Understanding and Improving Safe System Intersection Performance

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Research Report

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Abstract

Intersection crashes account for approximately 30% of severe injuries in Australia and New Zealand. This study sought to improve understanding of the key factors in intersection severe injury crashes, and to develop initiatives to improve the design of intersections for better alignment with the Safe System objective of minimising death and serious injury.

The study reviewed recent literature and data to synthesise the following Safe System intersection design principles: minimise conflict points, remove/simplify road user decisions, minimise impact angles, and minimise entry and impact speeds.

Using inputs from literature and data findings, a new safety analytical method, and practitioners, the study proposed nine innovative intersection design concepts seeking to increase Safe System alignment across a wide range of scenarios (urban/rural, new/retrofit). These design concepts form a starting point for practitioners' trials and refinement.

The study concluded that achievement of Safe System for intersections requires significant supporting contributions from emerging transport disciplines such as C-ITS, autonomous vehicles, and Movement and Place.

Keywords

Safe System, intersections, crashes, pedestrians

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About Austroads

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Austroads' purpose is to support our member organisations to deliver an improved Australasian road transport network. To succeed in this task, we undertake leading-edge road and transport research which underpins our input to policy development and published guidance on the design, construction and management of the road network and its associated infrastructure.

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- Transport Canberra and City Services Directorate, Australian Capital Territory
- Australian Government Department of Infrastructure and Regional Development
- Australian Local Government Association
- New Zealand Transport Agency.

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Summary

Intersection crashes account for approximately 30% of severe injuries (fatal and hospitalisation) in Australia and New Zealand. While research has been able to quantify the magnitude of the intersection problem, there is a lack of understanding surrounding the poor Safe System performance of traditional intersection designs. Current Austroads guides do not address this and there is little other practical guidance available to road agencies on how to modify intersection designs to minimise the occurrence of death and severe injury.

In response to these gaps, Austroads commissioned the Australian Road Research Board to seek initiatives to improve the design of intersections so that they would be better aligned with the Safe System objective of minimising death and serious injury.

The study involved a review of recent research and data relating to the Safe System performance of intersections to better understand who, where, and how people were severely injured at intersections.

The main conclusions from this investigation, based on Victorian and New Zealand data, were as follows:

- Intersection types with the greatest contribution to the severe injury problem were
  - urban priority-controlled intersections due to high crash rate, but also high number of crashes
  - urban signalised intersections due to high number of crashes, but also a relatively high crash rate
  - rural priority-controlled intersections due to the highest crash rate, but a lower number of crashes.
- The intersection type closest to the Safe System vision was the urban roundabout, followed by the rural roundabout.
- Three-leg intersections were safer than four- or multi-leg intersections due to fewer conflict points and reduced complexity.
- The main traffic movements of concern, according to the leading fatal and serious injury (FSI) crash types, applicable to both investigated jurisdictions, were
  - adjacent direction movements
  - opposing-turning
  - pedestrians crossing or stepping out
  - off-path movements, i.e. loss-of-control.
- Among the vulnerable road users, the following urban scenarios presented the greatest concern for Safe System intersection design (based on Victorian data)
  - pedestrians at priority-controlled and signalised intersections
  - cyclists and motorcyclists at priority-controlled intersections and at roundabouts (a high proportion but not a high number).

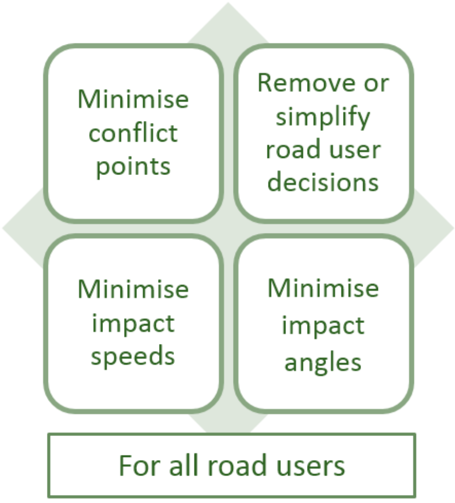
These learnings were extended by further, targeted analysis of US and Australian crash reconstruction research to develop a new research method for the analysis of severe injury probability when crashes occur at intersections. The method, called X-KEMM-X v0.5, focussed on impact speeds and angles, and different crash types (e.g. side, frontal, rear, pedestrian) at each conflict point. Thus, minimum, average and maximum severe injury probabilities can be estimated for any given intersection design.

The X-KEMM-X method was useful in demonstrating the relative alignment of selected conventional intersection design concepts with Safe System objective of minimising fatal and serious injury in vehicle-vehicle and vehicle-pedestrian conflicts. In general, priority and signalised intersections permitting impact speeds of 50 km/h and above, at approximately right angles, may be considered very poorly aligned with the Safe System. For such geometry, high Safe System alignment may be achieved at impact speeds at or below 30 km/h for vehicle occupants. High Safe System alignment for adult pedestrians may occur if impact speeds are at or below 20 km/h, regardless of geometry.

Roundabouts were shown to be highly aligned with the Safe System for vehicle-vehicle conflicts (except of cyclists and motorcyclists), but poorly aligned for vehicle-pedestrian conflicts.

Further review of local and international literature and road agency trials identified innovative intersection designs which seek to address the key severe injury risk factors, and to achieve greater Safe System alignment. These solutions were analysed using the available research information and X-KEMM-X results. This showed that roundabouts and their derivatives (e.g. signalised roundabout, flower roundabout) had the greatest potential to deliver Safe System outcomes.

The review of the literature and the findings of the data analysis led to development of the following Safe System intersection design principles, as shown by the figure:



Practitioner-level guidance was then proposed, based on these principles combined with the logic of the Safe System Assessment Framework (SSAF). This guidance may be considered for the future revisions of the Austroads guides.

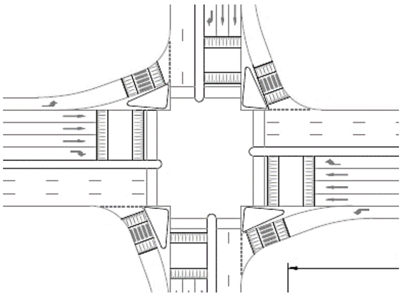
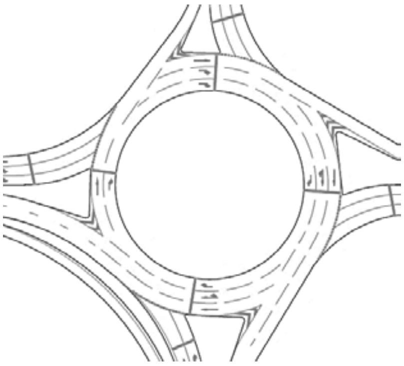
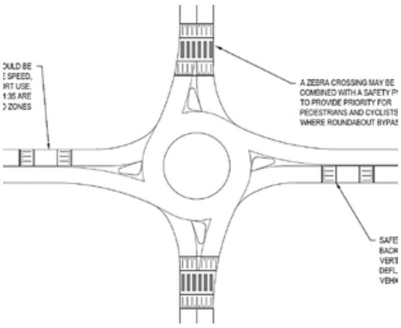
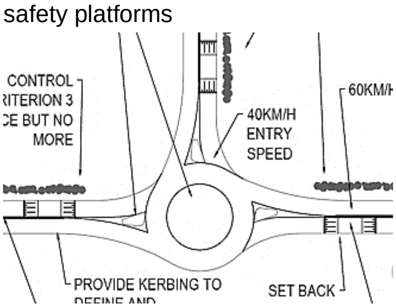
Nine innovative solutions were chosen for further concept development (summary table on the next page). Substantial practitioner consultation was undertaken to convey the Safe System design principles used in the design concepts, and to seek practitioner-driven concept improvements. These design concepts offer varying levels of network applicability, Safe System alignment and cost. Some of the ‘poorly aligned’ solutions still offer a notable severe injury risk reduction in comparison to the conventional solutions they could replace. These design concepts could act as supporting Safe System solutions.

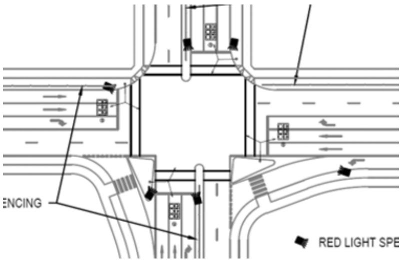
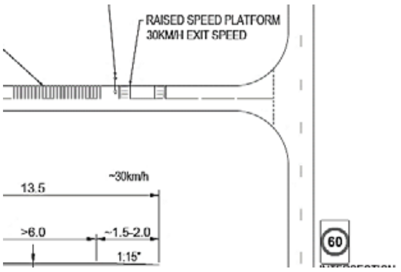
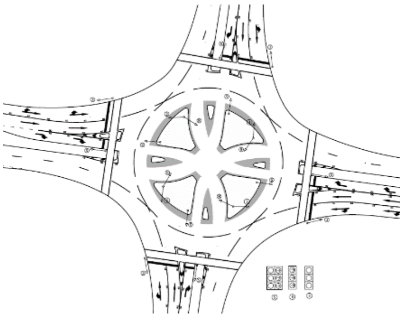
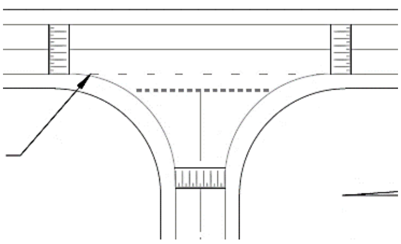
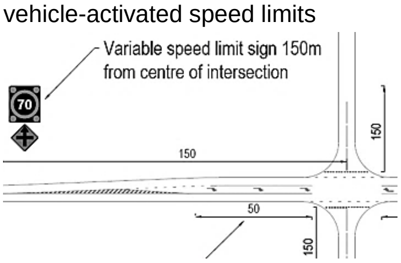
The Safe System performance for vehicle-pedestrian conflicts was generally poorer than for vehicle-vehicle conflicts. This was always due to intersection entry speeds being 40 km/h or 50 km/h, i.e. above the estimated biomechanical threshold for adult pedestrians of 20 km/h. Similar findings were applicable to cyclists and motorcyclists, although the impact speed threshold evidence was not precise for these two groups. The findings highlight that contributions from other Safe System pillars will be needed to make intersections safe for vulnerable road users (e.g. autonomous vehicle safety systems).

These design concepts form a starting point for practitioners’ trials and refinement. It is intended that some will become widely used to improve the Safe System performance of intersections, and will inform future revisions of the Austroads guides.

The study led to a conclusion that speed management and geometric design alone are unlikely to achieve Safe System outcomes for all user groups at intersections. Autonomous vehicle technologies, C-ITS and Movement and Place approach are some of the transport management initiatives which are likely to provide significant supporting contributions to the Safe System vision in near future.

Summary of innovative Safe System design concepts

Concept name	Applicability	Safe System alignment *		Crash reduction factor	Cost (retrofit/ new)
		Vehicle-vehicle	Vehicle-pedestrian		
Signalised intersection with safety platforms 	Urban Retrofit, greenfield Emerging solution, under trial	Poor to moderate	Poor to moderate	30% estimated casualty, retrofit to signals 50–60% casualty, replace priority-controlled (estimate)	Low to moderate
Signalised roundabout 	Urban, outer-urban Retrofit (large sites), greenfield Established traffic solution	Moderate to high	Poor	11% all-crashes, retrofit to roundabout 65% casualty, replace priority-controlled (estimate)	Moderate to high
Urban compact roundabout with safety platforms 	Urban, outer-urban Retrofit, greenfield Emerging solution already in use	High	Moderate	55% casualty, replace priority-controlled (estimate)	Low to moderate
Rural compact roundabout with safety platforms 	Rural Retrofit, greenfield Conceptual solution, not yet trialled	High	n.a.	70% casualty, replace priority-controlled (estimate)	Low to moderate

Concept name	Applicability	Safe System alignment *		Crash reduction factor	Cost (retrofit/ new)
		Vehicle-vehicle	Vehicle-pedestrian		
Signalised intersection retrofit combination treatment 	Urban, outer-urban Retrofit, greenfield Already in use	Poor	Poor	50% casualty and FSI, retrofit to signals (estimate)	Moderate
Priority-controlled rural intersection with safety platforms and reduced speed limits 	Rural Retrofit Conceptual solution, not yet trialled	Moderate to high	n.a.	Not available	Low
Cut-through signalised intersection 	Urban, outer-urban Greenfield Conceptual solution, not yet trialled	Moderate to high	Poor	Not available	High
Priority-controlled raised intersection 	Urban Retrofit, greenfield Emerging solution already in use	High	Poor to moderate	55% casualty, retrofit to priority-controlled	Moderate
Priority-controlled intersection with vehicle-activated speed limits 	Rural Retrofit Emerging solution already in use	Poor to moderate	n.a.	51% all crashes, 79% FSI crashes, retrofit to priority-controlled	Low to moderate

** Based on used case studies.*

Contents

Tables

Figures

1. Introduction

1.1 Background and Study Objectives

Intersection crashes account for approximately 30% of severe injuries in Australia and New Zealand. Severe injury is a fatal or serious injury (FSI). Terms severe injury and FSI are used interchangeably in the report.

While research has been able to quantify the magnitude of the intersection problem, there is a lack of understanding surrounding the poor Safe System performance of traditional intersection designs. Current Austroads guides do not address this, and there is little other practical guidance available to road agencies on how to modify intersection designs to minimise the occurrence of severe injuries.

Most existing intersection layouts permit vehicles to travel along conflicting paths at speeds higher than the impact speeds regarded as thresholds of severe injury. Also, most standard intersection layouts permit collision angles that do not optimise the protection to occupants given the limitations of modern vehicles.

In response to these gaps, Austroads commissioned the Australian Road Research Board (ARRB) to seek initiatives to improve the design of intersections so that they would be better aligned with the Safe System objective of minimising death and serious injury.

The objectives of the study were to:

- gain a better understanding of the Safe System performance of existing intersection forms and the specific movements under various conditions and environments
- develop initiatives to address the failings of existing intersections
- draft alternative intersection designs that better align with the Safe System objectives
- improve designers' understanding of the approach (practitioner consultation and inputs)
- inform future updates of the Austroads Guide to Road Design.

This study built on the previous Austroads research undertaken via the Improving the Performance of Safe System Infrastructure study (Austroads 2015) and Safe System Roads for Local Government (Austroads 2016a). These studies investigated Safe System intersection improvements, especially for vulnerable road users.

1.2 Outline of Work Undertaken

The study was conducted over a 2.5-year period to accommodate the time required to conduct in-depth literature reviews, collect and analyse data, and engage in extensive consultation and prepare the report.

The authors reviewed recently-published literature on safety performance of intersections of different types, in different road environments, and for different road user movement types. The review focussed on factors associated with the frequency and risk of severe crashes at intersections. This included review of results from statistical modelling and road safety evaluations from Australia, New Zealand and overseas. Some of the risk factors sought included the effect of approach AADT, intersection control type, intersection geometry and facilities on the safety of vulnerable road users. The findings of the review are reported in Section 2.1.

Re-analysis of road agency data from earlier studies was undertaken to support the findings of the reviewed international literature with Australasian evidence. Severe crash rates data from New Zealand and Victoria were used to draw attention to common trends. The findings of this analysis are presented, together with the literature review, in Section 2.1.

A separate literature review was undertaken to gain a better understanding of the critical intersection risk factors of impact speed, angle and type (e.g. frontal, side, rear). The review drew on the US literature from the crash reconstruction field. Analysis of the University of Adelaide Centre for Automotive Safety Research in-depth crash database was used to broadly confirm the international findings. The findings were then used to construct a theoretical method for crash severity estimation at intersections. The Extended Kinetic Energy Management System for Intersections (X-KEMM-X v0.5) is presented in Section 2.2 and summarised in more detail in Appendix B. Its aim is to assess the number of conflict points at an intersection, and then to predict a theoretical probability of a severe injury from a collision conflict at each point. Intersection-wide metrics point to the level of Safe System alignment.

This method was then applied to conventional intersection designs found in Austroads as a form of analytical critique showing how well the established intersection design forms align with the Safe System objectives (Section 2.3).

Building on the previous tasks, a literature review was undertaken on recent innovations in Safe System-focussed intersection design solutions. In particular, the review drew on the relevant published findings from MUARC's research on Safe System intersection design (Corben et al. 2010a, 2010b). The review referenced recent and concurrent Austroads research on improving safety at intersections through reduced speeds, and on urban/rural arterial speed management. The review was also informed by the recent research and policy publications from New Zealand, such as the High Risk Intersections Guide (NZ Transport Agency 2013). The findings of the review are presented in Section 2.4, including the knowledge gaps.

Synthesis of the knowledge developed in Section 2 informed the development of the Safe System intersection design principles presented and discussed in Section 3. The principles were developed with input from the Project Steering Group, which consisted of road agency road safety and design experts. The design principles may form a useful input into the relevant parts of the Austroads Guide to Road Design.

The Project Steering Group also provided inputs into the selection of innovative design concepts for further development to the design concept stage, based on agreed applicability criteria. Section 4 lists these criteria, along with the summary of Safe System alignment of the design concepts detailed in Sections 4.1 to 4.9.

Sections 4.1 to 4.9 present summary information on intent, application, design and costs of nine innovative intersection design concepts. Each section also provides Safe System analysis results and stakeholder inputs on potential improvements.

The general information on each treatment was sourced via extension of the literature review undertaken in Section 2.4. Inputs from international experts (EU mainly) and from yet unpublished work were successfully obtained to inform some of the design concepts. Examples of local and overseas application are provided, where available. Interviews with road agency experts provided inputs on network applicability and costs, likely road user acceptance and behaviour, constructability, asset maintenance and legality in the context of the road rules.

The authors used two methods to apprise the relative Safe System alignment of each design concept: Safe System Assessment Framework (SSAF) and X-KEMM-X.

SSAF is documented in Austroads (2016b) and summarised in Appendix A. The assessment was undertaken by multi-disciplinary teams during a series of 15 workshops across all state jurisdictions and New Zealand during late 2016. Workshops included a wide range of transport professionals such as transport planners, policy makers, road safety experts and senior road designers, the Police, asset managers and road designers. All workshops were attended by senior road agency managers.

The process involved a brief training of groups, four to eight in size, in the application of SSAF. Each group was then given an innovative design concept to evaluate and score. A Safe System challenge was then put to each team to improve the alignment of their design and this resulted in various proposed design improvements being suggested. Some of these were then incorporated into the designs presented in Sections 4.1 to 4.9. Other improvements deemed to be outside of the design intent were captured separately (e.g. too high-cost for a low-cost retrofit).

Each design concept was then evaluated using the X-KEMM-X method (v0.5). Various X-KEMM-X metrics were reported for each design concept including average Pr(FSI), i.e. the average probability of a fatal or serious injury in a crash event, maximum Pr(FSI), and the number of conflict points exceeding the nominal 10% Pr(FSI) threshold.

The workshop outcomes were collated and fed back into each design concept and used in the final refinements and in the preparation of this report. These findings can be trialled by road agencies, evaluated and refined. The lessons learned about in-service performance of the solutions may be used to expand practitioner design choices in future editions of the Austroads Guide to Road Design.

2. Safe System Performance of Intersections

Safe System vision has an objective of zero deaths and serious injuries as a result of using road transport system (Australian Transport Council 2011). The vision is based on these basic principles:

- Consideration of the role of roads and roadsides, vehicles, people and speed working together to minimise harm.
- Expecting that crashes will continue to occur due to human error, but seeking to eliminate systemic opportunities for such errors to occur.
- Where crashes do occur, managing their energy so that the outcomes are not severe.

The vision asks all participants in road transport, including road designers, traffic engineers and transport planners, to take responsibility for creating a system which is forgiving of human error.

In this human-centred context, Safe System seeks to put safety of users at the core of all other activities such as maximising transport efficiency, optimising system capacity, or asset improvement. The Safe System vision has formed the foundation of road safety in Australia and New Zealand for over a decade. Several recent Austroads publication provide more depth on the development and implementation of the Safe System approach for different elements of the road network and road use (Austroads 2012, 2014, 2015, 2016a, 2016b, 2016c).

This section draws on the key findings of recent and concurrent studies to present more in-depth understanding of where, how and for whom the current intersection designs fail to achieve Safe System outcomes. Some of the key severe injury factors are explored, which will need to be addressed to evolve intersection design towards the Safe System objective. Selected examples of Safe System innovation in intersection design practice from Australia, New Zealand and other countries are also reported in this section. These examples inform which elements of intersection design work towards minimising the identified severe injury factors.

2.1 Review of Research on Safe System Performance of Conventional Intersections

This section presents a summary of recent international research and data on the safety performance of intersections of different types, in different road environments, and for different movement types. The review focused on the key factors associated with the occurrence of severe crashes at intersections.

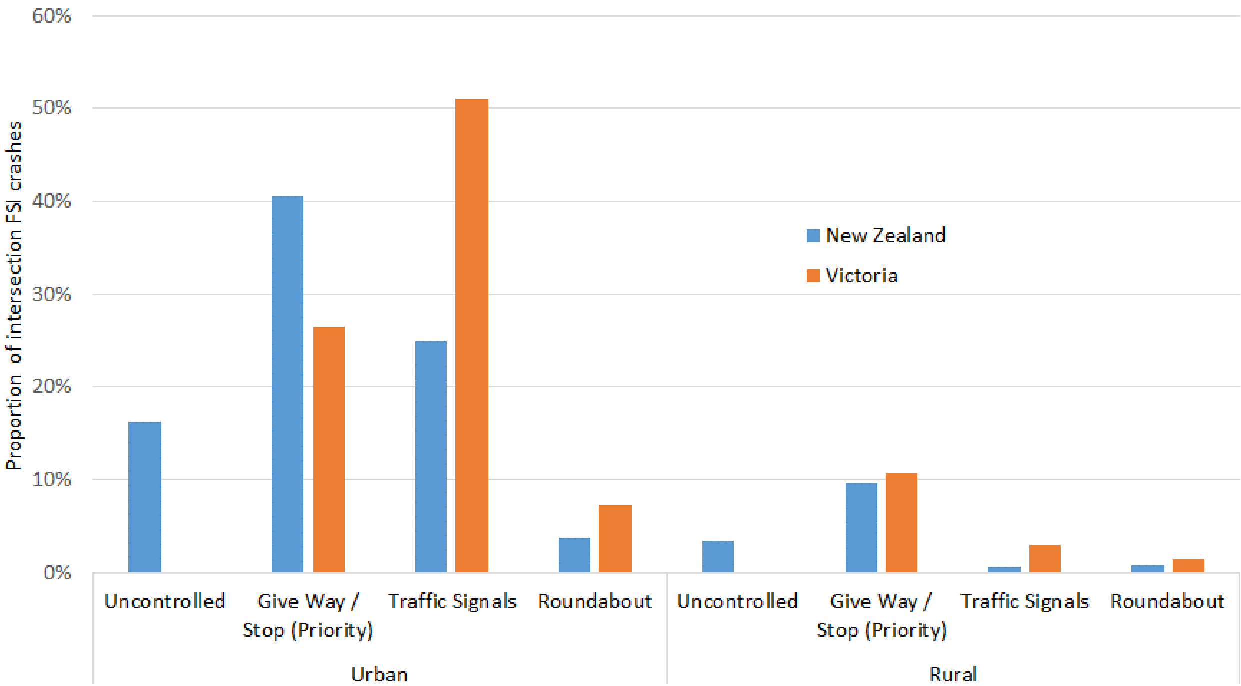
The review contains and extends some relevant Austroads research findings from a previous study on *Improving the Performance of Safe System Infrastructure* (Austroads 2015). It also utilised Victorian and New Zealand intersection crash data made available to the study team. While the data sets were representative of these jurisdictions at the time, and the findings do differ, they highlighted the top common intersection design issues which are likely to arise in other jurisdictions.

2.1.1 Road Environment and Intersection Type

Rural and urban road environments have the same intersection control types, but in different proportions. Rural roads have generally less intersections, but a greater proportion of them are controlled by priority rule only: uncontrolled (no signs), Give Way signs, or Stop signs. Very few rural intersections are signalised, or are roundabouts. In urban environments, there are more signalised intersections, and these also tend to control large traffic flows, i.e. there is a higher exposure to crash risk.

The effect of these differences on fatal and serious injury (FSI) crashes can be seen in Figure 2.1, based on New Zealand and Victorian data samples. It is clear that, in both jurisdictions, the bulk of the severe crash problem is in urban areas. New Zealand differs from Victoria in that most of its urban intersection crashes are associated with priority controls at intersections[1]. Regardless, urban priority control and signalised intersections and rural priority control intersections are the three intersection types that require further focus to address the bulk of the severe injury burden. This finding echoes the earlier findings based on 2000–2005 Victorian data analysed by Hoareau, Candappa and Corben (2011).

Figure 2.1: FSI crashes for different intersection types in New Zealand and Victoria



Note: Percentages relate to total of severe intersection crash sample in each jurisdiction separately.

Source: Victoria crash data 2006–2011, New Zealand CAS database 2006–2011, provided by NZTA.

While Figure 2.1 presents the relative magnitude of the FSI crash problem, it does not account for the 'exposure', or amount of traffic, using each intersection type. The individual vehicle FSI risk associated with different intersection types is shown in Figure 2.2 and Figure 2.3. This is based on the New Zealand and Victorian crash rates, i.e. adjusted for entering traffic volumes. Rural priority control intersections are highlighted as generating the highest risk of FSIs among the different control types. Notably, urban priority intersections are almost as hazardous in Victoria. This high risk ranking of priority intersections could be explained by the relatively high likelihood of road user error when giving way (e.g. poor gap acceptance, confusion).

