Advanced pedestrian detection technology as sometimes used at Puffin crossings in the UK could feasibly be used to achieve the same objective, but only provided their reliability is better proven.
- Signalised roundabouts can accommodate pedestrians at designated signalised crossing points, although, compared to unsignalised roundabouts, they are expensive to install and can result in greater driver delay during off-peak periods. It would therefore be desirable for the NZTA to review the legal situation with regard to part-time signal operation, which is currently not permissible.
- Raised pedestrian platforms offer an effective means of reducing vehicle speed and thus improving pedestrian safety at crossing points. This subject is further discussed in chapter 7.
- Current design guidelines for roundabouts in New Zealand require the use of lane arrows at multi-lane approaches. These can potentially have adverse effects for pedestrian safety at multi-lane crossings and would be better as an optional measure only.
- Visually impaired pedestrians are likely to find crossing the road problematic near busy multi-lane roundabouts. Their difficulty stems from the fact that traffic noise can sometimes make it difficult for them to tell audibly if drivers are stopping to let them cross. In order to cater for this specific user group, if present in some numbers (such as busy shopping precincts or near institutes for the blind), traffic engineers may need to consider the availability of alternative crossing points some distance from the roundabout. Sound strip treatments are potentially useful at single-lane crossing points, as they can assist visually impaired users to determine if vehicles are stopping to let them cross. For multi-lane situations, they are problematic, as users find it difficult to identify which lane the vehicles are in.
- Rear-end crashes are, in general, much more likely to be associated with pedestrian crossing facilities at roundabout exits than entries. Means of addressing this could feasibly include high-friction

surfacing or advance warning devices such as flashing road studs or signs. In addition, if crossings on exits are very close to circulating lanes then rear-end crashes might be expected to increase.

- Yellow cross-hatching on roundabout circulating lanes can be useful for reducing lane blockage caused by downstream pedestrian crossing facilities.

A practical application document for pedestrian crossings at roundabouts is provided in appendix F.

6.17 Recommendations

Based on the findings of this research, the following recommendations are made:

- The practical applications contained in appendix F should be referred to by RCAs for design of pedestrian facilities at roundabouts.
- The legal use of flashing signal displays as used for Pelican and Hawk type crossings is recommended to be considered for adoption by the NZTA, as they are a simple and practical means of reducing disruption to roundabout traffic flow from nearby signalised pedestrian crossings. In addition, flashing signal displays at signalised intersections is commonly used in the US as a means of reducing driver delays during off-peak periods, and are popular with the general public there (Kennedy and Sexton 2009). Even though an increased risk of collisions is possible, this application of flashing signal displays in New Zealand is also recommended to be reviewed.
- The legal use of part-time signals is recommended to be considered for adoption by the NZTA. This is particularly relevant to signalised roundabouts or metered signals near roundabouts, whereby signals could feasibly be switched off as a means of reducing driver delay during off-peak periods.
- Pedestrian crash rates at main road roundabouts and traffic signals should be better determined, as some indications suggest that roundabouts are a safer form of control for these users. This research would need to take into account related incidents such as jaywalking and associated zebra crossing facilities near the intersection. The results may potentially influence the selection of intersection control for urban centres where large volumes of pedestrians are present.
- Current design guidelines for roundabouts in New Zealand require the use of lane arrows at multi-lane approaches. These can potentially have adverse effects for pedestrian safety at multi-lane crossing points, and it is recommended that this requirement be amended to an optional measure only as per UK practice (refer to section 6.15.3).
- The current standard diameter for Belisha discs used at zebra crossings in New Zealand is only 400mm, which is not as visible to drivers as the beacons used overseas. It is recommended that the MOTSAM standard be amended to include a 750mm diameter or similar for roundabouts.

7 The use of vertical deflection devices at roundabouts

7.1 Introduction

7.1.1 Background

Vertical deflection devices (figure 7.1) are an effective means of vehicle speed control, and potentially are viable for use in the proximity of roundabouts for the benefit of cyclists and pedestrians in particular. Recent research undertaken by Campbell et al (2006) identified that the reduction of vehicle speeds on roundabout approaches is a principal factor in reducing cyclist crashes at roundabouts. Vertical deflection devices (speed humps, speed tables or speed cushions) offer one of the most economic methods of retrofitting existing roundabouts to achieve this. These devices can also be used at pedestrian crossing facilities, and may be particularly useful at multi-lane crossings where safety might be an issue (refer to chapters 5 and 6).

Figure 7.1 A low raised speed platform on a two-lane roundabout exit in the US

However, outside the context of shopping centres with large volumes of pedestrians, the use of vertical deflection devices on main roads is not usually considered to be appropriate by RCAs in New Zealand. The primary objections generally relate to:

- potential traffic diversion
- adverse effects on emergency vehicles
- increased noise adjacent to the device
- wear and tear on vehicle suspension (especially heavy vehicles)
- general annoyance and discomfort to the public, especially bus passengers.

The main objective of this project was to comprehensively examine the viability of installing vertical deflection devices near roundabouts in the context of main road intersections. Other aims were to investigate whether any particular vertical deflection device may satisfactorily address the aforementioned potential adverse effects, and to consider any other effect these devices might have on the safety and operation of a roundabout.

7.2 Methodology

This section of the research included the following tasks:

- to undertake a literature review of New Zealand and overseas research on this topic, and thoroughly evaluate any research that has been published
- to consult with bus operators, emergency services and local authorities in New Zealand with regard to this subject
- to research the noise effects of various vertical deflection devices
- to review the implications of/to heavy vehicles from continuous traversing of vertical deflection devices[6]
- to consider of any other identified safety or operational effects that the installation of vertical deflection devices at or near roundabouts might have
- to prepare some practical applications for practitioners.

7.3 Feedback from local authorities in New Zealand

Feedback regarding the use of vertical deflection devices on main roads was sought and received from local authorities in Auckland City Council, North Shore City Council, Manukau City Council, Waitakere City Council, Rotorua District Council, Christchurch City Council and Wellington City Council (see table 7.1).

Table 7.1 Individuals contacted for feedback on the use of vertical deflection devices

Name	Role	City/District Council
Irene Tse	Senior Traffic Engineer	Auckland City Council
Andrew Hunter	Acting City Traffic Engineer	Manukau City Council
Kit O'Halloran	Manager, Transport Development	North Shore City Council
Adam Moller	Senior Transport Engineer, Transport Services	Waitakere City Council
Elizabeth Wood	Roading Engineer	Rotorua District Council
Stuart Bullen	Senior Traffic Engineer, Infrastructure	Wellington City Council
Michael Thompson	Senior Traffic Engineer, Community Transport and Greenspace Unit	Christchurch City Council

In general, most of the local authorities contacted did not enthusiastically support the installation of vertical deflection devices on main roads, except for in CBDs or shopping centres where they might be installed for pedestrian safety reasons. Concerns raised include discomfort to vehicle occupants and bus passengers, noise, vibration and potential for traffic diversion.

The following questions were emailed to each respondent:

6 For this part of the research, we are particularly grateful for the help of Dr John de Pont of TERNZ Ltd, who used his considerable experience in heavy vehicle research to contribute to this chapter.

- Does your council have any vertical deflection devices installed on arterial roads? If so, would these be in shopping areas only or elsewhere? In particular, have any of these been installed at or close to roundabouts?
- Vertical deflection devices can be a very cost-effective means of reducing the speed of vehicles approaching roundabouts compared to geometric means (particularly in terms of land-take). Would your council consider their use on arterial roads for this purpose, even in situations other than just shopping precincts?

We gleaned the following responses:

> *In summary, [the] Network Performance team [does not] endorse the principle of installing any vertical deflection devices on arterial roads – this is to preserve and maintain the function and the accessibility of arterial routes.*
>
> *We have recently installed speed tables on three of the approaches at [the] Point England–Erima [Avenue] roundabout, at Point England as part of our liveable Street/School travel plan projects...*
>
> *There are a couple of multi-lane roundabouts in Auckland City where we have considered installing vertical deflection devices to create platforms for the existing (multi-lane) zebra crossings. They are [the] Royal Oak roundabout and the Dominion Road–Richardson Road roundabouts (both in the centre of shopping areas). However, due to budget constraints, we have deferred these proposals.* (Irene Tse, Auckland City Council, February 2010)

> *[Manukau City Council] does not have any speed humps on arterial roads even in shopping areas.*
>
> *[The] council has a set of criteria that it adheres to that govern where and how speed control devices may be installed. These criteria would need to be modified and ratified by the council before any changes could even be considered.*
>
> *Currently, there is only one site that I can recall as having a platform type control on the approach to a roundabout. This is in Manurewa, and we have difficulty with pedestrians assuming that they have right of way and walking out in front of vehicles. It is a fairly low-speed environment and the [roundabout] is a small diameter so probably doesn't qualify in your study.* (Andrew Hunter, Manukau City Council, February 2010)
>
> *I am fairly sure that we do not have speed humps or raised islands installed on any arterial roads.*
>
> *Whilst we would not rule out installing vertical deflection devices on approaches to roundabouts, we would need a lot of convincing that these would be safe and would not encourage traffic to take alternative, less desirable routes (through local or collector roads).* (Kit O'Halloran, North Shore City Council, February 2010)
>
> *With regard to the first question, we generally [do not] use vertical deflection devices on arterial roads. However, we do make some exceptions in town centre (shopping) areas where platforms/humps are sometimes used, eg Henderson (numerous platforms), Te Atatu (platform pedestrian crossing) [and] Titirangi (humps at each end of the village and platforms at [pedestrian] signals).*

Some of these are close to signals/pedestrian crossings, and the hump at the western end of Titirangi village would be approximately 30–40m from a major roundabout.

With regard to question two, there has been a strong reluctance to use vertical deflection devices on arterial roads in Waitakere (outside of the exceptions made for town centres) and even the use of vertical deflection on collector roads has been a source of considerable debate, particularly where it impacts on bus routes, although in some cases, speed humps have been installed on collector roads serving buses. It is unlikely we would use vertical deflection devices on arterial roads outside of shopping areas and highly unlikely we would use them on arterials in residential areas because of noise/vibration concerns. (Adam Moller, Waitakere City Council, July 2010)

(1) Yes, we have installed speed cushions on an arterial route where speeding was identified as a significant problem in an area with high pedestrian use.

(2) We might consider their use, but not prefer it to good geometric design. (Elizabeth Wood, Rotorua District Council, February 2010)

Our arterial roads are generally free from any vertical deflection devices, with the use of speed humps, cushions and raised platforms being focused on our local roads. We have installed raised platforms in our shopping areas throughout Wellington that have T-junctions, and have low-speed environment and plenty of pedestrian activity. [Speed limits of 30km/h] are also in place in shopping areas in Wellington to better serve vulnerable road users.

Speed cushions have been used on specific routes in Wellington (mainly coastal) that are on bus routes and have a high number of cyclists using the roads.

Speed humps are predominantly used on local roads to detract motorists from rat running[7] *and keep to traffic on arterial routes. 40km/h speed limits are also in place on local roads while speed limits on arterial routes remained at 50km/h.*

We have no vertical deflection devices on or near roundabouts in Wellington and probably would not consider this option just yet. We believe deflection and good forward visibility for motorists [have] the most benefit when controlling speed in and out of roundabouts rather than speed humps/cushions.

Our arterial routes generally have trolley buses running regular bus services... this limits the use of speed humps/platforms and, to a lesser, extent cushions.

We have very few multi-lane roundabouts in our jurisdiction, with most being single lane approaches. The multi-lane roundabout we do have in Johnsonville has very few cyclists at this location and we have not received requests to improve safety for cyclists who do use this roundabout.

Johnsonville roundabout has two pedestrian crossings in close proximity along with splitter islands that seem to serve pedestrians well. Approach speeds at this roundabout are slow apart from on one of the approaches where we are currently redesigning this approach leg to give better deflection for motorists. (Stuart Bullen, Wellington City Council, February 2010)

7 Rat running: when drivers use a quiet street as a quick way of getting to their destination, rather than using a main road.

CCC does not have or does not install traffic calming devices with vertical deflection on arterial roads. Any that we have are installed on classified local roads. There are two exceptions, being CBD roads where traffic speed[s are] low. These roads are classified 'collectors', and raised but elongated platforms are [used] at zebra pedestrian crossings. So the function of these devices is to slow traffic and raise approach awareness of a crossing point. They are elongated to allow for easy/comfortable use by passenger service buses. By being raised, they also remove problems of cross-section gradients for persons in wheelchairs, ie removing the cut down gradient followed by the opposing camber gradient.

We do not consider vertical deflection devices on our arterial roads for the following reasons:

- *political concern resulting in a policy that they be installed only on residential roads (due to public dislike of road humps)*
- *[the] majority of roads in city have soils with poor load bearing [qualities], the effect of [which] is potential vibration on adjoining properties etc*
- *[it does not] fit with our general policy of encouraging use of network roads (arterials/collectors) in preference to local roads.*
- *vertical deflection devices can increase traffic noise through acceleration/deceleration and traversing the device etc. Installing these on roads with higher volumes (our City Plan states that arterials usually have 10,000+ [vehicles per day]) will increase the mechanical noise associated with the device, and potentially decrease the amenity value of adjoining residents.* (Michael Thompson, Christchurch City Council, February 2010)

7.4 Vertical deflection device options

7.4.1 Raised platforms (flat-top humps)

In New Zealand, raised platforms can be used in town centres, local area or liveable street schemes. They are built with cobblestone or coloured concrete effects, and are often used in conjunction with pedestrian crossing points (figures 7.2 and 7.3). Ramp lengths and platform heights can vary, but generally are around 100mm high with ramps at 1 in 10 or 1 in 15 gradients for bus routes.

In the context of roundabouts, the advantage of these devices is that they can also double as pedestrian crossing points (either controlled or uncontrolled).

Figure 7.2 A typical speed platform with a zebra crossing installed in Glen Eden town centre, Waitakere

Figure 7.3 A platform arrangement at an informal crossing point in Henderson town centre, Waitakere

7.4.2 Round-top humps

Round-top humps are the most common devices installed in New Zealand residential streets, and the profile generally used is the Watts profile or Modified Watts profile (MWP) as shown in figure 7.4. The MWP is 5m long in the direction of travel and is specially designed to be more forgiving to heavy vehicles than the standard Watts profile, which is 3.7m long. Compared to speed platforms and cushions, they are generally the least expensive vertical deflection option by a significant margin.

In the context of roundabouts, round-top humps could be installed on approaches or exits, but would not usually be considered at pedestrian crossing points, given their curved profile.

Figure 7.4 A MWP speed hump in a local street, as commonly installed by many New Zealand jurisdictions

7.5 Other speed hump profiles

7.5.1 H and S road humps

Some other profiles that have been used in small numbers in the UK are sinusoidal profile ‘H’ and ‘S’ road humps. Diagrams of each are shown below in figures 7.5–7.11. The sinusoidal profile does apparently experience slightly increase driver discomfort as a consequence of a higher maximum vertical acceleration compared to platforms or speed humps (DfT 2007c). H and S humps have been used to reduce discomfort to bus passengers, but do not appear to be readily applicable to multi-lane approach situations at roundabouts.

Figure 7.5 Cross-section of a sinusoidal hump, which may also be used in conjunction with flat-top platforms (DfT 2007c)

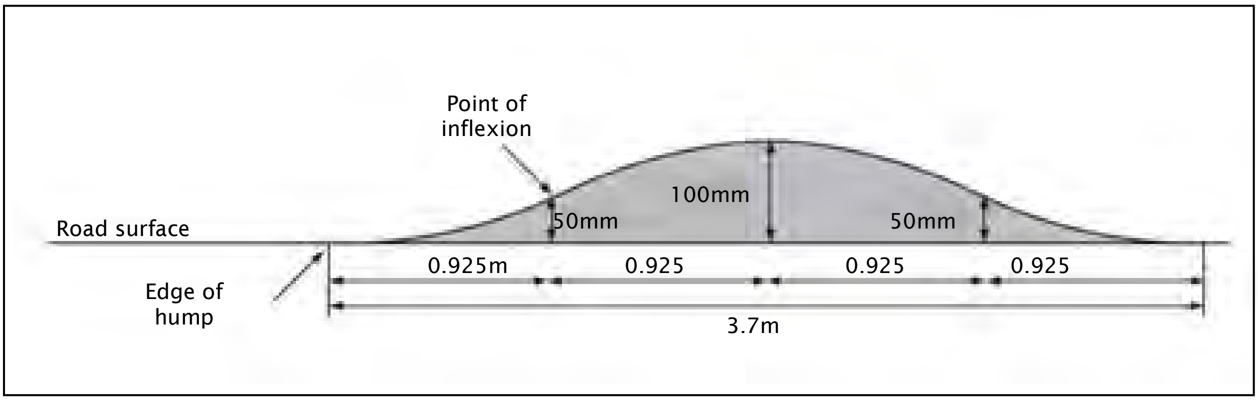


Figure 7.6 Plan view of a sinusoidal hump, which may also be used in conjunction with flat-top platforms (DfT 2007c)

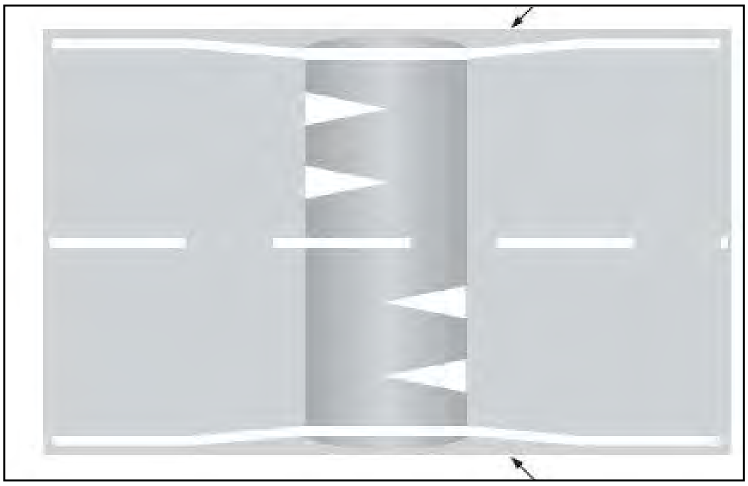
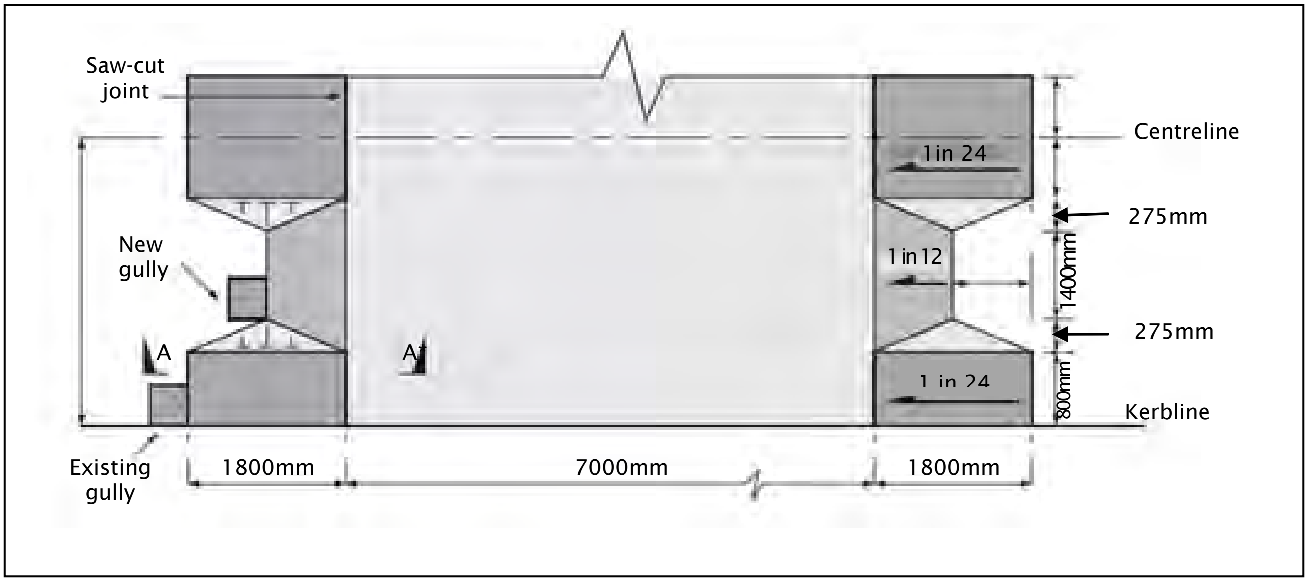


Figure 7.7 Plan view of an H speed hump (DfT 2007c)



*A–A indicates the cross-section shown in figure 7.8.

Figure 7.8 Cross-section view of an H speed hump (DfT 2007c)

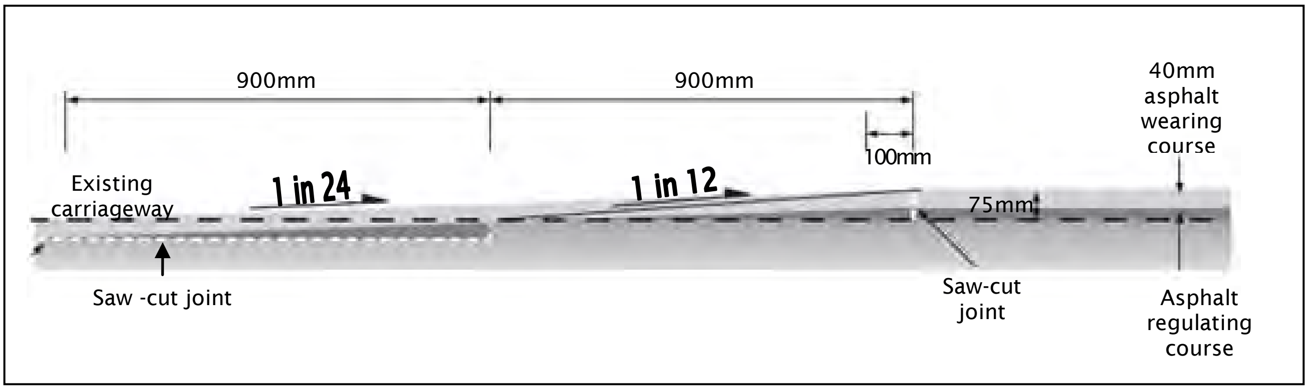
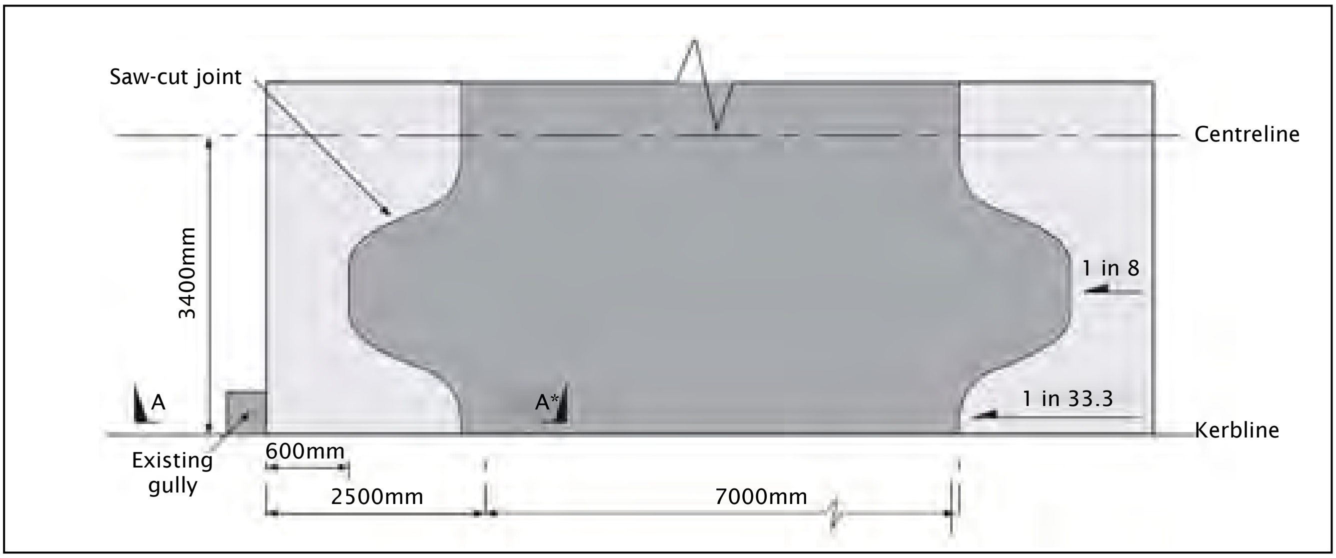


Figure 7.9 Plan view of an S speed hump (DfT 2007c)



* A–A indicates the cross-section shown in figure 7.10

Figure 7.10 Cross-section of an S speed hump (DfT 2007c)

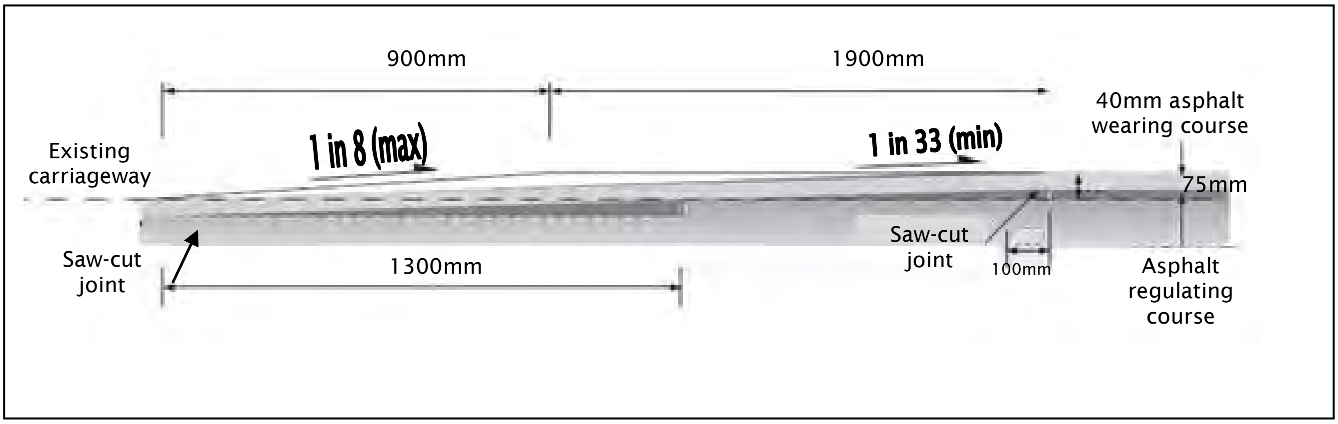


Figure 7.11 An S speed hump installed in the UK (DfT 2007c)

7.5.2 Speed cushions

Speed cushions were originally used in the UK in the 1990s and have been increasingly used by some New Zealand local authorities over the past decade (figures 7.12 and 7.13). Although they are generally used only on local roads, Rotorua District Council has installed them on an arterial route where speeding was identified as a significant problem in a residential area with high pedestrian activity.

Speed cushions have less disruptive effects on buses and other large vehicles, including fire service appliances because of the wider wheel tracks of these vehicles. Speed cushions incur only a minor bump when traversed centrally. In the UK, guidelines suggest a maximum height of 75mm and a maximum width of 1600–1700mm for bus or ambulance routes in order to minimise passenger discomfort (DfT 2007c). In general, cushions are less effective at speed reduction than raised platforms or humps.

Figure 7.12 Photo of a speed cushion scheme installed on Wattle Street, a local road in Waitakere City (these particular examples are constructed of asphalt based on a North American profile of 1.8m wide × ~5m long × 90mm high)

Figure 7.13 Photo of a 1.8m wide speed cushion installed on Pooks Road in Waitakere City (this 75mm high example is made of recycled rubber, which means it can be installed quickly and with minimum traffic management)

7.5.3 Dunlop Transcalm responsive speed hump

The Dunlop Transcalm responsive speed hump is a device just recently developed. It is an air-filled rubber device especially designed to reduce vehicle speeds to around 30km/h or less, and also to have a minimal effect on heavy vehicles such as buses or larger emergency vehicles, or any vehicle over ~3000kg (figures 7.14 and 7.15). It comprises an air filled rubber reservoir fitted atop a specially installed concrete mount. Dunlop has indicated that it would be uneconomic to consider shipping these to New Zealand currently (at least $7000 for each device plus freight), but a surface-mounted unit is being developed for export at the time of writing. Motorbikes do not get the same benefits as car drivers because of their lower weight but, according to the manufacturers, they apparently still prefer Transcalm-type devices to conventional road humps.

In the context of roundabouts, Transcalm-type devices could feasibly be installed on roundabout approaches or departures, and appear to be a viable means of speed control while minimising adverse effects to buses and emergency vehicles. They would be an expensive option to install, however, and their long-term maintenance requirements are still uncertain.

Figure 7.14 Typical example of a Transcalm device (photo supplied by Dunlop Transcalm Ltd)

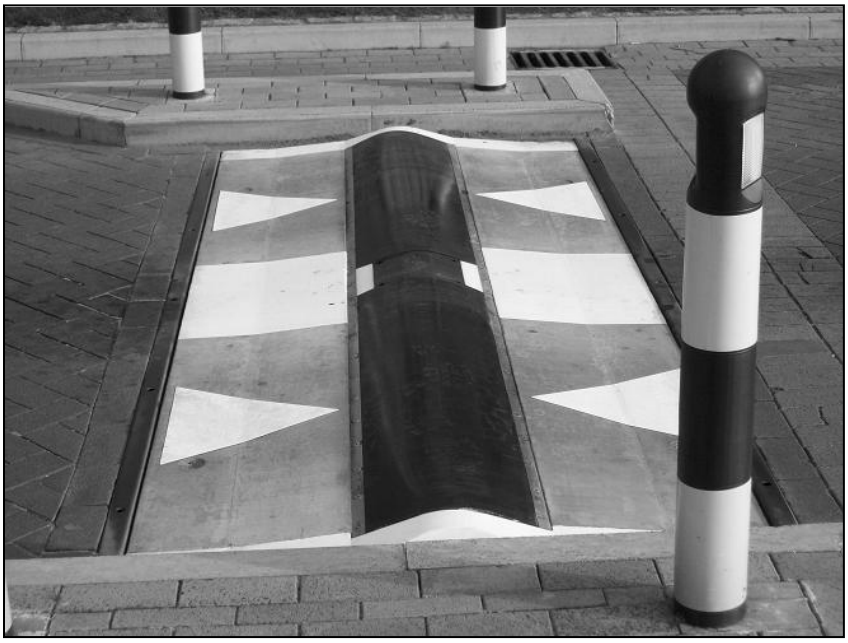


Figure 7.15 Example of a Transcalm in the UK installed near a single-lane roundabout on a busy bus route (photo supplied by Dunlop Transcalm Ltd)

7.6 Effects on vehicle occupants and bus service operators

Anecdotal evidence is available on the internet from the UK and the US of occasional spinal injuries to bus passengers and fire fighters when their vehicles traversed speed humps at inappropriately high speeds, and also of the impediment they can sometimes be to people with existing severe spinal conditions.

A study from the UK entitled *Impact of road humps on vehicles and their occupants* (Kennedy et al 2004) examined this topic in some detail and was motivated by the aforementioned public concerns. It was generally concluded that levels of discomfort were generally acceptable if devices were traversed at appropriate speeds of around 15–20mph. Passengers in the rear of vehicles such as taxis, ambulances or buses were likely to suffer the most discomfort, but this was substantially mitigated if drivers were duly aware and reduced their speed accordingly. It was considered that vehicle occupants are very unlikely to be injured as a result of single or repeated traversing of road humps, the exceptions being people with severe back conditions, who could be more susceptible. For major bus or ambulance routes, speed cushions were recommended as the preferred treatment if vertical deflection devices were to be used. Careful attention to signing and marking of the devices is also recommended in order to encourage drivers to slow down in good time for them, especially at night.

A 2007 guideline for traffic calming measures in the UK (DfT 2007c) is a useful document for reference, and includes a comprehensive evaluation of different types of devices. Vertical deflection devices are deemed acceptable for bus routes, provided they are under 75mm high and preferably not installed in great numbers. Flat-top platforms with approach ramps with a 1 in 15 angle are deemed to be an acceptable compromise between speed reduction and driver comfort, with a plateau length to match the wheelbase of buses that use the route (around 6m for standard buses and up to 12.5m for articulated buses). Shallower off-ramps with a 1 in 20 grade are recommended for one-way streets. Traffic calming guidelines for the cities of London and Manchester do not accept round-top humps for bus routes because of the double 'bump' they give passengers.

The New Zealand Bus Company, which operates the majority of bus services in Auckland, was approached for feedback in relation to this topic. We asked the following questions:

- Does your organisation have any objection to the use of vertical deflection devices (a minimum of 75mm high) on roads that are busy bus routes? If so, some reasons would be appreciated.
- Is there any particular type of vertical deflection devices that your organisation prefers, or at least has less of a problem with?

Garth Stewart, the Regulatory and Compliance Manager of the New Zealand Bus Ltd, responded as follows:

> *New Zealand Bus does not like speed humps, especially on bus routes; however, we also have to accept there is a need to control traffic speeds etc where there is a requirement on suburban streets and around schools etc.*
>
> *The proposals for a speed hump to be of a height of 75mm is acceptable but we would like to see the hump itself have a flat section on top so the bus can travel over a flat section prior to coming down to the main carriageway. Please note that the majority of our fleet is now Super Low Floor (fully accessible) and therefore are lower to the ground than earlier fleet.*
>
> *New Zealand Bus does not want deflection devices that will damage a bus, but to have some form of signage that reflects and will collapse if hit by a vehicle.*

7.7 Heavy vehicles

7.7.1 Summary

It has been concluded that adding speed humps or platforms to main road roundabout entrances should have no measurable effect on heavy vehicle chassis or suspension wear, and should have a positive safety effect by controlling truck traversing speeds.

As they traverse a vertical deflection device, some lightly-laden heavy vehicles with mechanical leaf-spring suspension – particularly those with three axles or more, or with two axles – may generate increased noise if driven at excessive speed. However, air suspension is becoming much more widely adopted for three-axle vehicles and trailers (with the current exception of tipper and concrete trucks), so this may not be a significant issue for many situations. If residential or similarly sensitive activities are very close to the proposed devices, then truck volumes by type and time of day could be reviewed as a means of assessing any potential adverse noise effects.

Speed humps or platforms should be designed longer than the wheelbases of the expected bus or truck types in order to reduce undue amplification of the 'bounce' when traversed. This should substantially address concerns with respect to bus passenger comfort in particular.

7.7.2 Introduction

Anecdotal evidence can be found on the internet from the UK and the US of fatigue damage to buses and fire service appliances, and of at least one media report of a bus company threatening to withdraw services if speed humps were installed on certain regular routes for this reason (Bell 2002). For these reasons, as well as the claimed issue of increased noise, this topic of heavy vehicles at vertical deflection devices was included as part of this study[8].

The Road Transport Forum New Zealand (RTFNZ) was approached regarding this issue. Mark Ngatuere, Senior Policy Analyst, comments that, in general, the RTFNZ does not support the proposal of using vertical deflection devices on main roads (pers. comm. March 2010). Issues include detrimental effects on road surfaces as large vehicles pass over a device, increased vehicle noise and some concerns about a reduction in braking performance.

7.7.3 Literature review

Lay (1998) outlines the basic guidelines for the design of speed humps and speed platforms. He states that each hump installation will have a maximum speed that will neither cause damage to the crossing vehicles nor discomfort to the vehicle occupants. This is called the design crossing speed and it is typically between 15km/h and 25km/h, and produces peak vertical accelerations of the order of 0.7g. Lay also refers to a maximum safe speed, which is the greatest speed which carries no risk of vehicular damage or unsafe behaviour. According to Lay, this speed is typically above 80km/h. Between the design crossing speed and the maximum safe speed, driving is safe but will result in noticeable and increasing occupant discomfort.

An experimental study conducted by the Transport Research Laboratory (TRL) for the DfT (Kennedy et al 2004) measured and simulated the response of five different vehicles travelling across four different hump shapes. The purpose of this research was to objectively study the possibility that speed humps might cause increased wear to vehicle components and injury to occupants, and to suggest ways of ameliorating these effects. The experimental tests involved traversing these bumps at speeds between 16km/h and 64km/h. Lower maximum speeds (40km/h) were used for the two buses tested. No visible damage to any of the vehicles was observed. One of the five vehicles experienced a reduction in damping on the front suspension after repeated passes over the humps. However, this was not caused by a reduction in the performance of the damper but rather by a 'bedding in' of the rubber bushes in a new suspension. Generally, the vertical accelerations experienced by the vehicle occupants were below 0.7g for typical crossing speeds (32km/h for the car and taxi; 24km/h for the minibus, bus and ambulance). The

8 Dr John de Pont, Director of Engineering Research at TERNZ Transport research Ltd has extensive New Zealand experience in the field of heavy vehicle research and has also contributed towards this project. The remainder of this section is authored by Dr de Pont, and some of the concerns expressed by RTFNZ are also addressed.

exceptions were a slightly increased value for the bus driver on two of the speed hump types, and higher levels for the taxi passenger on all bump types. This was attributed to the type of suspension used on the taxi. The study also noted that the forces experienced by the vehicle were no higher than those experienced in other driving situations such as rough roads[9], potholes or mounting a kerb. In terms of the focus of this section, it is worth noting that the vehicle set did not include trucks (the closest vehicle type was a bus).

Various authors have measured the dynamic wheel loads of heavy vehicles. Some of these have measured the vertical accelerations of the vehicle chassis (de Pont 1997; Streit et al 1998). These measurements showed that on rougher roads at moderate speeds, vertical accelerations on the chassis exceeded 2g. This is considerably higher than the 0.7g maximum expected from traversing a speed hump at the design speed, and implies that the wheel forces experienced on rough roads are higher than those experienced on speed humps at the design speed.

Various packaging studies (Marcondes et al 1992; Pang et al 1994) have also measured vertical accelerations on truck decks. These also show peak accelerations of 2g or more on rough roads.

7.7.4 Suspension and chassis wear

One of the postulated effects is that repeated travel over speed humps will generate additional suspension wear and chassis damage. Kennedy et al (2004) reported that bus companies suggest that vehicle maintenance costs for buses operating on routes with speed humps will increase but no direct evidence is provided. As noted in the previous section, the forces applied to the suspension and chassis from speed humps and platforms should be no higher than those experienced on rough roads. Of course, it is likely that vehicles operating largely on rough roads will experience higher maintenance costs than those operating only on smooth roads. Furthermore, traversing speed humps at speeds above the design speed will result in high chassis and suspension loads.

Except at excessive speeds, the forces generated while traversing a speed hump or platform should not cause any immediate damage to the suspension or chassis. Repeated load cycles can induce fatigue damage that accumulates over time, eventually leading to cracking and failure. However, the number of load cycles resulting from passing over speed humps and platforms is very small compared to the number generated by driving along. The body vibration modes of trucks are typically between 1.5Hz and 4Hz. This means that as the truck is driving along, the body is bouncing up and down at 1.5–4 times per second and thus load cycles are applied to the suspension and chassis at this rate. On a smooth road and/or at a low speed, the amplitude of these load cycles is small but on rougher roads at higher speeds the amplitude is greater than that experienced crossing a speed hump. On this basis, a five-minute drive on a rough road is equivalent to driving over 450–1200 speed humps. Adding speed humps or platforms to arterial roundabout entrances should have no measurable effect on chassis or suspension wear.

7.7.5 Braking and load-sharing

Some industry sources have suggested that traversing speed humps/platforms will result in load transfers between axles to the extent that the vehicle will no longer meet legal braking requirements. This issue is quite complicated to analyse but, in general, this effect should not occur.

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9 'Rough roads' are those with International Roughness Index values well above 5m/km or National Association of Australian State Road Authorities values above 150 counts per km. These generally would be sealed roads that have deteriorated to a point where some rehabilitation work is needed.

Larger trucks and trailers generally have groups of axles to enable them to carry higher weights. Axles within a group are usually required to be load-sharing, which means they must have a mechanism for equalising the load between the axles. (The main exception to this is trucks that have two steering axles at the front which are not required to be load-sharing). The nature of the load-sharing mechanism depends on the type of suspension. Mechanical suspensions with steel leaf springs usually share loads through mechanical linkages. These have a rapid response time but, because of friction in the joints, often do not achieve perfect load-sharing. Air spring suspensions, which are now dominating the fleet, share loads by equalising the air pressure between the axles. The air line connecting the suspensions on adjacent axles is usually not very large and thus the equalising process may take several seconds or more.

A typical speed hump is about 3.7m long and the distance over which the rise occurs is 1.85m. Speed platforms typically have a gradient of 1 in 15 and thus if the height is 75mm, the rise distance is about 1.125m. The typical axle spacing for a group is 1.3–1.4m, so for a platform, the first axle may already have mounted the platform before the next axle reaches the beginning of the rise. On the basis of a 1 in 15 gradient, the height difference between adjacent axles in a group will be about 90mm. At a 15km/h approach speed, an axle will take between 0.27s and 0.44s to reach the top of the platform or hump (at higher speeds, the time will be less). Within this timeframe, a mechanical suspension will share the load but a typical air suspension will not.

The load-sharing mechanism on a mechanical suspension can only accommodate a modest height difference between the axles. Once the height difference exceeds this value, the spring on the higher axle will compress and that on the lower axle will extend, and the load will be transferred. The vertical stiffness of mechanical suspensions ranges from about 1400N/mm to 2500N/mm on a per axle basis (Fancher et al 1986). For a tandem axle group loaded to 16 tonnes, complete load transfer (ie lift-off of the rear axle) will occur for spring compressions between 30mm and 60 mm depending on the spring stiffness. Because the other spring is extending by the same amount, this corresponds to a height difference between the axles of 60–120m above the height difference allowed by the load-sharing mechanism. The higher values are theoretical because, generally, steel springs do not have this much travel. At lower axle loads, the spring compression needed to achieve complete load transfer is proportionately less. Thus in many cases, the load will be completely transferred onto the leading axle as the vehicle mounts the speed hump or speed platform.

With air suspensions, the load-sharing mechanism does not have time to come into effect. However, the springs are much softer (250–1200N/mm per axle (Fancher et al 1986) and so the amount of suspension travel required to achieve complete load transfer is much larger at 65–300mm, which corresponds to a height difference between the axles of 130–600mm. Again, the larger values are theoretical because the suspensions do not have this much travel. Air suspensions adjust their stiffness in response to load changes and so this situation does not change with a reduced load. As the maximum height difference between adjacent axles is expected to be 75–90mm when mounting a speed hump or platform, for typical air suspensions with a stiffness of 700N/mm per axle when laden, the load transfer will be about 33–40%.

Normal in-service braking will be unaffected. Jarvis (1989) monitored the braking behaviour of heavy vehicle drivers in Australia and found that the maximum deceleration used was a little over 1.2m/s^2 (0.12g) on average. Very few maximum decelerations exceeded 3.5m/s^2 (0.35g). Even with one axle off the ground, a heavy vehicle with a compliant brake system will easily achieve these decelerations. Although, in theory, emergency braking performance could be affected, the circumstances are very unlikely. The vehicle should be approaching the speed hump or platform at below 30km/h (below the speed defined for the testing the braking requirements). Furthermore, the duration of the axle load transfer is relatively short. Finally, although the minimum requirement is that the vehicle can achieve a deceleration of 0.5g, individual axles can normally generate greater braking force than this. Note that the braking requirements are that the vehicle can stop within 7m from 30km/h on flat, level ground. The vehicle is not required to achieve this stopping distance while traversing a speed hump or platform.

7.7.6 Vehicle dynamics

Like any mechanical system, a vehicle has natural vibration modes which can be excited by applying forces. The main modes of interest here are the bounce and pitch of the vehicle body. These typically occur at frequencies between 1.5Hz and 4Hz, depending on the mass of the vehicle and the stiffness of the suspension.

If we consider a truck of wheelbase, w (m), passing over a speed hump at a speed of v (m/s), then the excitations at the front and rear axle sets will occur at an interval of w/v seconds. This will excite a bounce mode of v/wHz and a pitch mode of $v/2w$Hz. Consider a vehicle with a wheelbase of 5m travelling at 5m/s (18km/h). This would excite a bounce mode of 1Hz and a pitch mode of 0.5Hz. Both these values are below the normal truck modes and no significant response would be induced. Increasing the speed and/or reducing the wheelbase would increase the frequency of the exciting forces. Thus, traversing a speed hump at 36km/h would excite a 2Hz bounce, which may coincide with the natural response of the vehicle and thus be amplified. The truck's suspension will have a significant damping effect and this response will decay quite rapidly (in two or three oscillations).

Speed platforms that are designed to be longer than the wheelbase of the expected vehicle types will ensure that no interaction takes place between the excitation which occurs when mounting the platform and that which occurs when dismounting. This may be desirable for bus passengers in particular.

7.7.7 Safety and stability

When a vehicle travels through a curve, a sideways force is generated which is resisted by the tyres adhering to the road. In normal circumstances, if a passenger car travels too fast through a curve, it reaches the limit of the adhesion between the tyres and the road and begins to slide. If a loaded heavy vehicle travels through a curve too fast, it reaches the limit of its stability and the inside wheels lift off the ground, signalling the onset of rollover. This occurs at significantly lower speeds than loss of adhesion. Heavy trucks in New Zealand are required to achieve a static rollover threshold (SRT) of 0.35g. This means they must be able to withstand a sideways force of 0.35g without rolling over. Good driving practice would aim to keep the sideways force below half of the rollover limit to ensure a good margin of safety.

On roundabouts, the pavement surface often slopes radially outwards to facilitate drainage. However, this has a negative effect on rollover stability. A 3% adverse cross-slope means that a vehicle that had an SRT of 0.35g now has an effective SRT of 0.32g (0.35 – 0.03). Good driving practice would then suggest that the driver should aim for a maximum sideways force of 0.16g. For a two-lane roundabout with a 12.5m inner radius, a vehicle in the outer lane will be going through a curve with a radius of approximately 18m. For a curve of this radius, a sideways force of 0.16g is achieved at a speed of 19km/h. Thus the desirable maximum speed for a loaded truck with the minimum level of rollover stability is only 19km/h. On the inner lane where the radius is approximately 14.5m, the maximum desirable speed is only 17km/h.

Thus introducing speed humps or platforms at roundabout entries will have a positive effect on controlling the traversing speeds of trucks to safer levels.

