Improving the Performance of Safe System Infrastructure

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Improving the Performance of Safe System Infrastructure
Final Report

Improving the Performance of Safe System Infrastructure: Final Report

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Abstract

This report summarises the findings of a three-year study which reviewed the safety performance of selected road infrastructure elements and provided solutions that were more closely aligned with the Safe System ideal.

The review examined the performance of signalised intersections, roundabouts and wire rope barriers. The solutions were developed following a literature review, statistical analysis of site data, in-depth crash data analysis, and expert guidance.

The review found that the safety performance of signalised intersections can be improved by managing high entry speeds and unfavourable impact angles using signalised roundabouts, and horizontal and vertical deflections on entry.

Roundabouts showing poor safety outcomes for cyclists and motorcyclists can be made safer by reducing approach and entry speeds. In these cases, tighter geometric design or additional supporting infrastructure can help reduced speeds.

Wire rope barriers were seen to deliver positive safety improvements relative to other roadside design options. Guidance refinement could further optimise safety outcomes.

Keywords

Safe System, roads, infrastructure, roundabout, traffic signals, flexible barrier, wire rope barrier

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- promote improved practice and capability by road agencies
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- Roads Corporation Victoria
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- Department of Transport Northern Territory
- Territory and Municipal Services Directorate, Australian Capital Territory
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- Australian Local Government Association
- New Zealand Transport Agency.

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Summary

This project sought to identify areas of improvement which would bring safety performance of selected Safe System infrastructure elements closer to the vision's objectives. The report summarises the key aspects of Safe System performance for signalised intersections, roundabouts, and wire rope barriers in wide-median, narrow-median and roadside applications. It then documents findings of literature, statistical analysis of site data and in-depth severe crash analysis to identify factors contributing to their occurrence at these infrastructure elements. Further literature and expert inputs helped to identify suggested solutions to address these factors and to provide broad guidance for consideration in future Austroads guide revisions.

In the process, the project proposed a new approach to definition of what constitutes road infrastructure aligned with Safe System objectives. Further, the project proposed fundamental relationships between impact speed and probability of fatal and serious injury, based on recent US research.

For signalised intersections, the leading severe crash factors were high entry speeds and unfavourable impact angles (e.g. right-angle, head-on), followed by red-light running, lack of full right turn control, large size of site (multilane, high number of conflict points), inadequate signal visibility, and high pedestrian activity. The suggested solutions align the signalised intersection form closer to the Safe System ideal, and include signalised roundabouts, horizontal and vertical deflections on entry. A number of treatments were identified as supportive to any or all of these solutions e.g. movement control and management, lower speed limits, and red light/speed cameras.

For roundabouts, the focus was on improving safety performance for cyclists and motorcyclists. The key severe crash factors were related to high speed approach and entry into the roundabout, and included multiple approach and circulating lanes, or lack of effective approach deflection. Project stakeholders also identified high speed exit conditions as a potentially contributing factor in injury crashes. Confusing layout was also a factor leading to drivers not seeing, reacting and giving way to the two-wheelers. The proposed Safe System solutions included reduction in approach and entry speeds such as tighter geometric design and raised stop lines/platforms. Identified supporting measures included arterial traffic calming, cyclist bypasses, and signalising roundabouts.

Wire rope barriers generally deliver substantial safety improvement for most road users compared to other roadside design options. It is proposed that further research and development of guidance focuses on refinement based on application of optimal wire rope barrier systems for different locations, so that risk of severe injury outcome is minimised. Consideration of barrier system stiffness appears to be one area for further investigation. The report also noted a number of additional areas of interest in future wire rope barrier research.

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1. Introduction

A number of road infrastructure elements have been identified and promoted as Safe System solutions due to their strong performance in minimising death and serious injury. However, such elements do not always achieve the desired Safe System outcomes in all types of locations or for all road user groups (e.g. pedestrians or motorcyclists). Other infrastructure elements may require significant conceptual redesign to improve their safety performance towards the Safe System vision.

1.1 Purpose and Objectives

This report summarises the findings of a three-year research project seeking to understand and improve safety performance of selected road infrastructure elements considered in implementation of Safe System in Australia and New Zealand.

Safety performance of these elements was reviewed to establish how closely they align with the Safe System vision objectives. It then reports on the key infrastructure and operational factors which were found to contribute to occurrence of high severity crashes involving these elements.

The report then identifies areas of selection, application and management of these infrastructure elements which could be improved to bring their safety performance closer to the Safe System objectives. This constitutes broad practical guidance which may be used in future revisions of Austroads road design, traffic management and road safety guides.

1.2 Scope

The project steering group reviewed safety performance of a range of road infrastructure elements during the early part of the project reported in the interim report (Austroads 2013a). This included attention to their crash reduction effectiveness, applicability across the road network, and use as greenfield or brownfield solutions. Based on these criteria, five elements were prioritised for full investigation under the project:

- signalised intersections
- roundabouts
- wire rope barriers in wide medians (e.g. motorway)
- wire rope barriers in narrow medians (e.g. 2+1 design)
- wire rope barriers in passenger-side roadsides.

While signalised intersections are not generally identified and promoted as a Safe System solution, they were included for investigation by the project steering group as there was recognition that their safety performance must be improved in the direction of the vision.

This report makes numerous references to concurrent Austroads research on implementing Safe System infrastructure, i.e. SS1960 *Understanding and Improving Safe System Intersection Performance*, and SS1958 *Safe System Assessment Framework*. Relevant data and findings were cross-referenced with these projects.

2. Methods

The objective of was to identify in some detail the design and operational factors which may contribute to the prioritised Safe System failures, i.e. specific severe crash types/scenarios listed in the previous section.

This was followed by identification of potential solutions and design changes which would improve performance of the selected Safe System infrastructure elements towards the vision objectives.

Steering group workshops were held throughout the project, followed by five expert workshops in Australian capital cities to review suggested solutions during the first part of 2015.

2.1 Literature Reviews

The project reviewed existing literature on the effectiveness of the selected infrastructure elements in the Safe System context (e.g. crash reduction/modification factors). Identification of potential factors influencing the occurrence of targeted severe crash types at the investigated infrastructure elements was supplemented by literature reviews published in Austroads (2013a). Potential solutions to the identified factors were also sought from published Safe System research.

ARRB Library was used to identify sources from a wide variety of local and international sources. Key recent and concurrent research projects were also drawn on for sources, e.g. SS1960 *Understanding and Improving Safe System Intersection Performance* and SS1958 *Safe System Assessment Framework*.

2.2 Crash Data Analysis

Jurisdictional crash data analysis was carried out to tabulate the leading crash types, road user groups and conditions with high occurrence of severe injury. The main source of data was the Victorian crash database due to its broad and detailed crash attributes, and significant sample size. South Australian data was used to support wire rope barrier analysis. Comparisons and consistency checks were carried out using New Zealand data in the concurrent Austroads project SS1960. The majority of these tasks were carried out and documented in the interim report for this project (Austroads 2013a).

2.3 Severe Crash Site Analysis

2.3.1 Adopted Approach

This method aimed to determine the design, operational and site context factors which increase the probability of a site having severe crashes of the targeted type, i.e. failing the Safe System vision. It involved development of a probit model[1] based on two groups of sites: the 'fail' sites and 'Safe System' sites, and then, identifying the key influencing factors and estimating the magnitude of their effect.

[1] A probit model is a type of regression model where the outcome can fall only within one of the two categories, e.g. fail or success. The aim of such a model is to estimate factors which affect the probability that an outcome will fall into a specific category (e.g. fail).

2.3.2 Site Selection

Large-scale casualty crash data analysis was conducted across Melbourne and Brisbane metropolitan areas to select traffic signal and roundabout sites with history of one or more severe crash types/scenarios prioritised during Stage 1 (the Safe System 'fail' sites). Additionally, similar nearby sites with only minor injury crashes of the same types (Safe System 'success' sites) were selected as controls for the chosen analytical method. The five-year crash data period between 2007 and 2012 was used. Similarly, WRSB casualty sites were identified from Victorian and South Australian crash databases, both with severe and minor injury crashes.

Table 2.1 shows site sample sizes by element and crash type. In total, 404 sites were identified and included in the study.

Table 2.1: Number of sites by Safe System element and crash types

Safe System infrastructure element and crash types	Severe crash sites (Safe System fail sites)	Minor injury crash sites (Safe System sites)
Signals		
Opposing direction crashes	23	42
Adjacent direction crashes	27	47
Same direction crashes	NA	NA
Pedestrian crashes	21	41
Sub-total	*71*	*130*
Roundabouts		
Adjacent direction crashes	23	45
Off-path crashes	21	35
Same direction crashes	NA	NA
Sub-total	*44*	*80*
Wire rope safety barrier (WRSB)		
Run-off-road crashes	19	60
Total	***134***	***270***

Selection of traffic signal and roundabout sites was relatively unbiased. The key criterion was clustering of crashes of the required type and severity, i.e. two or more. Typically, traffic signal and roundabout sites had between two and four such crashes. The WRSB sites typically had a single crash at each location. There was a strong bias towards urban and outer-urban motorways dictated by the occurrence of these crashes (very few found).

It was not possible to find a sufficient number of signalised sites clustering severe rear-end crashes. Hence, this crash type was investigated through severe crash analysis described in the following sub-section.

Similarly, it was not possible to find enough roundabout sites which specifically clustered two-wheeler severe crashes of the targeted types. Given that half of severe crashes at roundabouts in the Austroads (2013a) data sample were two-wheelers, the investigation focussed on sites with severe crashes involving any vehicle group.

The selection of sites from the limited number of jurisdictions was restricted by the project budget and access to road agency crash data systems. Victorian and Queensland crash systems were adequate for intersection site selection in accordance with the project criteria. Melbourne and Brisbane metropolitan areas yielded sites with sufficient targeted crash numbers. The Victorian system was adequate for WRSB investigation, with additional data provided on request by South Australia.

Omission of other jurisdictions could potentially limit the applicability of findings to other jurisdictions. This could especially affect precise findings (e.g. identified high-risk widths or offsets, or traffic volume thresholds), or those with strong jurisdictional links (e.g. specific technical solutions, or rainfall). Such limitations would not be expected to be significant for broad-practice findings such as a given factor improving or degrading Safe System performance.

The initial goal of investigating WRSB applications in narrow medians (e.g. 2+1 design) proved elusive due to the limited number of crashes that could be located on such roads. There were only limited trials of such WRSB use occurring in Australia at the time, and few crashes occurred at these post-treatment.

2.3.3 Data Collection

The next step of the analysis involved collecting design and operational data from all the sites. The primary method involved manual coding of these attributes using Google Street View and NearMap services. This provided a record of relevant attributes corresponding to the crash period. The method assumed that the recorded attributes were in place at the time when the relevant crashes occurred at each site.

Numerous attributes were collected for signalised intersections and roundabouts, and they included:

- maximum approach speed limit
- number of intersection legs
- number of approach lanes at the intersection
- approach geometry – regular/irregular, with irregular meaning legs were not at approximately 90 degrees
- intersection conspicuity – conspicuous meaning that the presence of the intersection was visible from > 200 m on all approaches
- presence of right/left turn lanes
- land use intensity – type of land use from residential to commercial, a proxy for pedestrian activity
- right/left turn control arrangements (signalised intersections only)
- traffic separation (signalised intersections only)
- approach deflection (roundabouts only)
- central island diameter (roundabouts only).

Approach traffic volume data was sourced from VicRoads, Department of Transport and Main Roads Queensland (TMR) and City of Brisbane. A minority of traffic signal sites and very few roundabout sites had the required data. Where available, traffic volume attributes were categorised as ‘Major Road Maximum Approach AADT’ and ‘Minor Road Maximum Approach AADT’.

For WRSB sites, the attribute set differed and included:

- location on roadside vs. median
- WRSB type: 3- vs. 4- wire
- proximity to an intersection (within 100 m, or further)
- proximity of crash to a barrier terminal (within 200 m, or further)
- curve radius (m)
- post spacing (m)
- barrier offset from traffic lane (m)
- vehicle type.

Many other attributes were collected for the investigated elements and the list can be provided on request.

In order to ensure quality of data, different coders and other project team members were required to check all coded data and resolve coding/errors and differences. Selected site visits were conducted to validate the data on site.

Categorisation of coded data into larger logical groups was needed in order to boost the statistical power of the results. This was carried out carefully to also maximise the detail of findings.

Site attributes were checked for mutual correlation. Pairs of attributes that were strongly associated were dealt with by removing the less useful attribute from the data set (e.g. street lighting was correlated with all other variables as it was present at all sites). An exception was made for the speed limit variable, which was heavily correlated with most of the other road environment attributes. This was considered an important attribute in the context of the purpose of this investigation. Further discussion of this matter is provided in Section 5.

2.3.4 Statistical Analysis (Probit Modelling)

After reviewing several appropriate alternative methods, the binary probit modelling technique was selected as it best answered the research question of finding which factors contribute to the occurrence of severe crashes being targeted.

Binary probit modelling allows identification of variables (factors) which contribute to the site being either a minor injury crashes only site (a Safe System 'success'), or a severe injury crashes site (a Safe System 'fail').

The statistically significant variables in the model can be said to meaningfully contribute to the probability of occurrence of severe crashes, i.e. the site being a Safe System 'fail'. The model coefficients for these variables can be used to estimate incremental increase in the probability of severe crash outcomes given a defined change in site conditions (e.g. having filter right turns on all approaches vs other forms of right turn control).

Probit models were developed using EViews 8.0 software for signalised intersections, roundabouts and for the WRSB. For signalised intersections, the breakdown of crash sites and crash types in Table 2.1 led to three different models reflecting the three prioritised crash types. Two models were developed for roundabouts. Only one model was necessary for wire rope safety barriers, based on run-off-road crashes.

For the signalised intersection model analysis, preliminary data analysis showed that the required approach traffic volume data was only available for some sites. Consequently, the separate probit model analysis was carried out on that smaller group of sites to isolate the effect of traffic volume on the probability of the Safe System fail. These results were then combined with the main model results developed without traffic volumes (more robust being based on a larger data set).

There were too few roundabout sites with traffic volume data to include in the modelling.

The main advantage of the binary probit modelling method is that it produces site design conclusions exclusively relevant to the occurrence of the investigated severe crash type.

2.4 In-depth Crash Analysis

It was recognised that the methodology in Section 2.1 was constrained by availability of site data, e.g. lack of two-wheeler distinction in the data, no rear-end crash cluster sites. Such information could be provided by additional analysis of factors associated with occurrence of the targeted severe crashes.

In-depth severe crash characteristics analysis was possible by drawing on the high level of access to Victorian crash data. Police crash diagrams and narratives, sub-DCA codes, and visual appraisal via Google Earth/NearMaps were used. Methodical analysis led to descriptive synthesis of key factors present in the targeted severe crashes.

The approach allowed focussing on different factors present in crashes involving cyclists and/or motorcyclists, as intended. Logically, this led to potentially more detailed conclusions about treatments and design changes. This approach was similar to conventional black spot analysis.

The main point of difference to the site analysis method described in Section 2.1, was that the crash analysis method produced conclusions non-exclusive to severe crashes. The findings could be also associated with minor crashes of the targeted type.

2.5 Stakeholder and Expert Input

A series of project steering group workshops was held during the project to receive the interim findings and to provide direction for further analysis. The steering group consisted of subject area experts drawn from road agencies, and nominees of the Austroads Road Safety, Network and Assets task forces.

In April and May 2015, five multi-disciplinary expert workshops were held in Sydney, Melbourne, Brisbane, Adelaide and Perth to seek detailed inputs on the proposed technical solutions to bring safety performance of the selected elements closer to Safe System objectives. The workshops also provided inputs to the formulation of future guidance on these solutions.

The experts were asked to provide inputs across a range of areas associated with selection, application and management of the selected road infrastructure elements:

- Safe System alignment – effectiveness of a given solution in reducing impact speeds, impact angles, and conflict points, and addressing identified factors in the targeted and non-targeted severe crash types.
- Applicability across the road network – where and when they could be used.
- Design – footprint/land requirements, design considerations, constructability, capital costs.
- Traffic operations – flow efficiency, delays/queueing, network access by different road user groups, transport integration.
- Sustainability – maintenance, upgradeability, replacement, operating costs, emissions, vegetation and water flow.

Discussions included a combination of solutions to optimise applicability and performance across these areas.

3. What Is Safe System Infrastructure?

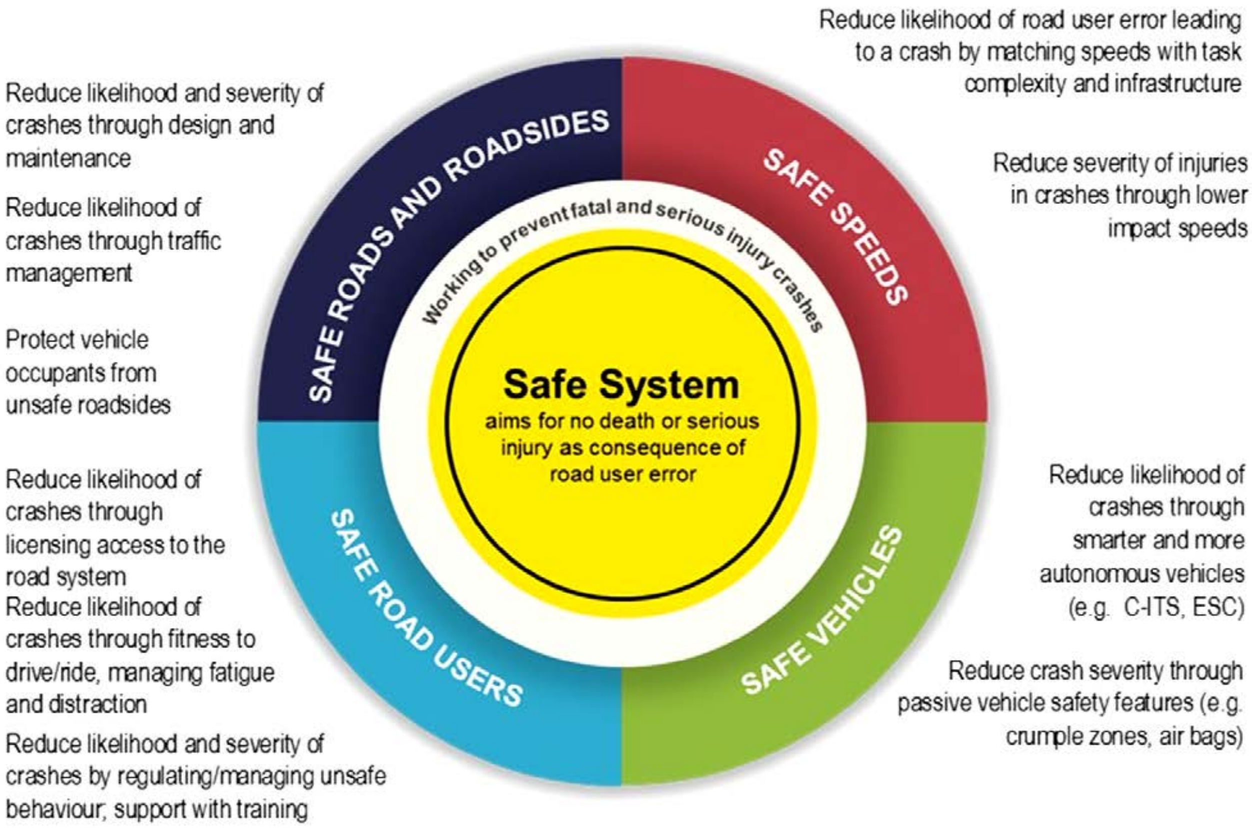
3.1 Interpreting the Safe System Vision

Safe System has been the backbone of Australian and New Zealand road safety strategies for a number of years. The key principles of the Safe System listed in the Australian Transport Council (2011) remain essentially unchanged:

- Road users make mistakes and the transport system must accommodate these. Use of the system should not result in death or serious injury as a consequence of road user errors.
- Human bodies have limited capacity to absorb impact force before injury occurs.
- The road system should be forgiving of human error and frailty. System designers and operators need to take into account the limits of the human body in designing and maintaining roads, vehicles and speeds. Forces in collisions resulting from human error must not exceed the limits of human tolerance.

The Safe System vision proposes a holistic approach to achieve these objectives. This approach involves careful consideration of interactions between road infrastructure, travel speeds, road users and vehicles. Figure 3.1 shows these four pillars and how they act to support the key objectives. No pillar alone can deliver the Safe System vision.

Figure 3.1: Holistic approach to achieving the Safe System vision



Source: based on Australian Transport Council (2008), Ministry of Transport (2010) and Office of Road Safety (2009).

Actions in the Safe Roads and Roadsides, and Safe Speeds pillars (i.e. road infrastructure design and management) have been gradually refocussed to minimise the risk of fatal or serious[2] injury to all road users regardless of mode of transportation. These two pillars are closely connected: road infrastructure influences driver selection of speed, and operating speed influences design of the road infrastructure. Thus, any road infrastructure objective seeking safety performance improvement towards the Safe System needs to focus on both pillars.

It could be summarised that road infrastructure is well-aligned with Safe System objectives if it:

- considers and performs for all relevant road users
- is forgiving of road users' errors
- has fail-safe redundancies
- focuses on fatality and serious injury minimisation.

The holistic nature of the Safe System means that it is not going to be achieved through safer roads, roadsides and speed alone. Severe crashes can be substantially reduced and even minimised using infrastructure solutions, but reaching the ultimate goal will need to be supported by changes in road user behaviour and vehicle technologies.

The following section presents the general approach to analysis of severe injury risk in road crashes drawing in both Safe Roads and Roadsides and Safe Speeds pillars. The approach was developed to assist the project in meeting its objective in a measured way. Section 4 proposes new evidence related to kinetic energy of crashes, and especially to impact speeds and angles.

It is intended that these findings will contribute, together with other concurrent work in this field[3], to further development and implementation of Safe System infrastructure.

3.2 Risk of Severe Injury and Road Infrastructure

Application of risk assessment to crash analysis over the past 15 years has gradually enabled policy makers and practitioners to understand the key road engineering factors controlling occurrence of severe injuries on the road network. Many studies presented conceptual frameworks for crash risk assessment within the Safe System paradigm (Austroads 2010a, concurrent Austroads project SS1958, or the Kinetic Energy Management Model (KEMM) proposed originally by Corben et al. (2004). More recent studies attempted to apply these frameworks to severe crash number estimation and quantification of safety benefits (e.g. Austroads 2014a, 2014d). These were complemented by practical network-level safety models such as Australian National Risk Assessment Model (ANRAM) or AusRAP. In parallel, new theoretical models are being proposed which seek to estimate crashes of a given severity by microscopic analysis of individual movements of vehicles, decisions and of individual road users (e.g. Tarko et al. 2009, Sobhani et al. 2011).

Proposed framework

This knowledge allowed synthesis of the key elements contributing to severe injury risk, potentially applicable to any part of the road network. They are: road user exposure, crash likelihood and crash severity. Figure 3.2 shows these three elements plus various groups of factors which feed into them. Some of the factor groups have influence across more than one element. Recognising this transiency helps to explain why some road safety questions do not have simple answers (e.g. the role of speed in crash likelihood and severity).

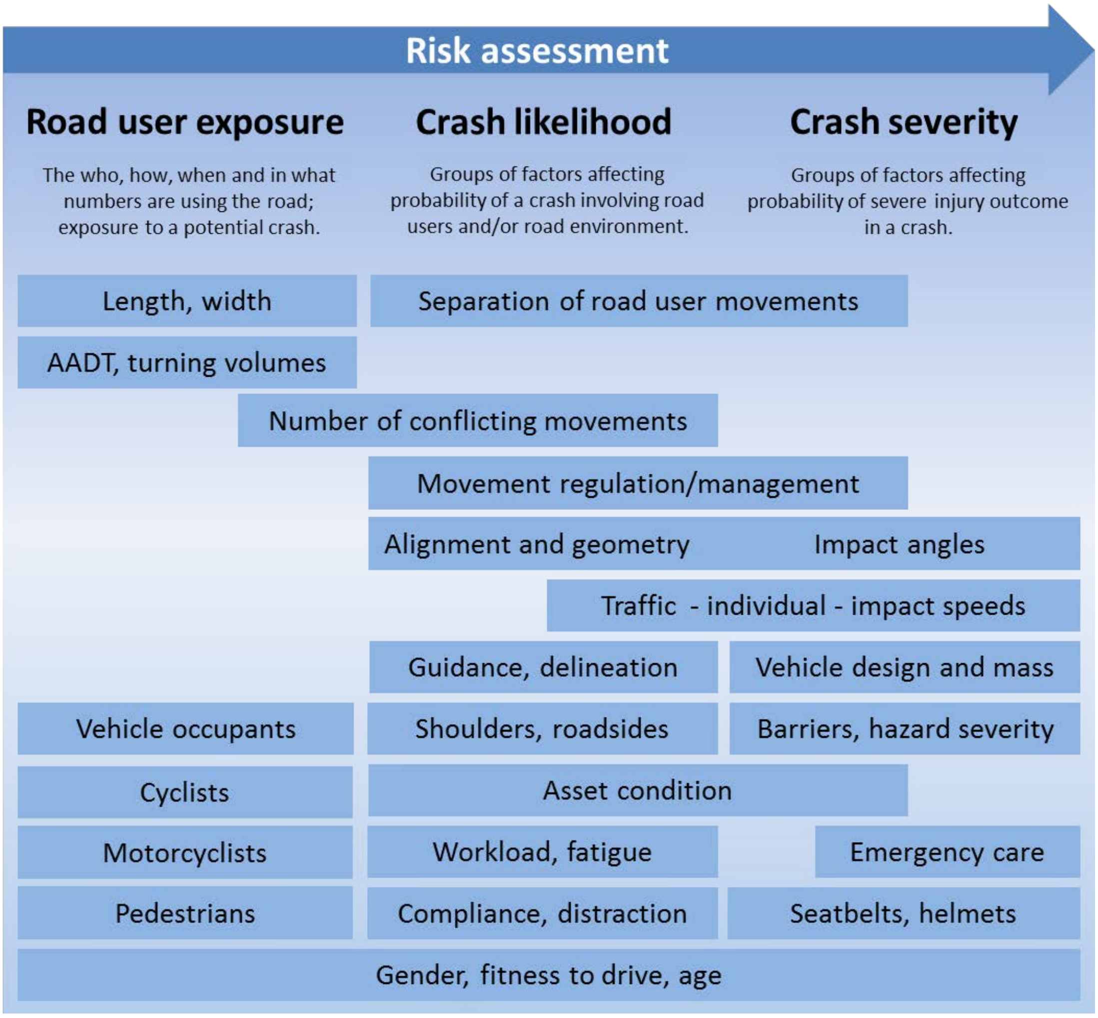
[2] Fatal and serious injuries will be referred to as severe injuries in this report.
[3] E.g. Austroads projects ST1958 *Safe System Assessment Framework*, and SS1960 *Understanding and Improving Safe System Intersection Performance*

Figure 3.2 proposes that assessment of severe injury risk in any given road system should start with consideration of its users. This element includes vehicle and vulnerable road user numbers, and appreciation of the physical dimensions of the system (e.g. road length). Understanding of traffic composition and local demographics are also needed. These exposure factor groups have a large part in defining how frequently crashes will occur and how severe they may be.

The second element contains groups of factors relating more to the likelihood of a crash occurring, exposure and severity being constant. Typically, crash likelihood can be informed by the number of conflict points between different road users, and by how road user error contributes to crashes actually occurring at these points. Many specific risk factors are proxies for road user error rates, e.g. levels of right turn control (ban, full, partial, filter), or presence/quality of road delineation. Understanding the likelihood of a crash occurring is important when considering its severity consequences.

The third element which needs to be assessed relates to factors which can increase severity of injury, should a crash occur. This is the most crucial area to the success of Safe System. Crash severity depends on impact speeds, angles, objects impacted, and on who is involved in a crash (vehicle occupants, pedestrians, cyclists, etc.). In vehicle-to-vehicle crashes, area of impact further controls the amount of kinetic energy passed on to the occupants. If the combination of impact speeds and angles exceeds the critical biomechanical threshold, the probability of severe injury is high.

Figure 3.2: Proposed framework for severe injury risk assessment and treatment hierarchy



The hierarchy of Safe System treatments starts with those excluding the possibility of a crash altogether through removal of road user exposure or removing conflict points (e.g. a tunnel, forgiving median barriers, intersection closures).

The second tier would involve treatments limiting injury severity should the crash occur. These could include using geometry and speed limits to deliver low impact speeds and angles[4], or distributing roadside crash forces with forgiving barriers.

If such treatments are not feasible, then solutions focussed on reducing crash likelihood and/or severity offer varying degrees of alignment with the Safe System objectives. Reducing the number of conflict points, managing them (e.g. with signals), lowering speeds and providing system redundancies (e.g. shoulders, medians) are some of the stronger supporting measures. Removing roadside hazards, shielding them with less forgiving barriers or incrementally reducing speed limits would act to reduce the occurrence of severe crashes. Guidance, warning and lighting also reduce the rates of road user error and crash likelihood, and thus contribute towards Safe System alignment.

Managing road user exposure to potentially severe crashes has been an area traditionally most difficult to address through engineering of road infrastructure, and typically rests with transport planning. For example, transport mode priority changes (e.g. light rail) have the potential to reduce car occupant numbers along the route, and thus reduce their exposure to roadside hazards, or high-risk turning provisions. Diversion of traffic from strip shopping centres to higher-order and better designed arterials will reduce exposure of pedestrians to vehicles. In recent years, integrated transport planning and smart roads policies have been already providing many such opportunities.

The proposed framework for severe injury risk assessment and treatment hierarchy in Figure 3.2 was utilised in the concurrent Austroads project SS1960 *Safe System Assessment Framework*. The project sought to develop a practitioner-ready process which could be applied to appraise the level of Safe System alignment of road infrastructure projects ranging from large-scale transport planning solutions to localised retrofits and minor improvements.

3.3 Relevance to the Project Objective

The above concepts emerged during the project's investigations and stakeholder discussions. The original scope of the project focussed on the crash severity element and factor groups in Figure 3.2. These have been typically associated with Safe System discussion to date, i.e.:

- impact angles, based on alignment and geometry
- impact speeds, as dictated by geometry, traffic speeds and speed limits
- safety barriers, specifically the wire rope type

while considering the type of road user (age, vehicle occupant, cyclist, motorcyclist, or pedestrian). Section 4 considers and proposes a theoretical model for the interaction of impact speeds and angles, the key variables believed to determine severity of crash injuries.

- The project also touched on factor groups associated more strongly with crash likelihood, such as:
- separation of road user movements
- number of conflicting movements/points
- conflicting movement regulation/management
- vehicle design and mass
- compliance (e.g. red light running, speeding).

Specific research reviews, analysis and proposed solutions for signalised intersections, roundabouts and wire rope barriers are presented in Section 5, Section 6 and Section 7.

[4] Note that speeds considered 'survivable' in the Safe System context still carry a 10% risk. Please refer to Section 4 for further findings on this subject.

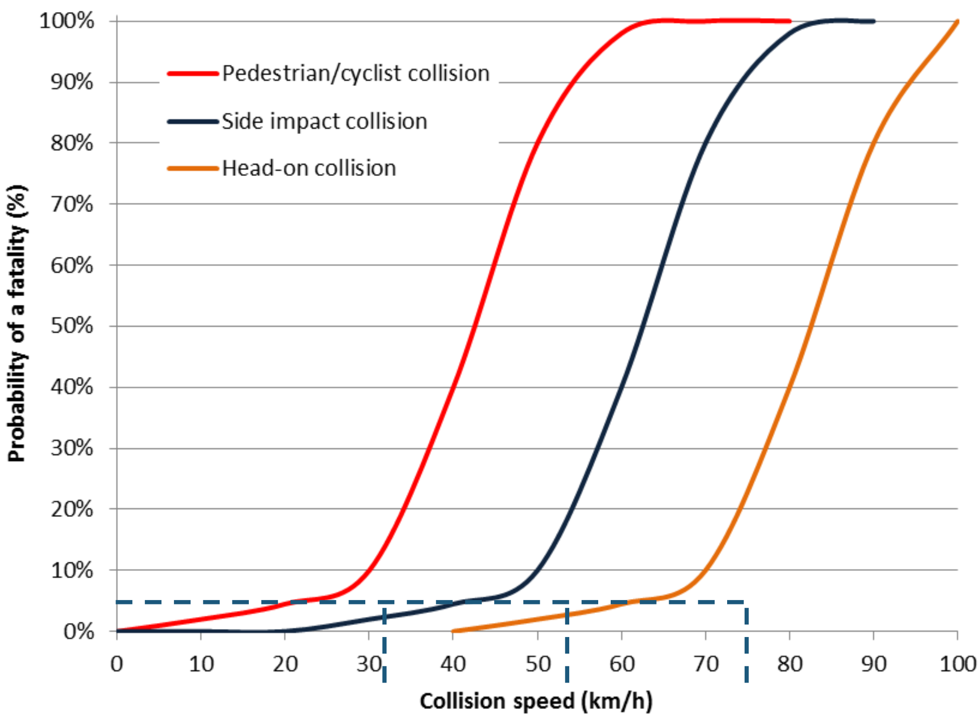
4. Impact Speeds and Angles

The previous section identified impact speed as the key factor in both injury likelihood and severity. The role of speed in crash likelihood has been confirmed through numerous studies. For example, Nilsson (2004) and then Elvik (2013) demonstrated that lower mean traffic speeds in response to speed limit reduction result in reduced likelihood of casualty crashes. Kloeden et al. (2001, 2002) presented relationships demonstrating that the likelihood of driver involvement in a casualty crash increased with his or her speed.

Severity of crash outcomes in response to speed has also been well researched. Studies by Elvik and others, e.g. Elvik (2013), showed that fatal crashes decline more substantially with the same amount of mean speed reduction than all injury crashes. In other words, severity of crashes decreases with reduced mean speed.

One model in particular has been adopted in Australia and New Zealand to illustrate the effect of impact speeds on severity of selected crash types. Wramborg (2005) proposed the three impact speed–fatality probability relationships as shown in Figure 4.1.

Figure 4.1: Wramborg's model for fatality probability vs vehicle collision speeds



Source: Based on Wramborg (2005).

These relationships assume equal mass and speeds of conflicting vehicles. According to these probability curves, there is a 10% chance of fatality outcome when vehicles impact at the following speeds:

- 30 km/h in pedestrian/cyclist crashes
- 50 km/h side impact collisions
- 70 km/h in head-on collisions.

These speed thresholds were also noted earlier in a conference paper by Tingvall and Haworth (1999). Much of the Safe System infrastructure discussion to date has been based around these thresholds. They are often quoted as the maximum or 'survivable' impact speeds which can be tolerated in relation to intersection design, pedestrian activity areas, or provision of medians.

There are several important issues which limit applicability of Wramborg's curves in this project. The first issue is that Wramborg's curves only provide information about the probability of fatal injury. As minimisation of fatal and serious injury is the key concern of the Safe System vision, any advice on Safe System infrastructure should reference probability of fatal and serious injury.

The second issue is that little is known about the source of these relationships. The Wramborg (2005) conference paper did not provide any research references or sources of information for the impact speed curves. There was no way of checking these relationships against similar or prior research. The context of the paper is establishment of the Vision Zero-based road hierarchy in Sweden, and this indirectly suggests that the curves were in use prior to 2005. Tingvall and Haworth (1999) also note the 10% fatality risk threshold speeds, referencing only high-level policy documents and keynote presentations as sources.

The third issue is that the curves in Figure 4.1 lack clarity. Does the term 'collision' imply a crash involving two or more vehicles, or the impact an individual vehicle has been subjected to? For instance, an adjacent direction crash involves a head-on impact by a bullet vehicle and a side impact into a target vehicle. Further, handling of different crash types is unclear: would opposing-turning crash be a head-on or side impact? Does the term 'collision speed' refer to the impact speed of one vehicle, or the closing speed of two vehicles (a vector sum of two speeds)? This lack of clarity has led to assumptions and conjecture in many past Safe System policy and implementation discussions.

Finally, a common interpretation of Wramborg's curves resulted in 'Safe System speeds' acknowledging a 'minimised' 10% fatality risk. In fact, an average fatality risk in a casualty crash is in the range 1–7% in the 80 km/h speed limit, depending on crash type (Victorian data, congested periods excluded). Since casualty crashes are a fraction of all impacts, these percentages would be actually much lower. Any Safe System-related design advice needs to result in a stepwise improvement on the current safety performance. Hence, application of Warmborg's curves and this commonly accepted fatality threshold in this project would be inappropriate for Safe System solutions.

Wramborg's impact speed-fatality probability relationships in Figure 4.1 represented the best evidence available to the road safety community at the beginning of the Safe System discussion in Australia and New Zealand. Given that more than a decade has passed since, and much new research has been published, the relationship between speed and injury severity may be due for review and discussion. This would be prudent given the 2021 horizon for the development of the new National Road Safety Strategy in Australia.

4.1 Delta-v and Severe Injury Probability

Review of crash reconstruction research suggests that estimated or measured impact speed of a vehicle is generally a poor predictor of crash severity, with the exception of pedestrian and cyclist crashes. It has been well stablished since the 1970s, that a vehicle's delta-v[5] is closely related to injury severity in two-vehicle crashes, e.g. side impact, head-on or rear-end. The only known drawback is accuracy of estimating delta-v in relation to roll-over, roadside hazard and safety barrier crashes (Joksch 1993, Rosén, Stigson and Sander 2011, Shelby 2011, Schmitt et al. 2014, Struble 2013).

[5] Change in velocity magnitude of a vehicle during the crash.

There has been a significant amount of quality empirical research on the effect of delta-v on severity of two-vehicle crashes based on crash reconstruction databases held in the US (NASS/CDS, CIREN) and UK (CCIS, OTS). One of the seminal studies was by Joksch (1993), cited by Evans (1994), who developed a ‘rule of thumb’ power function for probability of a driver fatality given a vehicle’s delta-v. This work was followed by Evans (1994) who used 22 272 crashes from the NASS database to create similar relationships for probability of driver fatality and injury. These relationships were based on crashes occurring between the early 1980s and early 1990s, and did not differentiate between crash types, e.g. head-on, side impact or rear-end. Applicability of these relationships to the three crash types was tested in this project and did not return results which correlated well with other research.

It is also worth noting other relevant studies investigating injury severity and delta-v, such as that by Richards and Cuerden (2009) in the UK. These used smaller crash samples which suffered from the lack of statistical power or direct relevance to this project.

Most relevant research on vehicle-to-vehicle collisions was carried out by a group of researchers associated with the National Highway Traffic Safety Administration (NHTSA) in the USA. Augenstein et al. (2003a, 2003b) and Bahouth et al. (2012, 2014) provided much more refined sets of delta-v vs severe injury probability relationships for occupants of vehicles involved in frontal, nearside (i.e. driver side), farside (i.e. passenger side) and rear-end impacts. These studies used large samples of crashes drawn from the ever-expanding NASS/CDS and CIREN databases in the USA (in excess of 100 000).