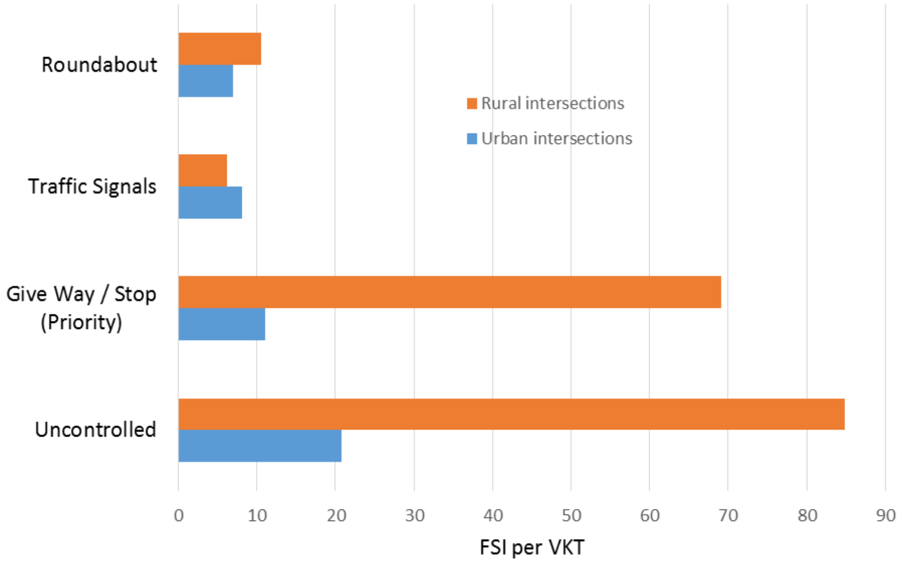
Signalised intersections and roundabouts have much lower levels of individual driver risk. The use of traffic signals to replace priority control was reviewed in Austroads (2013a). It provides a detailed analysis of safety performance of this element. The following are the headline parameters:

- 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).
- Average casualty crash reduction based on research reviewed in Austroads (2012) was about 30%, with findings ranging between 5% and 53%.

1 Stakeholder feedback suggests that the number of signalised intersections is lower in New Zealand cities compared to Victorian cities (dominated by Melbourne).

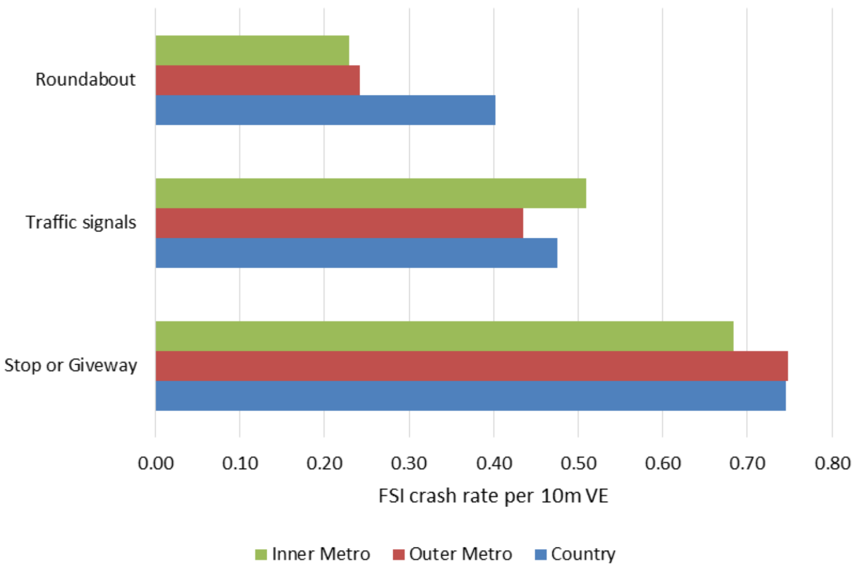
- Signalising four-leg intersections were more effective (23–30% typical crash reduction) than signalising three-leg intersections (about 15% reduction).
- Fully controlling right-turns was a particularly effective treatment at already-signalised intersections, with an expected reduction of 80–90% in opposing-turning casualty crashes (overall, a 45% reduction in all casualty crashes).

Figure 2.2: FSI crash rate per vehicle-kilometre of travel (VKT) for different intersection types in New Zealand



Source: New Zealand crash data 2006–2011, provided by NZTA.

Figure 2.3: FSI crash rate per 10m VE* for different three-leg intersection types in Victoria



** Per 10 million vehicles-entering.*

Source: Based on Victorian crash data 2002–2007. Crash rates controlled for number of approaches (three-leg intersections only).

Signalisation is frequently an urban solution, or one introduced in response to urbanisation and increasing traffic flows and crash history. The lower FSI risk at signalised intersections observed in Figure 2.2 and Figure 2.3 could be attributed to increased levels of traffic management, i.e. simplification of decision-making, guidance, and limited reliance on sight distance and gap selection.

Roundabouts generally have lower FSI risk per vehicle than signalised intersections[2]. Published research reviewed in this study showed that replacement of priority control with roundabouts reduces:

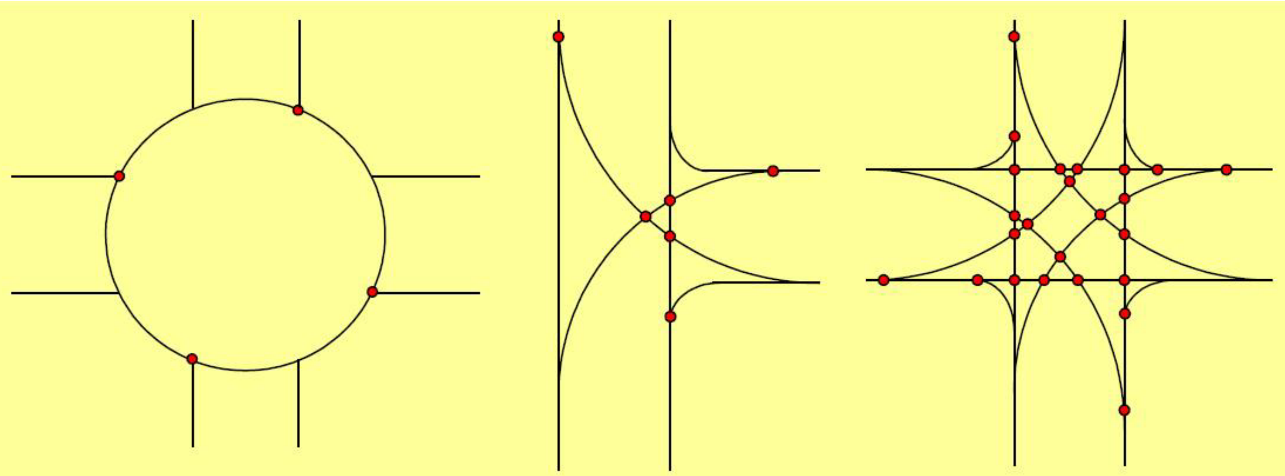
- all-casualty crashes by 45–87% (e.g. Persaud et al. 2000; Elvik et al. 2009; BITRE 2012)
- severe crashes by 37–90% (e.g. Persaud et al. 2000; Churchill, Stipdonk & Bijleveld 2010)
- fatal crashes by 63–100% (e.g. Rodegerdts et al. 2007; Isebrands 2009).

There was only one identified study which evaluated conversion of signalised intersections to roundabouts. Gross et al. (2013) found a 66% casualty crash reduction when signalised intersections were converted to roundabouts. Further, it was identified in Austroads (2015) that the average FSI crash rate for the urban roundabouts studied was about half that for urban signalised intersections. This is echoed in Figure 2.2 for the urban environment, and in Figure 2.3 for all environments (controlled for basic geometry), where FSI crash rates were much lower for roundabouts than signalised intersections.

There are multiple reasons why roundabouts have better Safe System performance than both priority control and signalised intersections. These can be categorised as follows:

- reduced number of conflict points (see Figure 2.4)
- approach and circulating speeds are lower and impact angles are smaller due to geometry, leading to crash types of lower severity (e.g. side swipes)
- entering drivers' expectation to give way (identified in Austroads 2015), as there is no assigned right-of-way to any approach at a roundabout
- simplified decision-making – drivers need to be concerned only with traffic already within the roundabout, typically to the right.

Figure 2.4: Conflict points at different types of intersections



Source: Institute for Road Safety Research (2012).

As shown in Figure 2.2 and Figure 2.3, rural roundabouts tend to be less safe than urban roundabouts. This may be due to higher approach, entry and circulating speeds. Section 2.1.2 seeks to explore this in more detail.

2 New Zealand rural roundabouts and signalised intersections in Figure 2.2 appear to be an exception, possibly due to the low crash numbers recorded, differences in treatment options (including the use of signalised seagulls at rural T intersections) and/or design elements (including presence of roadside hazards at rural roundabouts).

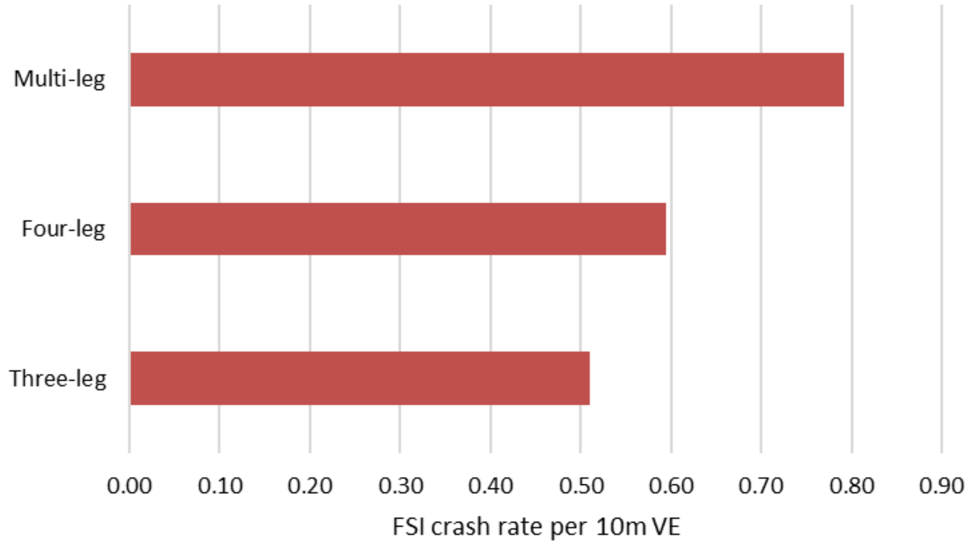
2.1.2 Intersection Geometry

There is consistent research showing that three-leg intersections are less hazardous than four- or multi-leg intersections (Austroads 2010a, 2012). As highlighted in Figure 2.4, this is partially due to a substantially reduced number of conflict points, especially those between fast-moving major road traffic and the traffic on the road which is giving way. Austroads (2015) used Victorian data to show the relative effect of geometric complexity on FSI crash rate (likelihood). As shown in Figure 2.5, the simplest, three-leg intersections had the lowest crash rate per entering vehicle.

The study reported in Austroads (2016a) used rural local government road data to show that the casualty crashes on four-leg intersection were, on average, more severe than those on three-leg intersections. As already discussed, there are more high-severity conflict points at a cross-intersections than T-intersections (e.g. adjacent directions, opposing-turning) (see Figure 2.4).

Previous studies indicated the role of collision angles, vehicle impact areas and collision speed changes (delta-V) in vehicle-to-vehicle crashes at intersections (Tolouei, Maher & Titheridge 2011; Bahouth et al. 2014). This evidence was used in Austroads (2015) to revise FSI-critical vehicle impact speeds, particularly relevant in intersection design and useful in this study (see Section 3 for further details).

Figure 2.5: FSI crash rate per 10m VE for inner-metro signalised intersections with different geometries



Source: Based on Victorian crash data 2002–2007. Crash rates controlled for traffic control type (signalised intersection).

The key findings from this work were that acute impact angles result in lower crash severities than right angles or obtuse angles (near-head-on). Also, crashes involving rear parts of the vehicle, or the unoccupied passenger-side of the vehicle, are substantially less severe. These points are supported by some of the crash severity findings discussed in the next section.

The Austroads (2015) analysis of casualty crashes at urban signalised intersections also found several design and operational factors related to increased crash severity, based on Melbourne and Brisbane data:

- higher speed limits
- large multilane sites, wide approaches – a potential link with higher intersection entry and turning speeds
- lack of full right-turn control
- sites with approaches at approximately 90 degrees had a 10% increased probability of having a severe crash than irregular-geometry sites. This may be an indication of the role of geometry in moderating impact speeds and angles.

Similarly, the geometry of roundabouts appears to play an important role in crash severity; geometry effects on approach, entry and impact speeds are implicated. The New Zealand Transport Agency (NZTA) investigated the statistical relationships between crashes, speed, traffic volume and sight distance at roundabouts (Turner, Roozenburg & Smith 2009). This study suggested some of the factors associated with casualty crashes at rural roundabouts:

- roundabouts with approach speed limits greater than 70 km/h had a 35% higher crash rate than those with speed limits of 70 km/h or lower
- a greater free mean speed for circulating vehicles led to a higher number of crashes
- crashes increased with increased visibility of vehicles approaching from the right, largely due to higher visibility being correlated with higher speeds
- multiple-entry-lane roundabouts had a 66% higher crash rate than single-lane roundabouts.

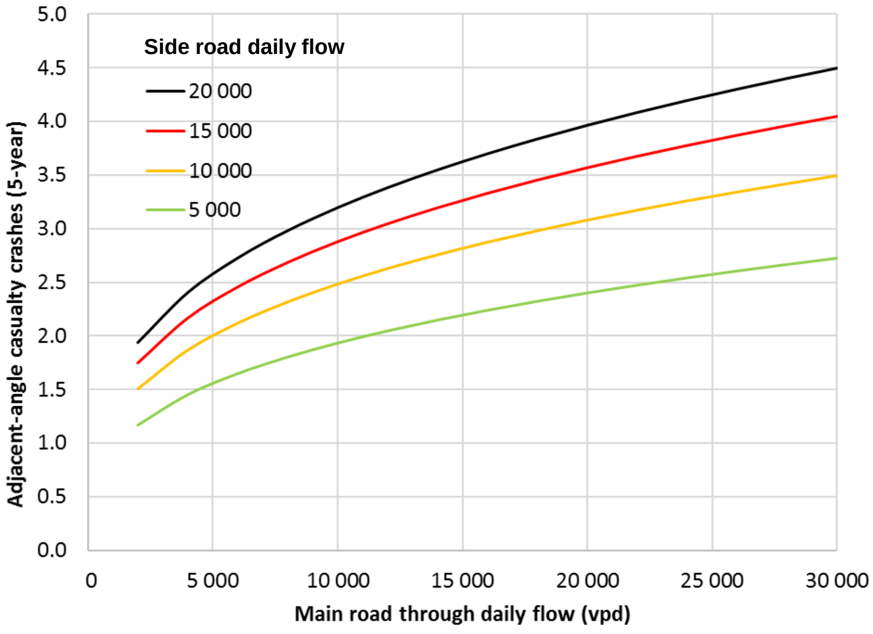
Ambros et al. (2016) used regression analysis of safety performance of Central European roundabouts to confirm Turner, Roozenburg & Smith's findings, showing that roundabouts with less deflection on entry had more injury crashes, all other roundabout design parameters being equal.

Further, Austroads (2015) showed increased probability of severe crash outcomes in 'adjacent' casualty crashes at roundabouts with inadequate horizontal deflection, multilane approach and circulating lanes, or due to small central island size. Increased risk of FSI outcomes in 'off-path' crashes was observed at sites which had irregular or very tight geometry for the approach speeds. Thus, greater focus on appropriate speed management in advance of, and at approaches to roundabouts was recommended.

2.1.3 Traffic Volumes

The relationship between increasing traffic flow and frequency of crashes has been long-recognised (e.g. Maycock & Hall 1984; Hauer, Ng & Lovell 1989). Turner, Singh and Nates (2012) developed casualty crash prediction models for signalised intersections in selected cities of New Zealand and Australia. These models show consistently that increased conflicting flows result in higher frequency of crashes. For example, the adjacent-direction casualty crash relationship is shown in Figure 2.6. The combined effect of higher through and/or adjacent daily flow is expected to result in an increased number of casualty crashes over a five-year period.

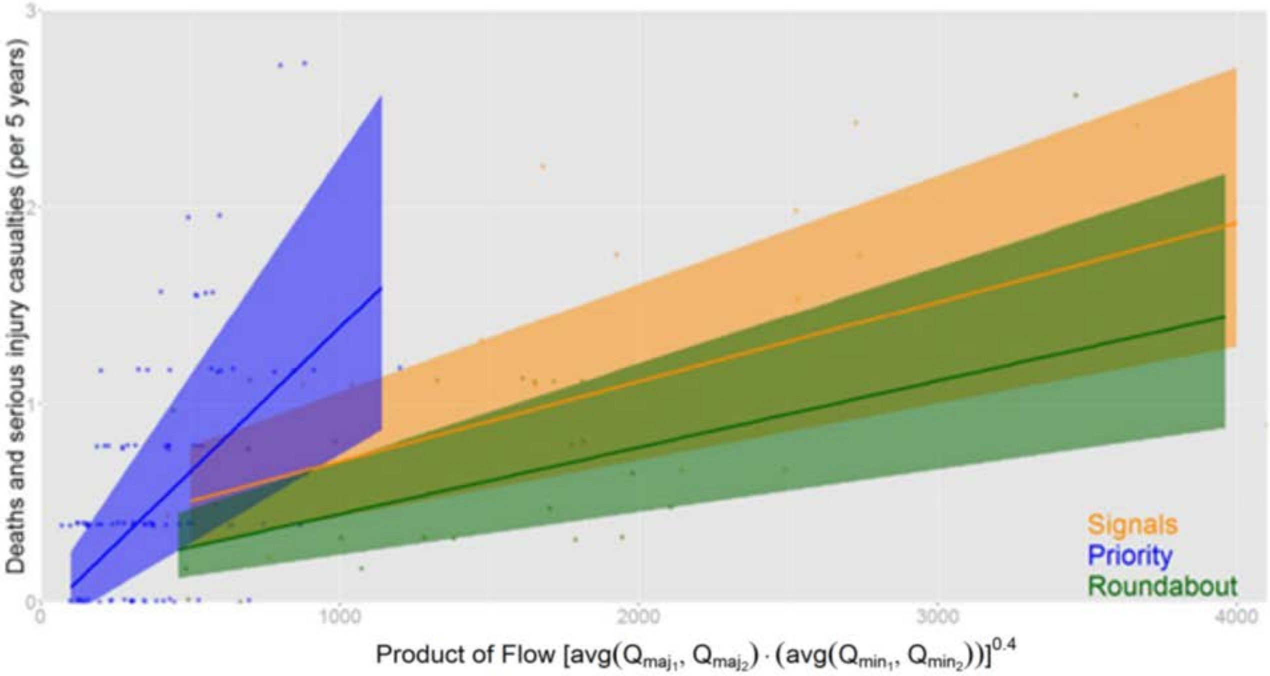
Figure 2.6: Adjacent-direction casualty crash model response to main- and side-road daily traffic flows at signalised intersections



Source: Based on Turner, Singh and Nates (2012); the plot contains several assumptions.

Similar analysis was undertaken for other traffic control types. NZTA (2013) proposed many safety-flow relationships based on New Zealand data. The FSI casualty relationship is compared with the product of flows for rural high-speed cross-intersections in Figure 2.7. In this example, the burden of increasing conflicting flows is offset by the safer modes of managing it. Maintaining priority-control at high volumes is clearly not sustainable from a Safe System perspective. Also, the safety benefit of roundabouts is greater than that of signalised intersections.

Figure 2.7: Example of FSI performance for different rural cross-intersection traffic controls vs. product of major and minor road flows



Source: NZ Transport Agency (2013).

2.1.4 Key Crash Types

The previous two sections discussed recent research on severe crash issues in terms of road environment and intersection type and geometry. This section will provide further detail on the leading severe crash types which should be the focus of Safe System intersection design.

Based on data provided by VicRoads and NZTA, Table 2.1 and Table 2.2 show the distribution of intersection FSI crash types by intersection and environment types in New Zealand and Victoria. The uncontrolled, Give Way and Stop sign intersections were combined into the priority-controlled category, as sample sizes in some individual categories were very small in both jurisdictions, leading to unreliable results due to statistical variation.

Table 2.1: Key FSI intersection crash types in New Zealand by road environment and intersection type

Speed environment	Intersection control	Adjacent	Opposing-turning	Off-path	Same direction	Pedestrian	Others
Urban	Priority-controlled*	29%	16%	22%	7%	14%	13%
	Signalised intersection	23%	29%	10%	7%	25%	6%
	Roundabout	43%	7%	24%	8%	7%	11%
Rural	Priority-controlled	35%	13%	26%	12%	1%	13%
	Signalised intersection	15%	26%	26%	15%	8%	9%
	Roundabout	20%	10%	52%	10%	0%	8%

** Uncontrolled, Give Way sign, and Stop sign.*

Legend: ≥ 35% 25–35% 15–25% 5–15% ≤ 5%.

Source: New Zealand crash data 2007–16, provided by NZTA.

Table 2.2: Key FSI intersection crash types in Victoria by road environment and intersection type

Environment	Intersection control	Adjacent	Opposing-turning	Off-path	Same direction	Pedestrian	Others
Urban	Priority-controlled*	56%	5%	9%	3%	6%	22%
	Signalised intersection	16%	28%	10%	15%	19%	12%
	Roundabout	36%	2%	29%	7%	10%	16%
Rural	Priority-controlled	65%	4%	16%	1%	0%	14%
	Signalised intersection	21%	38%	11%	19%	4%	7%
	Roundabout	23%	1%	47%	9%	1%	19%

** Uncontrolled, Give Way sign, and Stop sign.*

Legend: ≥ 35% 25–35% 15–25% 5–15% ≤ 5%.

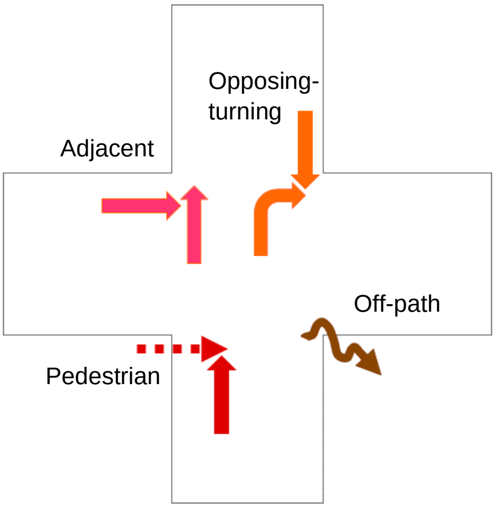
Source: Based on Victorian crash data 2006–2010.

Analysis of the data in the two tables suggests that there are some differences between New Zealand and Victoria, possibly due to crash coding, traffic exposure and potential inaccuracies due to small sample sizes. When considering the overall magnitude indicated by Figure 2.1 and the two tables, the following road user movement (crash) types emerge as leading contributors to severe injury at intersections:

- Common high FSI risk crashes in New Zealand and Victoria
  - urban signalised intersection – opposing-turning
  - urban signalised intersection – pedestrian
  - urban priority-controlled – adjacent
  - rural priority-controlled – adjacent.
- New Zealand-specific high FSI risk issues
  - urban priority-controlled – off-path
  - urban signalised intersection – adjacent
  - rural priority off-path.

Crash types of lesser magnitude, but with a clear pattern in both jurisdictions, were adjacent and off-path crashes on urban and rural roundabouts. Ignoring the environment and the intersection type, the crash/movement types shown in Figure 2.8 should be considered the main issues in future intersection design in the Safe System context.

Figure 2.8: Key movement types of concern in Safe System intersection design



Source: ARRB Group.

2.1.5 Vulnerable Road Users

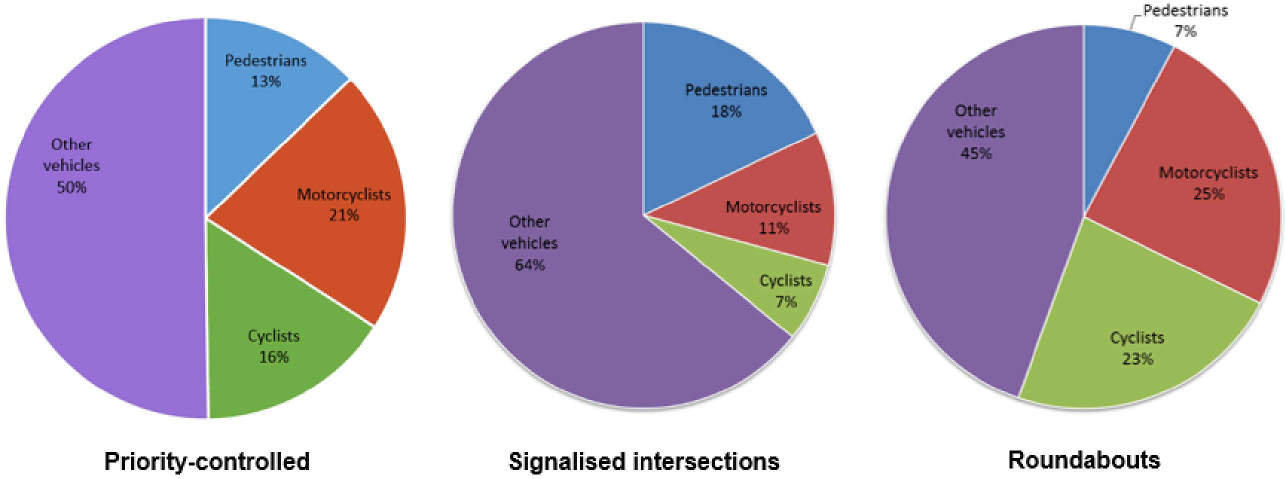
The Safe System seeks to provide safe roads and roadsides for all road users. Thus, understanding who is severely injured can help road system designers to prioritise their efforts. This also applies to intersection design. This section provides further detail on the leading groups of road users subjected to severe injuries at intersections. This will assist in focussing Safe System intersection design on their needs, especially on urban roads where road user mix is greater.

It has been acknowledged that pedestrians form an unusually large percentage of severely injured users at urban intersections (e.g. Table 2.2). This may be a function of absolute risk per road user (i.e. design and operation is unsafe for pedestrians), or a function of exposure (e.g. many pedestrians crossing). Figure 2.9, based on Victorian data, shows that pedestrians were involved in a substantial proportion of FSIs at urban priority-controlled and signalised intersections. These should be noted given the relative magnitude of the FSI crash problem for these two intersection types (Figure 2.1).