7.7.8 Noise

This is primarily a problem with mechanical suspensions and is worse for less loaded vehicles. Steel leaf springs are typically not fixed to the vehicle chassis at both ends. The ends are held captive within a spring hanger and the chassis is fitted with 'slipper' pads which rest on the spring ends. If the axle becomes unloaded, the spring separates from the chassis and is retained within the spring hanger by a pin which limits how far it can drop. As noted in section 7.7.5, with mechanical suspensions, particularly with less loaded vehicles, the rear axle in a group will tend to lift off the ground as the vehicle mounts the speed hump or platform. The springs then drop from the slippers to the pins. As the vehicle crests the hump or platform, the load returns to this axle and the spring moves back from the pin to the slipper. Leaving the hump or platform, the same thing occurs with the front axle of the group. Typically, the gap between the bottom of the spring and the pin is 15–30mm, and this motion causes a rattling noise.

Air suspensions do not exhibit the behaviour as described above. Increasingly more of the national truck fleet are using air suspension and this problem is reducing over time. According to a source at Isuzu, which is the market leader in truck sales in New Zealand, almost 100% of new large trucks sales used for freight operations for the past five years are fitted with air suspensions. However, these types of vehicles have a relatively long life, so existing vehicles could be expected to be around for some time. About 80% of the smaller two-axle trucks sold have mechanical suspensions but these have only one drive axle and do not generate noise through the load-sharing mechanism described above, except if driven at excessive speeds. More than 80% of 6 × 2 trucks (three-axle trucks with only one drive axle and a tag axle at the rear) are air suspended. However, a proportion of 6 × 4 trucks (three-axle trucks with both rear axles driving) and their trailers, particularly those used as tipper trucks or concrete mixers, are fitted with a type of mechanical suspension that is potentially the noisiest.

A way of assessing the noise effects at a particular location being considered for a speed hump or platform could be to review truck volumes by type, time of day and proximity to sensitive activities.

7.8 Emergency vehicles

One acknowledged negative effect regarding the use of vertical deflection devices is that they can cause delays to emergency vehicles such as fire appliances and ambulances. These vehicles may have to negotiate them slowly both for the welfare of passenger patients, and also in order to avoid damage to expensive onboard equipment. Delays of up to around 10 seconds per device are cited in a review of this topic from the US (Bunte 2000), which also documents evidence of damage to fire appliances based in districts with high numbers of speed humps.

In the context of using vertical speed hump type devices near roundabouts, the issue of delays to emergency vehicles is not expected to be of great significance, since they are likely to be isolated treatments rather than area-wide. However, St John's Ambulance would prefer them not to be located close to ambulance stations where a greater number of call-outs may be adversely affected. The New Zealand Fire Service also would prefer as low a profile device as possible.

We contacted representatives from the police, the fire service and ambulance operators (table 7.2) and asked them the following:

- whether their organisation had any objection to the use of vertical deflection devices (minimum 75mm high) at main road roundabouts and, if so, why
- if the organisation preferred (or at least had less of a problem with) a particular type of vertical deflection device.

Table 7.2 Representatives from the emergency service providers contacted for their opinion on vertical deflection devices

Individual	Role	Organisation
Brian Davey	National Manager Operational Standards	New Zealand Fire Service
Sergeant Ian Brenchley	Strategic Traffic Unit Henderson Police Station, Waitakere	NZ Police
Murray Holt	Assistant Regional Operations Manager	St John's Ambulance

The responses were as follows:

> *Fire appliance design allows for a ground clearance in front of, between and behind axles of approximately 300mm minimum. Vertical deflection devices (speed humps?) have been installed in many urban streets for a number of years,* [and] *there has been no reported issues by Fire Service personnel with regard to these. Distance from the roundabouts would appear to provide sufficient visibility to allow time to slow down before crossing the device and entering the roundabout.*
>
> *We have no experience on particular device types, and would suggest that the larger (100mm high) [devices] would potentially be of more concern with regard to possible vehicle damage and greater reduction to response times.* (Brian Davey, New Zealand Fire Service, April 2010)

> *In answer to your two questions, I am not personally aware of NZ Police policy on this matter. I would be surprised if we had one, and if we did, we would support any measures that assisted in reducing road trauma, including vertical deflection devices.*
>
> *My own view on (speed) cushions is that they encourage vehicles to swerve across the road as they approach the cushion so wheels on one side are affected by it. And they have little, if any, effect on motorbikes.* (Sgt Ian Brenchley, Strategic Traffic Unit Henderson Police Station, Waitakere, February 2010)

> *There is no doubt that deflection devises slow ambulance progress through areas where they are deployed. The effect of this has been mitigated to some degree as these devices have only really been deployed in side streets or non-arterial routes.*
>
> *We would have significant concerns if speed humps were deployed on main roads near ambulance stations (*[eg] *Wolverton St New Lynn and the Portage–Wolverton–Clarke St roundabout). These sort*[s] *of speed humps could have the effect of slowing our responses to many thousands of calls each year.*
>
> *I think the concern is around devices that are deployed near ambulances stations, like the New Lynn example I listed. If a device was deployed there, it would affect several thousand responses per year. On an individual basis, a 10-second delay is not a huge concern, but extrapolate that over thousands of responses and this will significantly reduce* [the] *average response time percentages that we are required to meet.*
>
> *There are also areas we respond to where one speed bump would not be an issue, but multiple speed bumps are. For example, there is a speed platform at the intersection of*

New Windsor and Blockhouse Bay roads and then multiple speed bumps in some of the side streets off New Windsor Road. An ambulance travelling to a call in this area can sometimes be required to cross many speed bumps and this cumulative effect significantly slows their response. (Murray Holt, St Johns Ambulance, St John Northern Region, April 2010)

7.9 Noise effects

7.9.1 Summary

Installation of vertical deflection devices can potentially increase adjacent noise levels to a noticeable degree, the extent to which can be largely dependent upon the volume and speed of the heavy vehicles traversing them. Research from the UK (see section 7.9.2) and an acoustic study of speed humps in a residential street in Waitakere, Auckland, demonstrate this. However as discussed in section 7.7, in the context of the lower expected speeds of heavy vehicles at roundabouts, it is the steel leaf suspension of lightly laden vehicles that is the most likely source of adverse noise effects.

Research from the UK (see section 7.9.2) also indicates that flat-top platforms can be expected to increase perceptible noise levels most greatly for roads with reasonable proportions of heavy vehicles, compared to round-top speed humps or speed cushions.

7.9.2 Research from the UK

A 1996 advisory leaflet from the UK entitled *Traffic calming: traffic and vehicle noise* took results from several studies undertaken in the early 1990s looking at traffic noise adjacent to speed hump and cushion schemes (DfT 1996a). It concluded that although installation of road humps and speed cushions will generally reduce maximum noise levels from cars, increases in noise from the bodywork of heavy vehicles can off-set these. The net effect of vertical devices on overall traffic noise will depend upon the proportion of large commercial vehicles as well as the speed these vehicles travel at. For example, for a road with 20% heavy vehicles, the adjacent traffic noise might be perceived as double that prior to a 75mm high flat-top hump being installed; for only 5% heavy vehicles, the difference may be only just perceptible.

An acoustic comparison was made during TRL track trials between differing profiles: speed cushions (both wide and narrow), a flat-top road hump (ie a speed platform) and round-top road hump. Some of the results are illustrated in figures 7.16 and 7.17, and tables 7.3 and 7.4. In summary, it was found that provided heavy commercial vehicles travel at around 20km/h or less, 75mm high round-top humps offered the best performance: overall traffic noise levels only started to increase once the proportion of large commercial vehicles exceeded about 20%. However, if the speeds of heavy commercial vehicles were substantially over 20km/h (eg outside normal working hours when traffic flow is light and drivers feel they can drive faster than normal), their acoustic performance deteriorates rapidly and narrow speed cushions offer the best solution to truck noise – although overall traffic speed levels are higher with speed cushions compared to humps. Flat-top platforms are likely to offer the poorest acoustic performance.

Figure 7.16 Comparing different noise levels for heavy commercial vehicles adjacent to different vertical deflection devices (adapted from DfT 1996a)

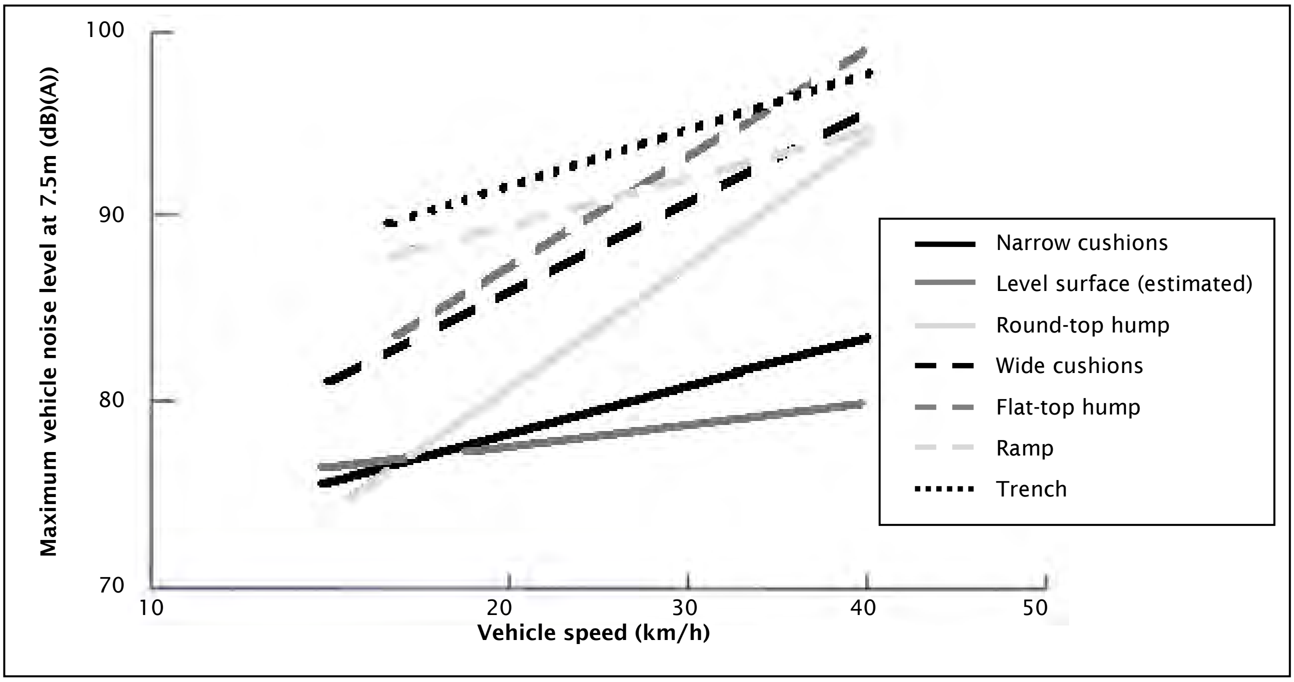
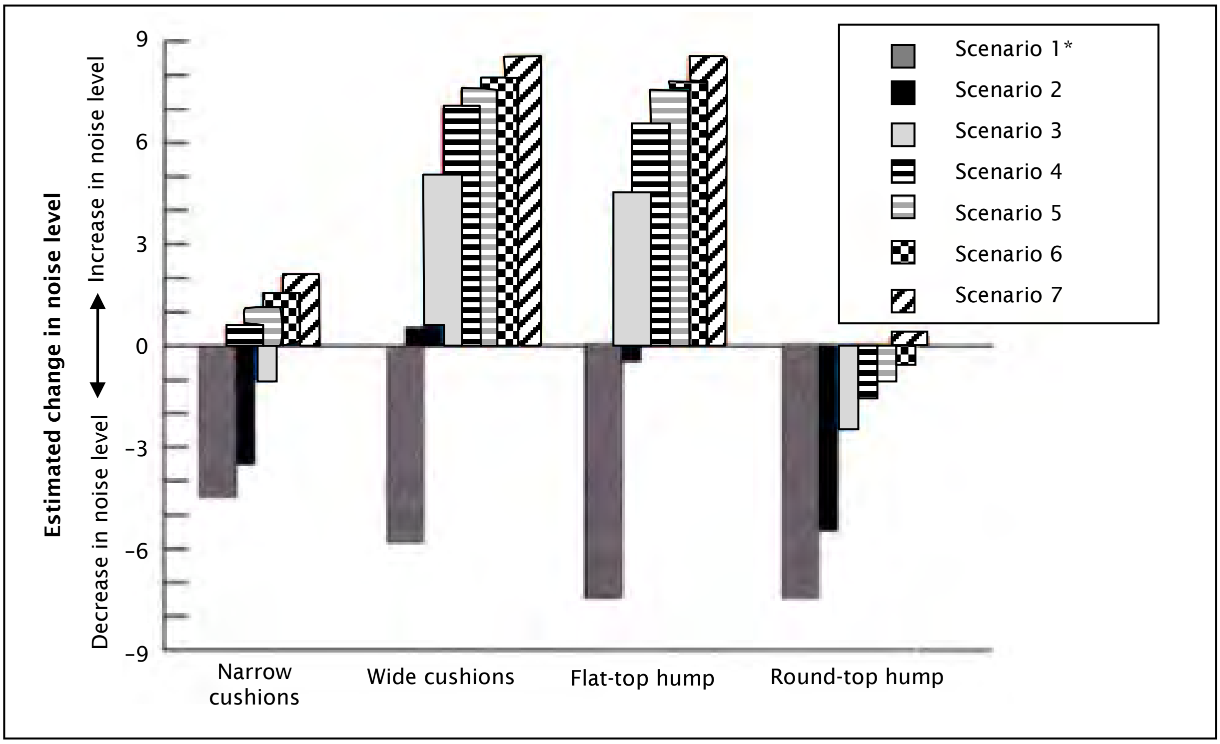


Figure 7.17 Estimated change in noise levels after installing different types of vertical deflection devices for a range of traffic volume scenarios (adapted from DfT 1996a)



*See table 7.3 for the scenarios; table 7.4 shows the typical vehicle speeds for different vertical deflection devices, as changes in traffic noise levels are highly sensitive to changes in vehicle speed.

Table 7.3 Traffic composition scenarios used for the change in traffic noise levels shown in figure 7.17 (adapted from DfT 1996a)

Scenario	Percentage of vehicle type in traffic stream		
	Cars	Buses	Heavy commercial vehicles
1	100	0	0
2	98	1	1
3	94	1	5
4	89	1	10
5	84	1	15
6	79	1	20
7	74	1	25

Table 7.4 Typical vehicle speeds (km/h) for each type of vehicle deflection device considered in figure 7.17

Vehicle type	Level road	Narrow cushion	Wide cushion	Flat-top hump	Round-top hump
Cars	45	30	22	22	22
Buses and heavy commercial vehicles	38	34	24	18	18

7.9.3 Acoustic study in Waitakere City

7.9.3.1 Introduction

In 2008, an acoustic study was undertaken by Marshall Day Acoustics for Waitakere City, in order to compare traffic noise before and after a 100mm high MWP speed hump was installed on a residential street (figure 7.18). Residents sometimes perceive that such devices increase street noise, and this study was instigated as a means of addressing future queries. A full copy of this study is attached in appendix G.

The study used a noise logging device located in the front garden of a Waitaki Street address in Kelston, Waitakere. Noise measurements were undertaken using a sound level meter for the following vehicles in both directions both before and six months after the speed humps were installed:

- local vehicles (mostly cars) using Waitaki Street
- a test bus supplied by Go West buses (figure 7.19)
- a test rental truck (figure 7.20).

The same rental truck and model of bus were used for before/after measurements, and the sound level meter was located 4.4m back from the road kerb edge in line with the centre of the speed hump.

Figure 7.18 Photo showing the assessment site at Waitaki Street, Waitakere. The MWP speed hump is 5m long by 100mm high, and spacing was approximately 100m between each device

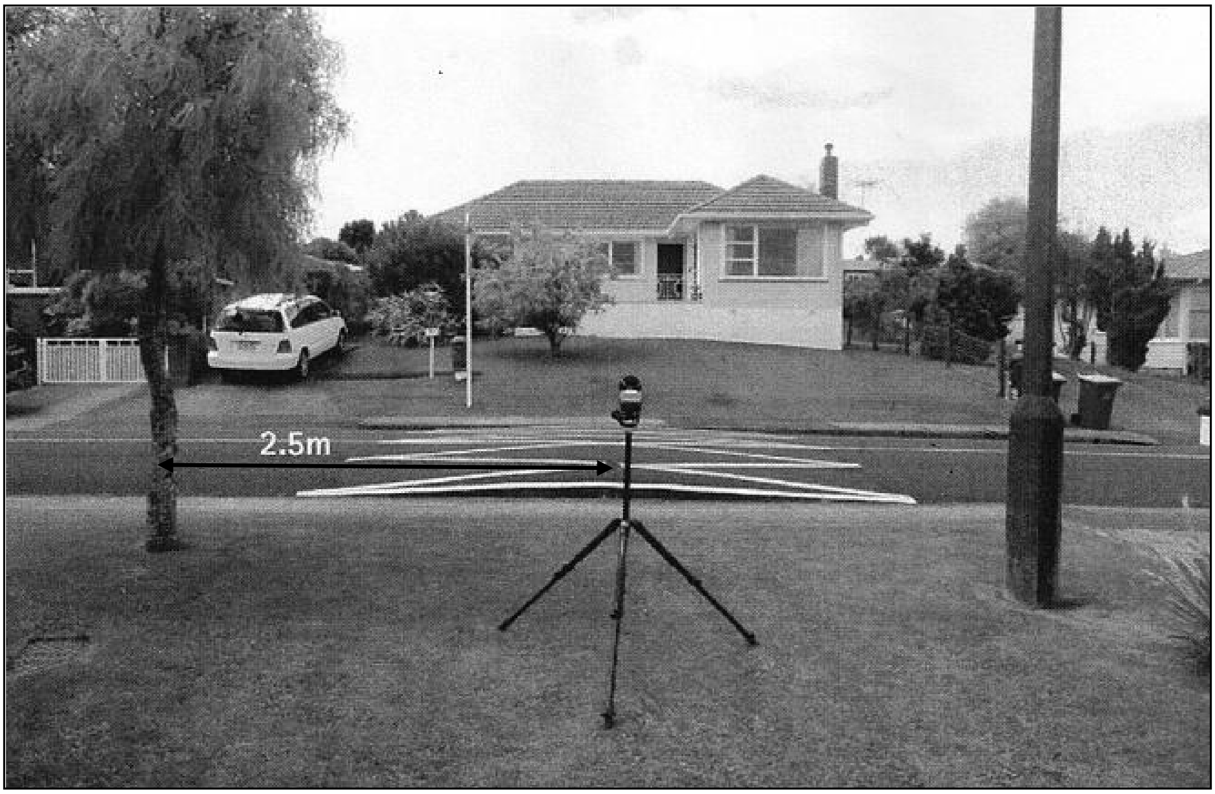


Figure 7.19 The bus used for the acoustic study

Figure 7.20 The truck used for the acoustic study

7.9.3.2 Change in noise levels

The subjective response to a change in noise level is widely variable from individual to individual, and is also different for a change that occurs immediately compared with a change that occurs slowly over many years. The dynamic range of the human auditory system is generally taken to be 0–140dB.

However, to give an indication of the meaning of the changes in noise level, the following general responses to an immediate change in noise are typical:

- An increase in noise level of 10dB sounds subjectively about 'twice as loud'.
- A change in noise level of 5–8dB is regarded as noticeable.
- A change in noise level of 3–4dB is just detectable.
- A change in noise level of 1–2 dB is not discernible.

7.9.3.3 Summary of results

A summary of the results is shown in table 7.5.

Table7.5 Averaged noise level results of the attended sample measurements

Vehicle	Vehicle direction	SEL (dBA)			L_{eq}* (dBA)			L_{max}* (dBA)		
		Before humps	With humps	Change	Before humps	With humps	Change	Before humps	With humps	Change
Single cars	Northbound	78	71	–8	67	61	-6	75	67	-8
	Southbound	76	69	–8	66	58	–8	70	66	–4
Bus	Northbound	80	86	+6	67	73	+6	79	83	+4
	Southbound	78	83	+5	66	69	+3	76	79	+3
Truck	Northbound	78	85	+7	65	71	+6	76	83	+7
	Southbound	78	84	+6	66	70	+4	75	83	+8

*L_{eq} = the time-averaged sound level over the measurement period.

**L_{max} = the maximum sound level recorded during the measurement period.

For individual car noise events, the average reduction in the sound exposure level (SEL)[10] was around 8dB. Reductions of 4–8dB were recorded for average (L_{Aeq}) and maximum (L_{Amax}) sound levels. For most cars, the dominant or controlling noise source was road–tyre interaction noise, which is related to vehicle speed. It was considered that the reductions in noise levels for individual cars were caused by a reduction in road–tyre interaction noise resulting from the decreased mean vehicle speed (an average reduction of 6km/h with the speed humps in place was recorded). It was also noted that most cars cruised over the speed hump without any significant engine revving or noise from suspension or tyres.

For individual bus and truck noise, the SEL increased by around 6dB. A significant increase in the maximum sound level (L_{max}) of 3–8dB was recorded for these vehicles. The observed dominant or controlling noise source for the test bus and truck was engine/exhaust noise (not road–tyre interaction, as with cars). It was observed that the bus and truck braked before each speed hump, coasted over the hump until the rear wheels reached the downhill side of the speed hump, and then accelerated away back to speed. Some brake squeal was audible during braking.

It was concluded that the speed humps had been very effective in reducing the traffic noise generated by cars but any reduction in the overall level was compromised by an increase in the noise generated by heavy vehicles using the route.

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10 SEL is the sound level of one second's duration which has the same amount of energy as the actual noise event measured.

7.10 Ground-borne vibrations

Some UK research was undertaken following some public concerns being expressed relating to damage to buildings close to speed humps as a result of vibrations from heavy vehicles. In summary, it was found that although vibrations could be felt up to 76m away, noticeable damage to buildings would only occur if they were less than 4m away at most.

A 1997 study from the UK (Watts et al 1997) examined this topic in some detail. Measurements of vibrations were made for a wide range of vehicle types crossing a selection of road humps, and the results were used to estimate the likely effects when placed on various soil types. *Traffic advisory leaflet 8/96* (DfT 1996b) was subsequently produced as advice for local authorities to help avoid creating possible nuisances to adjacent residents who might believe that damage would occur to buildings on their property.

Table 7.6 Predicted minimum distances (metres) between road humps and dwellings to avoid vibration exposure (DfT 1996b)

	Hump type	Soil type					
		Alluvium	Peat	London clay	Sand/gravel	Boulder clay	Chalk rock
Level of perception	A	56	16	15	4	2	1
	B	40	13	11	3	1	<1
	C	76	19	18	6	3	1
	D	41	13	12	3	2	<1
	E	45	14	12	3	1	<1
	F	57	16	15	4	2	1
	G	37	12	11	3	1	<1
Complaint	A	12	6	5	1	1	<1
	B	9	5	4	1	<1	<1
	C	17	7	6	1	1	<1
	D	9	5	4	1	<1	<1
	E	10	5	4	1	<1	<1
	F	12	6	5	1	<1	<1
	G	8	4	3	1	<1	<1
Superficial cracks from sustained exposure	A	3	2	2	<1	<1	<1
	B	2	2	1	<1	<1	<1
	C	4	3	2	<1	<1	<1
	D	2	2	1	<1	<1	<1
	E	2	2	1	<1	<1	<1
	F	3	2	2	<1	<1	<1
	G	2	2	1	<1	<1	<1
Minor damage	A	<1	<1	<1	<1	<1	<1
	B	<1	<1	<1	<1	<1	<1
	C	1	1	<1	<1	<1	<1
	D	<1	<1	<1	<1	<1	<1
	E	<1	<1	<1	<1	<1	<1
	F	<1	<1	<1	<1	<1	<1
	G	<1	<1	<1	<1	<1	<1

Notes to table 7.6:

Hump A: cushion; length 2m, width 1.9m, height 0.74m, side ramp 1 in 4, leading ramp 1 in 8.

Hump B; cushion; length 3.5m, width 1.9m, height 0.71m, side ramp 1 in 4, leading ramp 1 in 8.5.

Hump C: cushion; length 3.5m, width 1.9m, height 0.72m, side ramp 1 in 3, leading ramp 1 in 7.7.

Hump D: cushion; length 3.5m, width 1.6m, height 0.64m, side ramp 1 in 3.8 leading ramp 1 in 7.5.

Hump E: cushion; length 3.5m, width 1.5m, height 0.65m, side ramp 1 in 3.7m, leading ramp 1 in 7.4.

Hump F: flat-top hump; length 7.8m, height 0.73m, leading ramp 1 in 12.

Hump G: round-top hump; length 3.7m, height 0.64m.

The report states that ground-borne vibration diminishes as it radiates from its source. The firmer the soil in the vicinity, the more localised will the vibration effects be. Table 7.6 shows that flat-top humps 75mm high and certain cushion profiles gave the maximum ground-borne vibrations for larger vehicles. The highest levels were recorded for unladen vehicles with steel leaf suspension. It was concluded that even very minor hairline cracking should not occur unless road humps are placed less than 4m from a building for even the softest soil, although it is likely that the vibration effects of a heavy commercial vehicle crossing a hump could potentially be felt up to 76m away. Therefore, this issue appears to be mainly one of perception rather than of actual adverse effects to adjacent structures or buildings.

7.11 Potential for traffic diversion onto adjoining streets

Installing vertical deflection devices on any road can introduce delay or discomfort to drivers, who might subsequently choose to use alternative routes in order to avoid them. In the context of speed control at roundabouts, it is expected that one or two devices might not have a significant detour effect unless convenient routes with comparable travel time are nearby.

Some relevant examples are indicated below in figures 7.21–7.23. They serve to demonstrate that when vertical deflection devices are installed in any number, traffic diversion can occur and heavy vehicles, in particular, may be affected.

- Nine raised speed platforms were installed on Ireland Road (figure 7.21) in the 1990s, which had the effect of diverting previously substantial heavy vehicle traffic onto the adjacent Mt Wellington Highway, which, although not too dissimilar in length, has five signalised intersections.
- After several speed humps were installed on Walworth Avenue (figure 7.22) in the 1990s, regular traffic which was using the route to access Marvon Downs Avenue overwhelmingly began to use the longer route on Archmillen Avenue.
- When four speed humps were installed on Hakanoa Street (figure 7.23) in the 1990s, substantial traffic diverted onto adjacent Tutanekei Street until speed humps were installed on that route the subsequent year or so.

Figure 7.21 Ireland Road (dashed line) and the alternate route (Mt Wellington Highway; solid line) taken by heavy vehicles after nine speed platforms were installed on Ireland Road (photos courtesy of Google Maps)

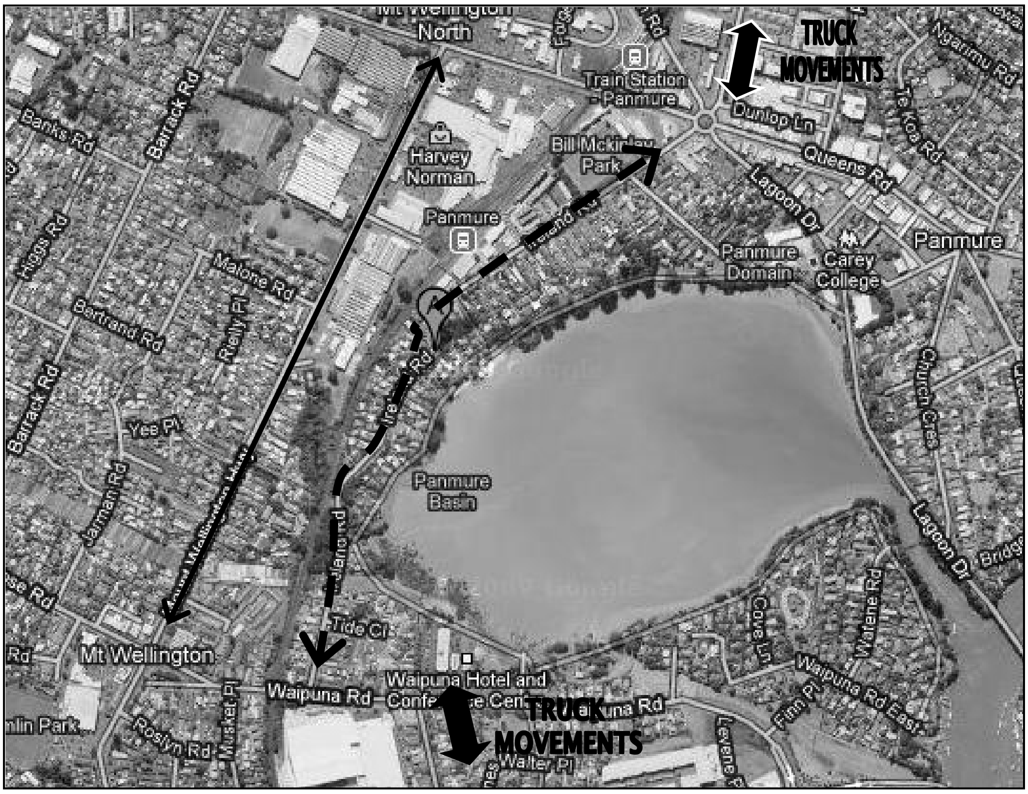


Figure 7.22 Walworth Avenue route (dashed line; speed humps shown as black boxes) and the longer Archmillen Avenue (solid line) (photo courtesy of Google Maps)

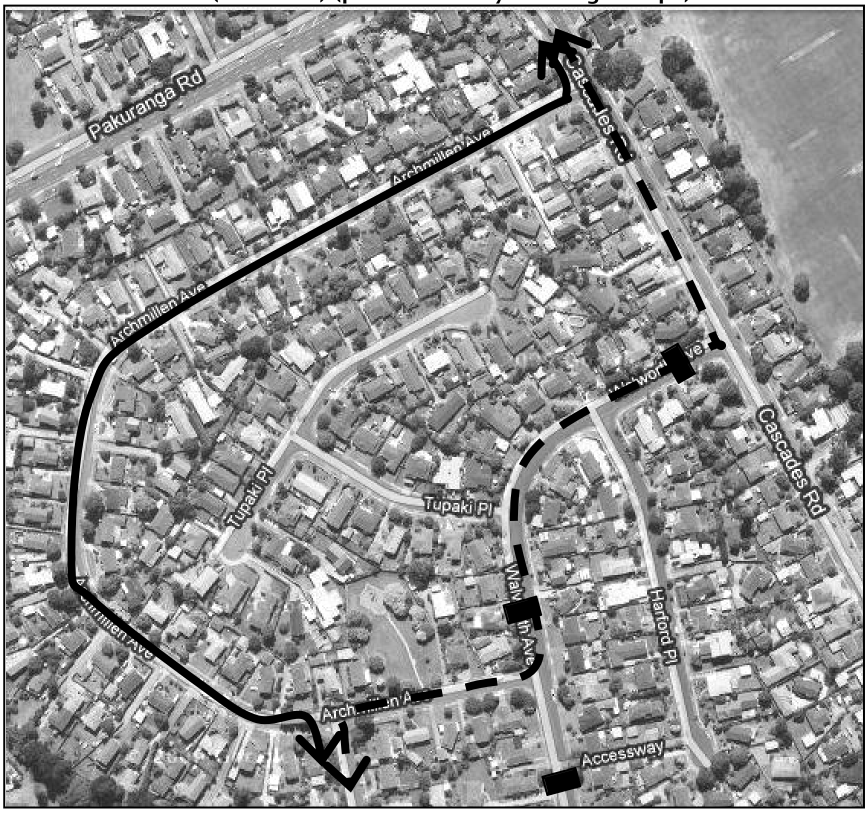


Figure 7.23 Hakanoa Street (dashed line) and the alternate Tutanekai Street route (solid line); both routes now have speed humps (photo courtesy of Google Maps)

7.12 Some roundabout examples using raised platforms

7.12.1 Relevant examples in New Zealand and overseas

Figures 7.24–7.29 show several examples that the authors have identified where platforms have been used at roundabouts in urban areas, all for the safety benefit of pedestrians in particular.

Figure 7.24 Whakahue Street–Tutanekai Street intersection in the Rotorua CBD: here, the entire roundabout (single-lane) is constructed as a raised platform, giving a low-speed environment that is conducive for pedestrians (photo courtesy of Google Maps)

Figure 7.25 The Studholme Street–Thames Street intersection in Morrinsville, Waikato: a single-lane roundabout in the main street of a small town that is effectively at a raised level with ramps on each approach (photo courtesy of Google Maps)

Figure 7.26 The Point England Road–Erima Avenue roundabout in Glen Innes, Auckland, which had raised speed platforms installed on the approaches to improve pedestrian safety in 2009

Figure 7.27 The Cecil Street–Coventry Street roundabout in Port Phillip, Melbourne, Australia: conventional raised platforms with zebra crossings on each of the four arms (photo courtesy of Google Maps)

Note: This site was evaluated before and after the platforms were installed, the overall result being decreased vehicle speeds and a presumed improvement in pedestrian safety (Candappa et al 2008).

Figure 7.28 A multi-lane zebra crossing on a short raised platform at an unidentified roundabout in the US

Figure 7.29 Another view of the multi-lane roundabout shown in figure 7.28

7.12.2 Roundabouts in Malmö, Sweden

The Swedish city of Malmö has recently constructed several multi-lane roundabouts with raised platform treatments for pedestrian and/or cyclist crossing points. An interesting difference here, though, is that they have used short ramps on the approach direction to each crossing point; and for the departure direction, the platform is ramped off at a slight gradient (see figures 7.30–7.35). This method of construction achieves a similar effect to that of a raised intersection treatment, in that it minimises the discomfort to road users (particularly bus passengers) while still maintaining a measure of speed control. This concept is considered to hold great potential for application in New Zealand.

The approach ramps used by RCAs in Malmö use are 100mm high with a 1 in 13 gradient (or typically 6–8%; figure 7.30). This ramp profile is considered to achieve good vehicle speed reduction without any potential adverse health effects to bus drivers who repetitively traverse them (Johansson et al 2009). The lengths of departure ramps are variable, but are generally in the order of 5m to achieve a gradient in the order of 1 in 50 (2%). Compared to a raised intersection (see figures 7.24 and 7.25), this would appear to be a relatively cost-effective method of achieving a similar result. Most examples so far have been received well by residents of Malmö, although one of these examples is located within 100m of residential housing. However, one installation on a main street did receive complaints regarding noise and vibration – the design engineer related this particular instance to an insufficient gradient on the approach ramp about 1 in 20 or 5%), which was resulting in higher than desirable heavy vehicle speeds when these hit the platform.

At least one of these roundabouts with platforms replaced a traffic signalised intersection, which, despite some initial hesitance from elderly pedestrians regarding crossing safety, has apparently been subsequently well received by them.

Figure 7.30 Rough plan of the approach and departure gradients used in the platform roundabout constructed in Malmö, Sweden

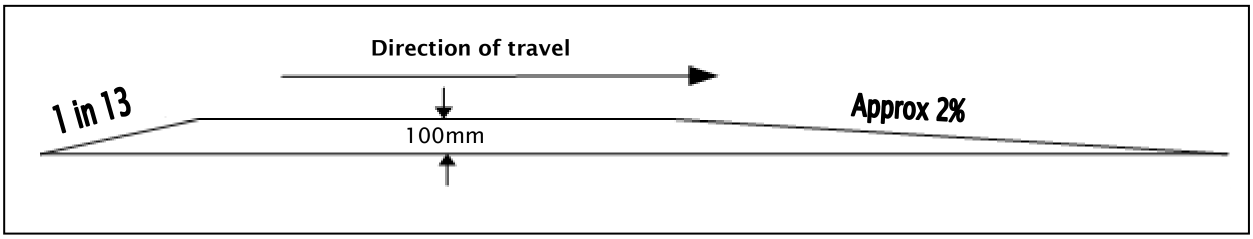


Figure 7.31 Side view of a platform from the Swedish city of Malmö with roundabout exit lanes in the foreground. For entry lanes in the background, this profile is in the opposite direction of vehicle travel. A median island of some length is required to allow for the differing carriageway levels in each direction (photo provided by Transport Department, City of Malmö)

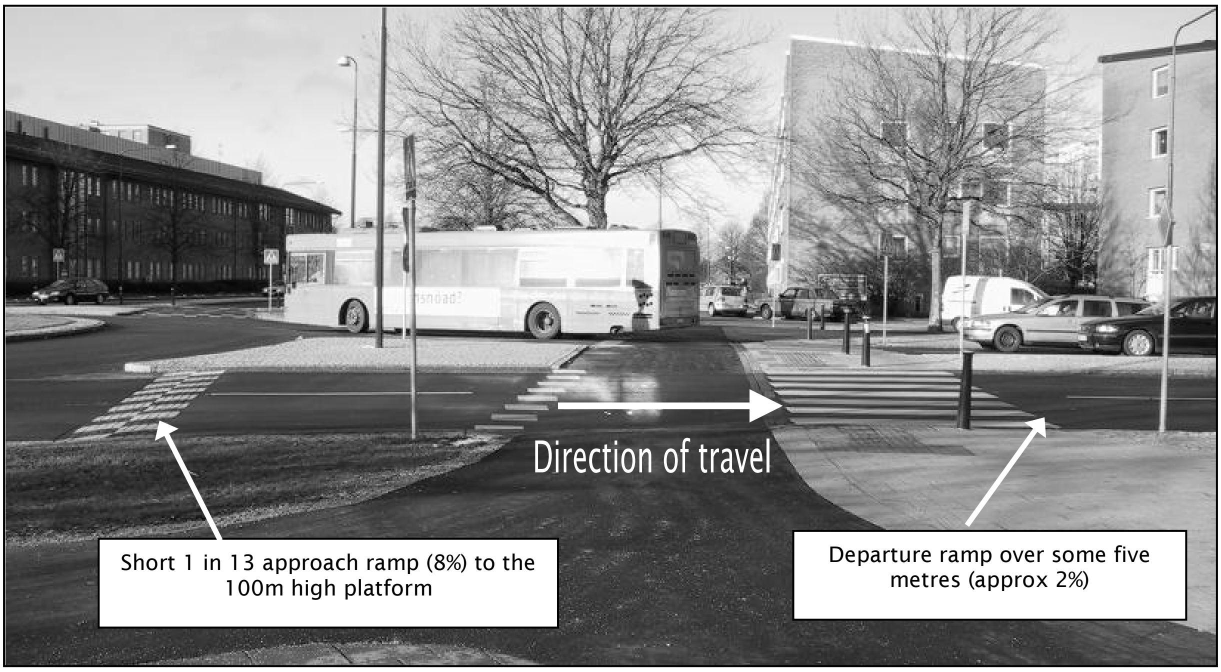


Figure 7.32 The Lorensborgsgatan–Stadiongatan roundabout in Malmö, Sweden (left-hand drive): 100mm high raised platforms are provided on each arm to facilitate the pedestrian and cycle path crossing points around the perimeter of the roundabout (photo provided by Transport Department, City of Malmö)

Figure 7.33 Lighting arrangements on the central island of the Lorensborgsgatan–Stadiongatan roundabout, demonstrating how aesthetics and amenity can be combined

Figure 7.34 Driver views at roundabout entry of the Pildammsvägen–John Ericssons Väg multi-lane roundabout in Malmö, Sweden: this roundabout has off-road pedestrian and cyclist paths on its perimeter as well as through the large planted central island, and has platforms at each crossing point (photo courtesy of Google Maps)

Figure 7.35 Driver view at the exit of the Pildammsvägen–John Ericssons Väg multi-lane roundabout in Malmö, Sweden (photo courtesy of Google Maps)

7.13 Conclusions

Based on this research, the following conclusions have been made with regard to the use of vertical deflection devices at roundabouts:

- Vertical deflection devices can be an effective means of speed control at roundabout approaches, and on these grounds alone should be seriously considered as an option for main road applications in urban speed environments, either as a means of improving pedestrian and cyclist safety or in lieu of geometric means of speed control. For every situation, the positive safety effects should be able to be weighed up against potential adverse effects. Available devices include raised speed platforms, speed humps and speed cushions.

- To better facilitate pedestrian movement on main roads, many local authorities in New Zealand use speed platforms in CBDs and shopping areas, including at single-lane roundabouts. In general, support for the use of vertical speed devices on main roads outside this context is not very enthusiastic. Some expected adverse effects include discomfort to vehicle occupants and bus passengers, noise, vibration and potential for traffic diversion.
- Significant discomfort to vehicle occupants is unlikely to occur if the devices are traversed at appropriate speeds, although they can potentially be a substantial impediment to people with severe back conditions. Guidelines from the UK recommend that flat-top platforms with a maximum height of 75mm and ramps with a 1 in 15 gradient should overcome objections of this nature (DfT 2007c). Speed cushions are the preferred device to cater for ambulances and bus routes in order to minimise passenger discomfort.
- Vertical deflection devices on roundabout approaches are expected to have no measurable effect on heavy vehicle chassis or suspension wear, and should have a positive effect on controlling truck speeds to safer levels. Overseas reports of fatigue damage to trucks or buses relate to routes with significant numbers of devices, rather than isolated installations such as at a roundabout.
- Increased noise may be generated by some heavy vehicles as they traverse a vertical deflection device, mainly lightly laden vehicles or trailers with mechanical leaf-spring suspension, particularly if they have three axles or more, or with two axles if driven at excessive speed. As the predominance of three-axle trucks sold have air suspension (with the current exception of tipper and concrete trucks), this may not be a significant issue in the future or for many situations. Some deceleration/ acceleration noise may potentially also be generated by heavy vehicles if devices are not located close to the roundabout, where speeds would be expected to be lower in any case. Noise effects for a particular location could therefore be assessed by a review of truck volumes by type, time of day and proximity to sensitive activities, although it may still be difficult to predict if nearby residents might find the noise a nuisance.
- In order to minimise ‘bounce’ effects to heavy vehicles, which can also increase discomfort to bus passengers in particular, speed platforms need to be constructed so they are longer than the wheelbase of the design vehicle, eg longer platforms may be required for routes that cater for articulated buses. Ideally, round-top speed humps should not be located on bus routes, as they can result in double ‘bumps’ for passengers.
- Although the adverse effects of vertical deflection devices on response times for emergency vehicles such as ambulances and fire appliances are acknowledged, overseas reports of this nature relate to routes with numerous devices rather than isolated installations such as at a roundabout. Ideally, vertical deflection devices would not be located near ambulance or fire stations where they will affect a greater number of emergency call-outs.
- Ground-borne vibrations caused by vertical deflection devices are very unlikely to result in structural damage to buildings more than around 4m away at most, but vibrations from heavy vehicles are still likely to be discernible a considerable distance further than this, depending upon local soil type.
- Some cities in Sweden and the US have two-lane suburban roundabouts where speed platforms are used to facilitate safer crossings for pedestrians and/or cyclists. In particular, the speed platform profile used by the Swedish city of Malmö appears to be a very good design that is effective in

controlling speeds while minimising adverse effects. This design could readily be used in New Zealand.

7.14 Recommendations

Based on the findings of this report, it is recommended that RCAs consider the use of vertical deflection devices on main roads more seriously as a means of speed control at roundabouts, and not just in the context of CBDs or shopping centres. They are beneficial for pedestrian and cyclist safety in particular, but can also be used as an alternative to geometric methods of speed control. However, their application does require careful consideration of potential adverse effects. Appendix H gives a practical application of these findings.

Vertical deflection devices could be used for safety reasons more commonly on main roads in New Zealand. It is therefore recommended that the possibility of introducing legislation to require or encourage the more widespread use of less noisy alternatives to mechanical suspension (such as air suspension) on larger heavy vehicles be explored.

8 The Dutch turbo-roundabout

8.1 Background

The turbo-roundabout (figure 8.1) was developed in 1996 by Mr LGH Fortuijn, a lecturer at the Delft University of Technology in The Netherlands. It is a generic spiral-type design with radial entry roads where drivers do not have to change lanes inside the roundabout, and are physically discouraged from doing so via solid lane dividers placed between the approach and circulating lanes. This type of design came about because of concerns in The Netherlands regarding the high vehicle speeds through multi-lane roundabouts, and the sideswipe crashes that can occur between vehicles changing lanes inappropriately on the roundabout. The turbo-roundabout appears to address these safety concerns satisfactorily, and can apparently achieve a substantially higher capacity than conventional multi-lane designs. In the province of South Holland, turbo-roundabouts are apparently considered at intersections where a single-lane roundabout would not provide sufficient capacity, following which a signalised intersection or signalised roundabout is considered (in that order of priority) (V Inman and G Davis 2007).

Figure 8.1 A turbo-roundabout in The Netherlands, showing the typical layout (CROW 2008)

Dutch literature on the turbo-roundabout includes English transcripts on topics of design principles and safety performance (Fortuijn 2009a), and also estimations of capacity (Fortuijn 2009b). A design guideline from The Netherlands for turbo-roundabouts has been available since 2008 and although only Dutch-language hard copy (print) versions currently available, a CD-ROM with a sample pdf and AutoCAD drawings are available (CROW[11] 2008). A report in English which contains some design guidelines for turbo-roundabouts is also available (Royal Haskoning 2009), and a copy of the relevant section of this report is contained in appendix I.

Around 70 turbo-roundabouts have been built in The Netherlands since 1998 (Fortuijn 2009a), and a small number have been installed in other countries. Germany apparently has at least seven of them, and Ruhr –

11 CROW is the standard acronym for Kenniscentrum voor Verkeer, Vervoer en Infrastructuur based in The Netherlands, also known as the Transport Research Knowledge Centre or the Information and Technology Centre for Transport and Infrastructure.

University Bochum is currently in the final stages of a research project on the safety and capacity of turbo-roundabouts (pers. comm. W Brilon, April 2010). Articles evaluating their operation and/or encouraging their introduction have been published in Slovenia (Tollazzi et al 2008), Hungary (van der Wijk 2009), Belgium (Yperman and Immers 2003), Italy (Mauro and Branco 2009) and South Africa (Engelsman and Uken 2007).

8.2 Methodology

This section of the research involved the following tasks:

- reviewing the literature of published articles on this subject, as well as any available video footage of the turbo-roundabout in operation
- consideration of the safety implications of the raised lane dividers to all road users, including cyclists and pedestrians
- consideration of capacity, as some evidence suggests that the turbo-roundabout has greater capacity than a conventional multi-lane roundabout in some circumstances
- evaluating the turbo-roundabout for potential use in New Zealand.

8.3 Design features

8.3.1 General

The main design features (shown in figure 8.2 below) of the turbo-roundabout are:

- radial alignment of approach roads
- spiral alignment of circulating lanes for a fluent driving path that requires no lane changing within the roundabout
- mountable lane dividers to discourage lane changing in the roundabout and to reduce vehicle speeds through the roundabout
- mountable aprons on the inner and outer of circulating lanes for longer vehicles to traverse
- entering drivers yielding to no more than two circulating lanes.

An important point to note is that many turbo-roundabout configurations do not permit U-turn manoeuvres from every direction.

Figures 8.3–8.14 show the range of turbo-roundabout options that have been developed, including their estimated approximate capacity in passenger car units (PCU) (Fortuijn 2009a). Figures 8.15 and 8.16 show some of the more unusual variants, which were identified from Google Maps.