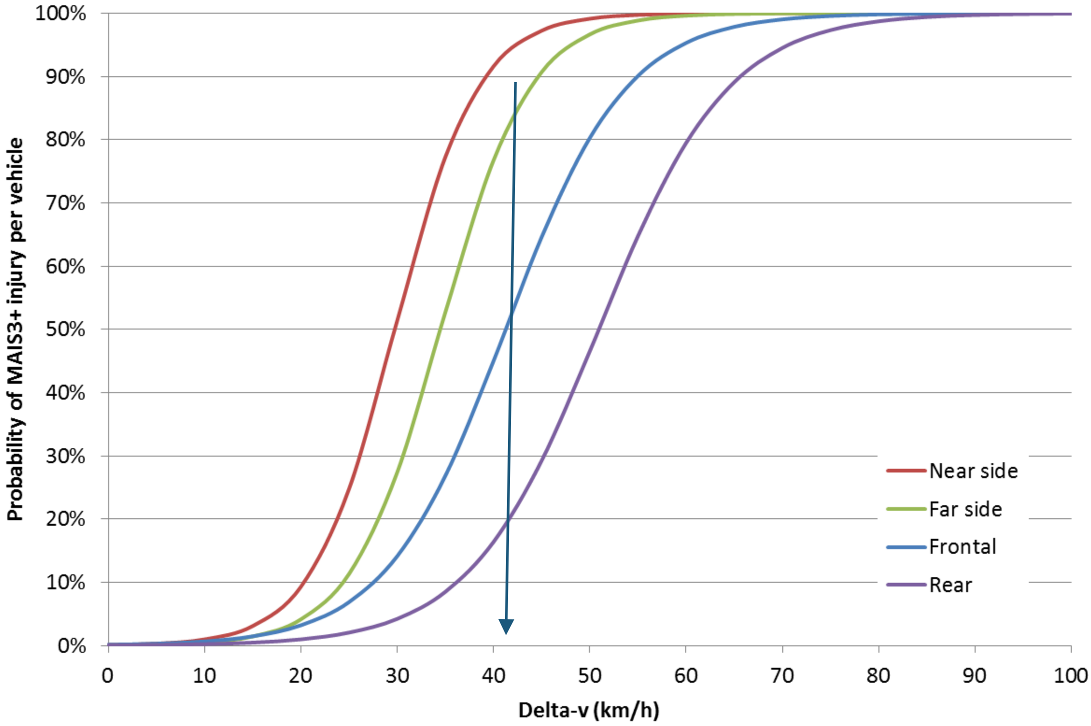
The objective of these researchers was to develop and refine reliable triggers for automated crash notification systems in vehicles. The baseline collision severity used in these studies was a non-injury tow-away crash. The authors applied strict limitations on the crash cases included in analysis to suit their objectives, e.g. availability of delta-v in the NASS records, focus on front seat passengers only, and the age of vehicle. The crash data in NASS/CDS was already weighted to match severity and type of crashes occurring across the USA. Also, all of these studies used a vehicle as a basic study unit, rather than a crash event (two or more vehicles).

Like the earlier studies, the Bahouth et al. (2014) study used logistic regression to develop relationships between the probability of a MAIS3+ injury for a front seat occupant of a crashed vehicle in given crash configurations. MAIS3+ is widely considered the serious injury threshold and includes fatality. In this study, the regression models were based on new vehicles (post 2002) and controlled for a range of factors such as: delta-v, seatbelt wearing, rollover, secondary impacts, and age of the front seat occupants. The logistic regression models were developed using a randomly selected 80% of the applicable 2002–12 NASS/CDS database and validated using the remaining 20% of data.

Figure 4.2 shows the resulting relationships between probability that a front seat occupant of a crashed vehicle will sustain an MAIS3+ injury and the vehicle’s delta-v for a range of vehicle impact types. These curves assume seatbelt use, no rollover or secondary impacts, and the occupant age between 16 and 55. Airbag deployment was not noted, but it can be assumed the vehicles were equipped with such, given the sample consisted of post 2002 vehicles only. Since authors make no statement on the vehicle types, it is assumed the data set included both passenger and heavy vehicles.

Bahouth et al. (2014) notes the principal directions of force (PDOF) on a vehicle which were used to categorise each impact into frontal, near side, far side, and rear types. The probability curves in Figure 4.2 reflect the logical expectations for these cases. For a given delta-v value, the near side impact was the most severe for the occupants. In this scenario, the impact occurs on the side of the driver and the amount of protection offered by the vehicle body is very low. The far side is next, showing the benefit of the crush zone to the left of the driver (assumed empty). Next is the frontal impact, with the crush zone benefit of the engine compartment but some likelihood of steering injuring the driver. The least severe impact type is into the rear of the vehicle, with the large and typically empty crush space behind the driver.

Figure 4.2: Probability of a severe injury of front seat occupants vs delta-v of a vehicle during a crash



Source: Based on Bahouth et al. (2014).

4.2 Impact Speeds, Angles and Severe Injury Probability

It is difficult to directly apply the delta-v concept to a Safe System road infrastructure discussion. It stems from the variable being a crash characteristic which lacks a direct relationship to road design inputs. Impact speed has been much more easily understood and related to design speed, or speed limit – variables under control of road agencies. Thus, it was important for this project to develop and demonstrate the generalised relationship between impact speeds, impact angles and severe injury probability. This would enable road agencies to modify this probability through improved design of infrastructure elements.

The delta-v–severe injury probability relationships for different crash types shown in Figure 4.2 can be transformed to show the effect of impact speeds if impact angles are considered and several simple assumptions made. This way the evidence from recent international research described in the previous section can benefit further Safe System infrastructure discussion in Australia and New Zealand[6].

As a first step, a useful derivation of delta-v was provided by Tolouei et al. (2011). Using Newtonian mechanics of momentum conservation, the authors showed that delta-v has the relationship with vehicle masses, impact speeds and the angle between their paths as shown by Equation 1.

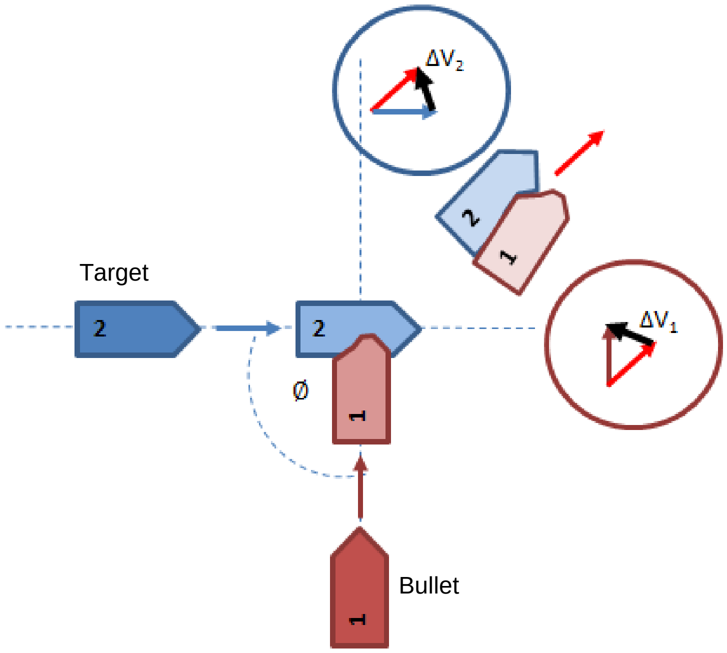
[6] Such generalised information would not be useful for assessment of individual crash cases.

$$\Delta V = \frac{m_1}{m_1+m_2}\sqrt{V_1^2 + V_2^2 - 2V_1V_2\cos\emptyset} \qquad 1$$

where

ΔV	=	vehicle change in speed due to the crash
m_1 and m_2	=	respective masses of 'bullet' and 'target' vehicles
V_1 and V_2	=	their impact speeds
$\emptyset$	=	angle between the axis of travel of both vehicles, as shown in Figure 4.3

Figure 4.3: Layout of colliding vehicles in Equation 1



Newtonian calculation based on Tolouei et al. (2011) in Equation 1 is a very simplistic approximation, as delta-v of an individual crash is a function of many additional factors such as:

- relative masses of the vehicles involved
- part of the target vehicle hit
- vehicle construction and stiffness
- brake application timing and skidding
- vehicle yawing (rotation)
- post-impact rebound, if any.

One of the first assumptions in creating the impact speed – severe injury relationship was to normalise the role of relative vehicle masses in Equation 1. This is not something which can be easily controlled by road agencies, hence has limited use in this investigation. Mass ratios affecting delta-v's and severity of injuries for individual vehicles is likely to have a normal distribution, i.e. it will be favourable for some vehicles (large) and worse for others (small), hence the net crash effect is likely to cancel out across a population of cases. It has been assumed from this point onwards that the masses of the two vehicles are identical. The term $m_1 / (m_1 + m_2)$ in Equation 1 thus becomes ½ and allows sole focus on the role of impact speeds and angles. This assumption may need to be reconsidered when investigating road design for traffic flows with a large percentage of heavy vehicles.

Another assumption in Figure 4.3 is that the collision is inelastic, i.e. there is no rebound. In such cases, ΔV has the same magnitude for both vehicles of equal mass, as they stick together after collision. This assumption leads to a more conservative estimation of the value of delta-v and of the critical impact speeds discussed further on.

The next step was to use Equation 1 to calculate a delta-v given a known impact speed of a bullet vehicle, speed of a target vehicle, and an approximate impact angle representing a given crash type. Since, the angle is a variable in delta-v (Equation 1), it can be varied to carry out sensitivity analysis (see Table 4.2).

As noted earlier, Bahouth et al. (2014) provided their results based on individual vehicles in specific impact types (frontal, near-side, etc.), rather than on crash events (two vehicles, two impact types). This limitation was carried over to this project. Thus, using the assumed impact speeds, angles and the delta-v relationships from Figure 4.2 it was possible to calculate Pr(MAIS3+) for each targeted crash type. This is plotted in Figure 4.4 for two-vehicle crashes, together with various assumptions indicating which impact type produced the highest severity[7].

For vehicle-pedestrian crashes, the physics of collision are different. The delta-v principle does not provide a good estimation of injury (Evans 1994). Davis (2001) provided an updated empirical relationship for pedestrian severe injury at different impact speeds. This relationship was chosen from a number of others reviewed by Rosén, Stigson and Sander (2011) on the basis of its relevance (severe injury) and solid methodology.

All five leading severe crash types are shown in Figure 4.4, with additional assumptions stated in Table 4.2. For a given bullet vehicle impact speed the pedestrian crash is the most severe, as expected due to the biomechanical vulnerability of the target. This is followed by head-on crash, where the very high delta-v outweighs the benefit of the vehicle's crumple zone. On par is the adjacent direction crash into the near side, where the lower delta-v is offset by greater vulnerability of the driver due to his/her position. Next is the opposing-turning crash which assumes the impact is on the far-side and shows benefits of the passenger space as a crumple zone. The least severe is the rear-end crash type, given the low typical value of delta-v and a large crumple zone. The most critical impact was in this case on the bullet vehicle. These severities follow the order of the average casualty crash severity findings from Austroads (2013a).

The main finding, however, consists of the potential Safe System critical impact speeds for each major crash type. Assuming that a 10% severe injury risk would represent a substantial improvement in performance, Figure 4.4 suggests critical impact speeds shown in Table 4.1.

These values are indicative only, due to many assumptions and model limitations. They have been rounded to the nearest 5 km/h. The pedestrian-vehicle critical impact speed could be extended to other vulnerable road users until more specific evidence can be identified.

[7] E.g. adjacent direction can occur on far- or near-side, but it is the latter which is more severe, and was thus used in the relationship.

Table 4.1: Approximate critical impact speeds for common crash types

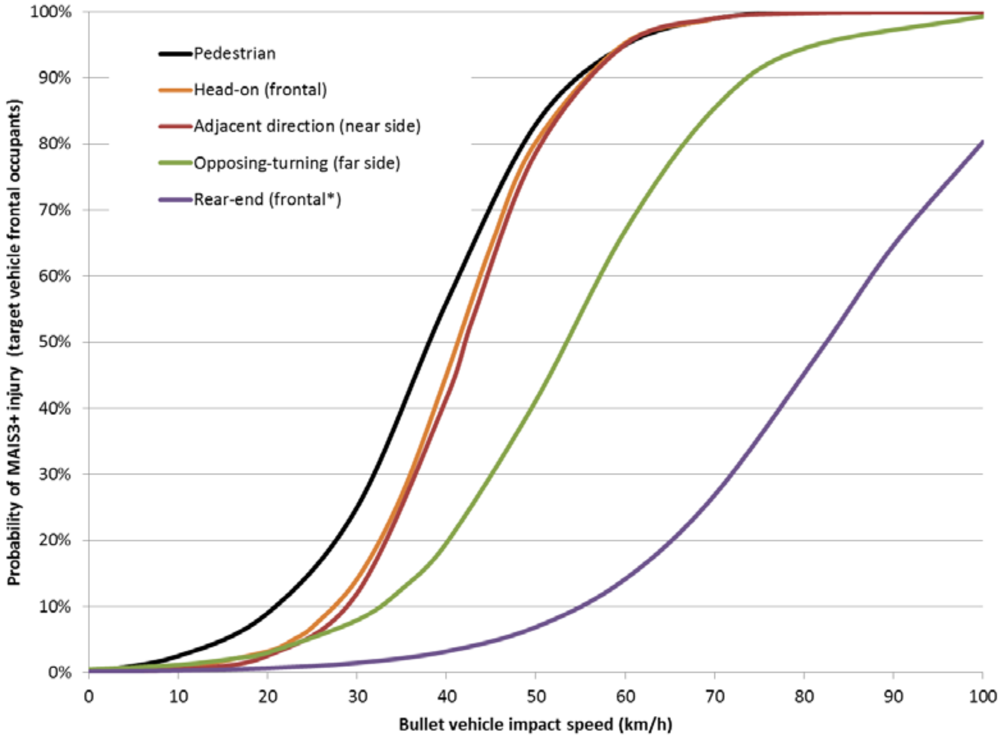
Crash type	Critical impact speed (km/h)*
Pedestrian-vehicle	20
Head-on	30
Adjacent direction	30
Opposing-turning	30**
Rear-end	55

** This is the speed of the bullet vehicle involved in the collision.*

*** Depending on the impact angle and the target (turning) vehicle speed, this value may vary.*

Further analysis was carried out for roundabouts, where adjacent direction and opposing-turning crash types are essentially the same type of impact (far side). For a typical roundabout with a 70 degree entry and impact angle, and a 40 km/h circulating speed, the critical entry speed would be 30 km/h (conversely, 40 km/h if the circulating speed was 30 km/h). As the entry angle is reduced at some larger sites, the critical entry speed increases. For a roundabout with a 30 degree entry and impact angle, and a 40 km/h circulating speed, the critical entry speed was calculated to be 60 km/h (lower speeds would reduce probability of severe injury below 10%). This demonstrates how geometric design can fundamentally improve safety performance.

Figure 4.4: Proposed model of severe injury probability vs bullet vehicle impact speeds in different crash types



** In rear-end crashes the frontal occupants of the bullet vehicle sustain greater risk of severe injury than those in the target vehicle.*

Source: Based on Bahouth et al. (2014), Davis (2001).

Table 4.2: Assumptions used in Figure 4.4, and sensitivity of Pr(MAIS3+) to angle of impact*

Crash type	Impact angle (Refer to Figure 4.3)	Target vehicle speed	Scenario adopted	Pr(MAIS3+) sensitivity to impact angle change ±10°
Pedestrian	NA	NA	Any	Unknown
Head-on	180°	Same as bullet	Frontal	Negligible
Adjacent direction	90°	Same as bullet	Near side	High, ~30% change
Opposing-turning	225°	20 km/h	Far side	Moderate, 15–20% change
Rear-end	0°	0 km/h	Frontal	Nil if the target vehicle is stationary

** General assumptions: baseline severity is a non-injury tow-away event, vehicle occupants were seat-belted, no secondary or roll-over collisions, applies to post-2002 vehicle models, front seat occupants only aged 16–55 (Bahouth et al. 2014); inelastic collision (no rebound), equal vehicle mass.*

Estimation of critical impact speed for run-off-road crashes into narrow roadside hazards or safety barriers is more complex. Delta-v is not a good predictor of severity which is also affected by the area of impact, the size, mass and rigidity of the hit vehicle (Joksch 1993). Hence, no simple impact speed–severity relationship could be found or developed at this time. As an indication, ANCAP uses an impact speed of 29 km/h in its rigid impact test which should result in low risk of severe injuries for a five-star vehicle (Australasian New Car Assessment Program 2015). This may act as temporary guidance until a more definitive relationship can be identified or developed for different roadside object types.

Figure 4.4 should be used as an indication only. Due to many assumptions in the preparation of the relationships, the threshold speeds should not be taken as precise values. Small size of the high delta-v collision sample in Bahouth et al. (2014) means the top end of these relationships is subject to a wide standard error and should not be considered as reliable at high speeds.

The impact speed relationship for opposing-turning crash type is the most complex of those in Figure 4.4. It is subject to several assumptions which influence the Safe System critical speed value. If a more conservative but less likely scenario is assumed where a passenger is present[8], the critical impact speed is about 25 km/h. These considerations were being included in the detailed analysis of designs in the concurrent project SS1960 on Safe System intersections.

A major shift in understanding of the impact speed–severity relationship relates to head-on crash type. While Wramborg (2005) suggests this is the most forgiving crash type, the new evidence indicates the opposite. It is possible, that Wramborg's curve was based on an earlier version of a delta-v relationship. It is the large drop in vehicle speed during a head-on crash, a complete stop is assumed, which elevates the severity of this crash type. Not incidentally, head-on collisions are the second most severe intersection crash types in Victorian data, after pedestrian crashes (Austroads 2013a).

The review of MAIS3+ probability–delta-v relationships from literature produced varied results, even when similar methods and data sources were used. This raises questions about the absolute accuracy of these relationships. For instance Bahouth et al. (2012) suggests a less harsh set of relationships than Bahouth et al. (2014) or Augenstein et al. (2003a, 2003b). Attempts to contact the authors to discuss these differences were not successful. It is clear that NASS/CDA data selection procedures, crash periods used, and other assumptions would influence the findings. Also, the studies had a specific objective in mind, which was different from this study's objective. It would be beneficial to have less exclusive relationships, e.g. for all vehicle occupants not just those in the front, and to include all ages of occupants.

[8] Previous investigations in Austroads (2014a) showed occupancy rates are low in urban areas ~1.3 persons per vehicle, 1.5 on rural highways and 1.7 on interstate freeways in Victoria.

For these reasons, it would be highly desirable to carry out further research in this area. The first objective would be to redevelop the statistical models for Pr(MAIS3+) – delta-v for Australasian policy context, i.e. for different crash types (e.g. adjacent direction), rather than for different impact types (e.g. near-side). Further, more inclusive model assumptions could be tested, e.g. regarding age and vehicle position of occupants, and vehicle age. Local verification of the models could be attempted using Australian and/or New Zealand crash reconstruction data, e.g. by combining CASR and ANSIS in-depth crash data bases if possible. Such relationships would need to be subjected to thorough peer scrutiny and discussion before they could be recommended for consideration in future road safety policies in Australia and New Zealand.

Appropriateness of a 10% MAIS3+ probability threshold as a critical benchmark should be confirmed. This could be done using data from a jurisdiction with current tow-away and casualty crash data. In the interim, rather than adopting an above/below 10% dichotomy, it would be preferable to evaluate and rank alternative design solutions in the later sections of this report according to their relative alignment with the Safe System objective of minimising severe injury.

The curves in Figure 4.4 shed a new light on the relationship between crash severity and impact speed. Given the clear research references and relevance to both fatal and serious injuries, these new relationships are considered more appropriate for use in this project than the Wramborg (2005) curves.

It is also clear that Safe System performance of road infrastructure cannot be wholly achieved by controlling impact speeds and angles (i.e. geometry and layout), especially where high speeds are required by the mobility function. This means that more weight can be placed on minimising the probability of road user conflicts. Road user separation, length/area of exposure, reduction in number of conflict points, and greater management of road user movements can all be used to provide solutions performing closer to the Safe System vision. These concepts were explored in Section 3.2 and are further developed by the following sections.

5. Signalised Intersections

This section summarises the project findings relating to signalised intersections, and establishes:

- how closely this infrastructure element aligns with the Safe System vision objectives (Section 5.1)
- what are the key infrastructure and operational factors found to contribute to occurrence of high severity crashes (Section 5.2)
- suggested solutions, i.e. areas of selection, application and management of signalised intersections which could be improved to bring their safety performance closer to the Safe System objectives (Section 5.3).

5.1 Safety Performance of Signalised Intersections in the Safe System Context

As noted in the introduction, signalised intersections have not been typically identified and promoted as a Safe System solution. Due to their proliferation on urban roads, there was a clear need to investigate the improvement in their performance towards Safe System objectives. Austroads (2013a) provides a detailed analysis of safety performance of this element. The following are the headline parameters:

- There was little published research on severe injury/crash reduction effectiveness of signalising previously unsignalised intersections. One study reported a 38% reduction in fatal crash rates (Pernia et al. 2004 reported in Austroads 2013a).
- Average casualty crash reduction based on research reviewed in Austroads (2012a, 2013a) was about 30%, with findings ranging between 5 and 53%.
- Signalising four-leg intersections was more effective (23–30% typical crash reduction) than signalising three-leg intersections (about 15% reduction).
- Fully controlling right-turns was a particularly effective treatment at already signalised intersections, with an expected reduction of 80–90% in opposing-turning casualty crashes (overall, a 45% reduction in all casualty crashes).

Signalisation changes intersection priority control from gap-acceptance to signal compliance. This means a change in control from one, which is very prone to road user error to one which is less so. The driver workload and skills needed to negotiate signalised intersections are much lower than for a comparable non-signalised intersection. It is proposed that the main source of safety improvement is through reduction in the likelihood of crash, as discussed in Section 3.2.

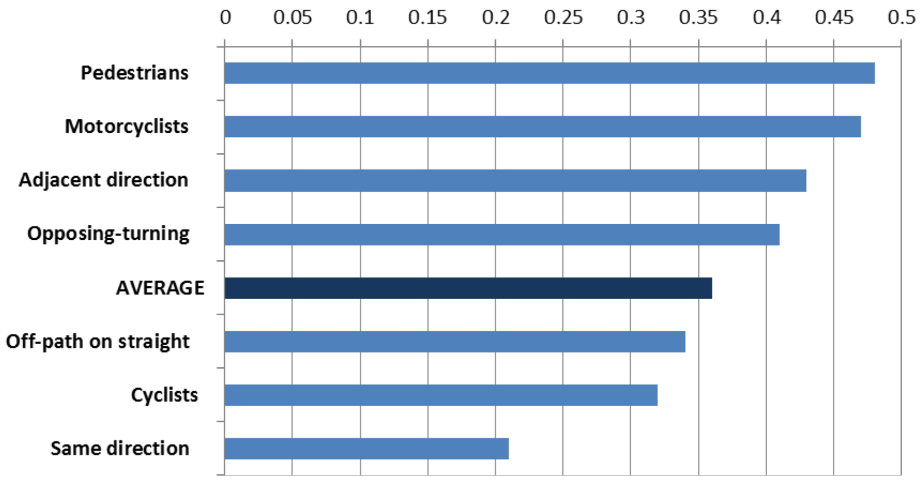
The crashes which occur are still very likely to be severe. An example in Figure 5.1, based on Victorian data used in Austroads (2013a), presents the average ratio of fatal and serious injury crashes to all casualty crashes for different crash type groups. This ratio, labelled as ‘average casualty crash severity’, is intended to demonstrate the range of typical crash severities, dependent on road users and on impact direction. This information was considered in more detail in Austroads (2013a).

Figure 5.1 shows that on average 36% of recorded casualty crashes at signalised intersections resulted in death or serious injuries (ratio of 0.36). Vehicle crashes into pedestrians and motorcyclists were the most severe (ratio of 0.48 and 0.47). Two-vehicle adjacent direction and opposing-turning crashes (sometimes referred to as right angle and right-turn-against crashes) were relatively less likely to be severe. Predictably, same-direction casualty crashes were the least likely to be severe (e.g. rear-end, side-swipe). This stratification appears logical and could be replicable in other jurisdictions.

Analysis of data from the concurrent Austroads project SS1960 showed that urban signalised four-leg intersections in Victoria had an average severe crash rate of 0.56 crashes per 10 million entering vehicles[9]. This can be approximated as 3.1 severe crashes over five years for an intersection of two arterials with AADTs of 20 000 and 10 000 vpd respectively. This average count increases to over 10 severe crashes for the same period, if these were major arterials with AADTs of 60 000 and 40 000 each. This example broadly demonstrates that safety performance of signalised intersections is not well aligned with the Safe System objectives, especially when considering the proliferation of signalised intersections in urban areas.

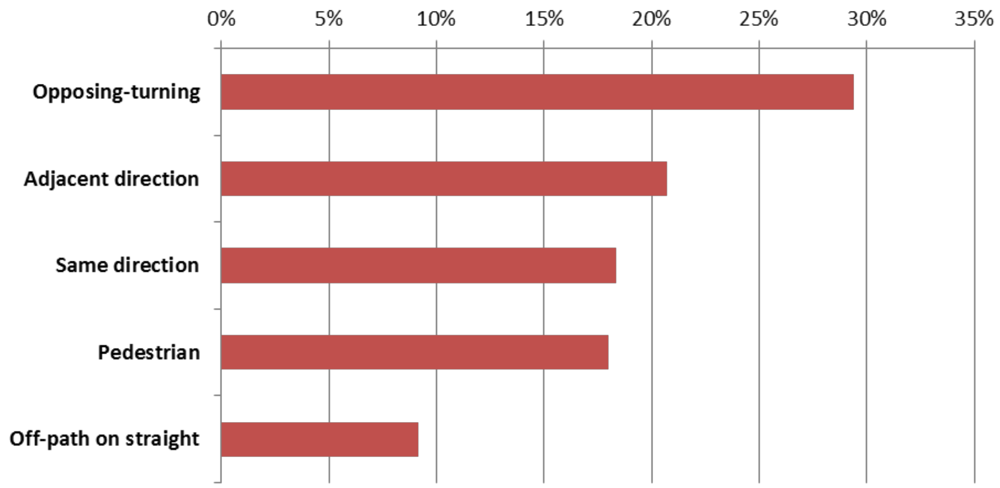
The most common severe crash types at signalised intersections found in the Victorian data were opposing-turn, adjacent direction, same direction and pedestrian crashes, as shown in Figure 5.2. This order of priority may vary between jurisdictions, as shown by similar analysis of New Zealand data under SS1960. It suggests that severe pedestrian crashes were the largest group. Regardless, the four crash types are likely to be among the top safety issues at signalised intersections across jurisdictions, and hence have been targeted for further analysis of factors in the following sections.

Figure 5.1: Average severity of different types of casualty crashes at signalised intersections



Source: Austroads (2013a) based on Victorian data.

Figure 5.2: Most common severe casualty crashes at signalised intersections



Source: Austroads (2013a) based on Victorian data.

[9] Data samples and examples were drawn from jurisdictions where the data was available to the project. Effort was made to cross-check results with literature and other data sets if possible. Findings based on data from one or two jurisdictions may not be directly replicable in another (e.g. order of importance, scope of the issue).

Overall, the information provided in this section indicates that signalised intersections do not currently perform close to the Safe System vision objectives. The key issue is the high probability of a severe outcome in a crash. The following sections provide project findings related to the factors which contribute to occurrence of high severity crashes at signalised intersections.

5.2 Severe Crash Factors

As described in Section 4, impact speeds and angles (delta-v) are the two major road infrastructure-related factors contributing to the probability that a crash will be a severe one. The following sections confirm this and summarise other important contributing factors.

Many of these factors contribute to both severity and likelihood elements of risk described in Figure 3.2 in Section 3.2. Some also extend beyond issues which can be addressed through road infrastructure (e.g. red light running). Detailed findings of the investigations are presented in Appendix A. The targeted severe crash types and scenarios were:

- opposing-turning
- adjacent direction
- same direction (rear-end)
- pedestrian.

These findings need to be interpreted in the context of key limitations based on:

- The probability of severe injury – impact speed relationships proposed in Section 4.2 are preliminary and the suggested critical impact speeds may be adjusted by future research. These values should be taken as general guidance only and should not be relied on for detailed assessment of designs (e.g. comparing impact speeds of 28 vs 33 km/h would be meaningless).
- The majority of research literature was based on studies using casualty crash data or all-crash data. This may skew the findings towards the factors affecting lower severity outcomes.
- The statistical analysis of severe crash sites vs minor injury-only sites with the probit model indicated many severe crash risk factors which were not statistically significant at $p \leq 0.1$. The non-significant results should be considered indicative of the general direction only; even so, there is a possibility that individual findings could be due to chance. The sample for each model was maximised within the project budget and timelines.
- The in-depth crash analysis relates only to severe crashes which have occurred and were randomly selected for the sample. The identified factors could be also present in lower severity crashes.

Overall, the findings need to be considered together by road safety experts and practitioners and discussed in the context of each suggested solution. This was achieved through discussions at a series of jurisdictional expert workshops to produce the findings reported in Section 5.3.

5.2.1 Opposing-turning Crashes

Severe opposing-turning crashes accounted for 29% of severe crashes at signalised intersections. Seventy-three per cent, of a sample of randomly chosen Victorian severe crashes of this type occurred in partially controlled or filter right turn conditions. This type of collision typically occurs due to the right-turning-driver's error in picking the gap across multiple opposing lanes, or an error by either driver at the hesitation point during the change of phase (yellow). Where fully-controlled turns were present in the random sample, red-light running was the only direct cause of crashes.

The results presented in Appendix A.1 have been summarised in Table 5.1 which presents the main design factors associated with occurrence of severe opposing-turning crashes. In all of the crashes in the in-depth sample (Appendix A.1.3), the target vehicle was right-turning, and the impact occurred on the passenger side (farside). Given low occupancy of vehicles in urban areas (1.3–1.4 persons per vehicle), it is likely that there is no passenger at the time of impact. Hence, the space next to the driver is likely to act as a crush zone. Overall, this makes opposing-turning crashes somewhat less severe than adjacent direction crashes (Austroads 2013a).

Table 5.1 shows the key factors associated with severe opposing-turning crashes were lack of full right turn control, large sites (many lanes and conflict points) and lack of signal visibility.

Table 5.1: Summary of factors associated with occurrence of opposing-turning severe crashes at signalised intersections

International literature (mostly based on casualty crashes)	Severe crash site analysis (probit model factors shown to increase probability of crashes being severe)*	In-depth crash analysis (observed site factors present in severe crashes)**
Lack of right-turn control	All-filter right-turns at the site, when compared to control group of all-FCRTs + mixed right turn controls.	PCRT or filter right turn
Lack of signal visibility	No mast arms on major road (strong effect) or on minor road (small effect)	–
Large sites, wide approaches	–	Multilane approaches, many lanes to filter across
Red-light running – strong reduction when speed/red light cameras are introduced	–	Red-light running where FCRT was already present

** Based on Melbourne and Brisbane data.*

*** Based on Melbourne data.*

Other notable factors included high major road and right turn volumes – these factors would drive the frequency of crashes rather than their severity.

The probit model noted that typical geometry sites (approaches at approximately 90 degrees) had a 10% increased probability of having a severe crash than irregular-geometry sites. This may be an indicator confirming the role of impact angles in crashes.

In-depth crash analysis identified that 60 km/h speed zones were over-represented in the sample. This is likely an association with the PCRT/filter issue, which tends to be more prevalent at lower speed sites.

There were no literature findings related to speed or speed limits for this crash type, although Austroads (2013a) shows a mild increase in the proportion of severe crashes with higher speed limit. The probit model also identified a 5% increase in the probability of a site being ‘severe’ for each 10 km/h increase in speed limit (not statistically significant). It is important to note, that speed limit cannot be equated to impact speed, especially at traffic signals where driver behaviour and red light compliance are likely to be closely related to impact speeds.

5.2.2 Adjacent Direction Crashes

Austroads (2013a) showed that 21% of severe crashes at signalised intersections were of this type (Victorian data). They were also, on average, more severe than opposing-turning crashes.

There was a significant amount of casualty crash factor literature, as reported in Appendix A.2. This provides some indication of the factors which may also be relevant for severe crashes of this type. The probit statistical model based on Melbourne and Brisbane data identified factors associated with an increased probability of severe crashes occurring at a given site. Further, in-depth analysis of 20 randomly-selected severe crashes from Melbourne provided additional insight into the site factors present in these crashes. The findings have been summarised in Table 5.2.

There was little uniformity in the results from these different sources. One thread which emerged is dominance of large multilane sites and red-light running. Large sites provide many potential conflict points. Large sites were also indirectly implicated either through high exposure (traffic flow) and higher speed limits (severity of impact).

Adjacent direction severe crashes at signalised intersections occur when one of the vehicles runs the red light and hits another vehicle. In-depth analysis of a random sample of these crashes showed that in 70% of cases the red-light running vehicle came from the major road. A slight majority of the impacts occurred on the nearside (driver, more severe), others occurred on the farside (passenger, statistically less severe). This is possibly one of the reasons why the average severity for adjacent direction crashes was a little higher than for opposing-turning crashes in Figure 5.1. Typically, severe adjacent direction crashes occur on high-speed urban roads. Secondary impacts were common.

Table 5.2: Summary of factors associated with occurrence of adjacent direction severe crashes at signalised intersections

Literature (mostly based on casualty crashes)	Severe crash site analysis (probit model factors shown to increase probability of crashes being severe)	In-depth crash analysis (observed site factors present in severe crashes)
High conflicting traffic movement volumes	Arterial-to-arterial intersection – indicates high volumes	–
Lack of right-turn control (strong result)	FCRT cf. PCRT and all-filter group (weak result)	–
Lack of signal visibility	–	–
Red-light running	–	Red-light running (100% of cases)
Large sites, wide approaches	Arterial to arterial intersection – may indicate larger sites	Large sites, major road approach, high speed limit

Again, the effect of impact speed (especially in the case of running the red light) and impact angle would be a key determinant of the severity of injuries. These parameters determine the delta-v and impact type, and thus, the crash severity.

5.2.3 Same Direction (Rear-end) Crashes

According to analysis in Austroads (2013a), severe same direction crashes at signalised intersections constituted 18% of all severe crashes at signalised intersections in Melbourne. The average severity of a casualty crash of this type was low, 21% being severe (cf. 48% for pedestrians). Average severity of these casualty crashes increased mildly in 70 km/h and 80 km/h speed limits (by about 5%). The high overall frequency of these events, however, resulted in a high number of severe outcomes.

In-depth analysis on a random sample of 28 such crashes from Victoria showed that 86% were simple rear-end collisions. The primary implied causal reason was drivers not reacting at all, or with delay, to presence of stationary/slowly moving vehicles due to a red signal ahead.

A high proportion of same direction severe crashes involved motorcyclists (32% in the sample vs typically 1.5% of urban AADT). Vulnerability of this road user makes them much more likely to sustain severe injuries.

Over half of same direction crashes occurred with a stationary vehicle, with a further third while the target vehicle was still moving but slowing down for a queue or red signal. Multivehicle crashes were common (39%) and typically involved colliding with the end of a queue. The PM peak and late evening were the over-represented times of day, suggesting congestion and fatigue as important human factors in these crashes.

Table 5.3 provides a summary of findings detailed in Appendix A.3. There were no identified sites which clustered severe same direction crashes. Thus, severe crash site analysis with a probit model could not be carried out.

Table 5.3: Summary of factors associated with occurrence of same direction severe crashes at signalised intersections

Literature (mostly based on casualty crashes)	Severe crash site analysis (probit model factors shown to increase probability of crashes being severe)	In-depth crash analysis (observed site factors present in severe crashes)
High approach traffic volume	Not carried out	Large, multilane sites – possible link
Improved control of turns		–
Lack of signal visibility		–
Presence of red-light cameras		–
Large intersection size		Large, multilane sites
High speed/speed limits		High speed limit sites
–		Presence of another traffic signal site nearby (50–200 m)

The most prominent common factors are high speeds/limits and large sites (many conflict points).

5.2.4 Pedestrian Crashes

Collisions with pedestrians made up 18% of all severe crashes at signalised intersections based on the Victorian sample used in Austroads (2013a). This crash type was the most severe of all – 48% of recorded casualty crashes resulted in a severe outcome. Pedestrians were almost exclusively the severely injured party. There was also a strong observed response to speed limit, with the proportion 'severe' being 47% at 60 km/h and 58% at 70 and 80 km/h. The vast majority of severe pedestrian crashes occurred at speed limits of 60 km/h or less (50% at 60 km/h) – this suggests the these crashes occur at intersections of lower and middle order roads, or in the inner city, especially implicating arterials running through shopping strips and neighbourhoods. A specific conflict involving right-turning vehicles was also identified.

In-depth analysis of a sample of 16 randomly chosen pedestrian severe crashes at signalised intersections showed two equal sub-groups: vehicles coming from an adjacent direction, and right-turning vehicles. The adjacent direction crash sub-group was mainly caused by pedestrians walking against the red pedestrian signal. These crashes all occurred at 50 or 60 km/h sites. There was no over-representation of night-time crashes.

The second sub-group involved a pedestrian being struck by a right-turning vehicle. In all cases the pedestrians were positioned in clear view of the turning vehicle while it was giving way to an oncoming vehicle (partially controlled or filter turns). This situation involves a complex decision making process involving the driver having to look at the traffic signal, the approaching traffic and the pedestrians crossing to the right. This simultaneous combination significantly increases the chance of driver error and a crash event. Higher speed limits were dominant for this sub-group (60 or 70 km/h). There was some over-representation of night-time crashes in this group, although sample size was too small to tell if this was due to chance or not.

Presence of these sub-groups is a possible reason for the numerous and sometimes inconsistent factors identified from literature, severe crash site analysis and in-depth data.

Table 5.4 summarises the literature, statistical modelling and in-depth crash analysis of pedestrian severe crash factors at signalised intersections. The factors common across the three areas of investigations were: pedestrian activity areas (shopping), large sites, lack of full right turn control, and high speeds/speed limits.

Table 5.4: Summary of factors associated with occurrence of pedestrian severe crashes at signalised intersections

Literature (mostly based on casualty crashes)	Severe crash site analysis (probit model factors shown to increase probability of crashes being severe)	In-depth crash analysis (observed site factors present in severe crashes)
Non-residential land use	High pedestrian activity areas	Sites in shopping/commercial areas
High pedestrian and traffic volumes	High pedestrian activity areas	Sites in shopping/commercial areas
Large sites	Road hierarchy: arterial with local	Large sites, long waiting time
Lack of staged crossing	Staged crossing	Majority had staged crossings
Lack of right turn control	All-filter right turns	Partially-controlled or filter turns on vehicle approach
High speeds	Speed limits > 60 km/h (weak)	Higher speed limits, especially in combination with lacking right control.
	Lack of mast arms on the major road	

The issue of pedestrians walking onto the road against the red may require strong Safe System solutions such as full separation. On the other hand, the findings suggest a clear link between high speeds, large sites and lack of right turn control. Solutions addressing the right turn problem have the potential to address up to half of the pedestrian severe crash problem.

Analysis did show the strong effect of speed on severe crashes. Figure 4.4 indicates that very low speeds are needed to minimise the risk of severe injury for pedestrians (20 km/h or less). Any lowering of potential impact speeds would be supportive of reducing the severe injury risk for pedestrians.

5.3 Suggested Solutions

Previous sections presented findings on different factors which affect occurrence of severe crashes at signalised intersections. These factors, further literature reviews in Appendix D and expert workshop inputs informed areas of selection, operation and management which could be improved to bring safety performance of signalised intersections closer to the Safe System objectives.