Figure 2.9 also highlights that cyclists and motorcyclists were involved in a substantial proportion of FSI crashes at urban priority-controlled and roundabout intersections (37% and 48% respectively). New Zealand evidence for FSI cyclist crashes also points to priority-controlled intersections as being the largest contributor to urban cyclist trauma (NZ Transport Agency 2017). In-depth analysis of cyclist and motorcyclist FSI crashes at roundabouts by Austroads (2015) confirmed that the 'look-but-fail-to-see' effect among vehicle drivers was a common cause of adjacent direction and side-swipe crashes. Heavy vehicles, vans and other large vehicles were over-represented in the analysis. Similar over-representation was also noted in the New Zealand reference. To a lesser degree, this observation also applied to motorcyclists, who also had a greater proportion of rider-error and speed-related causes (off-path crashes). Improving Safe System outcomes of two-wheelers at roundabouts should be a focus of dedicated design innovation projects.

In-depth crash patterns at priority-controlled intersections were not investigated in this study or in Austroads (2015). Given the relatively high magnitude of FSI crashes at urban priority-controlled intersections (Figure 2.1), cyclists and motorcyclists should be considered as a priority in future Safe System design. This need was highlighted by Austroads (2016a) in the context of local government roads where pedestrian and cyclist FSI crashes are form a greater proportion of the overall crash problem.

Figure 2.9: Severe (FSI) crashes for different road user types for different urban intersection types



Source: Austroads (2015), based on Victorian urban crash data (2007–11).

2.2 X-KEMM-X Method – Estimation of Severe Injury Probability in the Event of a Crash

The study sought to develop a systematic way of analysing the critical aspects of Safe System intersection performance. Drawing on the key crash types and other findings from Section 2.1, the authors reviewed recent international literature and drew on data available from the Centre of Automotive Safety Research (CASR) to propose such a method, and to provide several useful design tools for practitioners.

The current body of knowledge on the fundamental dynamics of safety performance of at-grade intersections was reviewed from the Safe System perspective (concurrently with research carried out for Austroads 2015). The authors tested this new knowledge against CASR crash reconstruction data. It was found that the US relationships between delta-V (change in velocity) and injury severity in vehicle-vehicle collisions broadly matched these available from Australian data.

The authors then used these findings to create a practical method for analysing crash severity at intersections. They drew on the previously-developed Kinetic Energy Management Model for Intersections (KEMM-X) (Corben et al. 2010a and 2010b), and extended it by:

- updating the research evidence on change in speed during impact (delta-V)
- considering multiple conflict points at a given intersection design
- considering key crash configurations (frontal, near-side, far-side[3], rear, pedestrian).

This extended method, named X-KEMM-X, focused on the effect of expected impact speeds and angles at approximated traffic movement conflict points to assist in assessment of geometric intersection designs. Pedestrian FSI probability was also included to cater for road crossing points. X-KEMM-X calculates a probability that at least one person will be severely injured when a vehicle-to-vehicle or vehicle-pedestrian collision occurs at each relevant conflict point. The assessment assumes that a collision will occur at each point at some time, and does not include consideration of exposure or likelihood (see Section 4.10 for future development direction).

Assumptions and limitations of X-KEMM-X need to be noted (e.g. both vehicle masses are equal, adult vehicle occupants in front seats only; see Appendix B for more information), but the method has proven itself to be useful when conducting relative comparisons of design options based on Safe System outcomes.

3 In this and similar recent studies, the term near- and far-side refers to impact on the target vehicle in relation to position of the driver, i.e. near-side is a crash into the side of the vehicle on the driver side.

Based on the new understanding of these FSI crash risk parameters, the authors used X-KEMM-X to analyse conventional and innovative intersection designs to demonstrate changes in the risk of FSIs with different proposed layouts (Section 2.3, Section 4). More information regarding the theoretical aspects of the development of X-KEMM-X is provided in Appendix B. The version developed under this study was v0.5 in recognition of the future development directions for X-KEMM-X discussed in Section 4.10.

One of the useful outputs of X-KEMM-X is a tabulation of the relative risks of FSI outcome given that collisions occur at different speeds and angles, shown in Figure 2.10. The Figure provides a quick reference check for intersection designers.

It can be seen from Figure 2.10 that the lowest probability of FSI (< 10%, green) can be achieved at right angles only when both vehicle impacts speeds are low (≤ 30 km/h). If the intersection design restricts the possible angles of impact, then the 'safe' impact speeds may increase. For example, at 30º impact angles, the vehicle impact speeds can be up to 70 km/h before the FSI risk becomes moderate (10–50%, orange). This is why most motorway merge ramps operate without significant numbers of severe crashes at relatively high speeds. This principle is worth observing in future design of intersections.

It is worth pointing out that the most severe crash type is the opposing-turning one, where a vehicle impacts at approximately 150°. At this angle, delta-V is very high due to the near head-on configuration of the crash. The crash is assumed to involve the near-side impact configuration (driver or passenger). This produces a combination of most severe crash conditions. This was confirmed as the most severe of the common intersection crashes at signalised intersections by Austroads (2015).

The results for 180–360° angle range mirror those for 0–180°, i.e. an impact angle of 210° has the same FSI probability distribution as the impact angle of 150º. Assumptions around this and other inputs are listed in Appendix B.

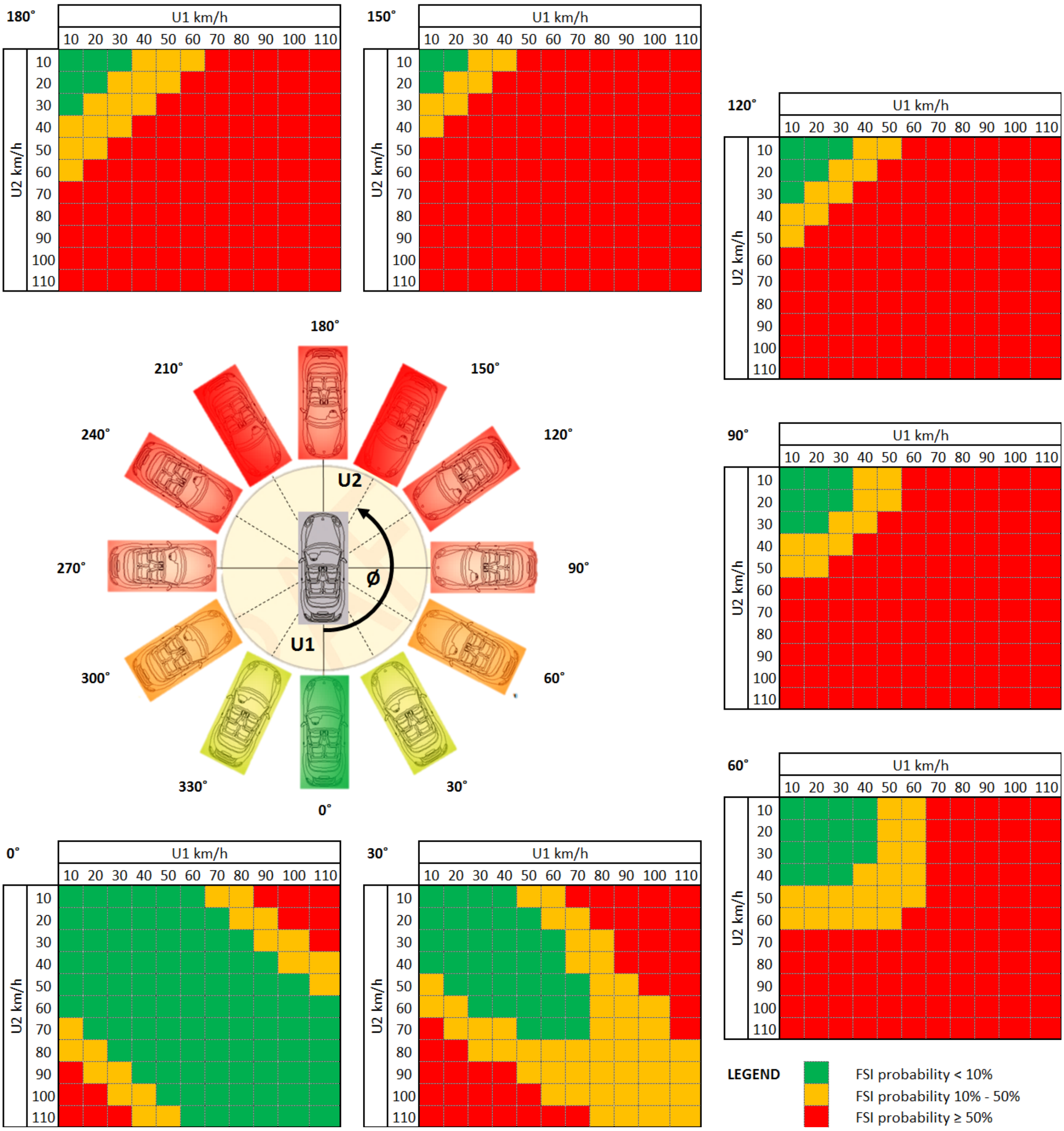
Overall, the X-KEMM-X results presented in Figure 2.10 suggest that, for impact angles greater than 60°, maximum tolerable impact speeds are very low, typically below 30 km/h. At low impact angles, however, higher safe speeds are possible; this may in fact reduce severity from the primary impact (e.g. in rear-end collision). The data shown in Figure 2.10 consciously omitted the relationship between vehicle impact speed and FSI probability for pedestrians[4], where a 20 km/h impact speed represents the FSI threshold (Davis 2001). Angle of impact and pedestrian travel speed are not believed to be significant factors in crash severity outcomes.

In practical terms, X-KEMM-X, and the evidence behind it, suggests a need to shift the Safe System intersection design focus towards:

- control of impact speeds through regulatory and geometric means, e.g. speed limits, approach traffic calming, geometry of the intersection
- control of impact angles through geometric design
- greater control of critical movements, e.g. turn bans, simplification of decision making.

4 At the time of writing only scant evidence was available for cyclists and motorcyclists, suggesting critical impact speeds could be around less than 30 km/h (ACEM 2009).

Figure 2.10: Relative FSI probabilities given impact speeds and angles



Source: ARRB Group.

The X-KEMM-X method could be further developed and become a useful practitioner tool for Safe System assessment of detailed intersection designs in the future. The proposed development steps are outlined in Appendix B, and include future addition of collision likelihood and exposure modules, and additional of cyclist considerations.

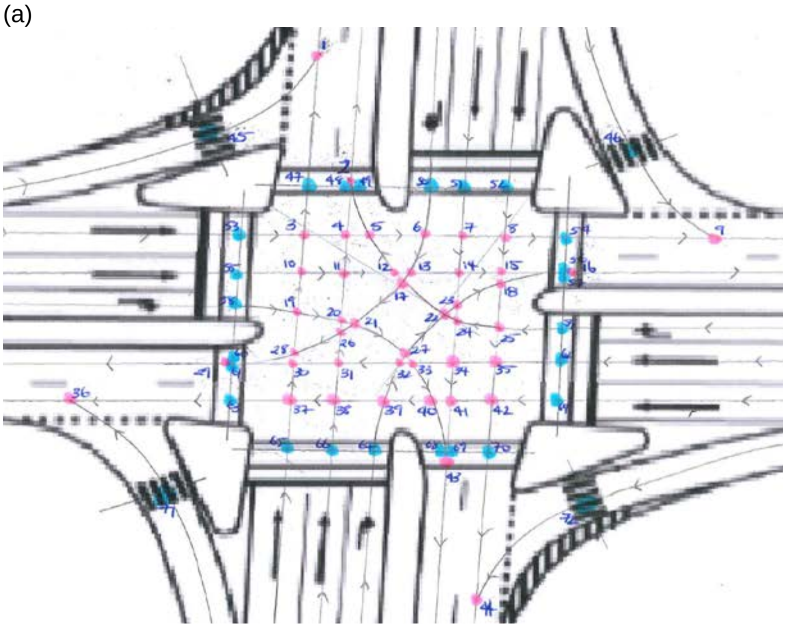
2.3 Conventional Intersection Design Case Studies

X-KEMM-X was applied to assess FSI probabilities for several conventional intersection designs – two of these are presented here to highlight the effects of the number of conflict points, impact speeds and angles.

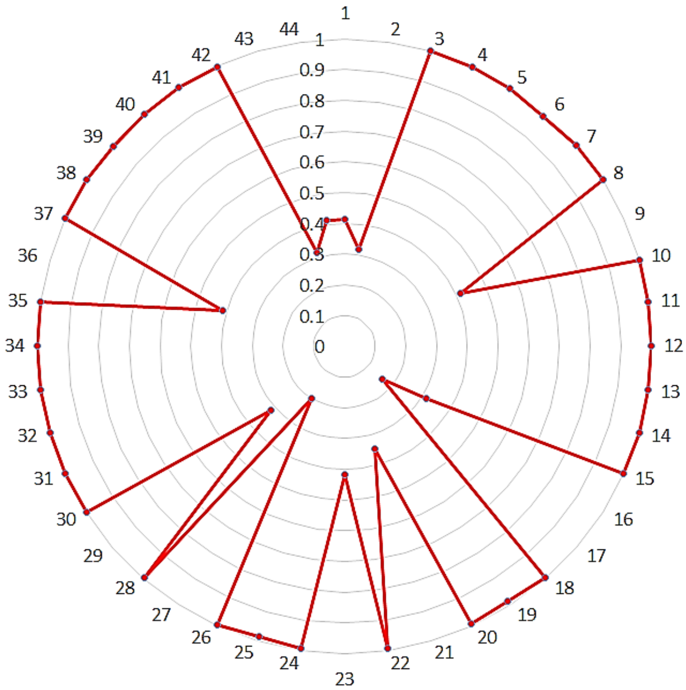
The first example is a major signalised intersection with two through approach lanes, a right-turn lane and a slip lane on each approach. The assumed impact speed for the through vehicles was 80 km/h, a common speed limit at outer-metropolitan signalised intersections. Figure 2.11(a) shows the conflict point diagram for vehicle-vehicle collisions (1–44) and for vehicle-pedestrian conflicts (45–72), whilst Figure 2.11(b) shows the assessment of FSI probabilities for each vehicle-vehicle conflict point (1–44). The probability of an FSI outcome was very high for most conflict points except several low-speed turns.

Figure 2.11: Signalised cross-intersection – conflict points (a) and their FSI probabilities in case of a crash (b)

(a)



(b)



Source: ARRB Group.

The summary of the main FSI risk parameters for the conventional design is presented in Table 2.3. Pedestrian FSI probabilities were generally high with a few moderate values at the left-turn slip lanes.

Table 2.3: Example of X-KEMM-X analysis results for the signalised cross-intersection in Figure 2.11

Result	Vehicle-vehicle conflict	Pedestrian-vehicle conflict
No. of conflict points	44	28
Average Pr(FSI)*	0.82	0.68
Maximum Pr(FSI)	1.00	1.00
Percent conflict points with Pr(FSI) > 0.1	100%	100%

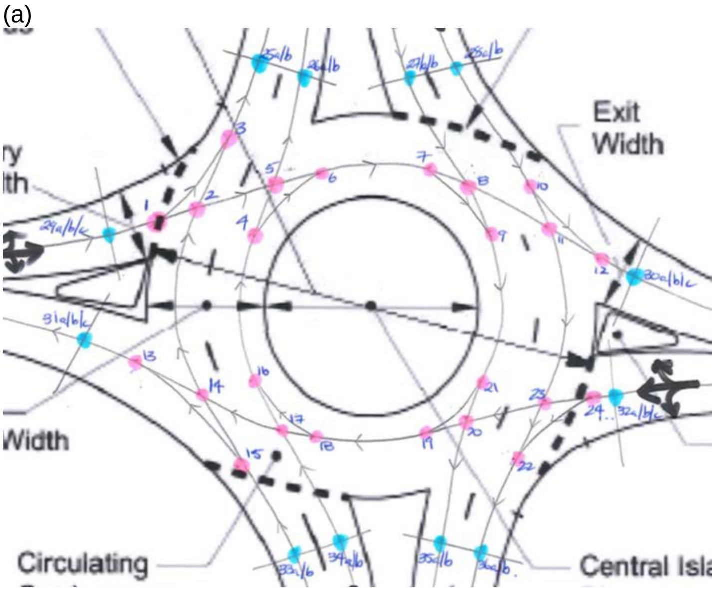
This assessment shows that in a case of (inevitable) road user error, this intersection design is not forgiving at the typical operating speeds, and severe injury crash outcomes are very likely. This is especially true for common errors such as failing to stop at a red signal (frontal/near-side impact, or failing to give way when turning right). These were identified as some of the leading FSI crash types for signalised intersections in Section 2.1.4. The level of alignment of this conventional design with Safe System objectives would be low.

The effect of reducing the number of conflict points, entry speeds and impact angles on minimising FSI probability is demonstrated by comparing the conventional signalised intersection in Figure 2.11 with a large two-lane roundabout presented in Figure 2.12. Such roundabout designs would be typically found on 80 km/h roads.

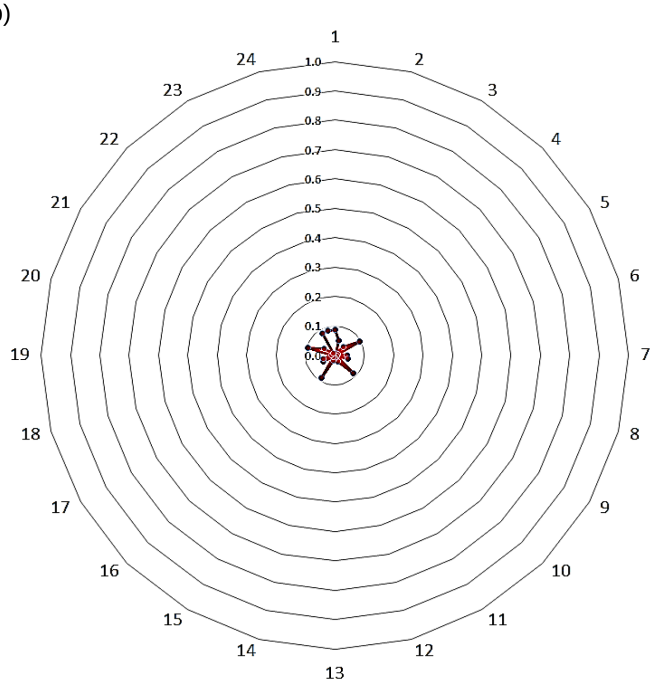
A four-leg roundabout, Figure 2.12(a) has substantially fewer conflict points than a signalised cross-intersection (see also Figure 2.4). The roundabout conflict points also have low FSI probabilities, shown in Figure 2.12(b), determined by low entry and exist speeds (50 km/h), low circulating speeds (40 km/h), and low impact angles (10° to 60°). Figure 2.12(b) shows that the maximum vehicle-vehicle FSI probability for a roundabout crash was just under 0.10. This shows that a roundabout is highly aligned with the Safe System objective of minimising fatal and serious injuries in vehicle-vehicle crashes.

Figure 2.12: High-speed roundabout (80 km/h) – conflict points (a) and their FSI probabilities (b)

(a)



(b)



Source: ARRB Group.

A summary of the X-KEEM-X results is shown in Table 2.4. The pedestrian-vehicle conflicts still carry high a probability of FSI, i.e. a high-speed roundabout is poorly aligned with the Safe System objective for these vulnerable road users.

Table 2.4: Example of X-KEMM-X analysis results for the signalised roundabout in roundabout Figure 2.12

Result	Vehicle-vehicle conflict	Pedestrian-vehicle conflict
No. of conflict points	24	28
Average Pr(FSI)*	0.04	0.50
Maximum Pr(FSI)	0.10	0.83
Percent conflict points with Pr(FSI) > 0.1	0%	100%

It is worth noting that the roundabout design was also free of the opposing-turning crash type (a near-head-on configuration), which was converted to a low-angle, low-speed near-side adjacent crash type. The magnitude of delta-V is reduced at low angles, which in turn translates to lower FSI probability. This observation confirms that reducing the number of conflict points involving near-side adjacent and opposing-turning impacts is important for reducing the overall vehicle-to-vehicle FSIs.

These two examples show that whenever pedestrian, adjacent direction and opposing-turning conflict points are retained in an intersection design, the impact speeds and angles would need to be substantially reduced to minimise FSI probability towards the Safe System objective.

These analyses make many assumptions about road users (e.g. adults behaving within context), vehicles (same mass) and assume designs are built to standard. Even at low Pr(FSI) values, rare catastrophic events can occur.

2.4 Recent Innovations in Safe System-focussed Intersection Design

2.4.1 Literature Summary

This section presents a practitioner-level summary of the overview of literature and international practice on innovations which may achieve closer alignment of intersection designs with Safe System objectives. Many of the Safe System intersection ideas identified in the review were incorporated into the design concepts presented in Section 4.

The literature review considered new designs that deviated from traditional intersection design practices. With few exceptions, most of the literature did not regard intersection design in the context of impact configuration and mitigation of injury severity.

Roundabout design and safety performance have received a significant focus in the recent literature. The contrasting European and Australian roundabout design philosophies are evident (radial vs. tangential), although safe roundabout design is fundamentally linked to the design elements controlling the amount and rate of horizontal deflection (i.e. angle of horizontal deflection, entry and circulating widths, Ambros et al. 2016). The most successful outcomes appear to be linked to geometric elements that reduce vehicle approach speeds and speeds within the roundabout to 40 km/h, or below where vulnerable road users are present. Current Austroads design guidance reflects this, recognising the importance of speed reduction at the approach to the intersection.

There is a growing body of literature on the safety of cyclists at intersections, particularly at roundabouts. Two differing philosophies have emerged, dependent on speed and traffic flow: cyclists can be either segregated from traffic, or mixed with traffic to the extent where they are encouraged to gravitate towards the centre of traffic lanes (e.g. Cumming 2012, VicRoads 2016a). Dutch and Norwegian design guides suggest 8 000 vehicles per day as the cut-off between the two regimes and appropriate speed management is again regarded as critical. The literature reported that bicycle lanes or cycling with traffic at conventional roundabouts could lead to an increased risk of crashes for cyclists, while segregated off-road paths reduced this risk (Reynolds et al. 2009, Mulvaney et al. 2015).

There is recent literature on pedestrian safety at intersections as it relates to priority-controlled intersection design. Many papers discussed positive pedestrian safety effects of design elements (e.g. Schneider et al. 2010: lower crossing pedestrian and traffic volume, presence of medians/channelization, absence of dedicated left-turn lanes, and absence of commercial driveways). Some papers discussed the positive effect of vertical deflection treatments on intersection approaches to demonstrate benefits for pedestrians as well (Makwasha & Turner 2017).

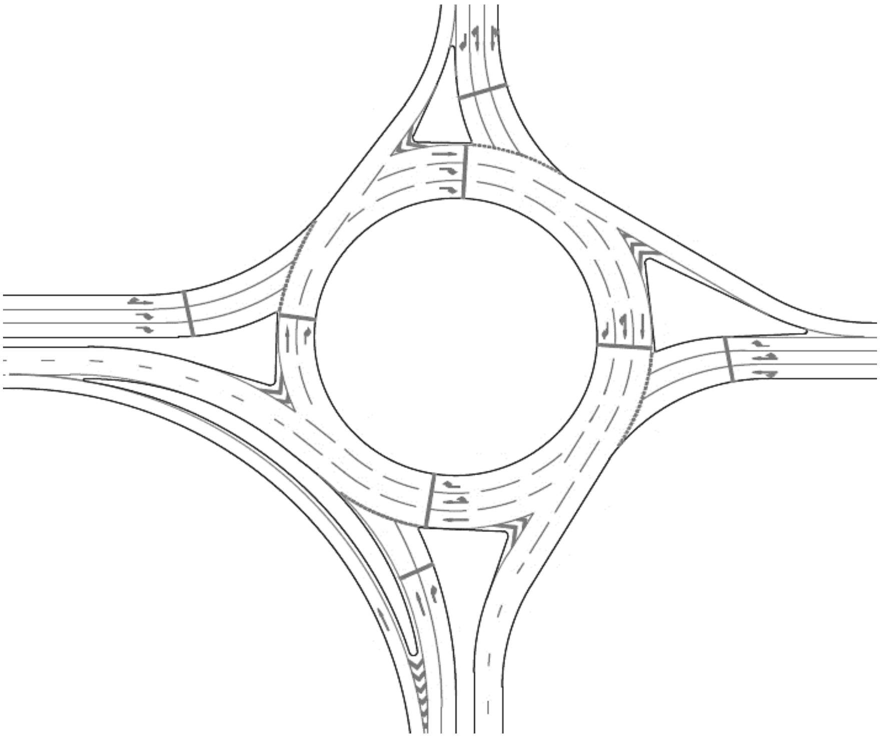
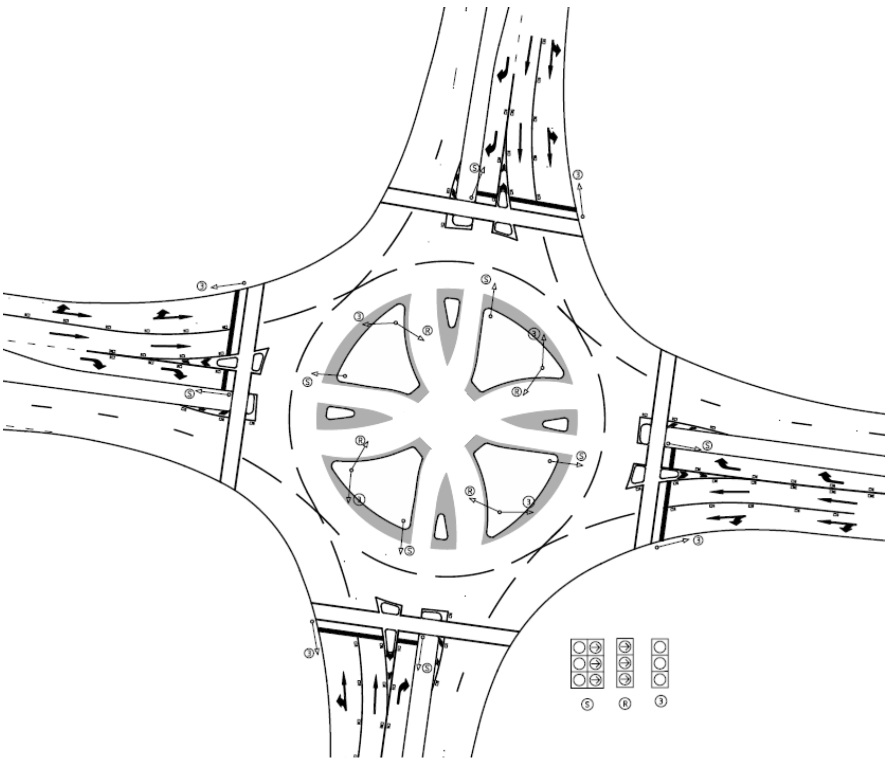
Other researchers focussed on positive pedestrian safety effects of signalised intersection design, phasing and operation, including shorter pedestrian waiting time, shorter cycle time, split-phasing, the provision of fully-controlled right turns, lower number of conflicting traffic lanes, lower volume of conflicting vehicular traffic (Turner, Singh & Nates 2012; Koh, Wong & Chandrasekar 2014). VicRoads (2016b) guidance proposes a range of traffic signal phasing solutions including all-pedestrian phases and full control of right turns as means of reducing the likelihood of direct vehicle-pedestrian conflict.