Figure 8.2 Features of a turbo-roundabout (adapted from Fortuijn 2009a)

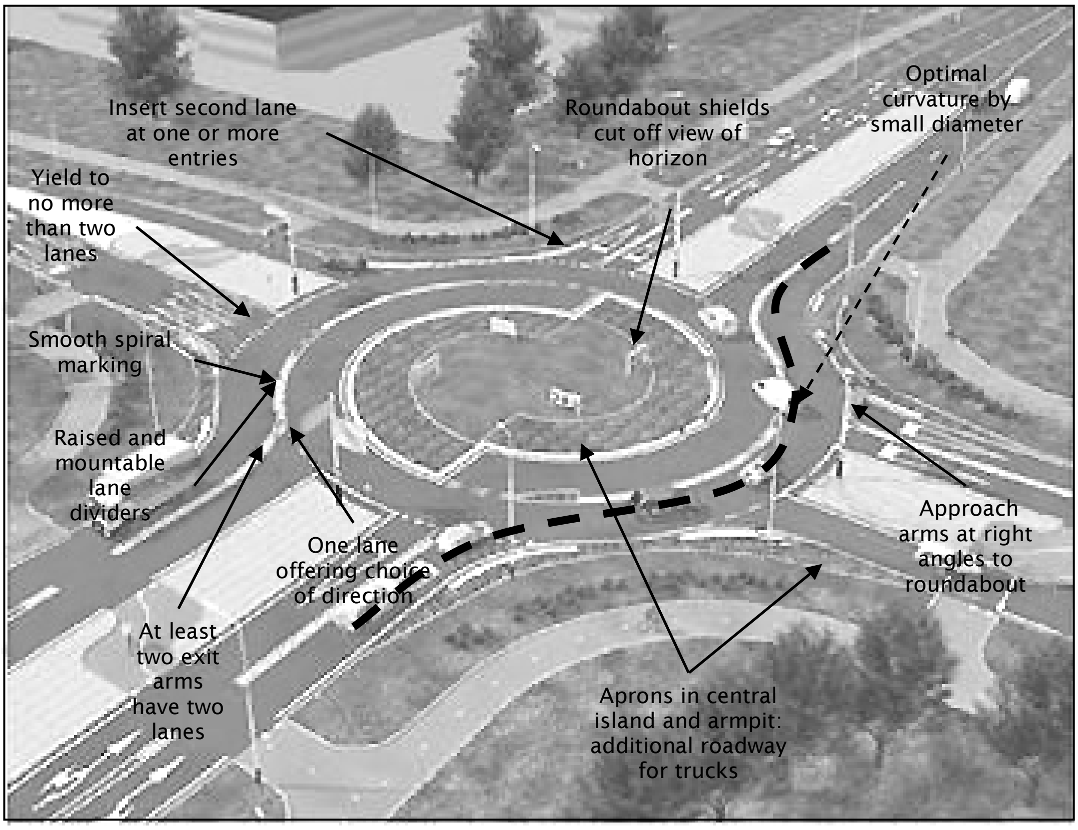


Figure 8.3 The four-arm 'knee roundabout' variant of the turbo-roundabout; capacity = 3500PCU/h; arrows indicate major flows (from Fortuijn 2009a)

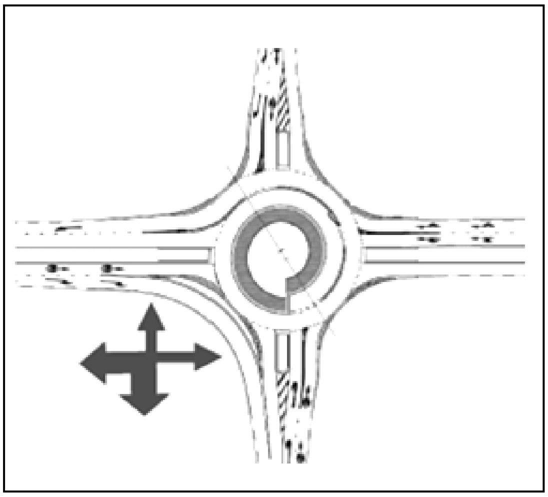


Figure 8.4 Two forms of the three-arm 'knee roundabout' variant of the turbo-roundabout

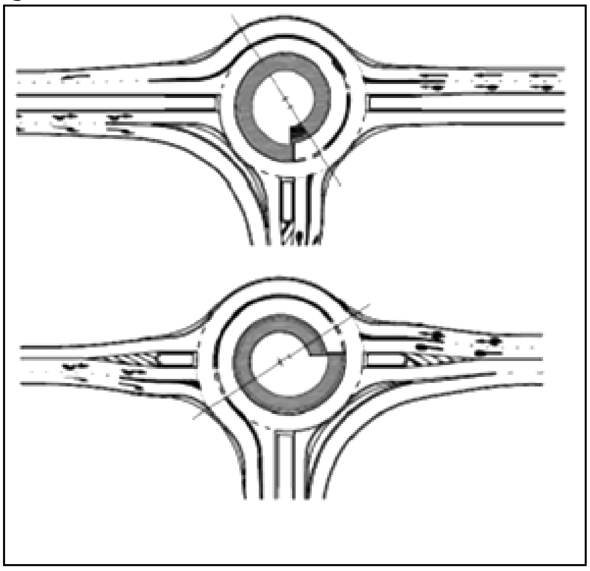


Figure 8.5 The three-arm 'stretched knee roundabout' variant of the turbo-roundabout; capacity 3800PCU/h; arrows indicate major flows (from Fortuijn 2009a)

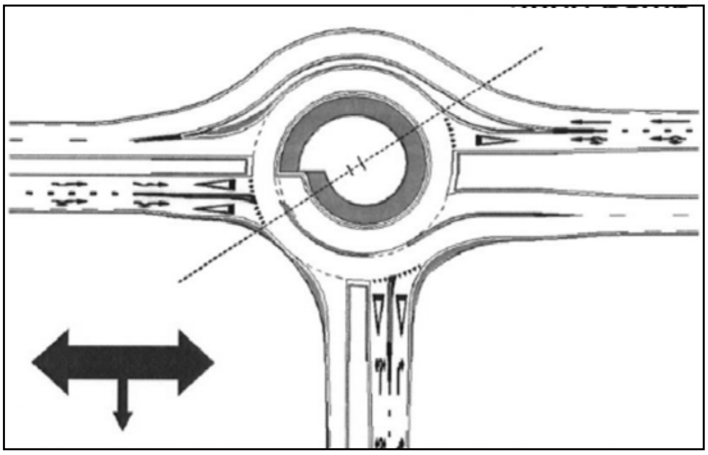


Figure 8.6 The three-arm 'star roundabout' variation of the turbo-roundabout; capacity = 5500PCU/h, translation axes = 120°; arrows indicate major flows (from Fortuijn 2009a)

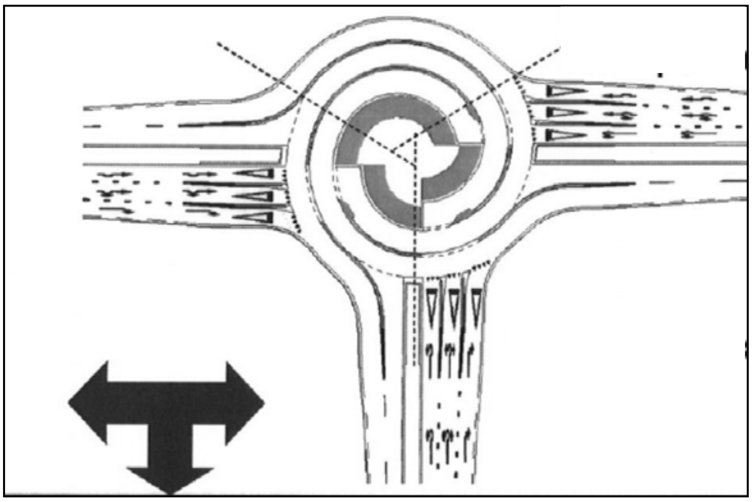


Figure 8.7 Four-arm 'egg roundabout' variant of the turbo-roundabout; capacity 2800PCU/h; arrows indicate major flows (Fortuijn 2009a)

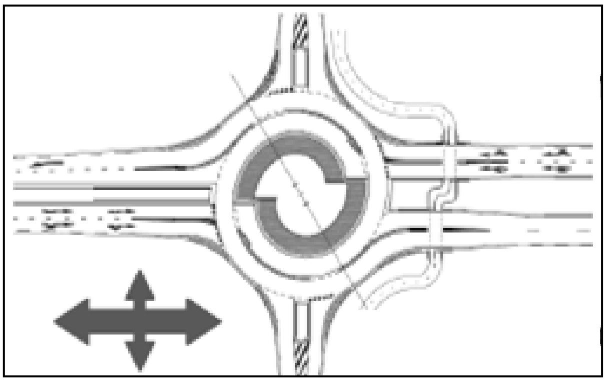


Figure 8.8 Three-arm 'egg roundabout' variant of the turbo-roundabout (Fortuijn 2009a)

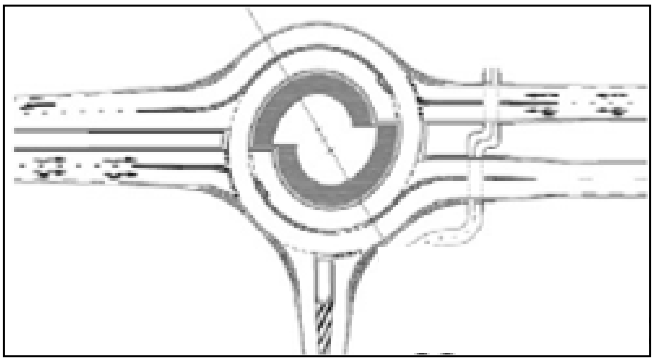


Figure 8.9 Four-arm basic turbo-roundabout; capacity 3500PCU/h; arrows indicate major flows (Fortuijn 2009a)

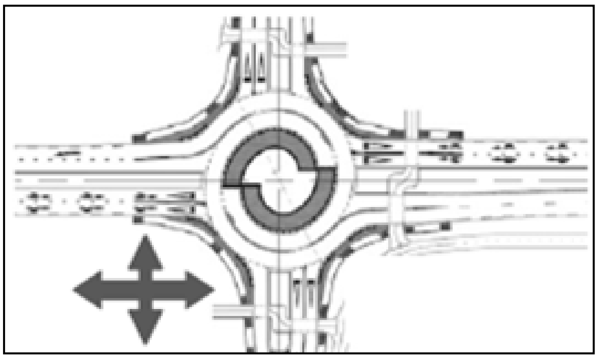


Figure 8.10 Three-arm basic turbo-roundabout (Fortuijn 2009a)

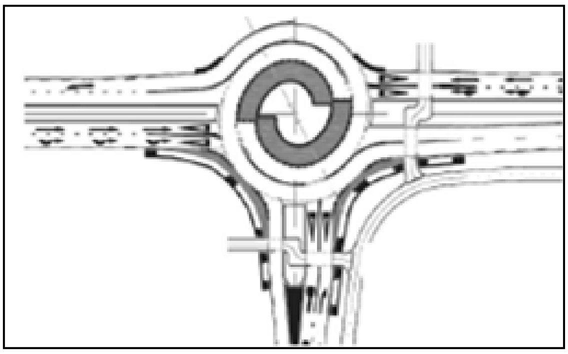


Figure 8.11 Four-arm spiral roundabout variant of the turbo-roundabout; capacity 4000PCU/h; arrows indicate major flows (Fortuijn 2009a)

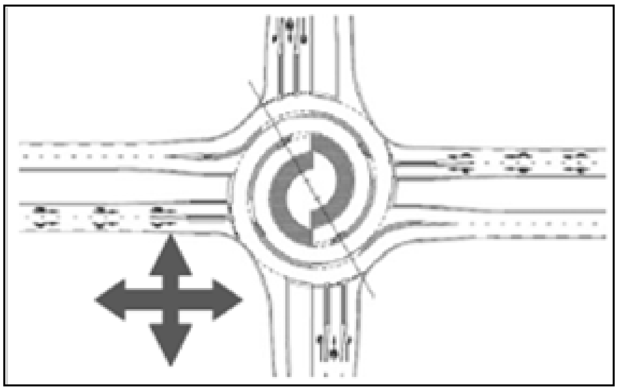


Figure 8.12 Three-arm spiral roundabout variant of the turbo-roundabout (Fortuijn 2009a)

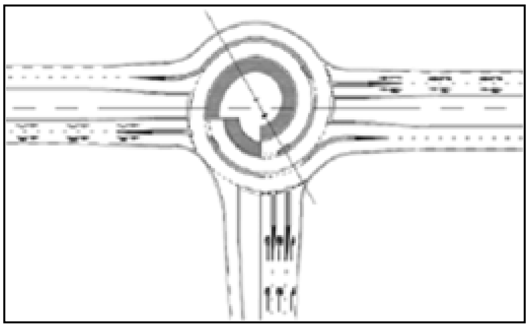


Figure 8.13 Four-arm rotor roundabout variant of the turbo-roundabout; capacity 4500PCU/h; arrows indicate major flows (Fortuijn 2009a)

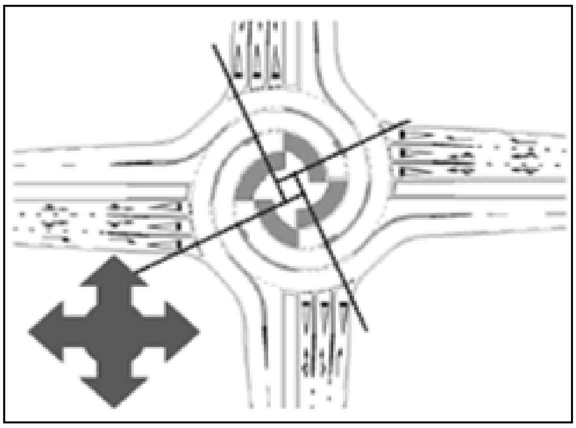


Figure 8.14 Three-arm rotor roundabout variant of the turbo-roundabout; this design is not functional (Fortuijn 2009a)

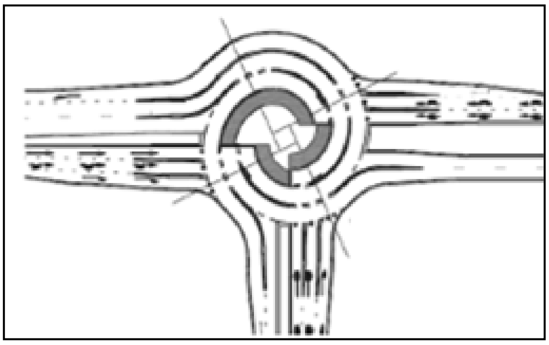


Figure 8.15 Birds' eye view of the Rien Cock Ovonde–Provinciale Weg intersection in The Netherlands (photo courtesy of Google Maps)

Figure 8.16 Street view of the Rien Cock Ovonde–Provinciale Weg intersection: this five-arm junction is best described as a partial turbo-roundabout, as not every approach has lane dividers – a minor road approach with paint markings only is shown (photo courtesy of Google Maps)

8.3.2 Raised lane dividers

One of the major motivating factors for the concept of the turbo-roundabout was the dilemma presented by the conflicting objectives of reducing traffic speeds via geometric means without increasing the chances of sideswipe crashes, which can be caused by increasing vehicle path curvature. The turbo-roundabout achieves this by the application of raised lane dividers as shown in figures 8.17 to 8.20, while figure 8.21–8.23 show the in situ construction process, and figures 8.24 and 8.25 show the lighting arrangements; figure 8.26 shows the results of incorrect construction of the lane dividers. These dividers are high enough to discourage driving over them, but not so high as to cause significant damage to vehicles if the dividers are struck at reasonable speeds. The 70mm high cross-section was arrived at in 1999 following some on-road trials using a variety of passenger car types (Fortuijn 2009a).

Figure 8.17 Cross-sectional view of the standard design for the raised mountable lane divider used at turbo-roundabouts in The Netherlands (measurements are in metres)

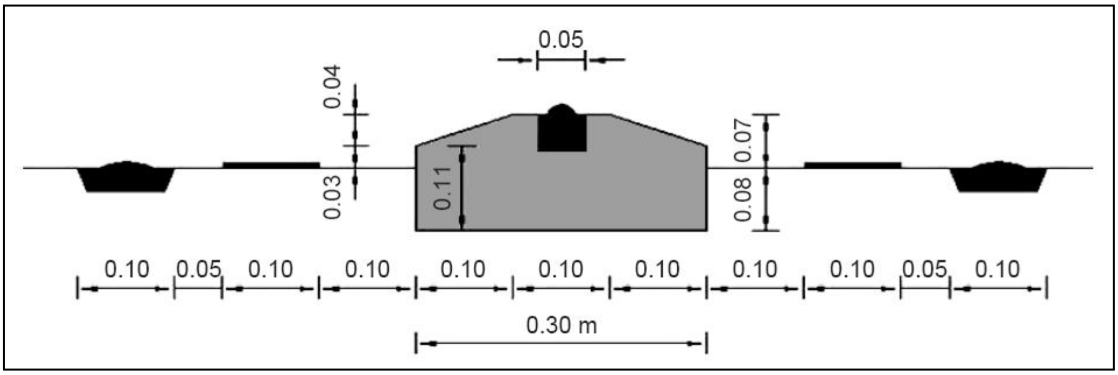


Figure 8.18 Cross-sectional view of a modified design of the raised divider used at turbo-roundabouts to accommodate snowploughs (Fortuijn 2009a)

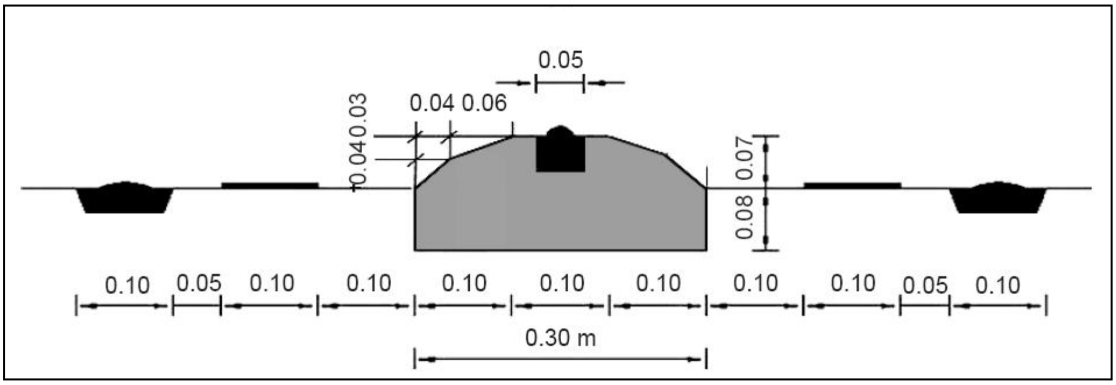


Figure 8.19 Rounded end treatment applied to the lane dividers (CROW 2008)

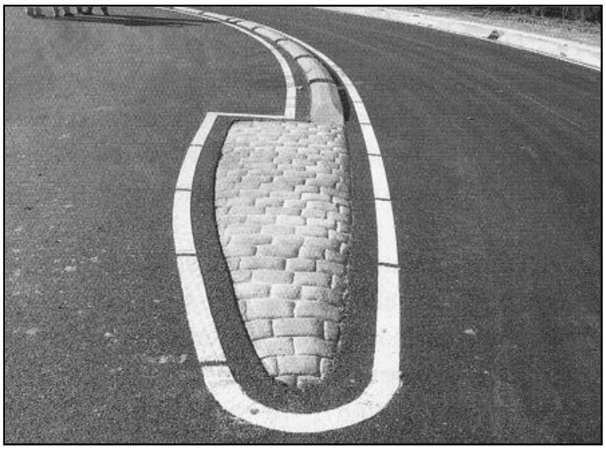


Figure 8.20 Pointed end treatment applied to the lane dividers (CROW 2008)

Figure 8.21 In situ construction of the mountable lane dividers: note the steel reinforcement (CROW 2008)

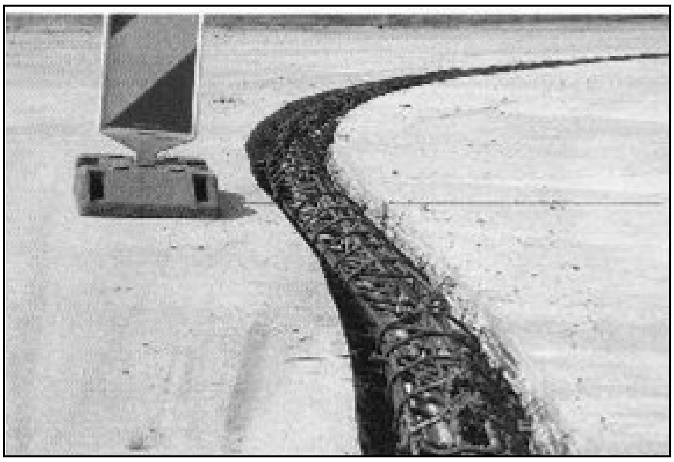


Figure 8.22 In situ construction of the mountable lane dividers: pouring the concrete (CROW 2008)

Figure 8.23 In situ construction of the mountable lane dividers: shaping the dividers (CROW 2008)

Figure 8.24 Wide-angle view of a typical lighting arrangement on the mountable lane dividers at a turbo-roundabout (CROW 2008)

Figure 8.25 Alternative view of the lighting arrangements on the mountable lane dividers at turbo-roundabouts (CROW 2008)

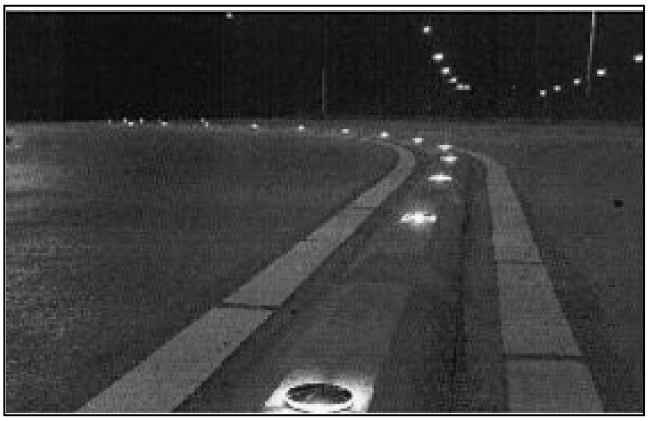
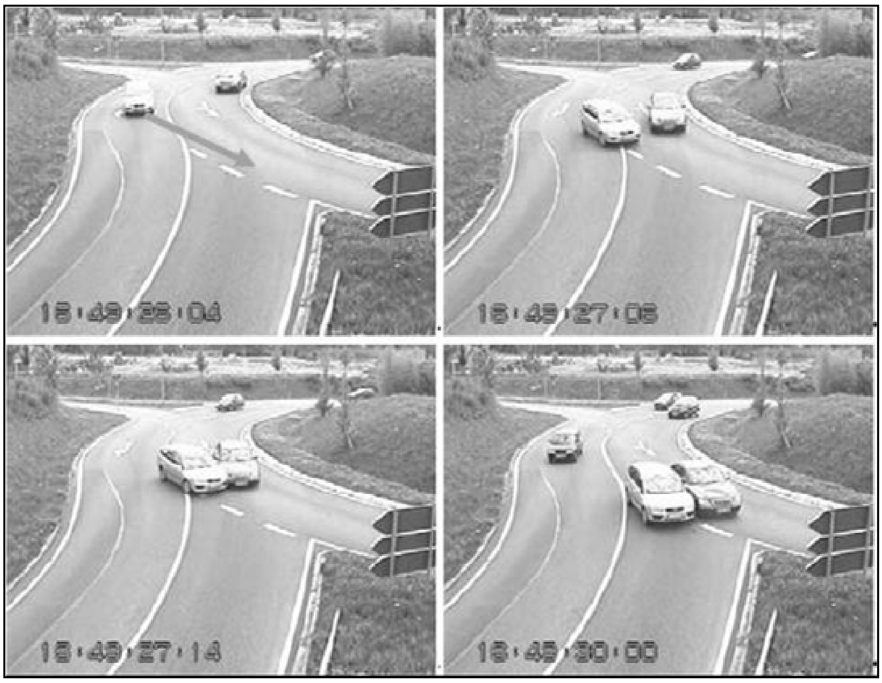


Figure 8.26 Photo of the damage that can occur if lane dividers are glued onto the roadway instead of cast in situ (CROW 2008)

Notably, the German turbo-roundabouts do not use lane dividers (Brilon 2008). The main reason given is that they are not considered necessary for safety reasons – sideswipe type crashes, which generally incur minor vehicle damage only, are not deemed to be a significant concern. Other reasons against using them include the increased cost of construction, perceived safety issues with motorcyclists and snow removal issues in winter. Figure 8.28 shows an example of the type of sideswipe crashes that can occur at the

German turbo-roundabouts without lane dividers, similar to those occurring at conventional multi-lane roundabout designs. In terms of capacity, according to Brilon, the German entry lanes experience near-equal lane use during peak periods, so it was perceived that the lane dividers would achieve little more in that regard.

Figure 8.27 Video clips showing an example of sideswipe crashes occurring at a German turbo-roundabout in Baden-Baden, which does not have the raised lane dividers (Brilon 2008)



8.3.3 Pedestrians and cyclists

Design guides for The Netherlands recommend against providing for on-road cyclists at multi-lane roundabouts (CROW 2008), so turbo-roundabouts are expected to be provided with off-road perimeter paths for these users (see figures 8.28–8.32).

In urban areas of The Netherlands, shared paths can be constructed so that cyclists and pedestrians are given priority over vehicle traffic. However, a Dutch study of cyclist crossings at roundabouts concluded that that cyclist injury crashes could be expected to be significantly higher at these 'cyclist priority' crossings (Dijkstra 2005). This was found upon review of three previous studies that showed 75–180% more cyclist injury crashes at these locations, taking cyclist and traffic volumes into account. In another separate study, it was concluded that double the number of cyclist injuries might be expected (Fortuijn 2005). The provision of 'cyclist priority' crossings in The Netherlands is thus motivated by a desire to attain greater mobility for cyclists rather than an absolute concern for their safety.

For 'cyclist priority' crossings, the authors of this report consider that safety at multi-lane crossings could potentially be an issue that would be exacerbated by the higher approach speed of cyclists compared to pedestrians, even though vehicle speeds may be lower at a turbo-roundabout. Speed platforms at the crossing point could substantially mitigate these concerns. However, at the moment, it is not legal to install 'cyclist priority' crossings in New Zealand, as drivers here are not legally obliged to stop for cyclists at zebra crossings, unless they are dismounted and walking as pedestrians (New Zealand Government 2004). The New Zealand Road User Rule would need to be changed, and this is recommended for review.

Figure 8.28 Turbo-roundabout configuration with perimeter paths for cyclists and pedestrians, using shared path facilities and with vehicle traffic having priority over path users – note the staggered island crossings (circled) to slow cyclists as they cross the carriageway (CROW 2008)

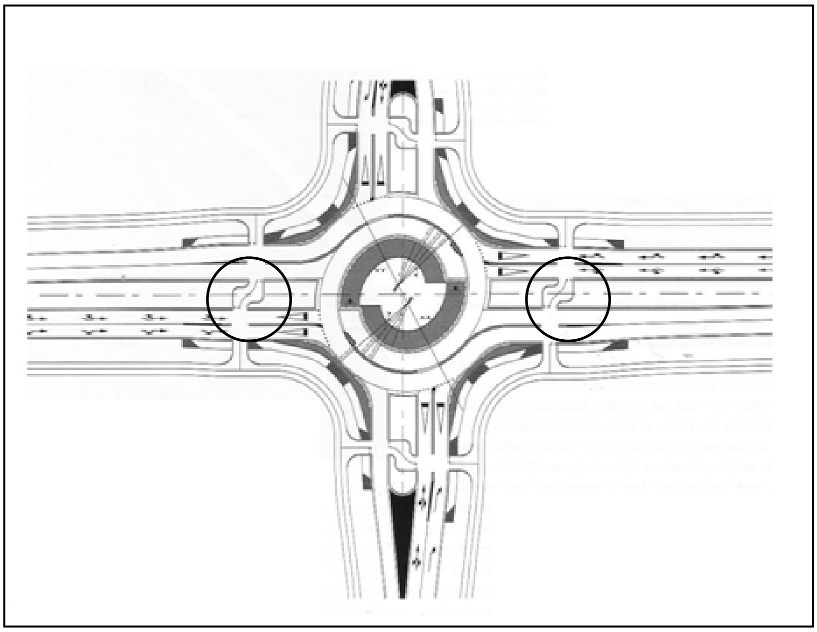


Figure 8.29 Turbo-roundabout configuration with perimeter paths for cyclists and pedestrians; this type is sometimes installed in urban areas, and the separate cyclist (dark grey) and pedestrian paths (black) have priority over vehicle traffic (adapted from CROW 2008)

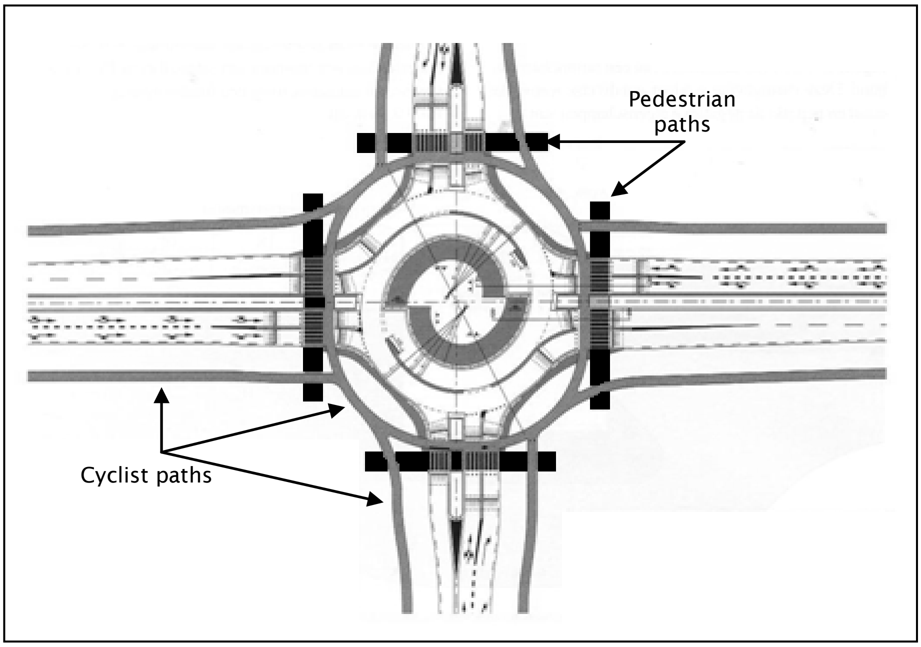


Figure 8.30 Example of a turbo-roundabout with at-grade perimeter paths for cyclists and pedestrians, who have priority over vehicles, much like zebra crossings for pedestrians in New Zealand (CROW 2008)

Figure 8.31 Closer view of the markings of the at-grade perimeter paths for cyclists and pedestrians at a Dutch turbo-roundabout – note the small white triangle markings that denote who has priority of way in The Netherlands (CROW 2008)

Figure 8.32 Cyclist using the at-grade cyclist priority crossings at a turbo-roundabout, with vehicles yielding (CROW 2008)

8.3.4 Motorcyclists

Two-wheeled users such as motorcyclists could potentially be at greater risk at a turbo-roundabout, owing to the presence of the lane dividers, which present a hazard if ridden over. Advance warning signage is duly recommended as shown in figure 8.33 below. Anecdotal evidence from The Netherlands suggests that motorcyclists prefer a turbo-roundabout, as the lane dividers reduce the lane changing behaviour of motorists, which is otherwise a concern at conventional designs (W Brilon, pers. comm. April 2010).

Figure 8.33 Advance warning sign for motorcyclists that reads 'Raised lane dividers' (Royal Haskoning 2009)

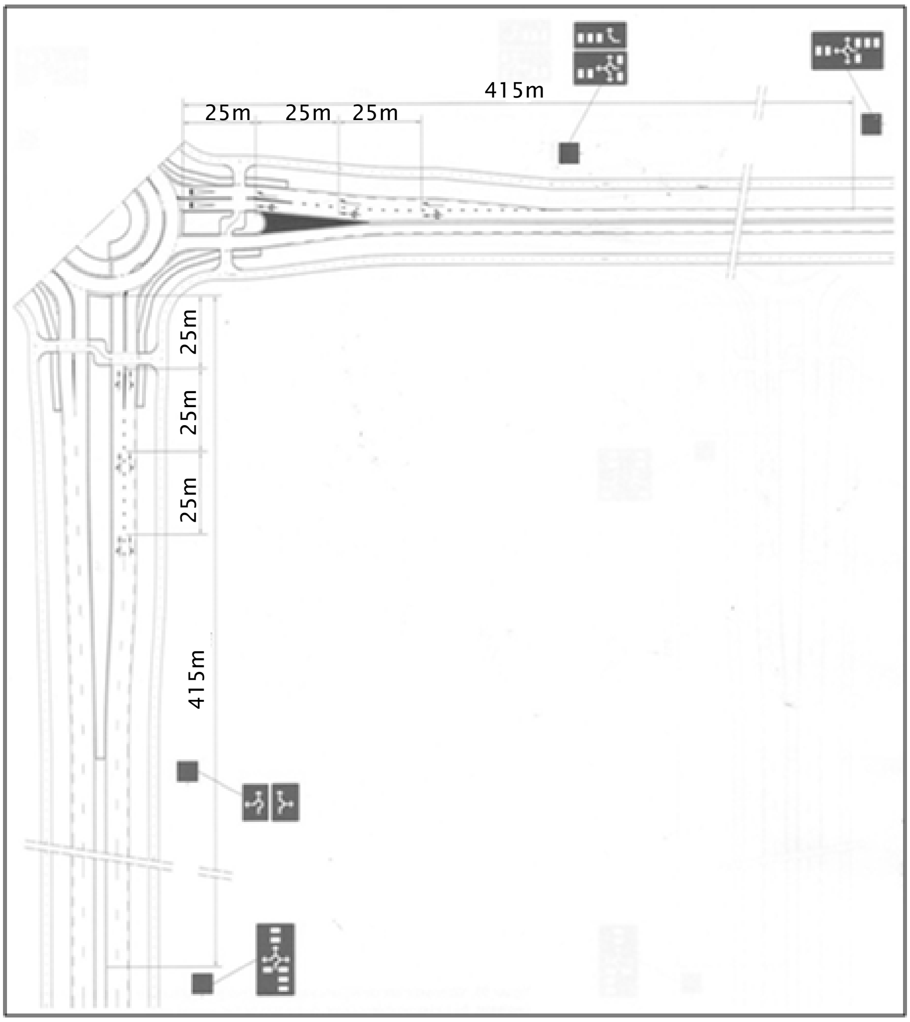
8.3.5 Advance signage and road marking

Because of the presence of the raised lane dividers in particular, some emphasis is put on good advance warning signage and road marking to let drivers know which lane they need to be in well before they reach the roundabout. Some examples of recommended signage are shown in figures 8.34–8.36.

Figure 8.34 Signage to be installed 400m in advance of the turbo-roundabout (CROW 2008)

Figure 8.35 Optional overhead signage to be installed 100m in advance of the turbo-roundabout (CROW 2008)

Figure 8.36 A signage and marking diagram example for a turbo-roundabout from the Dutch guideline document (CROW 2008)



8.4 Safety performance

8.4.1 General

A Dutch evaluation of seven intersections converted to turbo-roundabouts between 2000 and 2002 (including priority controlled, signal controlled and a roundabout) concluded that their crash rate is comparable with single-lane roundabouts which, in turn, are lower than conventional multi-lane types (Fortuijn 2009a). As an indication of the difference in crash rates, according to roundabout crash models from the UK for a roundabout with 10,000 entering average daily traffic (ADT), flaring the entry width from one to two lanes is likely to increase injury crashes by 25% (Bared and Kennedy 2000).

Figure 8.37 shows a Dutch comparison of expected driver speeds. It is understood these figures are calculated rather than measured on site, but the main point is that speeds at a turbo-roundabout might be expected to closely approximate that of a single-lane roundabout with a similar central island diameter. Figures 8.38–8.41 shows a comparison of potential conflict points.

One of the safety measures also emphasised in the 2009 publication by Fortuijn is that the central island should be provided with signs facing the radial approach roads. These are meant to emphasise to drivers that they are approaching an obstacle which can only be negotiated at low speed.

Figure 8.37 Diagram showing a Dutch comparison of expected vehicle speeds and type of roundabout, based on a 7m wide splitter island on approaches (Royal Haskoning 2009)

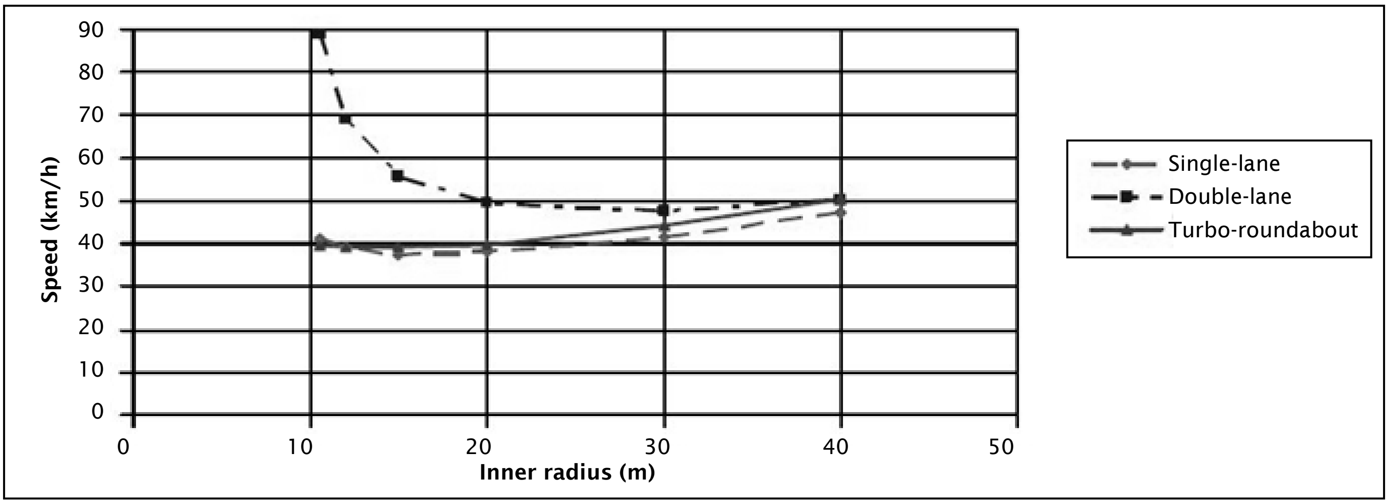


Figure 8.38 Conflict points (four) at a single-lane roundabout from (Royal Haskoning 2009)

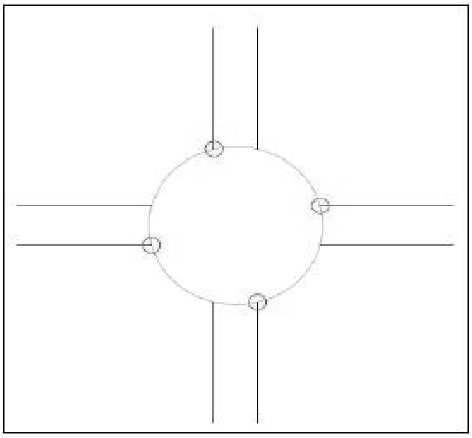


Figure 8.39 Conflict points (16) at a double-lane roundabout with single-lane exits (Royal Haskoning 2009)

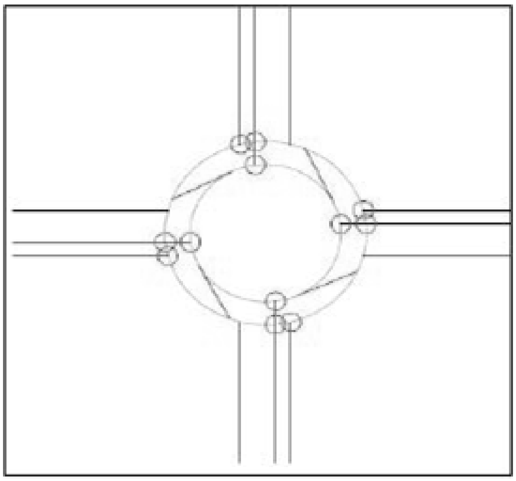


Figure 8.40 Conflict points (20) at a double-lane roundabout with dual-lane exits (Royal Haskoning 2009)

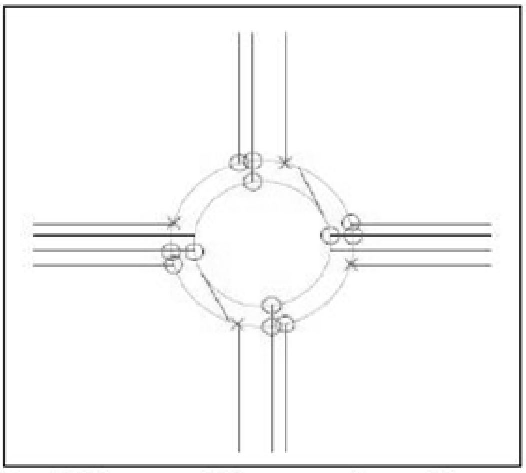
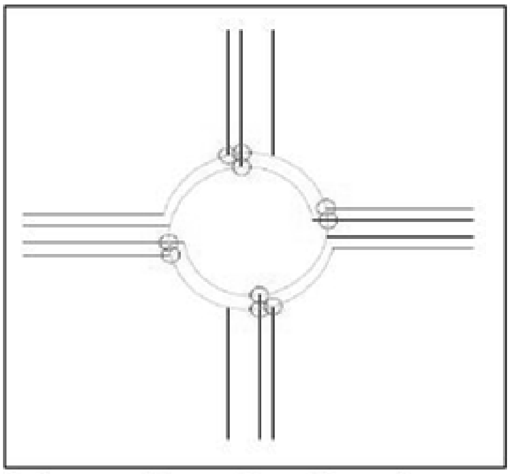


Figure 8.41 Conflict points (10) at a turbo-roundabout (Royal Haskoning 2009)



8.4.2 Sideswipe crashes in New Zealand

As a means of estimating the extent to which a turbo-roundabout may be used to address sideswipe crashes at multi-lane roundabouts in New Zealand, the 20 Auckland roundabout sites from chapter 3 and appendix A were briefly evaluated.

A review of CAS data from 2004–2008 showed 137 reported sideswipe type crashes at the 20 multi-lane roundabouts in Auckland that were studied in section 3.2, or around 21% of all reported crashes within a 50m radius of the intersection (664 crashes total). Just four of these sideswipe crashes involved injury (all minor), comprising 5% of total injury crashes at these locations. The site with the greatest number of these crashes was the Mt Wellington Highway–Vestey Drive roundabout, which has three circulating lanes running in the north–south direction (19 non-injury crashes, or around 33% of reported crashes at this location).

Thus it can be asserted that sideswipe crashes probably comprise a reasonable proportion of crashes at multi-lane roundabouts in New Zealand, and predominantly involve vehicle damage only. On this basis alone, it may be difficult to justify a turbo-roundabout in terms of the additional expenditure, but a lower speed environment should improve safety for pedestrians and cyclists, and also lessen the severity of any vehicle crashes that do occur.

8.4.3 Conclusion

In terms of safety, it would appear that turbo-roundabouts with lane dividers would be a safer alternative to conventionally designed multi-lane roundabouts. The lane dividers would substantially address sideswipe crashes, and the lower speed environment should improve overall safety for all road users. To construct a turbo-roundabout without lane dividers, as has been done in Germany, appears to negate their main safety advantages since the lane dividers create the desired lower-speed environment.

With respect to motorcyclists, anecdotal evidence seems to suggest that turbo-roundabouts from The Netherlands are a preferred design, as they prevent car drivers changing lanes in the roundabout. Clear delineation, advance warning signage and night-time illumination are obviously required for safety reasons; otherwise the severity of resulting loss-of-control crashes involving motorcyclists if they strike the lane dividers at speed could outweigh these benefits.

For cyclists, the Dutch convention is that they will not ride on the carriageway (as with any multi-lane roundabout) and will instead be provided with off-road facilities.

8.5 Capacity

Several published articles specifically evaluate the capacity of turbo-roundabouts, and all maintain they have greater capacity than a two- or three-lane conventional roundabout. However, most studies are theoretically based rather than having been validated with on-site measurements.

Fortuijn (2009b) developed some gap acceptance parameters from on-site observations of an operating turbo-roundabout for use in VISSIM microsimulation software. From some microsimulation evaluation using the PARAMICS software, Yperman and Immers (2003) concluded that a two-lane roundabout would exceed the capacity of a three-lane conventional roundabout by 12–20 %. Mauro and Branco (2009) used German KREISEL software to affirm that turbo-roundabouts could be expected to have superior capacity to a conventional roundabout with a similar number of traffic lanes, although they found that for balanced traffic situations, the difference might be small. It was also highlighted by Mauro and Branco that the area of a turbo-roundabout is likely to be similar to that of a conventional design with the same number of circulating lanes, so they should – in theory – be a superior solution in terms of capacity at least.