These suggested solutions are outlined in the following sections. Each section shows how the solution could address the identified risk factors; it then provides broad guidance on application, design, operation and long-term sustainability of the solutions.

Each section ends with a statement summarising the overall alignment of the solution with the objectives of Safe System, i.e. minimisation of fatal and serious injury. These statements identify each solution's ability to minimise severity and likelihood (and in some cases exposure) of the targeted severe crashes, but where possible also consider other relevant crash types. These statements are not to be confused with estimates of crash reduction factors (CRFs) which account for any changes in exposure due to treatment[10].

5.3.1 Low-speed Signalised Roundabout

This solution is suggested for arterial and local roads where lower speed limits and expected travel speeds permit significant entry and circulation speed reductions. Typically these could be considered in urban environments.

The County Surveyors' Society (1997) study noted that signalisation of existing roundabouts had the effect of an 11% reduction in crashes, and a 44% reduction in crash severity for full-time operation. No studies were identified which evaluated a change between a conventional signalised intersection to a signalised roundabout. Appendix D.1.3 provides more details on the identified literature related to signalising roundabouts. Figure 5.3, Figure 5.4 and Figure 5.5 show three existing designs of signalised roundabouts.

Full-time signalised roundabouts used in lieu of conventional signalised intersection design offer a significant potential for reduced crash severity. Approach speed and collision angle should provide the key benefits. As noted in Section 4.2 the critical impact speed range varies from 30 to 60 km/h depending on the entry angle and circulating speed. For most designs with an approximately 70 degree entry angle, the design achieving entry and circulating speeds in the 30–40 km/h range would minimise severe injury risk for four-wheel vehicle occupants of equal mass (passenger and commercial vehicles). The impact speeds would be close to the adopted critical threshold values for adjacent direction, opposing-turning, and well below for rear-end crashes. The severe injury probability for pedestrians and other vulnerable road users would be greatly reduced as well, although not minimised (critical impact speed of 20 km/h). Notably, consequences of the main cause of signalised intersection severe crashes – running the red light – would be substantially reduced. The likelihood of pedestrian and cyclist crashes could be further reduced by use of signalised crossings and cycle lanes/storage boxes.

The opportunity for a crash to occur should be also diminished, as roundabouts have less conflict points than comparably-sized signalised intersections (opposing-turning and adjacent direction are combined). Signalised roundabouts have an additional advantage over typical roundabouts: the priority decision is simplified from gap acceptance to obeying the red signal. This should further reduce the likelihood of a crash occurring, especially at larger multilane sites.

It can be assumed that full control of right turns would be required at all sites to manage the overlapping right turns. This means that a significant proportion of the turning-opposing and pedestrian crash problem caused by filtering right turners would be also addressed. Other risk factors identified in Section 5.2 may still be present in this design form, but with greatly reduced impact.

Very large sites could be accommodated using the above design assumptions; hence, Section 5.3.2 uses a different set of assumptions to consider the same type of solution.

Roundabout literature in Appendix E.1.1 and analysis in Appendix B.2 suggest that strong horizontal deflection on approaches to roundabouts increases probability of severe off-road crashes (compared with weak deflection). This finding may or may not be applicable to signalised roundabouts, due to a different priority control mechanism. Either way, design would need to consider this possibility by providing both adequate and gradual deceleration prior to entry (good roundabout design practice). Section 6.3.1 lists methods used at roundabouts.

[10] CRFs alone do not extend our understanding of how the treatment contributes to the Safe System. In some cases, they simply remove or redirect exposure to remaining risk (e.g. ban right turn) without addressing the root cause of severe injury. Also, most are based on casualty crash data and could provide a false indication of Safe System alignment.

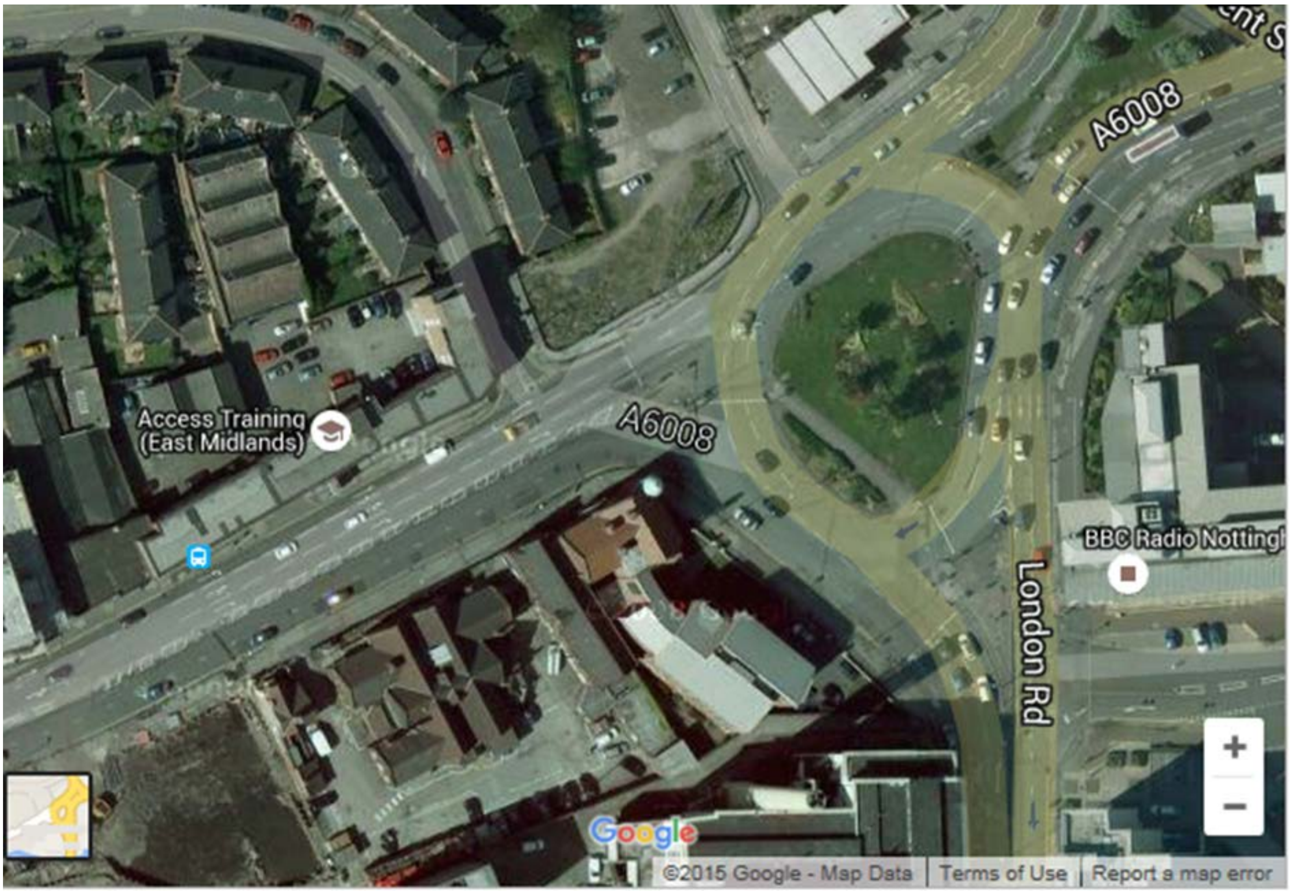
A separate investigation of the optimal design practice is required to guide optimisation of safety, design and operation at signalised roundabouts. This could involve collection of case studies from Australia, New Zealand and overseas, and analysis of their performance. Such a process would inform development of Australasian practitioner guidance.

There was a wide agreement among jurisdictional experts that this solution would be more attractive as a retrofit at sites with existing roundabouts, than as a signalisation solution for existing priority-control or signal sites. Nevertheless, the purpose of the solution in this case is to provide an alternative to a conventional signalised intersection in order to harness the safety gains of the roundabout form. Further discussion of this point is provided in Section 5.3.11.

Table 5.5 collates expert inputs on other aspects of signalised roundabout design, operation and management. These inputs provide broad guidance which could be considered in future Austroads guides. Overall, it was agreed that given the adopted assumptions (30–40 km/h entry speeds), this solution could achieve a high level of Safe System alignment for vehicles and moderate for vulnerable road users. This moderate alignment score was dictated by speeds exceeding the critical 20 km/h impact speed, but moderated somewhat by the improved level of movement management.

It may be that many sites will not be able to provide strong horizontal deflection due to site restrictions (i.e. entry speeds > 40 km/h). While the impact speeds would be compromised, the shallower collision angles would still provide crash severity reduction.

Figure 5.3: Multilane signalised roundabout examples from UK



Source: Google Maps 2015, 'Nottingham, UK' map data, Google, California, USA.

Figure 5.4: Multilane signalised roundabout example from Australia

Source: Google Maps 2015, 'Carlton, Victoria' map data, Google, California, USA.

Figure 5.5: Conversion of regular roundabout to fully signalised design in New Zealand

Source: Turner and Brown (2013).

Table 5.5: Assessment of low-speed signalised roundabouts (cf. conventional signalised intersection)

Assumptions:	Approach/entry speeds in the 30–40 km/h range, full-time signals operation, single or multi-lane design.
Safe System alignment:	High for vehicle occupants, moderate for vulnerable road users.

Applicability and design

- Selection ahead of conventional signalised intersection is likely to be driven by maximising safety, rather than capacity.
- May be more applicable to lower-order, lower-speed arterials (e.g. 50 or 60 km/h).
- May be generally more suitable for larger sites, which can accommodate right turn storage within a large centre island. Case-by-case assessment is needed for smaller sites.
- Potentially more difficult to apply as a retrofit solution at existing signals due to higher risk of service relocations and land acquisition. More likely to be higher cost at brownfield sites.
- May not be suitable for sites with high right turn volumes – subject to modelling (e.g. aaSIDRA, VISSIM, LinSig).
- Provision of roundabout bypass lanes would greatly improve operational efficiency, especially where heavy left turns are present (or for the through movement at the T-intersection).
- Careful management of approach speeds is needed to reduce the risk of off-road crashes. This could involve approach geometry (medians, line marking) or arterial speed management (kerb build-outs, pedestrian refuges, perceptual treatments).
- Visibility of signal displays needs to be considered in detail; also advanced lane management may be needed at some sites to reduce lane changes close to horizontal deflections (reduce risk of off-road crashes).
- Initially, drivers may require higher level of warning and advice so they do not mistake the treatment for a conventional roundabout.
- Irregular shape of the central circulation path should be avoided as motorcyclists have stability problems when faced with rapid change of direction.
- Efficient drainage (outward) vs superelevation (inward) – limitations may lead to water ponding esp. with pavement rutting.
- Stronger horizontal deflection may conflict with the need for wider swept path to accommodate trucks. May need to rely on central island aprons.
- Higher entry speeds could be considered as a design compromise (lower construction costs), still providing a significant safety gain due to lower impact speeds and angles.

Transport operations

- Comparative modelling of this solution vs conventional signals may be needed to fully understand efficiency trade-offs (capacity, degree of saturation, queueing, right turns).
- Will require full control of all right turns. Filter turns could lead to driver error of assuming roundabout operation (i.e. priority for the turning vehicle).
- Design limitations (e.g. storage) may lead to queueing restricting efficiency of some approaches.
- Tight turning circle is likely to slightly affect maximum lane capacity.
- Pedestrian access probably no different than for typical signals, although phasing arrangements may differ (e.g. left-turn-pedestrian conflict may be considered unsafe at some sites due to higher turning speed).
- May need shorter signal cycles to reduce right-turn queue lengths in the centre island where storage is likely to be limited.
- Increased inter-green/clearance time could lead to minor loss in efficiency at larger sites. Longer clearance times may be necessary where cyclists are present.

Sustainability

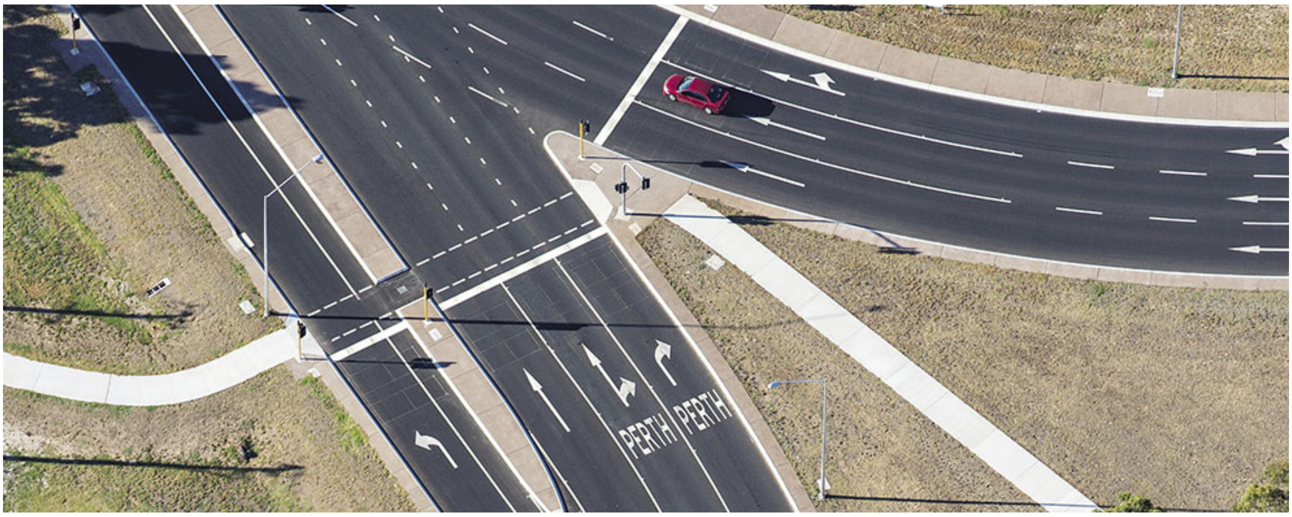
- Added wear to road surface in the circulating lanes may lead to quicker rutting.
- Consideration of life span and capacity during modelling; will further upgrades be required soon?

5.3.2 High-speed Signalised Roundabout

This is a sub-type of the previous solution which could be more applicable to high-speed arterials, typically found in outer metropolitan areas. An assumption is that approach speeds and circulation speeds would be higher than for the similar solution in the previous section. The mechanism of safety improvement towards the Safe System objective remains the same: reduction in impact speeds and angles, supported by a reduction in the number of conflict points.

The large format offers further opportunity to reduce impact angles as shown in Figure 5.6. It means that the critical impact speeds for adjacent direction crashes may increase towards 60 km/h at 30 degrees (essentially a merge crash). It could be assumed that entry speeds for this design would be around 50 km/h and no greater than 60 km/h.

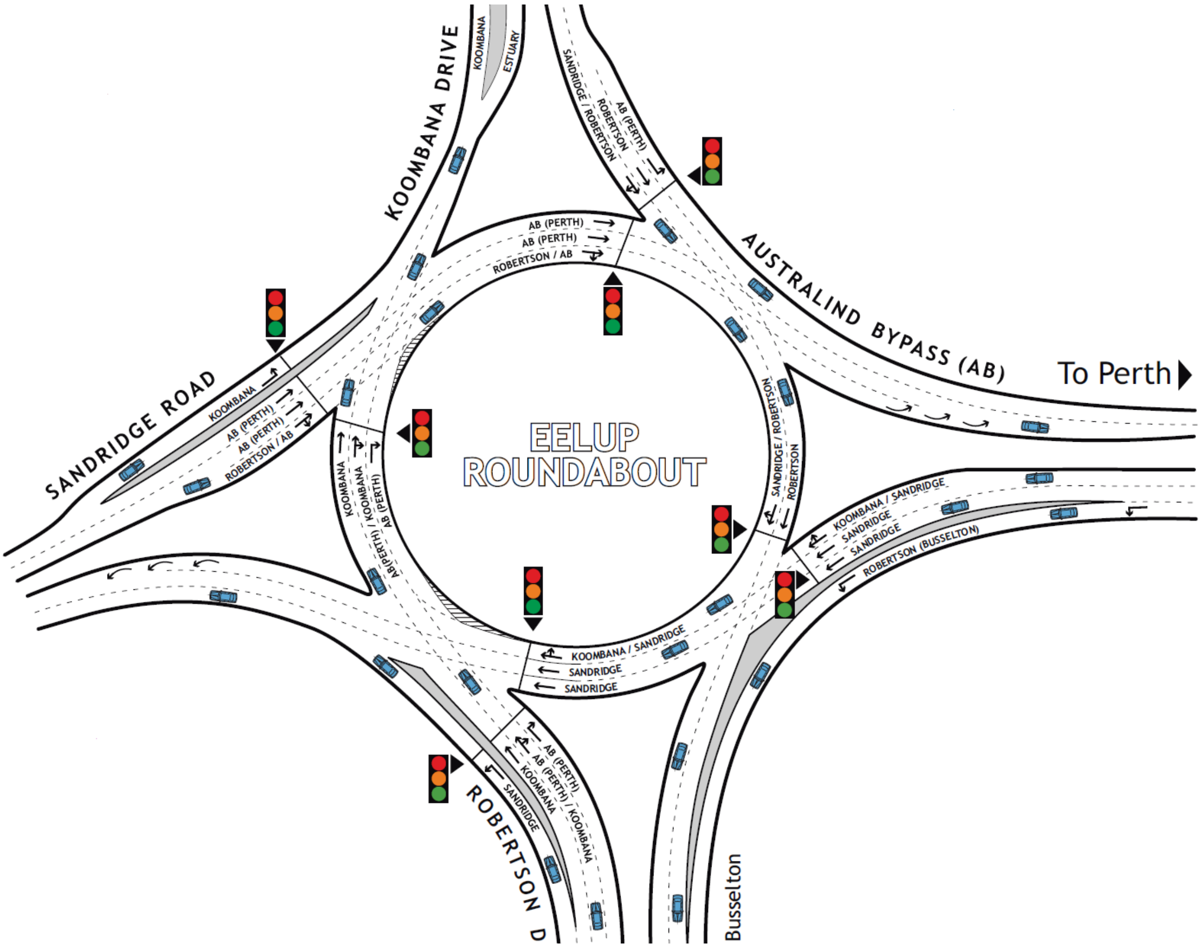
Figure 5.6: High-speed signalised roundabout entry with reduced conflict angles



Source: Main Roads Western Australia (2012).

Most other factors identified in Section 5.2 may still be present in this design form, although to a lesser extent, e.g. the number of conflict points at large sites is reduced. As shown in Figure 5.7, right turns would have to be fully controlled and could accommodate larger turning volumes thanks to storage. The larger format also makes it easier to communicate signal messages to drivers more clearly – the staging of movements is more defined than in the low-speed signalised roundabout. Consequences of red light running would be less severe due to lower entry and circulating speeds than at conventional intersections, but higher than at the low-speed signalised roundabouts.

Figure 5.7: High-speed signalised roundabout – schematic signals and line marking layout



Source: Main Roads Western Australia (2012).

Pedestrian movements can be conveniently staged or even offset from the main circulating carriageway, e.g. by providing walkways within medians of the approaches. Innovative designs could evaluate benefits of pedestrian walkways through the central island. Cyclists would be best removed from the carriageways by provision of bypasses. Overall, this solution could achieve a high level of Safe System alignment for vehicles but low for vulnerable road users, mainly due to high approach speeds.

Table 5.6 summarises expert inputs on guidance for application of this solution.

Table 5.6: Assessment of high-speed signalised roundabouts (cf. typical high-speed signalised design)

Assumptions:	Approach speeds in the 50–60 km/h range, full-time operation, multi-lane.
Safe System alignment:	High for vehicle occupants, low for vulnerable road users.
Applicability and design	
• Applicable mostly on outer urban arterials, 70–100 km/h speed limit. • Needs large road reserve, e.g. future interchange site, or at an existing roundabout. • Can utilise conventional large roundabout design. • High cost due to extensive road works ($2m–$3m) unless signalising an existing roundabout. • Can be applied where roundabout would not be desirable due to uneven flows, or where increased traffic flows/congestion warrant conventional signals. • Consider for areas with few pedestrians. • Cyclists preferably moved around via a bypass. • Sightlines to signals may be an issue due to curved design and high approach speeds. May require advanced flashing lights. • Consider approach legibility, may need additional signs and markings, or lane management. • Consider reducing sight distance to other approaches to create more driver reliance on signal displays (an idea to address potential confusion as to the control type).	
Transport operations	
• Flow efficiency should be approaching that of an equivalent signalised intersection, and be higher than a conventional roundabout. • Advantageous for heavy vehicles due to better turning radii. • There may be increased inter-green/clearance time for vehicles. • A motorist is likely to have to stop at multiple points through the roundabout, e.g. to complete a right turn. Phasing could be designed so that right-turning drivers only need to stop once.	
Sustainability	
• May impact vegetation within the reserve. • Drainage changed due to significant road works. • Consideration of life span and capacity during modelling; will further upgrades be required soon?	

5.3.3 Horizontal Deflections on Approaches

This is a range of design solutions employing horizontal deflections to capitalise on some of the safety characteristics of a signalised roundabout. Figure 5.8 (cut-through), Figure 5.9 (squircle) and Figure 5.10 (tennis ball) show different forms of such designs. The first two examples are hypothetical designs not yet implemented. The last design was under construction at the time of publication. The main point of difference from a signalised roundabout is the conventional operation, i.e. right turns proceed through the centre of the intersection.

The deflections guide drivers to reduce their speeds and potential impact angles. This would reduce severity of adjacent direction, opposing-turning and rear-end crashes. It is not possible to generalise on achievable entry speeds from this design. These depend on individual design parameters, but previous concept development by Corben et al. (2010) suggested 50 km/h for cut-through and squircle, and 40 km/h for the tennis ball designs (personal communication Perth expert workshop, 29 May 2015). The impact angle reductions varied by design, and for individual conflict points within each. Generally, the impact angles in the designs provided were in the 70–90 degree range, i.e. less favourable than for roundabout-based designs.

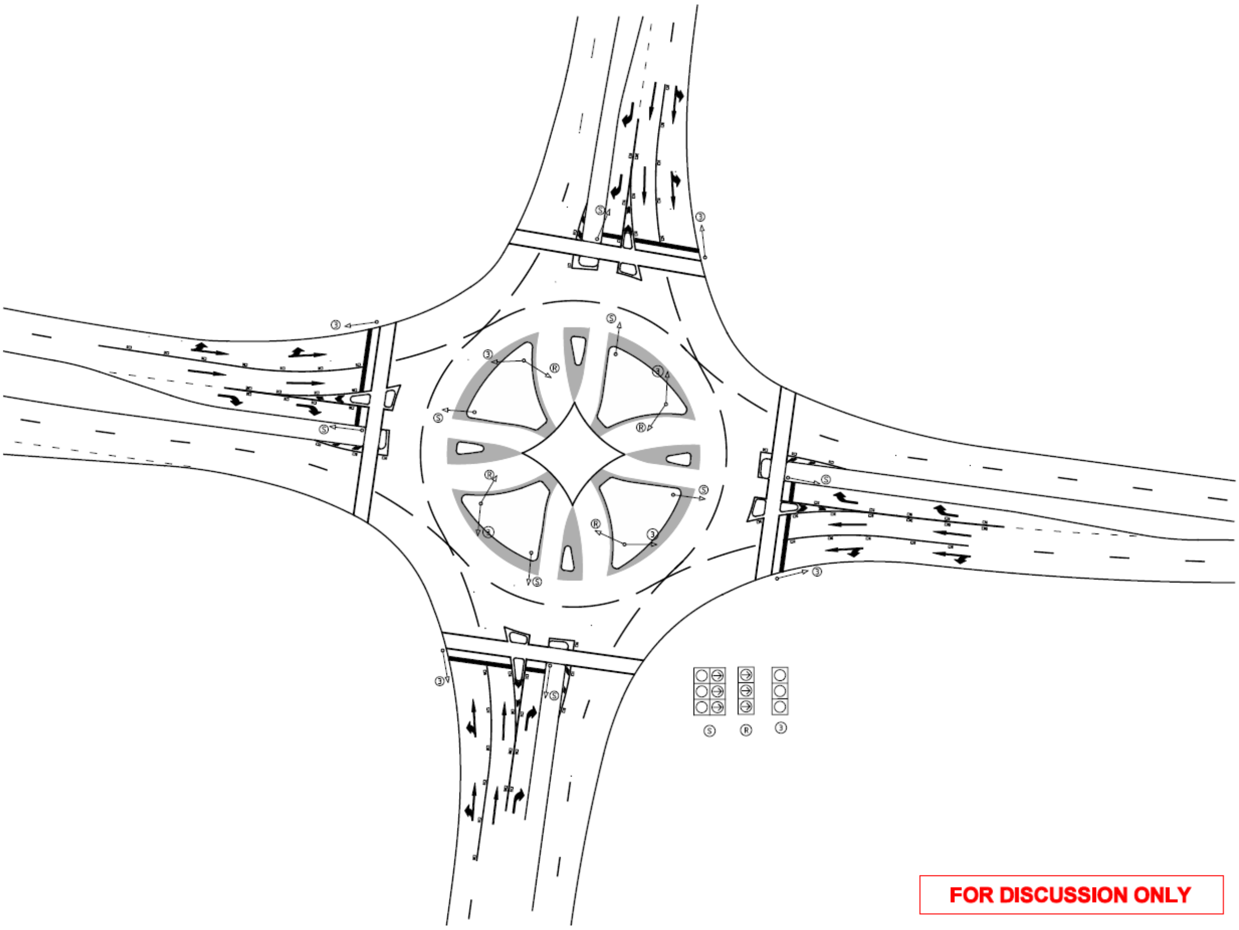
There is potential to reduce the probability of severe pedestrian injuries through lower speeds, but the effect is likely to be limited. Potential impact speeds are still likely to be well above the critical threshold of 20 km/h. Jurisdictional experts noted that left turn speeds may be higher at some cut-through designs than at conventional intersections due to larger corner radius. This could lead to the need to separate left turn and pedestrian movements (loss of efficiency). Cyclists could be retained within the intersection as per conventional arrangements (hold boxes, cycle lanes). Their safety gain would be minimal, as for pedestrians.

Other factors identified in Section 5.2 may still be present in this design form, e.g. a high number of conflict points at large sites, signal visibility, red light running, lack of right turn control. Their effect on severe crashes would be somewhat moderated by the lower impact speed and angles.

Jurisdictional experts considering this design suggested potential risks of off-path and side swipe crashes if the central traffic islands were not clearly lit and delineated, especially for motorcycle riders. This was noted with regard to the squircle design which has small islands and little approach deflection (Figure 5.9). Other suggested risks included driver confusion and non-compliance in the initial stages of operation (e.g. turning right as at a roundabout). Such potential issues could be explored through a driving simulator study.

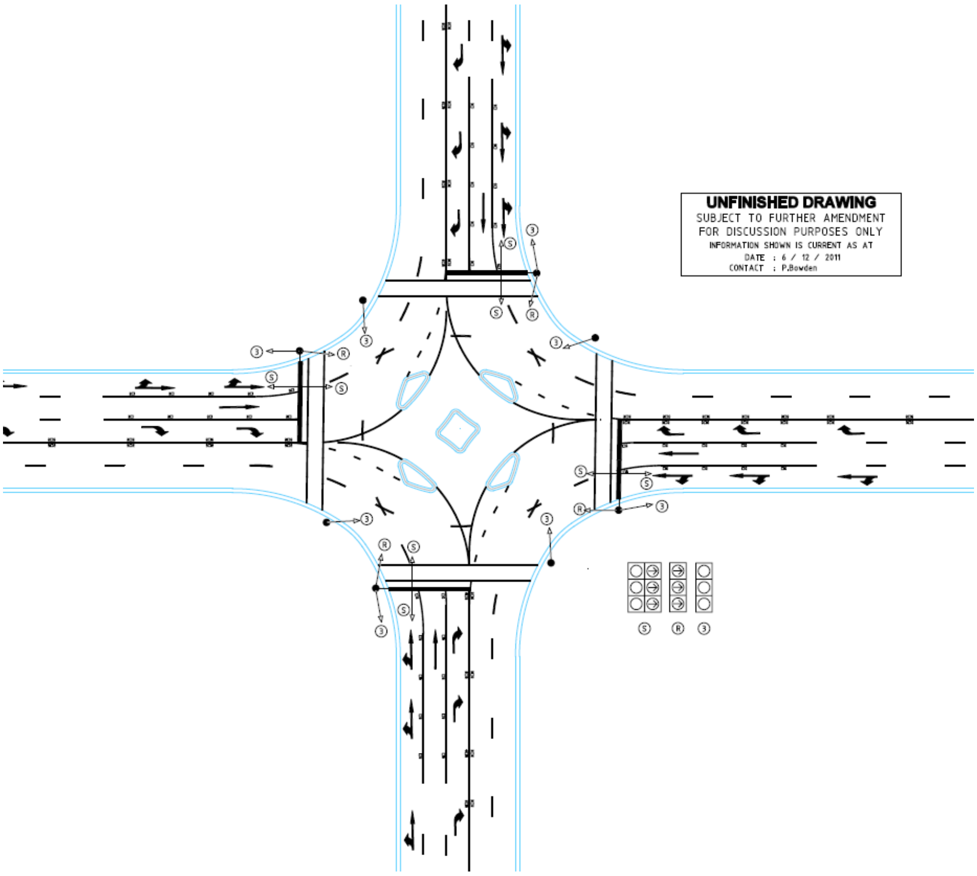
Overall, this design type presents an opportunity to achieve a moderate level of Safe System alignment for vehicle occupants, and low alignment for vulnerable road users.

Figure 5.8: A cut-through design



Source: Provided by VicRoads, based on Corben et al. (2010).

Figure 5.9: A squircle



Source: Provided by VicRoads, based on Corben et al. (2010).

Figure 5.10: Tennis ball design for signalised intersection (draft)

Source: Personal communication from Bruce Snook, Main Roads WA.

Table 5.7 presents the expert assessment and broad guidance on potential applicability, design, operational and maintenance issues to be considered with this proposed solution type.

Table 5.7: Assessment of signals with horizontal approach deflections (cf. conventional, no deflections)

Assumptions:	Approach speeds in the 40–50 km/h range, multi-lane.
Safe System alignment:	Moderate for vehicle occupants, low for vulnerable road users.
Applicability and design	
• Tennis ball design applicability to locations other than interchanges is yet to be tested. May evolve into signalised roundabout design at other sites. • Greater approach deflection on entry to the squircle could be considered to further reduce entry speeds. • Consider tighter corners to control left-turning speed. • Cut-through and squircle could be retrofitted at many sites with adequate road reserve. • Cut-through and squircle designs must accommodate heavy vehicle swept paths and all other required movements – likely to require intersection widening and service relocations, and possible land acquisitions. • Structural integrity of small traffic islands in the squircle needs to be considered. They are likely to be mounted by heavy vehicles.	
Transport operations	
• Capacity could be affected in a minor way by the design, e.g. by increase in inter-green/clearance time, and service rates, especially for tennis ball and cut-through designs. Detailed modelling should be carried out to confirm. • Cut through: no possibility of a safe or efficient U-turn.	
Sustainability	
• Accumulation of gravel/debris between central traffic islands may require increased frequency of sweeping.	

5.3.4 Vertical Deflections on Approaches

This solution seeks to achieve lower entry and potential impact speeds with vertical deflection. One key difference from the previously presented solutions is the lack of reduction in the angle of potential impacts. This results in the critical impact speed being only about 30 km/h.

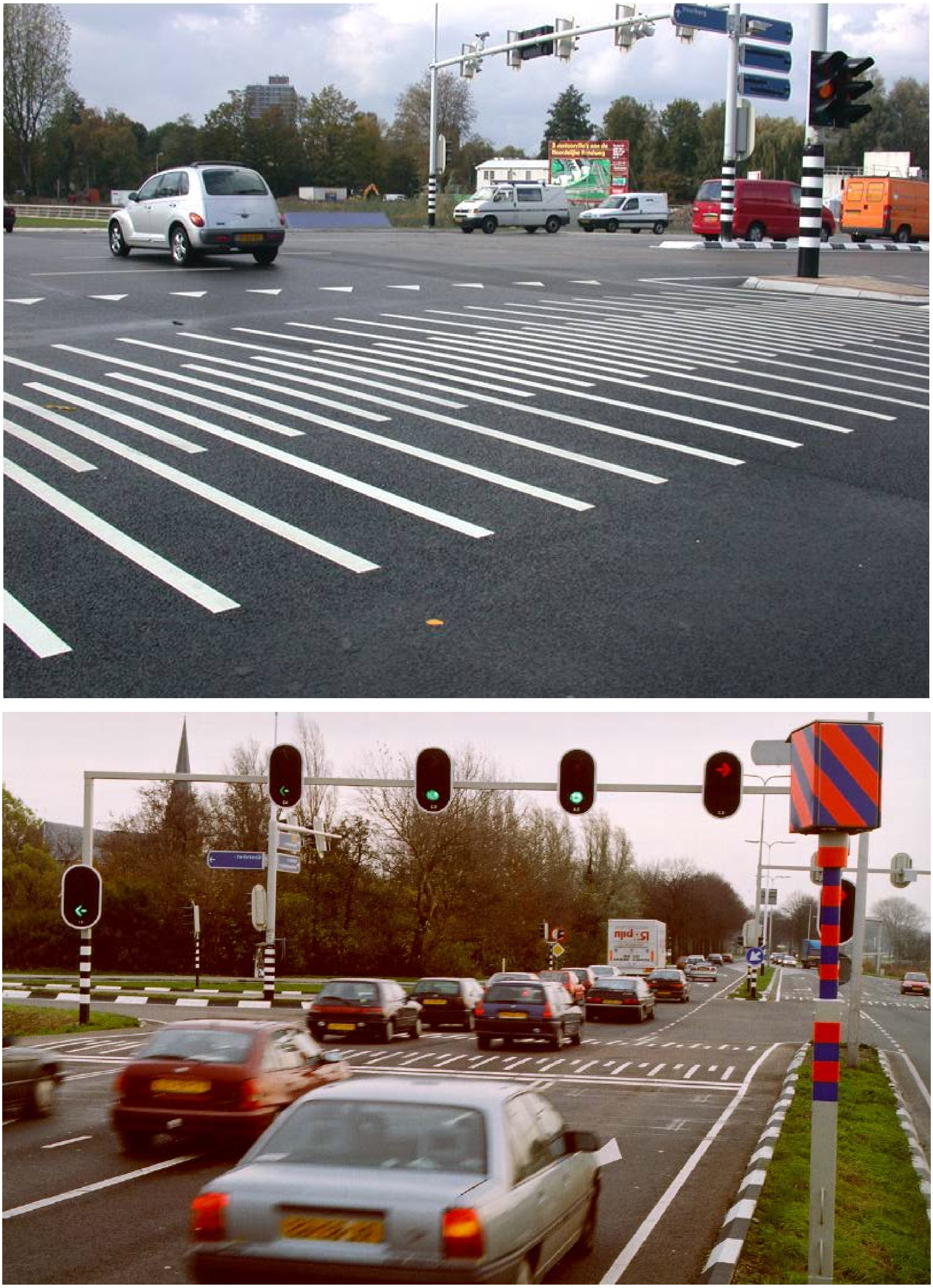
This solution encompasses various designs: raised stop bars (Figure 5.11), speed platforms (Figure 5.12), and raised intersections (Figure 5.13). The solution may have different design parameters, depending on location and road function, and could cater for very low entry speeds, e.g. in pedestrian areas. For high-speed arterial roads, the design needs to more sensitive to operation and comfort, and may not be able to provide low speeds (e.g. was designed for a 60 km/h traverse on a 70 km/h road with buses). This consideration is also important for safety of motorcyclists, who may lose concentration or balance under severe vertical acceleration.

The solution should have a positive effect on reducing severity of vehicle-to-vehicle crashes (adjacent direction, opposing-turning, rear-end) and off-path crashes. Depending on the circumstances of the site, speed reduction could be sufficiently large to produce substantial pedestrian safety improvement.

This design does not affect the number of conflict points, signal visibility or lack of right turn control. The effects of red light running would be moderated somewhat, depending on the speed reduction.

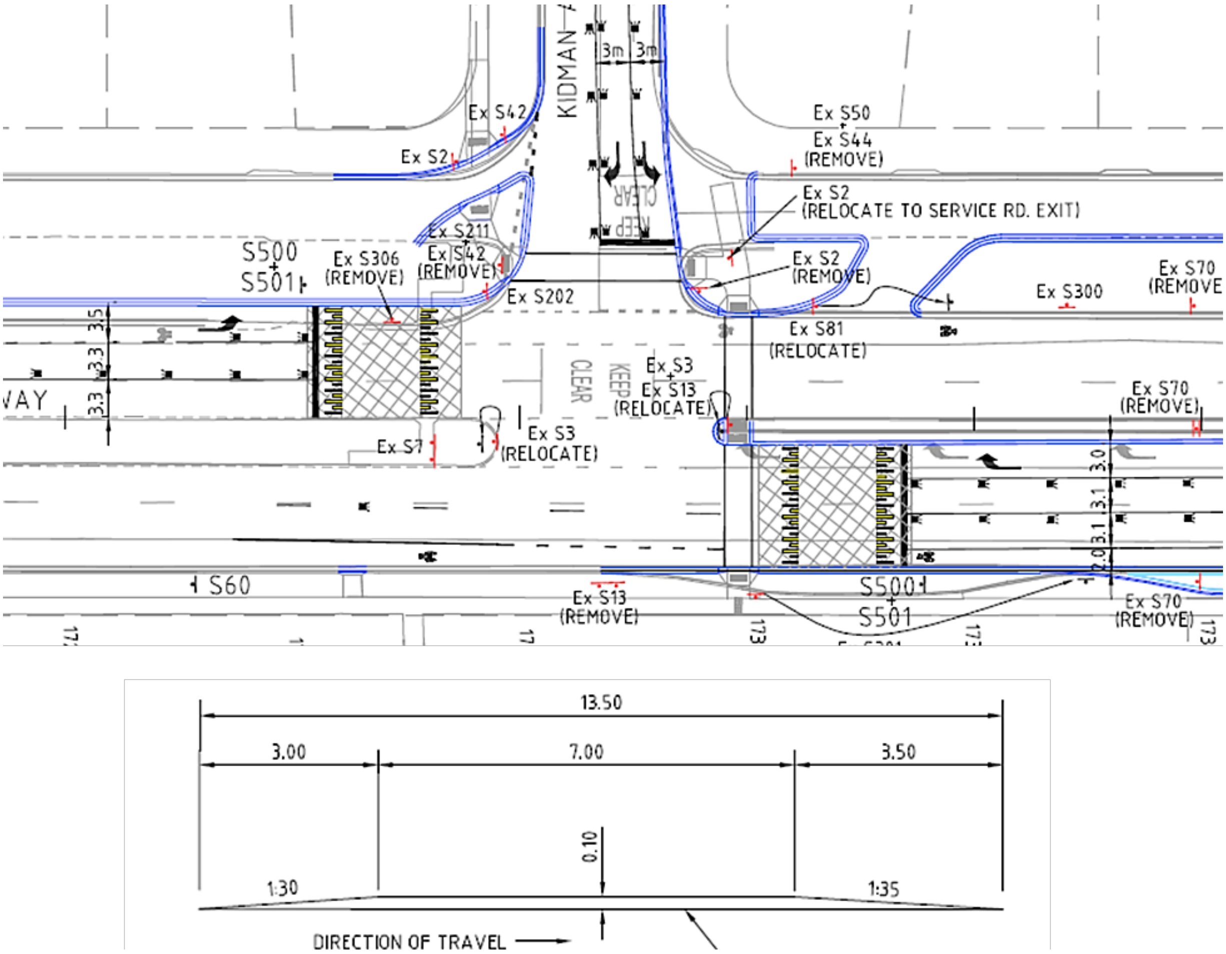
Overall, this design type presents an opportunity to achieve a low to high level of Safe System alignment for vehicle occupants and vulnerable road users, dependent on the entry speeds achieved (average or moderate). Table 5.8 summarises expert guidance and points of consideration in design and application of this solution.