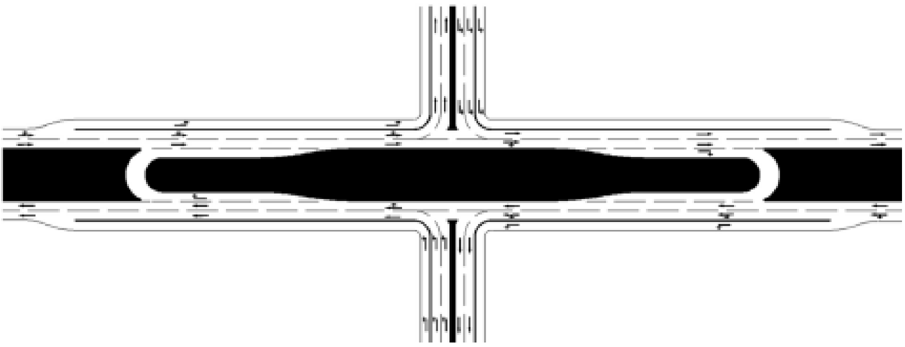
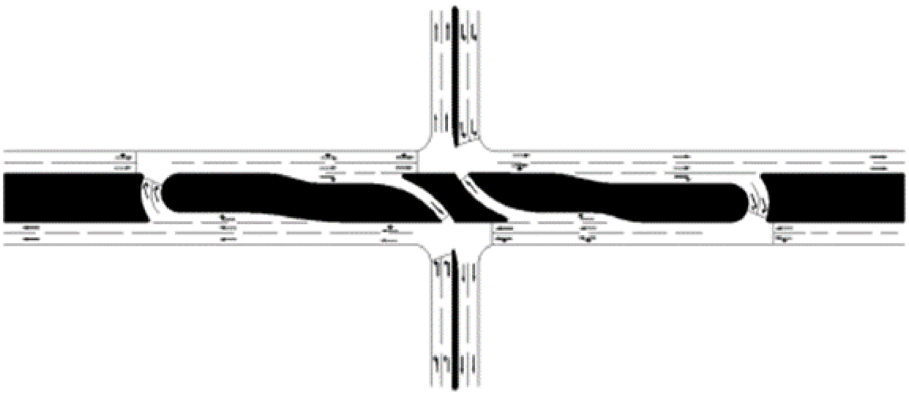
2.4.2 Innovative Intersection Designs

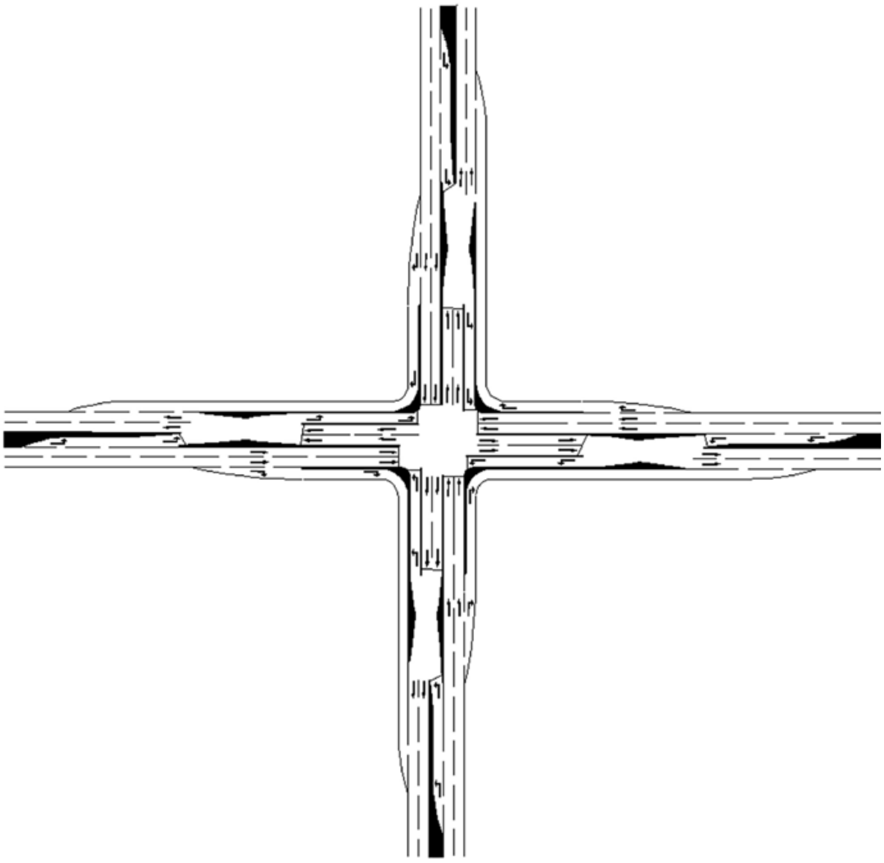
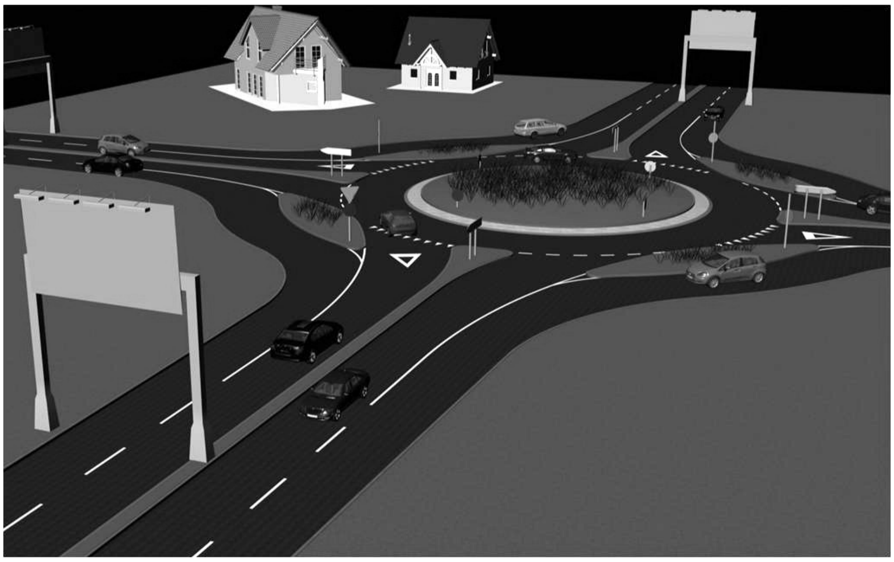
There is a considerable amount of literature on geometrically-innovative intersection designs. Most of these designs either eliminate or displace conflicting movements from the central part of the intersection resulting in increases in overall traffic efficiency at the site (i.e. a mobility focus). Several safety evaluations of these designs have emerged to demonstrate actual or potential benefits. Other identified solutions originated from the safety perspective, and some of these have been trialled or are awaiting trials.

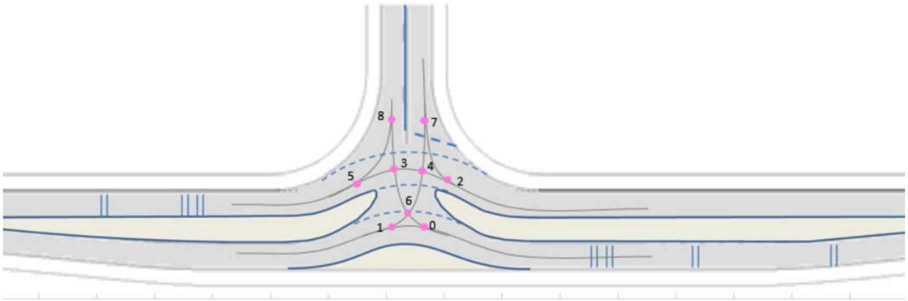
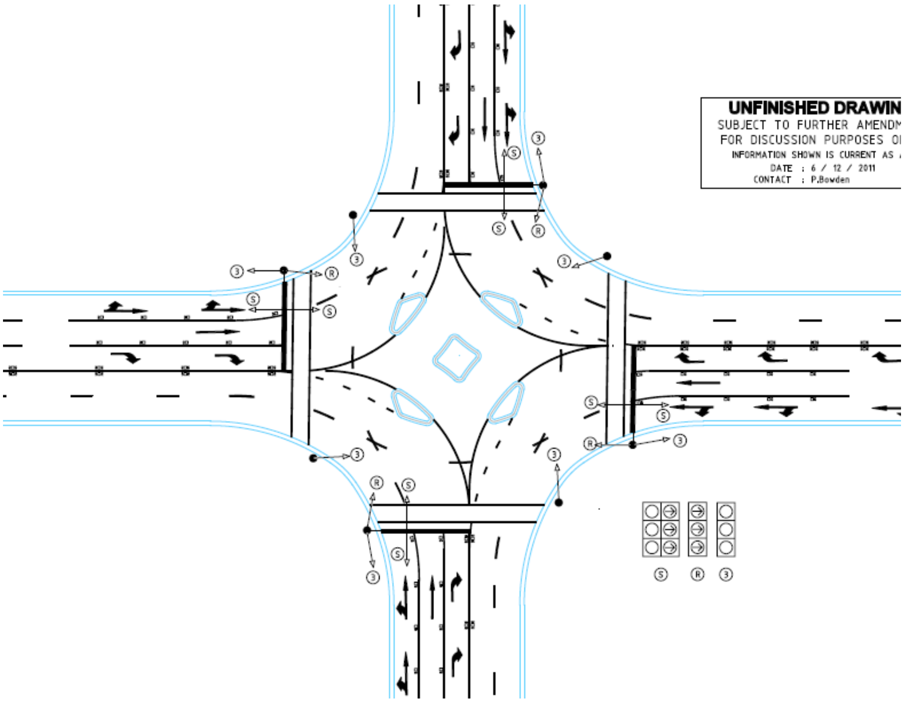
Based on reviewed evaluation literature (where available) and X-KEMM-X analysis performed under this study, Table 2.5 presents a selection of innovative intersection solutions which have shown some potential for overall safety improvement towards Safe System. With additional stakeholder input, nine solutions were either selected or developed from these for further investigation and refinement, as presented in Section 4.

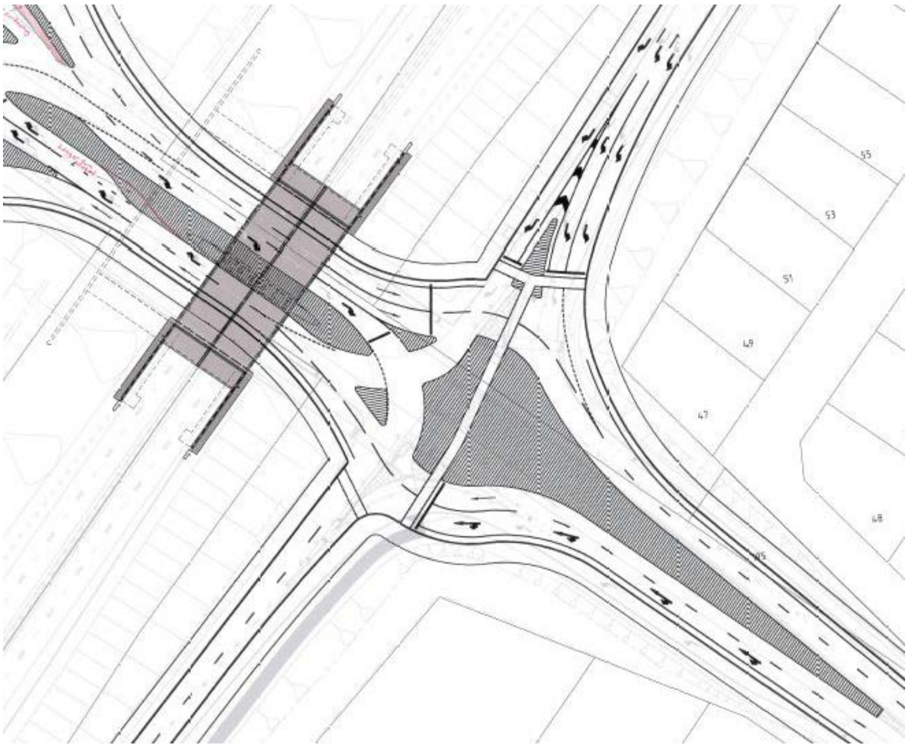
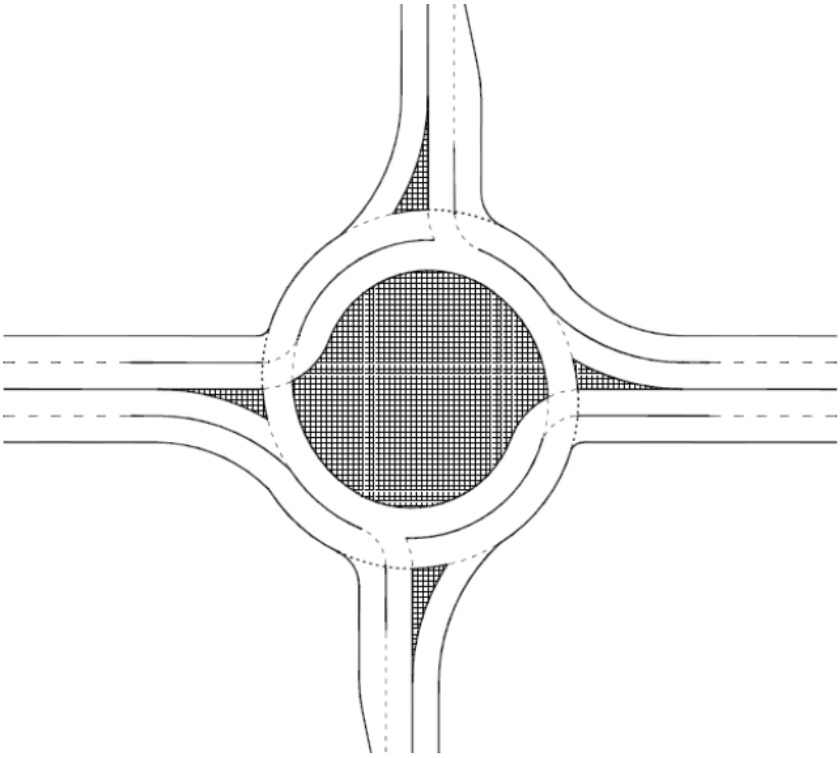
Table 2.5: Examples of innovative intersection designs

Innovative design type	Notes
Signalised roundabout (60 km/h speed environment)  *Source: ARRB Group.*	• Low max Pr(FSI), low number of conflict points per approach. • Expected further reduction in crash numbers and in severity compared with unsignalised roundabout (County Surveyors' Society 1997). • Already in use. Requires evaluation in Safe System context.
Cut-through signalised intersection (60 km/h speed environment)  *Source: VicRoads (n.d.).*	• Moderate max Pr(FSI), moderate number of conflict points per approach. • Moderate entry speed reductions were identified through a driving simulator study compared with a conventional signalised intersection (Stephens et al. 2017). • Yet to be trialled.

Innovative design type	Notes
Urban signalised intersection with safety platforms (50 km/h entry, 70 km/h speed environment)  *Source: VicRoads (n.d.).*	• Moderate max Pr(FSI), moderate number of conflict points per approach. • Estimated casualty crash reduction of 50–60% when replacing a priority-controlled intersection (based on Fortujin, Carton & Feddes 2005). • Evaluated overseas, under trial in Victoria.
Unconventional median U-turn (high-speed arterials)  *Source: Based on Hughes et al. (2010).*	• High max Pr(FSI), low number of conflict points per approach. • The estimated crash reduction factor was 60% based on observed reductions of 17%, 96% and 61% for rear-end, angle and side swipe collisions respectively, compared with prior condition (conventional priority-controlled cross intersection). (Jagannathan 2007 reported in El Esawey & Sayed 2013). • Evaluated overseas, limited application of similar concept in Australia.
Superstreet median  *Source: Based on Hughes et al. (2010).*	• High max Pr(FSI), low number of conflict points per approach. • 41% in the annual average of severe crashes based on one unsignalised site, compared with prior condition (conventional signalised intersection) (Hughes et al. 2010). • Limited trials overseas.

<table>
<tr><th>Innovative design type</th><th>Notes</th></tr>
<tr><td>XDL or continuous flow intersection

Source: Hughes et al. (2010).</td><td>High max Pr(FSI), moderate number of conflict points per approach.
Hughes et al. (2010) observed a 19% reduction in severe collisions after building the XDL intersection at one site, compared with prior condition (conventional signalised intersection).
Limited trials overseas, local trial in planning.</td></tr>
<tr><td>Flower roundabout (50–100 km/h speed environment)

Source: Based on Tollazzi, Renceli and Turnsek (2011).</td><td>Low max Pr(FSI), low number of conflict points per approach.
This design concept is intended to be a conversion fitting within a two-lane roundabout footprint.
Trialled overseas.</td></tr>
</table>

Innovative design type	Notes
Modified T-intersection (50–100 km/h speed environment)  *Source: Jurewicz and Sobhani (2016).*	• Low to high max Pr(FSI) (speed limit dependent), low number of conflict points per approach. • Used on urban local roads. • Yet to be trialled in rural context.
Squircle (60 km/h speed environment)  *Source: VicRoads (n.d.), based on Corben et al. (2010b).*	• High max Pr(FSI), moderate number of conflict points per approach. • Small entry speed reductions were identified through a driving simulator study when compared with conventional signalised intersection (Stephens et al. 2017). • Yet to be trialled.

<table>
<tr><th>Innovative design type</th><th>Notes</th></tr>
<tr><td>Tennis ball interchange (60 km/h speed environment)

Source: Courtesy of Main Roads Western Australia (n.d.).</td><td>Designed to reduce impact speeds and angles.
Trial under way in Perth.</td></tr>
<tr><td>Turbo roundabout (60 km/h speed environment)

Source: Based on Mauro and Cattani (2010).</td><td>Reduced number of conflict points and lower circulating speeds than on comparable multilane roundabouts. Raised separators are typically included between traffic lanes. It is expected turbo would have 20–30% less injury crashes than comparable two-lane roundabouts, based on mathematical conflict analysis (Mauro & Cattani 2010).
Applicability and legality of turbo roundabouts in Australian and New Zealand conditions was yet to be assessed.
Evaluated overseas, yet to be trialled in Australia/New Zealand.</td></tr>
</table>

Austroads (2016a) identified some of these as potentially applicable to local government roads. Also, mini-roundabouts were highlighted in that group, with relevance to local roads (although this application was not considered innovative in the context of this study).

In addition, numerous supporting Safe System solutions were identified. Stakeholder inputs via the workshops recognised the value of integrating these with the fundamental attributes of Safe System intersections (e.g. geometry to create low impact speeds and angles). These solutions would create synergy by supporting the geometric elements, i.e. amplifying the safety effect, (e.g. zebra on a safety platform). Supporting solutions can be also useful to create redundancies by acting should another element of the design fail (i.e. retroreflective delineation when street lighting is available).

Raised intersections

Makwasha and Turner (2017) evaluated ten priority-controlled raised intersections finding a 55% reduction in casualty crashes. Results for FSI crashes were not significant, most likely due to a small sample size. Notably, the study found pedestrian casualty crashes reduced by 58%, with low statistical significance of the finding ($p = 0.26$) still indicating a likely strong safety effect.

Formal trials of raised signalised intersections and roundabouts were being undertaken in Victoria, and previous evaluations from UK are noted in Section 4.1. Numerous examples of raised intersections were identified on local roads.

Rural vehicle activated intersection speed limits

This treatment involves traffic activated reduction in speed limits using variable speed limit signs. Some applications may also base speed limit reduction on time of day when traffic flows are high. Mackie et al. (2017) suggested an average 79% FSI crash frequency reduction based on evaluation of ten rural high-risk sites in New Zealand.

Banning selected movements

Relocation of road user movements to a location where they do not conflict with others is likely to provide the most significant safety benefits.

- Banning right turns – preferably strengthened with road design changes physically preventing the movement. Past evaluations show a significant reduction in opposing-turning crashes in the post-period (60% to 90% cited in Austroads 2012). Reductions in pedestrian crashes were also noted. There has been evidence of some crash migration due to increased exposure at nearby locations.
- Closing medians at intersections – this results in a left-in, left-out arrangement, with all right turns removed. This should be combined with controlled U-turn facilities nearby. Partial closures are also possible (e.g. can right turn in, but not out). Part-time bans are also used at times of increased risk.
- Preventing pedestrians crossing – it may be appropriate to prevent pedestrian crossings at selected high-speed intersections and channel pedestrians to safe crossing locations. This is often assisted by the landscape or opportunities which make this choice more acceptable (e.g. differences in levels between road and surrounding land, provision of pedestrian overpasses).
- Removing approaches and consolidating intersection design – this may be possible when irregular or confusing signal designs are rationalised. It includes the removal of access points or local street legs within a signalised intersection, and redirection of road access to a safer location, e.g. a service road.

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

Fully-controlled right turns

Less restrictive supporting solutions involve increasing the level of control for the conflicting movements. One common example of this is installation of full right-turn control phasing on all approaches to signalised intersections. Austroads (2015) identified a marked difference in frequency and severity of severe crashes where this solution was applied. Reviewed literature suggests that up to 90% of opposing-turning casualty crashes can be prevented by retrofitting this solution (Austroads 2012). Jurewicz, Sobhani and Makwasha (2017) showed that full-time application of full right-turn control reduced all FSI crashes by 69%. Part-time application of this phasing only during off-peak times reduced FSI crashes by 36% (not statistically significant).

Full right-turn control also has the effect of reducing the likelihood of severe pedestrian crashes during completion of a filter movement. Austroads (2012) 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 signalised intersection treatments.

Red light/speed cameras

This involves installation of enforcement cameras at signalised intersections. It is triggered either by speed limit being exceeded, by red light violation, or both. Budd, Scully and Newstead (2011) evaluated Victorian application of this treatment finding a 44% reduction in adjacent and opposing-turning severe crashes.

Speed limit reductions (permanent)

No robust research evaluating the effects of permanent speed limit reductions at intersections was identified. Modelling of a 20 km/h speed limit reduction found limited effect on safety in congested conditions, but greater effect when traffic was less congested or free-flowing (Austroads 2010b). The encouraging findings by Mackie et al. (2016, 2017) in relation to vehicle-activated speed limit reductions at rural intersections supported by flashing lights, suggest that permanent speed limit reduction may also be effective at these high-speed locations.

Improved signal display visibility

Studies cited in Austroads (2012) provide varying levels of crash reduction, typically under 40%. However, there was a notable pattern of stronger reductions for adjacent direction and rear-end crashes, and generally for lower severity crashes.

2.4.3 Knowledge Gaps

The following knowledge gaps have been identified in relation to innovative solutions:

- Most of the innovative solutions were still emerging and some were yet to be trialled. With any new designs, there is a need to monitor performance and risks and, if necessary, implement design refinements.
- Most of the available evaluations referred to casualty crashes, with limited or no reference to crash severity, or to FSI crashes.
- Similarly, there was little information available on benefits for different road user groups, including vulnerable road users.
- While technological solutions were out of scope of this study, the design integration of ITS, smart roads/pavements, and connected vehicles these should be pursued in future research.
- It is evident that roundabouts can provide a high level of safety performance over other intersection designs. However, it is also clear that there is still much scope for innovation and design variations that can yield high safety benefits at a reduced cost.

- Turbo and flower roundabout designs (see Table 2.5) should be further explored in the Australasian context.
- The strength of findings relating to cycling safety designs relate to the European experience. Whilst there is some strong evidence and guidance, the extent to which these can be translated to Australia and New Zealand is unknown (lower proportion of cyclists in traffic, high proportion helmet-wearing). There is also a need to account for different urban speed environments and geometric design philosophies, if comparisons were to be successfully attempted.

3. Safe System Intersection Design Principles

The key objective of this study was to propose new ways in which road agencies may better align intersection design guidance with the Safe System principles. This section draws on the previously-presented material to propose high-level principles for Safe System intersection design. These are then supported by more detailed guidance drawn directly from the research and best practice presented in the previous sections, and stakeholder inputs.

3.1 High-level Safe System Intersection Design Principles

The Safe System vision is based on a set of simple principles. The first principle accepts that people will continue to make mistakes and that the system must accommodate these. Secondly, the vision recognises that there are known physical limits to the amount of force our bodies can withstand before we are seriously injured. Thus, Safe System aims to ensure that the forces in collisions do not exceed limits of human tolerance (based on Australian Transport Council 2011).

System designers and operators need to share responsibility for safe travel outcomes when managing traffic speeds, designing the road and roadside environment, regulating and designing vehicles, and when managing behaviour of road users.

OECD and ITF (2008) proposed that the Safe System builds on existing road safety interventions by reframing how it is viewed and managed in the community. Safe System should address all elements of road transport system in an integrated way, balancing needs of different road users in different contexts (e.g. movement versus place, individual versus public transport, mobility versus access).

In the context of Safe System for intersections, Corben et al. (2010a, 2010b) identified the need to reduce the number of vehicles on the road as a way of reducing the opportunity for crashes to occur (exposure to risk). For the same reason, they challenged designers to consider having fewer intersections. They also proposed the need to reduce the number of conflict points per intersection, attain greater intersection simplicity, and to reduce impact speeds and angles.