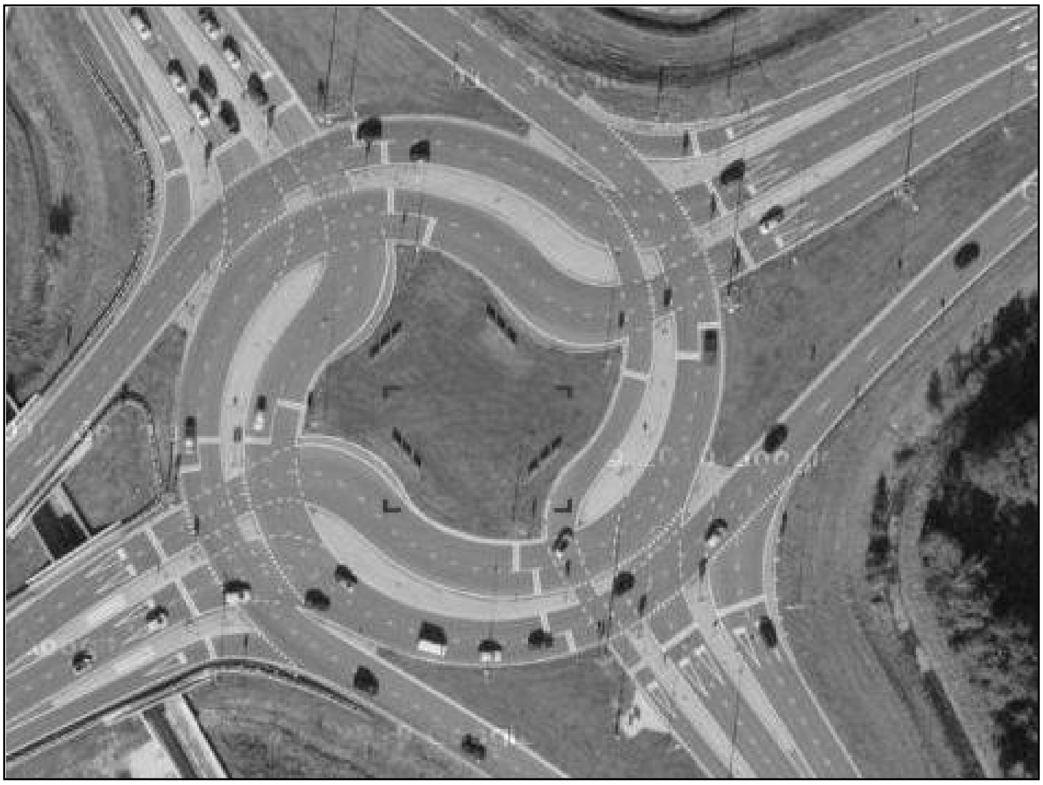
The main reason for improved capacity is attributed to improved lane use by drivers, motivated by the presence of the lane dividers, which give drivers some certainty that lane changing will not occur in the roundabout. However, the German experience without the lane dividers has been near-equal entry lane use during peak periods, and thus lane dividers would achieve little more in this regard (W Brilon, pers. comm. April 2010). Some post-evaluation studies carried out in New Zealand may therefore be useful to confirm whether or not the lane dividers significantly affect capacity at a turbo-roundabout.

8.6 Signalised turbo-roundabouts

Currently, two signalised roundabouts are installed in the province of Zuid-Holland in The Netherlands, both within approximately two kilometres of one another at Doenkadeplein (constructed 2006; figure 8.42 below) and Tolhekplein (constructed 2007). The estimated capacity for signalised roundabouts like these is around 11,000–12,000 vehicles per hour (CROW 2008). No design layout is standard for this type of intersection.

A road-user behavioural study of these two roundabouts was undertaken in 2007 (van der Horst et al 2008). Its main finding was that although signalised turbo-roundabouts may have a significantly higher capacity than unsignalised roundabouts, they are reasonably complex to negotiate, especially for unfamiliar drivers, and incorrect lane choice is not uncommon. Red light running may also be higher than at conventional signalised intersections. In terms of safety performance, though, these findings were not presented as problems of great significance.

Figure 8.42 Aerial view of the Doenkadeplein signalised turbo-roundabout in The Netherlands at the intersection of roads N209 and N471 (the outside diameter of the roundabout is approximately 110m; photo courtesy of Google Maps)



8.7 Potential for application in New Zealand

8.7.1 Safety, capacity and cost

The turbo-roundabout is a design that has demonstrable safety and capacity advantages compared to conventional multi-lane roundabout designs, but are likely to be relatively expensive to construct. The question for a particular location being considered, therefore, seems to be one of relative merits in terms of safety, capacity and cost. An important point to note is also that many turbo-roundabout configurations do not permit U-turn manoeuvres from every direction.

If Dutch guidelines (CROW 2008) are adhered to, the diameter of a turbo-roundabout is likely to be significantly larger than a typical Austroads design for a multi-lane roundabout (Austroads 2009b), although smaller sized central islands than the Dutch standards stipulate may be feasible. Circulating lanes at a turbo-roundabout are designed to cater for the largest design trucks driving alongside one another so the carriageway width will be larger than that of a conventional design – Austroads guidelines make some allowance for the fact that this is likely to be a rare event. The lane dividers, with their extensive delineation requirements and large advance warning signage, would also be a significant expense.

The question of motorcyclist safety is one that would have to be put to the test here. The provision of adequate street lighting and appropriate advance warning signage reportedly addresses this issue more than satisfactorily in The Netherlands and is of obvious importance for these users.

8.7.2 Cyclists

Although some guidelines suggest that cyclists could be disadvantaged users if off-road paths are not provided at a turbo-roundabout (Royal Haskoning 2009), it is postulated that the lower-speed environment could still be an improvement compared to conventional multi-lane designs. However, lane widths on roundabout approaches would have to be considered with regard to the pinch-points they can present alongside larger vehicles, and right turns may also pose difficulties for cyclists because of the lane dividers hindering access to the far-side lanes. Off-road circulatory paths would thus appear to be a desirable feature at turbo-roundabouts if inexperienced cyclists are to be catered for. Given the reduced speed environment of a turbo-roundabout and its relatively wide (5m) traffic lanes, it is considered that on-road use in New Zealand by cyclists is not necessarily out of the question for more experienced cyclists – larger vehicles should be travelling at similar speeds so the issue of them tracking over the entire lane might not be a problem. However, the problem with lane dividers hindering far-side lane access during right turns is still present, so therefore an off-road alternative (at least) would appear to be a desirable feature if inexperienced cyclists are present in any numbers.

8.7.3 Large vehicle tracking

One factor for consideration before installing a turbo-roundabout in New Zealand is the difference between the design largest trucks. The Dutch vehicles used are smaller (figures 8.43–8.46) (CROW 2008). A tracking comparison with the largest New Zealand design semi-trailer is also shown in figures 4.47–8.49, where it can be seen that the lane dividers and mountable areas could expect to be more regularly traversed by these larger New Zealand vehicles. If turbo-roundabouts are constructed in New Zealand as per Dutch dimensions, raised lane dividers and mountable sections would be traversed more often than in The Netherlands. These manoeuvres do not necessarily present a safety or operational problem of any significance, but the durability of the lane dividers needs due consideration, as does clearance from vehicles in adjacent traffic lanes.

Figure 8.43 The Dutch design vehicle for the turbo-roundabout (units are in metres) (CROW 2008)

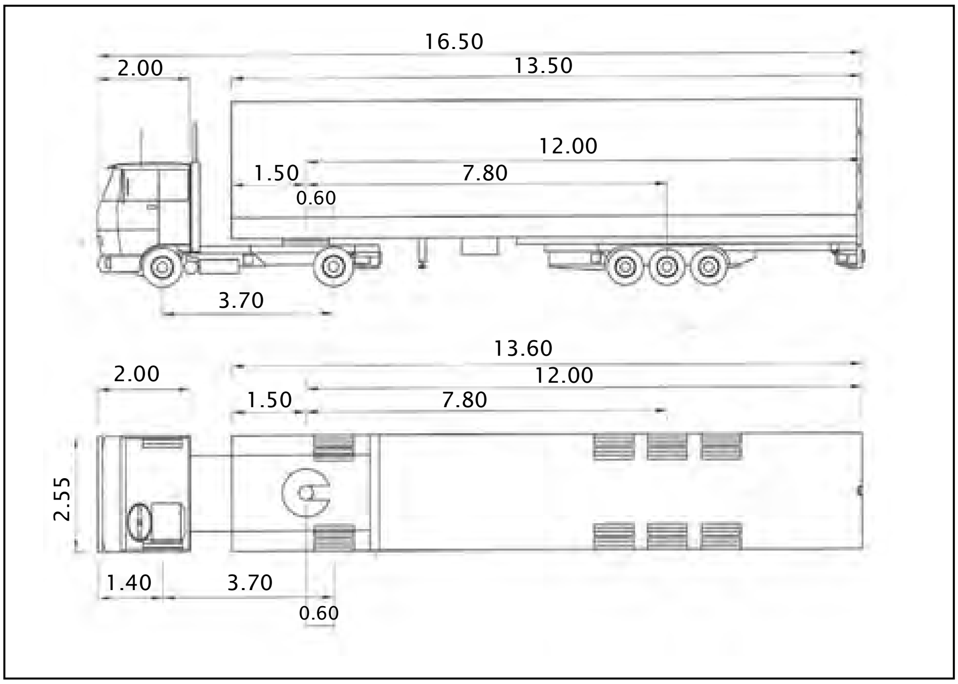


Figure 8.44 The Autotrack plot of the Dutch and New Zealand design vehicles, demonstrating that the largest legal design truck in New Zealand (17.9m) tracks significantly closer on the inside of turns.

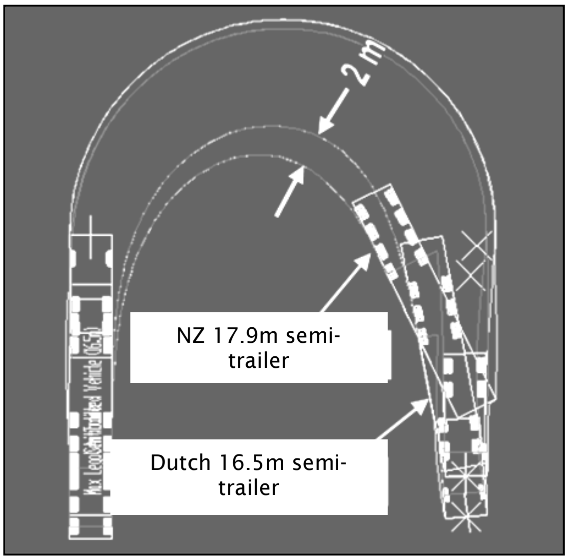


Figure 8.45 Photo showing a semi-trailer in The Netherlands negotiating a turbo-roundabout (CROW 2008). Note the mountable lane dividers between traffic lanes which the rear tyres are driving over (circled)

Figure 8.46 Simulation of the Dutch 16.5m vehicle (circled) negotiating a turbo-roundabout: this vehicle can negotiate the straight-through movement with only minor overlap of the mountable sections and lane dividers (CROW 2008)

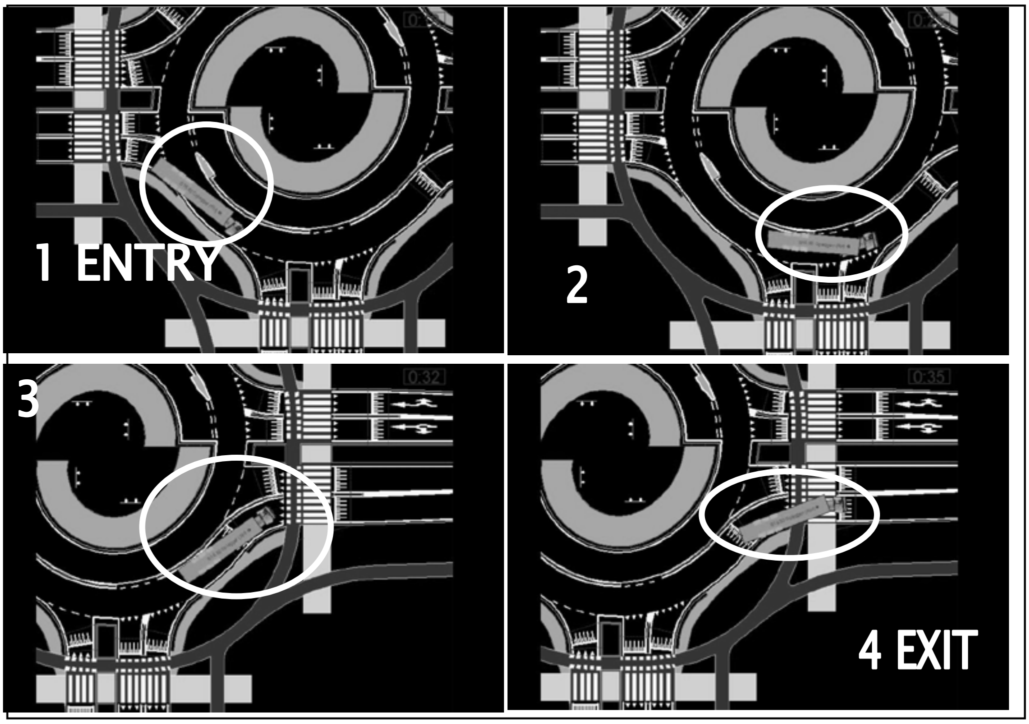


Figure 8.47 Swept path of the design 17m semi-trailer used in New Zealand when negotiating a turbo-roundabout built to Dutch dimensions (left-hand drive layout): left turn

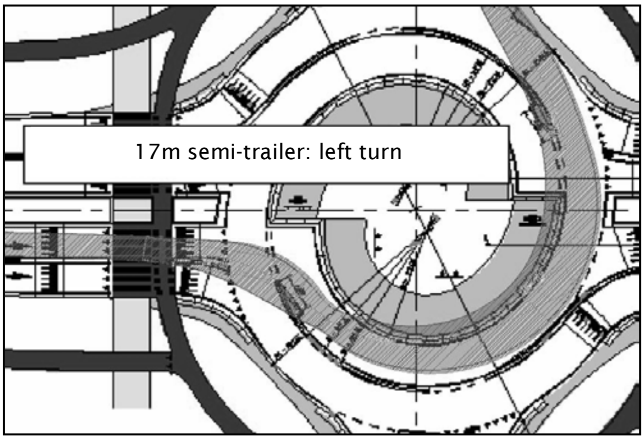


Figure 4.48 Swept path of the design 17m semi-trailer used in New Zealand when negotiating a turbo-roundabout built to Dutch dimensions (left-hand drive layout): right turn

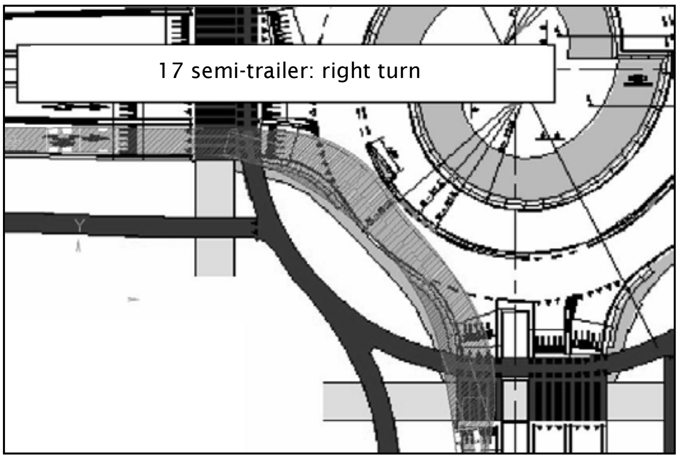
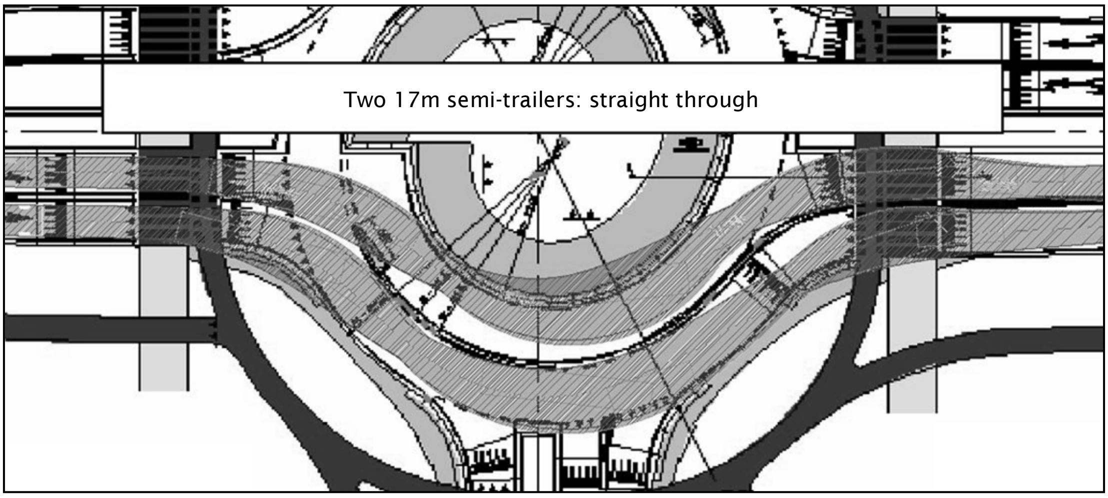


Figure 4.49 Swept path of the design 17m semi-trailer used in New Zealand when negotiating a turbo-roundabout built to Dutch dimensions (left-hand drive layout): straight through



8.7.4 Guidelines for reference

For any designers considering the installation of a turbo-roundabout in New Zealand, the following references are recommended:

- *Turborotundes* (CROW 2008): this is the design guide from The Netherlands, but is only currently available in Dutch language paper copy. However, it does come with a CD which includes AutoCAD templates, a simple capacity calculation spreadsheet, some animated VISSIM and drive-through simulations, a list of sites installed in The Netherlands, and diagrams and photos which still may be of some use.
- *Turbo roundabouts – estimation of capacity* (Fortuijn 2009b) and *Turbo-roundabouts – design principles and safety performance* (Fortuijn 2009a): these reports from The Netherlands (in English) give good background information and also some parameters for use with VISSIM software packages.
- *Roundabouts – application and design* (Royal Haskoning 2009): this document does not yet appear to be widely available and the relevant section on turbo-roundabouts is attached to this report as appendix I. It gives a good description (in English) of some geometric specifications for turbo-roundabouts, although not in as much detail as the *Turborotundes* report (CROW 2008).

8.7.5 Examples of potential applications in Auckland

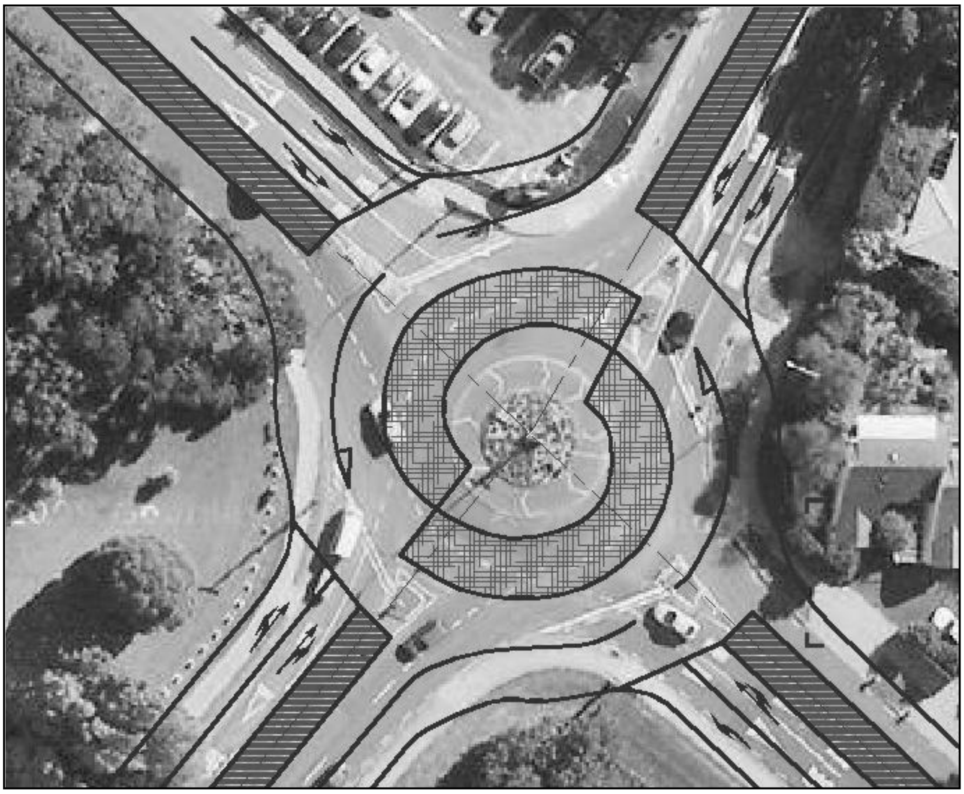
8.7.5.1 New Zealand design considerations

This section contains scaled representations of turbo-roundabouts at some sample sites in Auckland. Note that these are designed to Dutch specifications, so in order to allow for New Zealand's largest trucks, lane widths would need to be marginally wider. Turbo-roundabouts might be feasibly built with smaller sized central islands, although the circulating lanes would have to be wider to allow for large truck turning paths being wider for tighter turning radii.

8.7.5.2 Shore Road–Orakei Road

Figure 8.50 shows a basic turbo-roundabout overlaid atop the Shore Road–Orakei Road roundabout in Remuera, Auckland. Existing traffic volumes at this roundabout are in the order of 30,000 vehicles per day, which is within the assumed capacity of a basic turbo-roundabout. The existing roundabout approximately complies with Austroads guidelines (Austroads 1993); however, the inscribed circle diameter is larger for the turbo-roundabout and the current design would require significant road widening to accommodate a turbo-roundabout.

Figure 8.50 A turbo-roundabout layout as per Dutch specifications atop the Shore Road–Orakei Road roundabout in Remuera, Auckland



8.7.5.3 Robertson Road–Bader Drive Shore Road

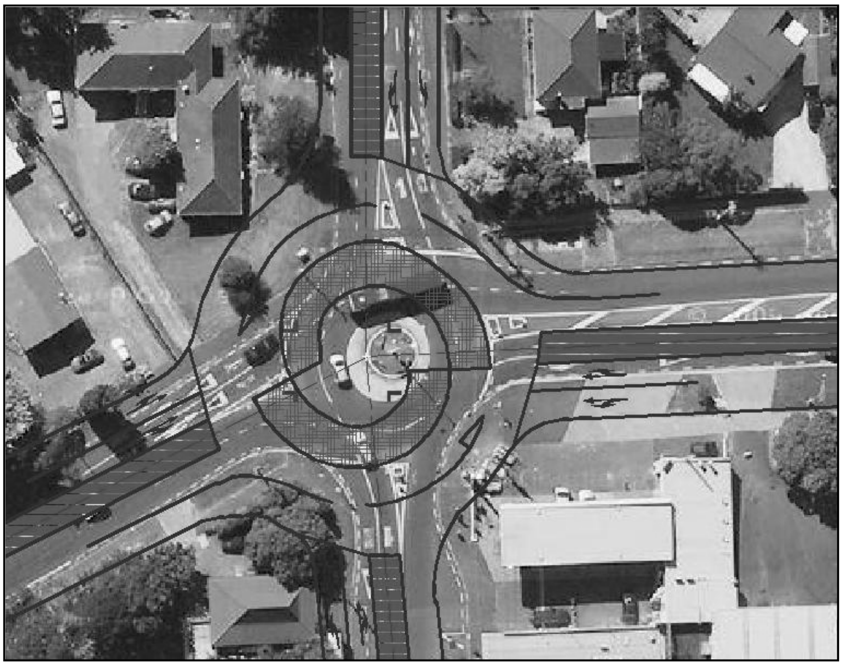
Figure 8.51 shows a basic turbo-roundabout overlaid atop the Robertson Road–Bader Drive roundabout in Mangere, Auckland. Existing traffic volumes at this roundabout are in the order of 25,000 vehicles per day, which is within the assumed capacity of a basic turbo-roundabout. Although this roundabout was part of some proposed cyclist route improvements being studied by Manukau City Council in 2004, no substantial work was undertaken at this location. A turbo-roundabout here could be a worthwhile improvement on the basis that it would achieve a safer low-speed environment for these users and potentially improve capacity, and could easily be accommodated within the existing road reserve.

Figure 8.51 A turbo-roundabout layout as per Dutch specifications atop the Robertson Road–Bader Drive roundabout in Mangere, Auckland

8.7.5.4 Blockhouse Bay Road–Tiverton Road

Figure 8.52 shows a basic turbo-roundabout overlaid atop the existing Blockhouse Bay Road–Tiverton Road roundabout in Blockhouse Bay, Auckland, which substantially complies with Austroads guidelines (Austroads 1993). Existing traffic volumes at this roundabout are in the order of 35,000 vehicles per day, which is just within the assumed capacity of a basic turbo-roundabout, for which the inscribed circle diameter is substantially larger. If additional traffic lanes were to be required for the north approach exit as per the existing arrangement, a spiral roundabout (refer to figure 8.11) would be required, as this design has a third entry lane for both north and south approaches. Clearly, a turbo-roundabout built to Dutch specifications would be a major investment at this location.

Figure 8.52 A turbo-roundabout layout as per Dutch specifications atop the Blockhouse Bay Road–Tiverton Road roundabout in Blockhouse Bay, Auckland



8.7.5.5 Seymour Road–Parrs Cross Road

Figures 8.53 and 8.54 show the C-roundabout which was installed in April 2009, compared to a turbo-roundabout overlaid atop the previous intersection layout. Existing traffic volumes at this roundabout are in the order of 2700 vehicles per hour, which is about the assumed capacity of the considerably larger three-arm egg turbo-roundabout (figure 8.8). As with the previous example, installing a turbo-roundabout here would be a considerable investment that could be difficult to justify.

The C-roundabout is a new type of multi-lane design developed in New Zealand that uses narrow traffic lanes that large trucks need to straddle in order to negotiate, and can be a very economic method of building multi-lane designs with lower vehicle speeds (this is described more fully in section 2.5).

Figure 8.53 The layout of a C-roundabout installed in 2009 at the Seymour Road–Parrs Cross Road roundabout in Glen Eden, Waitakere (photo shows the original layout of the intersection before the C-roundabout was constructed)

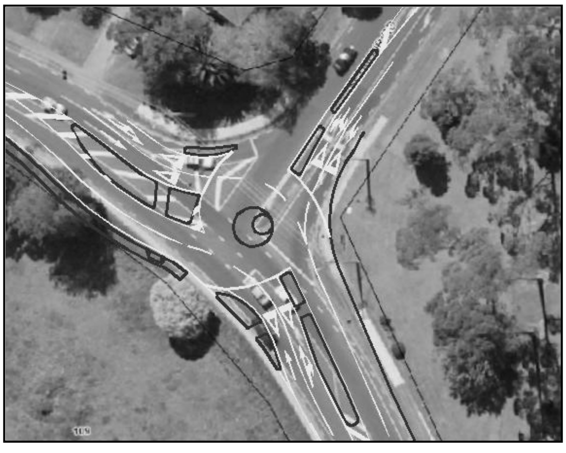
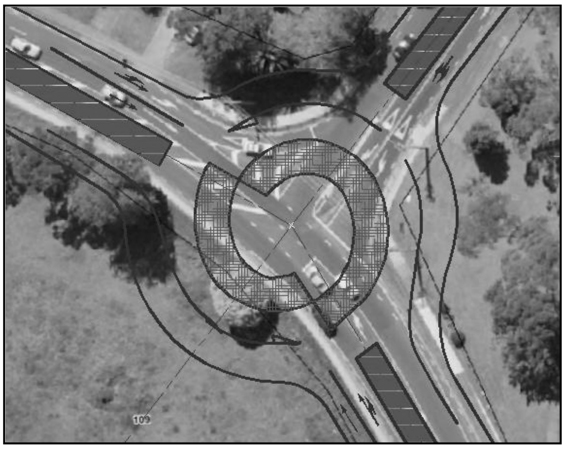


Figure 8.54 A three-arm egg turbo-roundabout superimposed on the former layout of the Seymour Road–Parrs Cross Road roundabout in Glen Eden, Waitakere



8.8 Conclusions

As a result of this investigation, the following conclusions have been drawn about the turbo-roundabout:

- The turbo-roundabout is likely to have superior capacity and safety performance to a conventional multi-lane design with a similar number of lanes. It is an accepted design type in The Netherlands, where over 70 have been built, and has received interest from several other countries. It is considered viable for application in New Zealand, although it is likely to be more expensive to construct because of the mountable lane dividers and the typically large diameter (although the smaller diameters that Dutch guidelines suggest may be feasible).
- Good delineation and lighting is required at a turbo-roundabout for the safety of motorcyclists in particular.
- New Zealand's largest truck dimensions mean that wider circulating lanes than Dutch turbo-roundabout specifications may be desirable; otherwise mountable sections and lane dividers would be traversed more frequently here.
- Guidelines from The Netherlands assume that cyclists will not ride on the road at multi-lane roundabouts. Although this is not the case in New Zealand, cyclists will need to be duly considered for each situation.

Construction of a turbo-roundabout is therefore recommended in New Zealand for evaluation, including a comparison of safety and capacity with or without the mountable lane dividers.

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Appendix A Matched roundabout and traffic signal sites in Auckland

Table A1 Paired roundabout and traffic signal sites in Auckland, comparing the number of crashes at each during 2003–2007

Intersection pair #	Intersection control type	Arms	Major intersecting roads[a]		Daily traffic volume	Total reported injury crashes[b]	Total reported pedestrian and cyclist injury crashes[b]	Total reported vehicle injury crashes[b, c]
1	Roundabout	5	Manukau Road	Mt Albert Road	50,000	6	3	3
	Traffic signal		Manukau Road	Broadway	45,000	10	6	4
2	Roundabout	5	Great North Road	St Judes Street	40,000	4	1	3
	Traffic signal		Lincoln Road	Swanson Road	35,000	17	0	17
3	Roundabout	4	Te Atatu Road	Edmonton Road	45,000	12	7	5
	Traffic signal		Mt Albert Road	Dominion Road	55,000	17	5	12
4	Roundabout	4	Cavendish Drive	Lambie Drive	45,000	5	0	5
	Traffic signal		New North Road	Blockhouse Bay Road	50,000	3	0	3
5	Roundabout	4	Blockhouse Bay Road	Tiverton Road	35,000	7	2	5
	Traffic signal		Mt Wellington Highway	Penrose Road	45,000	11	2	9
6	Roundabout	4	Mt Wellington Highway	Vestey Drive	35,000	2	0	2
	Traffic signal		New North Road	Carrington Road	45,000	8	6	2
7	Roundabout	4	Te Atatu Road	Great North Road	30,000	4	0	4
	Traffic signal		Remuera Road	Orakei Road	35,000	4	1	3
8	Roundabout	4	Shore Road	Orakei Road	30,000	0	0	0
	Traffic signal		Great South Road	Market Road	30,000	3	1	2

Intersection pair #	Intersection control type	Arms	Major intersecting roads[a]		Daily traffic volume	Total reported injury crashes[b]	Total reported pedestrian and cyclist injury crashes[b]	Total reported vehicle injury crashes[b, c]
9	Roundabout	4	Richardson Road	Dominion Road	30,000	0	0	0
	Traffic signal		Neilson Road	Onehunga Mall	30,000	7	1	6
10	Roundabout	4	Apirana Avenue	Marton Road	25,000	2	2	0
	Traffic signal		Great South Road	Atkinson Avenue	30,000	6	1	5
11	Roundabout	4	Pilkington Road	Tripoli Road	25,000	1	0	1
	Traffic signal		Great South Road	Portage Road	30,000	8	1	7
12	Roundabout	4	Ayr Road	Shore Road	25,000	1	1	0
	Traffic signal		Gillies Avenue	Epsom Avenue	25,000	0	0	0
13	Roundabout	4	Bader Drive	Robertson Road	25,000	3	0	3
	Traffic signal		Atkinson Avenue	Avenue Road	25,000	4	2	2
14	Roundabout	4	Bader Drive	Mascot Avenue	25,000	0	0	0
	Traffic signal		Atkinson Avenue	Princes Street	25,000	5	1	4
15	Roundabout	3	Parrs Cross Road	West Coast Road	35,000	6	3	3
	Traffic signal		Swanson Road	Rathgar Road	30,000	5	0	5
16	Roundabout	3	Edmonton Road	Alderman Drive	30,000	7	2	5
	Traffic signal		Great North Road	Hepburn Road	35,000	8	2	6
17	Roundabout	3	Rosebank Road	Patiki Road	30,000	1	0	1
	Traffic signal		Edmonton Road	Central Park Drive	30,000	4	2	2
18	Roundabout	3	Swanson Road	Metcalfe Road	35,000	4	1	3
	Traffic signal		Campbell Road	Wheturangi Road	25,000	2	0	2
19	Roundabout	3	Lunn Avenue	Ngahue Drive	35,000	2	1	1

Intersection pair #	Intersection control type	Arms	Major intersecting roads[a]		Daily traffic volume	Total reported injury crashes[b]	Total reported pedestrian and cyclist injury crashes[b]	Total reported vehicle injury crashes[b, c]
	Traffic signal		Kepa Road	Patteson Avenue	25,000	0	0	0
20	Roundabout	3	Kepa Road	Orakei Road	30,000	1	0	1
	Traffic signal		Kepa Road	Kohimara Road	25,000	1	0	1
Totals	Roundabouts				660,000	74	25	49
	Traffic signals				675,000	123	31	92

a Several of these roundabouts, especially the five-arm roundabouts, involved more than two roads; however, for the sake of conciseness, only the two major roads at each intersection are listed.

b Reported during 2003–2007.

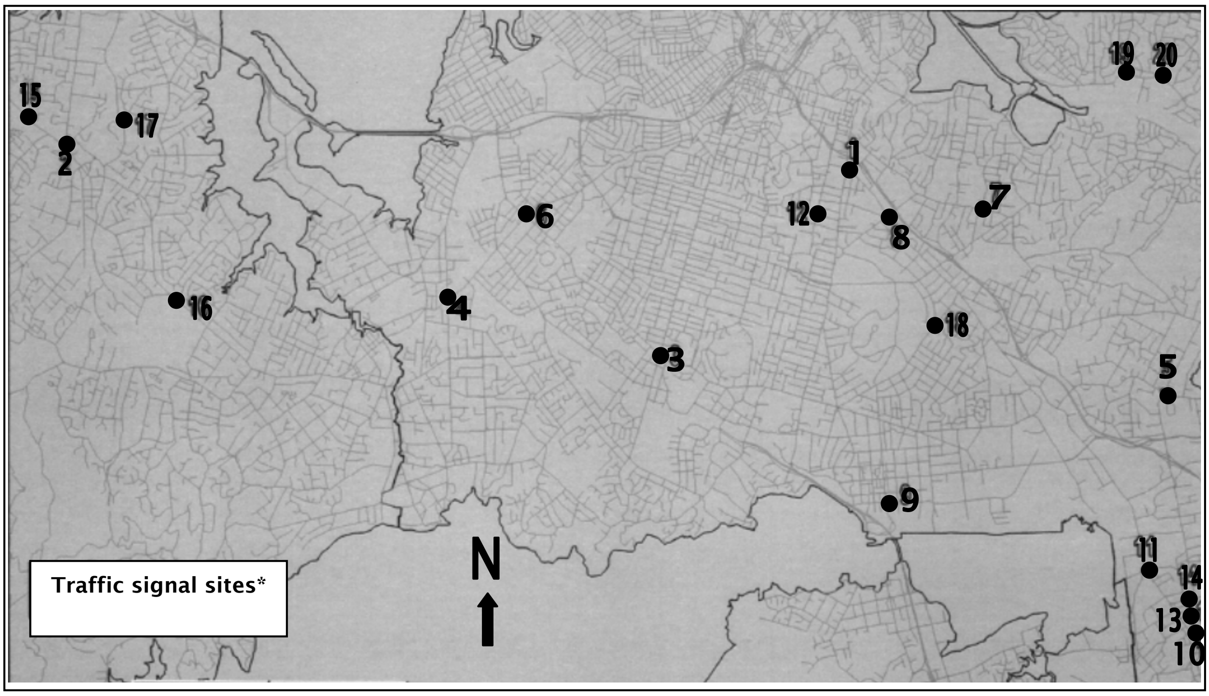
c Not including cyclist and pedestrian crashes, ie vehicle-only crashes.

Table A2 Binomial test results of the matched roundabout and traffic signal sites

Binomial test results		Roundabout sites	Traffic signal sites	Degree of significance	Crash savings at roundabouts (%)
Total crashes		675	743	0.0752	9%
Injury		74	123	0.0006	40%
Non-injury		601	620	ns*	–
Fatal		0	2	ns	–
Serious		6	17	0.0371	65%
Minor		68	104	0.0076	35%
Fatal	Vehicle	0	2	ns	–
	Pedestrian	0	0	ns	–
	Cycle	0	0	ns	–
Serious	Vehicle	4	10	ns	–
	Pedestrian	1	5	ns	–
	Cycle	1	2	ns	–
Minor	Vehicle	45	80	0.0024	44%
	Pedestrian	13	17	ns	–
	Cycle	10	7	ns	–
Vehicle injury		49	92	0.0004	47%
Total vehicle serious + fatal		4	12	0.0800	67%
Non-injury	Vehicle	593	614	ns	–
	Pedestrian + cycle	8	6	ns	–
Total vehicle crashes		642	706	0.0860	9%

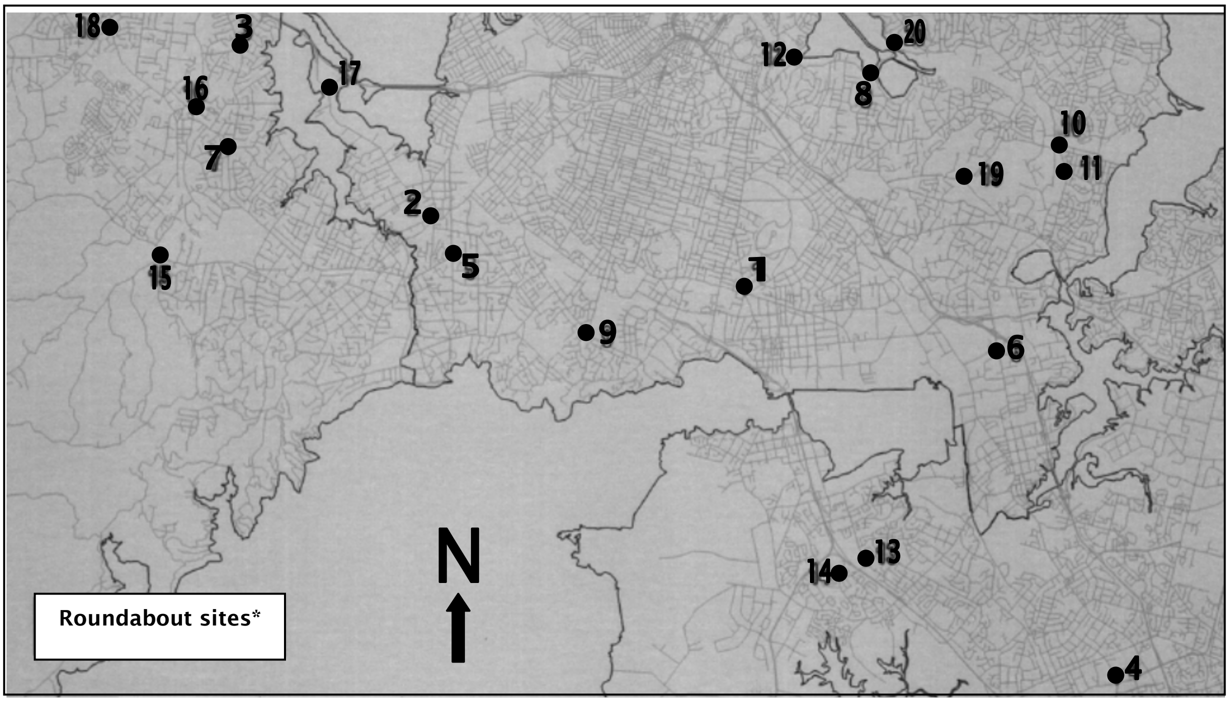
* ns, not significant

Figure A1 Location of traffic signal sites



* See table A1 for details of each intersection

Figure A2 Location of roundabout sites



* See table A1 for details of each of these roundabouts.

Figure A3 Matched pair 1: Manukau Road–Mt Albert Road roundabout (left) and Manukau Road–Broadway traffic signals (photos courtesy of Google Maps)

Figure A4 Matched pair 2: Great North Road–St Judes Street roundabout (left) and Lincoln Road–Swanson Road traffic signals (photos courtesy of Google Maps)

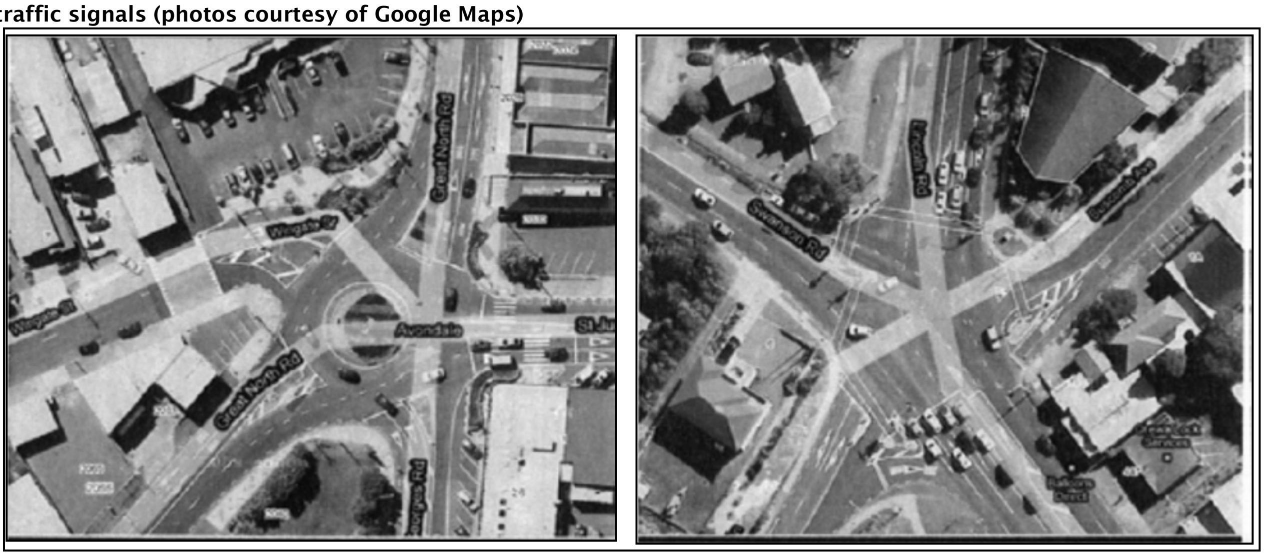


Figure A5 Matched pair 3: Te Atatu Road–Edmonton Road roundabout (left) and Mt Albert Road–Dominion Road traffic signals (photos courtesy of Google Maps)

Figure A6 Matched pair 4: Cavendish Drive–Lambie Drive roundabout (left) and New North Road–Blockhouse Bay Road traffic signals (photos courtesy of Google Maps)

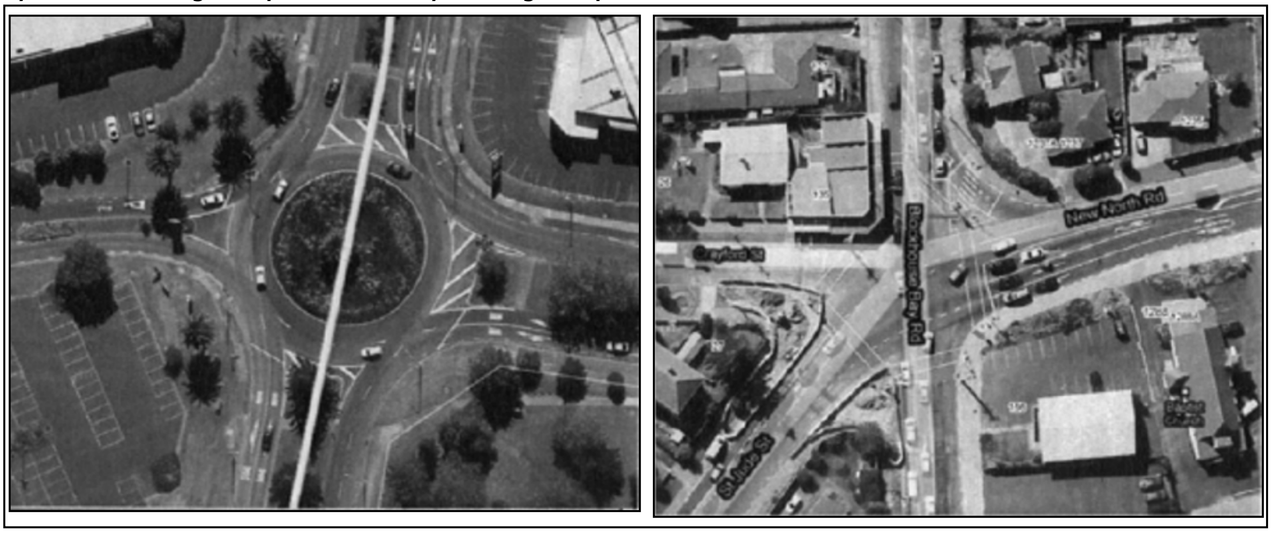


Figure A7 Matched pair 5: Blockhouse Bay Road–Tiverton Road roundabout (left) and Mt Wellington Highway–Penrose Road traffic signals (photos courtesy of Google Maps)

Figure A8 Matched pair 6: Mt Wellington Highway–Vestey Drive roundabout (left) and New North Road–Carrington Road traffic signals (photos courtesy of Google Maps)

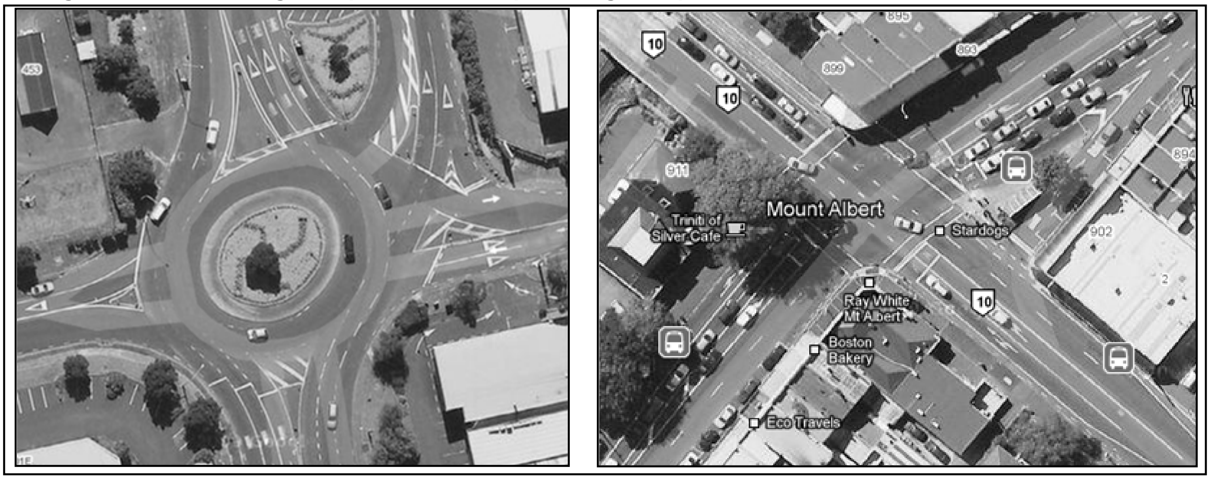


Figure A9 Matched pair 7: Te Atatu Road–Great North Road roundabout (left) and Remuera Road–Orakei Road traffic signals (photos courtesy of Google Maps)

Figure A10 Matched pair 8: Shore Road–Orakei Road roundabout (left) and Great South Road–Market Road traffic signals (photos courtesy of Google Maps)