Figure 5.11: Raised intersection stop line/bar solutions from the Netherlands



Source: Personal communication from John Matta, April 2015.

Figure 5.12: Proposed design at a signalised T-intersection in Victoria (50–60 km/h intersection entry speed)



Source: Personal communications from Richard Fanning, VicRoads, May 2015.

Figure 5.13: Raised signalised intersection, UK

Table 5.8: Assessment of vertical deflections on approaches (cf. conventional, no deflections)

Assumptions:	Approach speeds in the 40–60 km/h range, single or multi-lane.
Safe System alignment:	Averaged to moderate for vehicle occupants and vulnerable road users, but potentially ranging from low to high depending on the achievable entry speeds.
Applicability and design	
• Potentially applicable on all parts of the road network, depending on severity of design. • Low cost, no change in intersection footprint; useful for retrofitting. • Promising use on local and lower order arterial roads with lower speed limits, where site conditions restrict opportunity for horizontal deflections. • Reduction in speed could be achieved with use of additional milder humps/platforms some distance upstream of an intersection. This would increase effectiveness and reduce design impacts at the site. • May be evolved by application of alternative materials, e.g. rubber, brick, speed cushions (e.g. on bus routes). • Consider consequential drainage changes at the site. • Could be combined with pedestrian crossing points and lines. Avoid pedestrian confusion and crossing at platforms without a formal crossing (e.g. use footpath alignment and fencing, remove old crossing points). • Individual vertical ramps need to be well lit and delineated (not an ideal example in Figure 5.13). • Consider heavy vehicle dynamics, especially when cornering and for bus passenger comfort/safety. Also, consider motorcycle rider stability (refer to recent internal VicRoads investigation). • Design guidance needs to be developed to apply at a wide range of high speed sites, e.g. approach and departure slopes, and platform lengths given desired intersection entry speeds. Heavy vehicle, rider and bus issues to be covered.	
Transport operations	
• Slower clearance times could marginally increase inter-green time. • Needs advice/consultation with emergency services.	
Sustainability	
• Potential increase in operational maintenance costs (drainage/debris, line marking, low parts of vehicles gouging hump/platform). • Emissions would increase marginally due to introduced deceleration and acceleration.	

5.3.5 Grade Separation

Based on findings in Section 5.2, the most challenging scenario for Safe System is a large, high speed site located in proximity of significant pedestrian generators such as commercial and shopping centres, or public transport hubs. In such cases transformative works may be needed to safely manage high volumes of vehicular traffic and vulnerable road users. A localised solution requires consideration of grade-separated intersection for arterial roads (basic diamond interchange with signals).

It is worth considering the effect of a grade-separated intersection in the Safe System context. As seen in Figure 5.14, the main effect of a conventional interchange is removal of high-volume adjacent direction conflict points between the main and minor road traffic (separation). Road users on the minor road benefit from this as well, but there is little else in place to reduce likelihood and severity of crashes with other movements, e.g. right turners. The majority of other conflict points remain or are transferred elsewhere on the interchange. Same direction crashes would be largely removed for the major road, unless the exit ramp side swipes and rear-end crashes are counted. For the minor road, the number of these conflict points is typically doubled. Separation of pedestrian movements from traffic is also partial, but importantly applies to the high-volume major road movements. Pedestrians are still subject to exposure to all minor road and ramp terminal traffic.

Figure 5.14: Urban arterial interchange instead of traffic signals

Source: Public Transport Authority (2004).

In short, conventional grade separation reduces the number of conflict points with the highest exposure. The remaining conflict points (signals at entry ramps, pedestrians) do not benefit from similarly minimised crash likelihood and severity. Due to the significant overall capacity/efficiency benefits of grade separation, there is considerable opportunity to fully control vehicle and pedestrian movements. Perhaps this is why grade separation is a proven tool in road safety. Austroads (2012a) suggests a casualty crash reduction factor of 55%.

Overall, the Safe System level of alignment would be low to moderate at best for vehicle occupants and vulnerable road users. Interchange design could be supplemented by minor road treatments such as the tennis ball design in Section 5.3.3. Table 5.9 summarises points of guidance provided by jurisdictional experts on the concept of an arterial road interchange.

Table 5.9: Assessment of conventional grade separation (cf. conventional signalised intersection)

Assumptions:	Approach speeds in the range of 60–80 km/h, multi-lane.
Safe System alignment:	Low to moderate for vehicle occupants and vulnerable road users.
Applicability and design	
• Applicable to interchanges and large intersections only. • Poor legibility will require advanced lane management and signage.	
Transport operations	
• Studies and modelling have shown improvement in efficiency. • Minimal improvement due to less signal phases required.	
Sustainability	
–	

Grade separation without any access to the major road (no ramps) would have a high level of Safe System alignment.

Pedestrian and cyclist grade separation from vehicular traffic is also implemented through under- and over-passes. Such a solution can be viewed as fully aligned with the Safe System objectives for the targeted vulnerable road user groups.

5.3.6 Double Diamond Cross-over (DDC)

A set of alternative signalised intersection designs listed in Appendix D.2 propose ways of reducing the number of conflict points at a given signalised intersection location. They include displaced right turn, restricted crossing U-turn, jug-handle, quadrant roadway design, and the double diamond cross-over design shown in Figure 5.15.

The principal mechanism of safety improvement in Figure 5.15 is in removal of right turns. This is achieved by shifting main traffic movements to the opposite side of the road and executing right turns as left turns. Thus, there are no conflict points for right-turners vs the oncoming traffic. Some reduction in impact speeds may also be attained with the necessary approach deflections shown in Figure 5.15.

One important note is that this solution exposes all through movements to new conflict points not present in a conventional interchange design (through vs through at two locations). This new potential near-head-on collision would be, on average, slightly more severe than the opposing-turning collision it replaces[11], but are moderated by lower approach speeds due to deflections (degree of moderation depends on how much deflection). The change in crash likelihood due to the treatment was unknown at the time.

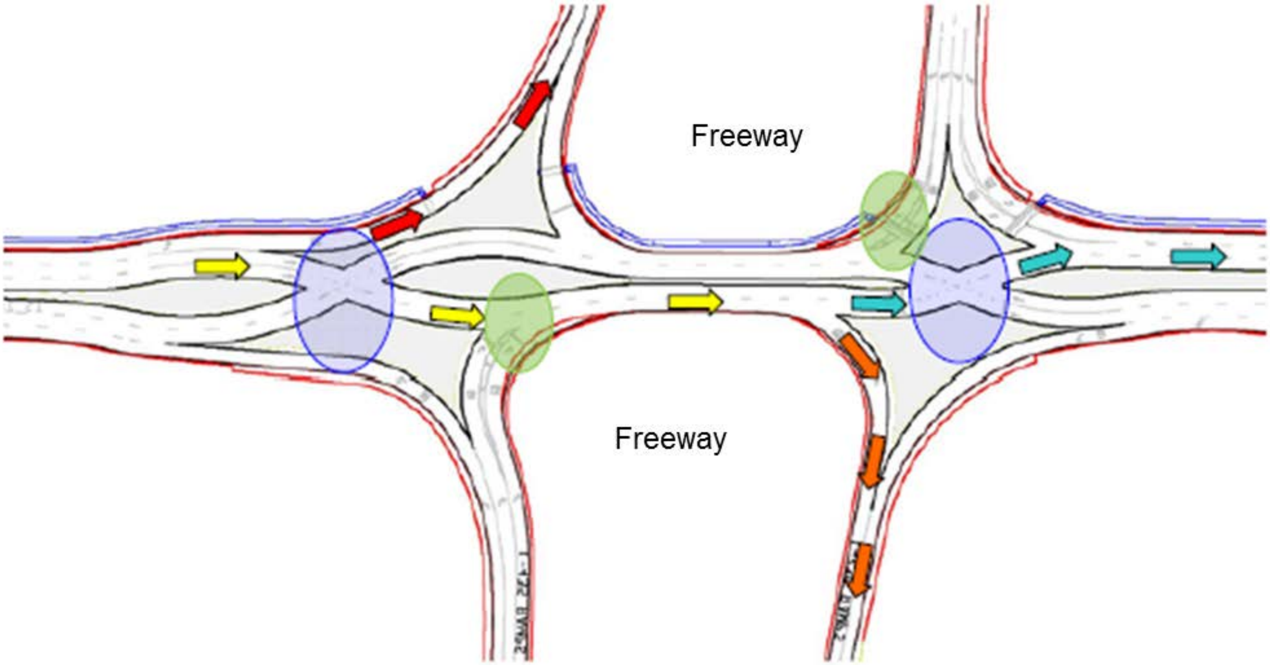
Sites where right turns match or outweigh through movements may benefit from this solution. The operational efficiency benefits would also be greatest at such locations. Chilukuri et al. (2011) showed a 72% minor injury crash reduction from an implementation at a site in Missouri, USA, which may address the crash likelihood concerns raised above.

Legibility and driver expectations need to be considered in detail, as the solution is unusual in Australasian practice. Lane management and advisory signs ahead of the interchange may be necessary. Consideration may be given to erecting visual screens between altered carriageways to reduce risk of driver confusion.

Overall, the Safe System alignment of this solution is between low (no approach deflections) to moderate (with strong deflections) for vehicle occupants and vulnerable road users. Its ability to reduce severe crash occurrence would be strongly dependent on the right proportion of traffic flows.

[11] Assuming an equal split between near-side and farside collisions at 45 degrees.

Figure 5.15: Double diamond cross-over interchange



Source: Federal Highway Administration (2010a).

Table 5.10 provides a brief expert guidance of different aspects of application of the double diamond cross-over interchange.

Table 5.10: Assessment of double diamond cross-over interchange (cf. conventional signalised intersection)

Assumptions:	Approach speeds in the range of 60–80 km/h, multi-lane.
Safe System alignment:	Low to moderate for vehicle occupants and vulnerable road users.
Applicability and design	
• Applicable to interchanges and large intersections only. • Poor legibility will require advanced lane management and signage.	
Transport operations	
• Studies and modelling have shown improvement in efficiency. • Legibility and design 'novelty' may be an issue. • May have significant reductions in delay due to less signal phases required.	
Sustainability	
–	

5.3.7 Red-light/Speed Cameras

Severe crash risk analysis summarised in Section 5.2 showed that red-light running was the most significant factor in severe adjacent direction crashes, and a major factor in pedestrian crashes. It was also the main factor in the severe opposing-turning crashes occurring at approaches with full right turn control (a small minority). Recent research reviewed in Appendix D.1.5 showed a 44% reduction in adjacent and opposing-turning severe crashes due to installation of a combined red light/speed camera (Budd, Scully & Newstead 2011).

In this light, installation of cameras alone provides a low level of Safe System alignment through reduced crash likelihood and severity (presumably slightly lower impact speeds). It is a likely strong Safe System supporting solution in combination with other supporting treatments such as mast arms, speed limit reductions and fully-controlled right turns.

5.3.8 Speed Limit Reductions

While speed limit reductions have been often shown to lead to significant reductions in crash likelihood and severity (Austroads 2013a, Elvik 2013), there has been little research done specific to signalised intersections (Austroads 2014b reviewed in Appendix D.1.8).

Lower approach speed would give drivers a greater margin of time to react to the surrounding road environment and actions of other road users. It would be reasonable to conclude that this would reduce occurrence of non-recoverable driver error leading to a crash.

Figure 4.4 shows that impact speed has a strong effect on severe injury probability in the event of a crash. It would be reasonable to assume that the Safe System objectives would be supported for all targeted crash types by reducing speeds of most vehicles entering a signalised intersection.

Effectiveness of speed limit reduction at signalised intersections is expected to be lower than for roads with uninterrupted traffic flow. This is mainly due to the proportion of time vehicles are stationary at traffic signals, or are travelling below the speed limit due to presence of other vehicles. Duration of heavily congested periods would also play a role in the level of effectiveness. For these reasons, a typical speed limit reduction of 10 km/h would have a low level of Safe System alignment for vehicle occupants and pedestrians.

Further research is needed to quantify the effect of speed limit reduction on safety performance of signalised intersections. This would determine the level to which this solution can support the Safe System objectives.

5.3.9 Improved Signal Visibility

One severe crash risk factor which appeared consistently in the analysis, summarised in Section 5.2 and detailed in Appendix A, was the lack of signal display visibility. The results suggest that provision of mast arms on all approaches would reduce the likelihood of most severe crash types. For high-speed or restricted visibility approaches, mast arms could be supplemented with flashing advance intersection warning signs.

Studies cited in Austroads (2012a) provide varying levels of crash reduction, typically under 40%, but there is a notable pattern of stronger reductions for adjacent direction and rear-end crashes, and for lower severity crashes. The logic of this pattern suggests that likelihood of a crash event reliant on the signal message is reduced, i.e. the road user error rates. This mechanism would have a flow-on effect of supporting reduced occurrence of severe crashes. The overall level of Safe System alignment for this treatment alone would be low for both vehicles and pedestrians.

5.3.10 Movement Control and Management

Controlling access to the road system is one way of improving safety without affecting mobility. Some signalised intersection movements could be prohibited if this is in line with the function of a given road. This would simply remove conflict points and minimise crash likelihood for selected crash types. In practice, this approach means relocating the movements to another convenient location, where they can be completed more safely. Often, public acceptance of such solutions needs to be sought. This may be elusive, limiting application of these solutions to major changes in the design of the road network (e.g. road duplication, major land use development). Some examples of this solution include:

- Banning right turns – preferably strengthened with road design changes preventing the movement. Past evaluations show a significant reduction in opposing-turning crashes in the post-period (60 to 90% cited in Austroads 2012a). Reductions in pedestrian crashes were also noted. There has been evidence of some crash migration due to increased exposure at nearby locations.

- Preventing pedestrians from crossing – it may be appropriate to prevent pedestrian crossings at particular high-speed intersections and channel pedestrians to safe crossing locations elsewhere with pedestrian fencing. This is often assisted by the landscape which makes the choice more publicly acceptable (e.g. differences in levels between road and surrounding land, presence of pedestrian overpasses or underpasses).
- Removing approaches and consolidating design – this may be possible when irregular or confusing signal designs are rationalised. It includes removal of access points or local street legs within a signalised intersection.

Overall, these solutions can provide a high level of Safe System alignment through removal of exposure to existing risk, although applicable only to selected movements.

A less severe approach involves increasing the level of movement management. One common example of this is installation of full right turn control on all approaches (Appendix D.3.1). There was a marked difference in frequency of severe crashes noted in Section 5.2. Reviewed literature suggests that up to 90% of opposing-turning casualty crashes can be prevented by retrofitting this solution (Austroads 2012a). This treatment has an effect of reducing the likelihood of pedestrian crashes during completion of a filter movement. Austroads (2012a) suggests a 35% casualty crash reduction for this user group.

Overall, this solution would have moderate to high level of Safe System alignment for right turners by substantially reducing the likelihood of road user error and collision. In this way, it can support other treatments.

5.3.11 Discussion and Summary

The previous sections considered areas of signalised intersection application and management which could be improved to bring this infrastructure element closer to the Safe System objective of zero severe crashes and injuries.

The most likely effective and innovative solutions consist of geometric design changes aiming to reduce crash severity through moderating both impact speeds and angles:

- low-speed signalised roundabouts (Section 5.3.1)
- high-speed signalised roundabouts (Section 5.3.2)
- horizontal deflections on approaches (Section 5.3.3)
- vertical deflections on approaches – where no changes to impact angles are intended (Section 5.3.4).

Broad guidance has been provided on selection of these solutions. Some appear to be limited in use to certain locations, as there are clear trade-offs in terms of footprint, cost and operational efficiency. These vary by solution and practitioners need to consider each carefully. Development of detailed guidance and case studies may resolve some of the raised concerns and extend application of these solutions.

Many of the other suggested solutions are changes in design and management of conventional signalised intersection form. When selected alone, these have a limited effect on improving Safe System performance, and are sometimes referred to as Safe System supporting solutions. They include:

- grade separation (Section 5.3.5)
- double diamond cross over (Section 5.3.6)
- red light/speed cameras (Section 5.3.7)
- speed limit reductions (Section 5.3.8)
- increasing visibility of signal displays (e.g. mast arms, Section 5.3.9)
- movement control and management (ban turns, close approaches, fully control right turns, Section 5.3.10).

However, these supporting solutions can be combined with conventional or innovative intersection forms to create synergistic designs supporting much higher levels of safety than currently expected. Drawing on Figure 3.2, careful selections can be made to address both severity and likelihood of crashes. Some examples include:

- signalised roundabout with full control of right turns, red light/speed cameras and mast arms on all approaches
- vertical deflections on approaches with full control of right turns, red light/speed cameras and mast arms on all approaches
- vertical deflections could be applied at signalised roundabouts to aid in approach speed reduction if horizontal geometry is not sufficient
- grade separation with tennis ball or signalised roundabouts for minor road, fully controlled right turns
- conventional signalised intersection with low speed limits and with vertical deflections on approaches.

Table 5.11 provides a summary of Safe System alignment of each of the suggested solutions (individually) according to their ability to address the key factors identified in Section 5.2. Combining these could further improve their performance towards the Safe System objective.

Table 5.11: Summary of Safe System alignment of each of the suggested solutions for signalised intersections

Proposed solution type	Vehicle occupants (30 km/h for adjacent direction and opposing-turning, 55 km/h for rear-end)	Pedestrians and other vulnerable road users (20 km/h)
Low-speed signalised roundabout (Section 5.3.1)	High	Moderate
High-speed signalised roundabout (Section 5.3.2)	High	Low
Horizontal deflections on approaches alignment: cut-through, squircle and tennis ball (Section 5.3.3)	Moderate	Low
Vertical deflections on approaches (level of alignment depends on entry speeds) (Section 5.3.4)	Moderate	Moderate
Grade separation (Section 5.3.5)	Low – moderate	Low – moderate
Double-diamond cross-over (Section 5.3.6)	Low – moderate	Low – moderate
Red-light/speed cameras (Section 5.3.7)	Low	Low
Speed limit reduction by 10 km/h (Section 5.3.8)	Low	Low
Improved signal visibility (Section 5.3.9)	Low	Low
Movement control and management (banning right turns) (Section 5.3.10)	High (selected movements)	High (selected movements)
Movement control and management (fully controlling right turns) (Section 5.3.10)	Moderate – high (selected movements)	Moderate – high (selected movements)

Further discussion is needed about application of signalised roundabouts in lieu of conventional signalised intersections. Most jurisdictional experts agreed that this solution would have lower ultimate capacity than a comparably-sized conventional site. There was a common view that the solution may be more viable as a retrofit to existing roundabouts before the ‘ultimate’ conventional signal design is introduced, and safety had to be compromised.

Further discussion and education may be needed to promote understanding of Safe System infrastructure solutions in the context of capacity and mobility impacts. Some key points for consideration include:

- What proportion of ultimate capacity, or what additional delay, are the system designers willing to compromise for significant improvement in safety? Why and when should this be a consideration?
- Is capacity always the ultimate consideration in intersection design? Capacity of many sites is determined by other factors, e.g. downstream bottlenecks, or public transport priority.
- Potential maximum capacity for an at-grade intersection may not be reached within a reasonable design horizon, or ever, due to low vehicle traffic growth, transport planning policies and other network-level constraints.
- In the context of smart roads, travel demand and Safe System policies, catering to maximise throughput may not always be the leading consideration in designing an intersection.
- An often-cited argument was increased delay in off-peak periods, e.g. at night, due to the geometric deflections. Given low traffic volumes at these times and over-representation in crash statistics, the net transport benefit would be through safety gains rather than individual driver time savings.
- Many local road signalised intersections are not designed for capacity, but to facilitate access to higher-order roads and to improve vulnerable road user safety. In such cases, many capacity-based arguments can be set aside.
- The large footprint argument may not be as relevant when full site development is considered at the design stage. If a given intersection site is to be progressively upgraded to a larger footprint over time (including future service relocations), then why not take up that footprint now with a roundabout form which can be further optimised in the future (e.g. more lanes, less horizontal deflection, but more vertical deflection).

Further analysis of these issues could be achieved through retrospective safety effectiveness evaluations of signalised roundabouts and micro-simulation modelling of capacity changes.

Some suggested solutions were noted to increase the risk of minor collisions, e.g. rear-end crashes, due to the need to slow down on approaches. This phenomenon of crash-type conversion is well documented in road safety. For instance, installation of traffic signals has been reported to increase property-damage rear-end and other crashes (e.g. AASHTO 2010, Pernia et al. 2004 and Persaud et al. 2003 in Austroads 2012a). While not critical in the Safe System context, an increase in overall incident numbers would increase delay through non-recurrent congestion. Detailed design techniques and practice refinements may need to be developed in trials to inform, warn and guide approaching motorists of the strong speed reductions ahead.

Some of the suggested solutions were yet to be trialled in practice by state road agencies. More demonstration projects are needed, together with national and cross-Tasman dissemination. It may be that detailed investigations of specific issues are needed for some solutions prior to trials. Such investigations could address specific design and constructability issues, perceptions, assess the level of public acceptance, check for road rules compliance and give more detailed consideration to maintenance.

6. Roundabouts

This section summarises the project findings relating to roundabouts, i.e.:

- how closely this infrastructure element aligns with the Safe System vision objectives (Section 6.1)
- what are the key infrastructure and operational factors found to contribute to occurrence of high severity crashes (Section 6.2)
- suggested solutions, i.e. areas of selection, application and management of roundabouts which could be improved to bring their safety performance closer to the Safe System objectives (Section 6.3).

6.1 Safety Performance of Roundabouts in the Safe System Context

From the Safe System perspective roundabouts act predominantly by reducing severity of impact: entry and circulating speeds are moderated by horizontal deflections and impact angles in adjacent direction crashes are lower than at other intersection forms (≤ 70 degrees). The expectation that entering drivers may have to stop to give way to vehicles within the roundabout may also contribute to lower speeds and increased driver alertness.

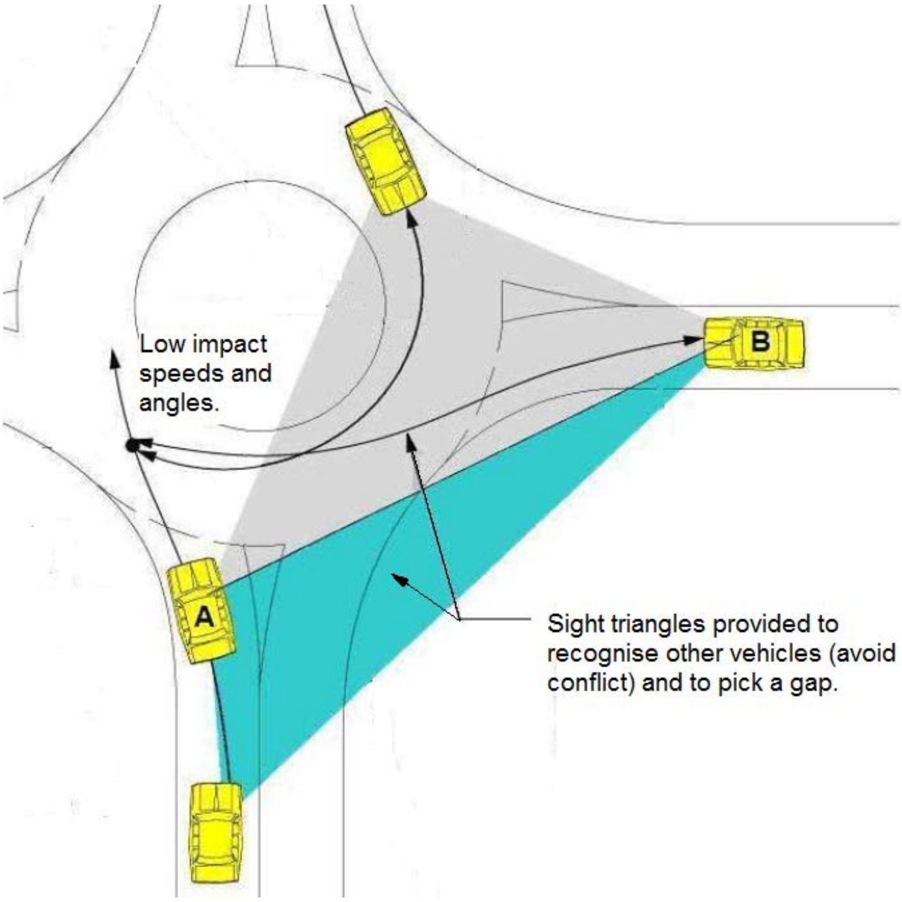
Roundabouts rely on gap acceptance to control traffic flow, a method prone to significant driver and rider error rates. This safety shortcoming is moderated by the limited area of the sight triangle from which approaching drivers take clues on potentially conflicting traffic (see Figure 6.1). When this variable is compromised, and sight triangles are large areas with multiple moving vehicles, then safety performance of roundabouts deteriorates. This is perhaps a contributing factor to large multilane roundabouts having lower levels of safety compared to small roundabouts.

Roundabouts have been previously identified as a Safe System infrastructure solution due to their known effectiveness in reducing severe crashes. Research reviewed in Austroads (2013a) showed the strong crash reduction potential of roundabouts when replacing priority intersections:

- 63–100% for fatal crashes
- 37–84% for severe crashes
- 45–87% for casualty crashes.

A further 60–78% casualty crash reduction was observed when converting from a signalised intersection to a roundabout. Roundabouts also provided strong reductions in pedestrian crashes (up to 90% compared with priority control) based on limited studies. Austroads (2013a) analysis of urban data from Melbourne showed that the severe crash rate per entering vehicle for a roundabout was half of that for a signalised intersection. This is important context for discussion of the remaining safety issues.

Figure 6.1: Key factors reducing severity and likelihood of crashes at roundabouts



Source: Based on Austroads (2011).

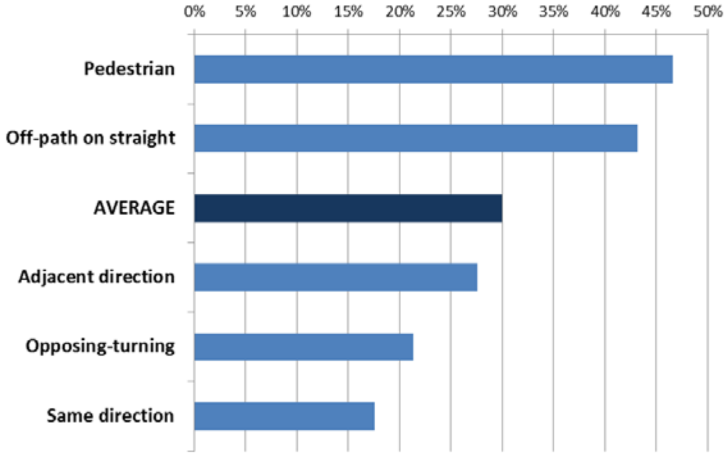
Figure 6.2, created from Victorian data used in Austroads (2013a), shows that on average 30% of recorded casualty crashes at urban roundabouts resulted in death or serious injuries. While this is somewhat comparable with urban signalised intersections (36%, Figure 5.1), the severe crash rate per entering vehicle at urban roundabouts was only half of that for urban signalised intersections.

Analysis of the same data set showed that adjacent direction and opposing turning casualty crashes at roundabouts were less severe than off-path crashes.

The analysis averaged the safety performance of all urban roundabouts. It is worth noting that design and use of local road single-lane roundabouts differs substantially from outer-metropolitan multi-lane roundabouts. It is therefore likely then, that the safety performance would differ for different types of roundabouts.

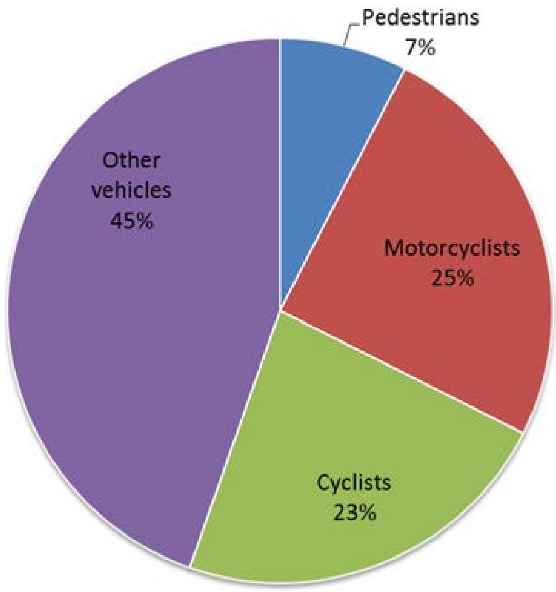
At this point it is important to note the over-representation of two-wheeler road users in severe crashes at roundabouts. It is potentially the key to understanding their Safe System performance. Figure 6.3 shows the Victorian example of urban roundabouts, where half of the severe crashes involved cyclists and motorcyclists.

Figure 6.2: Average severity of different types of casualty crashes at urban roundabouts (Victorian example)



Source: Austroads (2013a) based on Victorian data.

Figure 6.3: Proportion of severe crashes at urban roundabouts involving cyclists and motorcyclists (Victorian example)

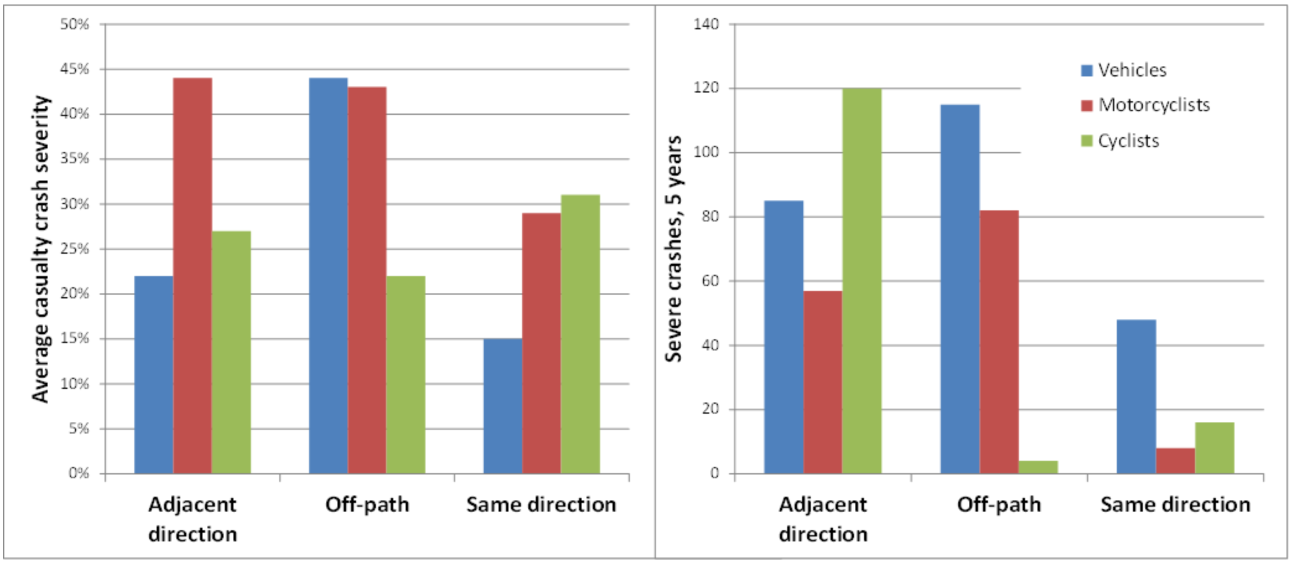


Source: Austroads (2013a) based on Victorian data.

Further analysis of this data set, shown in Figure 6.4, indicated that:

- Motorcyclist casualty crashes were almost twice as severe as vehicle or cyclist crashes (42% of casualty crashes being severe vs. 26 and 26% respectively), with off-path and adjacent direction crashes being the main issue in terms of numbers and severity.
- Cyclist crashes were of comparatively low severity, comparable with vehicles (26%), mainly due to their greater exposure to the low speed limit road network (local 50 and 60 km/h, Austroads 2013a); adjacent direction crashes were most numerous; same direction crashes were twice as severe as for vehicles (31 vs 15%), but not as numerous.
- Vehicle crashes were especially severe (44%) and numerous in off-path crashes.
- Pedestrian casualty crashes were by far the most severe (47%), but not numerous.

Figure 6.4: Average severity and size of the severe crash problem at urban roundabouts by mode (Victorian example)



Source: Austroads (2013a) based on Victorian crash data (2007–12).

The example data set suggests that vulnerable road users make up the majority of the severe crash problem at urban roundabouts, and represent the remaining Safe System gap for this infrastructure element. Motorcyclists (off-path, adjacent direction), cyclists (adjacent direction, same direction) and vehicles (off-path) are worthy areas of focus based on scale and severity of crashes. These will be explored in the next section.

6.2 Severe Crash Factors

Section 4 shows that impact speeds and angles (delta-v) are the two major factors contributing to the risk of severe injury. The following sections confirm these through other findings and identify a number of additional severe injury factors through literature review and data analysis. The details of the findings are documented in Appendix B.

Based on scale and severity of the crash problem discussed in the previous section, the prioritised severe crash types and scenarios at roundabouts were:

- adjacent direction (especially cyclists and then motorcyclists)
- off-path on straight (especially motorcyclists and vehicles)
- same direction (especially cyclists).

As explained in Section 5.2, the findings in the following sections need to be interpreted in the context of key limitations:

- The preliminary nature of the severe injury probability–impact speed relationships in Section 4.2.
- The casualty crash basis for majority of the identified research literature.
- The statistical probit modelling of severe crash probability factors was limited by available site data, resulting in many factors not being statistically significant (indicative only).
- The in-depth crash analysis relates only to severe crashes, and may be specific only to that level of crash severity.
- Data samples, information and examples drawn from one or two jurisdictions may not be representative of the situation in another (e.g. order of importance of factors, scope of the issue).

Overall, the findings need to be considered together by road safety experts and practitioners and discussed in the context of each suggested solution. This was achieved through discussions at a series of jurisdictional expert workshops to produce the findings reported in Section 6.3.

6.2.1 Adjacent Direction Crashes (Cyclists and Motorcyclists)

Austroads (2013a) noted that 83% of severe bicycle crashes and 36% of severe motorcyclist crashes at roundabouts were of this type (19 and 9% of all severe crashes at roundabouts respectively). Safety of these two road user types was noted as the dominant issue for progression towards the Safe System at roundabouts.

The key crash cause for both user groups, based on in-depth crash data analysis, was entering drivers not seeing/acknowledging the two-wheeler already within the roundabout. For motorcyclists, a significant minority were errors committed by the entering riders (40% run into cars already within the roundabout). For both user groups most impacts occurred in the entry area of the roundabout. There were no indications that the two-wheelers were obscured by or interfered with by other vehicles.

Table 6.1 provides a summary of the key factors associated with adjacent direction severe crashes for two-wheelers documented in Appendix B.1. The probit model analysis of site factors was based on crashes involving all vehicles as there were no identified sites which clustered two-wheeler crashes. Given, that half of severe roundabout crashes involve two-wheelers (Austroads 2013a), the identified factors should be broadly applicable to the target group as well.

Table 6.1: Summary of factors associated with occurrence of adjacent direction severe crashes at roundabouts (cyclists and motorcyclists)

Literature (mostly based on casualty crashes)	Severe crash site analysis (probit model factors shown to increase probability of crashes being severe)	In-depth crash analysis (observed site factors present in severe crashes)
High traffic flows, vehicle or two-wheeler, approach and circulating		Local roads mostly, 50/60 km/h speed limits
High approach and entering speeds: • large entry curve radius • high approach speed limits • multiple circulating lanes	High speed roundabout design via combination of: • small or large central island • multiple approach lanes • multiple circulating lanes	Indicators of high speed design: • poor approach deflection (cyclists and motorcyclists) • large diameter central island (cyclists) • small diameter central island (motorcyclists) • wide circulating lanes (motorcyclists) • multiple approach/circulating lanes (motorcyclists)
Lack of cyclist bypass facilities	Hidden roundabout – not conspicuous from approach	Odd/irregular roundabout designs, confusing layout (cyclists and motorcyclists)

Other notable factors included poor skid resistance and linemarking, and steep approach gradient. A significant minority of crashes occurred during the night.

The critical impact speed estimates based on Figure 4.4 are 30 km/h if the circulating speed was 40 km/h, or 40 km/h if the circulating speed was 30 km/h. For cyclists, the pedestrian value around 20 km/h is more appropriate as a severe injury threshold. It would be difficult to estimate Safe System critical speeds for motorcyclists, but biomechanical tolerance suggests a similar value.

Therefore, the current designs provide entry speeds which are too high for vulnerable road users. Proposed areas for improvement should seek ways to reliably reduce approach and entry speeds to less than 30 km/h to close the Safe System gap for all users.

6.2.2 Off-path Crashes (Motorcyclists and Vehicles)

Austroads (2013a) used the Victorian urban roundabout crash data sample to show that 'off-path on straight' crashes involving a motorcyclist made up 53% of all severe motorcyclist crashes at roundabouts (13% of all severe roundabout crashes). This was also the worst crash type for vehicles, making up 43% of all severe vehicle crashes (19% of all severe crashes). In that sample, 'off-path on curve' severe crashes constituted a very small proportion of the problem (several crashes in total), and so were not a subject of further investigation.

In-depth analysis of police report information from a random sample of motorcyclist off-path crashes indicated little evidence of streamlining (9%), i.e. crossing the roundabout in such a way as to minimise deflection e.g. crossing approach or circulating lanes). The analysis found the major causes of the crashes were near misses with other vehicles (21%), skidding in adverse pavement conditions (18%), and failing to react to presence of a roundabout (12%). Typically loss of control occurred well within the circulating lanes (58%), but a third occurred upon entry into the roundabout. There were no exit crashes in the sample.

Table 6.2 presents the summary of factors discovered through literature reviews, statistical modelling and in-depth crash data analysis presented in Appendix B.2. There was no published literature directly relevant to this crash type for motorcyclists, but some information was found for all-vehicle casualty crashes. Similarly, the probit model analysis of site factors was carried out using all-vehicle crashes. Only the in-depth crash data analysis was carried out specifically for severe off-path crashes involving motorcyclists. These issues may account for disparate results in Table 6.2.

It is worth noting, that a majority of riders in the study sample did not hit any objects, and where reported, injuries were due to hitting the pavement and kerbing. There were no reported cases of motorcyclists hitting objects within the central island. This suggests that current hazard management policies and practices need be maintained, i.e. avoiding placement of lighting poles in the central island or on departure.