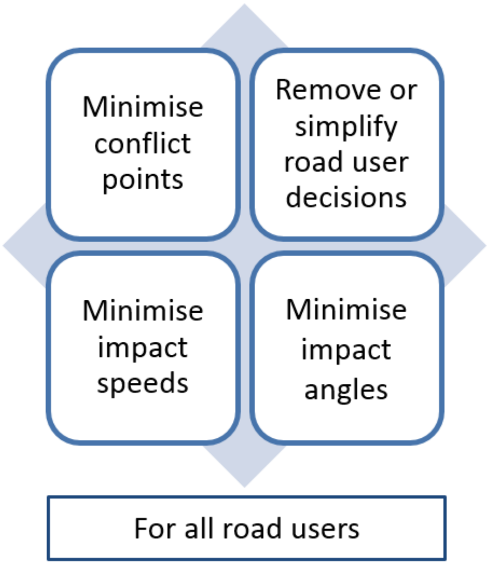
Points noted in Section 2, based on review of Safe System performance of intersections, X-KEMM-X analysis, and the review of best-practice in safety solutions for intersections, can be summarised as follows:

- Priority-controlled and signalised intersections pose the greatest challenge for achieving Safe System at intersections.
- The main crash types to be targeted by Safe System design should be adjacent-direction, opposing-turning, pedestrian and off-path.
- Cyclists and motorcyclists need special consideration at priority-controlled intersections and roundabouts.
- Pedestrians need special consideration at priority-controlled and signalised intersections, and multilane roundabouts.
- The key learnings in relation to minimisation of FSI crash factors through design were
  - reduction in the number of conflict points, e.g. via number of legs or geometry
  - simplification of road user decision making (movement bans, higher levels of traffic movement control, lower complexity)
  - reduction in intersection entry speeds via geometry, layout and/or speed limits
  - reduction in impact angles via geometry.

- For impact angles greater than 60˚, maximum tolerable vehicle-vehicle impact speeds are very low, typically below 30 km/h. At low impact angles, however, higher speeds may be safe.
- For vulnerable road users, the FSI-critical impact speed threshold is about 20 km/h.
- The most effective, or potentially effective, Safe System intersection designs included solutions which mimic or extend attributes of roundabouts: simple designs, few conflict points, low impact speeds and angles.
- Many design solutions supporting Safe System were identified. It was noted that Safe System designs should seek to integrate these appropriately to create design synergy and redundancy.

Drawing on these findings, Figure 3.1 proposes four high-level considerations in designing a Safe System intersection.

Figure 3.1: Proposed high-level principles for Safe System intersection design



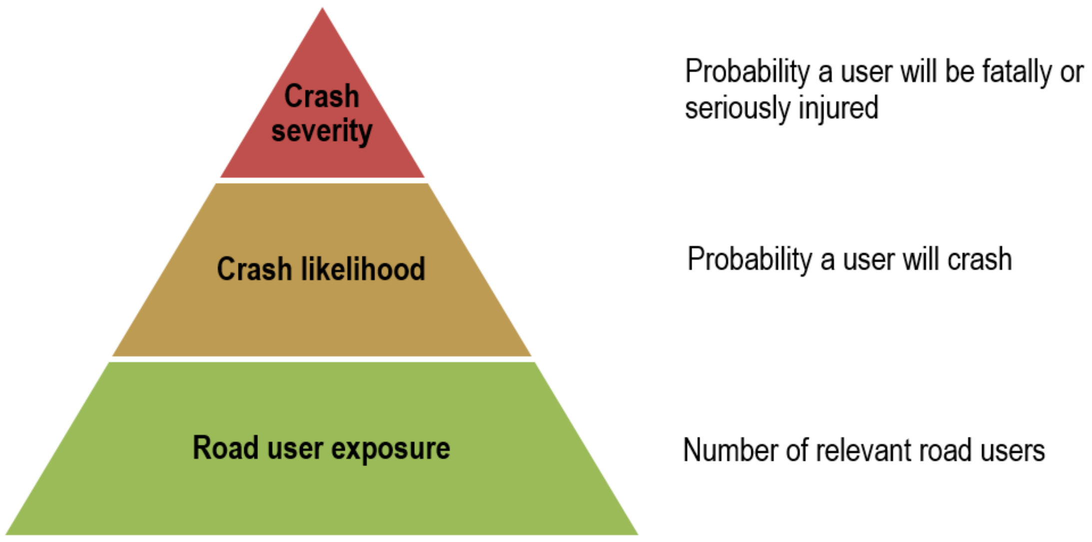
Moderation of vehicle, cyclist or pedestrian flows is not often under designer’s control, but is an important part of FSI risk (Corben et al. 2010a). Transport planning is highly relevant from the perspective of deciding on access to, or across, a road at a given location. This is where movement and place considerations should take precedence in guiding the choice of access at a given location in the context of the road function, road use and user amenity (Austroads 2016b).

The prompts and techniques guiding delivery of these Safe System principles include the detailed findings of this study are presented in the following section.

3.2 Proposed Design-level Guidance

Austroads (2016b) proposed the Safe System Assessment Framework, a qualitative approach to apprising design and operation of road infrastructure against the objectives of the Safe System. The key concept driving this approach focuses on the three main aspects of FSI risk: road user exposure to crash risk, likelihood of a crash, and its severity. This risk model, shown in Figure 3.2, provides a convenient structure for methodical consideration of the high-level principles from the previous section and the key Safe System intersection factors identified in Section 2.

Figure 3.2: Risk model for FSI crashes and injuries on the road system



Source: Jurewicz (2016).

Thus, more detailed guidance on Safe System intersection design takes on the form shown in Table 3.1. Design principles from Figure 3.1, and aspects of risk from Figure 3.2 are expanded and paired with practical prompts for designer's consideration. Generally, the first listed prompts in Table 3.1 lead to Safe System outcomes, also referred to as primary or transformative solutions. Further suggestion points tend to lead towards supporting solutions which may be considered a step towards Safe System. Practitioner feedback of this guidance was sought and received during the workshop series conducted throughout 2016.

Table 3.1: Proposed Safe System intersection design guidance

Design principle	What it means
Consider all relevant road users and their numbers (exposure)	Can the intersection be avoided? Can some road user groups be redirected to a safe facility, or separated (e.g. pedestrian overpass, a tunnel)? Who and in what numbers will use the intersection? What is the design horizon AADT, pedestrian crossing numbers, daily or peak-hour cyclist numbers? What are the numbers of heavy vehicles?
Minimise likelihood of a crash for each user (rates of system failure, human error)	Minimise the number of conflict points, e.g. ban turns or separate vertically (e.g. overpass). Apply strict movement control, separate in time, e.g. signalise all conflicting movements(1). Give road users more time to make decisions: reduce approach speeds. Simplify road user decisions: provide clear and logical traffic control. Provide guidance: inform, channelize, delineate. Warn (…last resort if risks cannot be removed).
If crash occurs, minimise probability of fatal and severe injury outcome (minimise kinetic energy and its transfer to road users)	Minimise intersection approach and potential impact speeds to 30 km/h or less (low speed limits, traffic calming, intersection geometry). Minimise impact angles to less than 60 degrees, closer to 30 degrees (speeds may be increased). Refer to Figure 2.10. Consider separating incompatible vehicles (mass difference, e.g. cyclists from motor vehicles). Redesign roadside environment to exclude infrangible poles, posts and trees. Provide for effective emergency access.
Build-in system redundancies	Create synergies from multiple supporting solutions to multiply the safety effect, e.g. red-light/speed cameras, off-road cycling facilities. Add redundancies where possible should one element fail (e.g. lighting and retroreflective delineation).

1 *The safest and simplest method of making a give way decision appears to be a response to a traffic signal. This is suggested by indicative UK findings of reduced crashes when conventional roundabouts were retrofitted with full-time signalised ones.*

4. Innovative Safe System Intersection Design Concepts

As outlined in the Introduction and in the previous sections, the study sought to develop innovative design concepts to guide practitioners in trialling, evaluation and designing intersections which are more closely aligned with Safe System objectives. The study sought stakeholder and expert inputs to draft alternative intersection designs that better align with the Safe System objectives.

Following consideration of the designs reviewed in Section 2.4.2, plus others proposed by road agencies, the stakeholders selected nine design concepts for further development according to the following criteria, driven by the findings in Section 2.1:

- solutions to high-speed conflicts between right-turning and through vehicles
- solutions to high-speed conflicts between vehicles from adjacent directions
- mix of rural and urban solutions
- Safe System primary and supporting solutions
- solutions applicable at greenfield and brownfield (retrofit) sites
- low-cost solutions
- solutions feasible where physical site limitations are significant (e.g. services, small footprint).

The following innovative Safe System design concepts were developed:

- signalised intersection with safety platforms (Section 4.1)
- signalised roundabout (Section 4.2)
- urban compact roundabout with safety platforms (Section 4.3)
- rural compact roundabout with safety platforms (Section 4.4)
- urban signalised intersection retrofit combination treatment (Section 4.5)
- rural priority-controlled rural intersection with safety platforms and reduced speed limits (Section 4.6)
- cut-through signalised roundabout (Section 4.7)
- urban priority-controlled raised intersection (Section 4.8)
- rural priority-controlled intersection with vehicle-activated speed limits (Section 4.9).

Each of these designs was then analysed using SSAF and X-KEMM-X techniques to assess their levels of Safe System alignment. The designs were presented, discussed and critiqued by over 750 practitioners through a series of 15 Safe System workshops held in Australia and New Zealand during 2016. These workshops generated further improvements which could be applied to the concepts to further enhance their Safe System alignment under different conditions. These have been included in the discussion on each treatment.

The design concepts presented in Sections 4.1 through to 4.9 should be viewed as starting points for further refinement and trial evaluation. Some have never been used. Others may be emerging treatments requiring evaluation in Safe System context. Successful solutions may be incorporated into jurisdictional guidance and eventually into Austroads guides.

Jurewicz (2017) proposed a pathway for Safe System infrastructure innovation. One of the key elements of this pathway is the process of Agile Trial, which seeks to build the minimum viable prototype[5], and to apply rapid cycles of measurement and on-site design refinements, until acceptable design is reached. The entire process from ideation of a new solution to its inclusion in guidance can be significantly accelerated.

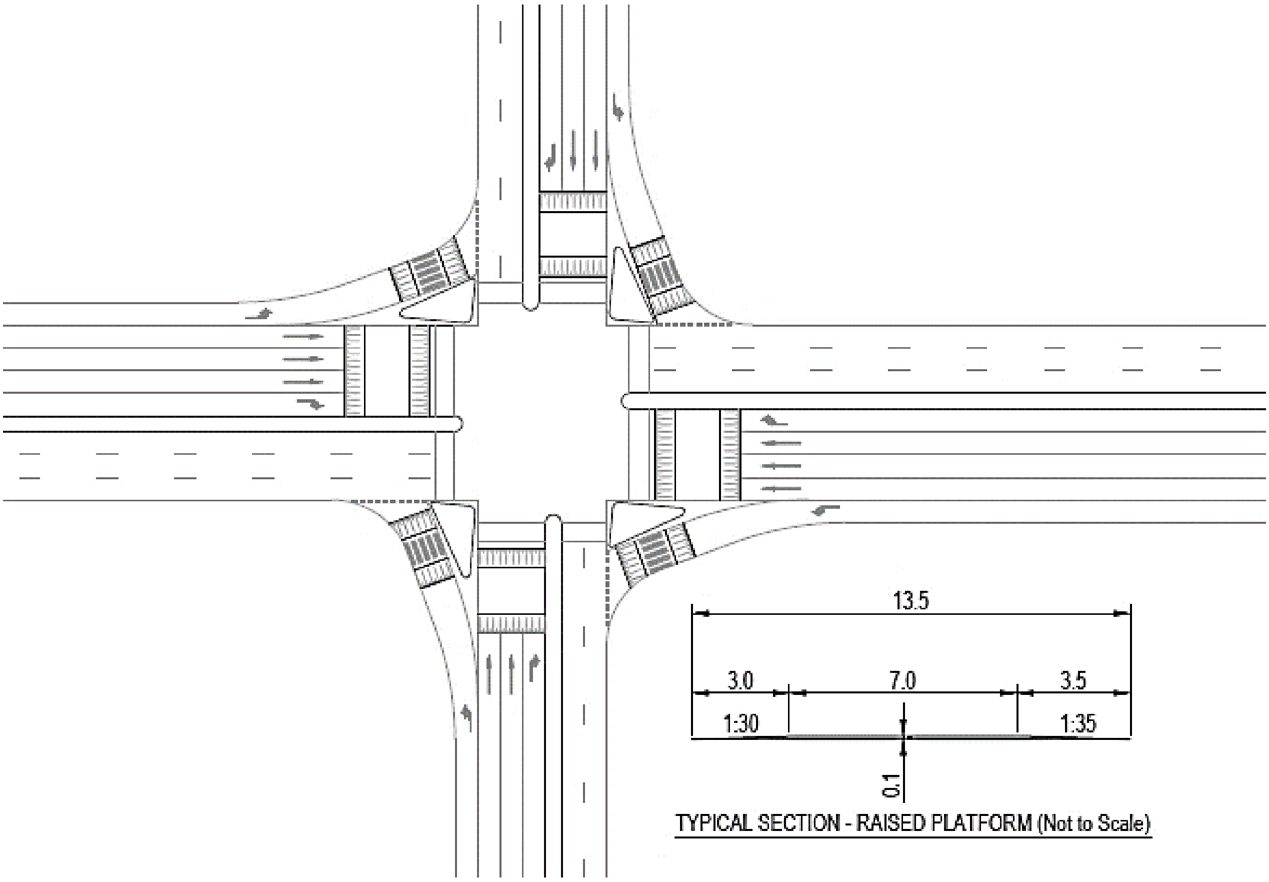
4.1 Signalised Intersection with Safety Platforms

4.1.1 Description and Design Intent

Safety platforms are also known as speed tables, or raised pavements (Austroads 2016d). Safety platforms can be installed ahead of the stop line of a signalised intersection approach to reduce entry and impact speeds to a level which is below the serious injury thresholds for different conflict points. This solution recognises that the conventional cross- or T-signalised intersection form will often have to be retained, and a roundabout is not feasible. Thus, the objective is to minimise the harm within existing site and design constraints.

Safety platforms are also installed to raise awareness of a high-risk intersection (e.g. presence of vulnerable road users), and can be line marked or coloured differently to highlight their presence. Figure 4.1 shows a conceptual layout of an urban signalised intersection with safety platforms. The platform cross-section is based on an existing example in Geelong, Victoria, designed for up to 80 km/h approach speeds.

Figure 4.1: Concept functional layout of a signalised intersection with safety platforms



Source: ARRB Group. The presented concept ramp was designed for speeds up to 80 km/h.

5 This should be preceded by creation of a trial evaluation framework, detailed design, and a thorough risk assessment. Jurewicz (2017) provides further details on Agile Trial methodology.

Safety platforms at signalised intersections are a standard treatment in the Netherlands, and several other European countries, and trial sites operate in Victoria (see Section 4.1.4). In the Netherlands, the platforms were installed at both urban and rural signalised intersection. They are more commonly found in urban areas where there is a high level of pedestrian traffic.

Safety platforms can also be installed on left-turn slip lanes to reduce vehicle turning speeds in conjunction with pedestrian crossing facilities. Another variant of the treatment involves creating a safety platform across the entire signalised intersection area (see example in Section 4.1.6).

The design intent for safety platforms at signalised intersections is proposed is a Safe System supporting solution applicable as a new or retrofit design for urban arterial intersections. It is expected to significantly improve levels of safety for passenger and heavy-vehicles, and to somewhat improve safety of vulnerable road users. The operation impacts of the treatment are intended to be minimal.

Section 4.1.4 presents examples of local and overseas intersections with safety platforms.

4.1.2 Application, Design Considerations and Costs

Safety platforms are well suited to urban arterials where there is a need to cater for high volumes of traffic, including pedestrians and cyclists, and for public transport access and priority. It may be a lower-cost alternative to a roundabout as safety platforms can be retrofitted onto an existing intersection without substantial changes in intersection geometry. Safety platforms are useful where the main objective is to reduce crash severity and likelihood without high expenditure.

The extent of the speed reduction can be regulated by the specific platform design features, i.e. height and length of the raised section and gradient of the ramp sections. The typical platform height is between 75 and 100 mm according to the traffic calming guide, with lengths up to 6 m (Austroads 2016d), although longer platforms are also used. The Guide suggests gradients between 1:12 and 1:20 (for bus routes) in speed environments of 60 km/h or less. Ramps in the 1:15–1:20 range are an upper limit of what is considered bicycle-friendly. Further, VicRoads design trials produced satisfactory vertical acceleration results with ramps of 1:30 on platform approach and 1:35 on departure. These were tested for intersection approach speeds up to 80 km/h with platform exit speeds of 60 km/h (Pratt, McGarrigle & Turner 2015).

Ramp gradients need to be carefully selected to balance entry speed reduction potential (improved safety) with risk of adverse operational effects such as ‘bottoming out’ by vehicles with lower suspension, or discomfort risk of falls for bus passengers. Consideration needs to be applied to turning heavy vehicles, as the combined horizontal and vertical forces on the axles may lead to increased risk of overturning. Water flow paths and drainage need to be considered as well to ensure water does not pond around traffic islands. Furthermore, the platforms should not be sloped down towards the kerb as this may create a hazard for cyclists. These details have been successfully worked through in previous designs, e.g. in Victoria.

Depending on the nature of the site, this design can be retrofitted at a low-moderate cost on an intersection with a small footprint. Additional costs for a new signalised intersection would be even lower.

4.1.3 Safe System Alignment

Installing a safety platform to assist in reducing the speed from 70 km/h to 50 km/h has a potential to reduce injury crashes by an estimated 30% at already signalised intersections (Fortujin, Carton & Feddes 2005). The authors evaluated the treatment effectiveness in the Netherlands in combination with other speed management measures at signalised intersections, e.g. signs, and red-light cameras finding casualty crash reduction in the 40–50% range. Greater improvement would be expected at priority-controlled sites being signalised with inclusion of vertical deflections on approaches (crash reduction factor, or CRF of 50–60%).

Safe System assessment

To better understand the Safe System value of safety platforms at signalised intersections, the concept was evaluated using the Safe System Assessment Framework (SSAF) based on Austroads (2016b), described in Appendix A. As part of the study's workshop series, eleven different multidisciplinary practitioner groups evaluated the design concept shown in Figure 4.1 as a case study.

Additional site-specific information was provided to each group, such as urban location, high traffic flows, 60 km/h speed environment, significant presence of pedestrians, cyclists and buses. The intersection entry/impact speeds were assumed to be 40 km/h, as would be expected from an appropriately designed ramp system. The average SSAF score produced by the participants was 207 out of 448, i.e. one the boundary of poor and moderate alignment with the Safe System objectives under the arterial conditions used in the case study[6]. The scores for vehicle-vehicle crashes were in the moderate range. The scoring of SSAF is detailed in Appendix A.4.1.

Pedestrian, cyclists and intersection type crashes were the most severely scored in this case study. SSAF demonstrated that this was due to the high exposure of pedestrians and cyclists to impact speeds above the 20 km/h FSI threshold, but offset by controlled interactions with vehicles (signals, zebra). It was noted that the safety platforms were effective in reducing the impact speeds, but not below the FSI threshold level for vulnerable users. Overall, the Safe System alignment for vulnerable road users was scored as poor to moderate.

For comparison, an equivalent conventional signalised intersection (same design and conditions, but no safety platforms) was evaluated by the authors as producing a score of 324 out of 448 (i.e. very poorly aligned with Safe System).

These total SSAF score values are qualitative metrics only, but indicate that safety platforms alone may reduce FSI risk by approximately a third, compared with a conventional design.

The Safe System Assessments during stakeholder workshops generated several optional design improvements seeking to achieve even better Safe System alignment, especially for vulnerable road users. Section 4.1.6 lists the specific ideas, mainly additional pedestrian and cyclist safety features. The average of 'after' scores given by the stakeholders following adoption of these improvements was 122 out of 448, a significant improvement which brings the concept close to being highly aligned with Safe System.

X-KEMM-X analysis

Further analysis of the crash likelihood and severity at signalised intersections with safety platforms were undertaken using the X-KEMM-X method described in Section 3.2 and Appendix B. The case study used was that shown in Figure 4.2 (the same concept as in Figure 4.1), i.e. a signalised intersection in a 60 km/h speed environment where entry speeds were reduced to 40 km/h with to safety platforms.

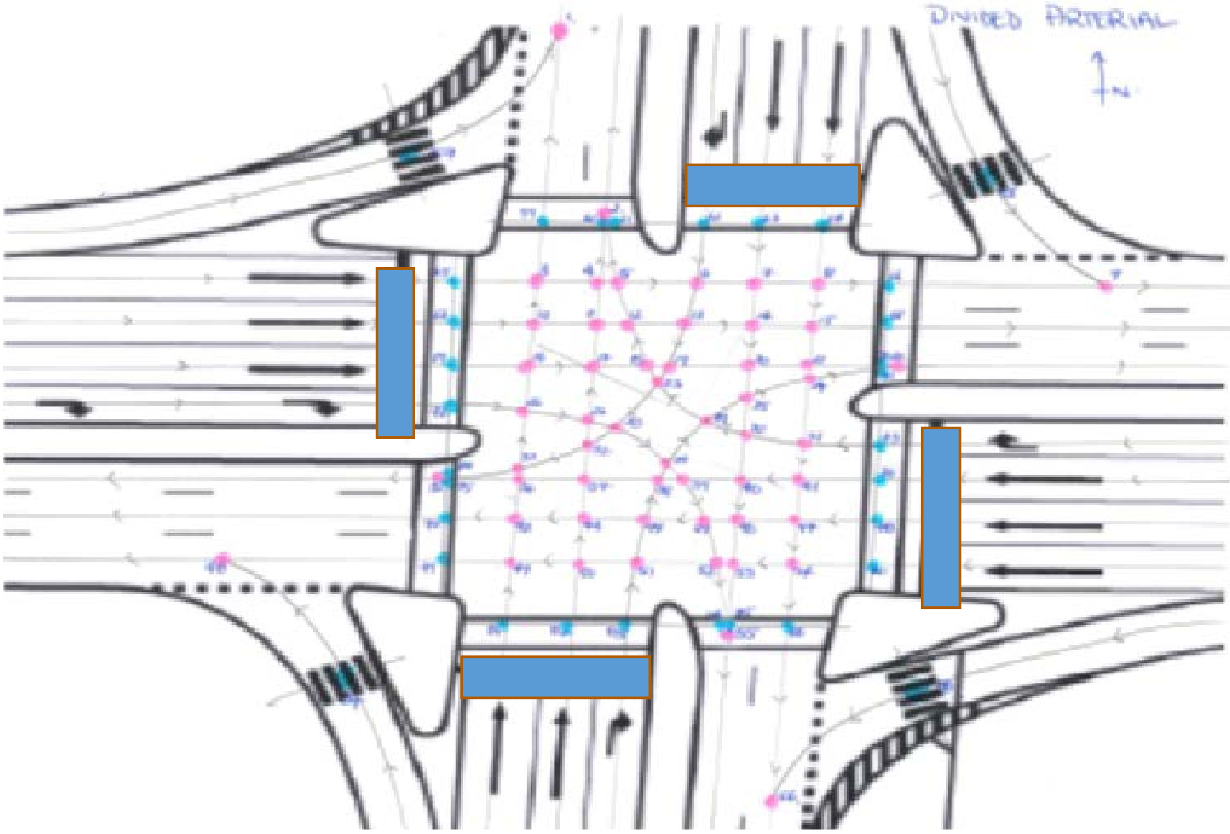
X-KEMM-X analysis results are shown in Table 4.1 for the design concept and for a conventional design (no platforms), for comparison. The main observation is that the number of vehicle-vehicle conflict points remained unchanged. Also, the impact angles remained the same, as there was no significant change in horizontal geometry.

There was a notable reduction in the average and maximum FSI probabilities for vehicle-vehicle crashes in the design with platforms, due to reduced entry speeds. Figure 4.3 demonstrates this effect clearly.

The analysis shows that probability of FSI at pedestrian-vehicle conflict points has not been addressed, and vulnerable road users are still exposed to high severity outcomes.

6 It is quite likely that the design concept could be highly aligned with Safe System in a different road environment. For instance, if applied on an already lower-speed mixed-use arterial, the safety platforms could be used to further reduce speeds into the 20–30 km/h range which is more forgiving to vulnerable road users.

Figure 4.2: Schematic of signalised intersection with safety platforms, showing major conflict points



Source: ARRB Group.

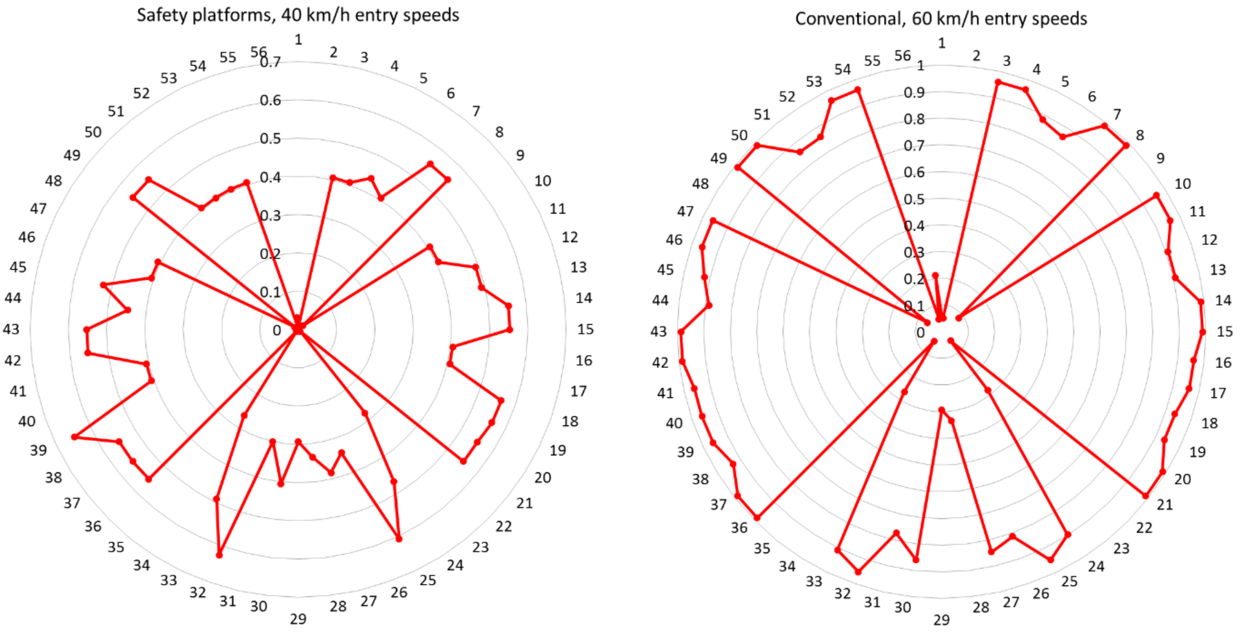
Overall, X-KEMM-X analysis of the case study suggested the Safe System alignment of the concept was poor to moderate for vehicle occupants, but an improvement from the conventional alternative. For pedestrians, the alignment was also between poor and moderate, with a significant improvement from the conventional design. This issue was also identified by the stakeholders during the workshops, and their design improvement suggestions are summarised in Section 4.1.6.