Figure A11 Matched pair 9: Richardson Road–Dominion Road roundabout (left) and Neilson Road–Onehunga Mall traffic signals (photos courtesy of Google Maps)

Figure A12 Matched pair 10: Apirana Avenue–Merton Road roundabout (left) and Great South Road–Atkinson Avenue traffic signals (photos courtesy of Google Maps)

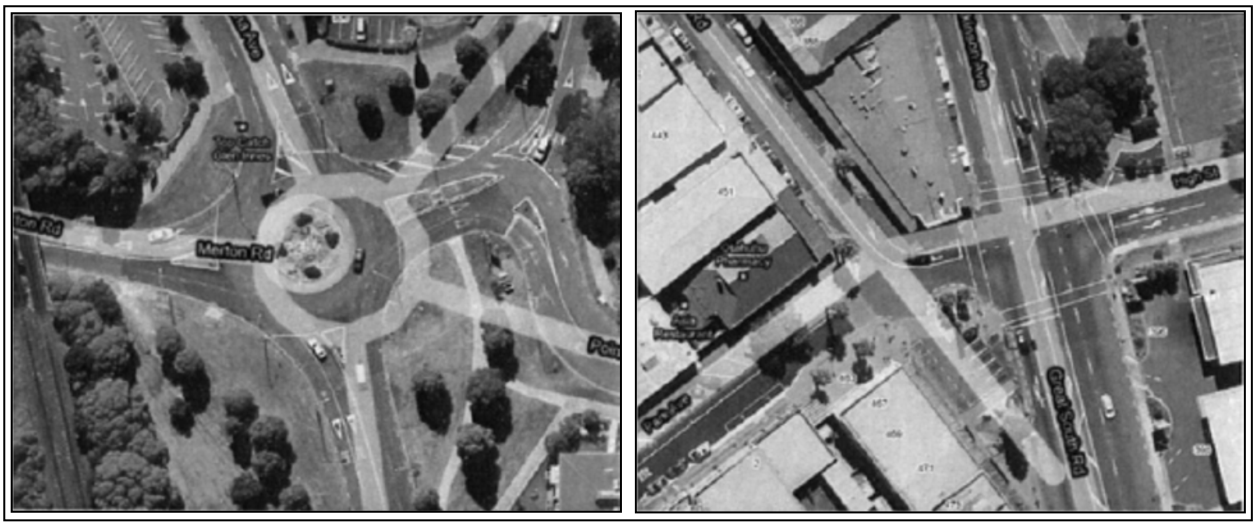


Figure A13 Matched pair 11: Pilkington Road–Tripoli Road roundabout (left) and Great South Road–Portage Road traffic signals (photos courtesy of Google Maps)

Figure A14 Matched pair 12: Ayr Road–Shore Road roundabout (left) and Gillies Avenue–Epsom Avenue traffic signals (photos courtesy of Google Maps)

Figure A15 Matched pair 13: Bader Drive–Robertson Road roundabout (left) and Atkinson Avenue–Avenue Road traffic signals (photos courtesy of Google Maps)

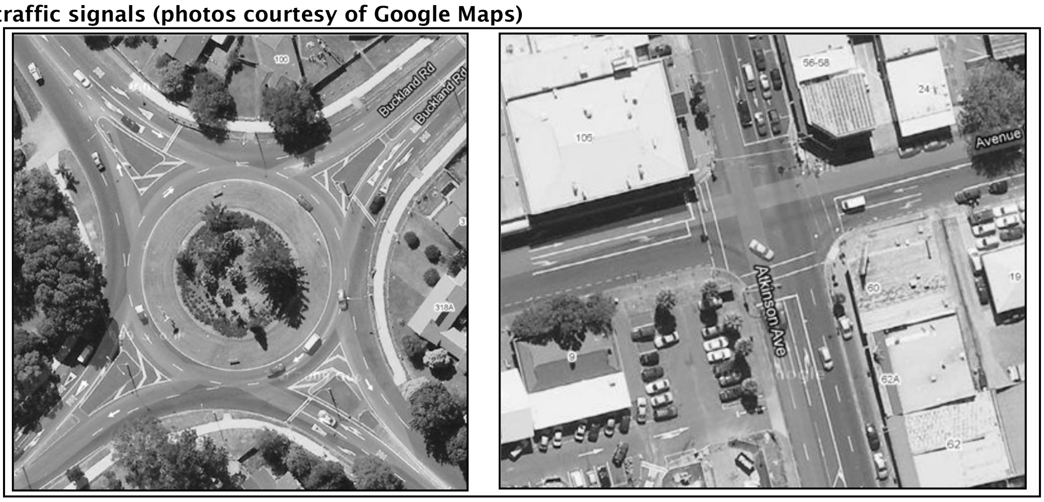


Figure A16 Matched pair 14: Bader Drive–Mascot Avenue roundabout (left) and Atkinson Avenue–Princes Street traffic signals (photos courtesy of Google Maps)

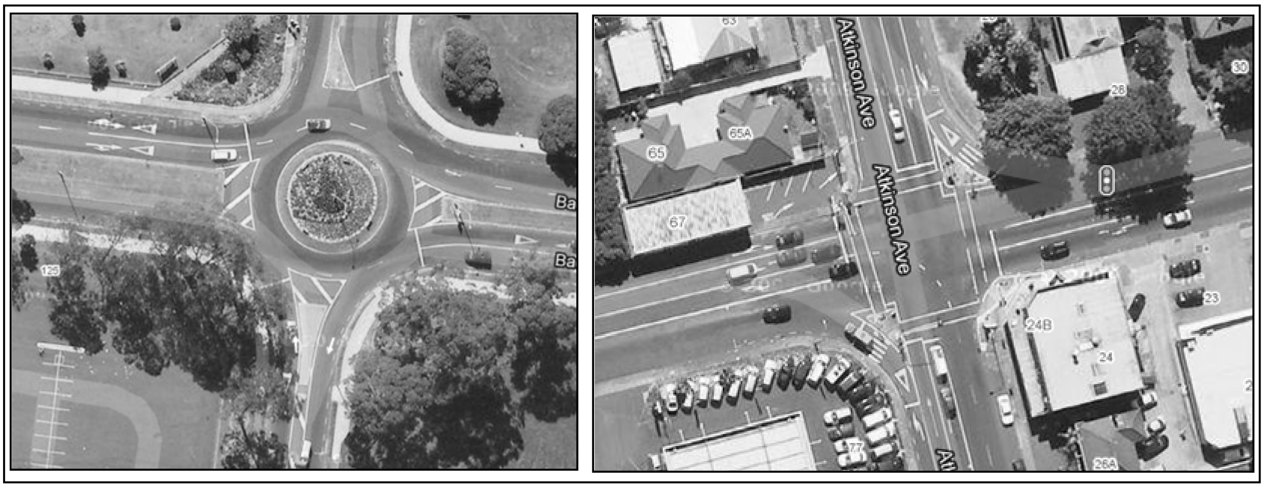


Figure A17 Matched pair 15: Parrs Cross Road–West Coast Road roundabout (left) and Swanson Road–Rathgar Road traffic signals (photos courtesy of Google Maps)

Figure A18 Matched pair 16: Edmonton Road–Alderman Drive roundabout (left) and Great North Road–Hepburn Road traffic signals (photos courtesy of Google Maps)

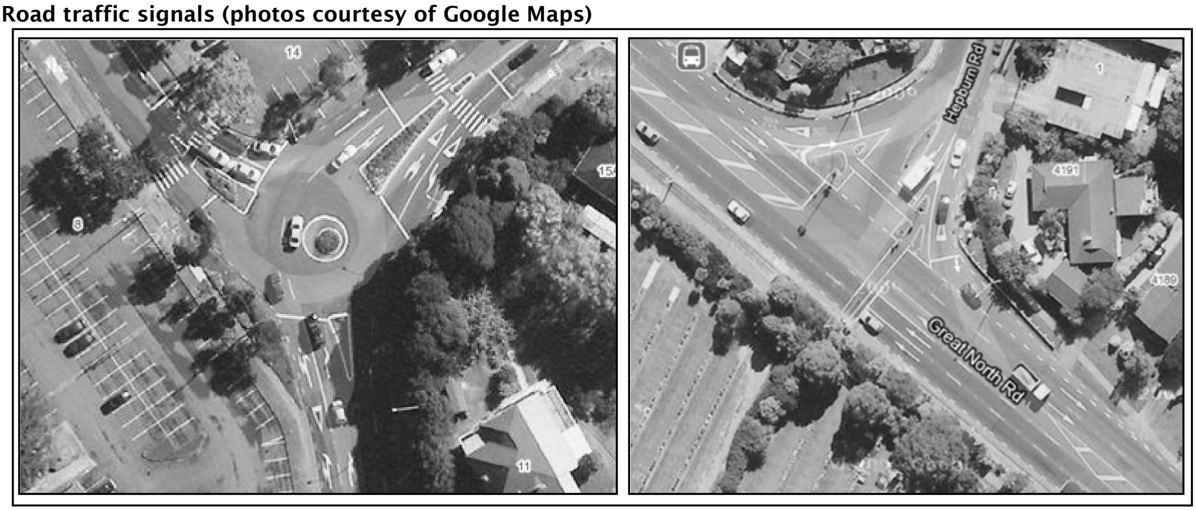


Figure A19 Matched pair 17: Rosebank Road–Patiki Road roundabout (left) and Edmonton Road–Central Park Drive traffic signals (photos courtesy of Google Maps)

Figure A20 Matched pair 18: Swanson Road–Metcalfe Road roundabout (left) and Campbell Road–Wheturangi Road traffic signals (photos courtesy of Google Maps)

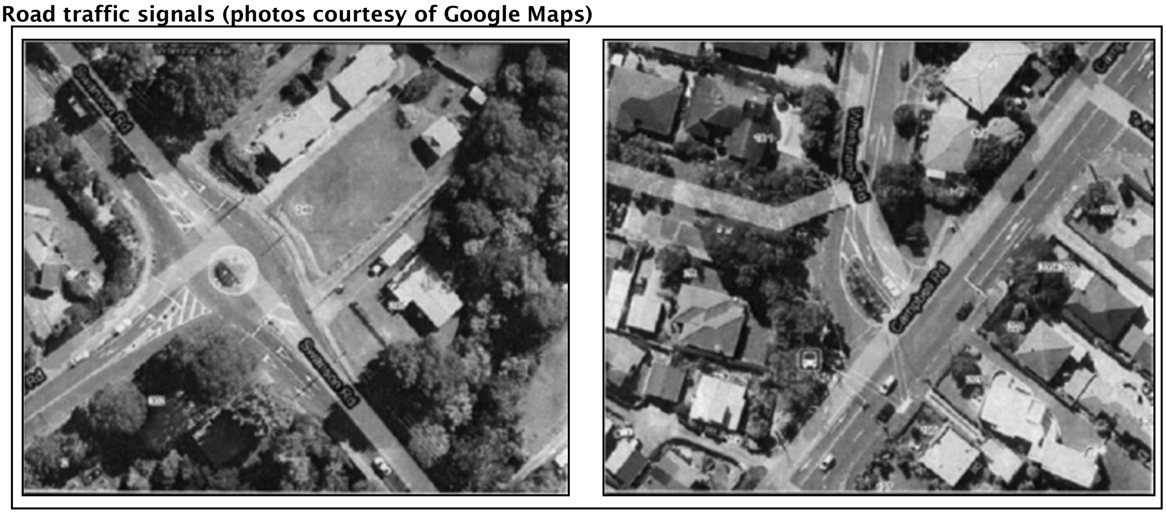


Figure A21 Matched pair 19: Lunn Avenue–Ngahue Drive roundabout (left) and Kepa Road–Patteson Avenue traffic signals (photos courtesy of Google Maps)

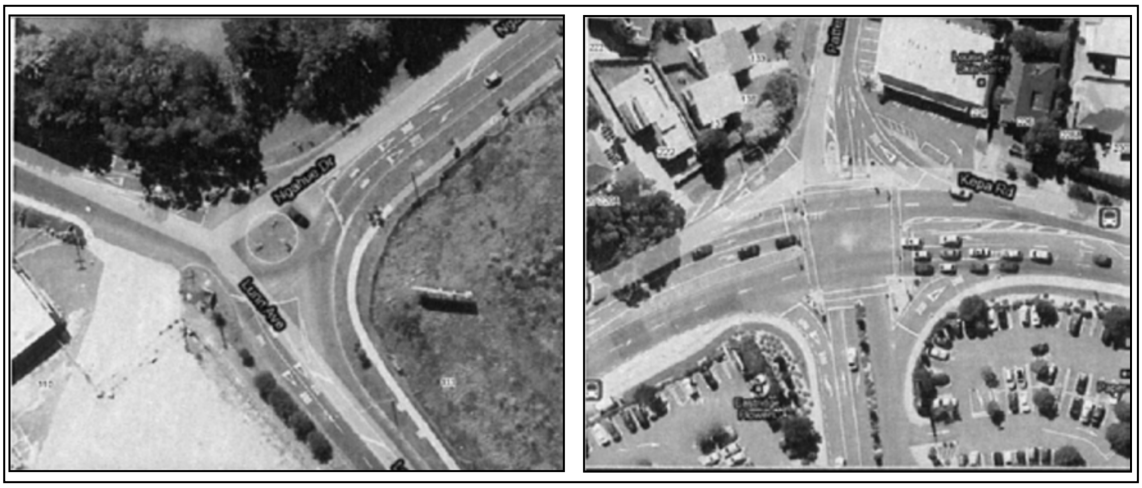
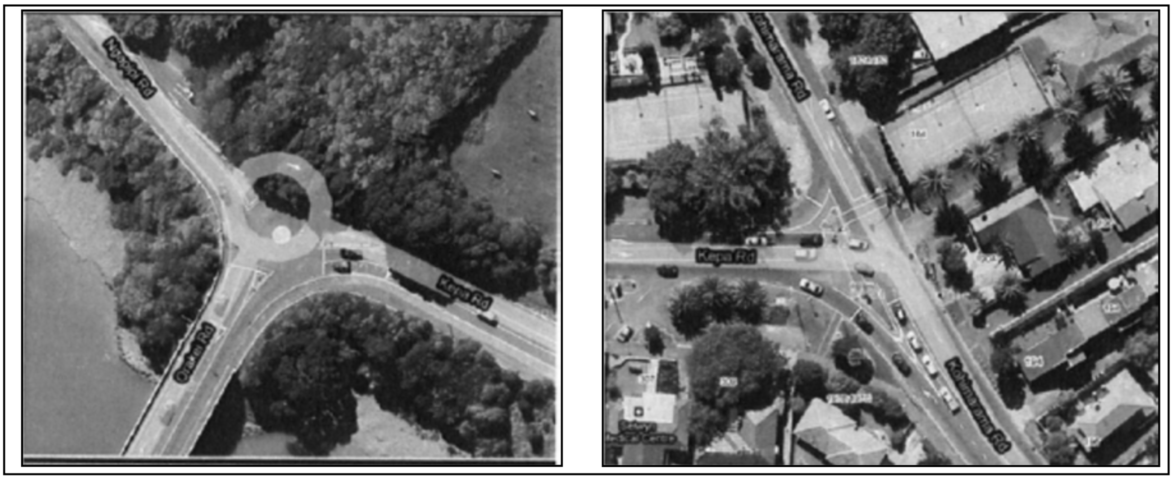


Figure A22 Matched pair 20: Kepa Road–Orakei Road roundabout (left) and Kepa Road–Kohimara Road traffic signals (photos courtesy of Google Maps)



Appendix B Beca APM toolkit modelling results[13]

B1 Analysis of six intersections

The Beca APM Toolkit was used to estimate crashes at a selection of roundabout sites as listed below:

- three-arm junction: Swanson Road–Metcalfe Road
- four-arm junctions: Shore Road–Orakei Road, Bader Drive–Robertson Road and Swanson Road–Universal Drive
- five-arm junctions: Great North Road–St Georges Street and Blockhouse Bay Road–Donovan Street.

Each of these sites was modelled as a roundabout, a signalised intersection without pedestrians and a signalised intersection with 100 pedestrians per approach per day. Cyclist traffic volumes of 100 cyclists per approach per day were also used.

The Beca APM Toolkit was used to directly predict the number of crashes at the three-arm and four-arm sites. The Toolkit is unable to predict crashes for five-arm intersections, however, and a different approach was undertaken for the same. This involved calculating the percentage increase in entering v circulating and turning v crossing crashes from four-arm to five-arm intersections. Available count data for the five-arm intersections was then analysed, and the arm with the lowest flow was ‘removed’ for the purpose of modelling, and its flow allocated to the respective turns from other arms of the intersection. This was then modelled as a four-arm roundabout/signal using the Beca APM Toolkit. Crash rate outputs obtained from the Toolkit were recalibrated using the estimate increases in crash rates to give a total number of predicted crashes for each of the five-arm intersections.

The number of predicted cycle crashes at these intersections was quite high, in keeping with the high average daily traffic volume at the selected sites. However, it must be noted that actual cycle traffic volumes in Auckland are quite low, and thus the actual number of crashes is likely to be lower than that predicted the APM Toolkit.

The three-arm and four-arm intersections were also modelled with flows corresponding to 50%, 75%, 125%, 150% and 200% of the actual flows. In general, motor vehicle and pedestrian crashes increase uniformly with an increase in traffic flow. However, in the case of signalised intersections, cycle crashes showed a very small increase as the flow at the intersection was increased, and tended to remain more or less constant even as the flow through the intersection was doubled.

For the three-arm roundabout at Swanson Road–Metcalfe Road, the rate of motor vehicle and pedestrian crashes was observed to be nearly the same in both the roundabout and signalised intersection scenarios, with the number of crashes being slightly lower at the signalised intersection in some cases. This, in addition to the drastically lower number of cycle crashes in the signalised scenarios, indicates that signals should be the preferred option for three-arm intersections from a safety point of view.

In contrast, the four- and five-arm intersection roundabouts were found to have a lower rate of motor vehicle and pedestrian crashes per year, as compared to corresponding signalised scenarios. However, the

13 The material in this appendix was taken from a letter by Shane Turner of Beca Ltd and was originally part of a personal communication on 24 December 2008. The material relates to section 3.4 and includes some sample output from the APM Toolkit.

rate of cycle crashes at the roundabout was far greater than those at signals, resulting in a cumulative higher accident cost at roundabouts as compared to signals.

From these observations, it seems reasonable to conclude that roundabouts are more suited to sites where cyclists constitute a relatively smaller percentage of the traffic stream. However, sites handling higher rates of cyclist traffic are better off being designed as traffic signals because of the corresponding lower total crash rates and accident costs associated with these.

B2 Sample output from the APM Toolkit

Figure B1 Flows used by the APM Toolkit for the Shore Road–Orakei Road intersection (average annual daily traffic, factored to the analysis year): roundabout layout

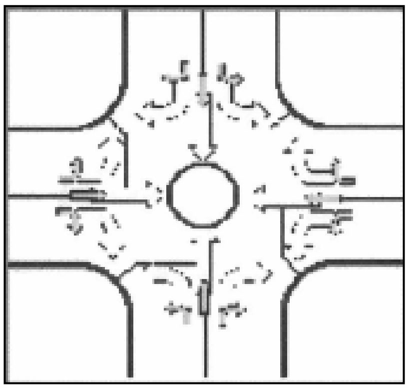
<table>
<tr><td colspan="3" rowspan="3"></td><td>Cycles</td><td>100</td><td>100</td><td>100</td><td colspan="3" rowspan="3"></td></tr>
<tr><td>Motor vehicles</td><td>2866</td><td>2461</td><td>1018</td></tr>
<tr><td></td><td>1</td><td>2</td><td>3</td></tr>
<tr><td></td><td>Cycles</td><td>Motor vehicles</td><td colspan="4" rowspan="4"></td><td>Motor vehicles</td><td>Cycles</td><td></td></tr>
<tr><td>12</td><td>100</td><td>2923</td><td>1329</td><td>100</td><td>4</td></tr>
<tr><td>11</td><td>100</td><td>1822</td><td>2977</td><td>100</td><td>5</td></tr>
<tr><td>10</td><td>100</td><td>853</td><td>132</td><td>100</td><td>6</td></tr>
<tr><td colspan="3" rowspan="3"></td><td>Motor vehicles</td><td>719</td><td>2845</td><td>296</td><td colspan="3" rowspan="3"></td></tr>
<tr><td>Cycles</td><td>100</td><td>100</td><td>100</td></tr>
<tr><td></td><td>9</td><td>8</td><td>7</td></tr>
</table>

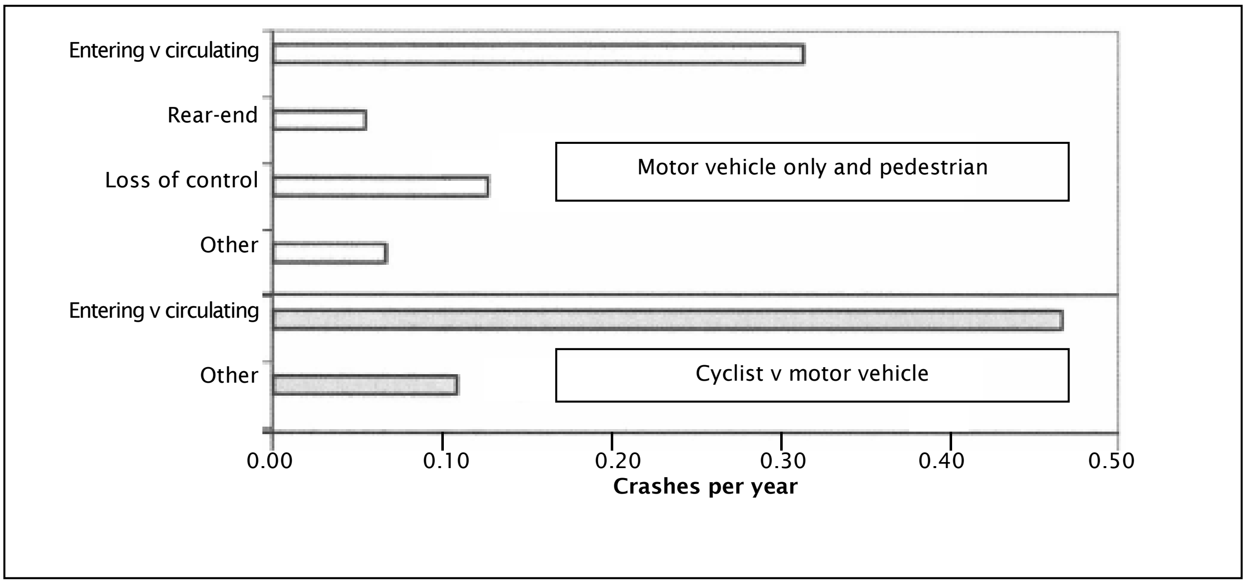
Table B1 Total crashes for the Shore Road–Orakei Road intersection: roundabout layout

Total crashes		**Maj**	**Min**	
0.56	Motor vehicle and pedestrian crashes per year	10,273	9756	OK
0.58	Cyclist crashes per year	600	600	OK

Table B2 Crashes by type and approach for the Shore Road-Orakei Road intersection: roundabout layout

Crash type	Crash code	Approach				Total
		N	E	S	W	
Motor vehicle only crashes						
Entering v circulating	HA, LB, JA, MB, K	0.069	0.082	0.083	0.079	0.314
Rear-end	FA to FD	0.018	0.012	0.010	0.015	0.055
Loss of control	C and D	0.037	0.0.30	0.028	0.033	0.128
Other	Other	0.018	0.016	0.016	0.017	0.067
Total	-	0.142	0.140	0.137	0.144	0.563
Cycle crashes						
Entering v circulating	HA, LB, JA, MB, K	0.141	0.106	0.095	0.124	0.467
Other	Other	0.033	0.025	0.022	0.029	0.109
Total	-	0.174	0.131	0.118	0.153	0.576

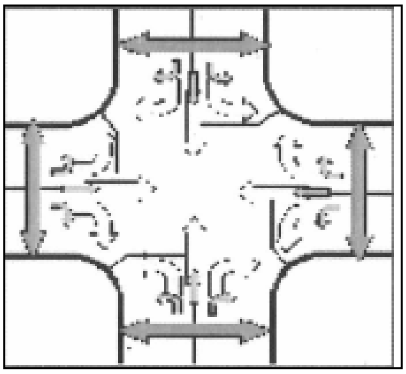
Figure B2 Crash types for the Shore Road-Orakei Road intersection: roundabout layout



The following were used to calculate the accident costs of the roundabout layout:

- speed limit on approaches: 50km/h
- total accident cost: $228,556.

Figure B3 Flows used by the APM Toolkit for the Shore Road–Orakei Road intersection with 100 pedestrians per peak hour (average annual daily traffic, factored to the analysis year): signalised intersection layout

<table>
<tr><td colspan="3" rowspan="4"></td><td></td><td>1</td><td>2</td><td>3</td><td colspan="4" rowspan="4"></td></tr>
<tr><td>Cycles</td><td>100</td><td>100</td><td>100</td></tr>
<tr><td>Motor vehicles</td><td>2866</td><td>2461</td><td>1018</td></tr>
<tr><td>Ped*</td><td colspan="3">100</td></tr>
<tr><td></td><td>Cycles</td><td>Motor vehicles</td><td>Ped</td><td colspan="3" rowspan="4"></td><td>Ped</td><td>Motor vehicles</td><td>Cycles</td><td></td></tr>
<tr><td>12</td><td>100</td><td>2923</td><td rowspan="3">100</td><td rowspan="3">100</td><td>1329</td><td>100</td><td>4</td></tr>
<tr><td>11</td><td>100</td><td>1822</td><td>2977</td><td>100</td><td>5</td></tr>
<tr><td>10</td><td>100</td><td>653</td><td>132</td><td>100</td><td>6</td></tr>
<tr><td colspan="3" rowspan="4"></td><td>Ped</td><td colspan="3">100</td><td colspan="4" rowspan="4"></td></tr>
<tr><td>Motor vehicles</td><td>719</td><td>2845</td><td>296</td></tr>
<tr><td>Cycles</td><td>100</td><td>100</td><td>100</td></tr>
<tr><td></td><td>9</td><td>8</td><td>7</td></tr>
</table>

* Pedestrian

Table B3 Total crashes per year for the Shore Road–Orakei Road intersection: signalised intersection layout

		Maj	Min	
0.69	Motor vehicle only	10,273	9766	OK
0.11	Cycle crashes	600	600	OK
0.11	Pedestrian crashes	200	200	OK

Table B4 Crashes by type and approach at the Shore Road-Orakei Road intersection: signalised intersection layout

Crash type	Crash code	Approach				Total
		N	E	S	W	
Motor vehicle only crashes						
Crossing (not turns)	HA	0.042	0.051	0.053	0.045	0.191
Right turn against	LB	0.044	0.068	0.122	0.071	0.306
Rear-end	FA to FE	0.020	0.013	0.012	0.017	0.061
Loss of control	C and D	0.012	0.008	0.007	0.010	0.037
Other	Other	0.026	0.022	0.021	0.024	0.092
Total	-	0.144	0.162	0.215	0.167	0.687
Cycle crashes						
Same direction	A, E, F, G	0.016	0.014	0.013	0.015	0.058
Right turn against	LB	0.001	.000	0.002	0.001	0.005
Other	Other	0.012	0.011	0.011	0.012	0.046
Total	-	0.028	0.026	0.026	0.028	0.109
Pedestrian crashes						
Intersecting	NA, NB	0.010	0.010	0.010	0.010	0.041
Right turning	ND, NF	0.013	0.007	0.010	0.018	0.048
Other	Other	0.005	0.003	0.004	0.006	0.016
Total	-	0.028	0.020	0.024	0.034	0.106

Figure B4 Vehicle involvement at the Shore Road-Orakei Road intersection: signalised intersection layout

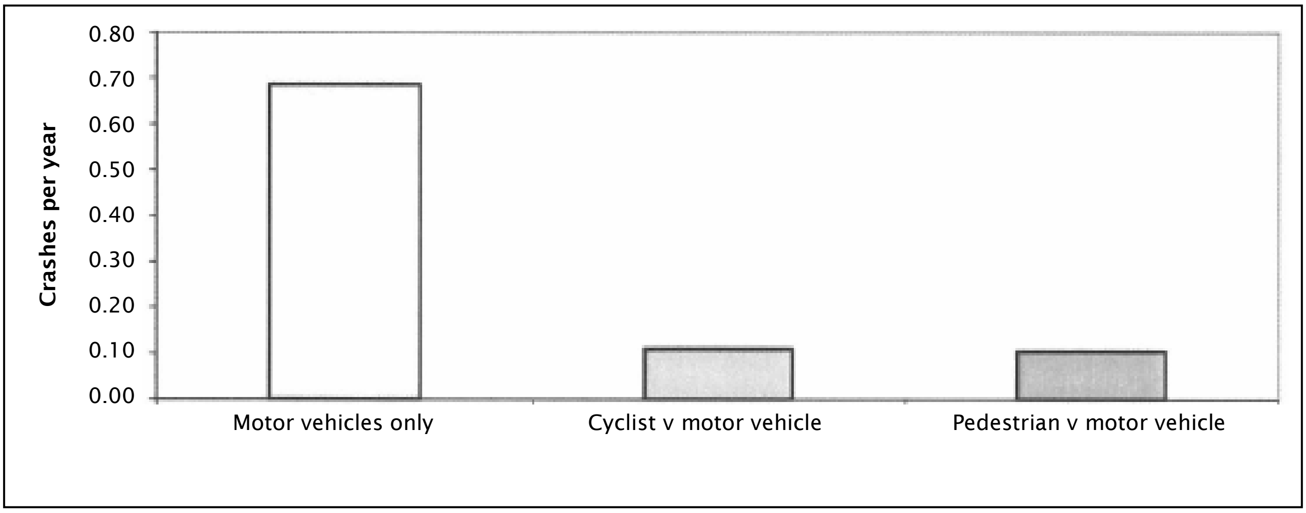
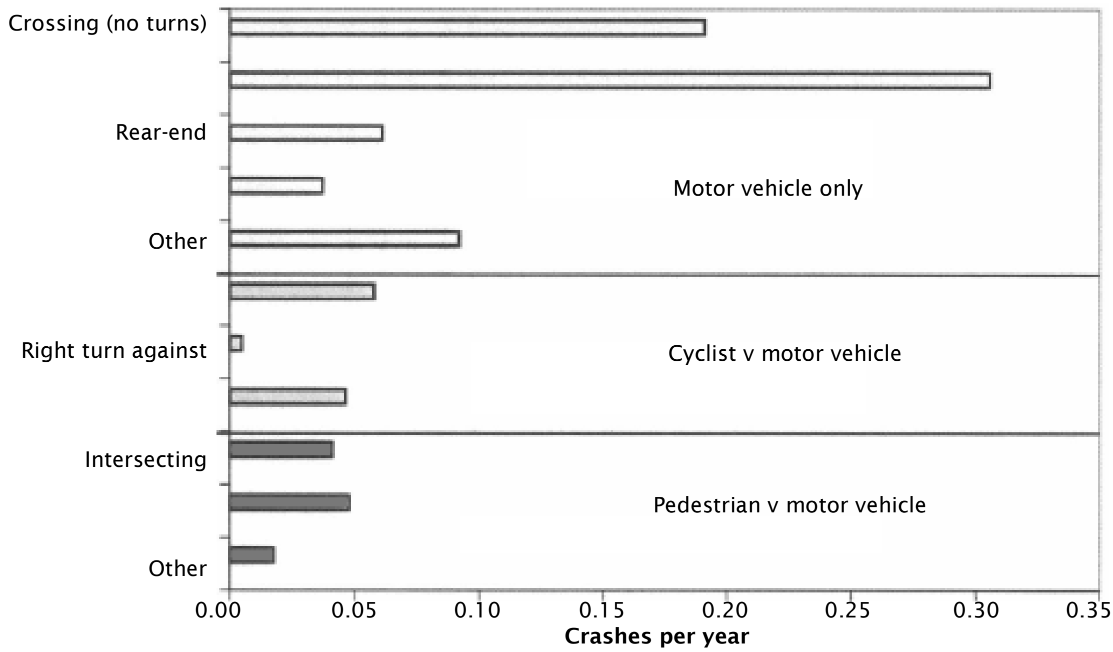


Figure B5 Crash types for the Shore Road–Orakei Road intersection: signalised intersection layout



The following were used to calculate the accident costs of the signalised intersection layout:

- speed limit on approaches: 50km/h
- total accident cost: $162,126.

Appendix C Sample plans of a roundabout with visibility screens from Leicestershire County Council, UK

This roundabout is located on the A511 (Little Shaw Lane) and A50 (Leicester Road) roadways just outside the township of Markfield. The M1 motorway passes over the roundabout on ramps, and both the A50 and A511 lead to entrances and exits to the M1.

Figure C1 Aerial view of the A50–A511 roundabout

Figure C2 Westbound approach of the A50–A511 roundabout

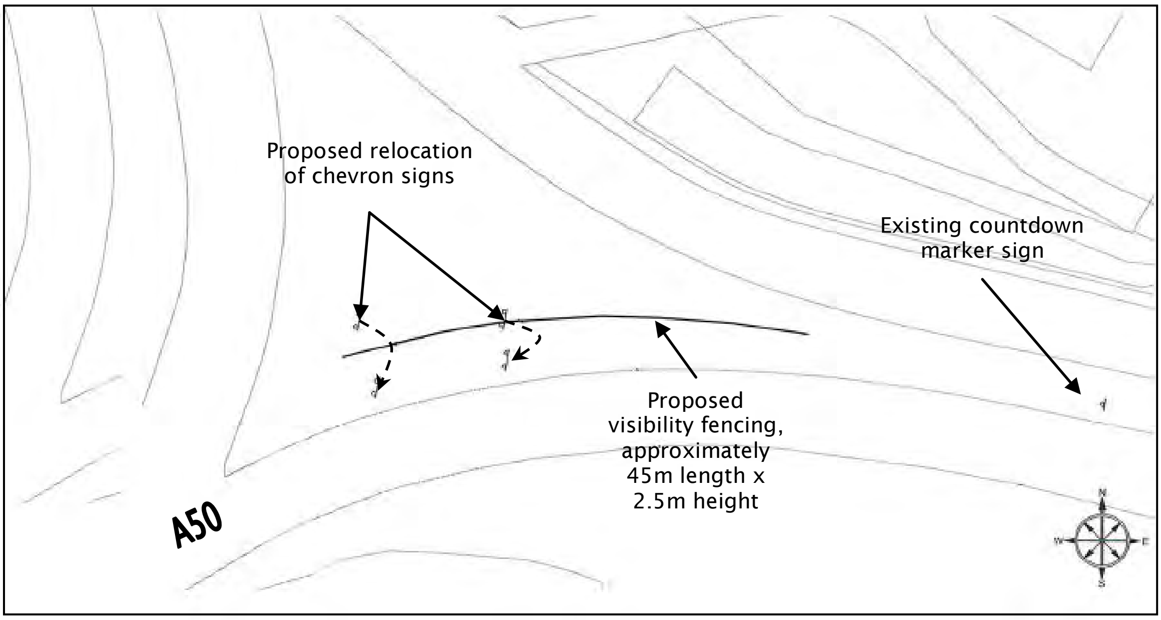
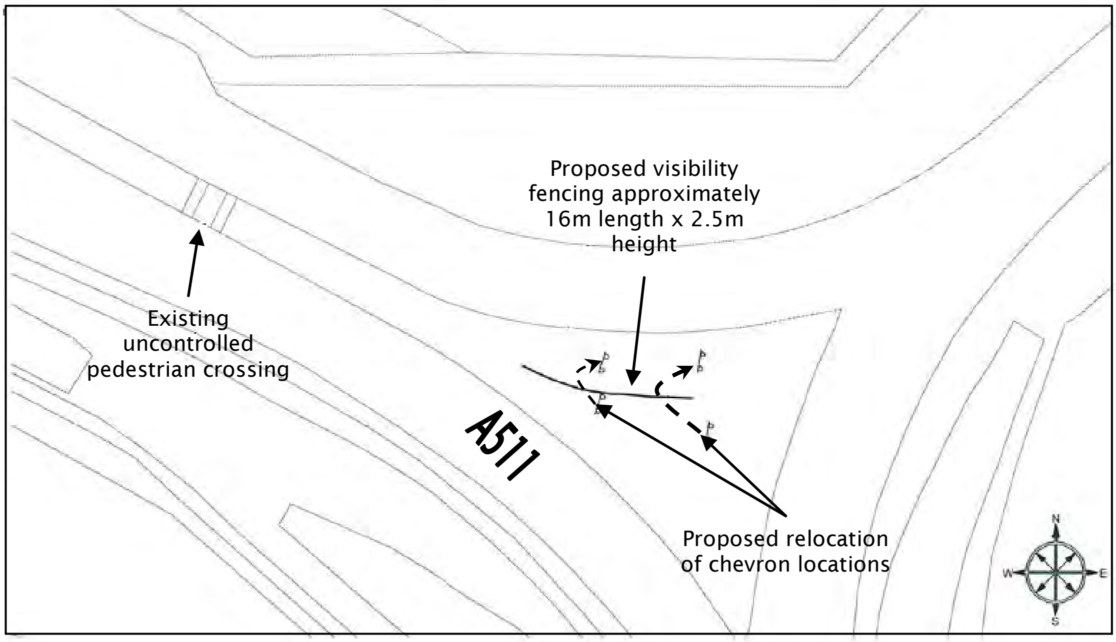


Figure C3 Eastbound approach of the A50–A511 roundabout



Appendix D Practical application: restricting sightlines to minimise crashes at roundabouts

D1 Introduction

Restricting sightlines, if properly designed, may potentially make a roundabout safer. This report is intended to assist traffic engineers to better design a roundabout with restricted sightlines which have the potential to reduce driver speeds at a roundabout and thus the associated crash frequency and severity. This can help designers where speed control via other means is difficult to achieve. This application can also be used to improve the safety of existing roundabouts that might be experiencing crash problems. The Austroads *Guide to road design part 4B: roundabouts* (Austroads 2009) should be referred to in the first instance as it is the accepted guideline for NZTA. It is expected this report may offer some assistance for certain situations.

Sightlines of opposing vehicles can influence a vehicle's speed as a driver approaches a roundabout, sometimes substantially more so than geometric deflection. Excessive sightlines to the right can contribute to higher than desirable driver speeds, which can subsequently increase crash types including loss-of-control, rear-end and entering v circulating crash types (particularly those involving less visible two-wheeled users). In the United Kingdom (UK), visibility barriers have been successfully used to address loss-of-control and rear-end crash types at roundabouts in 40mph (65km/h) dual carriageway higher speed environments (Thompson 2009). British design guidelines recommend this measure as an optional treatment (Department for Transport (DfT) 2007). However, careful application of sightline restrictions is required, as they can potentially make an intersection less safe in certain circumstances.

D2 Sightlines, speed and safety

As a driver is approaching a roundabout, they will generally be travelling at a speed they perceive is safe enough for them to stop if an opposing vehicle comes into view. If, when they are still some distance from a roundabout they do not see any opposing vehicles, their entering vehicle speeds will be accordingly higher than if sightlines were restricted by obstacles such as boundary fences where the environment is recognised to be less safe (figures D1 and D2).

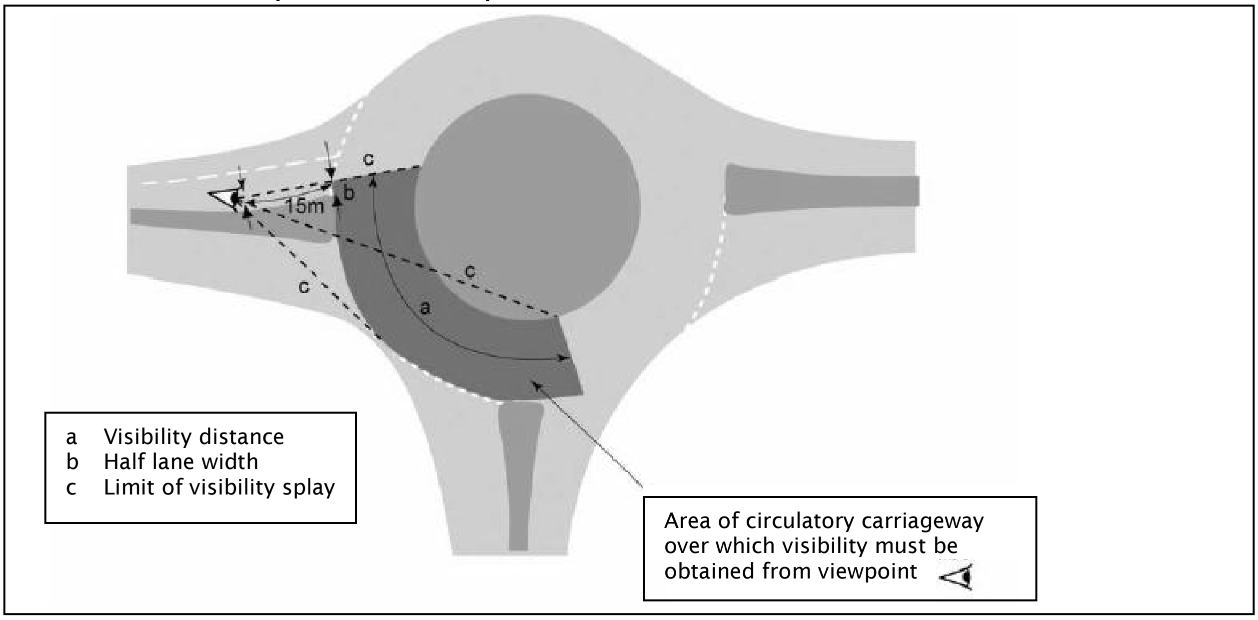
Roundabout guidelines from the UK suggest maximum sightline criteria as shown in figure D4 for dual carriageway locations with speed limits greater than 40mph which may be experiencing higher than desirable approach speeds and related crashes. It is suggested that for New Zealand, these criteria may also be applicable for roundabouts in all speed environments.

However, if sightlines to the right are restricted too much relative to the speed of circulating vehicles, then entering v circulating vehicle crashes may eventuate. This can happen if entering drivers are still travelling too fast to react and come to a stop for an opposing vehicle that comes into view.

Figure D1 Birds-eye view of the Church Street–Avenue Road roundabout in Otahuhu, Auckland, showing how sightlines are restricted from one approach

Figure D2 The driver's perspective, taken 10m back from the limit line of the Church Street–Avenue Road roundabout approach, demonstrating how the boundary fence restricts sightlines, encouraging drivers to reduce their speed

Figure D3 UK recommendations for visibility to right along circulating carriageway required at 15 metres in advance of limit lines (Department for Transport 2007).



D3 Sightline analysis

The following analysis of speeds and sightlines can be undertaken at a roundabout, either as a means of crash pattern investigation or for a new installation.

A conflict diagram can be drawn for each approach as per figure D4, and this speed/sightline analysis can be done for each approach in turn. Use the following parameters:

- Estimate or measure 85% speeds of straight-through unimpeded vehicles A and B (ie drivers travelling through without having to give way to opposing traffic). Preferably, this can be done at an exact location in advance of the conflict point (10m before the limit line is suggested).
- Allow for a driver reaction time of 0.7–1.0 seconds for an alert driver aware of the possibility that braking will be necessary (Green 2000).
- Assume a comfortable vehicle deceleration rate of $3.5m/s^2$.

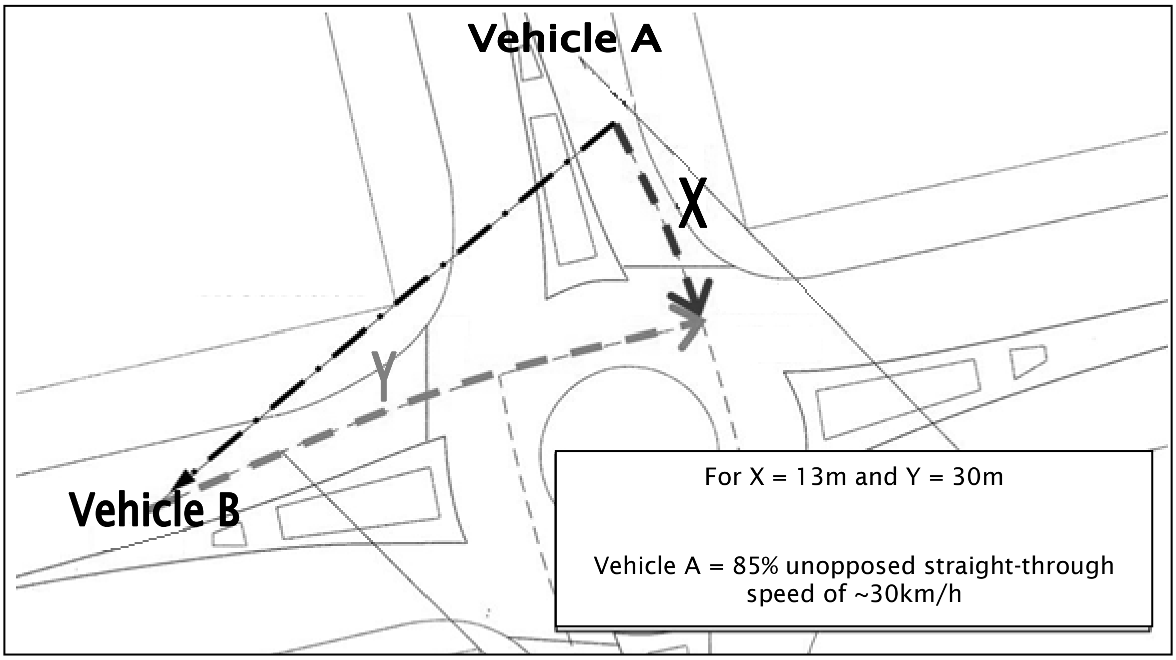
If vehicle B is travelling so fast that it will reach the conflict point before vehicle A can stop in time, the two vehicles are likely to collide. For example, a driver travelling at 30km/h requires ~10m to stop if decelerating at $3.5m/s^2$, excluding reaction time. Even if already decelerating in preparation to stop for opposing vehicles, drivers travelling in excess of 30km/h at 10m back from the limit line may have to decelerate uncomfortably hard in order to prevent a collision.

The probability of crashes occurring at a particular location will depend upon the number of vehicles from each approach that are travelling at higher speeds. If a large number of two-wheeled users (cyclists or motorbikes) use the roundabout then slower approach speeds are particularly desirable, as these users can be more difficult for drivers to discern.