Table 6.2: Summary of factors associated with occurrence of off-path severe crashes at roundabouts (motorcyclists)

Literature (mostly based on casualty crashes)	Severe crash site analysis (probit model factors shown to increase probability of crashes being severe)	In-depth crash analysis (observed site factors present in severe crashes)
Approach traffic flow (all vehicles)		There was little consistency of message given to the driver/rider in relation to the deceleration that may be required to negotiate the roundabout.
Tight entry curvature (all vehicles)	Tight speed management on approach and through roundabout: • single circulating lane • medium or large central island • strong deflection on approach (tight radius of entry curve)	Approach deflection and the number of approach and circulating lanes had no effect.
Long sight distance from approach		

It is reasonable to deduce that the key factor in these crashes was high speed prior to entering the roundabout – too high to safely negotiate the roundabout or to give way to vehicles already within. Strong deflection on entry may be a contributing factor in losing control and crashing off-path. Stakeholders also identified high speed exit conditions as contributing factor in off-road injury crashes, although this was not supported by data used in the analysis.

Thus, proposed solutions should consider ways of reducing speeds for drivers and riders well before they approach the entry to the roundabout.

6.2.3 Same Direction Crashes (Cyclists)

Overall, 11% of severe cyclist crashes were due to same direction collisions. This represented only 2.5% of all severe roundabout crashes (Austroads 2013a). Analysis of an in-depth sample of these crashes showed that they were associated with small local road roundabouts, a factor of exposure, with more cyclists present on the local road network.

Side-swipes made up two-thirds of same direction severe cyclist crashes, and were mostly associated with turning movements by vehicles. A third were rear-end crashes – these tended to be more severe. Crashes occurred on approach/entry and in the middle of the roundabout (47 and 47% respectively).

In 60% of the crashes a driver hit a rider; this ratio was similar for side-swipe and for rear-end crash sub-types. Police descriptions suggest that drivers failed to see the riders, or were unaware of their position at the time. Nearly half of the drivers were in station wagons, vans or trucks. A majority of crashes were at the low end of the severe crash injury spectrum.

Findings are detailed in Appendix B.3. Again, there was little literature on this crash type in relation to cyclists. Much of it related to driver and cyclist behaviour (e.g. streamlining). Some literature pointed to the prevalence of severe cyclist crashes on low-speed local roads, suggesting that traffic calmed speeds were still too high, or simply that exposure of cyclists to traffic was greater. There was no probit model severe crash site analysis carried out due to lack of sites clustering this type of severe crash.

Almost all crashes in the in-depth severe crash analysis occurred at roundabouts with small central islands and minimal or no deflection. It is curious that large radius was a factor in adjacent direction cyclist crashes, but small radius was a factor for same direction crashes. Both crash types are caused by drivers not seeing/acknowledging the rider’s position. It is possible that higher speed on the approach and entry to roundabouts plays a more significant role in same direction crashes. A critical impact speed of 20 km/h could be assumed in lieu of more refined evidence.

6.3 Suggested Solutions

The following sections offer suggested areas for improvement in selection, operation and management of roundabouts. These suggested solutions are likely to bring safety performance of roundabouts closer to the Safe System objectives. Stronger focus was placed on vulnerable road users who form the majority of the severely injured (Figure 6.3), and this influenced the speed assumptions for the solutions.

The solutions are based on literature reviews documented in Appendix E, an understanding of the risk factor findings in Section 6.2, and on the expert inputs at the series of jurisdictional workshops. Section 6.3.7 discusses and summarises the solutions.

The following sections aim to demonstrate how each solution could address the targeted severe crash factors identified in Section 6.2, as well as others that may be relevant. Each section provides broad guidance on application, design, operation and long-term sustainability of the solutions.

Each section ends with a statement summarising the overall alignment of the solution with the objectives of Safe System i.e. the minimisation of fatal and serious injury. The typical areas of improvement are in geometric design, leading to lower crash severity and sometimes to lower crash likelihood.

6.3.1 Horizontal Deflections on Approaches

This solution proposes to use and extend current Austroads (2011) guidance to use horizontal geometry on approaches and within the roundabout to design roundabouts with entry and circulating speeds below 30 km/h. This is proposed to be achieved by means of reverse curves on approaches, control of the maximum entry path radius and central island radius.

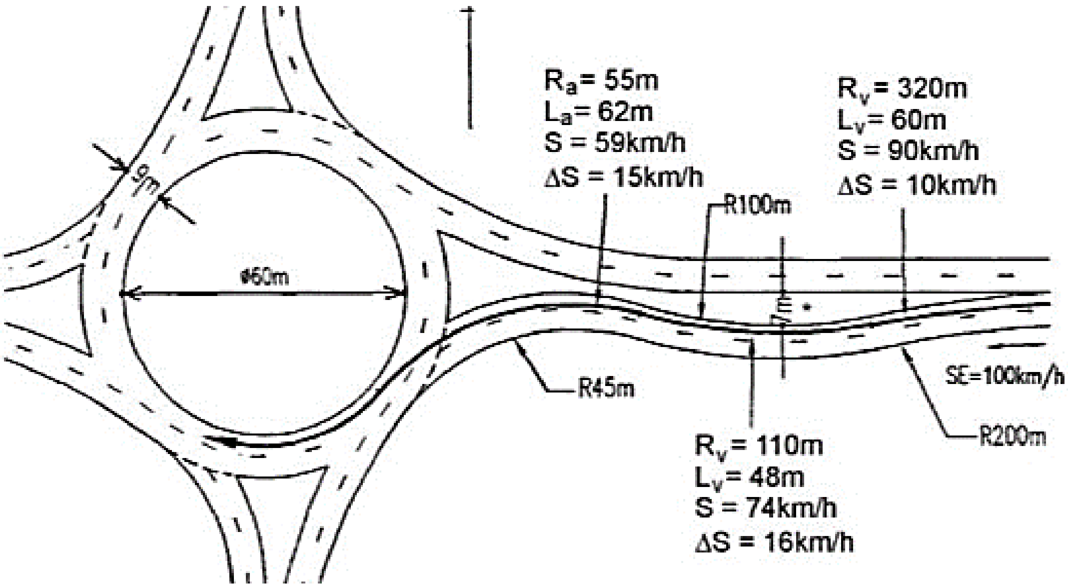
The example in Figure 6.5, drawn from the current guide, shows how horizontal curves are used to achieve entry speeds of 59 km/h. Appendix E.1.1 details research related to reducing entry speeds into roundabouts.

Low entry and circulating speeds of less than 30 km/h would act to minimise severity of cyclist and motorcyclist conflicts (critical impact speed of 20 km/h). This would also act to minimise the probability of pedestrian severe injury. Once a design attains such low speeds, the severity of vehicle-to-vehicle adjacent direction, opposing-turning and same direction crashes would be minimised as well.

As noted in Section 6.2.2, severe off-path crashes are a significant issue for motorcyclists and vehicles at roundabouts. Tight entry geometry has been associated with increased probability of these crashes (Appendix E.1.1). It is thus important to use reverse curves and other available solutions to gradually reduce speeds well in advance of the roundabout entry. This way, drivers are less likely to err on approach leading to lower likelihood of off-path crashes. Their severity may also be reduced if they occur at lower speeds.

Austroads (2011) provides a number of alternatives to reverse curves: long median islands, kerb build-outs, large warning signs, or rumble strips. Additional suggested solutions for approach speed reductions without using reverse curves are provided in the following sections.

Figure 6.5: Example of current approach to horizontal geometry design for roundabouts



Source: Austroads (2011).

Table 6.3 presents the inputs from expert assessment of potential applicability, design, operational and maintenance issues to be considered with this proposed solution type.

Overall, this change to current design would have a high level of Safe System alignment for vehicles and vulnerable road users. The impact speeds would be close to those considered critical for the targeted crashes. Other aspects of roundabout safety could also be enhanced by lower speeds, e.g. lower rates of error resulting in less frequent collisions.

Table 6.3: Assessment of achieving < 30 km/h roundabout speeds with horizontal deflections (cf. higher-speed design)

Assumptions: Approach/entry/circulating speeds in the 20–30 km/h range, single or multi-lane design.
Applicability and design
• Could be more applicable to smaller roundabouts, especially on local roads. Achieving low entry and circulating speeds at large, multi-lane roundabouts could be difficult. A cyclist bypass may be a better option for cyclists. • Austroads (2011) guidance stops at the entry speed of '≤ 40 km/h'. It is proposed that this guidance be extended to cover speeds of '30–40 km/h' and '< 30 km/h'. • Smaller and tighter design may conflict with the need for wider sweep path to accommodate trucks. May need to rely on driveable centre island aprons. • For designs with speeds well below 30 km/h, the cyclist safety level could be considered adequate to allow circulation without providing separation of cycling lanes. • Horizontal geometry may not need to be as severe if arterial speed management options are applied ahead of the roundabout (consideration for off-path crashes). • Could increase capital costs due to a wider intersection footprint of reverse curves (e.g. service relocations, more road works). • Entry angles need to be significant to prevent drivers and riders streamlining through.
Transport operations
• Capacity and efficiency could be marginally reduced by lower service rates. Not likely to be significant.
Sustainability
• No significant difference from conventional roundabout designs. • Future upgrades not affected (e.g. to signalised intersection).

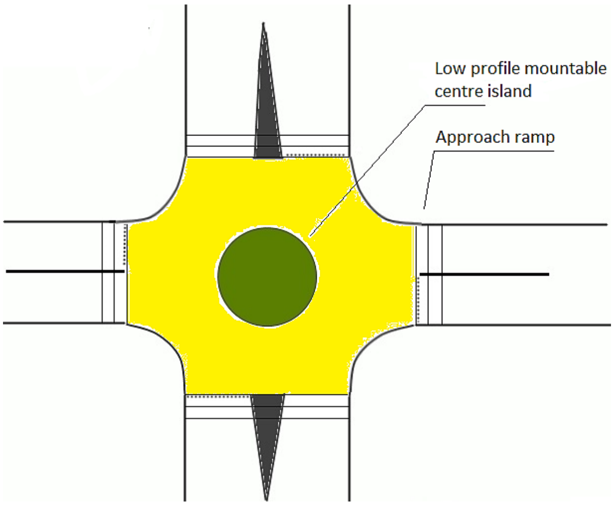
6.3.2 Vertical Deflections on Approaches

Where changes to existing roundabout geometry are not feasible, vertical deflection prior to the roundabout will help to reduce entry speeds to less than 30 km/h at a relatively low cost. The implementation of such a treatment should be undertaken with consideration of the impacts on truck stability in reference to horizontal deflection ahead. The two types of deflection should be adequately separated in space.

Vertical deflections can take the form of Wombat crossings, speed humps or platforms, or speed cushions. Alternatively, an elevated roundabout concept could be trialled. Figure 6.6 and Figure 6.7 provide two examples of this treatment. This treatment would provide improved safety to vehicles, cyclists and motorcyclists in all crash types through reduced impact speeds.

Figure 6.6: Speed humps on roundabout approaches in Sydney

Figure 6.7: Raised roundabout concept



As with signalised intersections, there is a potential for this treatment to have a wide effectiveness range dependent on design. Table 6.4 provides a summary of expert inputs forming broad guidance on aspects of applicability, design, operations and maintenance. Material in Section 5.3.4 is also applicable to roundabouts. Appendix E.1.2 provides further reference material on speed humps and platforms.

Overall, this solution may provide a high level of Safe System alignment for vehicle occupants and vulnerable road users.

Table 6.4: Assessment of achieving < 30 km/h roundabout speeds through vertical deflections (cf. higher-speed design)

Assumptions: Approach/entry/circulating speeds in the 20–30 km/h range, single or multi-lane design.
Applicability and design
• May be limited to smaller size roundabouts, as it would be difficult to maintain circulating speeds of 30 km/h at large sites. • Design guidance needs to be developed to apply at a wide range of high speed sites, e.g. approach and departure slopes, and platform lengths given desired intersection entry speeds. Heavy vehicle, rider and bus issues to be considered. • VicRoads investigation suggests speed platforms will be more inclusive of the full range of vehicles. • Retains existing intersection footprint; low cost. • The vertical deflections can complement inadequate existing horizontal roundabout geometry at low cost (retrofit solution). • Speed humps can be extended across the full carriageway to manage exit speeds as well. • May be combined with Wombat crossings for pedestrian and cyclist bypass priority. • Other arterial speed management options can be applied upstream of the roundabout in consideration of off-path crashes; advance warning is required, particularly for riders. • Heavy vehicle stability must be considered when combining vertical displacement with turning movement. • Visibility and adequate lighting of raised platforms needs to be considered in design. • May require redesign of drainage at a site. • For designs with speeds well below 30 km/h, the cyclist safety level could be considered adequate to allow circulation without providing separation of cycling lanes.
Transport operations
• Capacity and efficiency would be marginally reduced by lower speeds at the roundabout. Not likely to be significant.
Sustainability
• No significant difference from conventional roundabout designs. • Future upgrades not affected (e.g. to signalised intersection).

6.3.3 Signalisation

Previously discussed in detail in Section 5.3.1, Section 5.3.2 and in Appendix D.1.3, this solution offers a further improvement to safety for under-performing roundabouts. The main safety benefit would come from simplification in assignment of right of way. A signalised roundabout may be more safety-effective at large, multilane roundabouts, where gap acceptance is more prone to error (e.g. multiple lanes and directions of conflicting vehicles, higher circulating speeds). The main types of crashes affected would be adjacent direction and rear-end.

Signalised roundabouts may offer some additional benefits to cyclists and motorcyclists, especially when combined with low entry and circulating speeds. Drivers would no longer need to spot and give way to two-wheeler riders, and this may reduce the incidence of adjacent direction impacts.

Overall, signalising a large roundabout would have a low to moderate level of Safe System alignment for all road users, stemming mainly from a reduced likelihood of crashes.

Jurisdictional experts agreed that signalisation increases roundabout capacity, and is likely to extend the useful life of the asset.

6.3.4 Arterial Traffic Calming

Speed management in advance of roundabouts is a supporting treatment aimed at reducing speeds before the immediate approach to a roundabout. Section 6.3.1 noted the importance of gradual speed reduction while approaching a roundabout to reduce the likelihood of off-path crashes, especially for motorcyclists.

Several common options listed in Austroads (2011) include long median islands, road diet[12], kerb build-outs, large warning signs, and rumble strips. Concurrent Austroads project ST1768 *Achieving Safe System Speeds on Urban Arterial Roads* provides summaries of research on these solutions. Section 5.3.4 and Section 6.3.2 presented vertical deflection options for consideration on higher-order arterials. Perceptual treatments ahead of roundabout approaches such as rumble strips are discussed in Appendix E.1.2. Adequate lighting will also support these treatments.

This solution type provides incremental reductions in impact speeds and in injury severity. Some reduction in likelihood would be expected, especially if additional warning/guidance is provided. Overall, this intersection type has a low level of Safe System alignment if applied in isolation. It is intended to support effectiveness and applicability of other solutions.

No detailed expert assessment was carried out as this solution type includes many different solutions with varied technical parameters.

[12] Reducing the number of through lanes to create turning and cycling lanes.

Figure 6.8: Examples of urban arterial traffic calming

Source: Google Earth 2015, 'Tewantin, Queensland' map data, Google, California, USA.

Source: Google Earth 2015, 'Coolum, Queensland' map data, Google, California, USA.

6.3.5 Pavement Condition Improvement

One of the lesser factors identified in Section 6.2 was the adverse condition of the pavement, especially within the circulating lanes. This affected off-path motorcyclist crashes. In-depth crash data analysis noted events where motorcyclists skidded on loose material around the intersection (e.g. gravel from the roadside).

Improved pavement maintenance and replacement within high-volume roundabouts would be suggested as a solution to marginally reduce the likelihood of loss-of-control and off-path crashes. On its own, this solution would have a low level of Safe System alignment.

6.3.6 Cyclist Bypass

Multilane roundabouts pose significant issues for cyclists due to their complexity of negotiation, cyclist visibility to drivers and the relatively high speed of entering vehicles. Existing guidance suggests separating cyclists from such environments by providing clearly defined roundabout bypass opportunities (Austroads 2011). This approach seems to be supported by European research (Daniels et al. 2009, VTI 2000) which identifies bypass facilities as the safest way of managing cyclists through a roundabout.

Cyclist conflict points are less clearly defined than vehicles', as confirmed by the in-depth analysis in Section 6.2. This is a reflection of the 'look but fail to see' and visual tracking issues also observed in the data and noted by research reviewed in Appendix B. Thus the main safety benefit of cyclist bypasses comes from removing cyclists from the traffic stream and simplifying priority decision making for all parties, and thus reducing crash likelihood. Impact speeds and severity can be still very high. Nevertheless, bypasses also offer an opportunity to further enhance cyclist safety with crossing priority and speed management through vertical displacement, such as a Wombat crossing.

Figure 6.9 and Figure 6.10 shows 'Dutch style' cyclist bypasses typically associated with an off-road bicycle route. An alternative version of this solution may involve local redirecting of on-road bicycle lanes to an off-road path, providing crossings near the roundabout, and then reintroducing the bicycle lanes downstream of the roundabout. Cyclist and/or pedestrian crossing priority can be incorporated into the solution. A solution from Essen in Germany is illustrated in Figure 6.11.

Expert inputs during the workshops identified a potential safety issue with bypasses due to roundabout departure traffic. Without cyclist priority on the crossing, cyclists may be giving way to traffic turning left, which would be coming from a direction behind them. With cyclist priority, driver compliance may be compromised by not expecting such a feature on departure. In either scenario, exiting drivers are likely to be accelerating away from the roundabout, creating greater potential for error in give way decision making. Investigation of bypass crash performance and documenting on-site operation could provide conclusive input into further guidance.

While the cyclist crash likelihood would be reduced by a bypass, the overall level of Safe System alignment for a cyclist bypass would be only moderate due to the potential for vehicle impacts at speeds above the 20 km/h critical threshold. Cyclist bypasses alone do not offer safety gains for other targeted crashes, unless combined with other treatments such as vertical deflections. Table 6.5 summarises expert assessment of this solution across its applicability, design, operational and maintenance impacts.

Figure 6.9: UK trial of a Dutch-style cyclist bypass at a roundabout

Source: Sutton (2013).

Figure 6.10: A Dutch-style cyclist bypass in the Netherlands

Source: Google Earth 2015, 'Aachen, Germany' map data, Google, California, USA.

Figure 6.11: A German roundabout design with off-road redirection of bicycle lanes, provision of crossings near roundabout and reintroduction of bicycle lanes downstream

Source: Hembrow (2011).

Table 6.5: Assessment of cyclist bypasses at roundabouts (cf. bicycle lanes within roundabout)

Assumptions: High bicycle numbers.
Applicability and design
• Some cyclists may not feel safe giving way across exits of roundabouts where vehicles accelerate and may not expect to stop again. • Cyclists prefer having priority over motor vehicles in conflict areas. This would require supporting treatments such as crossing priority and vertical deflections (e.g. wombat). • Cyclist priority necessitates adequate storage on departure (one car length minimum). • These facilities are likely to be low cost (footpaths, ramps) and require a smaller roundabout footprint as cycle lanes are not necessary.
Transport operations
• Generally no impact on capacity or flow, unless priority is given to cyclists via zebra/wombat. • Cyclists may not use the provided bypass due to perceived increased delay, and/or risk.
Sustainability
• Additional maintenance may be required for new off-road assets.

6.3.7 Discussion and Summary

Roundabouts are already a very effective solution approaching Safe System. Their strong safety performance is not extended equally to vehicle and two-wheeler road users. Motorcyclists and cyclists are over-represented in the severe crash data.

The areas for improvement identified in previous sections point to the critical role of managing speeds on approaches, upon entry and within roundabouts. There is a synergy between solutions addressing vulnerable road user risks and those for vehicle occupants. Overall, the most promising areas of improvement towards Safe System involve reduction of impact speeds to less than 30 km/h through horizontal and vertical deflections.

Other solutions were shown to be supportive of the Safe System objectives. Arterial traffic calming techniques were shown to be very useful in addressing the risk of off-path crashes due to low-speed roundabout geometry. Signalisation of large multilane roundabouts could help to reduce give way errors. Cyclist bypasses may be effective in separating and simplifying cyclist movements.

Many solutions have been used successfully on local roads. Further investigations may be needed for some solutions to satisfy specific questions applicable to arterial road use, e.g. due to higher approach speeds and need to accommodate large heavy vehicles. There may be specific design and constructability issues, public acceptance, road rules compliance and more detailed consideration of maintenance.

Table 6.6: Summary of Safe System alignment of each of the suggested solutions for roundabouts

Proposed solution type	Vehicle occupants (30 km/h for adjacent direction & opposing-turning, 55 km/h for rear-end)*	Pedestrians and other vulnerable road users (20 km/h)*
Horizontal deflections on approaches (Section 6.3.1)	High	High
Vertical deflections on approaches (Section 6.3.2)	High	High
Signalisation (Section 6.3.3)	Low – moderate	Low – moderate
Arterial traffic calming (Section 6.3.4)	Low	Low
Pavement condition improvement (Section 6.3.5)	Low	Low
Cyclist bypass (Section 6.3.6)	Nil	Moderate (cyclists only)

** Critical impact speeds for targeted crashes suggested in Section 4.2.*

As noted in Section 5.3.11, there may be unintended consequences of the suggested treatments, e.g. additional low-severity collisions (rear-end, off-path). These need to be monitored and investigated through demonstration projects and trials, and detailed guidance may include supplementary treatments designed to inform, warn and guide approaching motorists of the strong speed reductions ahead.

Literature reviews and expert workshops have identified several additional points of discussion.

Radial roundabouts

Given risk factors already noted in Section 6.2.2, the application of a radial design roundabout[13] has a potential to increase the likelihood of off-path crash frequency and severity due to higher entry speeds. This is a theoretical position which requires further investigation. There are a few examples of such a design in Australia and New Zealand which could be used for comparison of Safety performance with Austroads designs.

Turbo roundabouts

Application of turbo roundabouts requires methodical consideration prior to trialling. There is much conjecture about potential benefits of the turbo design in Australian and New Zealand conditions based on its application to European radial roundabouts. The road rules and roundabout design standards in Australia and New Zealand provide better speed management on entry and reduce lane changing within roundabouts, compared to European designs. A systematic assessment of turbo roundabout operation against a range of safety, capacity, design and legal criteria should be carried out to inform their consideration for trials.

[13] The conventional European design, with no approach deflections and greater speed reduction required at entry.

7. Wire Rope Barriers

7.1 Safety Performance of Wire Rope Barriers in the Safe System Context

The project sought to investigate the following applications of wire rope barriers:

- wire rope barriers in wide medians (e.g. motorway)
- wire rope barriers in narrow medians (e.g. 2+1 design)
- wire rope barriers in passenger-side roadsides.

Austroads (2013a, 2014a) showed that wire rope barriers provide greater roadside safety benefits than other common roadside solutions on high-speed roads, and have become commonly used in Australia and in New Zealand. Austroads (2014a) investigated a sample of urban motorway run-off-road crashes of all severities concluding that only 3% of all impacts on wire rope barrier resulted in a severe injury[14] (there were no fatalities in the sample). This is a solution which approaches the Safe System vision.

Austroads (2012b) showed that only 20% of casualty crashes into wire rope barrier were severe. This proportion was approximately half of that for most types of guardrail installed on the Victorian road network. Effectiveness of wire rope barrier reviewed in Appendix C can be summarised as follows:

- Wide median applications
  - ≥ 90% reduction in fatal cross-median crashes
  - 64% severe CRF for all median crashes
  - overall median crash frequency increases.
- 2+1 and 2+2 design:
  - 58–63% reductions in severe run-off-road and head-on crashes
  - close to 100% reduction in casualty head-on crashes.
- There were no studies identified focussing solely on roadside (passenger side) application of wire rope barrier.

Reviewed studies highlighted the continuous application of barrier was important for success. Wire rope barriers show similar or better containment levels as guardrail[15].

Analysis of severe rope barrier crashes is difficult due to their rare occurrence. Also, the current crash recording procedures are only beginning to specify the type of barrier hit (e.g. in South Australia).

The key point to note is that wire rope barriers, across a range of in-service conditions, have been shown to be fundamentally safer than other roadside solutions, including wide clear zones (Austroads 2014a). The discussion in the following sections should be seen as minor variations around already very good safety performance.

[14] The barrier product investigated is no longer approved for installation in Victoria where the study was undertaken, and may differ in performance to currently approved products.
[15] All currently accepted WRSB have been crash tested to NCHRP 350 test level 4, i.e. up to an 8 tonne truck.

7.2 Severe Crash Factors

There was no information about factors which influence severe crash occurrence for the three application types noted in the previous section. Further analysis focussed on available literature and data to identify general run-off-road and head-on severe crash factors applying to this barrier type.

The literature review, severe crash site analysis and in-depth crash analysis provided insight into wire rope safety barrier performance, such as maximum dynamic deflection/stiffness, and characteristics of severe crashes. Some of the factors identified from the literature were used in statistical modelling of severe crash probability. The full findings are provided in Appendix C and summarised in Table 7.1.

All of the sample crash data (62 sites) came from motorways/divided highways and occasionally on urban divided arterials. This was dictated by application of the wire rope barriers on high-speed, high-volume roads, generally in response to past crash numbers or jurisdiction policy settings. Data was provided by Victoria and South Australia.

The key message which emerges from the findings is that design factors which increase barrier stiffness (limit maximum dynamic deflection) are generally the same or similar as those which increase the probability of severe injury outcome. This suggests a link between greater wire rope barrier stiffness and increased crash severity.

Stiffer system designs are generally applicable at more locations. Less deflection means that narrower working width is required, and the barrier can be applied in front of hazards close to a road, on curves, at edges of embankments and within narrow medians. Table 7.1 demonstrates some of the design attributes which increase stiffness of wire rope barriers. It should be noted, that some of these factors contribute to improved barrier performance in crash tests, e.g. higher test level (i.e. ability to restrain heavier vehicles), or better rope engagement with a wider range of colliding vehicle sizes. Also, temperature variation can affect rope tension and substantially reduce stiffness on hot days.

The marginal variation around already very good safety performance of wire rope barriers should be explored and quantified further. It is important that noted safety limitations inform further guidance and product development rather than restrict use of the wire rope barriers.

Table 7.1: Summary of factors associated with occurrence of run-off-road severe crashes into wire rope barriers

Literature (mostly based on casualty crashes)	Severe crash site analysis (probit model factors shown to increase probability of crashes being severe) *	In-depth crash analysis (observed site factors present in severe crashes)
Factors associated with higher stiffness of barrier: • weaved pattern • four-rope design • closer post spacing • closer terminal spacing • increased rope tension.	High crash severity factors: • four-rope design • closer post spacing • terminal close by.	No specific findings.
Greater barrier offset from traffic (minor effect).	Greater barrier offset from traffic (minor effect, weak result).	
Steeper embankment slope.		
	Midblock application – away from a ramp.	
	Roadside application (passenger side).	
	Curve location (R < 1700 m).	

** Based on 62 sites from motorways/divided highways in Victoria and South Australia.*

There was an indicative finding that the roadside application of WRSB leads to a 15% increase in the probability that a casualty crash will be severe relative to a median application. As Table C 2 shows, this result was not statistically significant.

Descriptive analysis of in-depth crash data showed that secondary crashes with vehicles occurred in 11% of cases, all but one were minor injury crashes. Rollovers occurred in 10% of cases – 5% of minor injury cases, and 20% of severe crashes. While undesirable, these occurrences do not weigh heavily on the overall effectiveness of the barrier. It would be valuable to compare these proportions against performance of other currently used barrier types.

Heavy vehicle and motorcyclist crashes into wire rope barrier formed a very minor proportion of the sample (3 and 3% respectively). Heavy vehicles were clearly under-represented given their higher percentage of traffic flow on the motorway system (10–20%). The reasons for this could be numerous. Improved driver characteristics could lead to lower likelihood of road departure, e.g. due to training, fatigue management, zero BAC. Also, risk of injury could be lower due to vehicle size and driver protection, leading to heavy vehicle crashes simply not being recorded. Nevertheless, safety performance of wire rope barrier for this vehicle classification needs to be closely monitored, especially on routes with a higher percentage of heavy vehicles. Many currently approved wire rope barrier systems are tested to safely contain single-unit (rigid) trucks up to 10 tonnes at 15º impact speed of 90 km/h (TL4). This means that such systems may not safely contain very large trucks, such as semi-trailers or B-doubles, especially at high speeds.

There was also a valuable observation that both the vehicle trajectory and orientation angles in severe wire rope barrier crashes exceeded those applied by the current test standards. A higher crash angle into any barrier system has been associated with high severity injuries.

The findings related to barrier stiffness can be applied to narrow and wide median applications. There was little research published on crash severity factors specifically relating to narrow-median or non-median applications of wire rope barriers.

7.3 Suggested Solutions

The key input from literature and data analysis is the potential link between factors limiting maximum dynamic deflection (increasing stiffness) and higher severity of crashes. It would be premature to simply propose wire rope barrier designs allowing greater dynamic deflection, or to propose ceasing to apply stiffer designs. Also, the findings of this project are too preliminary to develop detailed guidance.

It is proposed to consider refinement of Austroads guidance on application of wire rope barriers to minimise the probability of severe crash outcomes, following further detailed research. Refinements should consider the noted factors, and any relevant future research findings, in order to allow designers to adopt more flexible designs in situations where maximum dynamic deflection can be easily accommodated during the barrier’s design life (e.g. wide motorway medians). In other applications, where deflection needs to be limited, stiffer designs should be encouraged (e.g. narrow medians, 2+1). Proposed steps towards developing such guidance include:

- extension of statistical analysis of in-service performance in Appendix C.1.2 with additional crash data from other jurisdictions and factors aligned with wire rope barrier design/system criteria, e.g. weave pattern, containment level, anchor spacing, etc.
- exploration of crash test data, if available, or mathematical modelling (similar to Marzougui et al. 2009)
- inputs from practitioners relating to use, limitations and alternatives to wire rope barrier application
- consideration of jurisdictional and proprietary guidance
- consensus of safety barrier experts leading towards formulation of improved guidance.

Potential factors which may influence such guidance include:

- engagement of ropes with different vehicle types and sizes (includes number of ropes, their relative position and height)
- in-service consequences of barrier failure, e.g. penetration to hazards beyond the barrier including opposing traffic, secondary impacts
- containment test levels
- capital cost of different systems vs safety benefits
- repair costs, e.g. more posts needing replacement in case of a crash
- residual effectiveness when damaged
- terminal types
- need for access and protection of field staff during maintenance works behind the barrier, and for emergency access.

7.4 Discussion and Summary

As shown by previously reviewed literature, wire rope barriers deliver substantial safety improvement for most road users compared to other roadside design options (hazards, no hazards, other barrier types). It is proposed that further development of guidance focuses on refinement based on application of optimal wire rope barrier systems for different locations, so that risk of severe injury outcome is minimised. Consideration of barrier system stiffness appears to be one of several important indicators of this risk.

These additional factors may be considered in the revision of AS3845. Based on the investigation of severe crashes, Stolle and Sicking (2013) recommend increasing test angles for cars and SUVs from 25° to 39°. Stolle (2014) used crash reconstruction techniques to recommend optimal heights for the top and bottom wires to reduce the risk of under- and over-riding penetrations (330–381 mm and ≥ 889 mm on approaches to V-drain slopes 6:1 or steeper).

Expert inputs added the following suggestions for consideration in future research activities and in development of guidance:

- Need for clear and more defined guidance on wire rope barrier system selection for design practitioners.
- Assess the benefits of post colouring for improved delineation.
- Need to refer to the ‘most safety-effective barrier’ in guidelines rather than always to ‘wire rope barrier’. This is needed to acknowledge developments in other barrier types (e.g. weak post guard rail systems) which achieve similar test results as wire rope barrier.
- Refer to recent research findings to dispel the ‘cheese cutter’ myth in relation to motorcyclists.
- Role of exposure to risk needs to be recognised in barrier selection. Deployment of high cost systems needs to occur where it will shield the highest number of road users from roadside hazards. This includes both AADT and length as measures of exposure.
- The role, needs and benefits of sealed shoulders in front of wire rope barriers.
- Maintenance of wire rope barrier in terms of keeping vegetation under control and replacement of damaged elements in a safe manner on high speed roads.
- Access for fauna crossing low volume roads should be considered in future investigations.

8. Discussion Summary

Previous sections identified alternative views and knowledge gaps to be addressed by future research. The main points are summarised below to facilitate further discussion:

- There is a need to discuss the fundamentals of injury severity – impact speed relationships and confirm them for Australia and New Zealand using local data sources. Such investigation would be timely in the context of informing the next National Road Safety Strategy by 2020.
- There is little formal research published on safety effects of signalised roundabouts. If this was to be considered as a mainstream Safe System solution, there is a need to bring together existing research on safety, operational efficiency and accessibility (e.g. public transport, heavy vehicles, cyclists, pedestrians), and to supplement this knowledge with safety evaluations of existing designs (e.g. effect on different crash types and severities). Such a project would draw on the findings to propose detailed design considerations applicable to signalised roundabouts.
- Evaluation of effectiveness of intersection speed limits needs to be carried out across a range of environments.
- Turbo roundabouts require systematic in-depth analysis of effectiveness, road rules compliance and applicability in Australian and New Zealand contexts before undertaking trials.
- Similarly, radial roundabout design has been a subject of much conjecture. In-depth consideration of this design type’s benefits and draw-backs is needed, especially its effect on off-path crashes.
- It would be highly desirable to extend and revise the wire rope barrier statistical analysis undertaken under this project with a view to include additional variables aligned with wire rope barrier design/system criteria, e.g. weave pattern, NCHRP test level (TL), and anchor spacing. This would help to develop the Austroads guidance recommended in Section 7.

9. Conclusion

The project has used a range of literature and data analysis techniques to identify factors associated with severe injury crash outcomes at the following Safe System infrastructure elements – signalised intersections, roundabouts, and wire rope applications in wide and narrow medians, and in roadsides. This new knowledge was augmented with further literature reviews and expert inputs to identify the areas of practice which could be improved to bring the safety performance of these elements closer to the Safe System objective of zero fatal and serious injury.

In the process, the project proposed a new approach to understanding Safe System performance of infrastructure based on its exposure (road user groups, traffic flow), crash likelihood (conflict points, opportunity for error) and severity of crash outcomes (impact speeds and angles). This process enabled better definition of what constitutes Safe System infrastructure, and how well aligned a given solution may be with the vision (hierarchy of treatments).

The objectives related to the two intersection types required a revision of the fundamental relationships between impact speed and injury severity. Sourcing recent US research, new relationships between probability of severe injury and impact speed were proposed. These are better aligned with the Safe System objectives, than existing relationships based on fatality probability and unclear research sources. While these new relationships require further discussion and refinement, they provided a meaningful benchmark for assessing severity of suggested solutions for the two intersection elements.

Improvement solutions best aligned with the Safe System objectives involved lowering crash severity through reduced intersection entry speeds and crash angles, and other features reducing crash likelihood. For signalised intersections, application of a signalised roundabout format in lieu of a conventional layout was best aligned with achieving the Safe System objectives. Secondly, other horizontal deflection layouts were shown to be moderately well aligned (cut-through, tennis ball, squircle). Application of vertical deflections such as raised pavement platforms or humps was also shown to have potential for a moderate level of alignment. A host of strong supporting solutions were identified, such as full control of right turns and use of mast arm signal displays.

For roundabouts, which already show moderately high level of alignment with Safe System, the highly-aligned Safe System solutions involved greater control of entering and circulating speeds using horizontal geometry. It was shown that there was a need for better speed dissipation in advance of the roundabouts (lower risk of off-road crashes). Where tighter approach geometry was not possible, vertical deflections could be considered for the same outcome.

Expert inputs on the suggested solutions provided numerous points of guidance on their applicability, design, operation and maintenance. These will be of use in future revisions of the road safety, road design and traffic management guides.

The project stopped short of suggesting guidance on wire rope selection. Evaluations showed very good safety performance, however the findings suggested questions for further research and consideration by barrier experts. It may be possible to further refine current guidance to maximise safety returns from the use of wire rope barriers.

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Appendix A Results – Signalised Intersections

The following sections provide the findings relating to factors contributing to the occurrence of severe crashes at signalised intersections prioritised during Stage 1 of the project. The factors identified relate to mostly non-geometric parameters such as phasing, signal hardware, approach environment and speed limit. Geometric design factors relating to speed and angles should be based on the findings in Section 3.

A.1 Opposing-turning crashes

A.1.1 Literature

Austroads (2013a) showed that this crash type represented the largest overall severe crash problem at signalised intersections, producing the highest number of severe injuries. A supplementary review of literature sought to identify a number of factors associated with occurrence of these crashes.

Table A 1 shows the identified factors based on before and after evaluations of traffic signal design changes. Further evidence was sourced from statistical modelling. The most relevant study was carried out by NZ Transport Agency (2012) which built a series of statistical models predicting frequency of casualty crashes at signalised intersections based on New Zealand and Australian data. The models produced risk factors for crashes relevant to this study. Given the variability in values of these risk factors between cities and between model variants, only the directions of the risk values were referenced (e.g. increase/decrease). In most cases the magnitudes of the risk factors were in the moderate range of 0.5–2.0.

The key limitation of the information in Table A 1 is that most of the evidence comes from studies using all injury severities crash data. There were almost no relevant findings based on severe injury crash data. Another limitation is that before-after studies and conventional statistical models provide information about frequency or likelihood of casualty crashes. Such information cannot directly infer which factors influence severity of crash outcomes – a question central to the Safe System vision.

Table A 1: Literature-based factors associated with opposing-turning casualty crashes at signalised intersections

Casualty crash factor	Explanation
Lack of right-turn control	Upgrading from filter turns to partially-controlled right turns resulted in mixed results. Bui, Cameron and Foong (1991) reported an increase in casualty crashes (18%), while Bahar et al. (2008) suggested a reduction of 16%. Upgrading from filter turns to fully-controlled right turns resulted in 82% reduction in casualty crashes (Bui, Cameron & Foong 1991). Upgrading from already partially-controlled right turn phasing to fully-controlled was shown to reduce the remaining crashes by 93%. Banning right turns was found to be exceptionally effective. VicRoads uses a value of 95% casualty crash reduction based on observed practice (source: VicRoads CRFs, September 2014). NZ Transport Agency (2012) also confirmed that full RT control was associated with lowered likelihood of crashes than other forms of control.
Lack of signal visibility	Upgrading from regular pedestals to mast arms: 12% reduction; not clear if this was for all-severity crashes or casualty crashes only (FHWA 2009)
Red-light running	Budd, Scully and Newstead (2011) found a 44% reduction due to speed/red light cameras, presumably a combined effect of improved speed and red-light compliance. They noted no effect on crash severity.
High right turn volumes	Models developed by NZ Transport Agency (2012) showed that an increase in right turn volumes (only) was associated with a mild effect of increasing the frequency of crashes.
Large sites, wide approaches	Presence of multiple lanes to cross for right turners was associated with higher likelihood of crashes NZ Transport Agency (2012)

Casualty crash factor	Explanation
Degree of saturation	Increasing degree of saturation had an effect of increasing crash likelihood, especially at low to medium values, but less at higher values (NZ Transport Agency 2012).
Short cycle time	Shorter cycle time and all red time were two variables associated with higher likelihood of crashes (NZ Transport Agency 2012)
High speed limit	Austroads (2013a) noted a modest effect of higher speed limits, e.g. 80 km/h vs 50 km/h, on increased crash severity. NZ Transport Agency (2012) did not indicate speed environment (limit) to be a significant effect in casualty crash occurrence.