Table 4.1: Example of X-KEMM-X analysis results for a signalised intersection with safety platforms (Figure 4.2)

	Design concept with 40 km/h safety platforms		Conventional 60 km/h, no platforms (comparison)	
Risk attributes	Vehicle-vehicle conflict	Pedestrian-vehicle conflict	Vehicle-vehicle conflict	Pedestrian-vehicle conflict
No. of conflict points	56	32	56	32
Average Pr(FSI)*	0.40	0.42	0.77	0.69
Maximum Pr(FSI)	0.65	0.56	0.99	0.99
Per cent conflict points with Pr(FSI) > 0.1	86%	88%	88%	88%

** Pr (FSI) is the probability of a severe injury given the assumed impact speeds, angles and crash configurations.*

Figure 4.3: X-KEMM-X FSI probabilities for different conflict points, for vehicle-vehicle crashes, compared between the case study with safety platforms and without (Figure 4.2)



Source: ARRB Group.

Further design improvements, especially for the vulnerable road users, would promote the design concept towards the high alignment (see Section 4.1.6).

4.1.4 Practice Readiness

Safety platforms at signalised intersections are an emerging treatment with trial applications in several jurisdictions (e.g. Victoria and South Australia). However, throughout Europe, raised platforms are commonly used in urban areas with a high level of pedestrian movements.

Examples of raised safety platforms are shown in Figure 4.4 and Figure 4.5 where:

- Figure 4.4 is a Victorian urban arterial treatment aiming to reduce through traffic speeds from 70 km/h down to 50 km/h entry speeds (designed for 60 km/h as a compromise to maintain bus passenger comfort).
- Figure 4.5 and an urban arterial in the Netherlands.

Figure 4.4: Surf Coast Hwy and Kidman Ave, Belmont, Victoria, showing the safety platform

Source: VicRoads (n.d.).

Figure 4.5: Urban arterial signalised intersection with safety platform in the Netherlands

Source: Corben et al. (2010b).

4.1.5 Knowledge Gaps and Concerns

The review of available evidence and stakeholder inputs highlighted some knowledge gaps which need to be addressed through evaluations of recent and future studies:

- Post-crash care – emergency access may be slightly delayed by the platforms.
- Community acceptance – potential rejection of innovative treatment by the community. Public acceptance of the Surf Coast Highway trial suggests that extensive public consultation and communication are essential, at least in the emerging treatment period.
- Effects on intersection capacity and delay were not evaluated at the time.
- Drainage needs to be considered – relocation of pits.
- Relocation of signal pedestals and lanterns, and of lighting, especially on traffic islands and in medians.
- Maintenance of the ramps (e.g. rutting).

Several general concerns were raised by the stakeholders in relation to the concept:

- noise from trucks mounting ramps
- application with varying pavement types, e.g. bituminous seal, concreate.

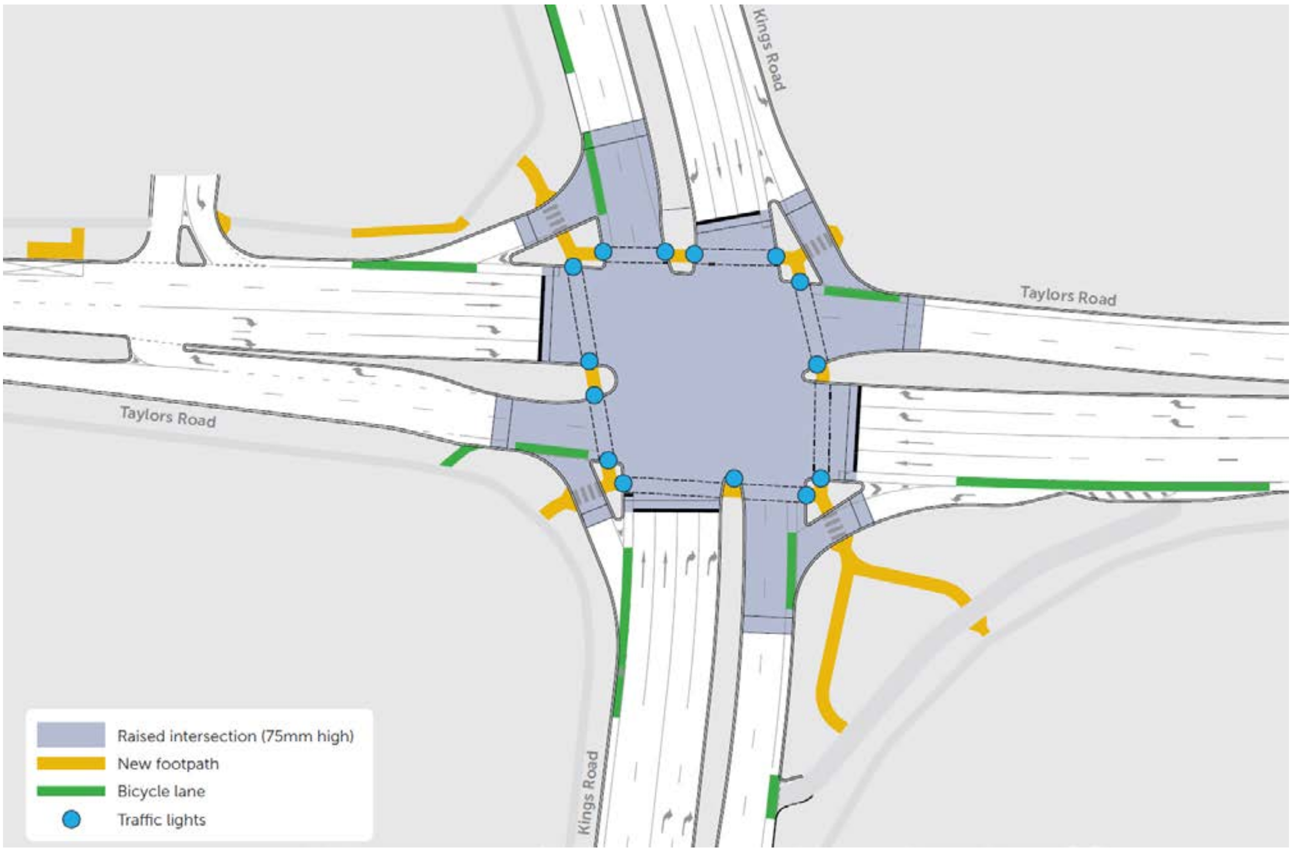
4.1.6 Further Design Improvements

The following design improvements were suggested through stakeholder workshops with the intention to improve the level of Safe System alignment. Many were identified via application of SSAF. These suggested improvements were directed at the case study design in Figure 4.1 and Figure 4.2, but could be considered in all future safety platform designs at signalised intersections:

- Provide bike lanes and stand up boxes to accommodate cyclists. Alternatively, provide shared off-road pedestrian and cyclist user paths.
- Signalise and fully control left turn movements to reduce pedestrian conflict (instead of zebra crossing), or eliminate slip lanes.
- Install red light cameras at all approaches.
- Extend platforms to incorporate pedestrian crossings.
- Apply a skid resistance overlay to assist braking in wet weather condition.
- Use smart LEDs to guide and delineate platforms.

Another valuable suggestion was to raise the entire intersection as a platform, rather than providing individual approach platforms (see Figure 4.6). In many ways, this simplifies many of the design concerns raised in the previous section. This related design concept was being trialled in Victoria in 2017. Figure 4.7 shows an existing arterial example from the UK.

Figure 4.6: A variation on the concept: raised signalised intersection



Source: VicRoads, email communication, Stephanie Aldover, 5 December 2016.

Figure 4.7: High St, New Malden, UK

Source: ARRB Group.

4.2 Signalised Roundabout

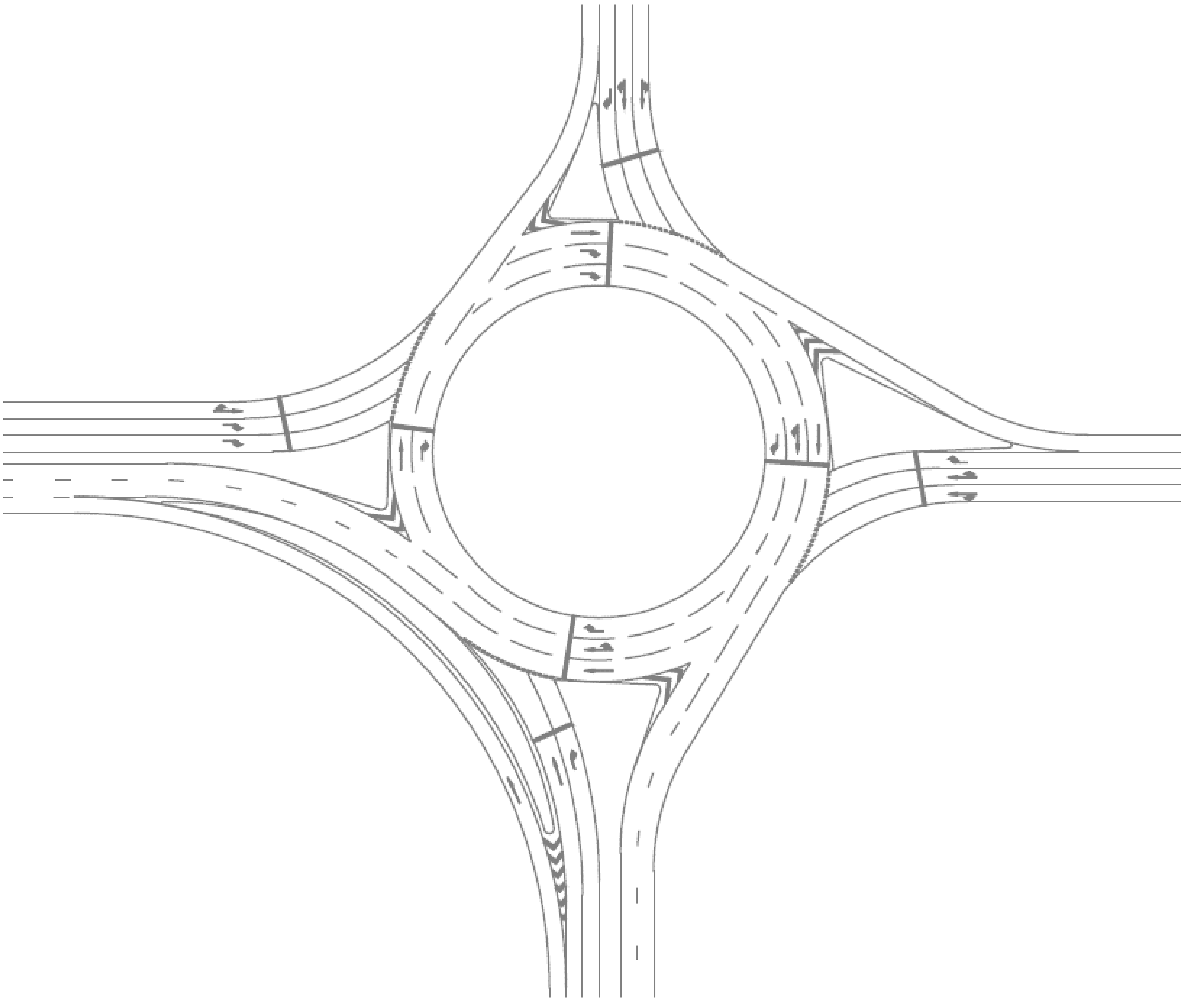
4.2.1 Description and Design Intent

Signalised roundabout generally provides full-time use of signalised approaches and provides signal phasing for all major movements. This design concept is not the metered roundabout already used in several jurisdictions.

A fully signalised roundabout is a roundabout where movement priority is controlled by a traffic signal rather than a roundabout sign. The design benefits from the roundabout design characteristics of low-speed approaches and low angles of entry, while having drawing on additional benefits of reliability and flexibility of signalisation.

Signalisation of movements offers a simplification of the give way decision-making process. Thus, a signalised roundabout should be more reliable in managing multi-lane traffic flows at a large site. Figure 4.8 shows a conceptual example of a signalised roundabout.

Figure 4.8: Concept functional layout of a large signalised roundabout



Source: ARRB Group.

Signalised roundabouts frequently include turning traffic storage within circulating area. This enables more flexibility of phasing, making the signals operation more akin to a large conventional intersection. Generally, all movements are fully controlled; however, examples exist where low-volume approaches remain unsignalised.

The UK Department for Transport (2009) noted that signalised roundabouts in England have several safety benefits compared to conventional roundabouts:

- reduction in crashes resulting from poor judgement of gaps in circulating traffic
- reduction in the incidence of rear-end crashes between vehicles waiting to join the roundabout
- regulation of traffic patterns, reduced need for weaving and merging
- reduced speeds
- are easier and more predictable entry for trucks and public transport
- prioritise pedestrian and cyclist crossings.

Signalised roundabouts are common in Great Britain and Ireland, where they have been introduced to alleviate traffic congestion at existing roundabouts, or to prevent some flows of traffic dominating others (Department for Transport 2009). They have also been introduced in other EU countries, and in New Zealand during the last decade.

The proposed design intent is for signalised roundabout to be a viable Safe System alternative to conventional urban signalised cross- or T-intersections in certain circumstances. The concept may offer improved cyclist safety through signalising the off-road bypasses of the roundabout.

Section 4.2.4 presents a wide range of local and overseas examples of signalised roundabouts.

4.2.2 Application, Design Considerations and Costs

Signalised roundabouts are suited to urban arterials where there is a need to cater for high volume of traffic, pedestrian and cyclist movements, and for public transport access and priority. Traffic signals can be retrofitted at some existing roundabouts, e.g. when existing design can no longer adequately cater for increased traffic flow and complexity of traffic movements. The signalisation of existing roundabout offers a potential safety advantage due to simplification of the give way rules (Department of Transport 2009). Alternatively, signalised roundabout can be introduced as a greenfield design in preference to conventional signalised intersection design. This should also offer a safety improvement (see Section 4.2.3).

The design of signalised roundabouts differs from conventional roundabouts. The UK Department of Transport produced guidelines for the design of signalised roundabouts (Department of Transport 2009). The guidelines highlight many criteria which need to be considered in detail; however, they are not prescriptive.

Right-turn storage within the intersection is often a design challenge, leading to increased size of the central island and thus the intersection. Lane assignment within the roundabout needs to be carefully planned to minimise lane weaving or queues blocking other movements. Directional guidance and lane management on approaches to the roundabout also need to be included in the design.

Many signalised roundabouts have a large footprint, however smaller designs are also found (see Figure 4.15). According to Chard, Thomson and Bargh (2009) a three-leg signalised roundabout is ideal for its efficiency of phasing and progression through the roundabout.

From the Safe System perspective, it is important to retain low angles between conflicting movements (e.g. entry vs. circulating) and to maintain approach deflections to minimise entry speeds.

Visibility of signal displays requires specific attention given the curved approach paths and then circulation within the roundabout (Department for Transport 2009).

It is not always necessary to signalise all approaches of a roundabout. Leaving one or more minor entries under priority control sometimes results in better overall traffic efficiency. Examples exist, where local access lanes, commercial driveways and public transport right-of-way were retained with give-way signs.

Geometric design, traffic management options, phasing and signal design need to be assessed in detail in each case. As suggested by past practice, comprehensive traffic modelling is recommended for important sites to ensure the final design can efficiently accommodate existing and projected traffic demands including pedestrians, cyclists and public transport.

For greenfield sites, a signalised roundabout is likely to be a higher-cost solution than a new conventional signalised intersection, due to a larger footprint. This generalisation may not apply where an existing roundabout is signalised in lieu of a full re-development in form of a conventional signalised intersection. As discussed in the next section, safety benefits are likely to significantly offset capital costs at many sites.

4.2.3 Safe System Alignment

Gross et al. (2013) developed a casualty CRF of 65% for conversion of conventional signalised intersections to conventional roundabouts, confirming an earlier study by Rodegerdts et al. (2007). Further, a 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.

Further published literature search did not find a CRF or crash modification factor (CMF) for conversion of a conventional signalised intersection to a signalised roundabout. In combination, the two references provide an indication of significant safety benefit of signalised roundabouts, with CRF possibly more than 65%.

The UK Department for Transport (2009) cites its own evidence that the introduction of signals at roundabouts can reduce risks for two-wheeled vehicles, an FSI problem reported on in depth in Austroads (2015).

Safe System assessment

The concept was evaluated using the Safe System Assessment Framework (SSAF) to better understand its Safe System value (Austroads 2016b).

Eleven independent, multidisciplinary stakeholder workshop groups assessed the signalised roundabout concept using the three-leg design in Figure 4.9 as a case study. The assumptions included a 60 km/h approach speed (lower entry speeds), a 30 km/h circulating speed, and high vehicular, pedestrian and cyclists traffic volumes. The average SSAF score produced by the participants was 218 out of 448, i.e. moderately aligned with Safe System for this scenario (borderline with poorly aligned). The main FSI risk contributors were pedestrian, cyclist and motorcyclist crashes, which were the most heavily scored in this case study. This was due to high volume of vulnerable road users (inner city university precinct) and inability of the case study design to limit the impact speeds below the FSI threshold level for vulnerable road users (approximately 20 km/h).

An equivalent signalised T-intersection was evaluated by the authors producing a score of 296, i.e. poorly aligned. Thus, despite the noted limitations, the case study signalised roundabout design was noticeably more aligned with Safe System objectives than a comparable conventional design option.

Figure 4.9: Swanston St/Cemetery Rd/College Cres, Melbourne, Victoria

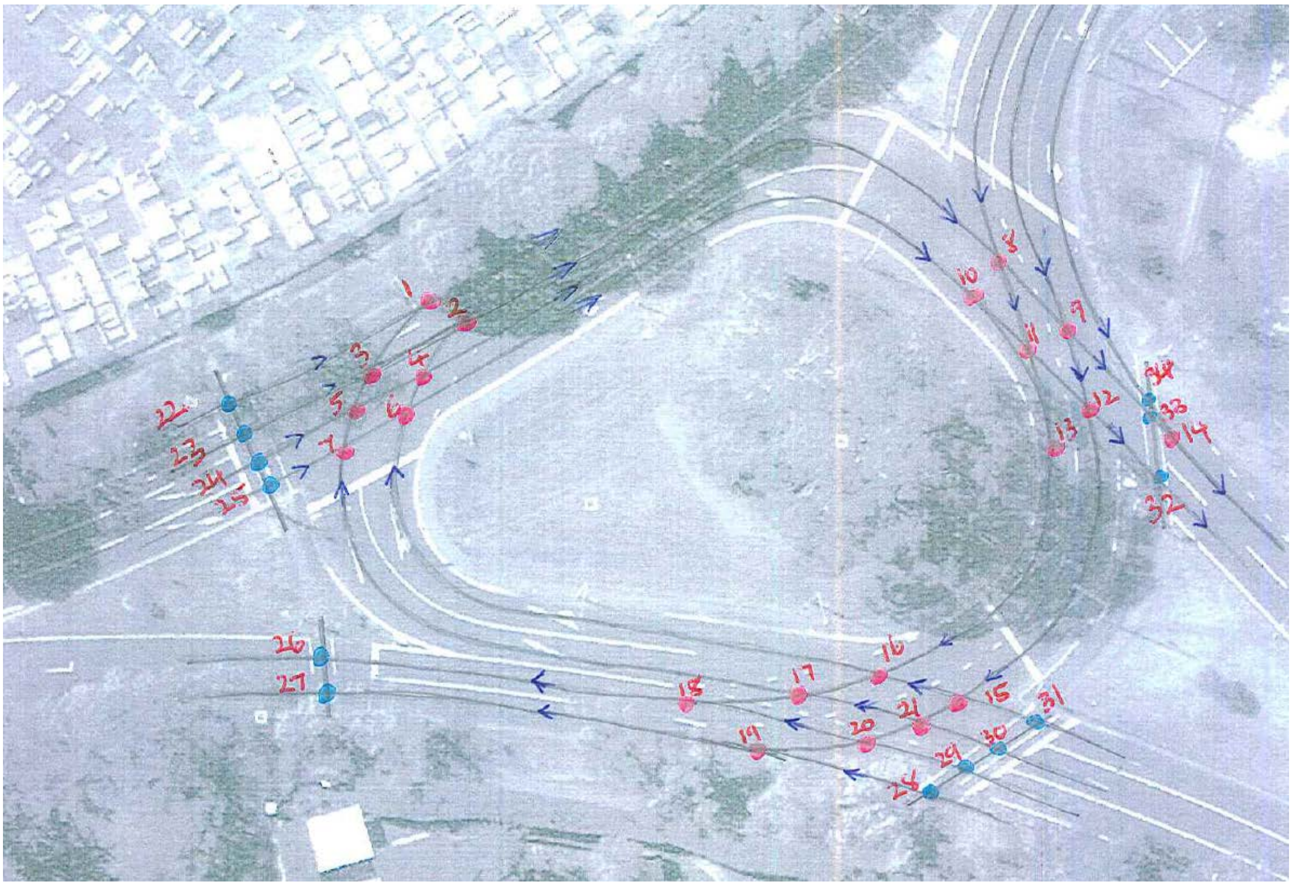
Source: Google Maps (2016), 'Victoria', map data, Google, California, USA.

The Safe System Assessment generated many relevant additional design improvements to achieve closer Safe System alignment for vulnerable road users, as listed in Section 4.2.6. The average of 'after' assessments by the stakeholders was 104, i.e. highly aligned with Safe System. This was mainly achieved through better approach and entry speed controls, and addition of cyclist and motorcyclist safety features.

X-KEMM-X analysis

Further analysis of the crash severity aspects of the signalised roundabout design were undertaken using the X-KEMM-X method (Appendix B). The example used was that shown in Figure 4.10, a large urban arterial application in 60 km/h speed environment, with 50 km/h entry and 30 km/h circulating speeds.

Figure 4.10: A Victorian example of a signalised roundabout, showing major conflict points



Source: ARRB Group.

X-KEMM-X analysis results are shown in Table 4.2. The main finding is that the number of vehicle-vehicle conflict points is relatively low for this large multi-lane three-leg intersection. Secondly, the probability of FSI outcome in vehicle-vehicle conflicts is also very low, mostly below the nominal FSI threshold of 0.1, as demonstrated in Figure 4.11.

On the other hand, Table 4.1 shows that there are many pedestrian-vehicle conflict points due to the multi-lane character of the intersecting roads. As indicated by the SSAF analysis, the severity of these conflicts would be high for pedestrians due to relatively high speeds (either 30 or 50 km/h).

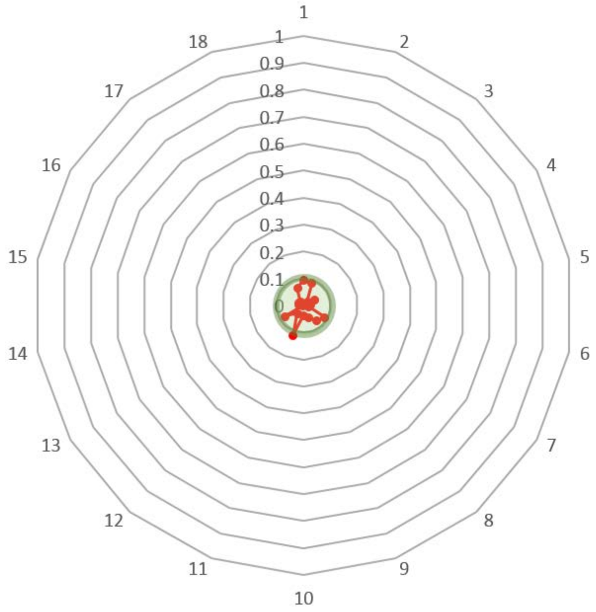
Overall, X-KEMM-X confirmed that the signalised roundabout design presented in the case study would be very highly aligned with Safe System for car vehicle occupants, but poorly aligned for pedestrians (and other vulnerable road users by logical extension). This prompted several potential concept improvements discussed in Section 4.2.6.

Table 4.2: Example of X-KEMM-X analysis results for the signalised roundabout in Figure 4.10

Result	Vehicle-vehicle conflict	Pedestrian-vehicle conflict
No. of conflict points	21	13
Average Pr(FSI)*	0.08	0.67
Maximum Pr(FSI)	0.23	0.95
Percent conflict points with Pr(FSI) > 0.1	29%	92%

** Pr(FSI) is the probability of a severe injury given the assumed impact speeds, angles and crash configurations.*

Figure 4.11: X-KEMM-X results for vehicle-vehicle conflicts for the multilane signalised roundabout in Figure 4.10



Source: ARRB Group.

4.2.4 Practice Readiness

Signalised roundabouts have been implemented infrequently in Australia and New Zealand, but are more common in UK and other European countries. Figure 4.12 to Figure 4.15 provide some examples of fully signalised roundabouts, including those in Australia and New Zealand.

Figure 4.12: Barton Highway/Gundaroo Drive/William Slim Drive, Canberra

Source: nearmap (2016), 'Western Australia', map data, nearmap, Sydney, NSW.

Figure 4.13 is an example of high-speed signalised roundabout catering to road trains in an 80 km/h speed zone.

Figure 4.13: Eelup roundabout, National Route 1, East Bunbury, WA

Source: nearmap (2016), 'Western Australia', map data, nearmap, Sydney, NSW.

Figure 4.14 shows an existing high-volume signalised roundabout managing complex routes coming together in the centre of Hobart, Tasmania. Figure 4.15 shows a recent upgrade of a small metered roundabout to a fully-signalised roundabout on the junction of two arterials in Melbourne, Victoria.

Figure 4.14: Brooker Hwy/Bathurst St/Liverpool St – Hobart, Tasmania

Source: nearmap (2016), 'Tasmania', map data, nearmap, Sydney, NSW..