Predicting vehicle approach speeds for a range of sightline combinations is desirable but requires further research. However, close analysis of a roundabout in Otahuhu, Auckland, demonstrated the relationship shown in figure D5 (NZTA 2012). Although vehicle deflection curve radii through the roundabout ranged between 75m and 600m, 85% unopposed straight-through-vehicle speeds were still in the order of

30km/h for the three approaches with these sightline restrictions. However, one approach with virtually unrestricted sightlines created by an adjacent park experienced significantly higher approach speeds that resulted in a substantial crash pattern involving these vehicles on the roundabout. From this analysis, it was concluded that a roundabout might feasibly operate safely enough without regard to other means for speed control, but only if sightline constraints are such that approaching vehicles are travelling slowly enough relative to opposing vehicle speeds (ie slow enough that they can comfortably stop in time if an opposing vehicle at speed comes into view). Given that this could potentially be a very cost-effective means of reducing vehicle approach speed at roundabouts, it is suggested that this concept is worthy of future experimentation.

Figure D4 Speed / sightline relationship gathered from analysis of the Church Street / Avenue Road roundabout in Otahuhu (NZTA 2012)



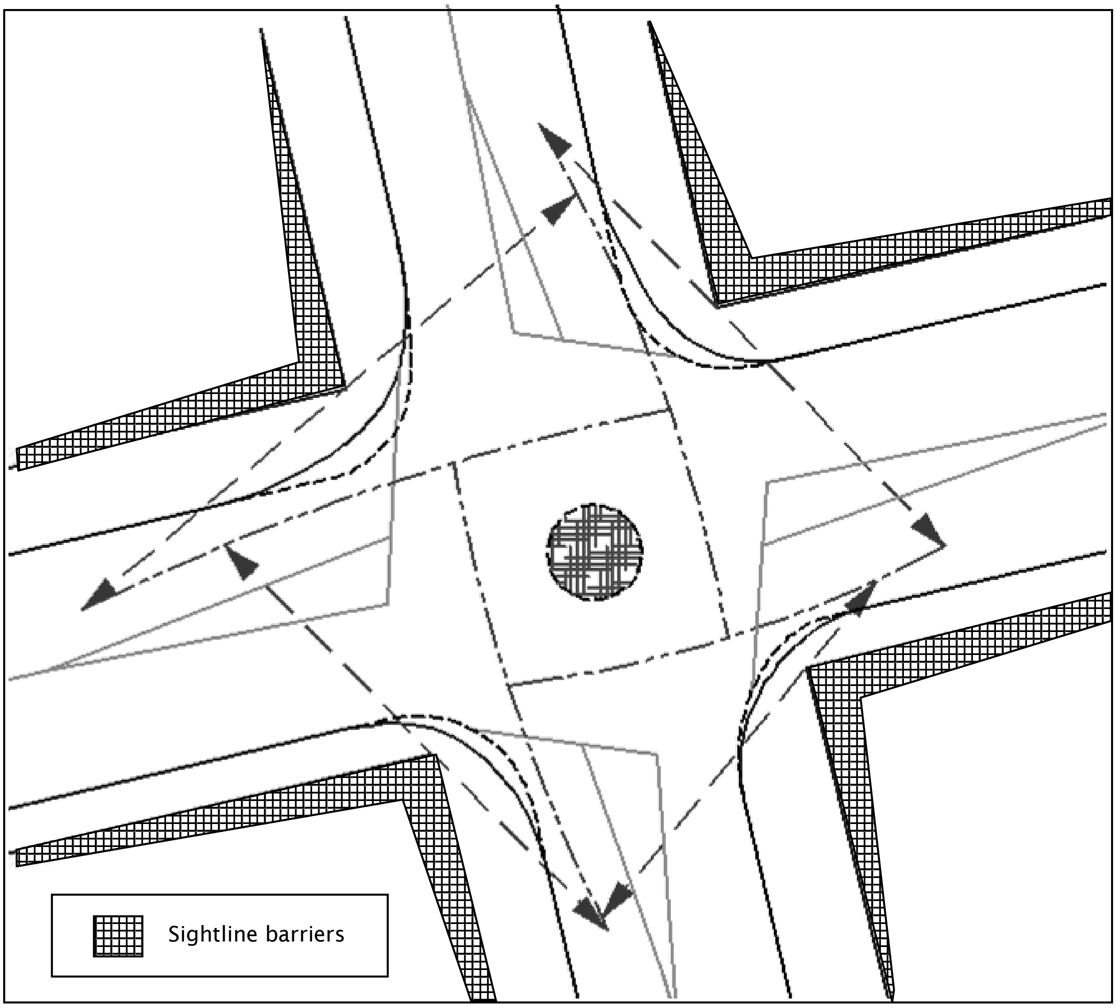
D4 Examples of using sightline restrictions to design safer roundabouts

D4.1 Example 1: single-lane four-arm roundabout

Figure D5 below shows an example of a single-lane roundabout with sightline restrictions of around 30m along all four approach roads at a point ~10m back from limit lines as per figure D4). Sightline restrictions could comprise of fences, buildings, hedges etc of a height that should block visibility for passenger car drivers (ie at least two metres). In order to prevent large trucks from driving through at high speeds, then either these sightline restrictions should be high enough for their drivers (say, three metres or higher) or the roundabout geometry should designed specifically to reduce the speed of these vehicles to around 30km/h. Other means of speed control might not be as critical to provide a result.

On the basis of the analysis at the roundabout in Otahuhu, it is expected that such a design should result in a low-speed environment and be relatively safe in practice (ie experience very occasional non-injury crashes only).

Figure D5 Sightline triangles for a four-way single-lane roundabout that is expected to experience 85% unopposed straight-through-vehicle speeds of around 30 kph for each approach.

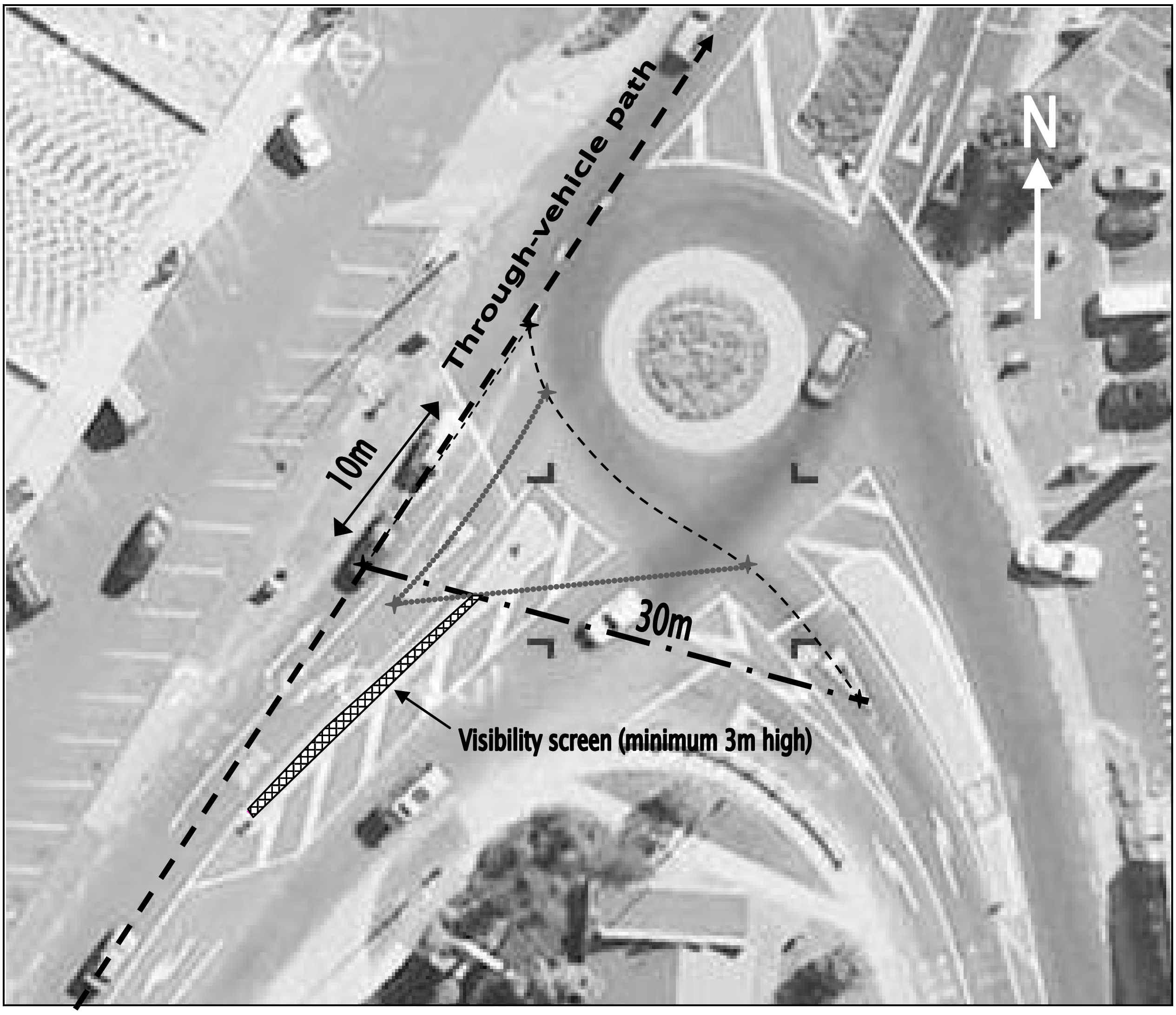


D4.2 Example 2: single-lane three-arm roundabout

Figure D6 shows a three-arm roundabout with inadequate speed control for the northbound direction. A visibility screen could feasibly be installed on the approach island, which has no pedestrian crossing facilities. Sightline triangles would need to be checked for drivers in each lane 10m back from the limit line as shown to confirm that driver speeds for the right-turn movement from the side road are not so high that entering v circulating vehicle crashes might increase, in particularly for drivers in the right-hand lane, where sightlines would be most restricted (shown as a dotted dark grey line). For this example, vehicle speeds from the conflicting westbound approach would be quite low because of the sharp-right-hand turn required. For a four-way intersection, where conflicting vehicle speeds might be higher, additional means of speed control for conflicting approaches are likely to be required (eg visibility screens if feasible).

The potential use of visibility screens at larger roundabouts such as these may be more limited because of larger kerb radii. Approach islands are often used for pedestrian crossing facilities, and for safety reasons, pedestrians need to be easily visible to drivers. In an urban context such a screen might not be desirable for aesthetic reasons, so alternative means of speed control such as a raised platform could also be considered (see appendix H).

Figure D6 Example installation of a visibility screen at an existing roundabout which has inadequate speed control in the northbound direction as shown



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Appendix E Comments on zebra crossing sites in Auckland[14]

E1 Edmonton Road–Alderman Drive: straight-through zebra crossing

Of all the sites, this one (Edmonton Road–Alderman Drive) appeared to work the best. The **advantages** were as follows:

- The location of the crossing relative to the traffic exciting the roundabout allowed approximately one vehicle length clear of the roundabout lanes. The location was still close enough to the roundabout to be visible to exiting traffic, and vehicle speeds at this point were still low. The location was close enough to the roundabout entry to be visible to entering traffic and vehicle speeds were low in preparation for entry.
- The straight-through design at this location enhanced pedestrian visibility and allowed drivers to predict passage times of pedestrians coming from opposite sides.
- The crossing was divided and gave pedestrians a small refuge to wait for traffic to clear halfway across if needed.

E2 Sel Peacock Drive–Alderman Drive: straight-through zebra crossing

This site did not work nearly as well as the one described above and could even be more hazardous than a staggered configuration. Some of the main **disadvantages** were as follows:

- The location of the crossing relative to the roundabout was much too far away. The distance from the roundabout actually reduced crossing visibility (drivers were already focusing further down the street by the time they reached the crossing). Exiting traffic had already begun to build up speed, so when a driver had to stop for pedestrians, their deceleration was more sudden and increased the likelihood of a nose-to-tail collision with following traffic. Traffic approaching the roundabout were focused on the roundabout entry at that point (and thus pedestrian visibility was reduced) and higher speeds meant that any collision with pedestrians would be more hazardous. Sudden deceleration when pedestrians were detected also increased the probability of nose-to-tail collisions with following traffic.
- The limit lines were so far in advance of the crossing they had little or no effect.
- No pedestrian refuge of stopping point halfway across was provided, and pedestrians could be left exposed to traffic in the middle of their crossing.
- The distance from the roundabout also resulted in pedestrian desire lines that could lead to jaywalking for all or part of the crossing distance.
- At this location, the straight-through configuration may encourage some high-speed pedestrian crossings by joggers and cyclists.

14 The material in this appendix was taken from a letter written by Dr Samuel Charlton of the Psychology Department of the University of Waikato, given as a personal communication to the authors on 17 February 2010.

E3 Avondale (St Jude Street–Great North Road): staggered zebra crossing

Of the sites with a staggered crossing configuration, this one was the better of the two and had the following **advantages**:

- The location of the crossing relative to the traffic entering the roundabout meant that pedestrian visibility was good and approach speeds were relatively low.
- The stagger discouraged some rapid crossing manoeuvres and provided a pedestrian refuge halfway across the roadway.

The site also had some significant **disadvantages**:

- The location of the crossing relative to traffic exiting the roundabout was too close. Some traffic stopping for pedestrians interfered with traffic circulating the roundabout.
- The proximity of the crossing to the exit of the roundabout reduced the visibility of pedestrians: the crossing point was in a very busy/cluttered part of the drivers' visual field. For drivers exiting from the circulating lane, the presence of pedestrians could be obscured by traffic waiting to turn left.

E4 Royal Oak (Manukau Road–Mt Albert Road): staggered zebra crossing

Of all the sites reviewed, this one appeared to be the most problematic and least safe, with the following **disadvantages**:

- The location of the crossing was much too far back relative to the roundabout. It was so far away, in fact, that some could question whether it really 'counted' as a roundabout crossing and whether its presence had an effect on roundabout traffic.
- However, the roundabout did have an effect on the crossing. At the location of the crossing, drivers approaching the roundabout were looking ahead to the roundabout entry (reducing pedestrian visibility), and drivers exiting the roundabout were focused further down the road and had already gathered appreciable speed.
- Although the stagger may have discouraged some rapid crossing manoeuvres – but not all, as can be seen in the video clips – and provided a pedestrian refuge, the size of the stagger may also have made pedestrians who were halfway across the roadway more difficult for drivers to detect (the pedestrians were moving towards the traffic or were stationary, as opposed to moving across the drivers' visual field).
- The limit lines were so far in advance of the crossing they had little or no effect.

E5 General conclusions

- Placement of the crossing relative to the roundabout appears to be very important. Too far a distance results in higher vehicle speeds and decreased visibility of the pedestrians owing to the drivers' focus of attention past the crossing point. A location too close to the roundabout, particularly relative to the exiting traffic, can result in stopped vehicles blocking other traffic on the circulating lanes and can decrease the visibility of pedestrians. Crossings too far back from the roundabout can also be incompatible with pedestrian desire lines, leading to jaywalking by pedestrians. A distance of approximately one car length between the crossing and the roundabout appears to be about optimal, particularly as regards traffic exiting the roundabout.

- Straight-through crossings may provide superior visibility of pedestrians owing to their direction of movement through the drivers' visual field. When a straight-through crossing is used, however, a pedestrian refuge (non-staggered/not offset) should be included to reduce exposure times and improve safety.
- Although the offset staggered configuration can have some benefits by providing a refuge and discouraging high-speed crossings by joggers and cyclists, the direction and degree of the offset could be improved. For example, figure E1 shows a staggered/offset configuration as used at the Avondale site. Figure E2 shows a configuration with the direction of offset reversed and the degree of stagger reduced. I believe the effect of this alternative configuration would be:
  - improved visibility of pedestrians by virtue of the placements of the crossings relative to where the drivers are looking as they exit or approach the roundabout, as well as the reduction in the offset making crossing pedestrians more conspicuous
  - some reduction in the blockage of circulating lanes by exiting traffic stopped for pedestrians
  - crossing locations that are more congruent with pedestrian desire lines.

Figure E1 Standard staggered/offset zebra crossing configuration

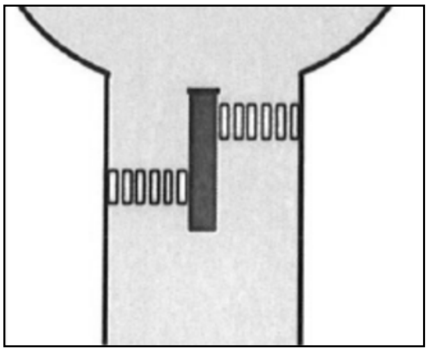
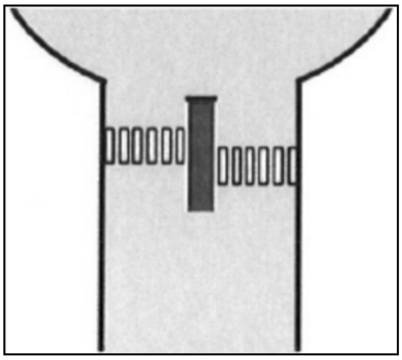


Figure E2 Alternative zebra crossing configuration with the offset reversed and the degree of stagger reduced



- The use of raised pedestrian platforms or speed tables, as suggested elsewhere in the report, would be compatible with and enhance any of the pedestrian crossing options described above.

Appendix F Practical application of research findings: pedestrian facilities at roundabouts in New Zealand

F1 Background

In general, well-designed roundabouts can be significantly safer than signalised intersections for vehicle users (especially for junctions with four arms or more), but pedestrians may be disadvantaged, depending upon the facilities provided for them and whether speed control is inadequate at the roundabout. It can be difficult for pedestrians to judge the intended paths of traffic at roundabout exits; at multi-lane roundabouts, the extra distance to cross can exacerbate this.

The Austroads *Guide to road design part 4B: roundabouts* (Austroads 2009) should be referred to in the first instance as it is the accepted guideline for NZTA. It is expected that this appendix will offer added value for certain situations.

F2 Consideration of particular pedestrian groups

F2.1 Elderly pedestrians and children

Elderly pedestrians have slower reflexes and are less able to take evasive action if vehicles do not stop for them, and can be over-represented in casualties at zebra crossings near multi-lane roundabouts. The concern with young children aged less than 10 years or so is their lack of the cognitive skills which are required at unsupervised zebra crossings to judge traffic speeds and driver intentions.

At locations where a high proportion of pedestrians are children or elderly (such as at shopping precincts or near schools), particular attention should be made to ensure crossing points are conservatively designed to take these factors into account.

F2.2 Mobility and visually impaired

Visually impaired pedestrians can find it difficult to cross the road close to any roundabout. Their difficulty stems from the fact that they cannot use audible clues to distinguish through-traffic from turning traffic as they can at a normal junction. In addition, at multilane roundabouts, traffic noise can make it difficult for them to tell audibly if drivers are stopping to let them cross at zebra crossings. In order to cater for this specific user group, traffic engineers may need to consider the availability of crossing points some distance from the roundabout. In general, the Royal New Zealand Foundation for the Blind (RNZFB) would prefer signalised crossings if facilities are located near the roundabout, or crossing points further away. For areas where substantial numbers of visually impaired pedestrians could be expected (such as heavily pedestrianised areas in shopping precincts (figure F1), or near blind institutes), this factor needs to be taken into account. Consultation with orientation and mobility instructors from RNZFB is recommended for new intersection installations, particularly for accessible routes to schools and shopping centres.

In order to assist mobility impaired users with wheelchairs or mobility scooters, central islands should be installed at grade for easy access, and kerbside pram crossings should comply with RTS 14 as a minimum (NZTA 2003).

Figure F1 Zebra crossing facilities at a roundabout near a shopping centre, showing elderly pedestrians and children using these facilities

F3 Choice of facility

F3.1 Pedestrian refuge islands

Roundabout approach islands also act as pedestrian refuge islands and should be designed accordingly. They are normally the only pedestrian facility needed. Zebra crossings can be considered where traffic volumes result in undue delay. Traffic engineers should ensure that sightlines are adequate for pedestrians to cross the road, taking expected driver speeds into account. Refuge islands should ideally be set back around one to two car lengths from roundabout limit lines, as this is where vehicle speeds are lower and where pedestrians can cross between queued vehicles.

F3.2 Zebra crossings

Zebra crossings are some of the most common facilities installed at New Zealand roundabouts where substantial volumes of pedestrians are present and traffic volumes create poor pedestrian levels of service caused by undue pedestrian delay. Ideally, zebra crossings will be located as near to pedestrians' desire lines as possible. In general, zebra crossings are relatively safe for pedestrians to use, provided traffic speeds are well managed.

However, crossing points located further than 20m from the roundabout can experience safety problems, as vehicle speeds can be higher. For multi-lane crossings, vehicles stopping to let a pedestrian cross in one lane can obscure visibility to drivers in the adjacent lane and the higher traffic speeds can exacerbate the severity of any collisions that might occur. Similarly, inadequate speed control at the roundabout can result in less safe conditions for pedestrians. This may be the case for roundabout exits in particular, where drivers are accelerating away from the roundabout and are less likely to yield to pedestrians. Section F4 of this appendix gives some advice for the design of zebra crossings at multi-lane roundabouts.

In the context of a lower-speed environment near a well-designed roundabout, zebra crossings may also be preferred if the location gives importance to pedestrians in the road user hierarchy.

F3.3 Mid-block pedestrian signals

Mid-block pedestrian signals can be an effective method of providing for pedestrians near roundabouts, and appear to be a satisfactorily solution to multi-lane crossing points greater than 20m from the roundabout. However, unless pedestrian wait times are reasonable (say, less than around 30 seconds or so, but this will depend upon the perceived level of danger), jaywalking will probably occur, adversely affecting safety performance. The Auckland Traffic Management Unit (TMU) provide guidelines on how to achieve this in their *Traffic signal design guidelines* (Auckland TMU 2010). The following factors also need to be taken into account:

- The visibility of signal displays to approaching drivers is an important consideration for reducing run red incidents. Overhead signal displays are recommended in multi-lane situations.
- All-red times could be increased to reduce the chance of late runners hitting pedestrians. This is more viable for staggered island crossings.

Intelligent signal technology such as 'Hawk', 'Pelican' or 'Puffin' signal crossings can reduce disruptive effects to roundabout traffic flow by reducing pedestrian clearance times. Although flashing signals, as used by Hawk and Pelican crossings are not currently legal to use in New Zealand (this situation is being recommended for review by the NZTA), the pedestrian detection technology sometimes used at Puffin crossings in the United Kingdom could feasibly be used to achieve the same objective. The reliability of this detection technology needs to be better proven.

F4 Other considerations

F4.1 Disruptive effects of zebra crossings and signals on traffic flow

Disruption to traffic flow will primarily depend upon volumes of pedestrians, and these effects can be modelled using AASIDRA, VISSIM or other simulation packages. When pedestrian volumes exceed a certain threshold for a given traffic volume, pedestrian signals with regular call-ups can be a means of reducing disruptions to vehicle flow compared to zebra crossings.

For roundabout exits where stopped vehicles can queue back into roundabout circulating lanes, this can be modelled to determine an optimum pedestrian crossing location to minimise the frequency of this occurring. If queuing across circulating lanes is unavoidable, yellow cross-hatching can reduce the periods of lane blockage.

F4.2 Rear-end crashes at pedestrian crossing points

Rear-end crashes can be a particularly prevalent crash type at busy roundabout exits. Measures to address this crash type can include:

- redesigning the roundabout to incorporate appropriate speed control
- installing a staggered island arrangement at zebra crossings (the numbers of vehicles stopping for pedestrians can be minimised with a staggered island arrangement, with no apparent compromise to pedestrian safety relative to a straight across island)
- using high friction road surfacing at roundabout exit approaches to pedestrian crossing points
- installing flashing road studs or flashing signs in advance or at the pedestrian crossing points, which can be called up by pedestrian detection (or, in the case of signals, during amber or red phases); the use of these devices is expected to be approved by the NZTA in the near future.

F5 Safer zebra crossings at multi-lane roundabouts

Provided vehicle speeds are well managed, zebra crossings can function satisfactorily at a multi-lane roundabout and can provide good mobility for pedestrians compared to refuge islands or signalised crossing points. However, if vehicle speeds are too high at crossing points, pedestrian safety may be compromised.

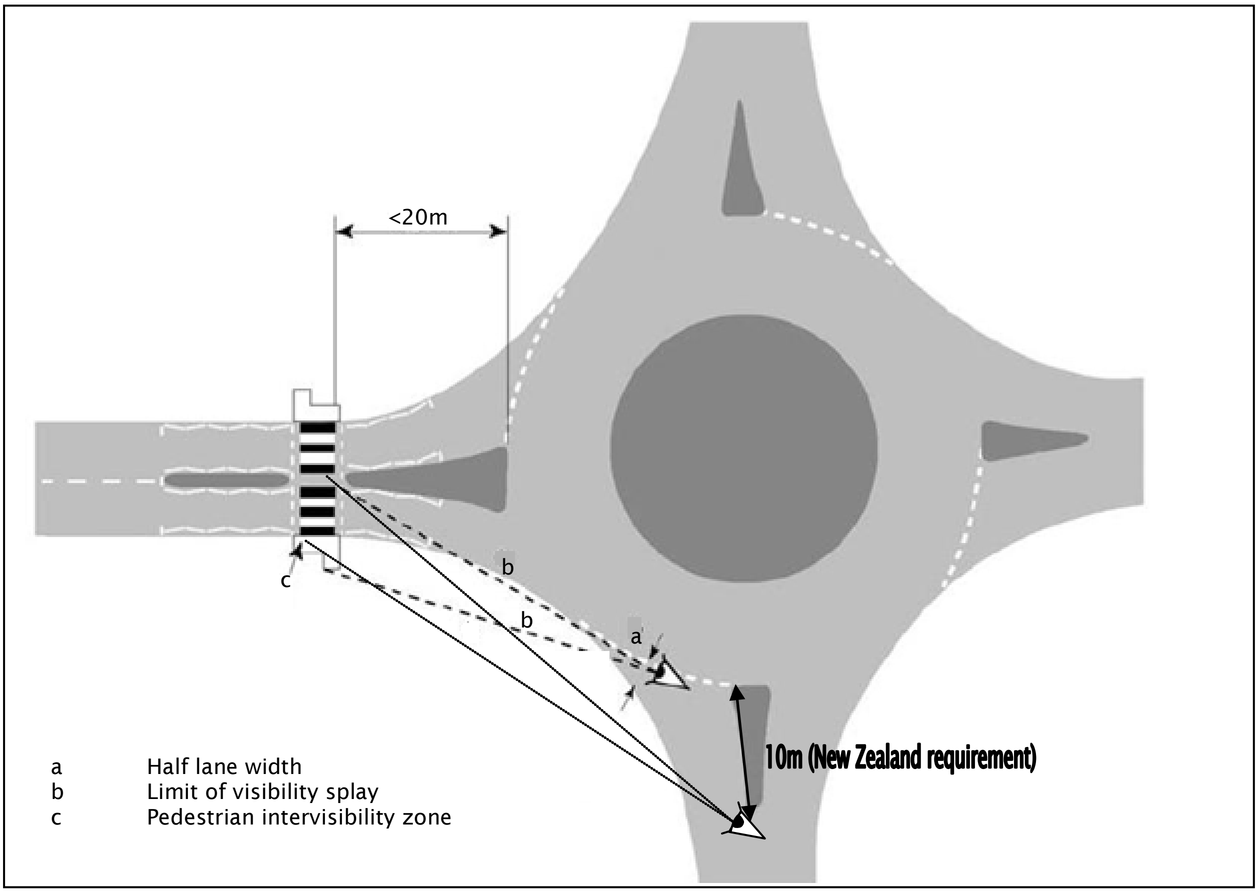
Vehicle speeds are generally lower close to circulating lanes, and this research has shown that crossings further than 20m away are more susceptible to injury accidents occurring.

The following measures are recommended:

- Multi-lane zebra crossings should be less than 20m from circulating traffic lanes to ensure they are in a lower-speed environment (preferably 5–15m). The roundabout should also have good vehicle speed control to around 30–40km/h, with less than 50km/h being the absolute maximum and 30km/h being the desirable maximum.
- If a zebra crossing is further than 20m from circulating lanes, then additional measures such as a raised platform and active warning devices (flashing road studs or signs) are recommended for consideration. At zebra crossings with two lanes or more in one direction, queued vehicles in one lane can impede visibility of pedestrians to adjacent lane drivers and this deserves careful consideration. Signalised crossing points can also be a safer option in these circumstances, and are preferable with a staggered island arrangement.
- At zebra crossings with more than two lanes in one direction, raised platforms or signalised crossing points may be desirable.
- For crossings on collector or arterial roads, use 5m long zebra crossing bars in thermoplastic for increased conspicuity in all weather conditions.
- If a zebra crossing is experiencing pedestrian safety problems, then the problem should be carefully diagnosed to develop a solution that considers all the options described in this appendix. Active warning devices such as flashing road studs or signs should be considered. These can better alert drivers that pedestrians are using the crossing.
- Sightline splays, as shown in figure F2, should be clear of all obstacles in order to ensure good intervisibility between pedestrians and drivers entering the roundabout from adjacent roads.
- Vehicle limit lines might be better dispensed with for crossings close to circulating lanes at exits, as queued vehicles in circulating lanes can cause rear-end crashes and obstruct traffic flow. For low-speed situations, stopping distances should be low in any case, and according to *Manual of Traffic Signs and Markings* section 2: markings; clause part 4.02.03B (NZTA 2010), they are not compulsory if they are impractical to install.
- Staggered island arrangements can be a desirable safety feature at zebra crossings as they give drivers and pedestrians more time to discern each other's intentions. However, they are not ideal near busy roundabouts, as they can push exit vehicle queues into circulating traffic lanes.
- Visually impaired users can find it difficult to hear gaps in traffic near busy roundabouts, which can be noisy. If large numbers of these pedestrians are likely to be at a particular roundabout (such as near a blind institute), alternative crossing points away from the roundabout should be sought.

Recommended pedestrian sightline splays are shown in figure F2.

Figure F2 Visibility requirements for zebra crossings in the UK (DfT 2007), but with an additional requirement for use in New Zealand also that the crossing point also be visible from a point 10m before the limit line



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Appendix G Waitakere City acoustic study[15]

G1 Introduction

Marshall Day Acoustics (MDA) has been engaged to undertake a 'before and after' noise study in relation to the installation of Modified Watts Profile Speed humps in Waitaki Street, Henderson.

The purpose of this study was to establish if there were any significant changes in noise received by local residents as a direct result of installing the speed humps.

G2 Speed hump application

The location and number of speed humps installed on Waitakere City Council plans, drawing number 15903, sheets 1 and 2 (contract number TA07013a). A total of seven 'Modified Watts Profile' speed humps (maximum height of 100mm in the centre and a total length of 5m) were installed along the length of Waitaki Street between View Road and James Laurie Street in Henderson.

Waitaki Street runs parallel with Great North Road and is situated approximately 155m to the west of Great North Road.

One of the speed humps installed outside 18 Waitaki Street is depicted in figures G9 and G10 in section G8.

G3 Methodology

G3.1 Assessment site

A noise assessment site was chosen at 18 Waitaki Street adjacent to the second speed hump when approaching from the View Road end of Waitaki Street (refer figure G1 in section G8). This site provided good vision in both direction (refer figures G2 and G3 in section G8) and would require vehicles to negotiate a speed hump (from either direction once installed) before approaching the speed hump adjacent to the assessment site.

G3.2 Scenarios

Two scenarios were considered as follows:

- scenario one: before the installation of the speed humps (before humps)
- scenario two: six months after the installation of the speed humps (with humps).

Data collected from the two scenarios were compared and assessed in order to identify any changes in noise resulting from the installation of the speed humps.

15 This appendix was originally prepared by Marshall Day Acoustics and has been reproduced with their permission, with minor modifications to make the report conform to NZTA house style.

G3.3 Noise data collection

Two forms of noise data collection were used for both scenarios as detailed below.

G3.3.1 Noise logger

A noise logging device was placed in the front garden of 18 Waitaki Street (refer figures G1 and G4 in section G8). Measured noise data was logged in 10-second intervals for a period of one week for each of the two scenarios.

G3.3.2 Attended measurements

Attended noise measurements were undertaken for the following:

- local vehicles (mostly cars) using Waitaki Street, travelling in both directions
- a test bus travelling in both directions along Waitaki Street
- a test rental truck travelling in both directions along Waitaki Street.

The same rental truck and model of bus (refer section G3.5 below for details) were used for both scenarios. The measurement position was located 4.4m back from the road kerb edge in line with the centre of the speed hump. The measurement position (ie sound level meter on a tripod) is depicted in figures G1, G10 and G11 in section G8.

G3.4 Vehicle count data

In order to quantify vehicle use of Waitaki Street during the noise study (ie during the two weeks of noise logging), a vehicle tube count was installed to record data such as speed, vehicle type, direction and the number of vehicle movements etc.

For scenario one, the tube count was placed across the road outside 5 Waitaki Street (refer figure G5 in section G8). For scenario two, the tube was placed across the road outside 10 Waitaki Street (refer figure G6 in section G8).

G3.5 Test vehicles

Details of the test buses and truck used for attended noise measurements are as follows:

- Scenario one
  - bus: supplied by Go West Buses
bus no. 1448 – 2003 MAN 17.223 SLF – registration no. BNK103 (refer figure G7 in section G8)
  - truck: supplied by Henderson Rentals Ltd
1998 Hino FD 3HLKA – registration no. WT9132 (refer figure G8 in section G8)
- Scenario two
  - bus: supplied by Go West Buses
bus no. 1450 – 2003 MAN 17.223 SLF – registration no. BNK111 (refer figure G9 in section G8)
  - truck: same truck used for scenario one.

G4 Noise measurements

G4.1 Equipment

A Brüel & Kjaer type 2238 mediator (S/N 2160281) fitted with a Brüel & Kjaer Type 4188 half-inch microphone (S/N 2157060) was used for the noise logging. The 2238 was calibrated using a Brüel & Kjaer sound level calibrator type 4231 (S/N 2095392).

A Brüel & Kjaer type 2250 analyser (S/N 2619895) fitted with a Brüel & Kjaer type 4189 half-inch microphone (S/N 2621090) was used for attended measurements. The 2250 was calibrated using a Brüel & Kjaer sound level calibrator type 4231 (S/N 2402639).

All equipment carried current calibration certification provided by Electroacoustic Calibration Services Ltd, Auckland.

G4.2 Noise logger

Measured noise data was logged for the durations as noted in table G1 below.

Table G1 Noise logger measurement durations

Scenario	Start time/date	Finish time/date
One	12:00pm, Tues 08/04/08	12:00pm, Tues 15/04/08
Two	12:00pm, Tues 28/10/08	12:00pm, Tues 4/11/08

The recognised descriptor for assessing traffic noise is $L_{Aeq24hr}$, which represents the time-average A-weighted sound pressure level over one full day from 0000 hours to 2400 hours.

The measured noise data was analysed to determine the $L_{Aeq24hr}$ noise levels for each day of the week and for the five-day (Monday to Friday) and seven-day (week) averages. Noise data suspected as not being related to traffic events, or noise data not associated with the attended bus and truck measurements, was excluded.

A summary of the resulting $L_{Aeq24hr}$ noise levels is presented in table G2 along with total vehicle numbers for the same periods.

Table G4 $L_{Aeq24hr}$ noise levels & vehicle numbers summary

Period	$L_{Aeq24hr}$ (dB)[a]			Vehicle numbers[b]		
	Before humps	With humps	Change	Before humps	With humps	% change
Monday	54	52	–3	817	697	–15
Tuesday	56	52	–2	957	715	–25
Wednesday	55	53	–2	967	793	–18
Thursday	55	54	–1	1028	803	–22
Friday	55	53	–2	1044	823	–21
Saturday	54	54	0	942	756	–19
Sunday	55	53	–2	775	554	–29
Five-day average	55	53	–2	963	766	–20[c]
Seven-day average	55	53	–2	933	736	–21[c]

Notes to table G2:

a Determined from noise logger data.

b Determined from tube count data. Includes both southbound and northbound vehicle trips. Excludes vehicle trips associated with the attended measurements for the test buses and truck.

c A 20% reduction in traffic volume equates to a reduction in noise level of one decibel.

Mean vehicle speed data and the percentage of vehicles exceeding the posted speed (both determined from the tube count data) are presented in tables G3 and G4 below.

Table G3 Mean vehicle speed – Waitaki Street (all vehicles)

Direction	Before humps	With humps	Change
Northbound	44km/h	38km/h	–6km/h
Southbound	46km/h	40km/h	–6km/h

Table G4 Percentage of vehicles exceeding the posted speed

Direction	Before humps	With humps	% change
Northbound	18%	2%	–89%
Southbound	33%	5%	–85%

G4.3 Attended measurements

Attended measurements were undertaken as presented in table G5 below.

Table G5 Attended measurement dates/times

Scenario	Date	Times
One	Friday 11/04/08	8:04am to 12:00pm
Two	Thursday 30/10/08	8:14am to 1:08pm

A number of measurements of individual vehicles were undertaken in order to ascertain a sample of SEL sound levels for individual vehicles from which an average SEL sound level could be determined. The SEL is the sound level of one second's duration which has the same amount of energy as the actual noise event measured. The number of useable sample measurements are summarised in table G6 below.

An audio recording (taken while the noise measurement was in progress) was also obtained for each measurement.

Table G6 Number of useable attended sample measurements

Vehicle	Vehicle direction	Before humps Friday 11/04/08	With humps Thursday 30/10/08
Single cars (local)	Northbound	20	12
	Southbound	27	12
Bus (test)	Northbound	6	5
	Southbound	5	5
Truck (rental)	Northbound	5	5
	Southbound	5	5

The test bus and truck drivers were asked to drive in a typical manner without exceeding the 50km/h speed limit. The average speed of the bus and truck recorded by the tube count is noted in table G7.

Table G7 Average speed recorded by tube count for bus and truck tests

Vehicle	Vehicle direction	Average speed (km/h)		
		Before humps	With humps	Change
Bus	Northbound	42	35	-7
	Southbound	44	38	-6
Truck	Northbound	40	40	0
	Southbound	37	42	+5

For scenario two (ie with speed humps):

- The bus driver advised that he approached the 18 Waitaki Street at about 30km/h and exited the speed hump at between 10–15km/h.
- The truck driver advised that the speed hump was approached and exited in fourth gear and that the brakes were applied briefly before travelling over the speed hump (a slight brake squeal was audible for a short duration).

The averaged noise level results of the attended sample measurements are presented in table G8 below.

Table G8 Averaged SEL L_{eq} and L_{max} noise levels from attended measurements

Vehicle	Vehicle direction	SEL (dBA)			L_{eq} (dBA)			L_{max} (dBA)		
		Before humps	With humps	Change	Before humps	With humps	Change	Before humps	With humps	Change
Single cars (local)	Northbound	78	71	−8	67	61	−6	75	67	−8
	Southbound	76	69	−8	66	58	−8	70	66	−4
Bus (test)	Northbound	80	86	+6	67	73	+6	79	83	+4
	Southbound	78	83	+5	66	69	+3	76	79	+3
Truck (rental)	Northbound	78	85	+7	65	71	+5	76	83	+7
	Southbound	78	84	+6	66	70	+4	75	83	+8

Notes to table G8:

Refer to section G7 for glossary of terminology.

G5 Discussion

Based on the data in tables G2 to G4, installation of the speed humps has resulted in the following:

- a two-decibel reduction in the overall $L_{Aeq24hr}$ noise level
- a 20% overall average reduction in vehicle numbers (ie traffic volume) (Note: this assumes no reduction in vehicle traffic that may have been due to petrol price increases between April 2008 and October 2008)
- a reduction of 6km/h in the mean speed
- an 85% to 90% reduction in the number of vehicles exceeding in the posted limit.

The two-decibel reduction in the $L_{Aeq24hr}$ noise level is considered to comprise:

- 1 decibel reduction due to the 20% reduction in traffic volume
- 1 decibel overall cumulative reduction comprising
  - lower noise levels from cars due to the slower mean vehicle speed
  - higher noise levels associated with heavy commercial vehicle trips.

While carrying out attended measurements with the speed humps in place, it was observed that most cars typically cruised over the speed hump located outside 18 Waitaki Street without any significant engine revving or noise from suspension or tyres.

During test measurements of the bus and truck with the speed humps in place, it was observed that the bus and truck braked (decelerated) before each speed hump, coasted over the hump until the rear wheels reached the downhill side of the speed hump, and then accelerated away back up to speed. This pattern was typically repeated for each speed hump. Some brake squeal was audible during braking.

Based on the data in table G8, installation of the speed humps has resulted in the following:

- a reduction in the noise level at the measurement position of around 8dB for individual car noise events travelling along Waitaki Street
- an increase of around 6dB at the measurement position for individual test bus and truck noise events travelling along Waitaki Street

- a decrease in the maximum sound level (ie L_{max}) for single car events at the measurement position
- a significant increase in the maximum sound level (ie L_{max}) for heavy vehicles (ie bus and truck) at the measurement position.

For most cars travelling along Waitaki Street, the dominant or controlling noise course is 'road-tyre interaction noise' which is related to vehicle speed. It is considered that the reduction in noise levels for individual cars is due to a reduction in road-tyre interaction noise resulting from the decreased vehicle speed (6km/h speed reduction with the speed humps in place).

For the test bus and truck, the dominant or controlling noise source is engine/exhaust noise. With the speed humps in place, the bus (or truck) generally took longer to travel along Waitaki Street as it slowed down to take each speed hump as well as travelling at a slower speed between consecutive speed humps.

This means that a given receiver is exposed to the noise source (eg engine noise) for a longer period of time, resulting in a higher overall noise level being received for that particular vehicle movement. This is demonstrated by the fact that the measured time-averaged sound pressure level (ie L_{eq} in table G8) increased by 3-6dB at the measurement position with the speed humps in place.

Because the bus and truck both decelerate before negotiating the speed hump, a burst of acceleration (ie increased engine revs/noise) is used past the hump in order to regain lost speed. The result is an increase in the maximum noise levels (ie L_{max}) generated at each speed hump. This is also demonstrated by the measured data in table G8, whereby the L_{max} levels increased by 3-8dB.

Based on the measured noise data, the installation of the speed humps has been very effective in reducing traffic noise generated by cars. However, any reduction in the overall level is compromised by an increase in noise generated from heavy vehicles (ie bus and truck) using the same route.

Based on the tube count data, there were approximately 60 heavy commercial vehicle trips along Waitaki Street during the first week (ie scenario one without speed humps) and about 70 heavy commercial vehicle trips during the second week (ie scenario two with speed humps). This indicates that there appears to be no reduction in the number of heavy commercial vehicles as a result of the speed humps being installed.

G6 Conclusions

Marshall Day Acoustics has undertaken a 'before and after' noise study in relation to the installation of Modified Watts Profile speed humps in Waitaki Street, Henderson.

Based on the measured noise level data obtained, the installation of the speed humps has resulted in an overall reduction of 2dB in the $L_{Aeq24hr}$ noise level comprising:

- 1 decibel reduction due to a 20% reduction in traffic volume
- 1 decibel reduction from the cumulative effect of
  - decreased noise contribution from cars travelling at slower speeds, resulting in reduced road-tyre interaction noise
  - higher noise contribution from heavy commercial vehicles due to slower travel speeds and increased noise levels from engine revving under acceleration when exiting speed humps.

Noise levels from individual car movements driving past the specific measurement position have significantly decreased due to a reduction in 'road-tyre interaction noise' resulting from decreased vehicle speeds.

The dominant or controlling noise source for the test buses and truck was engine/exhaust noise (not road–tyre interaction noise as with cars.

With the speed humps in place, the test vehicles slowed down (braked) before each speed hump, accelerated when exiting the speed hump to regain lost speed, and generally travelled more slowly between consecutive speed humps. This resulted in:

- increased time-averaged sound pressure levels (ie L_{eq} levels) due to the receiver position being exposed to engine/exhaust noise for a longer duration
- increased maximum noise levels (ie L_{max} levels) due to increased engine revs under acceleration when exiting the speed hump.

The installation of the speed humps have been very effective in reducing traffic noise generated by cars, but any reduction in the overall level is compromised by an increase in noise generated from heavy vehicles (ie bus and truck) using the same route.

For residential streets with very low heavy commercial vehicle use, it is expected that the installation of Modified Watts Profile speed humps would result in a reduction in traffic noise. The magnitude of the reduction would be dependent on the number of heavy vehicle movements.

For streets located within commercial or industrial areas (with more heavy commercial vehicles), it is likely that the installation of speed humps would result in an increase in noise from traffic.