A.1.2 Severe Crash Site Analysis

Probit models were created from site data collected in Brisbane and Melbourne for each priority crash type considered in this study. The opposing-turning crash type model estimated the effect that presence of factors listed in Table A 2 had on traffic signal sites being a ‘Safe System fail’, i.e. having a history of severe opposing-turning crashes, rather than only minor injury crashes. Hence, this model explicitly deals with the crash severity issue, rather than with the frequency issue.

Table A 2: Factors and their effects on probability of severe opposing-turning crashes at signals

Severe crash factors*	Increased probability of a severe outcome	Subject to design change?	
No mast arms on major road	41%	Yes	Provide
All-filter RTs cf. all-FCRTs/mixed RT controls	25%	Yes	Apply FCRT or ban turns
Low pedestrian activity areas cf. high and moderate	16%	No	Function of land use
No mast arms on minor road	15%	Yes	Provide
No parking within 50 m of intersection on minor road (cf. parking)	12%	Maybe	Association or causal link?
Regular geometry (cf. irregular, i.e. approaches at odd angles)	10%	Yes	Related to crash angles
Lack of a slip lane on minor road	9%	Maybe	Association or causal link?
No mast arms at all at the intersection	7%	Yes	Provide
Conspicuous intersection cf. hidden from view	6%	No	Association or causal link?
An incremental 10 km/h speed limit increase	5%	Yes	Lower approach speeds
Another road intersection within 50 m	3%	Yes	Very minor effect
Major road maximum traffic volume (incremental decrease by 1000 vpd)	1%	No	Very minor effect, not easily controlled

** The model is based on minor injury crashes occurring. It thus does not provide input on factors which wholly eliminate the possibility of conflict (e.g. banning a turn).*

The key factors contributing to opposing-turning crash severity may be related to the dynamics of crashes. The strong association of lacking mast arms with high severity sites could imply the mode of crash: through driver error leading to red light running and hitting a right turner at high speed. Regular geometry implies less favourable approach speeds and conflict angles. Low pedestrian activity areas may imply the generally higher speed environment of outer suburban areas.

Other factors suggest an indirect link to crash frequency. For example, lack of right turn control could be associated with higher frequency of opposing-turning crashes, some of them leading to severe outcomes.

A.1.3 In-depth Crash Analysis

The factors summarised in this section should complement the literature and analytical factors reported in the two previous sections.

Analysis of 30 randomly selected opposing-turning severe crashes at signalised intersection sites was undertaken to further explore factors present during these crashes. In some cases, this descriptive approach can flag crash and infrastructure factors which are indicative of the causal patterns. One of the limitations of this sort of analysis is inability to distinguish if such indication is applicable to all crashes of this type or just the severe ones.

The following factors were the most significant contributors in the selected opposing-turning severe crashes at signals:

- Failing to give way to oncoming traffic. Hesitation at the point of change of phase under partially controlled right turn (PCRT)/filter phasing – 73% of cases had PCRT or filter control at the relevant approach.
- Red-light running on right turn or through movements (33%). All of the crashes from approaches with fully-controlled right turn (FCRT) phasing involved red-light running.
- 57% of sites were in the 60 km/h speed zone – a high speed for near-side impact.

A.2 Adjacent Direction Crashes

A.2.1 Literature

Austroads (2013a) confirmed that this was one of the most severe vehicle-to-vehicle crash types at intersections, surpassed only by head-on and off-path (into object) which were not numerous. Studies reviewed in Austroads (2013a) showed that this severe crash type was successfully reduced by installation of signals.

As in the previous section, supplementary literature provided limited information about adjacent direction casualty crash factors at signalised intersections, as shown in Table A 3.

Table A 3: Literature-based factors associated with adjacent direction casualty crashes at signalised intersections

Crash factor	Explanation
Lack of right-turn control	Upgrade from filter to partial control of right turn crashes was shown by Bahar et al. (2008) to reduce crashes by 12%. No significant effect shown by Bui, Cameron and Foong (1991). Bui, Cameron and Foong (1991) showed empirically that upgrade from filter to fully controlled right turn phases reduced crashes by 48%. A change from partially to fully controlled right turns reduced these crashes by 51%. NZ Transport Agency (2012) also confirmed that split-phasing (running a separate phase for each approach) was associated with lowered likelihood of crashes.
Lack of signal visibility	Upgrading from regular pedestals to mast arms: 74% reduction; not clear if this was for all-severity crashes or casualty crashes only (FHWA 2009). Confirmed by statistical modelling by NZ Transport Agency (2012).
Red-light running	Budd, Scully and Newstead (2011) found a 44% reduction due to speed/red light cameras, presumably a combined effect of improved speed and red-light compliance. They noted no effect on crash severity.
High conflicting traffic movement volumes	Models developed by NZ Transport Agency (2012) showed that increase in conflicting flows had a mild effect on increased frequency of crashes.
Lack of traffic separation / channelisation	Lack of raised medians and splitter islands were associated with higher crash occurrence (NZ Transport Agency 2012)
Large sites, wide approaches	High number of lanes and depth of intersection confirmed as crash factors by statistical models (NZ Transport Agency 2012).

Crash factor	Explanation
Short cycle time, short all-red time	Shorter cycle time and all red time were two variables associated with higher likelihood of crashes (NZ Transport Agency 2012).
High speed limit	Austroads (2013a) noted a modest effect of higher speed limits, e.g. 80 km/h vs 50 km/h, on increased crash severity. NZ Transport Agency (2012) did not indicate speed environment (limit) to have a significant effect on casualty crash occurrence.

Identical conclusions about speed were reached for adjacent direction crashes as for the opposing-turning crashes, based on the same two studies.

A.2.2 Severe Crash Site Analysis

Probit models were created from Brisbane and Melbourne site data. The adjacent direction crash type model estimated the effect of factors listed in Table A 4 on the probability of the site having severe crashes vs minor injury only (i.e. probability of Safe System fail for this crash type).

Table A 4: Factors and their effects on probability of severe adjacent direction crashes at signals

Severe crash factors*	Increased probability of a severe outcome	Subject to design change?	
Arterial to arterial road hierarchy cf. local to local	25%	No	Function of road planning
All-FCRTs and mixed RT controls cf. all-filter RTs	13%	No	Would increase crash frequency
Parking anywhere within 50 m of intersection (cf. none)	10%**	Maybe	Association or causal link?
Major road maximum traffic volume (incremental decrease by 1000 vpd)	6%	No	Very minor effect, not easily controlled

** The model is based on minor injury crashes occurring. It thus does not provide input on factors which wholly eliminate the possibility of conflict (e.g. banning a turn).*

*** Not statistically significant at $p \leq 0.1$.*

There were no clear factors in Table A 4 which could be readily acted on. Possibly, removal of parking may act to reduce frequency of driver error (distraction), and thus fewer collisions and severe collisions. Provision of a higher level of right turn control may be potentially linked to longer red and yellow time – logically, the period when the most severe adjacent direction crashes would occur. Notably, a higher speed limit did not have a significant effect on the increased severity of adjacent direction crashes.

A.2.3 In-depth Crash Analysis

The following statements summarise observations and factors present in a sample of 20 severe adjacent direction crashes:

- 100% of cases in the sample involved red light running (where information was provided)
- 70% of crashes were crashes originated from the major road
- 65% were in 70/80 km/h speed limit, 30% in 60 km/h
- 60% crashes occurred in the far quadrant of the intersection, almost all on the driver side. 30% were hits in the near quadrant on the passenger side
- 56% of vehicle-to-vehicle crashes were nearside (driver), 44% were farside (passenger)

- 50% of crashes occurred at large sites (≥ 4 lanes on the vehicle 1 approach) – all were 80 or 70 km/h speed limit
- 60% of sites had mast arms on the approach with the red-light running vehicle
- 40% of cases, a vehicle hit other vehicles or objects, this was 70% at large sites
- mast arms present in 50% of the crashes – no clear trend without appreciation of typical conditions
- 40% of cases occurred at night, more common at sites with fewer crashes reported
- see-through problem not observed at any of the sites.

The causal link appears to be a high speed limit and large sites contributing to running a red light on the major road approach. There was a high occurrence of secondary impacts as well.

There were no observed links to lack of mast arms or street lighting.

A.3 Same Direction Crashes (Rear-end)

Installation of traffic signals is generally associated with an increase in casualty same direction crashes, most of which are rear-end collisions (Austroads 2010b, 2012a). Analysis reported in Austroads (2013a) showed that same direction crashes were the less severe than other leading crash types noted in the two previous sections, but more numerous.

A.3.1 Literature

Given the lack of prominence of this crash type, there were few studies which focussed on the design factors associated with their occurrence and severity at signalised intersections. Those which were identified in Table A 5 related to frequency of the casualty crashes, and may not be the best indicator of the factors influencing severe crash occurrence.

Table A 5: Literature-based factors associated with same direction casualty crashes at signalised intersections

Crash factor	Explanation
Permission and improved control of turns	Permission of left, right or U-turn movements can be considered a risk factor. Banning of individual turns was associated with a 50% reduction in crashes (Austroads 2010b). NZ Transport Agency (2012) noted that free-flowing left turn lanes (slip lanes) were also associated with increased risk. Bui, Cameron and Foong (1991) showed an increase by 72% following upgrading of filter right turns to fully controlled phasing.
Lack of signal visibility	These is some evidence in Austroads (2012a) that additional signal displays, pedestals, and mast arms have a strong effect on reduction of crashes, although crash severity is not clear in the cited US studies (either all-crashes or all-casualty). Federal Highway Administration (2009) suggested a 41% reduction in crashes from upgrading pedestals to a mast arm.
Presence of red-light cameras	Austroads (2015) noted from recent US research that installation of red-light cameras at high-speed sites contributed to increased rear-end crash occurrence (severity not stated, most likely all-crashes).
Lack of auxiliary lanes	These is some evidence in Austroads (2012a) that provision of right-turn lanes and other auxiliary lanes at signalised intersections leads to a reduction in crashes.
High approach traffic volume	Models developed by NZ Transport Agency (2012) showed that increase in approach traffic volume had a moderate effect on increasing the frequency of crashes.
Large intersection size	A higher number of approach lanes was associated with a higher likelihood of a crash (NZ Transport Agency 2012).
High speed/speed limits	NZ Transport Agency (2012) noted that high speed limits were associated with a higher likelihood of this crash type. Confirmed by observation of increased crash severity at higher speed limits in Austroads (2013a) and by literature review in Austroads (2015).

All of the literature reviewed in Austroads (2010b) relating to the effect of skid resistance was for general applications of pavement resurfacing and was based on all casualty crashes. It is logical that intersection approach severe rear-end crashes would be affected by such treatment. The direction of change is unclear (potential increase due to more rapid deceleration).

A.3.2 Severe Crash Site Analysis

Severe crash site analysis was not carried out due to lack of sites clustering this crash type at the severe injury level.

A.3.3 In-depth Crash Analysis

The following statements summarise the observation of crash data and site conditions based on in-depth analysis of 28 randomly selected same-direction severe crashes at signalised intersections.

- 86% of the cases were simple rear-end crashes, without turning
- 32% were two-wheelers – over-represented
- 57% of cases occurred when the target vehicle was stationary, typically at the end of a queue or at the stop line
- 32% of cases occurred when the target vehicle was still moving while braking for the end of a queue or lights, or on exit from the intersection
- multi-vehicle crashes were common (39%) and typically involved the end of queue
- manoeuvring before the crash only a factor in a small minority of cases
- 70/80 km/h sites possibly over-represented (39%)
- more than half of locations were large, multilane sites
- presence of other signal sites nearby (50–200 m) was a common factor (25%) suggesting that confusion and driver workload could be a factor.

There was no evidence that shared lanes were over-represented in comparison to auxiliary lanes (50/50 but difficult to tell without control sample of sites).

The primary implied causal reason was drivers not reacting at all, or with delay, to presence of stationary vehicles due to a red signal ahead.

A.4 Pedestrian Crashes

Austroads (2013a) identified that casualty pedestrian crashes at signalised intersections were the most severe among all other crash types. The study identified lower-order urban roads (50, 60 km/h) as the highest focus for concern due to the high number of severe pedestrian crashes observed. These roads correspond to local roads and shopping precincts where pedestrian exposure to traffic is typically the greatest. The study also identified that the conflict between right-turning vehicles and crossing pedestrians accounted for a third of severe pedestrian crashes at signalised intersections.

A.4.1 Literature

Table A 6 shows all-casualty pedestrian crash risk factors available from the literature.

Table A 6: Literature-based factors associated with pedestrian casualty crashes at signalised intersections

Crash factor	Explanation
Lack of right turn control	Bui, Cameron and Foong (1991) showed a reduction of 35% following upgrading of filter right turns to fully controlled phasing. NZ Transport Agency (2012) showed a substantial reduction in risk of pedestrian crashes with through vehicles when split phasing was used. Also, fully controlled right turns showed a strong reduction in the risk of crashes with the right turning vehicles.
Shared lanes (through + turn)	This affected crashes with through vehicles according to NZ Transport Agency (2012).
Direct pedestrian access	Installation of pedestrian fencing and barriers was shown to reduce crashes by 20% (Austroads 2012a).
Lack of staged crossing	Provision of refuges was associated with a 45% crash reduction factor based on review of many studies in Austroads (2012a). NZ Transport Agency (2012) showed a strong reduction in crash likelihood of crashes with through vehicles where medians/traffic islands were present.
High pedestrian and traffic volumes	NZ Transport Agency (2012) showed that pedestrian crossing volumes at a given approach had a stronger effect on the crash occurrence than traffic volumes.
Non-residential land use	Residential land use was associated with the reduced incidence of crashes with turning vehicles (NZ Transport Agency 2012).
Large sites, wide approaches	A high number of traffic lanes was associated with pedestrian crashes with through vehicles according to NZ Transport Agency (2012).
High speeds	Austroads (2013a) showed that increasing speed limit was more strongly associated with the severity of pedestrian crashes. A change from 60 to 80 km/h resulted in a 22% increase in probability of a casualty crash being severe.

A.4.2 Severe Crash Site Analysis

Severe crash analysis for pedestrian crash type is summarised in Table A 7. The main severity-driving factor appears to be lack of mast arms on the major road. Lack of full right turn control was also noted, although this was not statistically significant. As expected, this crash type had multiple factors contributing to the severe outcome probability.

Table A 7: Factors and their effects on probability of severe pedestrian crashes at signals

Severe crash factors*	Increased probability of a severe outcome	Subject to design change?	
Lack of mast arms on the major road	29%	Yes	Provide
Road hierarchy: arterial with local cf. local to local	19%**	No	Function of road planning, not easily changed
All-filter RTs cf. all-FCRTs and mixed RT controls	15%**	Yes	Apply FCRT or ban turns
Traffic separation at intersection on either major, minor or both roads cf. none	14%	No	Removal would increase crash frequency
Parking anywhere within 50 m of intersection (cf. none)	14%	Maybe	Logically, removal would also reduce frequency
Lack of slip lanes on both major and minor roads	12%	Maybe	Association or causal link?
High pedestrian activity areas cf. low and moderate	11%	No	Function of road planning, not easily changed
Lack of slip lane on major road	11%	Maybe	Association or causal link?
Adverse approach (e.g. odd curves, bends, steep grades on any approach) cf. none at all	11%	Yes	Reinforce guidelines

Severe crash factors*	Increased probability of a severe outcome	Subject to design change?	
Low/moderate standard of delineation cf. high	8%	Yes	Improve
Maximum approach speed limit > 60 km/h relative to approach speed ≤ 60km/h	8%	Yes	Reduce
Major road maximum traffic volume (incremental increase by 1000 vpd)	0.2%	No	Very minor effect, not easily controlled

** The model is based on minor injury crashes occurring. It thus does not provide input on factors which wholly eliminate the possibility of conflict (e.g. banning a turn).*

*** Not statistically significant at p ≤ 0.1.*

A.4.3 In-depth Crash Analysis

A sample of 16 pedestrian severe crashes was drawn from the Victorian database for in-depth analysis. There were two equal sub-groups: adjacent direction and right turn. Adjacent direction crashes with pedestrians were strongly associated with:

- pedestrians crossing against the red (85%) as the main causal factor (i.e. pedestrian error)
- all were 50 and 60 km/h sites
- the majority of these (71%) occurred at large sites surrounded by shopping/commercial land use
- it appears that pedestrian decision-making could have been influenced by negotiating large sites (possibly due to long waiting times).

Pedestrian crashes with right turning vehicles occurred in almost all cases with vehicles emerging from minor road approaches with filter/PCRTs. Further:

- in all cases pedestrians stepped from the side of the road, i.e. in good view of the turning vehicle. In 70% of these cases vehicles failed to give way to pedestrians
- all were 60 and 70 km/h sites
- more than half of these crashes occurred on large sites (57%), of which the large majority (86%) were in shopping/commercial areas.

It appears that RT control from minor roads plays a more significant role in these crashes than other factors.

Majority of sites in the sample (75%) had staged crossings or medians.

A.5 Other Crashes

Recent Austroads studies (2010a, 2012a, 2013a) reviewed multiple research sources to provide additional factors relevant to all-severity or all-casualty crashes at signalised intersections, not mentioned in the previous sections:

- cross- vs T-intersection form
- poor skid resistance on approaches
- lack of street lighting
- lack of pedestrian-exclusive phasing
- severe curve on the intersection approach.

Appendix B Results – Roundabouts

The following sections provide the available information relating to factors contributing to the occurrence of severe roundabout crashes prioritised during Stage 1 of the project.

Austroads (2013a) provided a literature review of roundabout features which influence risk of crashes. The studies related to all-casualty crashes. The key factors which increased the crash risk were confirmed by further literature reviews in the later part of the project:

- multilane roundabouts (confirmed by Polders et al. 2015 and Turner, Wood & Roozenburg 2006)
- high vehicle volumes, high cyclist volumes (confirmed by VTI 2000)
- lack of cyclist lanes (cyclist crashes)
- large radius of entry and/or negotiation path, high entry speed/speed limit (confirmed by VTI 2000, Arndt 2008)
- large size of the roundabout (related to the above).

The following sections focus on the specific crash types which were prioritised for analysis.

B.1 Adjacent Direction Crashes (Cyclists and Motorcyclists)

This part of the investigation sought to focus on factors affecting adjacent direction severe crashes, especially involving cyclists and motorcyclists, although a wider investigation was carried out in Section B.1.2.

Austroads (2013a) noted that 83% of severe bicycle crashes and 36% of severe motorcyclist crashes at roundabouts were of this type (19% and 9% of all severe crashes at roundabouts respectively). Safety of these two road user types was noted as the dominant issue for progression towards the Safe System at roundabouts.

B.1.1 Literature

Turner, Wood and Roozenburg (2006) provided statistical regression models for counts of different casualty crash types at New Zealand roundabouts. The models included several design and operational factors which were significant in increasing crash risk. For adjacent direction crashes, the influencing factors were: high mean circulating speed, higher circulating and approach flows.

There was little literature specifically related to this crash type for these two road user groups. Concurrent Austroads project in the Technology Program *Bicycle Safety at Roundabouts* (TT1967) is exploring practical measures affecting cyclists at roundabouts.

Again, Turner, Wood and Roozenburg (2006) provide the most relevant source of adjacent direction casualty crash risk for cyclists. The study showed that both entering traffic flow and the number of circulating cyclists had a moderate effect on increasing crashes, stronger at low volumes. Higher free mean speed of vehicles entering the roundabout (at the give-way line) was associated with higher likelihood of adjacent direction crashes. This effect was strongest at the lower speed range, i.e. there was little effect between high and very high entry speeds.

Campbell, Jurisich and Dunn (2006) and VTI (2000) identified multiple circulating lanes and multilane approaches as casualty crash factors (all types) for cyclists due to increased speed. The authors went on to note, that cyclists and motorcyclists are less of a collision ‘threat’ to drivers than cars, and hence are less likely to be acknowledged.

Cumming (2012) suggests, based on the review of European literature that peripheral lane position of cyclists on approaches and within the roundabout contributes to the ‘look but fail to see’ phenomenon among drivers. This affects adjacent direction crashes, side swipes and rear end crashes. The author goes on to point out the observed streamlining through the roundabout (taking the path of least deviation) by the majority of cyclists and suggests this may be connected to drivers not acknowledging their position/movement within the roundabout.

Maycock and Hall (1984) provided detailed modelling of changes in net crashes and crash proportions with different levels of speed management using the tighter entry curvature. Generally, the tighter entry curve resulted in reduction of adjacent direction crashes at the cost of increasing same direction and off-path crashes. These findings were confirmed by casualty crash modelling results presented by Arndt (2001).

Austroads (2013a) investigated the literature relating to the effect of cycle lanes on the risk of cyclist injury crashes. Crash risk difference between on-road and off-road facilities was not statistically significant. VTI (2000) showed that the crash risk was 2.5 times higher where cyclists were mainly facilitated on road (lanes or not) compared with a ‘bypass crossings’ arrangement.

B.1.2 Severe Crash Site Analysis

Severe crash site analysis was carried out for all vehicles, as there were no sites identified which clustered severe cyclist and/or motorcyclist crashes. Using the same probit modelling method as for signalised intersections, the model identified the factors which increase the probability that the roundabout will have severe adjacent direction crashes, rather than minor injury only.

Table B 1 shows the factors identified by the model. While not statistically significant at p ≤ 0.1, the largest effect on the probability of severe crash occurrence was having multiple circulating lanes. The finding is supported by the effect of multiple entering lanes.

The centre island diameter finding cannot be considered in isolation. The number of approach and circulating lanes determine the island size. Strong deflection and low entry speeds are essential – the size of the centre island may be part of the design solution to achieve this.

Table B 1: Factors and their effects on probability of severe adjacent direction crashes at roundabouts

Severe crash factors*	Increased probability of a severe outcome	Subject to design change?	
≥ 2 vs 1 circulating lane	33%**	Maybe	Strong and logical effect, but not robust. Opposite of effect on off-path crash type. Dictated by capacity needs.
Centre island diameter < 10 m cf. 10–20 m	30%	Yes	Seems 10–20 m diameter is optimal for this crash type, although it increases probability of off-path crashes cf. < 10 m
Centre island diameter > 20 m cf. 10–20 m	23%		
Hidden intersection cf. conspicuous	26%**	Maybe	Strong and logical effect, but not robust. Consider strengthening guidelines.
Total number of lanes entering the intersection (increase by 1)	24%	Yes	Logical result, but function of capacity. Not easily changed.
Maximum approach speed limit reduction by 10 km/h	4%	No	Association or causal link? Most likely confounded by correlations.

** The model is based on minor injury crashes occurring. It thus does not provide input on factors which wholly eliminate the possibility of conflict (e.g. banning a turn).*

*** Not statistically significant at p ≤ 0.1.*

There was a weak but counterintuitive effect of lower speed limit. This is not supported by Austroads (2013a) data analysis or the findings from other research. Given the small magnitude of the result (large expected) it is likely that it was confounded by internal data correlations.

B.1.3 In-depth Crash Analysis

In depth analysis was carried out using a sample of 30 roundabout adjacent direction crashes where cyclists or motorcyclists were involved. The analysis considered the sub-DCA codes, police diagrams and commentaries, and visual appraisal of each site to arrive at observations relating to the main severe crash factors.

Cyclists

The factors observed for cyclists in adjacent direction severe crashes were:

- In all cases, a vehicle driver failed to give way to a cyclist who was already within the roundabout. Only some cases reported the driver not seeing the cyclist, but this can be assumed the leading cause of failing to give way. There was no evidence suggesting that cyclists were obstructed by or interfered with by other vehicles within the roundabout.
- In almost all cases the cyclist was struck in the entry area of the roundabout.
- 25% of cases involved odd roundabout arrangements, i.e. twin roundabouts or elongated.
- Three-quarters of cases occurred on local roads with a 50 km/h speed limit.
- Most crashes occurred on 4-leg roundabouts with single circulating lanes and single-lane approaches – this is consistent with the exposure, i.e. cyclist presence on roads of lower hierarchy.
- There were several recurring contributing site factors such as:
  - confusing roundabout layout and large central islands (60%)
  - poor approach deflection (47%)
  - darkness (20%)
  - steep approach gradient (13%)
  - faded/missing linemarking (13%).

It was noted that in two cases bicycle lanes were dropped off before the roundabout. There were no sites with bicycle facilities within the circulating lanes.

In summary, the key crash cause for cyclist adjacent direction severe crashes was that entering drivers did not see/acknowledge the cyclist already within the roundabout. The main site factors contributing to this were confusing layout and inadequate entry speed control.

Motorcyclists

The factors observed for motorcyclists in adjacent direction severe crashes were:

- In 60% of the cases, a vehicle driver failed to give way to a motorcyclist. In 40%, a motorcyclist failed to give way to a motor vehicle.
- There was no evidence that motorcyclists were obstructed/interfered with by other vehicles within the roundabout.
- In the vast majority of cases, impact occurred immediately in the entry area of the roundabout.
- A third of cases involved odd roundabout arrangements, i.e. oblique, combined multi-single lane circulations.

- Almost all cases occurred on local roads, with more than half being in 50 km/h speed zones, and a further 33% in 60 km/h speed zones.
- All were 4-leg roundabouts.
- Two-thirds were single approach lane roundabouts; a third involved multi-lane approaches.
- There were several recurring contributing factors such as:
  - wide circulating lanes (33%)
  - small diameter roundabout (20%)
  - poor delineation or signposting (20%).

As for cyclist crashes the leading cause of crashes was that entering drivers did not see/acknowledge the motorcyclist, however, a significant minority were errors committed by entering riders. Approach speed management appears to have also played a significant role (wide circulating lanes, small central island).

B.2 Off-path on Straight (Motorcyclists)

This severe crash type was to be investigated in relation to motorcyclists, although a broader investigation was carried out in Section B.2.2. According to Austroads (2013a), off-path on straight crashes involving a motorcyclist formed 52% of all severe motorcyclist crashes at roundabouts (13% of all severe crashes at roundabouts). There has been a long-held practitioner opinion that collisions with the central island and roadside hazards are the main contributing factors to these crashes. The following sections test this hypothesis.

B.2.1 Literature

There was very little literature identified specific to this crash type in relation to motorcyclists. Polders et al. (2015) confirmed analysis in Austroads (2013a) that motorcyclists had a higher probability of injury crash at roundabouts.

Turner, Wood and Roozenburg (2006) provided a model for all-vehicle casualty off-path crashes. Approach traffic flow and sight distance to approaching vehicles 10 m back from the give-way line were found to be two factors moderately increasing the likelihood of a crash. Campbell, Jurisich and Dunn (2006) noted that longer sight distance has been associated with increased crash rates at roundabouts possibly due to higher approach and entry speeds when expectation to give way is lessened with longer sightlines.

Maycock and Hall (1984) and Arndt (2001) among others note that increased entry curvature, i.e. low-speed roundabout design, will act to increase off-path crash rates (based on all vehicles).

B.2.2 Severe Crash Site Analysis

Severe crash site analysis was carried out for all vehicles, as there were no sites identified which clustered severe cyclist and/or motorcyclist crashes. The probit model was developed and provided the factors associated with higher probability of a site having severe off-path crashes, as per Table B 2.

Table B 2: Factors and their effects on probability of severe off-path crashes at roundabouts

Severe crash factors*	Increased probability of a severe outcome	Subject to design change?	
1 vs ≥ 2 circulating lanes	84%**	Maybe	Strong and logical effect (a tighter roundabout), but not robust. Opposite of effect of adjacent direction crash type. Dictated by capacity needs.
Centre island diameter between 10 and 20 m cf. < 10 m	49%	Yes	Suggests smaller diameter is better for this crash type, but it would increase the probability of severe adjacent direction crashes, which are more numerous. This variable needs to be optimised through further research.
Centre island diameter > 20 m cf. < 10 m	46%	Yes	As above.
Strong deflection (one car width or more) cf. some or nil	37%	Yes	Seems some deflection (between nil and one car width) works best for this crash type.
Lack of cyclist provisions on any/all approaches	22%	Maybe	Association or causal link?
Arterial-to-arterial road hierarchy cf. local to local	22%	No	Function of road planning, not easily changed.
Irregular geometry (roads come into intersection at odd angles)	17%	Yes	Try to provide predictable entry conditions.
Closest road intersection (between 50–200m) cf. < 50 m	12%**	No	Association or causal link? Not robust.
Maximum approach speed limit increase by 10 km/h	1%	No	Association or causal link? Most likely confounded by correlations.

** The model is based on minor injury crashes occurring. It thus does not provide input on factors which wholly eliminate the possibility of conflict (e.g. banning a turn).*

*** Not statistically significant at $p \leq 0.1$.*

The main effect (statistically non-significant) was that of a single circulating lane. This goes against other findings, where dual circulating lanes typically lead to reduced safety performance. For this crash type, however, tighter speed management within the roundabout leads to higher probability of severe off-path crash. This risk is supported by the effect of a larger central traffic island and strong deflection which also lead to increased risk.

This is not an isolated finding. Maycock and Hall (1984) and Arndt (2001) developed a number of statistical models involving roundabout flow and geometry parameters. Both studies state that increasing the amount of entry curvature will result in an increase in the rate of off-path (single vehicle) while reducing the risk for adjacent direction. The two studies differed in the estimation of the effect on rear-end crashes due to tighter entry curvature (Arndt noted a decrease; Maycock and Hall noted a weak to moderate increase).

B.2.3 In-depth Crash Analysis

A sample of 33 severe off-path crashes involving motorcyclists was studied to observe any associated or causal patterns. The key findings were:

- Most crashes appear to have been through movements.

- There was little information provided about rider lane choice on multilane approaches. Where available, most were in the correct approach and circulating lane, i.e. there was limited evidence of streamlining (9% of cases).
- The major causes of this type of crash were:
  - near misses (21%)
  - adverse pavement condition (18%)
  - failing to react to the roundabout (12%).
- Loss of control appeared to occur well within the circulating lanes, while negotiating the centre island (58%). A lesser percentage occurred upon entry (33%). No severe crashes were reported where the rider lost control on exit from the roundabout.
- The number of approach and circulating lanes, and the amount of approach deflection had little effect on these crashes. However, roundabouts with a minimal amount of deflection were somewhat over-represented.
- The majority of injured motorcyclists did not hit any objects, and where reported, the injuries resulted from impacting and sliding on the pavement, and impacts with kerbing.
- There were no reported cases of motorcyclists hitting objects within the central island. There were only two reports of motorcyclists hitting objects on the departure side of the roundabout.
- The designs of roundabouts varied considerably even within the same speed limit and environment. This mostly relates to the amount of deflection on approaches and through the intersection. There was little consistency of message given to the driver/rider in relation to the deceleration that may be required to negotiate the roundabout.

The majority of the severe crashes were serious injuries at the lower end of the scale. Crashes were often reported later for insurance claim reasons. Injuries typically involved broken or injured extremities, often with hospital attendance.

It is reasonable to deduce that the key factor in these crashes was that speed reduction on the approach to the roundabout (i.e. prior to entry) was insufficient to safely negotiate the roundabout or give way to vehicles already within.

B.3 Same Direction (Cyclists)

This part of the investigation sought to focus on factors affecting same direction severe crashes involving cyclists. This crash type includes rear-end and side swipe collisions. Austroads (2013a) identified this crash type as the last area of concern in Safe System performance of roundabouts. Eleven percent of severe cyclist crashes at roundabouts were of this type. Overall, only 2.5% of all severe roundabout crashes in the study sample were same direction crashes involving cyclists. This was confirmed by independent investigation by Cumming (2012).

B.3.1 Literature

Several sources identified this crash type as significant for cyclists, however little specific information was available on contributing factors. Austroads (2013a) noted that an increased speed limit was generally associated with increased casualty crash severity for cyclists.

Campbell, Jurisich and Dunn (2006) noted in their literature review that more speed-managed multilane roundabout designs may increase occurrence of side swipes as drivers seek to streamline their path through the roundabout. They also note that providing a clear approach and circulating lane assignment, as practised in Australia and New Zealand helps to reduce this problem.

Cumming (2012) suggests that streamlining by cyclists on single lane roundabouts (kerb to centre island, back towards kerb) may be connected to drivers not acknowledging the cyclist position/movement within the roundabout.

B.3.2 Severe Crash Site Analysis

Severe crash site analysis was not carried out due to lack of sites clustering same direction crashes at the severe injury level.

B.3.3 In-depth Crash Analysis

Analysis of 15 severe same direction crashes involving cyclists was undertaken to note crash and site trends. The following observations were made:

- Nearly all crashes occurred on local streets (50 and 60 km/h). Small roundabouts (≤ 8 m radius) dominated, with 60% of cases.
- Side-swipes made up two-thirds of crashes, and were mostly associated with turning movements. These crashes were typically occurring in single approach lane, low deflection roundabouts (80%). This is an over-representation.
- A third were rear-end crashes. These tended to be more severe based on the police description of injuries.
- Same direction crashes occurred on approach/entry and in the middle of the roundabout (47 and 47%).
- In 60% of the crashes the driver hit a rider; the ratio was similar for side-swipe and for rear-end crash sub-types. Police descriptions suggest that drivers failed to see the riders, or were unaware of their position (nearly half of the drivers were in station wagons, vans or trucks).

The majority of the reported FSI crashes were at the lower end of the severity scale. There were two notable high severity cases, both rear-end crashes, but no fatalities.

Appendix C Results – Wire Rope Safety Barriers

The following sections document the detailed findings of the literature reviews, severe crash site analysis and in-depth crash analysis. The investigations sought to address applications of wire rope barriers in wide and narrow medians, and in roadsides.

C.1.1 Literature

The majority of the published research focusses on their effectiveness in preventing such severe injuries. Wire rope barriers are exceptionally effective in addressing run-off-road and head-on crashes. A number of sources reviewed in Austroads (2013a) noted that continuous deployment of wire rope barriers can reduce targeted severe crashes by over 83–87% (Candappa et al. 2011). The recent Australian and New Zealand evaluations have indicated results towards the upper end of the scale.

There is still a small residual casualty crash risk following installation of the barrier. This refers mostly to barrier penetrations via under- and over-runs and rollovers. Heavy vehicle performance has been identified in Austroads (2012b) as one of the concerns, especially for semi-trailers and B-doubles. There is also a risk of secondary crashes due to vehicles re-entering the traffic stream and hitting other vehicles, or hitting other unprotected hazards. Finally, motorcyclist safety needs are generally not served well by any barrier system. This is no different for wire rope barrier, especially in relation to post impacts and catapulting above the barrier (Bambach, Grzebieta and McIntosh 2010).

Table C 1 presents a collection of factors related to all-casualty and severe crashes into wire rope barriers identified through review of recent literature. Many of the findings relate outcomes to changes in maximum dynamic deflection. Lower maximum deflection means a stiffer barrier design. Increased barrier stiffness can be linked to a greater risk of severe injury in a crash. Such is the case with guardrail or concrete barriers, which are stiffer than wire rope barriers and have a greater risk of severe injury (Austroads 2014a).

There is a point to be made about comparing in-service performance of wire rope barriers to legacy guardrail and concrete barrier systems which exist on the network. Many of these are subject to wear deficiencies and outdated standards. There are now new proprietary semi-rigid barrier systems which claim to have similar test performance properties to wire rope barriers. It would be worthwhile to compare their in-service performance with wire rope barriers.

The main point arising from the literature is that wire rope barriers, across a range of design conditions, have been shown to be fundamentally safer than other roadside design solutions in use, including wide clear zones (Austroads 2013a, 2014a). The discussion around wire rope barrier stiffness should be seen in the context of variations around already very good safety performance.

Table C 1: Literature-based factors associated with wire rope barrier casualty crashes

Crash factor	Explanation
Higher barrier stiffness	It appears that the older low tension designs had marginally better severe crash reduction performance, greater maximum deflection, but were not as widely applicable due to the greater working width required (see the literature reviewed below the table).
Weaved rope pattern vs parallel	Marzougui et al. (2009) used validated computer simulation of barrier crashes to conclude that a weaved rope pattern had consistently lower maximum dynamic deflection, i.e. it is a stiffer barrier design. This design attribute had a strong influence on barrier stiffness.
Four vs three ropes	Marzougui et al. (2009) showed that the maximum dynamic deflection was much lower for parallel four-rope systems, than parallel three-rope systems. This difference was still present but less pronounced for weaved systems.
Post spacing	Marzougui et al. (2009) found that closer spacing of barrier posts equated with substantially less deflection across a range of design scenarios, including on curves. This was one of the strongest effects on barrier stiffness.
Terminal spacing	Marzougui et al. (2009) noted the effect of anchor spacing on barrier deflection concluding that deflection reduced with spacing. For weaving rope patters, the maximum deflection was reached at 300 m, for parallel patterns maximum deflection continued to slowly increase with greater spacing. Candappa et al. (2011) showed that continuous lengths of wire rope barrier were almost twice as effective as short sections installed in reaction to past crashes.
Embankment slope	Hu and Donnell (2010) found that wire rope barriers located on median slopes between 10:1 and 6:1 (10 to 17%) had higher probability of severe outcomes, compared with installations on 1:10 or flatter.
Barrier offset	Zou et al. (2014) showed that injury risk in run-off-road crashes (all severities) into median wire rope barriers offset > 9 m was 7% higher than for barriers 3–9 m away. Austroads (2012b) showed that wire rope barrier crash severity (proportion of casualty crashes being severe) increased with offset; the relationship was not statistically significant.
Rope tension change, temperature	Marzougui et al. (2009) found that changing tension between 15 and 24 kN had little effect on dynamic deflection regardless of the system type tested. Higher tension resulted in a small reduction in deflection. This tension range simulated changes due to temperature (lower tension on very hot days), but could be extended to the design of the barrier itself.
Heavy vehicles	Slightly lower effectiveness in impacts by light trucks (Alluri, Haleem and Gan 2013, Austroads 2012b).

A Washington state study investigated flexible barriers on wide medians on state motorways (Washington State Department of Transportation 2009). There was a mix of high- and the older, low-tension systems. The low-tension systems provided a greater deflection, which led to fewer cars being redirected back into travel lanes. The high-tension systems allowed fewer cross-median collisions and were able to be used in narrower medians due to the narrower working width required.

Stolle and Sicking (2013) investigated motorway median wire rope barrier failures and severe crashes. They found that the older low-tension systems had the lowest severe crash ratio of 1.7% (based on all-severity crash data) when compared to high-tension systems. This was despite higher penetration and rollover ratios of 9.1 and 7.8% for low-tension systems.

The above research suggests a possible general relationship between increasing stiffness of the barrier and crash severity. It does not rule out, however, that differences in application between older low- and newer high-tension designs play a role in crash severity, e.g. flat medians vs curves and embankments. This would require a modelling approach which controls for such variables.

It is noted that all wire rope barriers used in Australia and New Zealand are the high-tension type.

Alluri, Haleem and Gan (2013) analysed Florida's motorway median wire rope crash data. Of the vehicles which hit the median barrier 98.1% of cars and 95.5% of light trucks were prevented from crossing the median into the opposing lane. Further, 16.4% of vehicles crossed the barrier but did not cross into the opposing lane. A higher proportion of under- and over-ride penetrations was not matched by a higher proportion of severe injuries.