Figure 4.15 shows a smaller footprint signalised roundabout, created by conversion of an existing conventional roundabout.

Figure 4.15: Mickleham Rd/Melrose Dr roundabout, Melbourne, Victoria

Source: nearmap (2016), 'Western Australia', map data, nearmap, Sydney, NSW.

4.2.5 Knowledge Gaps and Concerns

The review of available evidence and stakeholder inputs highlighted some knowledge gaps which need to be addressed through evaluations of recent and future signalised roundabout projects:

- Large footprint – which traffic and design conditions would allow signalised roundabouts to function well in a smaller format?
- Lack of robust evidence for the overall safety effect compared to conventional signalised intersections. Likewise, for the vulnerable road users such as pedestrians, cyclists and motorcyclists.
- If signalised roundabout extends functional life of a conventional roundabout, then for how long, and is it worth the expenditure, before conventional signals are adopted?[7]
- There will be a need to provide Australian and New Zealand guidance for analysis and design of signalised roundabouts.

Several general concerns were raised by the stakeholders in relation to the concept:

- It may be challenging to balance approach horizontal deflections (for speed control) with heavy vehicles turning circles.
- Irregular shape of a central island may cause some stability problems for motorcyclists (an FSI factor highlighted in Austroads 2015).
- Conventional signalised intersections produce designs which are broadly consistent and legible to drivers. Signalised roundabouts may need to be larger and more customised designs, resulting in lower legibility to users.

7 This question carries several assumptions, for instance, that a signalised roundabout would have a lower capacity, or higher delay than a comparable conventional signalised intersection design.

4.2.6 Further Design Improvements

The following design improvements were suggested through stakeholder workshops with intention to improve the level of Safe System alignment. These were directed to the case study design in Figure 4.9, but could be considered in all future signalised roundabout designs:

- Reduce approach speed limits to 50 km/h (may be time-based).
- Realign approaches to further reduce entry angles into the roundabout (less than 70 degrees).
- Install raised pedestrian crossings, and/or safety platforms on approaches to moderate entry speeds.
- Install safety barriers and rub rails to reduce run-off-road risk, especially to motorcyclists.
- Provide bypass cyclist lanes entirely off-road with signalised crossing points.
- Provide additional directional signage and lane management well in advance of the site due to reduced legibility of a large intersection.
- Consider left turn free-flow lanes (bypass) to eliminate some of the conflict points.
- Install red light/speed cameras on all approaches.

4.3 Urban Compact Roundabout with Safety Platforms

4.3.1 Description and Design Intent

There are many locations on the urban road network where safety of an existing roundabout is under-performing due to inadequate geometric deflection. This can be dictated by the need to accommodate large heavy vehicles, or due to challenging approach alignment, or simply due to approach speeds being higher than anticipated in the design. At other times, greenfield sites pose such significant limitations (e.g. services), that installation of a new conventional roundabout would be cost-prohibitive, and instead, less safe intersection options are selected.

In such situations, a smaller or less deflective roundabout can be augmented by addition of safety platforms at approaches. These speed platforms act to moderate approach and entry speeds in a similar way that approach curves and a large central island would do at a conventional roundabout.

The proposed design intent is for a compact roundabout with safety platforms to be a viable Safe System alternative to a signalised urban arterial or local intersection, to an expensive conventional roundabout, or to retaining a Give Way/Stop sign traffic control. Figure 4.16 shows an arterial design concept, with safety platforms retrofitted to moderate speeds ahead of a compact roundabout. The concept can be also applied in a rural environment, and this variant is presented in Section 4.4.

Roundabouts may also be combined with raised zebra (Wombat crossings) and cyclist crossings where there is strong demand. This removes potential confusion as to the intent of the raised pavement area. This would also provide a shift in traffic priority towards active transport, if such was desired. A successful implementation of safety platforms combined with zebra crossings exists in Richmond, Victoria (see Figure 4.19).

4.3.2 Application, Design Considerations and Costs

The urban variant of the concept is well suited to low speed urban environments (≤ 60 km/h), where current knowledge on safety platforms in traffic calming context may be applied directly as per the Austroads (2016d) guide. For higher-speed environments (60–80 km/h), the design information noted in Section 4.1.2 in relation to signalised intersections with safety platforms may be considered. Monitoring of site performance would be recommended in case minor adjustments of ramp dimensions are needed.

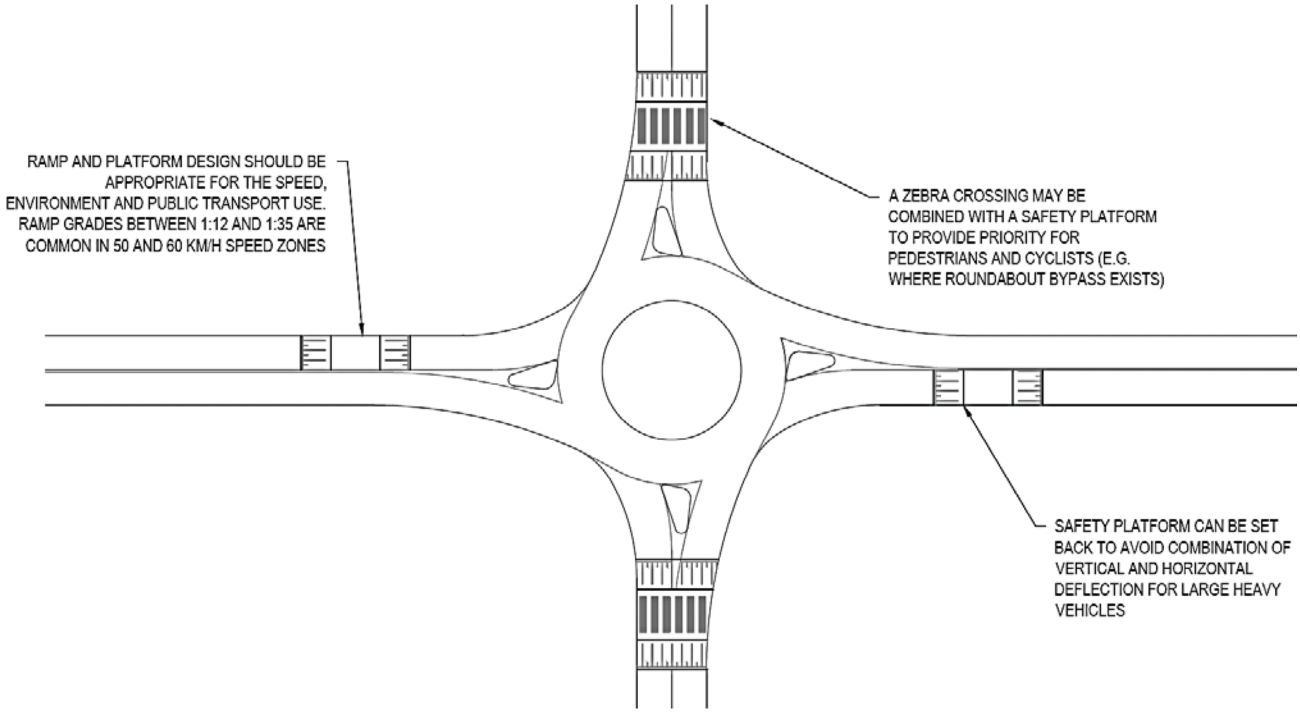
There was still a need to develop design guidance for application of safety platforms at high speed sites, i.e. where approach operating speeds would be over 80 km/h. This was especially important in relation to catering for safe movement of heavy vehicles, buses and motorcyclists. One emerging solution was to apply a double set of platforms as showcased for the rural variant of the design concept in Section 4.4.

On local roads, or where operating speeds are low, safety platforms can take more varied forms, e.g. raised zebra crossings, speed humps or speed cushions. This treatment would provide improved safety to vehicles, pedestrians and cyclists through reduced impact speeds. Also, cost reductions are expected as the design would rely less on creation of tight horizontal deflections.

It is important to stress that safety platforms are intended to support the objective of low entry speeds into the roundabout. A degree of horizontal deflection is still required to achieve lower impact angles. This can be achieved using splitter islands and the central island.

Initial applications of the concept will require inputs of experienced civil designers to achieve desired entry and circulating speeds in the 30–40 km/h range or lower[8]. Also, prototype testing can be carried out on site, with physical corrections to ramp grade being a relatively low-cost design refinement. Detailed guidance can be developed in time.

Figure 4.16: Concept functional layout of a compact roundabout with safety platforms



Source: ARRB Group.

The cost of retrofitting safety platforms at an existing roundabout is expected to be relatively low. Platforms should fit into the existing roundabout footprint (within kerbs), and no service relocations would be necessary in most cases, although surface drainage needs to be considered carefully. Overall, this could be considered a low-cost solution, or moderate if additional pavement and power pole relocations were required.

Cost of a new compact roundabout with safety platforms (and a smaller footprint) is expected to be much lower than cost of a conventional roundabout or signalised intersection.

8 Austroads (2015) recognised that urban roundabouts where cyclists are mixed in the traffic flow will require roundabout design speeds of ≤ 20 km/h to achieve Safe System objectives. This design concept lends itself to achieving this objective.

4.3.3 Safe System Alignment

The objective of this innovative design concept it to obtain similarly high level of Safe System alignment as a conventional urban roundabout, but at a lower cost (see information in Section 2.1.1 and Section 4.2.3). The average casualty crash reduction for urban roundabouts, based on many reviewed studies was 80% (Austroads 2013a), with one study reporting CRF of 90% for severe crashes (Persaud et al. 2001).

Safe System assessment

To better understand the Safe System value of the roundabout, the design concept from Figure 4.17 was evaluated using the SSAF. The assumed conditions were that of 60 km/h approach speeds, 40 km/h entry speeds and moderate traffic flows (15 000 and 11 000 veh/day per approach). Pedestrian and cyclist flows were moderate.

Eleven multidisciplinary stakeholder groups evaluated the design concept. The average SSAF score given was 115 out of 448, i.e. considered borderline between highly and moderately aligned with Safe System. The scores for vehicle-vehicle crash types were highly aligned with Safe System. Off-path, cyclist and motorcyclist crash types were the most heavily scored in this case study. The case study scored pedestrian impact severity as moderately high due to impact speeds > 20 km/h, but this was offset by reduced impact likelihood thanks to staged crossings (i.e. moderate score).

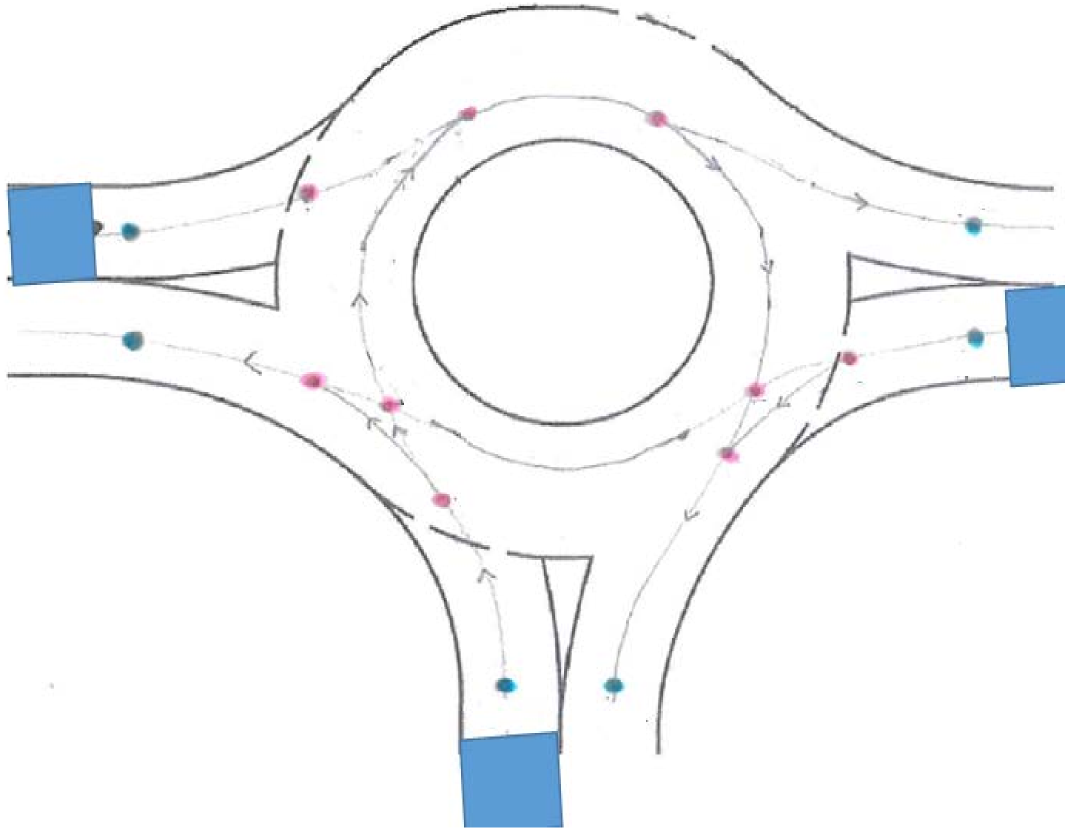
An equivalent urban signalised intersection was evaluated by the authors and produced a score of 264. Thus, despite the high risk to cyclists and motorcyclists, the case study was 56% more aligned with Safe System objectives than the signalised intersection.

The Safe System Assessment also generated several relevant design improvements for road users, as listed in Section 4.3.6. The average 'after' score given by the stakeholders were 73, i.e. a further 36% reduction. This was mainly achieved through advanced warning signs and rumble strips to better alert vehicles and motorcyclists of coming geometric changes, and through application of a roundabout bypass for cyclists.

X-KEMM-X analysis

Further analysis of the crash severity aspects of the compact roundabout with safety platforms design were undertaken using the X-KEMM-X method. The example used was that shown in Figure 4.17, i.e. an urban three-leg roundabout in an assumed 60 km/h speed environment, with 40 km/h entry and circulating speeds.

Figure 4.17: Conceptual drawing of a compact roundabout with safety platforms, showing major conflict points



Source: ARRB Group.

X-KEMM-X results are shown in Table 4.3. The main finding is that reducing entry speeds with safety platforms eliminated the possibility of FSI outcomes greater than 0.1 in vehicle-vehicle conflicts, as demonstrated in Figure 4.18.

Vehicle-pedestrian conflict severity was just below moderate level at 40 km/h due to the high crash severity inflicted on pedestrians with impact speeds of 40 km/h.

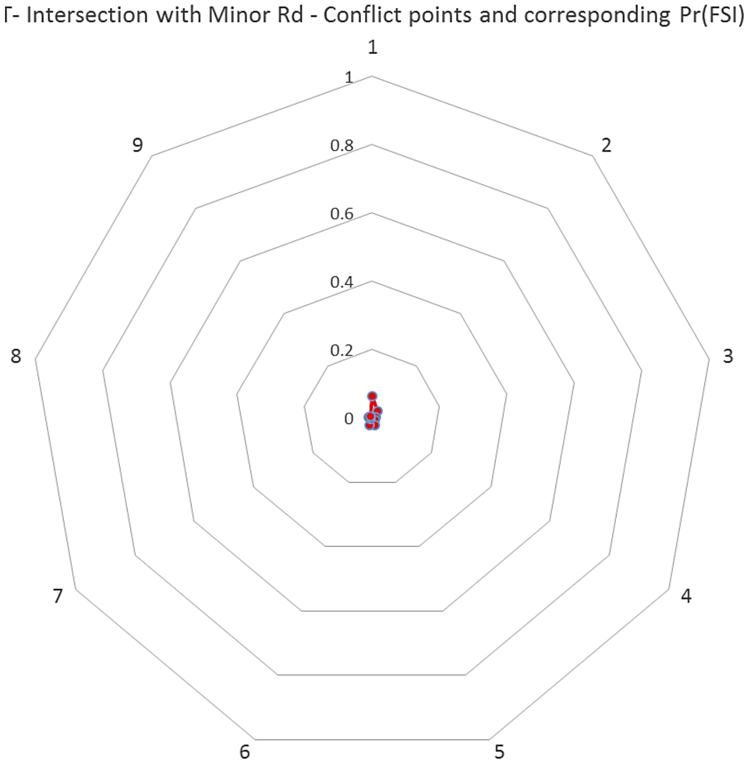
Overall, X-KEMM-X confirmed that safety platforms at roundabouts enhances the safety benefits of a conventional roundabout. Further improvements were suggested in Section 4.3.6 to make the concept more Safe System aligned for vulnerable road users.

Table 4.3: Example of X-KEMM-X analysis results for the compact roundabout with safety platforms in Figure 4.17

Result	Vehicle-vehicle conflict	Pedestrian-vehicle conflict
No. of conflict points	8	12
Average Pr(FSI)*	0.0027	0.29
Maximum Pr(FSI)	0.0027	0.56
Percent conflict points with Pr(FSI) > 0.1	0%	58%

** Pr(FSI) is the probability of a severe injury given the assumed impact speeds, angles and crash configurations.*

Figure 4.18: X-KEMM-X results for vehicle-vehicle conflicts for the compact roundabout with safety platforms in Figure 4.17



Source: ARRB Group.

Based on the case study analysis, this concept appears to be highly aligned with Safe System objectives for vehicle-vehicle crashes, and moderately aligned for pedestrians.

4.3.4 Practice Readiness

Safety platforms and other vertical deflection devices can be seen at various local roundabout sites around Australia. Figure 4.19, Figure 4.20 and Figure 4.21 show examples of some of these local road implementations. The last example uses low-cost speed cushions rather than safety platforms.

As noted in Section 4.3.2, arterial road applications of safety platforms at roundabouts can be undertaken with monitoring as design standards for speed environments above 60 km/h still required some refinement and guidance development at the time of writing.

Figure 4.19: Busy collector road roundabout with raised zebra crossings and cyclist-friendly low-speed design (Lennox St/Erin St, Richmond, Victoria)

Source: Google Maps (2016), 'Victoria, map data, Google Maps, California, USA.

Figure 4.20: Speed humps at Dumaresq St/Beaumont St roundabout, Hamilton, NSW

Source: Google Maps (2015), 'New South Wales', map data, Google, California, USA.

Figure 4.21: Speed cushions at the Essex St/Summerhill Rd roundabout, West Footscray, Victoria

Source: Google Maps (2016), 'Victoria', map data, Google, California, USA.

4.3.5 Knowledge Gaps and Concerns

A desirable part of developing design standards for safety platforms for moderate to high speed environments (> 60 km/h) would involve development of relationships between platform and roundabout design characteristics which produce desirable entry and circulation speed ranges (30–40 km/h, or ≤ 20 km/h where cyclists are included in the traffic flow).

The review of the available evidence and stakeholder inputs highlighted some knowledge gaps and risks which need to be addressed through evaluations of recent and future trials:

- vulnerability of motorcyclists and vulnerable road users (which ramp designs pose a stability threat?)
- noise pollution from heavy vehicles
- visibility of platforms – what would be adequate standards of line marking and lighting.

4.3.6 Further Design Improvements

The following design improvements were suggested through stakeholder workshops with intention to improve the level of Safe System alignment. These were directed to the case study design in Figure 4.16, and could be considered as parts of future designs:

- rumble strips on approaches to warn of the safety platforms and the roundabout ahead
- cyclist bypass and cyclist priority crossings at the platforms
- advance warning signs.

Another suggestion which was outside the design intent, was to raise the centre of the roundabout, i.e. to provide a speed ramp upon entry. A similar concept is noted in Section 4.4.6.

4.4 Rural Compact Roundabout with Safety Platforms

4.4.1 Description and Design Intent

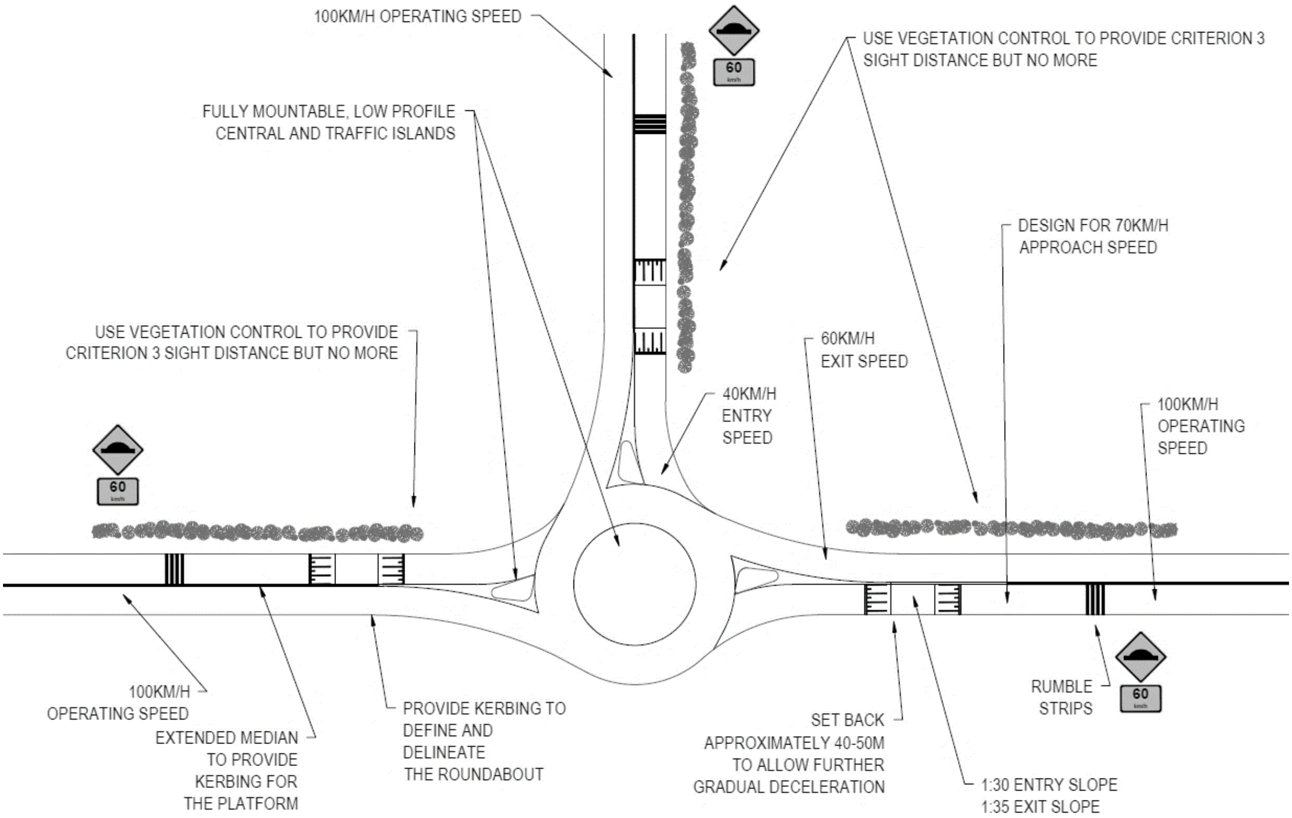
This design concept is similar to that presented in Section 4.3, but has been developed for a high-speed rural context.

The high cost of land acquisition, service relocation and construction was noted by stakeholders as barriers to greater use of roundabouts in rural areas. This design concept aims to provide a comparatively low-cost roundabout design, and thus, to promote greater application of this primary Safe System treatment.

Roundabouts are considered primary Safe System solutions, with details outlined in Section 2. However, it was noted that rural roundabouts had a higher FSI crash rate than their urban versions. Also, Table 2.1 and Table 2.2 both show that off-path FSI crashes were leading crash type at rural roundabouts, but not at urban. Thus, an additional intent of this design concept is to address some of the potential causes of this, e.g. high approach and entry speeds.

The design concept, shown in Figure 4.22, is a compact roundabout with a single deflection curve and with a fully or partially mountable centre island. In most situations, heavy vehicles could drive over the centre island apron, e.g. to execute a turn. Compact roundabouts work in the same way as normal roundabouts in terms of right of way and reducing speeds through deflection.

Figure 4.22: Concept functional design of a low-cost rural roundabout



Source: ARRB Group.

In addition, the design concept proposes installation of appropriately designed safety platforms to moderate approach speeds prior to entry into the roundabout. It is intended that the safety platforms would reduce approach speeds from 80–100 km/h range towards 60 km/h range, and the approach deflection would act to produce ≤ 40 km/h entry speeds.

4.4.2 Application, Design Considerations and Costs

It is expected this design concept would be applicable on low-volume high-speed roads with speeds exceeding 80 km/h, typically in rural areas. As noted previously, ramp design for such high speeds has not yet been trialled. A trial in Victoria proposes to use 1:40 ramps for a rural roundabout in an 80 km/h speed zone (maximum safe speed tested by Pratt, McGarrigle & Turner 2015). The concept may be applied in conjunction with a localised intersection speed limit reduction from 100 km/h to 80 km/h or less.

The intent is to gradually reduce approach operating speeds from 100 km/h to 80 km/h, then to 60 km/h across the platforms, with further reduction due to presence of the roundabout to less than 40 km/h upon entry. Therefore, the design of the roundabout entry can be similar to that used at compact local road urban roundabouts, with significant use of central island aprons, or fully mountable central islands.

Significant consideration needs to be given to heavy vehicle dynamics, especially when turning. Placement of the safety platform some distance back from the roundabout (20–30 m) may prevent a situation where a heavy vehicle is negotiating vertical and horizontal deflection at the same time.

The conspicuousness of the roundabout during both day and night is a point of consideration, especially for motorcyclists. Additional warning signage and/or rumble strips may be required early on the approaches. Visibility can be improved through use of coloured concrete on the central and splitter islands.

Stakeholders suggested provision of long splitter islands to improve structural stability of the safety platforms and to provide additional warning of changed conditions to approaching drivers.

Lighting the roundabout and the platforms should be considered. Innovative lighting options may need to be considered to avoid introduction of multiple roadside poles (e.g. ground level solar studs).

Rural compact roundabouts with safety platforms should be relatively inexpensive, compared to conventional roundabouts, because they typically require minimal or no additional footprint, or service relocations. In cases where localised widening is required and power pole relocation, the costs could be considered moderate.

4.4.3 Safe System Alignment

Provided that low entry speeds into the roundabout can be achieved through gradual deceleration, compact roundabout should have similar Safe System effectiveness as regular rural roundabouts (average 82% casualty crash reduction, Austroads 2013a).