G7 Appendix: glossary of terminology

dB: Decibel – a measurement of sound level expressed as a logarithmic ratio of sound pressure *P* relative to a reference pressure of P_r = 20μPa, ie dB = 20 x log(P/P_r)

dBA: A measurement of sound level which has its frequency characteristics modified by a filter (A-weighted) so as to more closely approximate the frequency bias of the human ear

L_{eq}: The time-averaged sound level (on a logarithmic/energy basis) over the measurement period (normally A-weighted)

L_{eq24hr}: The time-averaged sound level (on a logarithmic/energy basis) over a full day (normally A-weighted)

L_{95}: The sound level which equalled or exceeded for 95% of the measurement period. L_{95} is an indicator of the mean minimum noise level and is used in New Zealand as the descriptor for background noise (normally A-weighted)

L_{10}: The sound level which is equalled or exceeded for 10% of the measurement period. L_{10} is an indicator of the mean maximum noise level and is used in New Zealand as the descriptor for intrusive noise (normally A-weighted)

L_{max}: The maximum sound level recorded during the measurement period (normally A-weighted)

Frequency: The number of pressure fluctuation cycles per second of a sound wave. Measured in units of Hertz (Hz)

Noise: A sound that is unwanted by or distracting to the receiver

SEL: The sound level of one second's duration which has the same amount of energy as the actual noise even measured

G8 Appendix: photos

Figure G1 Assessment site at 18 Waitaki Street (11/4/08)

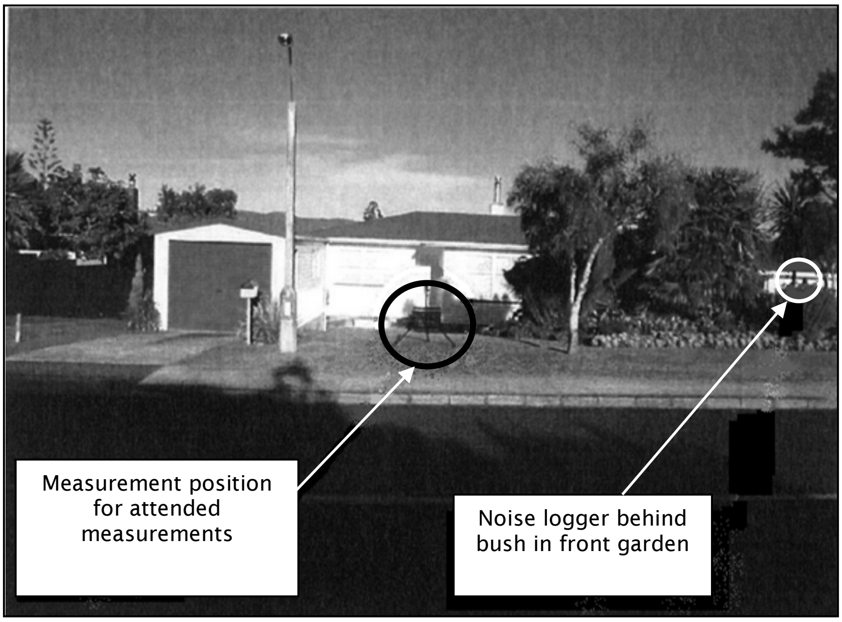


Figure G2 Assessment site – view north (11/4/08)

Figure G3 Assessment site – view south (11/4/08)

Figure G4 Noise logger behind bush (8/4/08)

Figure G5 Tube count outside 5 Waitaki Street (8/4/08)

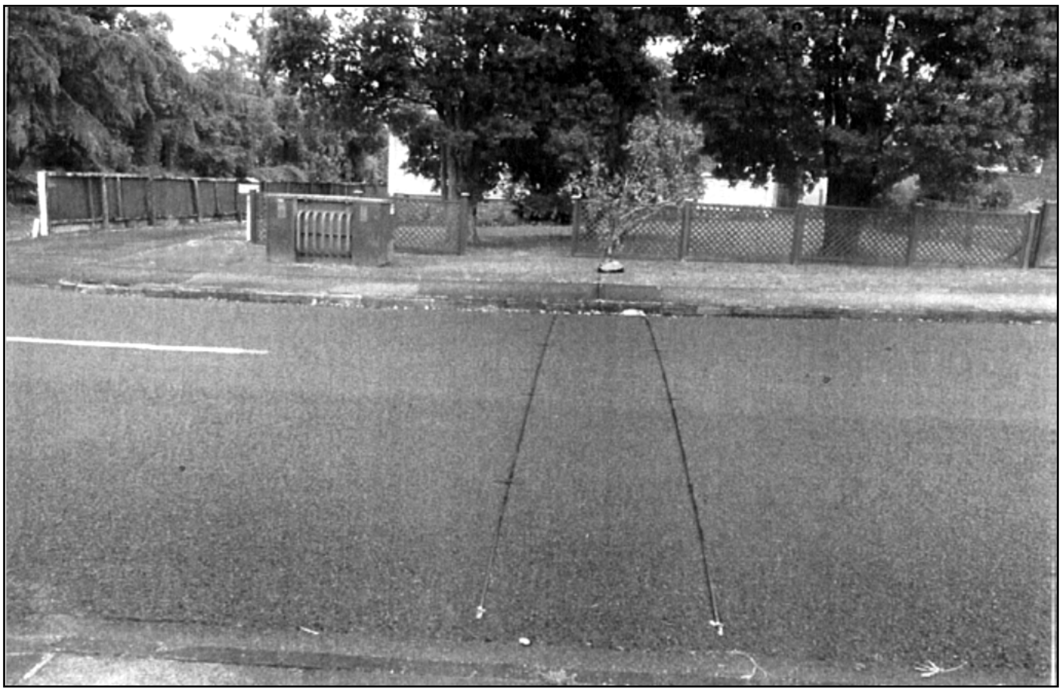


Figure G7 Bus no. 1448 (11/04/08)

Figure G8 Test truck (30/10/08)

Figure G9 Bus no. 1450 (30/10/08)

Figure G10 Speed hump outside 18 Waitaki Street (30/10/08)

Figure G11 Speed hump viewed from 18 Waitaki Street, showing attended measurement position (30/10/08)

Appendix H Practical application for application of vertical deflection devices on main road roundabouts in urban speed environments

H1 Introduction

Vertical deflection devices such as raised speed platforms, speed humps and speed cushions can be an effective method of reducing driver speeds at roundabouts, and can be effective for improving cyclist and pedestrian safety in particular. They are also an economic addition to other means of speed control at roundabouts where vehicle deflection may be difficult to attain because of land constraints. The purpose of this application is to give designers some brief advice as to their application, and to enable an objective analysis of any potential adverse effects. Note that this form of speed control will generally only be suitable for urban 50km/h speed environments and, in general, is a less desirable form of speed control compared to other methods.

The Austroads *Guide to road design part 4B: roundabouts* (Austroads 2009) should be referred to in the first instance as it is the accepted guideline for NZTA. It is expected that this report may offer some assistance for certain situations.

H2 Vertical deflection device options

H2.1 Choice of profile

Choice of profile will primarily depend upon the speed environment that is to be achieved. For example, shopping areas with high volumes of pedestrians would be more appropriate for 100mm high platforms that are only comfortable to traverse at 20km/h compared to an industrial area with large volumes of trucks. For raised speed platforms and humps, the height and gradient of approach ramps are the main influencers on vehicle speed; for speed cushions, the device’s width is the greatest influence.

H2.2 Raised speed platforms

Raised speed platforms will generally be 50–100mm high. Although comprehensive speed data is not available for various platform profiles, heights of less than 50mm and/or ramp gradients any slighter than 1 in 15 are considered unlikely to result in a useful speed reduction. For most applications, 75mm high is suggested.

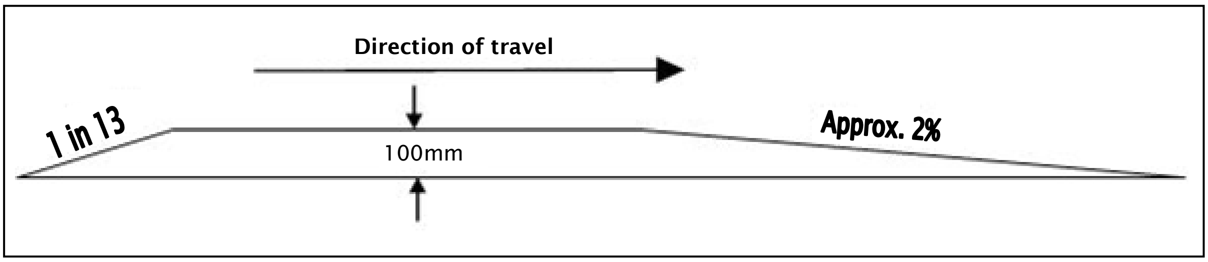
Guidelines from the United Kingdom suggest that a good compromise between speed reduction and bus passenger comfort is to use 75mm high platforms with 1 in 15 gradient ramps (Department for Transport 2007). By similar reasoning, the Swedish City of Malmö uses 100mm high platforms with 1 in 13 ramps (refer to figures H1 and H2), and use less steep ramps of around 2% or less on the departure side of each platform to reduce the ‘bounce’ effect – note that this requires median islands between each direction of travel.

The flat-top length of a speed platform between steep ramps should ideally be greater than wheelbase of longest trucks or buses for the route in order to avoid bounce amplification or double bounce as they are traversed. This is important for bus passenger comfort in particular (eg for articulated buses, the flat-top might need to be around 12m long). One study from Auckland City demonstrated 85% vehicle speeds of

25–30km/h immediately adjacent to six 100mm-high speed tables with ramps that ranged from 1:10 to 1:15 gradients (Auckland City Council 2001).

Figure H1 The Lorensborgsgatan–Stadiongatan roundabout in Malmö, Sweden (left-hand drive) which uses 100mm-high raised platforms on each entry and exit arm to facilitate pedestrian and cycle path crossing points around the perimeter of the roundabout (photo provided by Transport Department, City of Malmö)

Figure H2 Profile of each platform shown in figure H1



H2.3 Round-top speed humps

The 100mm high Watts Profile or Modified Watts Profile (MWP; figure H3) can achieve similar vehicle speed control to platforms and are usually the cheapest devices to install. MWPs are 5m long (along the direction of travel) and are specially designed to be more forgiving to heavy vehicles than the standard Watts profile, which is 3.7m long. However, they can result in discomfort to bus passengers if drivers are not considerate. Tube counters immediately adjacent to three MWP speed humps on local roads in Waitakere City, Auckland, demonstrated 85% speeds of 35–40km/h (Waitakere City Council 2010). In addition, a study from the United Kingdom measured 85% crossing speeds of around 50km/h at seven local road sites with round-top speed humps 50mm high and 900mm long (Department for Transport 1994).

Figure H3 Photo of a MWP speed hump, as commonly installed in some New Zealand jurisdictions

H2.4 Speed cushions

A variety of profiles for speed cushions (figure H4) are available. In the United Kingdom, speed cushions 75mm high and 1.6m wide are preferred to platforms or humps for bus or ambulance routes on local roads (Department for Transport 2007). Some guidance from the United Kingdom for expected vehicle crossing speeds at speed cushions on local roads is given in figure H5.

Although, as far as the authors are aware, it has not been tried before, speed cushions also might feasibly be used at multi-lane approaches to roundabouts as per figure H6. In general, the wider the cushion, the lower the speeds.

Figure H4 Photo of a speed cushion scheme installed in Waitakere City, Auckland

Figure H5 Expected vehicle speeds at speed cushions (adapted from Department for Transport 2007)

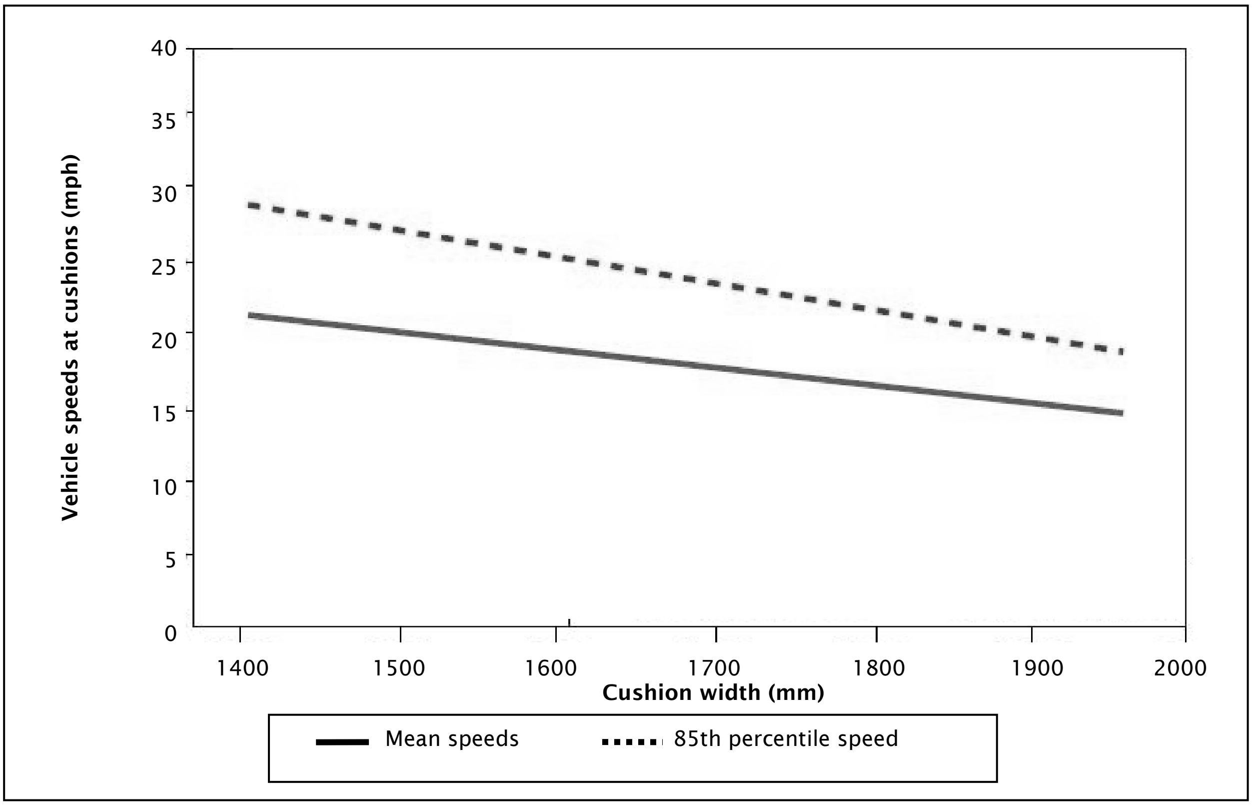


Figure H6 Example of speed cushion layout that could be used at a multi-lane situation

H3 Factors to consider

While vertical deflection devices can offer a very practicable means of speed control, the following factors need to be considered:

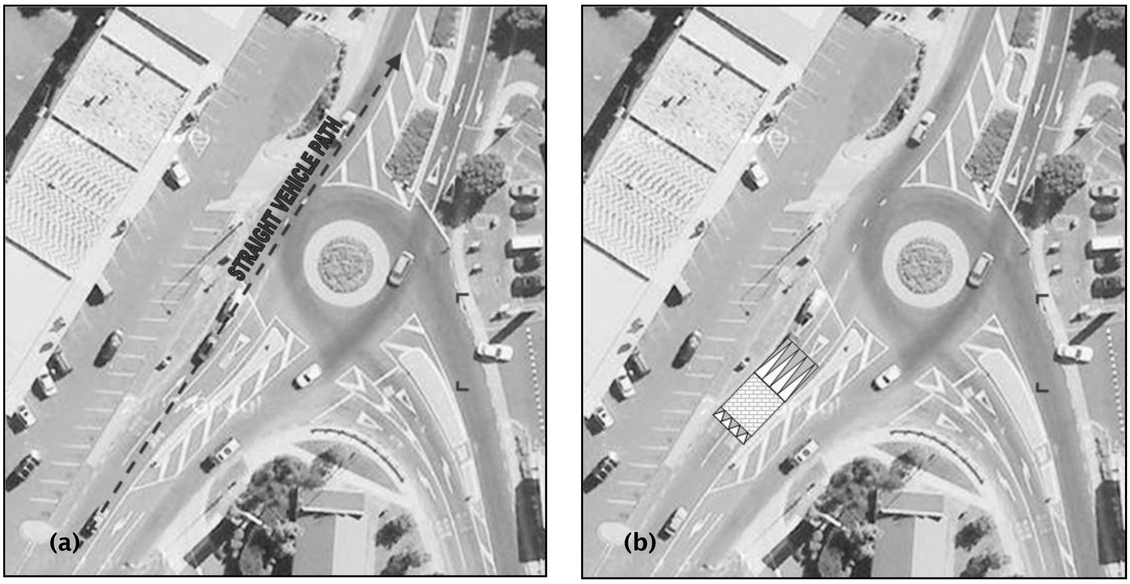
- In general, the application of vertical deflection devices at a roundabout is not a desired form of speed control compared to other means, and should not be 'designed in' unless part of a specific strategy to improve safety for cyclists and pedestrians in particular.
- Consideration of desired vehicle speeds at each device is important. Cyclists primarily benefit from speeds reduced to around 30km/h at roundabout entries, as this where most of their injury crashes occur (Campbell et al 2006), whilst pedestrians may need assistance at multi-lane crossings in particular (also refer to appendix F). Otherwise, a 50km/h maximum speed environment is not

inappropriate for roundabouts on main roads. Also, if devices are located very close to roundabout exits, the lower speed some vehicles will traverse them may need to be taken into account with respect to traffic flow and potential for rear-end crashes.

- Increased noise may be generated by some heavy vehicles as they traverse a vertical deflection device, mainly by lightly laden vehicles or trailers with mechanical leaf-spring suspension – particularly if they have three axles or more, or with two axles if driven at excessive speed. Some deceleration/ acceleration noise may potentially also be generated by heavy vehicles if devices are not located close to the roundabout, where speeds would be expected to be lower in any case. Noise effects for a particular location could feasibly be assessed by a review of truck volumes by type, time of day and proximity to sensitive activities.
- Good signposting and lighting is important to increase driver awareness so they know well in advance to decelerate before they traverse a device.
- Consideration of potential traffic diversion should also be taken into account, although it is anticipated that one or two devices at a roundabout might not have a significant effect of this nature, unless convenient alternative routes are comparable in time or distance.
- Care should be taken with regard to colour of platforms at pedestrian crossing points. Platforms should not match surrounding footpaths if vehicles have priority, as this could give pedestrians a false sense of security that they are a continuation of the footpath.
- Vertical deflection devices can potentially present an impediment for some drivers with severe back conditions, so if a large number of these people might be affected then alternative routes for them would be worthy of consideration.
- Ideally, any devices would not be located close proximity fire or ambulance stations, where a greater number of call-outs may be adversely affected by having to traverse the devices at low speed for protection of patients and/or expensive equipment.

Figure H7 below shows an example of where a Swedish-style platform could be used as a retrofit to a roundabout with deflection problems. The platform would reduce the through-vehicle speeds being experienced there, and would be a far more economic solution to the alternative of revising the roundabout's geometry, which would probably require substantial land-take.

Figure H7 Possible installation of a Swedish style platform (see figures H1 and H2) at an existing roundabout which has inadequate speed control in the northbound direction: (a) the existing roundabout; (b) potential changed roundabout layout



H4 References

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Campbell, D, I Jurisich and R Dunn (2006) Improved multi-lane roundabout designs for cyclists. *LTNZ research report 287.* Wellington: LTNZ. 140pp.

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Appendix I Turbo-roundabout guidelines, Royal Haskoning[16]

I1 Turbo roundabouts

As stated before, in The Netherlands multi lane roundabouts are no longer built, and existing multi lane roundabouts will be reconstructed into turbo roundabouts. The main reason is the disappointing performances of multi lane roundabouts on both capacity and road safety

Turbo roundabouts are almost only used in The Netherlands. In 2007 only 70 of such roundabouts were in operation. One (experimental) example is known in Baden Baden in Germany. The first experiences in Germany are slightly positive. Differences in design details, especially the absence of raised lane dividers, may be the cause of an unexpected high number of accidents at one of the entries. Due to the minimal number of turbo roundabouts in other countries the following is based on Dutch experiences only.

Figure I1 Standard layout of a turbo roundabout

I1.1 Characteristics

A turbo roundabout is a multi lane roundabout with spiral road markings and separated lanes, at which road users have to choose the correct lane before entering the roundabout, in order to leave it in the desired direction. The main characteristics of a turbo roundabout are (see figure I2):

16 The material in this appendix was originally published by Royal Haskoning (2009) as section 5.2 of a document entitled *Roundabouts – Application and Design*. It is reproduced here with permission of the publishers, as English versions of these guidelines are hard to come by. The numbering of the headings, etc has been altered to suit NZTA house style.

1 a turbo roundabout has more than one lane;

2 the correct lane has to be chosen before entering the turbo roundabout;

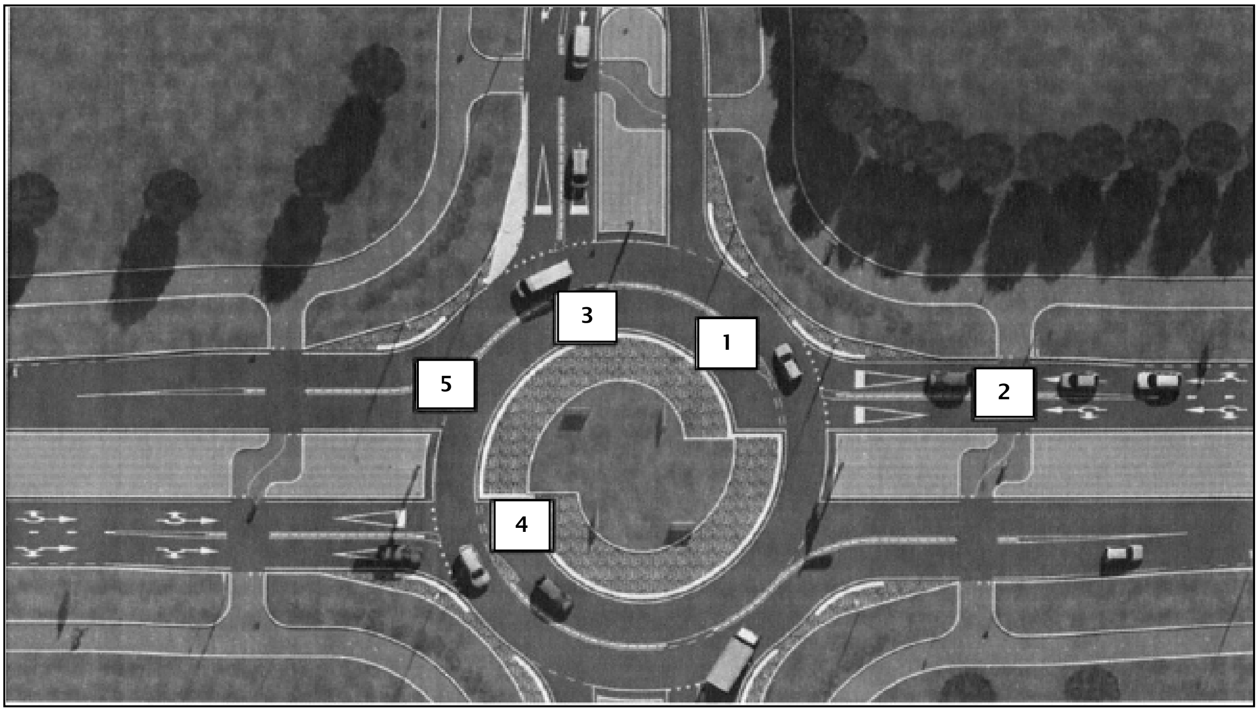
3 entering traffic has to give way to circulating traffic, which is limited to a maximum of two lanes; within the roundabout itself no entering or exiting is possible;

4 the roundabout can only be left via the previous chosen lane.

This type of multi lane roundabout has the following advantages:

- a surveyable situation when a driver enters the roundabout; drivers need only to give way to traffic in a maximum of two well-demarcated lanes;
- no risk of accidents due to lane changing on the roundabout;
- low driving speed through the roundabout because of raised lane dividers.

Figure I2 Main characteristics turbo roundabout



The main reasons to choose a turbo roundabout rather than other intersection types are:

- Increase capacity at the intersection. The capacity of a turbo roundabout is higher than a single lane roundabout (1½ to 2½ times as high) or a two lane roundabout (1 to 1½ time as high).
- The capacity of a turbo roundabout is equal or higher than a signalized intersection. The delays are less than at a signalized intersection.
- Increase road safety on the intersection. A turbo roundabout is safer than a give way intersection (± –70% in fatal accidents or accidents with hospital treated injuries) and safer than an intersection with traffic signals (about –50% in fatalities and hospital-treated injuries), although not as safe as a single lane roundabout (turbo roundabout 20% to 40% greater accident rate).

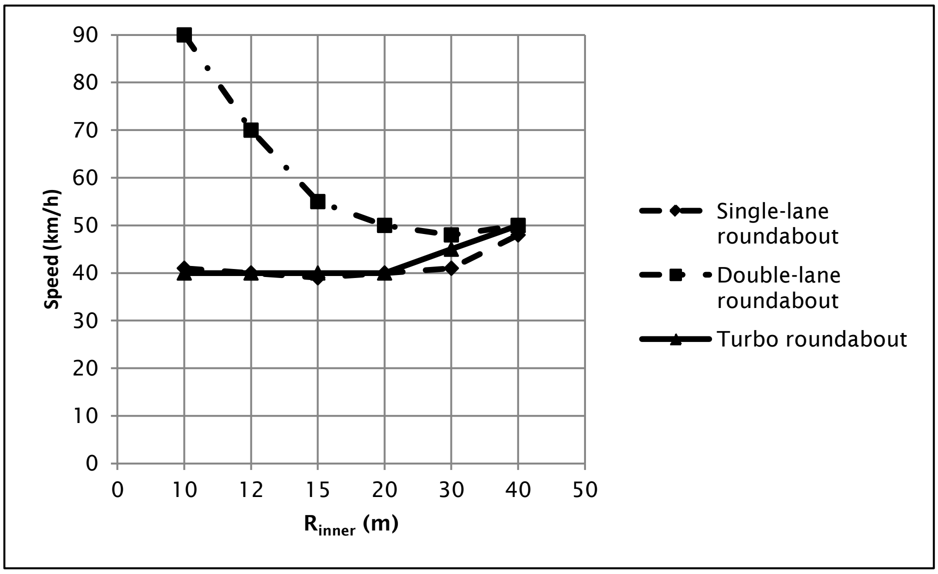
- The spatial need (m^2) of a turbo roundabout is about the same as a signalized intersection (assuming that the signalized intersection would also offer two trucks driving in parallel, in all directions).
- The construction costs of a turbo roundabout are higher than an intersection with traffic lights, but the life cycle costs and social costs are less.

The capacity of a turbo roundabout is about 3500 to 4500 PCU/h for a roundabout with a diameter of about 50m. The capacity of a three-leg turbo roundabout is 5500 PCU/h. The driving speed is low in comparison to normal signalized intersection or two lane roundabouts (see figure I3).

Five types of four-leg turbo roundabouts can be distinguished based on differing number of entry and exit lanes and bypasses. The need for these variations is mainly to do with differences in the distribution of traffic volume over the legs of the intersection:

- the basic turbo roundabout (figure I4);
- the egg roundabout (figure I5);
- the knee roundabout (figure I6);
- the signal roundabout (figure I7);
- the rotor roundabout (figure I8).

Figure I3 Relationship between speed and type of intersection (width of splitter island = 7m)



The standard designs of these types of turbo roundabout are given later in this section. Relative traffic volumes for the chief movements affecting the roundabout design are represented by the thickness of the [black] arrows. When available, the capacity is also shown.

Figure I4 Basic turbo roundabout

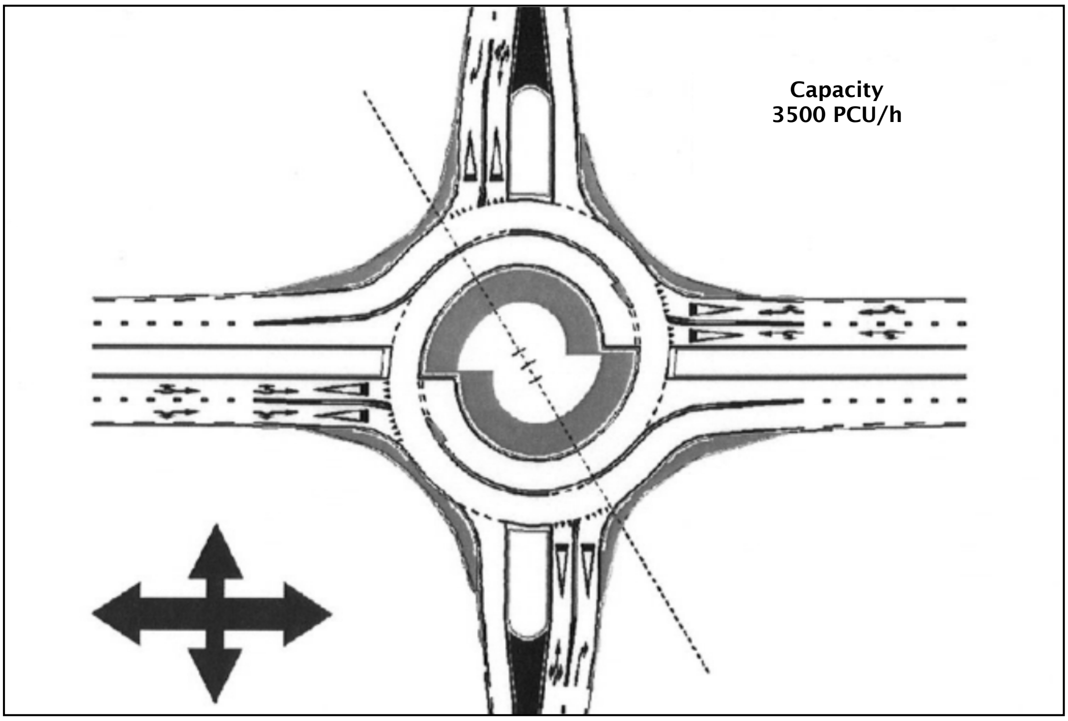


Figure I5 Egg roundabout

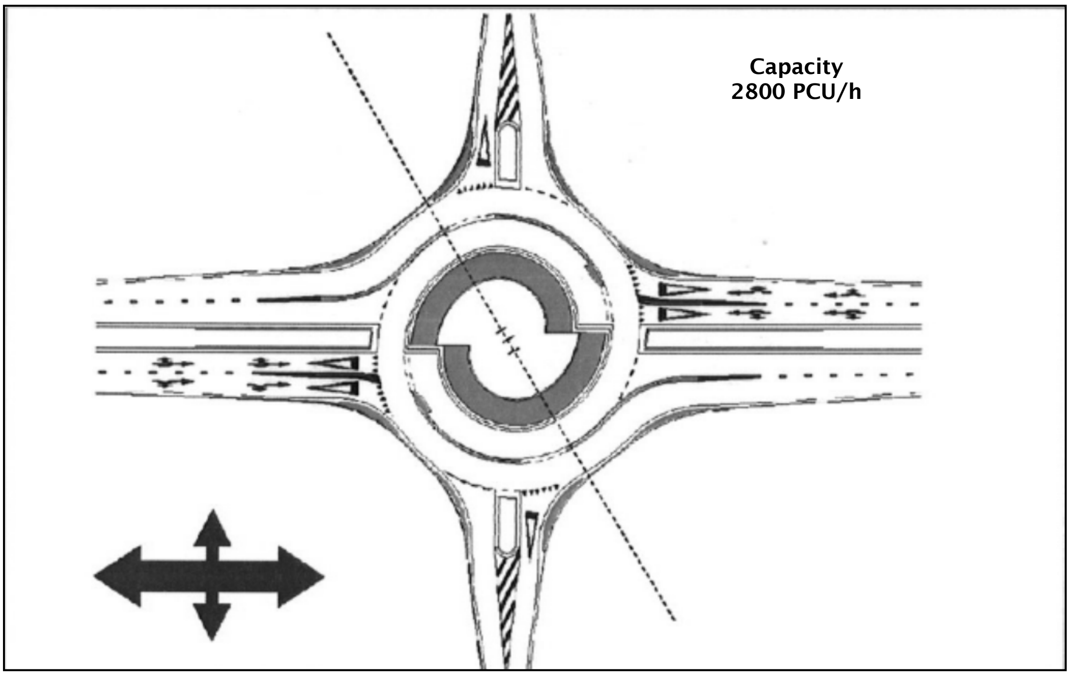


Figure I6 Knee roundabout

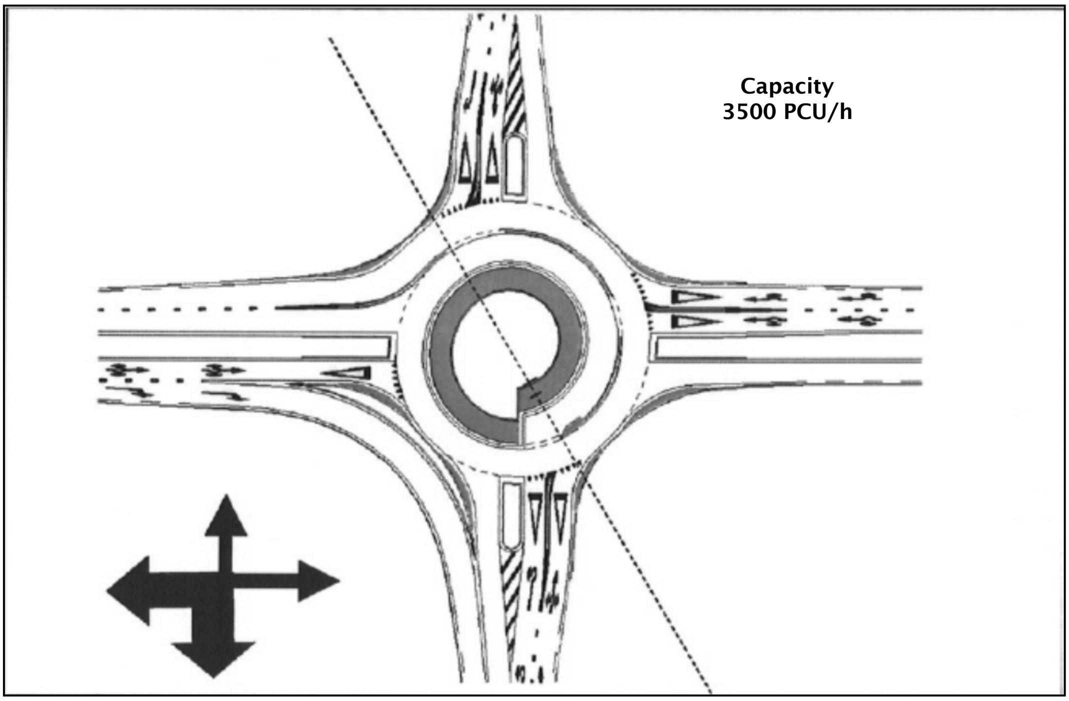


Figure I7 Spiral roundabout

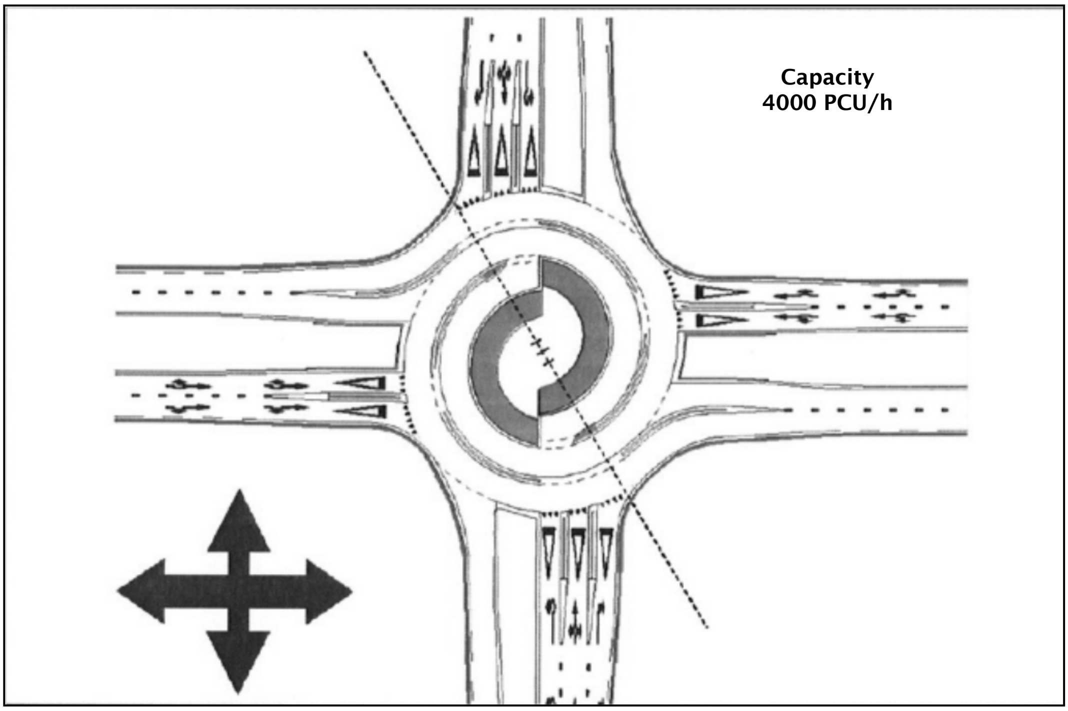
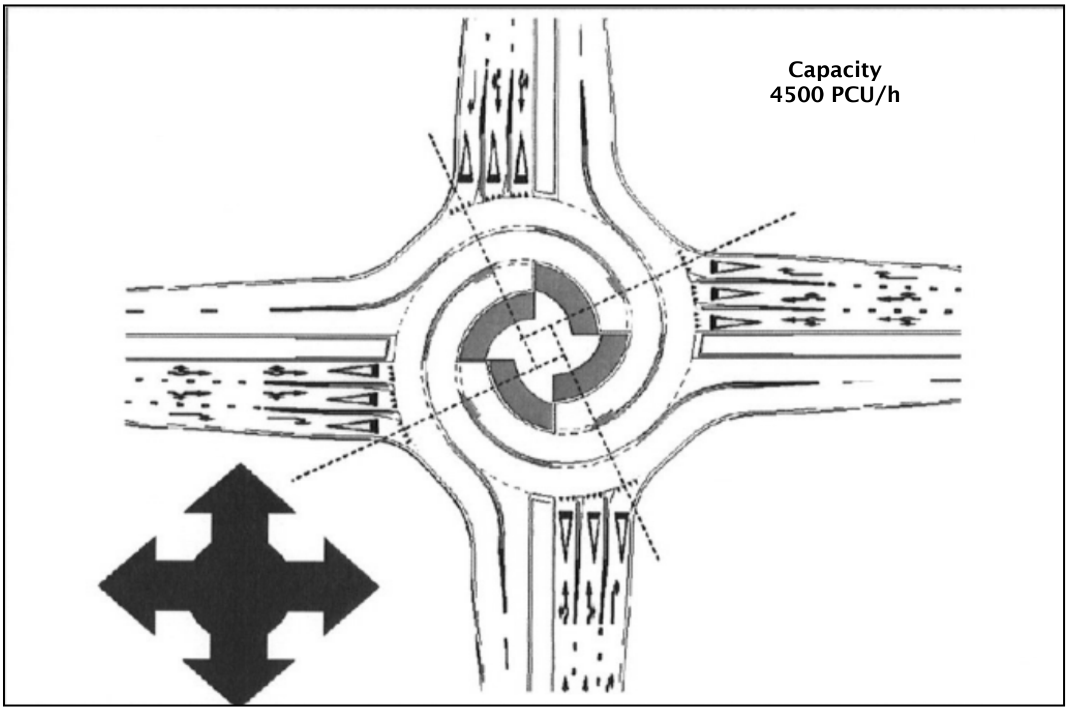


Figure I8 Rotor roundabout



For three-leg roundabouts there are only two types of turbo roundabouts:

- stretched-knee roundabout (figure I9);
- star roundabout (figure I10).

Figure I9 Stretched-knee roundabout

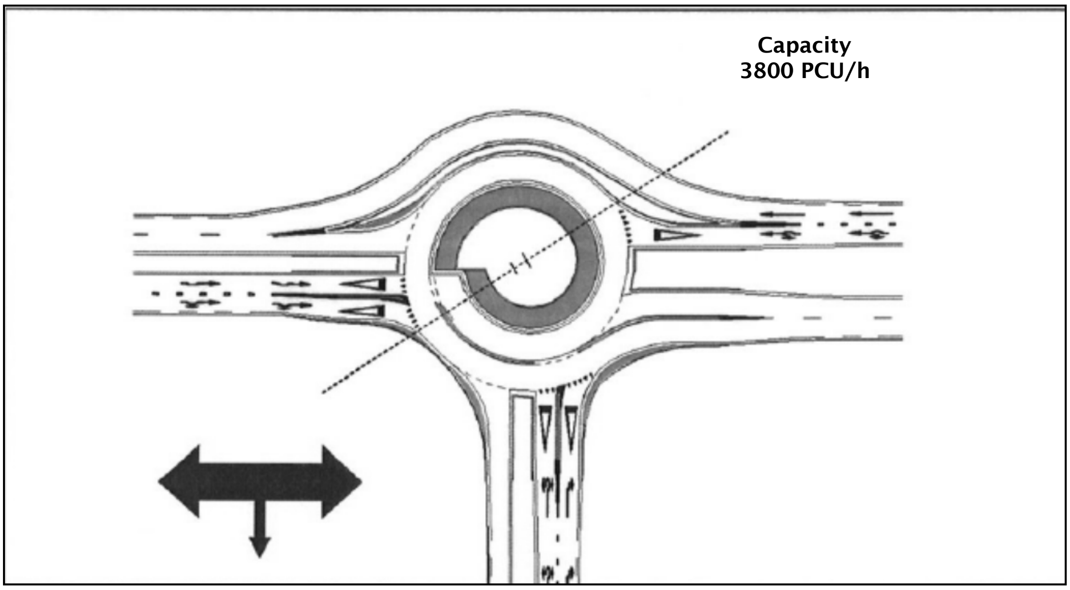
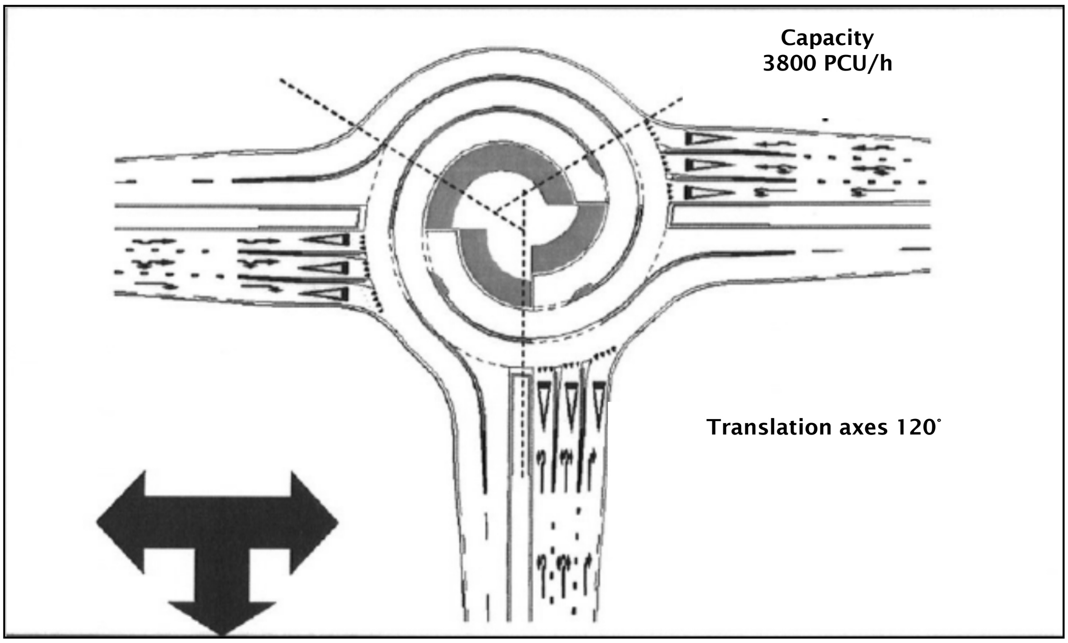


Figure I10 Star roundabout



Factors that determine the most suitable type are:

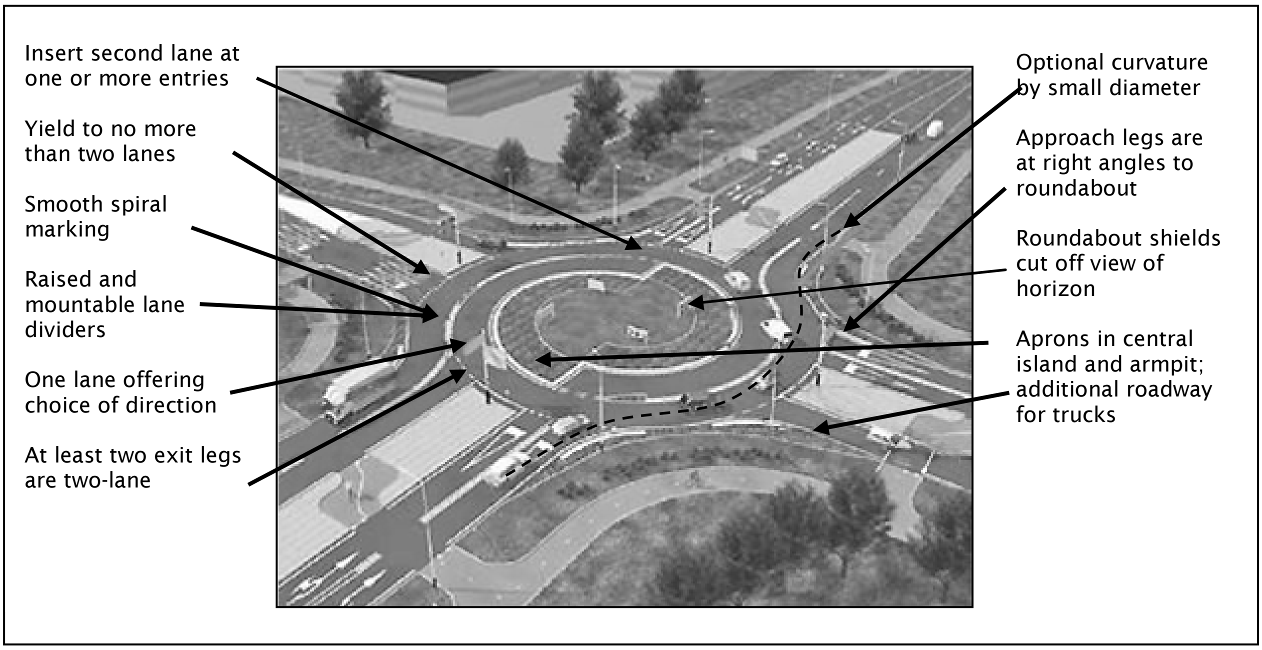
- saturation level;
- average delay time;
- spatial need;
- investment costs.

The province of Zuid-Holland in The Netherlands has developed a tool to compare the various types of turbo roundabouts, the 'multilane roundabout explorer'.

I1.2 Design elements

Figure I11 illustrates the chief design features of a turbo roundabout. The features on the left are essential for a turbo roundabout; the features on the right are similar to those of a well-designed single lane roundabout.

Figure I11 Design features of a turbo roundabout



Essential design features

A number of design features can be called 'essential' in the sense that without these elements the intersection is not a turbo roundabout. These essential features of the turbo roundabout are:

1 opposite at least one entry a second lane is inserted on the central island side;

2 at least two entry legs (one leg at a three-leg roundabout) give way to traffic on two but no more than two lanes;

3 spiral markings fluently guide traffic from inside to outside, avoiding weaving and cutting conflicts on the roundabout;

4 mountable-raised lane dividers cause optimal vehicle curvature by keeping vehicles in their lane and by using a small diameter;

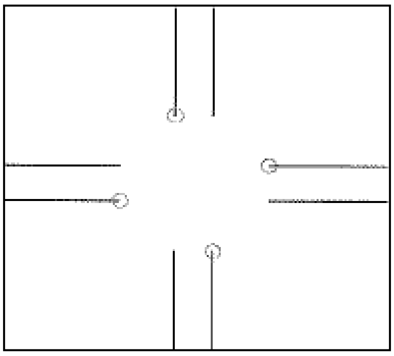
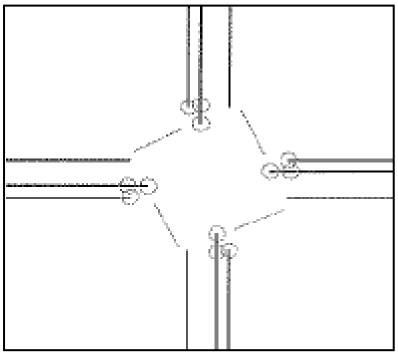
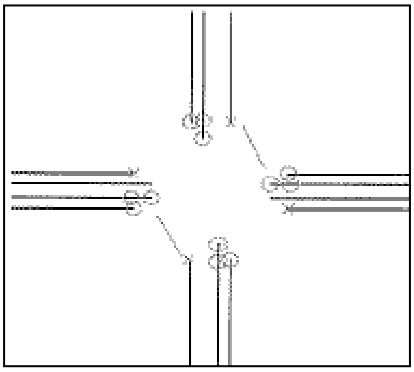
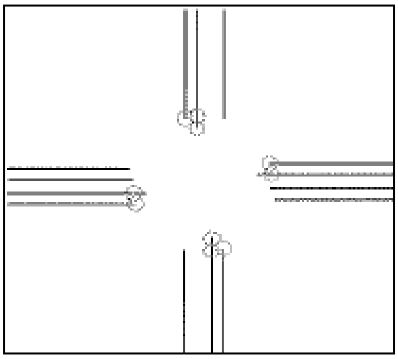
5 at least two exit legs are two lane;

6 on entry section there is a decision point at which traffic can choose to exit or continue on the roundabout.