Stolle and Sicking (2013) noted that severe crashes' 85th percentile trajectory angle to the barrier was 39° – higher than the current Manual for Assessing Safety Hardware (MASH) standard testing requirement of 25°. In further work, Stolle (2014) analysed motorway median wire rope penetration crash data noting that the vehicle orientation angle was almost perpendicular to the barrier when the impact occurred, even when the trajectory angle was lower. This suggests that large barrier offsets from the original lane of the vehicle are likely to contribute to the risk of penetration (e.g. wide carriageways, wide barrier offsets).

Stolle (2014) also proposed optimal heights of the top and bottom ropes to reduce the risk of under- and over-riding (330–381 mm and ≥ 889 mm on approaches to V-drain slopes 6:1 or steeper).

C.1.2 Severe Crash Site Analysis

Analysis of severe rope barrier crashes is difficult due to their rare occurrence. Also, the current crash recording procedures do not specify the type of barrier hit (except in South Australia) and this has to be ascertained manually from site visual records.

Severe crash site analysis in this study was carried out for all vehicles, including motorcyclists and heavy vehicles. The data sample consisted of 62 crash locations from Victoria and South Australia. The average ratio of severe to all casualty crashes was 0.30, similar but higher to that found in Austroads (2012b). The crash data was not filtered, and included rollovers and secondary crashes.

In departure from other similar analyses in this project, each site had only a single crash (there were no crash clusters). Otherwise, the same method was used, i.e. site data collection, categorisation of variables, probit model development and interpretation of findings. The model identified and quantified site factors associated with higher probability of the casualty run-off-road crash being severe, as per Table C 2. Variables which were highly correlated were excluded. The model indicates the effect of each factor, all other things being equal.

Table C 2: Factors and their effects on probability of severe run-off-road crashes at wire rope barriers

Severe crash factors*	Increased probability of a severe outcome	Subject to design change?	
4-rope design cf. 3-rope design	30%	Maybe	Consider with other design factors
Midblock location (ramp > 100 m away)	27%	Maybe	Consider with other design factors
Curve with radius ≤ 1700 m	17%***	Yes	Consider with other design factors
WRSB in roadside vs median	15%***	Yes	Consider with other design factors
A WRSB terminal within 200 m of the crash site	12%***	Maybe	Termination of WRSB
Fewer carriageway lanes (e.g. 1 vs 2, 3 vs 4)	9%***	No	Association or causal link?
0.1 m reduction in WRSB post spacing (near crash site)	6%***	Yes	See note**
Incremental 1 m increase in barrier offset from traffic lane	1%***	Maybe	Note only – small effect, not robust

** The model is based on minor injury crashes occurring. It thus does not provide input on factors which eliminate the possibility of a casualty crash (e.g. a very low speed limit).*

*** Applicable in the observed post spacing range of 2.0–9.0 m. The estimated increase in severe crash probability by reducing post spacing from 5.0 to 3.0 m would be by 120%, i.e. more than double. The factor is not statistically significant in its current form of 0.1 m increment.*

**** Not statistically significant at $p \leq 0.1$.*

It should be noted, that not all relevant wire rope design data was collected, e.g. weaving vs non-weaving, or the actual distance between anchors. This means that the effect included factors (e.g. four ropes) may reflect unseen correlations, e.g. with weaving pattern. This means that their effects could be over- or underestimated.

The main finding from the analysis is that the factors increasing probability of severe injury are the same or similar to those which Marzougui et al. (2009) found to reduce maximum deflection. This suggests a link between stiffer wire rope barrier design and increased risk of severe crash outcome.

Being well clear of a motorway ramp and proximity to a barrier terminal are puzzling findings which are explored in more detail in the next section.

The statistically non-significant findings in Table C 2 illustrate the direction of change caused by a given factor; robustness of many factor values is very low. Some of these factors seem to confirm existing knowledge about severity of roadside crashes, e.g. effect of a curve on increased relative angle of vehicle trajectory, and thus higher lateral impact speed on the barrier. Also, there were indications that application of the WRSB barrier in the non-median roadside was shown to increase severity of run-off-road crashes by a small margin. The results were not significant and require further investigation.

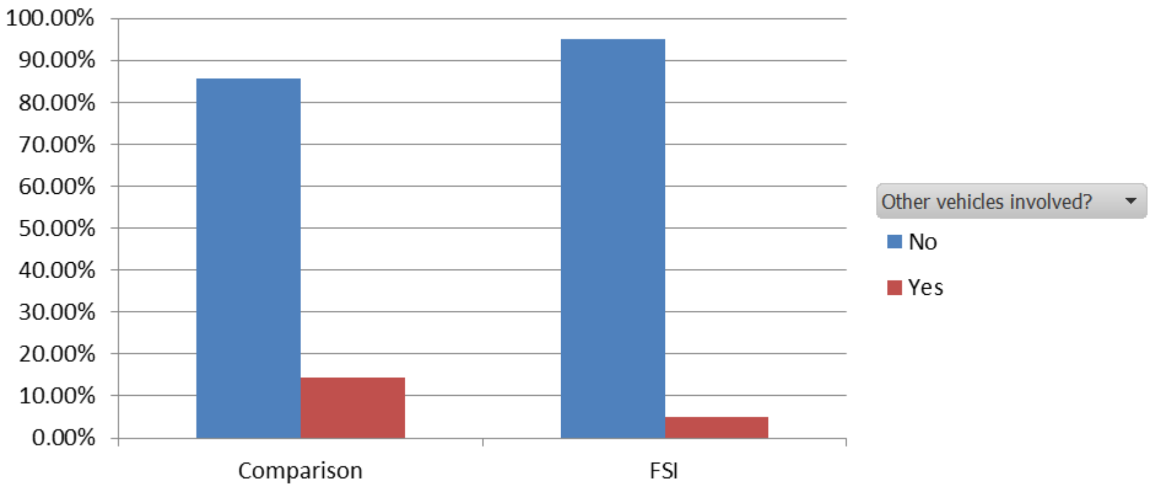
C.1.3 In-depth Crash Analysis

The site and crash data used in the statistical analysis was assumed generally representative of the current application of wire rope safety barriers in Victoria and South Australia. While it was not possible to correct for traffic exposure, this should not result in significant distortion, as application of the barrier is closely prioritised by past crashes and high AADT. The 62 crashes came predominantly from the urban and rural motorway system with a 100 km/h speed limit.

The data set provided rich site information for each crash which has been analysed to answer some interesting questions about general wire rope barrier performance.

There has been some discussion about wire rope barriers having a greater propensity for secondary crashes with other vehicles following a rebound back into traffic. Figure C 1 shows the percentages of severe run-off-road crashes involving wire rope barriers (FSI group) and minor injury crashes (comparison group) which involved other vehicles. The percentages are small in both groups which is the main finding (sample average 11%). The difference between FSI and the comparison group is not statistically significant.

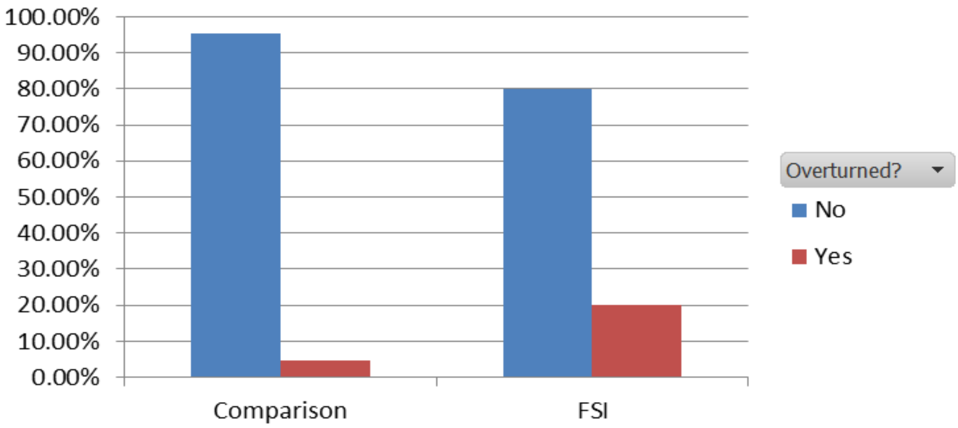
Figure C 1: Secondary crashes with other vehicles by crash severity



All but one of these crashes were of a minor injury level (comparison), and nearly half of them occurred near ramps. This aspect of wire rope barrier performance needs to be monitored over time, as higher traffic volumes will increase the risk of secondary vehicle collisions.

Another subject of discussion relates to failure of wire rope barriers via vehicle rollover. The absolute number of rollovers in the sample was small (n = 6 or 10%), however FSI crashes had a 20% rollover rate, while the comparison group only 5%,as shown in Figure C 2. It is difficult to state whether 10% average is high without comparing this to proportions for other barrier types. Crash data did not state whether the rollover occurred prior or post collision with the wire rope barrier.

Figure C 2: Wire rope barrier rollovers by crash severity



Another interesting finding was that the proportion of crashes in the sample involving heavy vehicles was very low (3%), and both were severe. This is a small number, but one which suggests under-representation as heavy vehicles make up a larger proportion of traffic on the motorway system (10–20%). Similarly, there were only two motorcyclist crashes (3%), again both severe. This finding provides a perspective on the gains which may be achieved by improving wire rope barrier performance for these two vehicle types.

Another part of the investigation sought to explain the ambiguous result of statistical modelling relating to the effect of midblock location. Police crash diagrams and accounts, and visual site assessments were used to better understand the pre-crash and crash dynamics.

The new information did not provide any significant additional insights. Several crashes near ramps implied lane changes by the errant vehicle as expected. Only one crash was associated with entering the motorway (none with leaving). There were no tangible links to crash severity factors such as speed or angle of impact. It may be that this factor needs to be investigated as part of a dedicated study which looks at the factors associated with safety of motorway interchange areas.

The second factor being investigated in more depth was the proximity of a crash to a barrier terminal (more likely to be severe, not statistically significant). There was a question raised if errant vehicles hit the terminal itself.

Again, the police crash records and visual information did not add much to the findings. There were no reported direct hits on terminals and the crash location data lacked precision to determine the exact point of impact. In some cases the crashes were close to a transition with another barrier. In other cases secondary impacts occurred on a different barrier type downstream.

Appendix D Design Innovations for Signalised Intersections

This appendix reviews selected literature to identify innovative design solutions which would bring signalised intersections closer to the Safe System ideal. The review focussed on findings related to three prioritised severe crash types: opposing-turning, adjacent direction and pedestrian. The range of design solutions included management of approach speeds and geometry (incidence angle), reduction in conflict points and vehicle movement control.

D.1 Managing Intersection Speeds

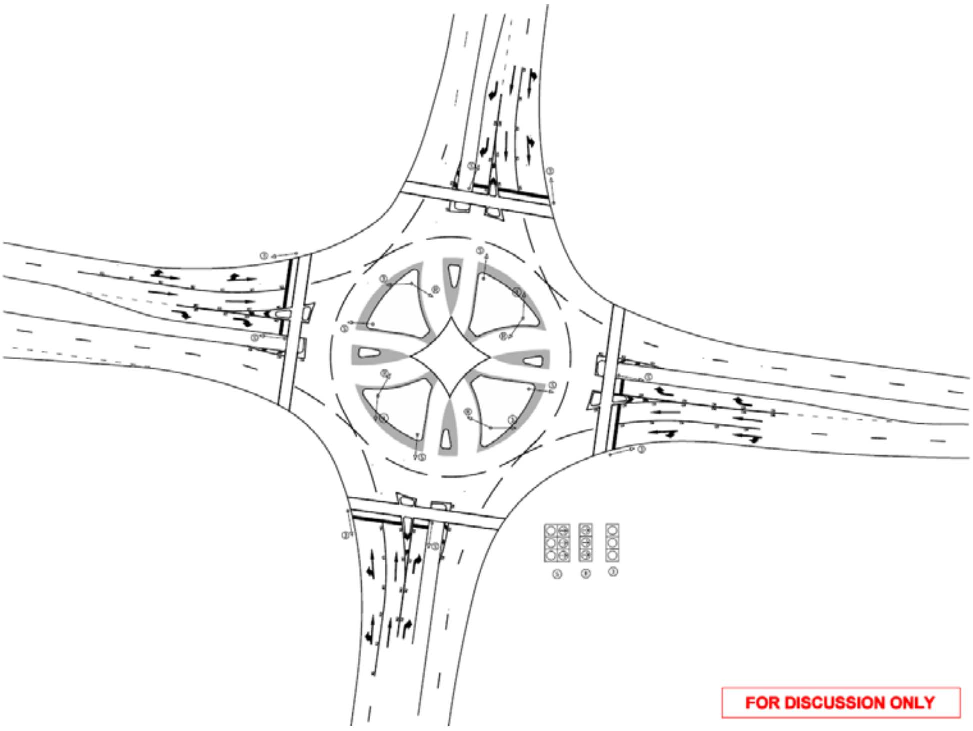
As previously discussed, the speeds at which vehicles traverse intersections are such that there is little room for recovery if driver error occurs. A component of moving signalised intersections closer to a Safe Systems ideal requires that these speeds are reduced to a level which sees a reduction in fatalities and serious injuries. The following treatments were investigated for efficacy in reducing approach speed at signalised intersections.

D.1.1 Cut-through Roundabout and Squircle

Cut-through roundabouts consist of a central island within a signalised intersection. Right turning vehicle movements are directed through cuts within this central island, while through drivers travel around the island as seen in Figure D 1 (Corben et al. 2010). Through the use of deflection, angles of collision are minimised and drivers are slowed on approach in order to traverse the central island. Candappa et al. (2015) derive speed and angle combinations that produce Safe System levels of kinetic energy for speeds up 100 km/h for this design and envisage it as being suitable for use in intersections between arterial roads with high risks of side impact crashes.

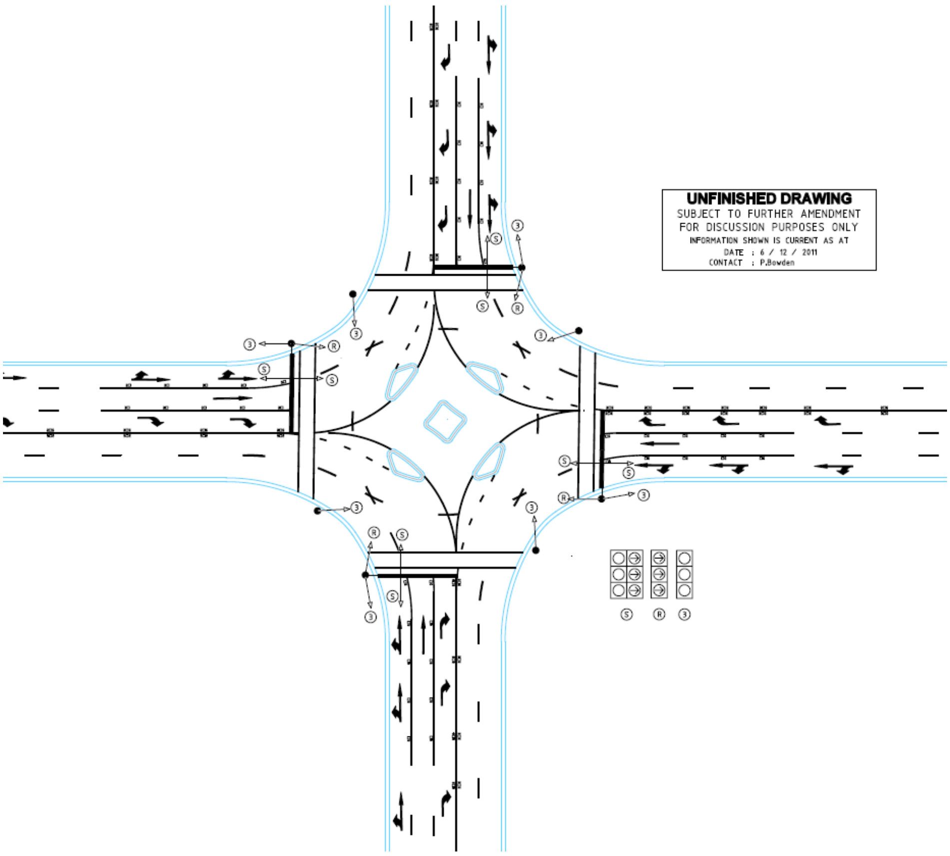
Operating on similar principles to the cut-through roundabout, the squircle as seen in Figure D 2 is considered to be appropriate for use at local road intersections with the use of traffic signals to assist the flow of traffic.

Figure D 1: Cut-through roundabout



Source: Provided by VicRoads, based on Corben et al. (2010).

Figure D 2: Squircle



Source: Provided by VicRoads, based on Corben et al. (2010).

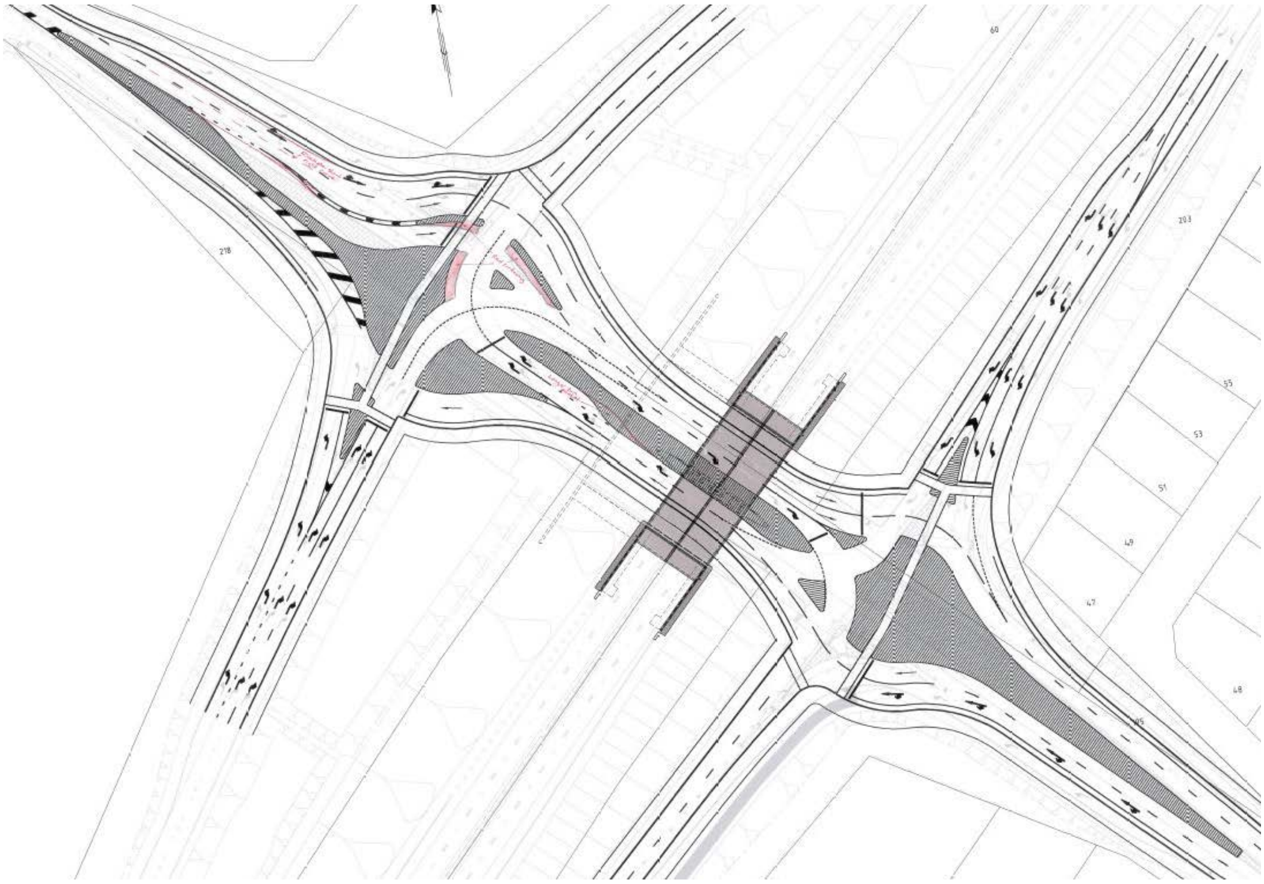
D.1.2 Deflection at Approaches

There have been a number of approaches to modifying existing traffic signal approaches using roundabout principles. This has the effect of reducing approach speeds to ≤ 50 km/h and reducing angles between converging vehicles (or maximising them if one applies the terminology in Section 3).

One example of this is a draft proposal for a 'tennis ball' design from Western Australia shown in Figure D 3. The main feature of this freeway interchange design is roundabout-like deflection introduced for the minor road through movements, resulting in lower intersection speeds. In some cases, conflicts would occur at more favourable angles, although this feature plays a lesser role when speeds of both conflicting vehicles are low.

This design concept could be extended to full at-grade intersections by routing the major road through vehicles via similar deflections. This would then result in twin-roundabout operation with a wide median. Clearly this option would be limited to locations where future interchanges are planned and there is ample road reservation. An alternative may be installation of a signalised roundabout.

Figure D 3: Tennis ball design for signalised intersection from Western Australia (draft)



Source: Personal communication from Bruce Snook, Main Roads WA, April 2015.

D.1.3 Signalised Roundabouts

Signalised roundabouts fall within signals and roundabout categories, but would be best discussed in this appendix as a means of achieving greater control of approach speeds (Figure D 4).

Figure D 4: Example of a lower-speed signalised roundabout

Source: Turner and Brown (2013).

In the context of roundabout design discussion, signalisation is often seen as a means of extending the capacity horizon of a roundabout. Signalisation of roundabouts can be full-time or part-time (e.g. peak demand periods, or approach metering triggered by an algorithm). There are numerous texts published on the efficiency gains of signalising some or all of the approach legs.

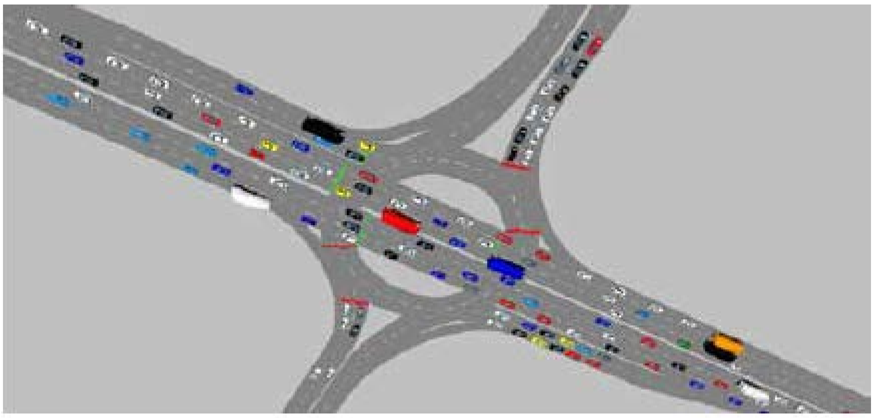
There is little published research on the safety effects of signalised roundabouts. Turner and Brown (2013) cite a study by County Surveyors Society (1997) noting that signalisation of roundabouts had the following effects:

- 11% reduction in crashes, and a 44% reduction in crash severity for full-time operation
- 8% crash reduction during part-time operation, 66% increase in off-periods; no net effect on crash severity.

Richards and Cuerden (2009) extended the same study by surveying additional UK roundabouts. The authors found a growing preference for full-time signal roundabout control since 1997. This change was driven by the better pedestrian provisions of full-time designs, and no need to compromise layout to accommodate both signal and priority control.

The hamburger roundabout goes beyond mere signalisation of roundabouts and instead allows for a through movement of the major road as seen in Figure D 5. There is minimal literature relating to the safety benefits or operational effectiveness of this design, Candappa and Corben (2011) note that four such roundabouts exist in the UK but that no data had been collected on their safety performance.

Figure D 5: Hamburger intersection movements



Source: FHWA (2010a).

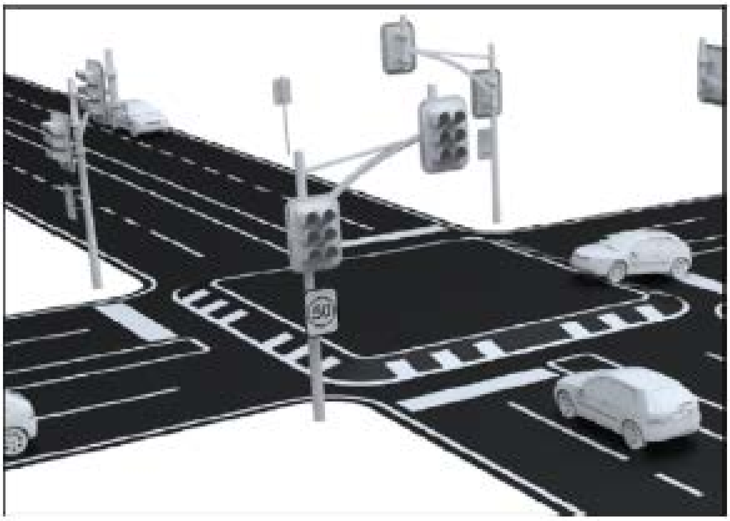
Signalisation of roundabouts offers most of the geometric design benefits of regular roundabouts (low entry speeds, moderate impact angles). There is additional potential to reduce certain road user errors such as not giving way to cyclists or motorcyclists, or misjudgement in acceptance of gaps. Also, legibility of more complex roundabout sites may be improved by provision of signals.

Much further research needs to be carried out to quantify safety benefits of signalised roundabouts.

D.1.4 Signalised Raised Platform Intersection and Raised Stop Lines

Candappa et al. (2015) draw upon research into the speed reduction and traffic calming effects of raised humps to suggest the placement of a raised platform at signalised intersections as seen in Figure D 6. Such an intersection is suited for low volume areas and is incompatible with trams.

Figure D 6: Raised platform intersection



Source: Corben et al. (2010).

An example of a raised intersection stop bar is shown in Figure D 7.

Figure D 7: Raised intersection stop line/bar in the Netherlands

Source: Personal communication John Matta, VicRoads, July 2015.

Pratt and Aumann 2014 research for VicRoads (internal report) analysed required parameters of arterial raised stop lines at signalised intersections. The aim of a raised stop line is to reduce entering intersection speeds to 50 km/h or less, a speed deemed to be significantly safer than allowed by a ≥ 60 km/h speed limit. The review included international research on the subject, and recommended the following treatment dimensions for consideration:

- Watts profile: maximum height of 100 mm and length of 9.5 m
- flat top profile: maximum height of 100 mm, length of 15.0 m
- platform length of 6.0 m, and grade no steeper than 1:30
- raised intersection: height of 100 mm (or flush with footpath) and grade no steeper than 1:30.

In general, the flat top profile was seen as the least restrictive in terms of ease of installation and replication, benefits to different road users and lower cost.

Other design considerations were to ensure adequate warning is provided to drivers on approach to the treatment, that they accommodate emergency and bus services. Impacts on turning heavy vehicles could be avoided by installing the devices clear of the turning movement (e.g. ramping clear of the intersection). Importance of minimising speed differentials between vehicle types was also noted. Additional issues included catering for pedestrian activity at intersections, noise pollution, impacts on neighbouring streets/service lanes, damage to vehicles/pavement, and retrofitting constructability.

Informed by the 2014 reviews and analysis, site and simulation trials by Pratt, Roper and Wright showed that a 1:30 on-ramp, 0.10 m x 7 m platform and 1:35 off-ramp was more effective than an alternative profile 0.14 m x 6 m platform with 1:30 ramps (2015 internal VicRoads report). The preferred profile showed the smallest speed differential between vehicle types, with the following expected speed results if the treatments were deployed on public roads:

- passenger vehicle speeds reduced to 60 km/h
- rigid truck and semi-trailer speeds reduced to 50 km/h
- airbag and spring suspension bus speeds reduced to 40 km/h.

The trials used vertical acceleration as a limiting factor of both ride discomfort and safety. It is noted that the passenger vehicle speeds were in excess of the 50 km/h target in order to safely accommodate larger vehicles.

D.1.5 Speed and Red Light Cameras

Speed camera use in Australia has been shown to be effective in lowering average speeds, vehicle speeding rates and casualty crashes (Austroads 2010b). Further research by Budd, Scully and Newstead (2011) showed that red light/speed cameras delivered a 44% reduction in turning-opposing and adjacent direction casualty crashes, and the same result for severe crashes of these types.

D.1.6 Advanced Warning Flashing Lights

National Cooperative Highway Research Program (2011) analysed the use of warning flashing lights linked to the signal. These are placed in front of the intersection at such a distance that drivers will reach the intersection at its red phase. Results indicated a reduction in total crashes, angle injury and heavy vehicle crashes. Consistent results were not seen in terms of a reduction in rear-end crashes.

A study of advanced warning flashing lights at signalised intersection approaches with speed limits ranging from 70–100km/h in Western Australia found that while crash rates remained unchanged, there was a decrease in their severity. The change in severity was caused by a decrease in high severity right turn against and right angle crashes, while low severity rear-end crashes increased. (Radalj 2003).

D.1.7 Speed Activated Warning and Dynamic Warning Signs

Trials of dynamic speed advice signs which provided drivers with their measured speed if above a pre-set value as well as the speed limit were found to reduce mean approach speed by 2.5 km/h when placed with an intersection warning sign alongside (National Cooperative Highway Research Program 2008).

Makwasha and Turner (2014) reviewed a number of international evaluations of intersection-based speed activated warning signs demonstrating reductions in speed of 4 km/h.

D.1.8 Intersection Speed Limits

Austroads (2014b) reviewed available evidence for reductions of speed limits at high-speed outer metropolitan signalised intersections. Two trials were identified, both registering a casualty crash reduction. The trial evaluations were of limited robustness, but of sufficient crash reduction magnitude to include the speed limit reduction option in the model guidelines by expert consensus (already in line with existing state practice). The Austroads report proposed minimum lengths of speed zones. It also called for further trials and evaluations of the treatment.

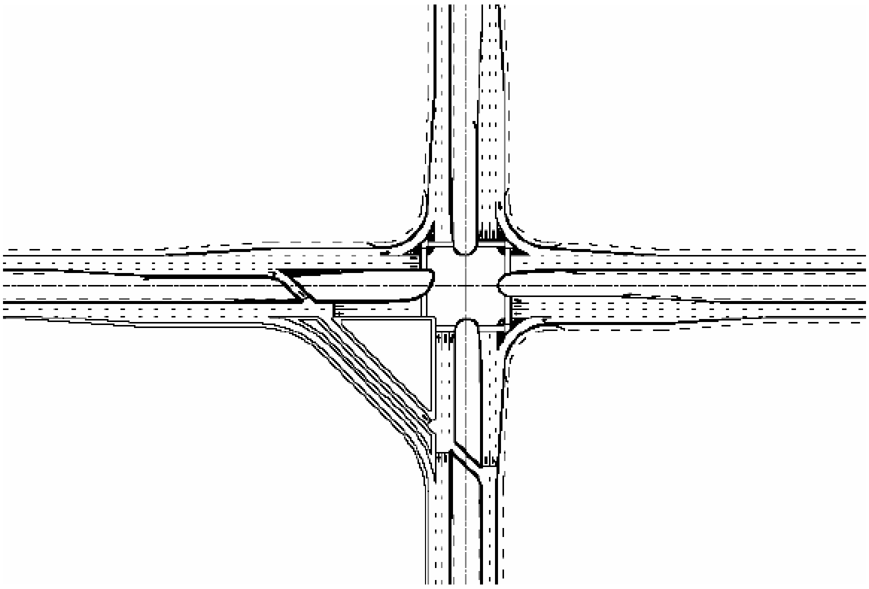
D.2 Reducing Conflict Points

The following alternative intersection designs offer safety benefits beyond those found in traditional at-grade designs. Safety is enhanced in these designs through the reduction and removal of conflicting traffic manoeuvres. The removal of conflicting manoeuvres also allows for a reduction in the number of signal phases required, allowing for shorter cycle lengths and increased capacities than might otherwise be possible.

D.2.1 Displaced Right Turn (DRT)

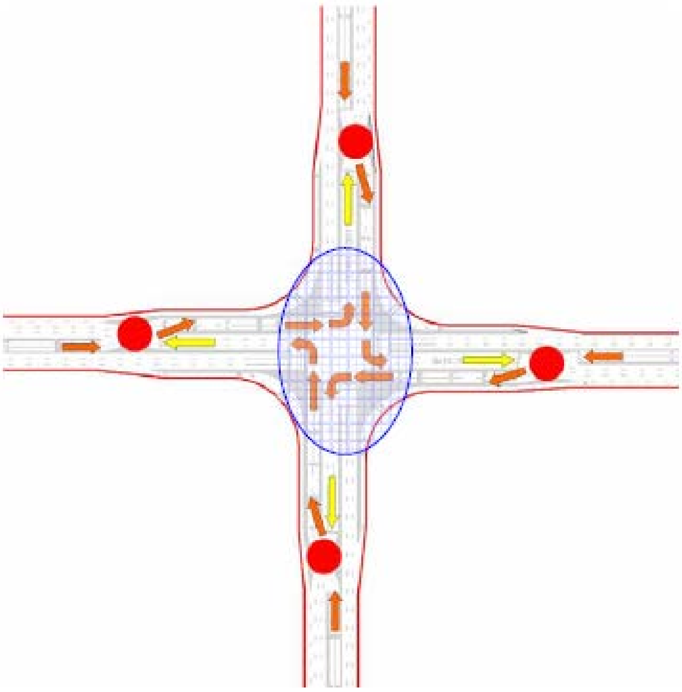
Federal Highway Administration (2010a) outlines the potential benefits of the installation of a DRT. A DRT removes the right turn phase of an intersection by directing right turn movement to the other side of the opposing roadway as seen in Figure D 8. Traffic signals are placed at the conflict points of the intersection and must be carefully coordinated in order to ensure efficient traffic flow. The displaced turn may be used on only one approach as seen in Figure D 8 or on all approaches as seen in Figure D 9.

Figure D 8: Displaced Right Turn Intersection



Source: Pyke, Sampson and Schmid (2006).

Figure D 9: Full displaced right turn intersection



Source: Federal Highway Administration (2010a).

The safety benefits of such an intersection design are derived from the reduced number of conflict points compared to a four leg intersection. A before/after crash comparison in Los Angeles found a 24% reduction in total crashes and a 19% reduction in FSI crashes.

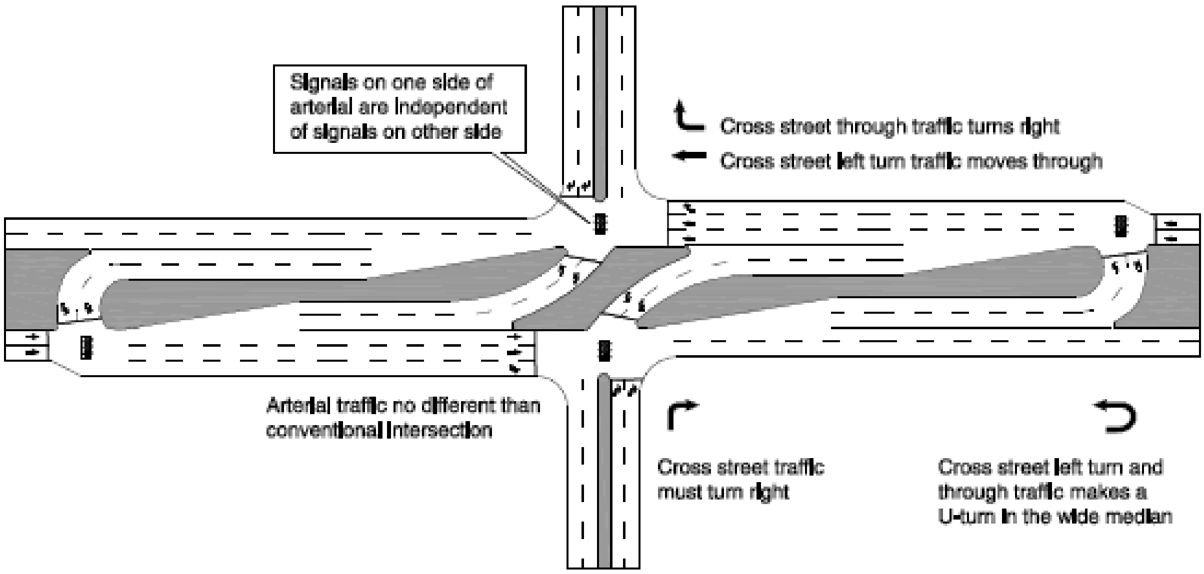
While pedestrians benefit through reduced cycle times facilitating quicker crossing, the DRT also presents negative safety outcomes. This is due to an increase in pedestrian conflict points, pedestrian unfamiliarity and the presence of a counter-intuitive direction of traffic for pedestrians. These issues can be managed using appropriate signalling and the installation of pedestrian refuges and wayfaring signage.

Modelling suggests that the DRT offers improvements in terms of increased vehicle throughput and reductions in delay, stopping and queue length. While it has a greater footprint than a conventional intersection it requires less space than a grade-separated interchange.

D.2.2 Signalised Restricted Crossing U-turn Intersection (RCUT)

Federal Highway Administration (2010a) outlines the potential benefits of the installation of a signalised RCUT intersection, which shows potential for use on arterials with dominant flows on the major road. RCUT intersections redirect right turn and through movements from minor street approaches which are directed to make a U-turn downstream as seen in Figure D 10 and Figure D 11.

Figure D 10: Signalised RCUT intersection (right-hand drive version)



Source: Federal Highway Administration (2014).

When signal control is used, only two signal phases are required, compared to the four that would be needed at a conventional four-leg intersection.

As pedestrians may be required to cross three legs at this intersection type, appropriate treatments must be used to ensure pedestrians cross safely. These include wayfaring signs, placement of barriers and channelisation of pedestrians.

RCUT intersections offer safety advantages due to their reduced number of conflict points as seen in Figure D 11.

Figure D 11: Conflict points at a signalised RCUT intersection

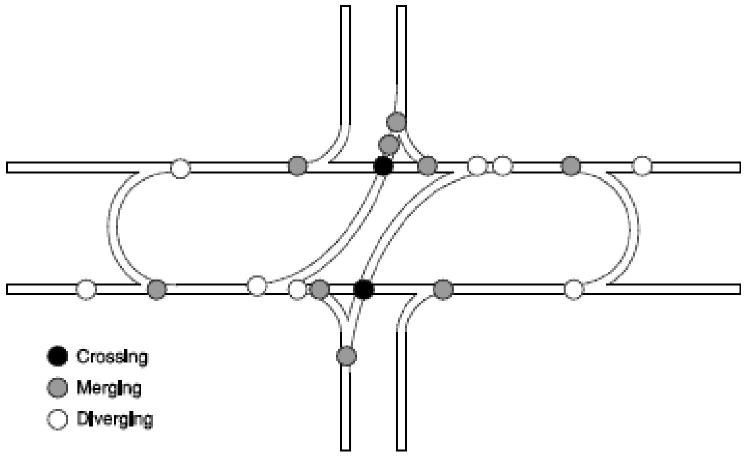


Exhibit 4-3. Vehicular conflict points at a four-approach RCUT intersection.