Conflict points

The overall road safety performance of an intersection is highly dependent on the number of conflict points. A turbo roundabout has fewer conflict points than multi lane roundabouts, but more than a single lane roundabout (see figure I12.

Figure I12 Number of conflict points different types of roundabouts

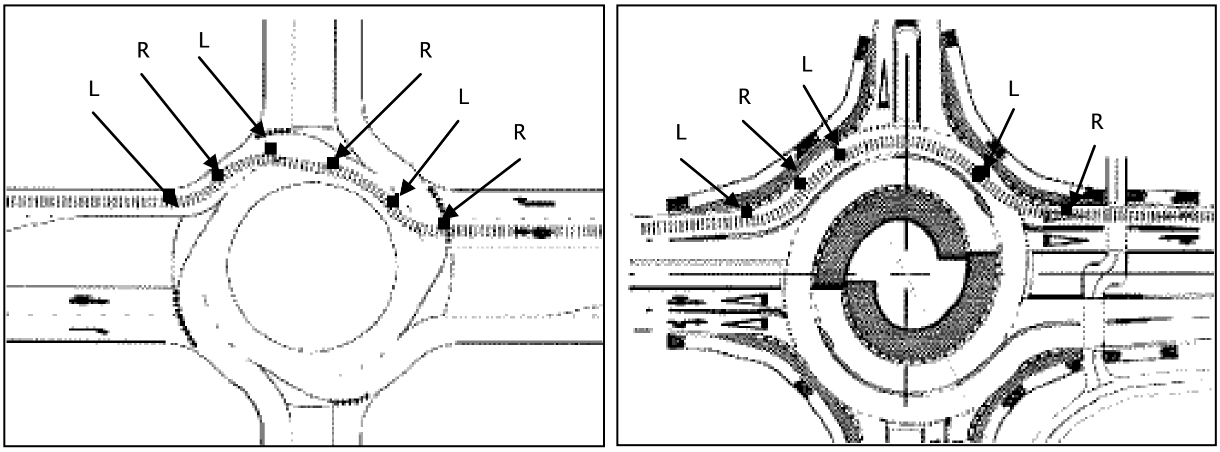
	
Single lane roundabout: 4 conflict points	**Double lane roundabout, single lane exits: 16 conflict points**
	
Double lane roundabout, two lane exits: 20 conflict points	**Turbo roundabout: 10 conflict points**

Not only the number of conflict points but also the type of conflict influences road safety performance. On turbo roundabouts there are not weaving and cut-off conflicts; instead, the conflicts all occur as vehicles enter the roundabout, where they have the opportunity to stop if necessary. Traffic behaviour is predictable, because vehicles keep to their lane. Furthermore the lane dividers contribute to a low speed on the turbo roundabout.

Driving lanes

The connection of the approaching lanes should be as radial as possible. Because of the shape of a turbo roundabout and the principle of staying in your lane, drivers can pass through the roundabout n a fluent way. Compared to a concentric roundabout with spiral lanes, the driving path in a turbo roundabout requires fewer corrections to (see figure I13)

Figure I13 Steering corrections* on roundabout with spiral markings and on turbo roundabout



Concentric roundabout with spiral lanes **Turbo roundabout**

*R = right steering, L = left steering; the second L at the turbo roundabouts is still a left turning movement, but with a bigger radius. The driver has to make a slightly right steering correction.

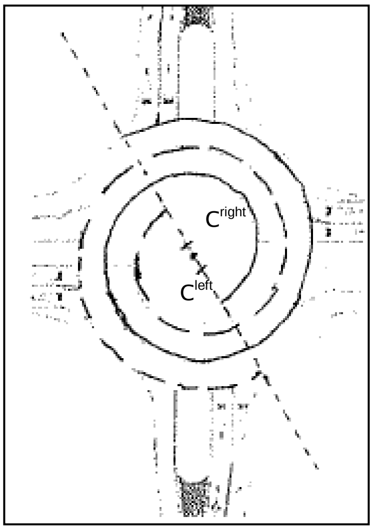
Spirals

A turbo roundabout consists of spirals. These spirals are composed of segments of circular area, often semicircles, with each arc having a larger radius than the previous arc. When the radius of the arc changes, the centre of the arc changes by a corresponding amount so that the curve remains continuous.

In an idealised geometry, the basic turbo roundabout consists of two nested spirals, which represent lane boundaries. Each spiral consists of three semicircles with successively larger radii. The semicircles meet at a line called the translation axis. The arcs on the right side of the translation axis have a centre C^{right} that is above the overall centre of the roundabout. The arcs on the left side of the translation axis have a centre C^{left} that is below the overall centre. The distance between the centres of the arc segments is called the *shift* along the translation axis. The *bias* of an arc is the distance from the centre to the overall centre, and is therefore half the shift. In order for the spiral to be continuous, the shift must equal the change in radius.

Ideally, the shift is one roadway width, because the spiral moves out by one roadway width with every 180 degrees. A sketch [figure I14] showing these spirals is called a ‘turbo block’, a useful design tool in the geometric design of a turbo roundabout.

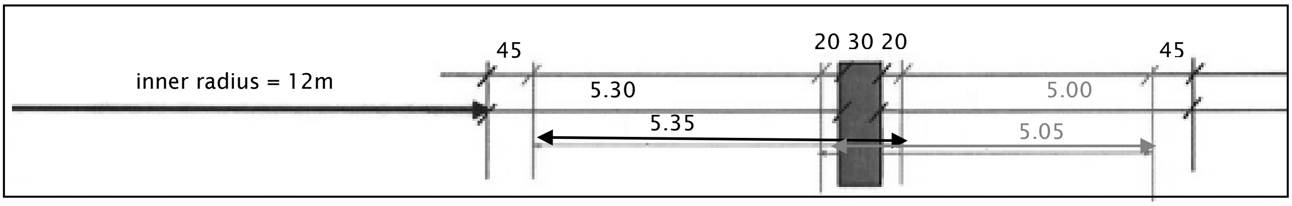
Figure I14 'Turbo block' sketch



Design process

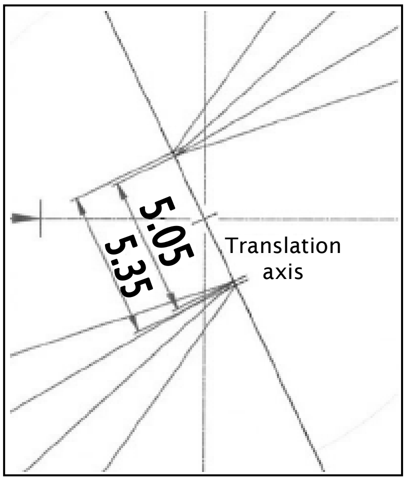
The geometric design process has five stages. Step 1 is to select widths of the basic elements – the inner radius, the inside and outside roadways, the lane divider, and the offsets between the roadway edges and the lane lines. Figure I15 shows an example. Lane widths should be determined by analyzing the swept path of the design vehicle. Because swept paths are wider when the radius is tighter, the width of the inside lane (4.65m measured line to line, or 5.30m measured from pavement edge to divider) is 0.30m.

Figure I15 Lane, edge strip and median strip widths, and distances between edge lines in a turbo roundabout



Step 2 is to determine the shifts that the lane lines make, and the resulting biases for drawing the semicircular arcs. Unlike the ideal geometry, the actual geometry of a turbo roundabout's spirals is complicated by the need to account for different lane widths and for the width of the lane divider. Instead of a single centre point C^{right} for the semicircular arcs on the right side of the translation axis, there are two right-side centre points, one with a slightly larger bias than the other. The centre point with the larger bias is used for the innermost semicircle, to make the transition from inside edge to middle divider; the other centre point is used for the remainder of the spiral. These two centre points can be seen in the turbo block sketch (see figures I16 and I17) of the example. Likewise, the arcs on the left side of the translation axis have two centres with slightly different biases.

Figure I16 Detail showing centres for the arcs in a turbo roundabout



Shifts can be calculated from a cross section sketch such as in figure I15. There, one can see that the inner lane lines shift 5.35 in when transitioning from the inside of the roundabout to the lane divider. One can also see that the outer lane lines shift 5.05m as they transition from the lane divider to the outside of the roundabout.

Step 3 is to calculate the radii of the circular arms, and to sketch the turbo block. Depending on the need, one can focus on spirals representing lane lines, whose arcs have radii R1' to R4', or spirals whose arcs represent the roadway edges, with radii R1 to R4. Table I1 shows how these radii are defined and calculated.

The fourth step is the global rotation and translation of the turbo block to match the entering legs. Figure I16 shows the right position of the translation axis when the main stream is east-west. For a correct positioning of the translation axis, the distance between the right edge of each entry leg and the inner curve of the outer lane of the roundabout after ¼ turn should be more or less equal (A equals B, see figure I18).

Table I1 Turbo roundabout geometry calculations

Cross section elements	**Width**				
Inner radius	12.00				
Inner edge line offset	0.45				
Inside lane	4.65				
Divider inner line offset	0.20				
Divider (divider)	0.30				
Divider outer line offset	0.20				
Outside lane	4.35				
Outside edge line offset	0.45				
Roadway widths, shifts and biases					
Inside roadway width	5.30				
Outside roadway width	5.00				
Shift 1 (inside to middle)		5.35			
Shift 2 (middle to outside)			5.05		
Bias 1 = shift 1/2 (applies to R1 and R1')		2.675			
Bias 2 = shift 2/2 (applies to all other radii)			2.525		
Bias difference			0.15		
Radii for lane lines	**Arc centre bias**	**Radius**	**Start position***	**End position****	
R1' = inside lane, inner line	2.675	12.45	9.775	15.125	R1' = inner radius + inner edge line offset
R3' = outside lane, inner line	2.525	17.65	15.125	20.175	R3' = R1' + shift 1 – bias difference
Difference			*5.350*	*5.050*	*Differences match shift 1 and shift 2; also, end position of R1' matches start position of R3'.*
R2' = inside lane, outer line	2.525	16.95			R2' = R3' – width of divider and divider offsets
R4' = outside lane, outer line	2.525	22.00			R4' = R2' + shift 2 = R3' + outside lane width

Table I1 cont. Turbo roundabout geometry calculations

Radii for roadway edges	Arc centre bias	Radius	Start position**	End position	
R1 = inside roadway, inner edge	2.675	12.00	9.325	14.675	R1 = inner radius
R2 = inside roadway, outer edge	2.525	17.15	14.675	19.675	R2 = R1 + inside roadway width – bias difference
Difference			*5.30*	*5.00*	*Differences match roadway widths*
R3 = outside roadway, inner edge	2.525	17.45			R3 = R2 + divider width
R4 = outside roadway, outer edge	2.525	22.45			R4 = R4 + outside roadway width

* Position is relative to the overall centre.

** Start position = radius – bias; end position = radius + bias.

Figure I17 Turbo block of a standard turbo roundabout adjusted to the entries when the main traffic flow is east-west

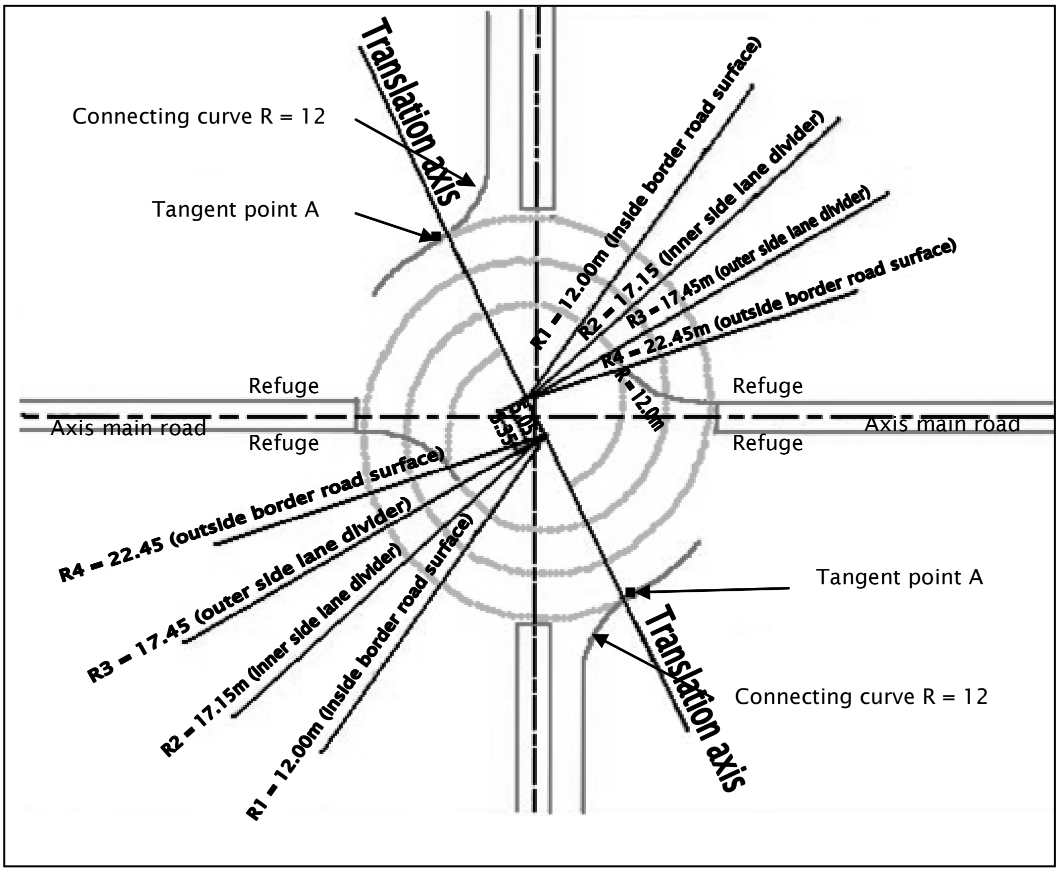
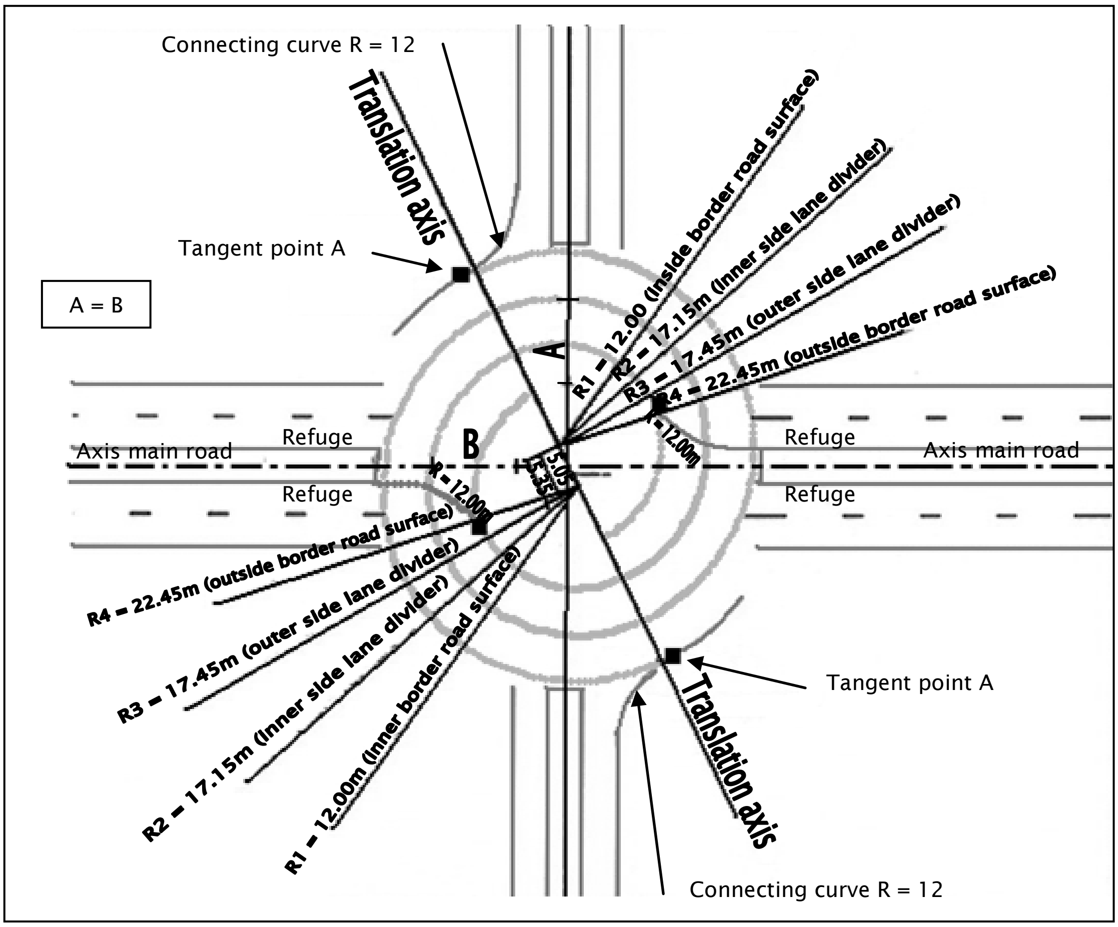


Figure I18 Checking position of the translation axis and overall centre



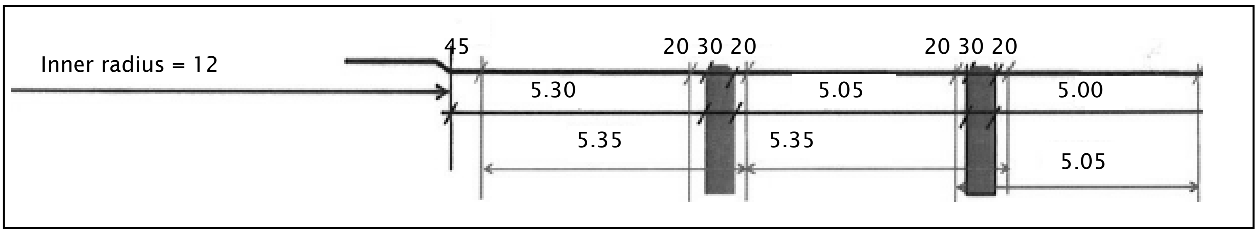
The fifth step is ‘fine tuning’ the position of the translation axis: tangent point A, where the inner curve of the entrance lanes connects to the roundabout’s outer lane, should be positioned after the translation axis.

Design of other types of turbo roundabouts

The design process just described for the basic turbo roundabout is also valid for the egg roundabout, which also has two circulating lanes drawn from two nested spirals. Other roundabout types have different spiral patterns, and therefore require modifications to the geometric design.

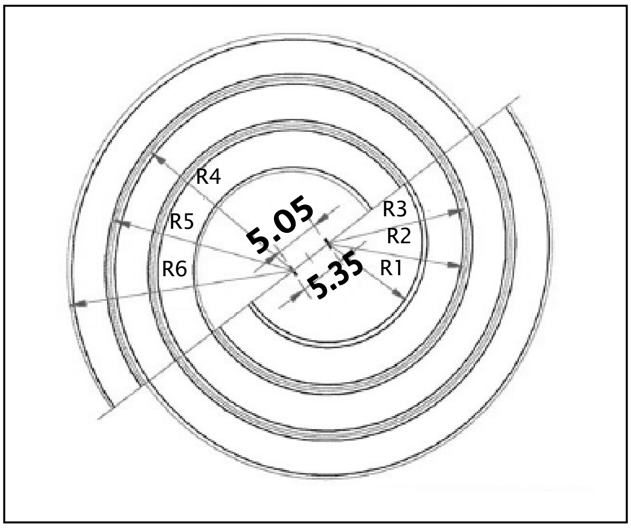
A spiral roundabout has a similar geometry to the basic turbo roundabout, based on two nested spirals. However, its spirals have an additional semicircle in order to create a third circulating lane. Figure I19 shows an example of a cross section for a spiral roundabout.

Figure I19 Lane width and distances between edge lines for a spiral roundabout



Because the shift in lane lines is 5.35m for the transition from the inside to the first divider and from the divider to the second divider, arcs corresponding to the inside of the roundabout and the first divider (radii R2, R2 and R3, as well as R1', R2'and R3') are drawn from a centre with bias equal to 5.35/2; the remaining, outer arcs are drawn from a centre with smaller bias 5.05/2. Calculation of the arc radii follows a similar logic to that used for the basic turbo roundabout.

Figure I20 Turbo block detail for a spiral roundabout



The knee and stretched knee roundabouts (see figures I6 and I9) are based on a single spiral, rather than two nested spirals. Also, its spiral shifts only half of a roadway width with each semicircle. Therefore they have a simpler turbo block, with a single spiral whose arc centres shift half the shift of the turbo roundabout.

The rotor roundabout (see figure I8) consists of four nested spirals; therefore, the turbo block has four translation axes (figure I21). For the star roundabout (see figure I10), which consists of three nested spirals, the turbo block has three translation axes (figure I22).

Figure I21 Turbo block for a rotor roundabout

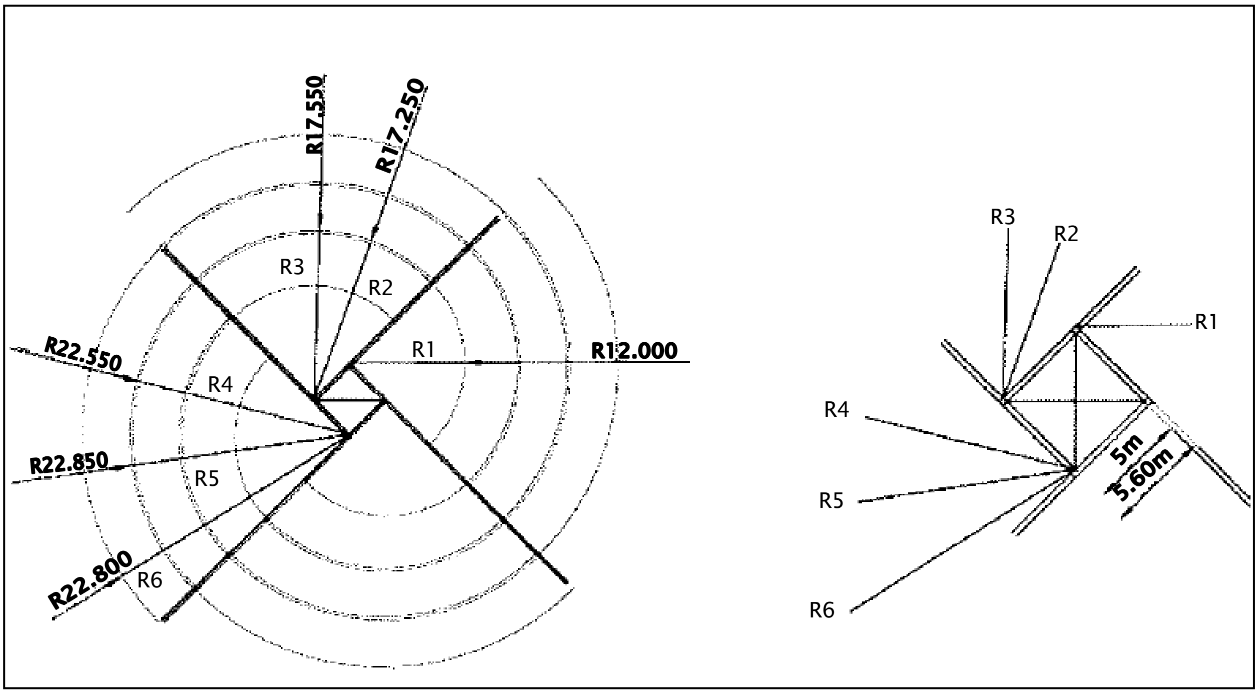
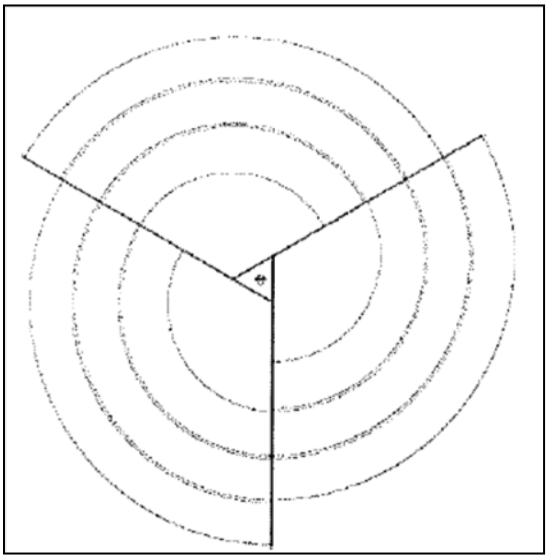


Figure I22 Turbo block for a star roundabout



Key parameters

The key parameters that determine the performance of a turbo roundabout are the radii for the different circular arcs and the lane widths. They are all related to each other. According to experiences in The Netherlands, the speed on the roundabout is the lowest when the radius of the inner curve of the inner lane is about 12m. Because low speed is the most important goal for safety, in The Netherlands, the standard dimensions are based on a radius of 12m for the inner edge of the inside lane (see table I2).

Table I2 Design elements of turbo roundabouts

Feature		Radius and measurement (m)			
R_{inside} of the inner lane (all designs)	R1	10.5	12	15	20
$R_{outside}$ of the inside roadway (all designs)	R2	15.85	17.15	20.00	24.90
R_{inside} of the outside roadway (turbo-egg-spiral)	R3	16.15	17.45	20.30	25.20
$R_{outside}$ of the outside roadway (turbo-egg-spiral)	R4	21.15	22.45	25.20	29.90
Width, inside roadway		5.35	5.15	5.00	4.90
Width, outside roadway		5.00	5.00	4.90	4.70
Width, inside lane		4.70	4.50	4.35	4.25
Width, outside lane		4.35	4.35	4.25	4.05
Lane divider between driving lanes		0.30	0.30	0.30	0.30
Shift of inner arc centres along the translation axis		5.75	5.35	5.15	5.15
Shift of outer arc centres along the translation axis		5.05	5.05	4.95	4.75
Largest diameter		47.35	49.95	55.35	64.55
Smallest diameter		42.60	45.18	50.64	59.99
R, curve entry and exit		10.00	10.00	10.00	10.00
R, curve lane divider entry		12.00	12.00	12.00	12.00
R, curve lane divider exit		15.00	15.00	15.00	15.00
Width, overrun area for vehicles with length 22 to 27m		5.00	5.00	5.00	max 5.00
Speed, passenger car (km/h)		37–41	37–39	38–39	40

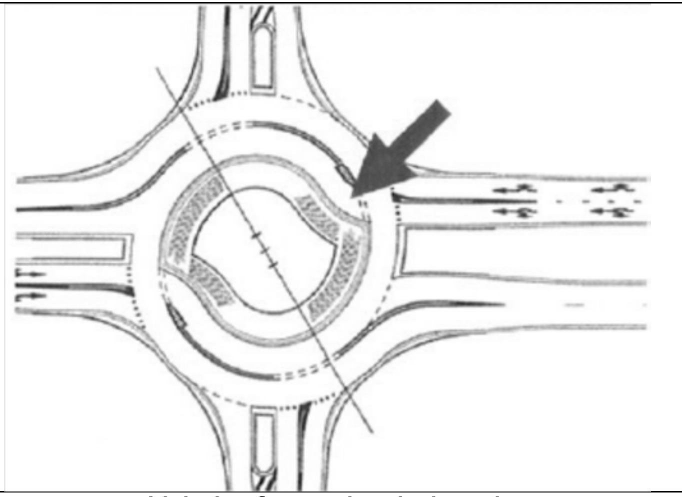
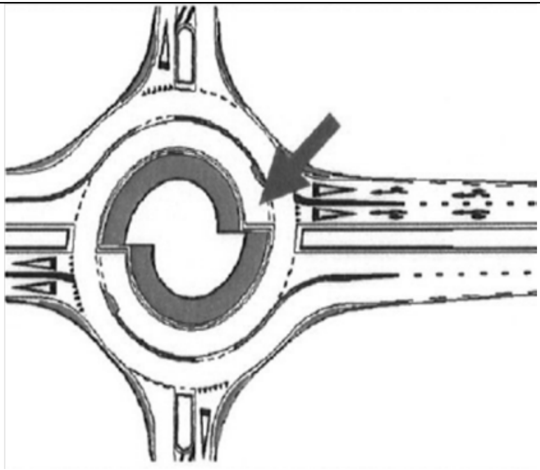
The key parameters for egg, knee and spiral roundabouts are the same as for the basic turbo roundabout. For key parameters of rotor and star roundabouts, see appendix 2[17].

Start of the inner lane

In the past, the start of the inner lanes of turbo roundabouts were designed with smooth curves in order to provide the approaching traffic from the left entry lane with guidance that matched the vehicle path (see figure I23). However, sometimes this approach caused confusion, as drivers entering the roundabout in the right entry lane mistakenly expected continuing traffic on the roundabout shift into the inner lane. Therefore, as shown in figure I23, nowadays the preferred design is for the inner lane to start abruptly.

17 Part of the original Royal Haskoning document, but not presented in this report.

Figure I23 Old and new designs for starting the inner lane

	
Old design for starting the inner lane	**New design for starting the inner lane**

Lane divider

For the desired performance of a turbo roundabout, lane dividers are essential. The lane divider has four functions:

- prevents weaving and cut-off conflicts;
- prevents vehicles from straightening curves during low traffic periods;
- reduces fear of vehicles in the other lanes;
- higher capacity due to lower speed (smaller critical gap for entering vehicles).

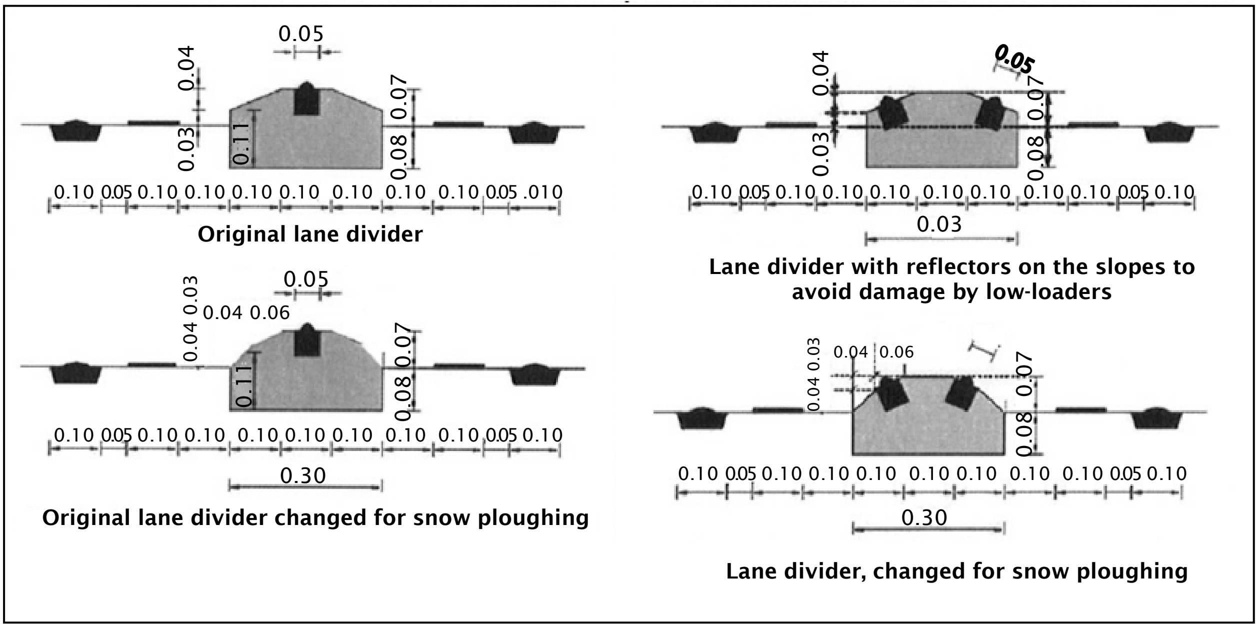
The lane dividers have to be elevated, strongly founded and introduced by a negotiable element, the so called ‘frog’, slightly wider than the lane divider. This ‘frog’ increases the visibility of the lane divider and protects against cutting the curve by passenger cars.

Figure I24 Examples of lane dividers

The design of different types of lane dividers can be altered to specific needs. In the example in figure I25 ([in the second row]) the original lane divider is adapted for the use of snow ploughing machines on roads.

The difference of the changed design from the original is a seamless connection between the road and the lane divider. Figure I25 shows also a lane divider adapted to avoid damage by low-loaders.

Figure I25 Types of lane dividers

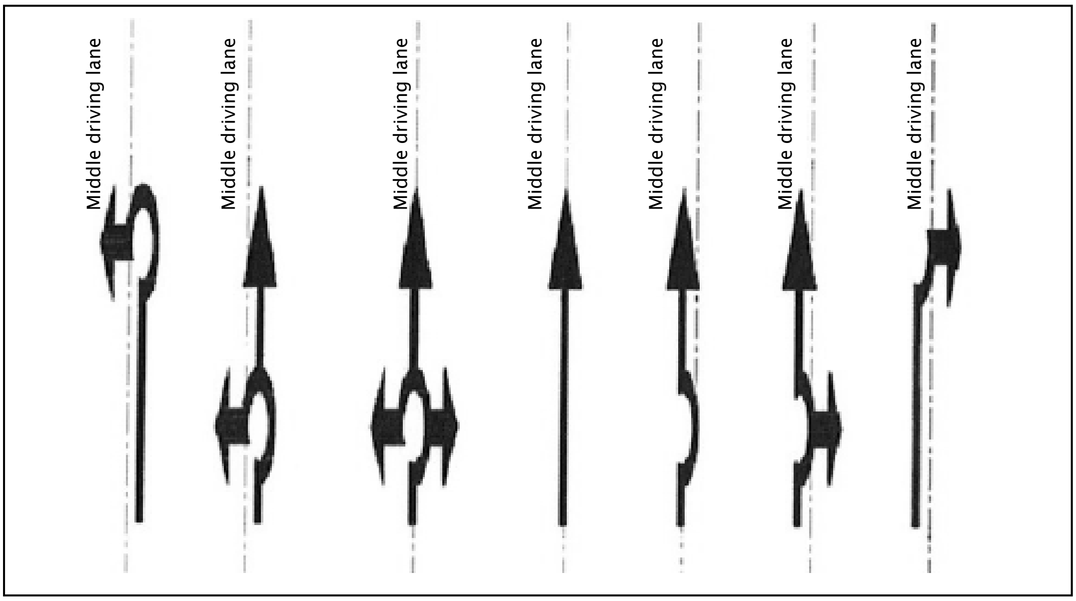


I1.3 Road marking, signposting and public lighting

Road marking

For the right use of a turbo roundabout it is important that road users are clearly informed before reaching the roundabout about what lane they have to choose in order to proceed in the desired direction. On turbo roundabouts driving a full circle to correct a wrong choice for the direction is not possible (unlike on conventional roundabouts). In addition to signposting, markings that mimic the information carried on signs are recommended. Figure I26 shows the different arrows used in The Netherlands.

Figure I26 Arrows used on entry lanes, ahead of the roundabout



Arrows are used only on the entry lanes. Within the roundabout itself arrows are not repeated, because they do not provide the road user with additional, useful information.

Signposting

Because drivers need to choose the correct lane before entering the roundabout, clear signposting is very important. The first sign has to be posted at least 400m ahead of the roundabout. At about 40m of the roundabout signs have to be placed either at the verge or above the traffic lanes, with the information stated per lane. It is important that the configuration of the arrows on the sign(s) is the same as the configuration used on the pavement (marking). Figure I27 shows examples of signposting ahead of the turbo roundabout. In order to guide the final decision on the roundabout itself, destinations are also signposted at the splitter island of the connecting road (see figure I28).

Figure I27 Signposting at 400 metres ahead of the roundabout

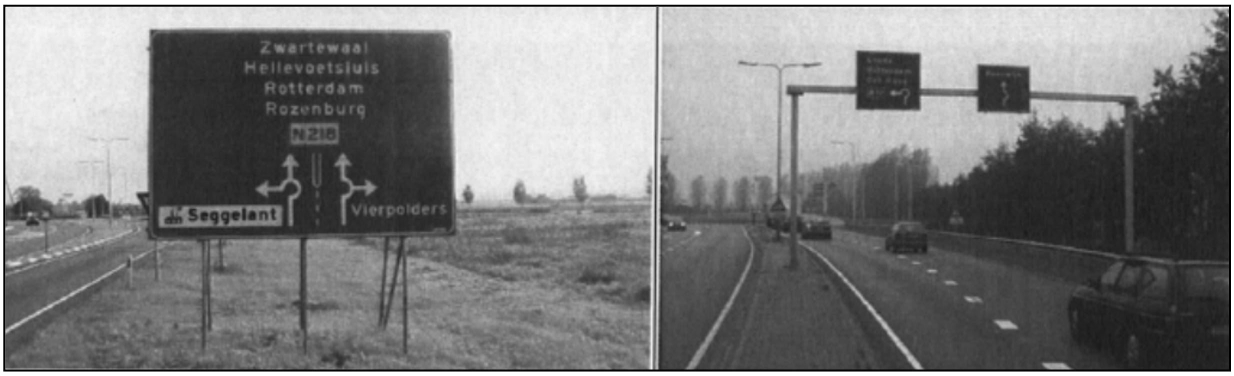
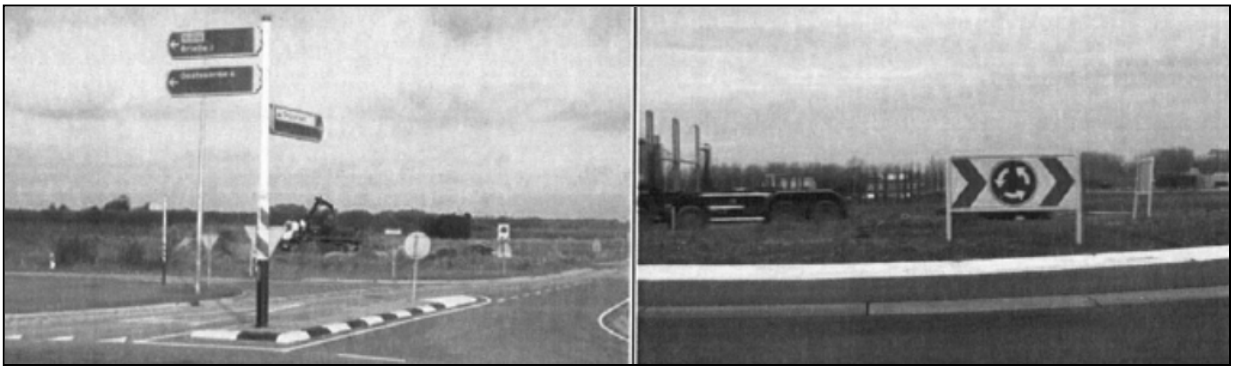


Figure I28 Signposting at the splitter island and traffic sign on the central island



Traffic signs

The turbo roundabout also demands a specific configuration of traffic signs. On the middle island there should be no hard elements, due to passive safety. Only the roundabout traffic sign is needed to block approaching drivers' view across the roundabout (see figure I28). The sign should be made 'collision friendly'.

Road users on the turbo roundabout have to resolve and interpret much information. Therefore it is important to design markings, signposting and traffic signs as one concept in order not to overload the road user with information. Be sure that the road user is clearly informed in plenty of time using a minimum of signs. After leaving the turbo roundabout, drivers need time to recover and pay renewed attention. Therefore there should be a distance of at least 200m between the exit of a turbo roundabout and the first signposting of a next intersection.

Public lighting

The aim of public lighting on turbo roundabouts is drivers. Of course the visibility of the intersection and the alignment of the lanes have to be assured. Specifically for turbo roundabouts, public lighting should be used to improve visibility of the middle island and the lane dividers, (see figure I29). It can also be used to pay extra attention to conflict points or specific elements of the turbo roundabout.

Figure I29 Example of road lighting (LED) to improve visibility of the lane dividers

I1.3 Special user groups

Pedestrians and cyclists

As on multi land roundabouts, pedestrians and cyclists should not use a turbo roundabout (see section 5.1.4 [of the original Royal Haskoning document]) but should be provided with an alternative route.

Powered two wheelers

Lane dividers create a risk for powered two wheelers, which can easily fall when driving over a lane divider. Nevertheless, experience in The Netherlands shows that motor cyclists prefer turbo roundabouts to multi lane roundabouts because they do not have to fear cars changing lanes on the roundabout. For the safety of the motor cyclists, it is essential to put clear signs to warn them about the lane dividers (see figure I30; 'verhoogde rijbaanscheiding'= raised lane divider).

Figure I30 Warning sign 'raised lane dividers' for motor cyclists

Figure I31 Rumble area for articulated vehicles

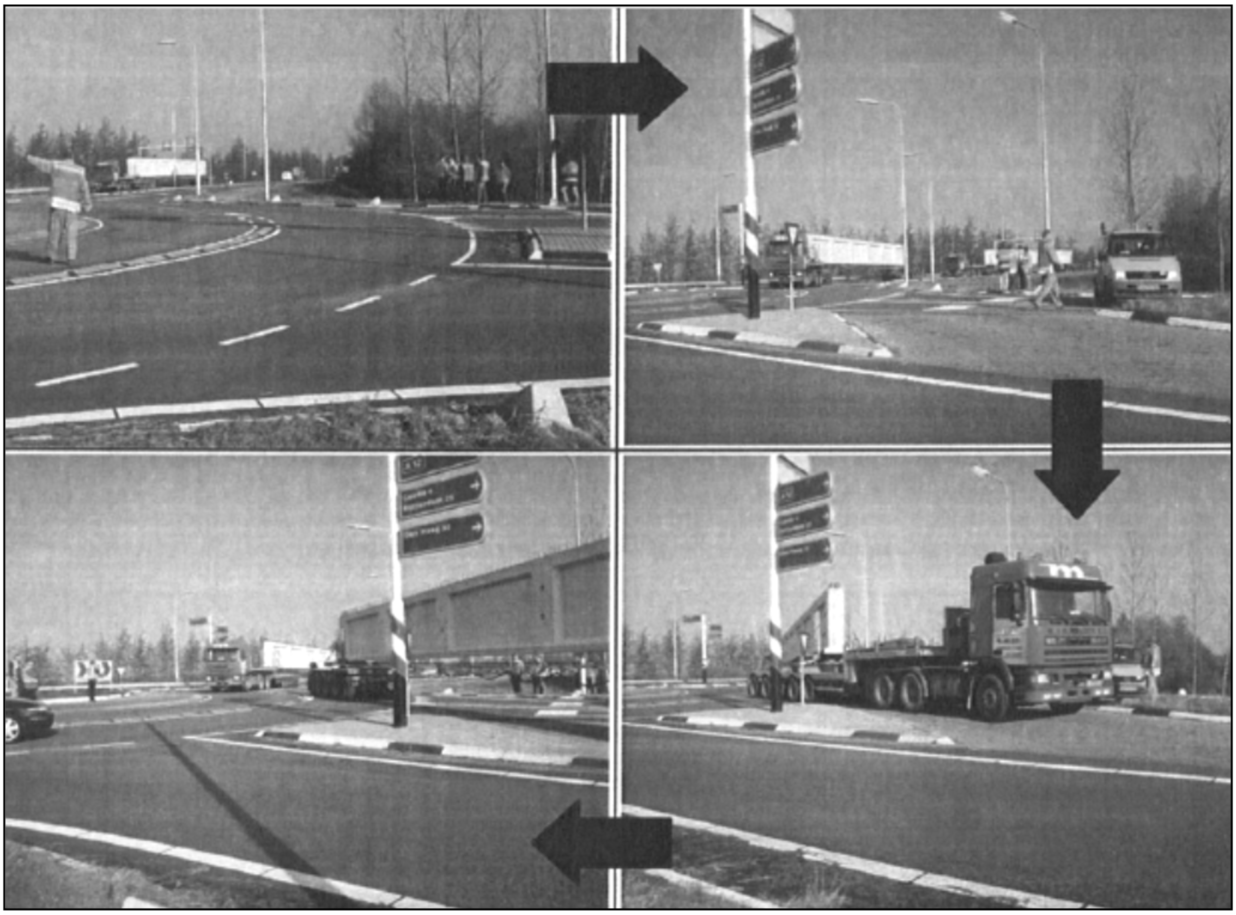
Public transport

Adding special lanes for public transport on a turbo roundabout is more difficult than on a multi lane roundabout (except for right turning public transport). For road safety reasons (unexpected conflict points) it is not recommended.

Exceptional transport

Exceptional transport can make use of the rumble areas (see figure I31) that also provides normal trucks with manoeuvring space without other dimensioning of the road surface, leading to (too) high speed of passenger cars. Another possibility is to add special features, which can be especially useful when exceptional transport takes place in a particular direction (see figure I32).

Figure I32 Exceptional transport guided by a traffic organiser



Appendix J Abbreviations and acronyms

ADT: Average daily traffic

APM: Beca APM Toolkit

ASD: Approach sight distance

CAS: Crash analysis system

CBD: Central business district

CCS: Crippled Children's Society, now officially known as CCS Disability Action

CROW: CROW is the Dutch abbreviation of the Information and Technology Centre for Transport and Infrastructure. This abbreviation is only used in official documents. Its more common title is the 'Information and Technology Platform for Infrastructure, Traffic, Transport and Public Space'

DfT: Department for Transport (UK)

EEM: *Economic evaluation manual*

IHT: Institute of Highways and Transportation

ITE: Institute of Transportation Engineers

MOTSAM: *Manual of Traffic Signs and Markings*

MWP: Modified Watts profile

NZTA: NZ Transport Agency

PCU: Passenger car units

RCA: Road controlling authority

RNZFB: Royal New Zealand Foundation for the Blind

RRFB: Rectangular rapid flashing beacon

RTFNZ: Road Transport Forum New Zealand

SEL: Sound exposure level

SRT: Static rollover threshold

TERNZ: Transport Engineering Research New Zealand

TMU: Traffic Management Unit

TRL: Transport Research Laboratory

UK: United Kingdom

US: United States