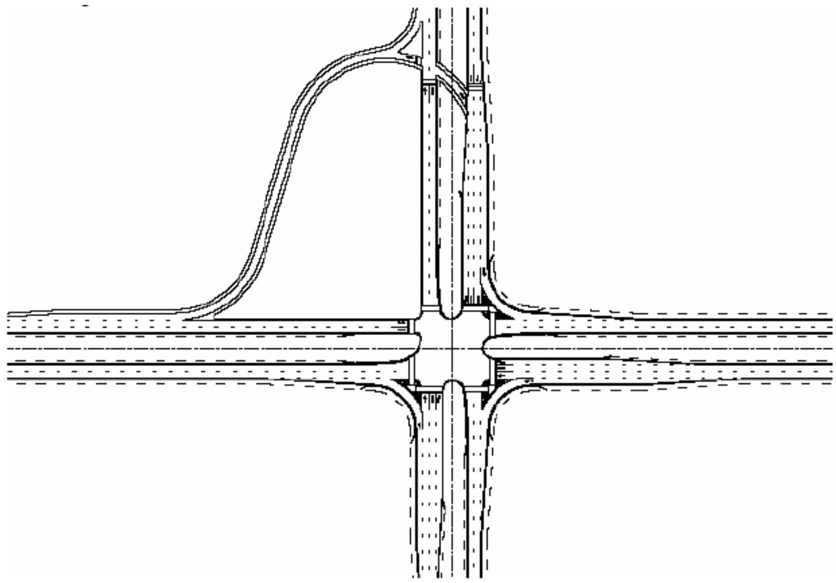
Source: Federal Highway Administration (2014).

Federal Highway Administration (2014) notes that while the safety performance of signalised RCUT intersections compared with a traditional signalised four-leg intersection is currently unknown, replacement of stop-controlled conventional intersections with stop or merge controlled intersections has shown a 33% reduction in crashes and 50% reduction in injury crashes. The FHWA is currently undertaking a study on the safety outcomes of signalised RCUT intersections

D.2.3 Jughandle Intersection

Jughandle intersections remove a right turning vehicle movement from an intersection through the provision of a one way path found on the left approach to an intersection. Vehicles intending to turn right exit on the left before the intersection and are directed to an adjacent approach where they enter via a right turn at a T-intersection, as seen in Figure D 12.

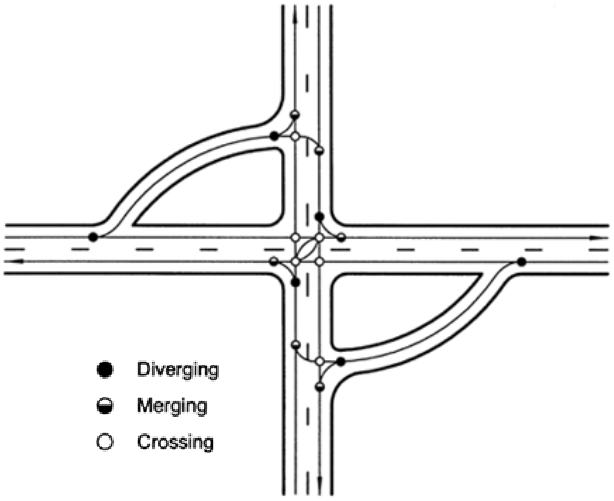
Figure D 12: Jughandle intersection



Source: Pyke, Sampson and Schmid (2006).

As jughandle intersections remove right-turning vehicles from through lanes they result in a reduction in potential conflict points when compared to conventional four-leg intersections as seen in Figure D 13.

Figure D 13: Jughandle conflict points



Source: Federal Highway Administration (2013).

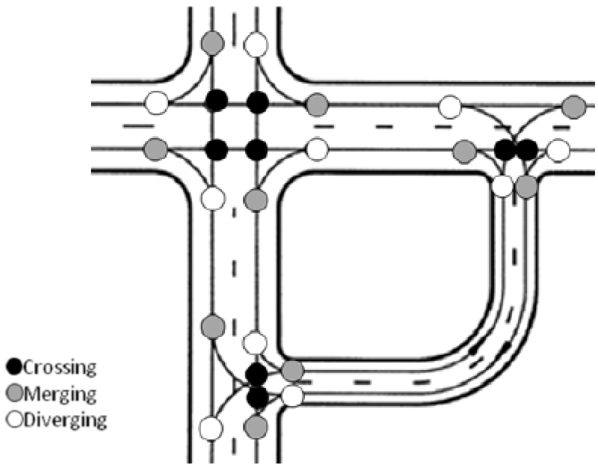
Safety concerns over such a treatment include driver confusion which can be mitigated through appropriate visual cues. Pedestrians may also have to cross an extra intersection. Implementation of jughandle design did not result in a reported change in crashes.

D.2.4 Quadrant Roadway Intersection (QR)

A QR moves beyond a jughandle and removes all right turn movements from a four leg intersection through the addition of a connector roadway on which all right-turn movements are rerouted as seen in Figure D 14.

This review was unable to find any literature relating to the successful implementation of a QR, however Federal Highway Administration (2010a) notes that there are 28 vehicle-vehicle conflict points, compared to the 32 found in a conventional four leg intersection and as such QR should offer some safety benefit.

Figure D 14: Movements at QR intersection



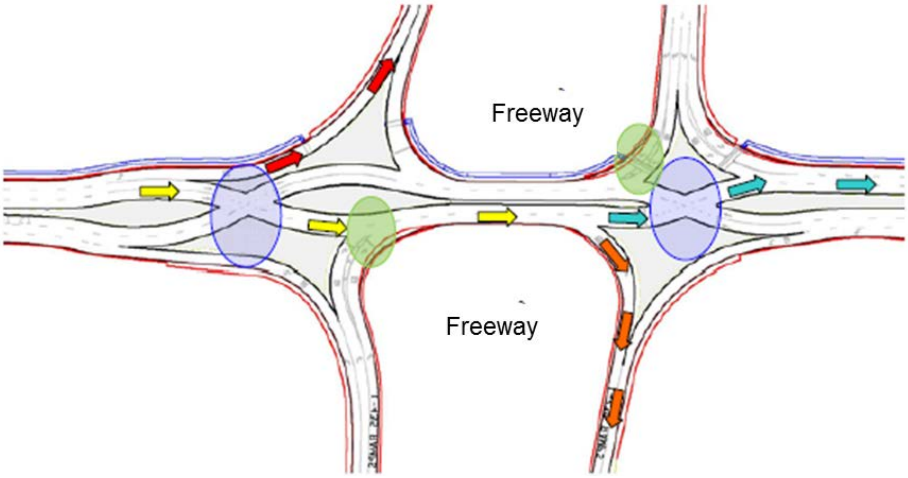
Source: Federal Highway Administration (2010a).

D.2.5 Double Diamond Crossover (DDC) – Synchronised Split-phasing Intersection

Also known as Diverging Diamond Interchange, these interchanges remove the need for right turn bays and associated signal phases at on-ramps connecting to freeways. This is done by switching the sides that traffic travels on between ramp terminals as seen in Figure D 15.

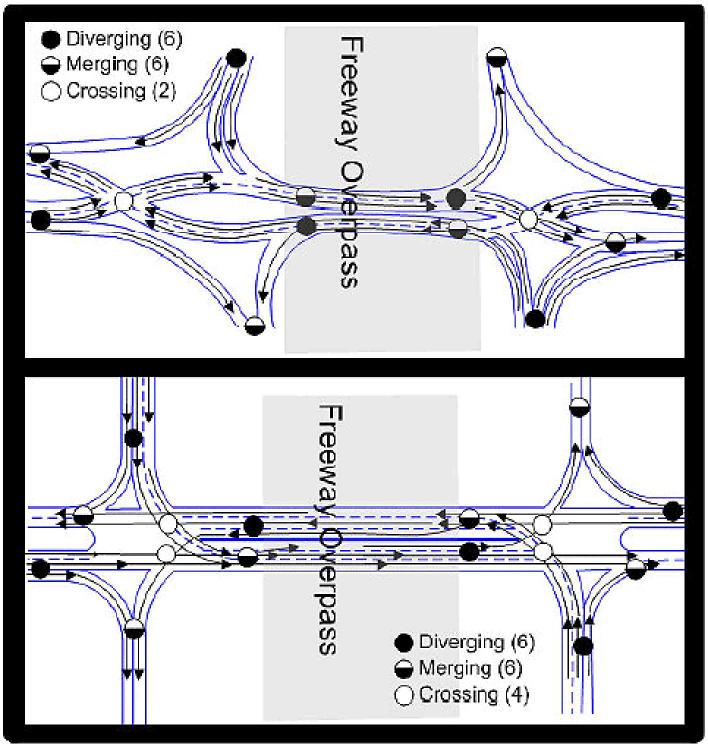
DDC offers improved operational performance and is able to reduce delays and increase service volumes through its changes to vehicle movement when compared to a traditional diamond interchange as seen in Figure D 16.

Figure D 15: DDC interchange



Source: Federal Highway Administration (2010a).

Figure D 16: Comparison of conflict points between DCD and traditional diamond interchange



Source: Federal Highway Administration (2007).

The safety benefits of a DCD Interchange are derived from the reduction in vehicle conflict points as seen in Figure D 16. A before/after comparison of crash data for an implementation of a DCD interchange in Missouri found total crashes were down 46%, minor injury crashes 72%, rear-end crashes down 29%, right-turn angle crashes 72% and a complete elimination of right-turn crashes (Chilukuri et al. 2011).

Driver confusion as a result of changing sides was not found to be an issue in traffic simulations (Federal Highway Administration 2007). However, Chilukuri et al. (2011) found this to be the case for the interchange used in their study. The issue was remedied easily after introduction of lane management signage ahead of the interchange.

D.3 Managing Movements

As signals are used to control this type of intersection, modifications to signal phasing may offer potential safety benefits. A number of modifications have been investigated and their effects are discussed in this section.

D.3.1 Fully-controlled Right Turns

Providing dedicated phasing for all right turn movements has been well established as a significant safety improvement at signalised intersections. The key literature has been reviewed in Table A 1 in Appendix A.1.1.

D.3.2 Increased All-red Time

Increases to the time allocated for the change interval of intersections have been investigated in order to determine their potential to change crash rates. This can be done through increasing both yellow and all-red phases or increasing either the all red phase or yellow phase only.

National Cooperative Highway Research Program (2011) analysed the impacts of changes to interval times ranging from 0.8 to 2 seconds for various scenarios, finding that they led to significant reductions in total, injury and rear-end crashes.

D.3.3 Modified Cycle Length

Cycle length has the potential to impact signalised intersection safety and analysis at individual intersections may be required for optimal safety. Longer cycles may lead to red light running due to driver frustration but reduce driver exposure to yellow lights overall. As pedestrians may have to wait for longer periods of time, this change may lead to reduced pedestrian compliance (Federal Highway Administration 2013).

D.3.4 Rest-on-red

Rest-on-red (Dwell-on-red) sees the addition of a phase which displays a red traffic signal in all directions as the default setting for signals within the intersection; green signals are activated as road users are detected. Such a setting is thought to improve safety as drivers enter intersections at reduced speed. This treatment has been trialled at night in areas with alcohol-affected pedestrians on sections of road with high numbers of pedestrian crashes. Archer et al. (2008) and Lennè et al. (2007) both found significant reductions in driver speed when trialling this treatment.

D.3.5 Turn-to-red

Turn-to-red operates by connecting speed detection equipment to traffic signals. If vehicles are travelling above a set speed, a red traffic signal is triggered forcing the vehicle to stop at the intersection. A pilot study of the efficacy of such a system is currently underway in Swindon, UK (email document provided by Swindon Council, March 2014)

D.4 Pedestrian Safety

Pedestrians are vulnerable road users whose safety depends on their separation from vehicles travelling at high speeds. The behaviour of both pedestrians and motorists should be a key consideration when attempting to reduce the level of incidents at the intersection. The University of North Carolina Highway Safety Research Center (1999) offers the following advice:

- Pedestrians will generally wait 30 seconds at a signalised intersection before looking for gaps in traffic through which to cross.
- Motorist behaviour observed even when pedestrians are crossing at marked crosswalks[16]:
  - Motorists are likely to stop for pedestrians when traveling at 20 mph (32 km/h).
  - Motorists are not likely to stop for pedestrians when traveling at 35 mph (56 km/h).
  - Motorists rarely stop for pedestrians when traveling above 45 mph (72 km/h).

The impacts of such behaviour can be seen in crash statistics. Signalisation of intersections should minimise vehicle-pedestrian accidents by providing clearer and more enforceable priority control. Nevertheless, Koh, Wong and Chandrasekar (2014) found that 22% of fatal pedestrian accidents occurred at signalised pedestrian crossings, with one-third occurring when pedestrians faced a red signal. Such results suggest that a transition towards a Safe Systems ideal requires modifications to increase both pedestrian safety and pedestrian compliance at signalised intersections.

Without requiring complete intersection redesign, innovative signalling for pedestrians offers a means to increase compliance and safety. Vallyon and Turner (2011) recommended a number of pedestrian phasing changes aimed at reducing pedestrian delay (linked with crossing on red) and reducing the potential for pedestrian-vehicle conflict. Most suggestions are already in selective use in Australasia, but could be utilised more frequently to improve pedestrian safety at signalised intersections, for example:

- automatic demand for 'walk' phase
- scramble phase where pedestrian volumes are very high
- double-cycling, i.e. use of cycle length that allows pedestrian phases to be introduced twice as often as the other intersections in the coordinated chain.

While not directly addressing motorist behaviour, the placement of animated eye displays at intersections alongside pedestrian signals has been seen to increase pedestrian observation of traffic thereby reducing pedestrian-vehicle conflict (Van Houten et al. 1998, Van Houten, Malenfant & Steiner 2001, as cited in Federal Highway Administration 2013).

[16] In the USA, 'marked crosswalks' is the term used for pram crossing locations; they provide automatic pedestrian priority without the need for a zebra-crossing or other pedestrian solutions. The findings need to be considered in this context.

Countdown displays provide pedestrians with the time left for them to cross the intersection, reducing the chance that a pedestrian may cross when it is unsafe to do so. Pulugurtha, Desai and Pulugurtha (2010) review the performance of countdown displays at 106 signalised intersections on roads with speed limits of 35 and 45 mph. In each intersection the timer began at the flashing 'Don't Walk' signal. Decreases in the total number of crashes were seen to be greater at high crash intersections, smaller at medium crash intersections, with an increase in the total number of crashes at low crash signalised intersections. Results showed a statistically insignificant 13% decrease in the mean number of vehicle-pedestrian crashes alongside a 21% reduction in crashes overall suggesting that installation did not have an overall negative consequence.

Australian unpublished behavioural trials of the countdown timers in New South Wales, Victoria and South Australia showed no improvement in pedestrian behaviour in presence of countdown displays. The studies suggested there was no observed basis for crash reductions due to the treatment.

D.5 Addressing Other Factors

Enhanced signal visibility at intersections increases the time in which drivers have to respond to the requirements of the intersection, leading to a reduction in crash numbers. Sayed, Esawey and Pump (2007) conducted Bayesian analysis of 139 intersections that had signal visibility enhanced through the addition of increased signal lens size, installation of reflective backboards, reflective tape and new signal heads. Results showed an overall reduction in daytime, night-time and total collisions of 5.9, 6.6, and 7.3% respectively. Other studies of signal visibility are outlined below.

Federal Highway Administration (2010b) reported on the installation of retro-reflective back plates at signalised intersections selected for their high levels of crashes caused by traffic signal violations. Before/after evaluation found reductions of 28.6, 36.7 and 49.6% for total crashes, injury crashes and late night/early morning crashes respectively.

Amparano and Morena (2006) suggest the following treatments to increase the visibility of the signals:

- addition of supplementary signal heads at far-left and far right locations
- use of 30 cm diameter signal lenses, which are four times as conspicuous as those with a 20 cm diameter
- use of LEDs instead of incandescent globes for increased reliability and improved luminance efficiency
- installation of 'Red T Display' signals at intersections. This signal layout features two red lights at its head. Its installation across 12 intersections was shown to reduce right angle crashes by 35%.

Installation of a signal head above each lane of traffic on the approach to the intersection has been seen to result in a 28 and 35% reduction in all collisions and angle collisions respectively (Felipe, Mitic & Zein 1998, cited in Federal Highway Administration 2013).

Appendix E Design Innovations for Roundabouts

The safety benefits of roundabouts are derived from their reduction of vehicle speed and reduced vehicle angles leading to a reduction in crashes and their severity (Austroads 2013b).

The success of roundabouts will vary based upon the size of the central traffic island, speed approaching and through the intersection, the number of lanes, movement of vehicles through the intersection and crash energy management within the intersection. While roundabouts have proved to be a successful intersection treatment, there is room for improvement in terms of safety outcomes particularly in relation to the management of higher levels of traffic. The following review investigates literature relevant to continued innovation in the use of roundabouts for traffic management.

E.1 Strategies for Reduced Approach Speed at Roundabouts

Turner et al. (2009) find that approach speed plays a role in roundabout crash rates, with a 35% greater crash rate for roundabouts with an approach speed limit above 70 km/h compared to those 70 km/h or less. Speed within the roundabout also plays a factor as crashes within the roundabout decrease as the difference in speed between vehicles circulating and entering is reduced (Arndt & Troutbeck 1998). Treatments that will reduce vehicle entry speed will have a positive influence on intersection safety.

Use of a combination of vehicle speed reduction treatments is thought to increase potential speed reductions, however once drivers feel they are operating at a safe speed, additional speed reduction treatments are unlikely to have additional impact. The efficacy of such an approach is yet to be proven and research is ongoing (National Cooperative Highway Research Program 2008).

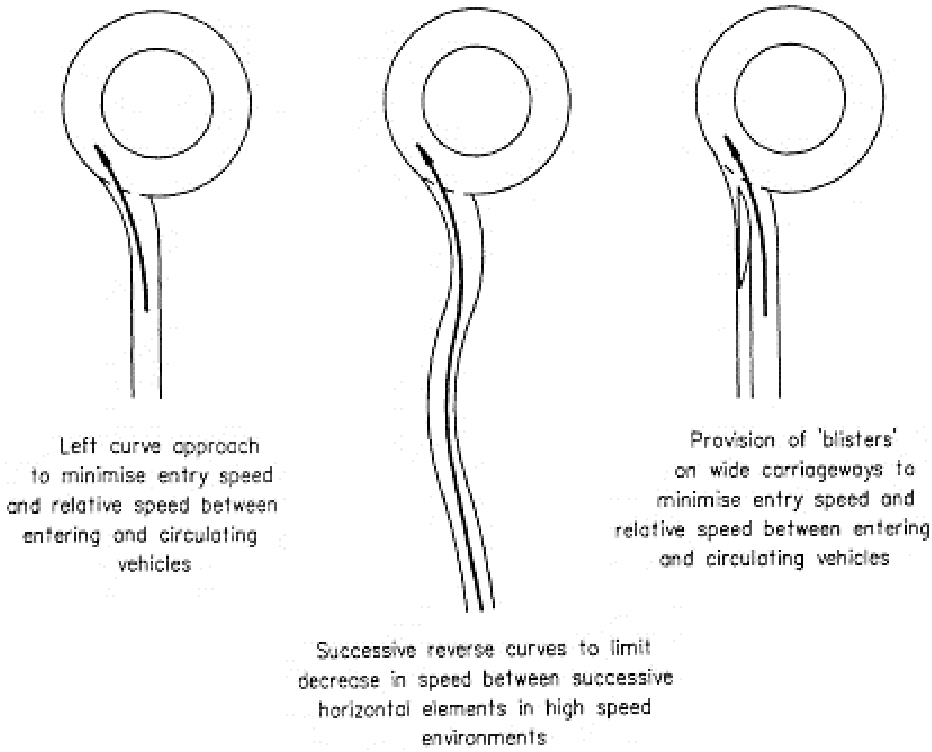
A summary of speed reduction performance of various treatments discussed in reviewed literature is outlined in Table E 1. Some of the methods are described in more detail in the following sections.

E.1.1 Horizontal Deflection on Approach

Roundabout approach curvature can be optimised for safety by introducing horizontal deflections that force vehicles to reduce their speeds. Approach geometry can be optimised by using a left curve approach with a radius that will require vehicles to reduce their speeds. Additionally, reverse curves can be used in order to achieve the desired speed decrease in higher speed environments (Arndt 2001). Control of the maximum entry path radius into the roundabout is also used. Examples of some of these approaches can be seen in Figure E 1. Installation of blisters and medians can also be used with similar effect in terms of forcing drivers to manoeuvre on approach.

Campbell, Jurisich and Dunn (2006) sought to identify the optimal maximum path radius for roundabouts to maintain 20–30 km/h negotiation speeds perceived as much safer to cyclists. Review of literature confirmed by field trials concluded that achieving a 30 m maximum path radius would provide the desired speed environment. Austroads (2009) derived a maximum path radius-negotiation speed relationship based on single-lane local road roundabouts. It suggested an optimal maximum path radius figure of 40 m. This work was based on operating approach speeds of 55 km/h, which were possibly lower than those in the Campbell, Jurisich and Dunn study.

Figure E 1: Approach geometry



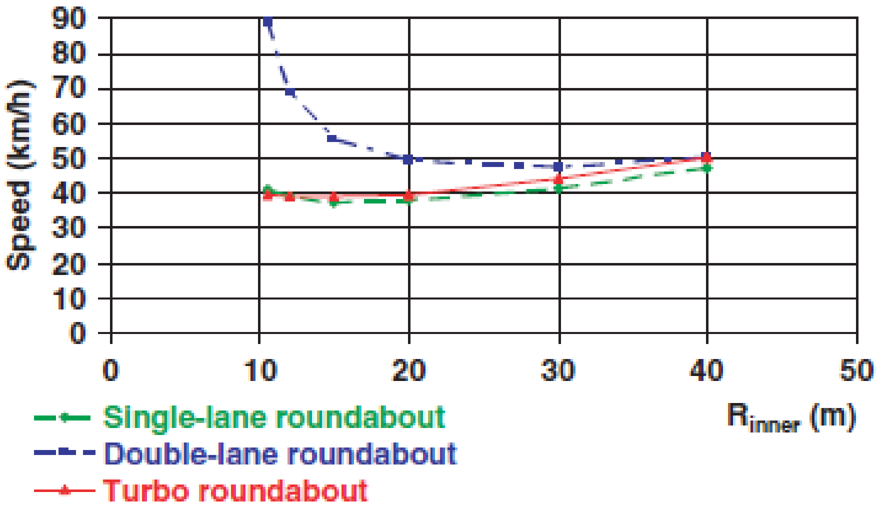
Source: Arndt (2001).

Campbell, Jurisich and Dunn (2006) also draw on Maycock and Hall (1984) to point out the inverse relationship for Austroads-type roundabouts, where tightening of the entry radius results in reduction in expected adjacent direction crashes, which were partially offset by increasing off-path crashes. The net safety gain was, however, for the tighter roundabouts. Arndt (2001) also confirms this finding.

Key considerations in terms of roundabout design include the radii of the path followed by vehicles on entry and the radius of the central traffic island itself, as the sharpness of deflection required by vehicles to negotiate the roundabout will influence the speed at which vehicles travel. Tighter roundabouts will generally require larger swept paths to accommodate heavy vehicles. This may require use of driveable centre island aprons.

Fortuijn (2009) shows that the speed of vehicles travelling through single lane roundabouts increases as the inner radius of the roundabout increases, while speeds are substantially larger for double-lane roundabouts at smaller radii as vehicles cut through the roundabout in low traffic situations as seen in Figure E 2.

Figure E 2: Relationship between pass through speed, roundabout type and inner radius



Source: Fortuijn (2009).

Increased roundabout entry width allows for the provision of additional lanes and capacity through the intersection at a cost of decreased safety. Analysis of UK and US crash data shows a relationship between entry width and entering-circulating crashes (National Cooperative Highway Research Program 2007). Further evaluation of crash frequency at roundabouts in the USA found that despite only making up one-third of the database investigated, 8 out of the 10 highest crash frequency sites were multilane. Turner, Roozenburg and Smith (2009) found that when compared to single entry lane roundabouts, those with multiple entry lanes had 66% more crashes. Such results suggest limitations in traditional roundabout designs when higher capacity demands are placed on the intersection.

When designing multilane roundabouts the use of one lane entry and exit for the minor roadways within the intersection may simplify navigation for cyclists (National Cooperative Highway Research Program 2010).

E.1.2 Vertical Deflection on Approach

While often used for midblock speed reduction, vertical deflection treatments may be used in order to reduce approach speeds to intersections. Vertical deflection treatments include road humps, road cushions, flat top road humps, wombat crossings and raised pavements.

Road humps and cushions are able to provide significant reductions in vehicle speeds but are not appropriate for placement in environments above 60 km/h. As it is recommended that they are placed away from intersections their placement in front of roundabouts should be considered carefully (Austroads 2008).

Wombat crossings are flat top speed humps with appropriate markings to give pedestrians priority while crossing. Installation of such crossings has been shown to reduce injury crashes by 39% Vaa (2006), while pedestrian injury crashes after installation were reduced by 42% when compared to ordinary crosswalks (Elvik et al. 2009). Wombat crossings should not be installed at the intersection and instead a raised pavement with a platform extending a car length should be used. In order to ensure that pedestrians do not believe they have right of way, if placed at an intersection the raised pavement should be separated from kerb ramps and refuges and not extend beyond the throat of the intersection (Austroads 2008). It should be noted that a Melbourne trial of a wombat crossing at the entrance to a roundabout was seen to reduce vehicle speeds and improve pedestrian safety. Through increased pedestrian compliance when crossing the intersection, such a treatment was also deemed likely to reduce accidents as pedestrian/vehicle conflict was confined to the crossing point (Candappa et al. 2005).

On local streets, innovative speed calming has been successfully achieved by combining speed humps with roundabouts. Figure E 3 shows an existing solution (likely a retrofit) in a busy residential and commercial precinct in Sydney. Site observations suggested satisfactory operation for both motorists and pedestrians.

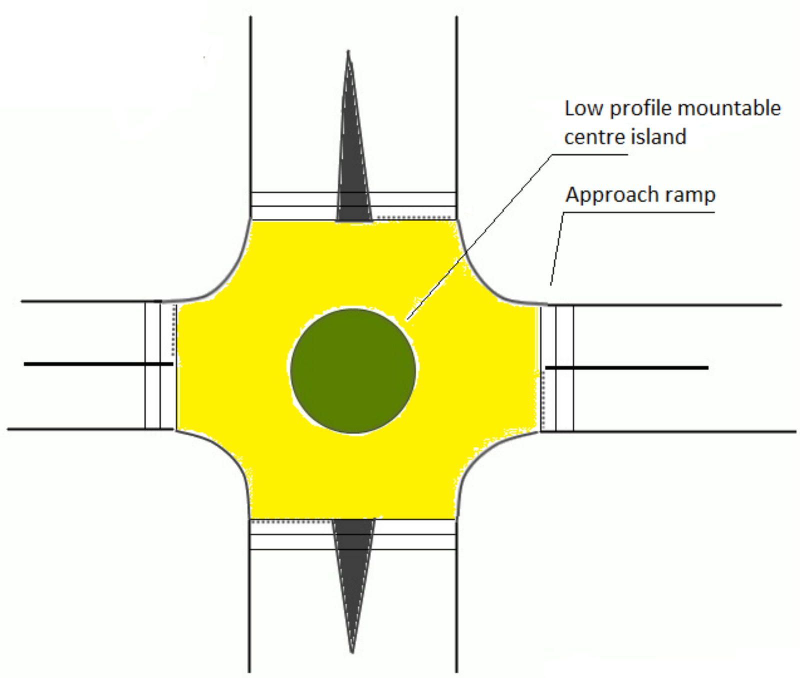
Figure E 3: Speed humps on roundabout approaches in Sydney

In situations where the installation of speed humps is deemed inappropriate due to higher operating speeds speed platforms using a shallow entrance ramp and flat top section still allow for speed reduction. Installation of platforms across seven urban arterial road sites in Australia found the average 85th percentile speed between platforms dropped from 66.1 km/h to 48.9 km/h. Speeds were seen to be lower for shorter platforms and for greater ramp gradients (Hawley et al. 1993). Moreno et al. (2011) found similar results in terms of the interaction between platform length and ramp gradient with five 50 km/h cross town roads showing a 20–25 km/h reduction in 85th percentile speed as a result of the introduction of speed tables (Figure E 4).

Figure E 4: Speed tables in use at shopping strip

There were no identified publications showcasing raised roundabouts. The principle is relatively simple, a combination of a platform intersection and a mini-roundabout as seen in Figure E 5. This concept could be tried in environments where a roundabout solution is desirable, but additional speed management is needed to achieve low speeds which cannot be achieved via horizontal deflections.

Figure E 5: Raised roundabout concept



E.1.3 Vehicle Activated Signs

Vehicle activated signs activate if an approaching vehicle is traveling above a set speed in order to warn motorists of the presence of a potentially hazardous location**.** Average mean speed reduction on approach to intersections in the UK was found to be 4 mph (6.4 km/h) (Winnett & Wheeler 2002).

Austroads (2014c) analysed literature surrounding VAS treatment sites in Australia finding that speed enforcing VAS led to an average mean speed reduction of 3 km/h and 85th percentile speed of 4 km/h. Average mean speed fell by 2 km/h and average 85th percentile speed by 4 km/h for intersection warning signs. Direct comparisons between the figures should not be made due to the different datasets used and the different situations in which the VAS were applied. These findings suggest that further research is required to understand the relevant location-based factors that lead to these results. Cost benefit analysis was also seen to be advisable due to the increased expenses of VAS when compared to static signage.

Table E 1: Measures to reduce approach speeds

Treatment	Author	Description of treatment	Changes to mean speed	85th percentile reduction
Vehicle activated signs	Winnett and Wheeler (2002)	Vehicle activated signs activate if an approaching vehicle is traveling above a set speed in order to warn motorists of the presence of a potentially hazardous location	Reduced by 6.4 km/h	
Vehicle activated signs	Austroads (2013b)		Speed enforcing: reduced by 3 km/h Intersection warning: reduced by 2 km/h	Speed enforcing: 4 km/h Intersection warning: reduced by 4 km/h
Rumble strips	Isebrands (2011)		Reduced by 4.7–6.9 km/h	
Speed control median	Forbes and Gill (2000)	Speed control medians used to slow traffic to 50 km/h by causing uncomfortable navigation at higher speeds	Reduced from 54–43.9 km/h	
Chicane	Sayer et al. 1998 (in Department for Transport 2007)		Speeds above 40 km/h for path angle 10 degrees or less. Speed below 19 km/h for path angle 15 degrees or greater	
Speed platform	Hawley et al. (1993)		Reduced from 66.1 km/h to 48.9 km/h	
Speed platform	Moreno et al. (2011)			Reduced by 20–25 km/h
Perceptual countermeasures		Affects driver perception of speed by using chevrons, patterns or bars on the side of the road		
Herringbone pattern	Macaulay et al. (2004)		Reduced by 2–4 km/h	
Converging chevron pattern	Corkle 2001 (cited in Hallmark et al. 2007)		Reduced by 4.8–8 km/h	

E.1.4 Perceptual Countermeasures

Road features which affect a driver's perception of the road result in safer driving behaviours, although it has been suggested that this change may be a result of the markings acting as a visual warning rather than because of any change in perception.

Horizontal bar markings on the approach to roundabouts were seen to result in a 60% reduction in accidents. Herringbone patterns that were tested gave the perception of a narrowed road and resulted in speed reductions of 2–4 km/h (Macaulay et al. 2004). A converging chevron pattern as a traffic calming measure was also seen to reduce speed 3–5 mph (4.8–8 km/h) with this effect maintained over time (Corkle (2001, cited in Hallmark et al. 2007)).

Figure E 6: Herringbone

Source: Macaulay et al. (2004) and converging chevron patterns (Corkle (2001, cited in Hallmark et al. 2007).

E.2 Reducing Severity of Vulnerable User Injury at Roundabouts

E.2.1 Cyclists

The negative safety implications of roundabouts placed at intersections for cyclists are well documented. Jensen (2013) analysed roundabouts in Denmark finding that converting intersections to roundabouts led to a 65% increase in bicycle crashes and 40% increase in injuries. Before and after safety comparisons based on speed found overall safety improvements for speed limits 80–130 km/h but declines for limits between 40–50 km/h. Analysis of the various treatments used for bicycle movements found that a cycle path with no priority for cyclists crossing the arms of the roundabout had the best safety effects, while cycle lanes offering cyclists priority had the worst safety outcomes. When roads approaching the roundabout have bicycle lanes, it is recommended that they terminate at a point that will result in cyclists merging with traffic. Such a design will move cyclists away from the edge of the roundabout where they could be hit as vehicles enter and exit (National Cooperative Highway Research Program 2010).

Rather than using a separate bicycle lane, the c-roundabout design seen in Figure E 7, aims to reduce vehicle speeds to 30 km/h, a speed which has been found to allow cyclists to safely mix with traffic (Campbell, Jurisich & Dunn 2006). A comparison between a c-roundabout and traditional roundabout can be seen in an analysis of the implementation of such a design at the intersection of two minor arterial roads in Auckland which found reduced speeds, but a longer time period is required to determine an increase in safety (Asmus et al. 2012).

Along arterial roads where such reductions in speed may be undesirable, signalised roundabouts also show safety benefits for cyclists. Studies have found that adding signals to roundabouts leads to an 80% reduction in crashes (Transport for London 2005), while their presence was also noted to lead to an 18% reduction in injuries (Jensen 2013).

Austroads (2011) offers a number of design treatments to improve the safety of cyclists at roundabouts but notes that their benefits have not necessarily been confirmed. In cases of physical separation between a bike lane and drivers, the suggested treatment for collector or arterial roads is the provision of marked lanes with a contrasting surface to alert motorists of the likely presence of cyclists. For roundabouts without a physical separation, vehicle entry path radius should be such to prevent cars from cutting across the bike lane when cyclists are not present. The difficulty faced by cyclists in multilane roundabouts is such that there is no treatment that will allow for a safe right turn to be made, despite this, placement of bike lane markings is recommended to heighten the awareness of motorists of the possibility that cyclists may be present and to assist cyclists that choose to use the intersection.

Figure E 7: Comparison between regular roundabout and c-roundabout

Source: Asmus et al. (2012).

E.2.2 Motorcyclists

Rates of personal injury at roundabouts have been connected exponentially to motorcycle usage. Such a relationship suggests current management of motorcyclists through roundabouts is unsatisfactory (Federal Highway Administration 2000). While installation of roundabouts leads to a reduction in severe injuries for motorcyclists the benefits are not as substantial as they are for car users.

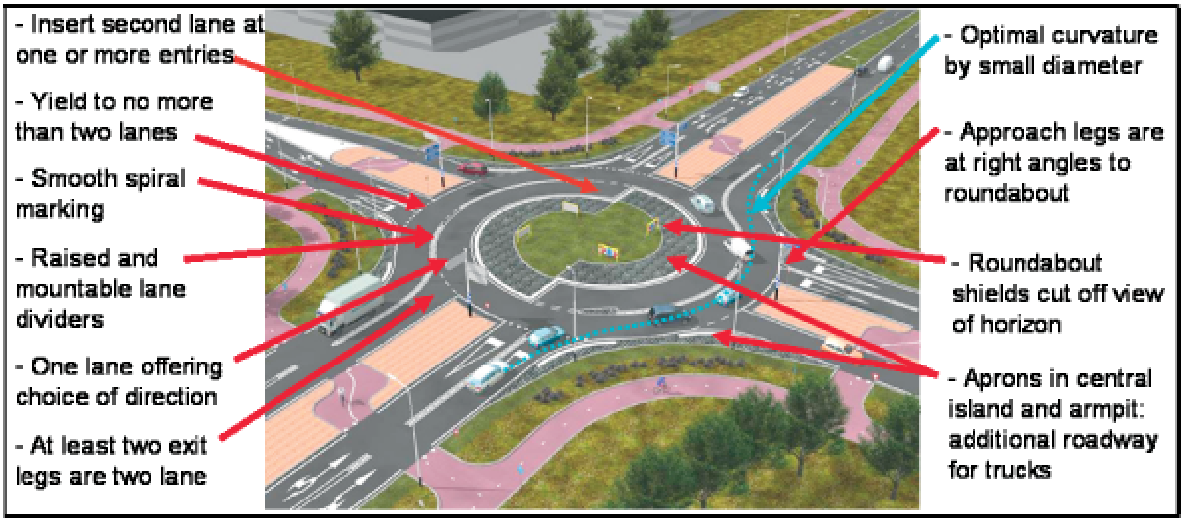
E.3 Alternative Designs

E.3.1 Turbo-roundabout

Multilane roundabouts are used when traffic volumes are too great for a single-lane roundabout to manage effectively. The relationship between vehicle path curvature and speed presents a safety challenge as the crash rate benefits resulting from increased curvature and reduced speeds seen in single lane roundabouts can lead to vehicles cutting across lanes thereby increasing the potential for sideswipe collisions in double lane roundabouts. Fortuijn (2009) also notes that changing lanes within the curve may be required to exit and that attempting this from the middle lane results in conflict between users and reduced capacity.

These issues can be managed by the introduction of a turbo roundabout, which requires drivers to use specific lanes based upon their desired exit and uses raised lane dividers to ensure drivers remain on the required curvature as seen in Figure E 8. This maintains lower speeds and reduces the possibility of a sideswipe collision. This implementation sees safety outcomes similar to that of a single lane roundabout, for seven intersections in the Netherlands that were converted, a 72% reduction in casualties was measured (Fortuijn 2009). Beyond safety benefits, modelling also suggests a 25–35% increase in capacity when compared to a regular two-lane roundabout (Engelsman & Uken 2007). It should be noted that turbo-roundabouts may also be designed without raised lane dividers, however the safety of such a roundabout is comparable to a standard multi-lane roundabout (Macioszek 2013).

Figure E 8: Turbo-roundabout



Source: Fortuijn (2009).

As road users may be unfamiliar with the manner in which a turbo-roundabout operates, appropriate markings are required to ensure that drivers are able to select the appropriate lane on entry to the roundabout. Consistent road signs and lane markings should be used emphasising both the shape of the intersection as well as the number of lanes and exits which they service (Macioszek 2013).

E.3.2 Mini-roundabout

Mini-roundabouts are small roundabouts that can be installed where there is insufficient space to install a full roundabout at the middle of an intersection as seen Figure E 9.

Figure E 9: Mini-roundabout

Source: Department for Transport (2011).

The central island of a mini-roundabout can either be painted or consist of a traversable raised pad allowing for larger vehicles to pass through the intersection. Mini-roundabouts offer similar benefits to regular roundabouts in terms of improvements to junction operation, accident reduction and as a traffic calming measure. While vehicle capacity is similar to a compact urban roundabout, the installation of a mini-roundabout may be done at a lower cost when retrofitting intersections due to their reduced footprint (Federal Highway Administration 2000). Control of vehicle approach speeds is important to ensure that the mini-roundabout operates safely, the marked or slightly raised central island should not be relied upon to reduce vehicle speed alone (Department for Transport 2011).

Severity of crashes (fatal and serious injury) at mini-roundabouts at three-legged intersections is lower than found at signalised or T-intersections (Department for Transport 2011). Installation of 35 mini-roundabouts in the City of Monash as a result of cross-traffic crashes have seen casualty crashes at these intersections drop from 20 in the previous five years to one in the years post-installation (concurrent Austroads project on Safe System for local government). Positive results were also seen in the conversion of 13 unsignalised intersections in Germany which saw a 29% reduction in crash rate (Brilon 2011).

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