Safe System assessment

A Safe System Assessment was undertaken for the roundabout example in Figure 4.22 as a case study by several workshop groups. The average SSAF score produced by the participants were 44 out of 448, i.e. highly aligned with Safe System objectives. The low score was in part due to low traffic volumes.

The most harshly scored were crashes involving run-off-road, intersection and other. This was due to the high speed rural environment that encompasses the intersection and the possibility of limited visibility during darker lighting conditions. An equivalent T-intersection was evaluated by the authors producing a score of 116 out of 448. Hence, despite some concerns and limitations, the compact roundabout with safety platforms was 62% more aligned with Safe System objectives compared to a conventional T-intersection.

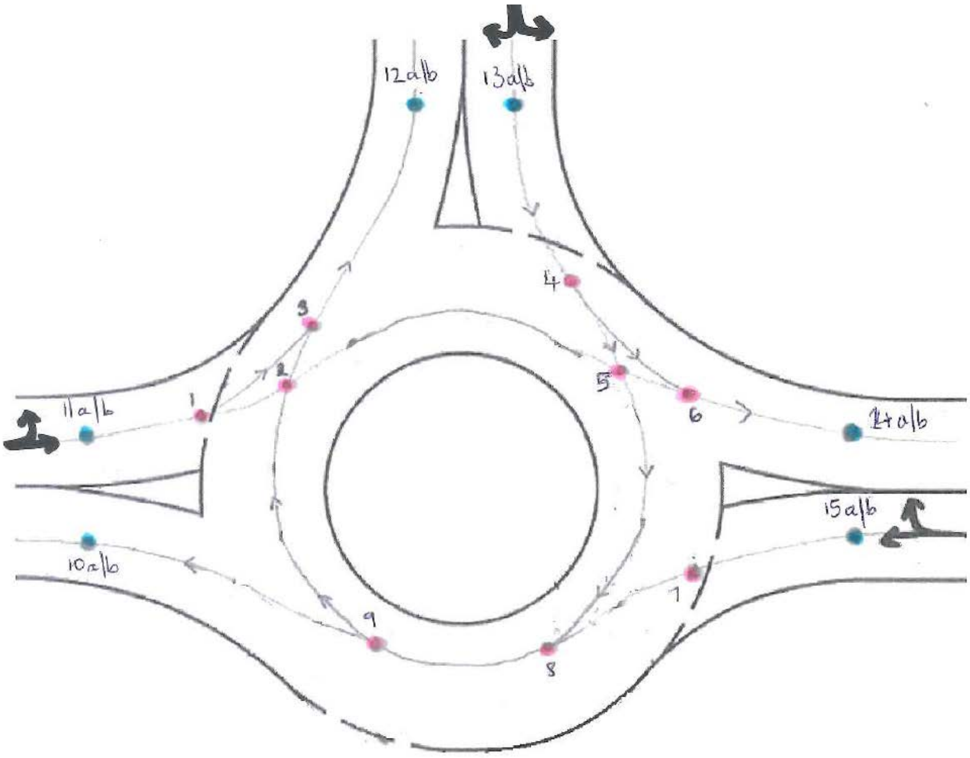
The Safe System Assessment also identified several further design improvements which could be considered in future designs, as listed in Section 4.4.6.

X-KEMM-X analysis

In addition to the Safe System Assessment, the mini-roundabout design was also subjected to X-KEMM-X analysis to identify the crash severities. The example used was that shown in Figure 4.23, a rural compact roundabout in 80 km/h speed environment with entry speeds of 40 km/h.

X-KEMM-X analysis results are shown in Table 4.4. The main finding is that by reducing entry speeds through use of safety platforms have eliminated the possibility of FSI outcomes greater than 0.1, as demonstrated in Figure 4.24.

Figure 4.23: Example of a single-lane compact rural roundabout, showing conflict points



Source: ARRB Group.

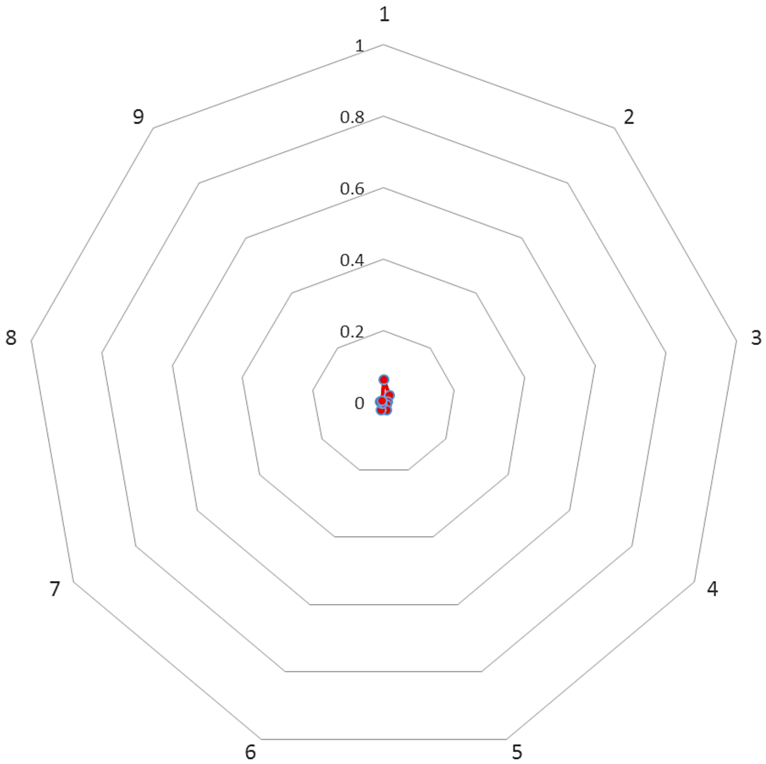
On the other hand, vehicle-pedestrian conflict points remained high due to the high crash severity inflicted to pedestrians with speeds of 40 km/h. However, due to the likely location of the design (rural), there may be low volumes of pedestrian traffic and the exposure would be very low, or nil.

Table 4.4: Example of X-KEMM-X analysis results for the mini-roundabout in Figure 4.23

Result	Vehicle-vehicle conflict	Pedestrian-vehicle conflict
No. of conflict points	8	12
Average Pr(FSI)*	0.0027	0.29
Maximum Pr(FSI)	0.0027	0.56
Percent conflict points with Pr(FSI) > 0.1	0%	58%

** Pr(FSI) is the probability of a severe injury given the assumed impact speeds, angles and crash configurations.*

Figure 4.24: X-KEMM-X results for vehicle-vehicle conflicts for the mini-roundabout in Figure 4.23



Source: ARRB Group.

In summary, the design concept in its rural case study application has a very high level of Safe System alignment for vehicle-vehicle and vehicle-pedestrian crashes.

4.4.4 Practice Readiness

This concept attracted attention in Victoria. A trial of a similar design was proceeding in Victoria, see Figure 4.25. This solution would require further refinement before adoption into mainstream design guidance.

4.4.5 Knowledge Gaps and Concerns

Engineering risk assessment would be advisable before proceeding with trials. Monitoring, review and design refinement cycles could be used during a trial to address any residual safety and operational risks. Jurewicz (2017) outlines a pathway for rapid development of innovative road design solutions.

The review of available evidence and stakeholder inputs highlighted some knowledge gaps which need to be addressed through evaluations of recent and future trials:

- Street lighting may be required without introduction of additional poles, often in areas with no power supply. Innovative ground contrast LED lighting could be considered to highlight presence and alignment of the roundabout.
- Safety ramps for 100 km/h approach speeds need research and development.
- Stakeholder inputs suggested that detailed trials and designs need to resolve issues around stability issues for turning large heavy vehicles.
- Multiple platforms may be considered to gradually reduce approach speeds. Dynamics and human factors effects of such solution have not been considered yet.

4.4.6 Further Design Improvements

The following design improvements were suggested through stakeholder workshops with intention to improve the level of Safe System alignment. These were directed to the case study design in Figure 4.22, but could be considered in all future raised intersection designs:

- Consider a wide centreline treatment on approaches for increased warning.
- Consider advanced warning and directional roundabout signage to improve the level of driver alertness.
- Remove roadside hazards (including relocation of lighting poles).

Stakeholders noted the need for spot lighting, especially in the context of significant speed reductions necessary for successful operation. There was concern about introduction of new pole hazards and potential lack of power at some locations remote locations. Innovative solutions such as in-pavement LED lighting or photo-luminescent road markings could be explored to meet this design need.

The Victorian trial involved additional safety platforms as shown in Figure 4.25. The approach speed limit for this intersection was 80 km/h and significant percentage of heavy vehicles use the route.

Figure 4.25: Victorian trial or a compact roundabout with safety platforms

Source: VicRoads, email communication, Wayne Moon, November 2016.

4.5 Urban Signalised Intersection Retrofit Combination Treatment

4.5.1 Description and Design Intent

Conventionally, signals are installed at existing intersections to provide access for new traffic, where there are operational issues, or to rectify an existing safety problem. Issues relating to pedestrians and cyclists may also influence the decision to signalise an intersection (Austroads 2013b).

Existing signalised intersections are often retrofitted with additional safety treatments when the use of the intersection exceeded its original design (e.g. higher AADT, more pedestrians, or cyclists), which resulted in increased crash history. Common treatments include phasing changes, red light/speed cameras, mast arms and fully controlled right turns (FCRT), or pedestrian fencing. These conventional treatments need to be recognised for providing a supporting contribution towards the Safe System. Figure 4.26 shows a conceptual example of a signalised intersection retrofitted with combination of conventional treatments.

For the case study presented below, the safety effect arises mainly from reductions in crash likelihood by:

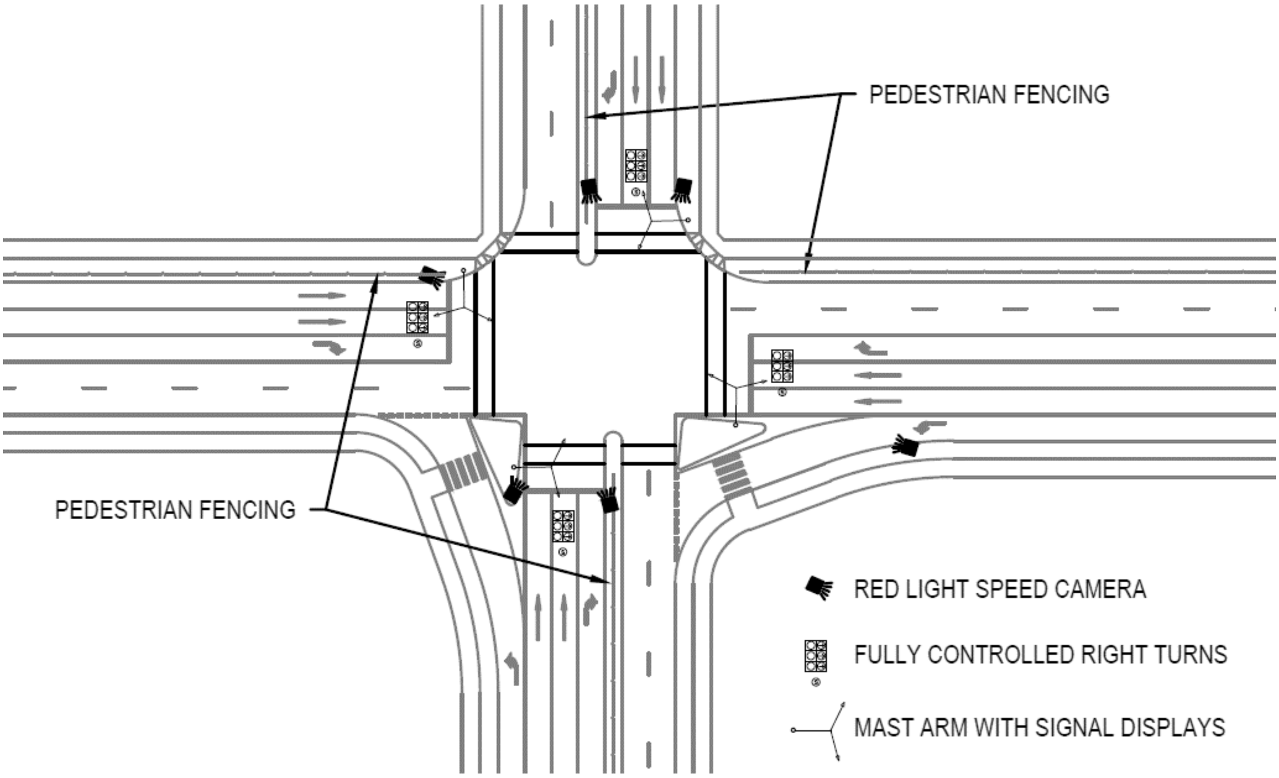
- simplifying driver decision making (FCRT)
- providing clarity to support driver decision making (mast arms)
- preventing pedestrian movements at high-risk locations (pedestrian fencing)
- reducing high-risk driver behaviour (red light/speed camera).

The reviewed literature showed that this combination of treatments may not have a large impact on the severity of crashes. However, the combined treatments should reduce the likelihood of crashes occurring in the first place.

Combination treatments like that shown in Figure 4.26 are already a common practice in urban intersections in Australia and New Zealand. They are most often implemented at high-risk intersections where crash history suggests risk of opposing-turning, adjacent direction and pedestrian crash types.

The intent of this design concept is to deliver a significant step towards Safe System at locations where design choices are limited by road function, site conditions and budget.

Figure 4.26: Concept functional layout of a signalised urban arterial with combination treatment



Source: ARRB Group.

4.5.2 Application, Design Considerations and Costs

Combination treatments in Figure 4.26 are suited for signalised intersections in all types of urban environments.

Red light/speed cameras are triggered by either running a red light, exceeding a predetermined speed, or both events, and result in an automated fine being issued to the vehicle's owner. They have been shown to be effective in making driver behaviour at signals more conservative, i.e. braking earlier in response to yellow signal, rather than accelerating to enter and clear the intersection during the yellow and red. Cameras may help to mitigate crashes involving right-turning movements and pedestrian crossings (Transport for NSW 2013). Special site selection criteria may apply for use of the cameras in each jurisdiction.

Mast arms allow placement of signal displays above traffic lanes, thus making signal phasing displays visible to drivers much earlier. This clarity provides more time to make an appropriate decision about entering an intersection.

Pedestrian fencing near intersections helps to guide pedestrians to the crossing facility and reduces jay-walking. They are particularly beneficial at locations near schools and bus stops, and in shopping strips along arterial roads. The design of the fencing should not restrict the visibility of drivers to other vehicles or pedestrians. In many locations, pedestrian fencing may not be appropriate, e.g. where it would restrict access from parking to footpath, or separate cohesive community hubs.

Fully-controlled right turns are very effective in reducing turning-against crashes and right turn vs. pedestrian crashes. The change requires upgrade of phasing and signal displays. Typically, the phasing increases delays incrementally, although impacts on the network operation may be negligible. In some cases, installation of FCRT requires longer right turn lane storage and this could add cost and complexity to a project (e.g. localised road widening, service relocations).

These types of treatments can be retrofitted to an existing intersection without the high costs of reconstructing the whole intersection. The cost of installing the red-light cameras, mast arms, FCRT (no civil works) and pedestrian fencing would be a moderate-cost project.

4.5.3 Safe System Alignment

Combination treatments offer little change to the average severity of crashes as only excessive speeds are addressed by the speed camera. While vehicles travelling excessively fast have very high crash risk (Kloeden, McLean and Glonek 2002), they account for only a small percentage of traffic flow. The treatments mainly reduce the likelihood of a crash through reduction in road user error and system failures. The estimated FSI reduction is still very high:

- Fully-controlled right turns – Austroads (2012) estimated a 60% CRF for opposing-turning crashes from numerous studies, while Bui, Cameron & Foong (1991) found a 93% reduction from Victorian sites. Austroads (2012) also estimated a 45% CRF for adjacent-direction casualty crashes. Findings from a recent evaluation study in Victoria found an overall FSI crash reduction of 69% (Jurewicz, Sobhani, Makwasha 2017).
- Red light speed cameras – a 44% FSI CRF for crossing & right turn against (Budd, Scully & Newstead 2011).
- Mast arms – a 7–35% reduction in all crashes (Austroads 2015).
- Pedestrian fencing – a 20% casualty CRF for pedestrians (assume 10% of signalised intersection crashes involve pedestrians) (Austroads 2012).

The estimated contribution to Safe System alignment is an approximately 50% reduction in casualty and FSI crashes.

Safe System assessment

The design concept in Figure 4.26 was evaluated by eleven multidisciplinary practitioner groups during the study's workshop series. The case study was based on a 70 km/h speed limit, high approach traffic volumes and moderate pedestrian and cyclist volumes. The assessment produced an average score of 237 out of 448. This is a score just below that considered a threshold of poor level of Safe System alignment.

Intersection and head-on crashes were the most heavily scored by participants, followed by pedestrians and cyclists. This was due to the relatively high-speed environment contributing to serious injuries. An equivalent urban signalised intersection without the treatment was evaluated by the authors producing a score of 324, i.e. very poor. Thus, despite the limitations, the case study was 27% more aligned with Safe System objectives.

The practitioners carrying out the Safe System Assessment also identified various residual FSI risks and generated several relevant design improvements to achieve closer Safe System alignment, as listed in Section 4.5.6. Many of these were outside of the low-cost intent of this design concept. The average of 'after' scores by the stakeholders was 137, showing that a significant further improvement is possible. The primary suggested improvements were application of lower approach speeds and additional pedestrian and cyclist treatments.

X-KEMM-X analysis

The concept was not intended to change the number of conflict points, impact speeds or angles. Hence, no X-KEMM-X analysis was undertaken. The main contribution to Safe System outcomes would come from the reduced system failures due to road user error (i.e. lower crash likelihood).

The overall alignment of this design concept would be 'poor to moderate'. Reduction of speed limits to 60 km/h would place it in the moderate range.

4.5.4 Practice Readiness

All the treatments are part of the current practice, with appropriate guidelines in Austroads and/or jurisdictional supplements.

4.5.5 Knowledge Gaps and Concerns

The review of available evidence and stakeholder inputs highlighted some knowledge gaps which need to be addressed:

- The concept does not address key Safe System requirement of minimising crash severity.
- Potential 'corralling' issue in narrow median with fencing clearance to vehicles from fence.
- Mast arm poles are non-frangible structures that will increase severity of off-path crashes if hit. Austroads (2014) notes a 93% probability of a severe injury in a run-off-road casualty crash involving a pole on 60 km/h urban roads. This is a significant concern, given that a frangible pole impact on 80 km/h urban roads had a 57% probability of producing a severe injury – frangible poles were not present on 60 km/h roads, but were used on 80 km/h roads used in the study. Consideration should be given to adoption of impact absorbent mast arm poles.

4.5.6 Further Design Improvements

The following design improvements were suggested through stakeholder workshops with intention to improve the level of Safe System alignment. These were directed to the case study design in Figure 4.26. While they were beyond the design intent, they could be considered in all future designs:

- signalised zebra crossings

- reduced speed limit to 60 km/h or below
- queue detectors and advanced signal change warning
- safety platforms at slip lanes
- dedicated bike lanes and head start boxes
- replace all poles with frangible ones, or shield with safety barriers
- eliminate right turns from all approaches
- consider removing slip lanes to reduce turning speeds (subject to design vehicle swept path).

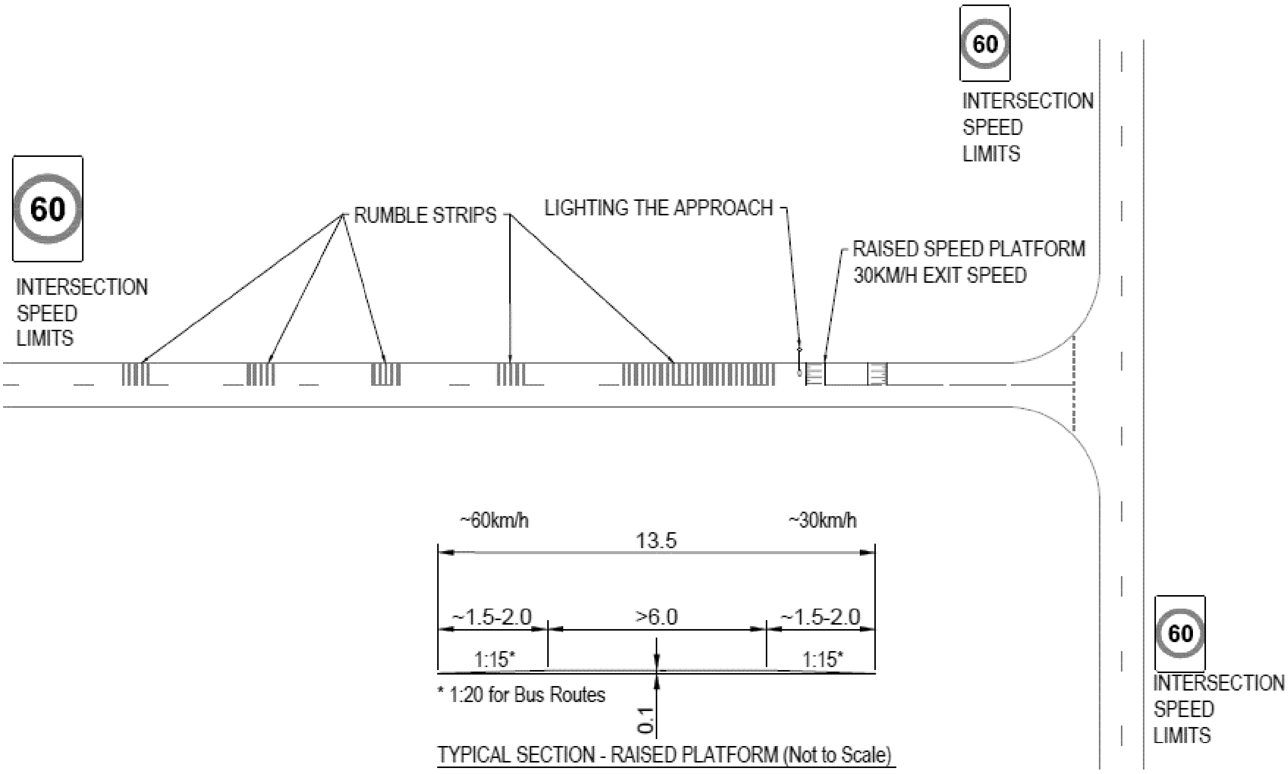
4.6 Rural Priority-controlled Intersection with Safety Platforms and Reduced Speed Limits

4.6.1 Description and Design Intent

This design concept is a conventional priority-controlled intersection design supported by additional safety measures to moderate speeds on approaches. The design concept shown in Figure 4.27 shows a rural T-intersection with reduced speed limits, a safety platform and rumble strips on the minor road approach. The main intent of the concept was to reduce the likelihood and severity of system failure: failing to stop on the minor road resulting in an adjacent-direction crash. The presence of platforms and rumble strips should increase drivers' alertness and reduce error at the give way line. Lower speed limits should also create longer gaps and make turns easier. Finally, lower speeds should reduce the severity of crashes.

The proposed design concept is intended to be a low-cost retrofit option which could become part of a mass-action plan.

Figure 4.27: Concept functional layout of a rural priority-controlled intersection with safety platforms



Source: ARRB Group.

4.6.2 Application, Design Considerations and Costs

Rural intersections with safety platforms and reduced speed limits are suited to high-risk rural intersections on low volume roads where it is difficult to justify high cost solutions.

In terms of additional costs, the costs of installing new speed limits, rumble strips and warning signs are relatively low. The major cost would be related to installation of the one safety platform. Overall, compared to alternative Safe System solutions, this is considered a low-cost solution.

4.6.3 Safe System Alignment

As noted earlier in this section the main benefit from this treatment would be provided by increased intersection awareness by the side road drivers (reduced conflict likelihood), and reduced entry speeds on both minor and major roads (reduced conflict likelihood and severity).

There were no CRFs available from research and the design is yet to be trialled and evaluated. Mackie et al. (2017) noted that New Zealand experiences with vehicle-activated speed limit reductions at rural intersections suggest a high FSI CRF.

Safe System assessment

The design concept of a rural priority-controlled intersection with safety platforms and reduced speed limit was evaluated using the SSAF to better understand its Safe System value.

The design concept in Figure 4.27 was used as a case study for a SSAF conducted by seven stakeholder workshops groups. The average score produced by the groups was 81 out of 448. This low value was dictated by very low traffic volumes, while the crash likelihood and severity were moderate to high. Run-off-road and head-on crash types were amongst the highest scored in this case study. This was largely due to the lack of any design measures to address these crash types. Overall, the analysed case study could be said to be highly aligned with Safe System due to low traffic volumes, rather than its design.

This case study was compared against a rural T-intersection at 100 km/h speed. The score given by the authors for the rural T-intersection was 102 out of 448, i.e. highly aligned. There were high risks for run-off-road and head-on crashes, although traffic volume was low. The design concept case study was 21% more aligned with Safe System objectives than the comparable rural T-intersection.

From the Safe System assessment, several relevant design improvements were suggested by stakeholders to achieve closer Safe System alignments, as listed in Section 4.6.6. The average 'after' assessment given by the stakeholders was 51. This was mainly achieved through implementation of Safe System infrastructure such as roadside barriers and narrow medians – improvements considered outside of the low-cost intent of the design concept.

An alternative concept was proposed by the stakeholders which raised the entire intersection as a platform, in combination with lower speed limits (similar to the design shown in Section 4.8).

X-KEMM-X analysis

Further analysis was undertaken with X-KEMM-X to assess the crash severity aspects of the intersection crashes. The example taken is of a rural intersection with safety platforms and reduced speed limit of 60 km/h, as per Figure 4.27.

The X-KEMM-X results are shown in Table 4.5. The main finding is that the vehicle-vehicle conflict points remain unchanged from the original design, but the probabilities of FSI have experienced an average drop of 0.3 compared with the original 100 km/h design. This can be considered a good outcome for this type of intersection and the high-speed environment that usually surrounds it. Figure 4.28 shows that right turning movements facing through movements have the highest probability of an FSI outcome in a crash.

The crash severity for pedestrian-vehicle conflict remains high as indicated by the SSAF due to speeds more than 20 km/h. However, given the rural environment, there are likely to be no pedestrians.

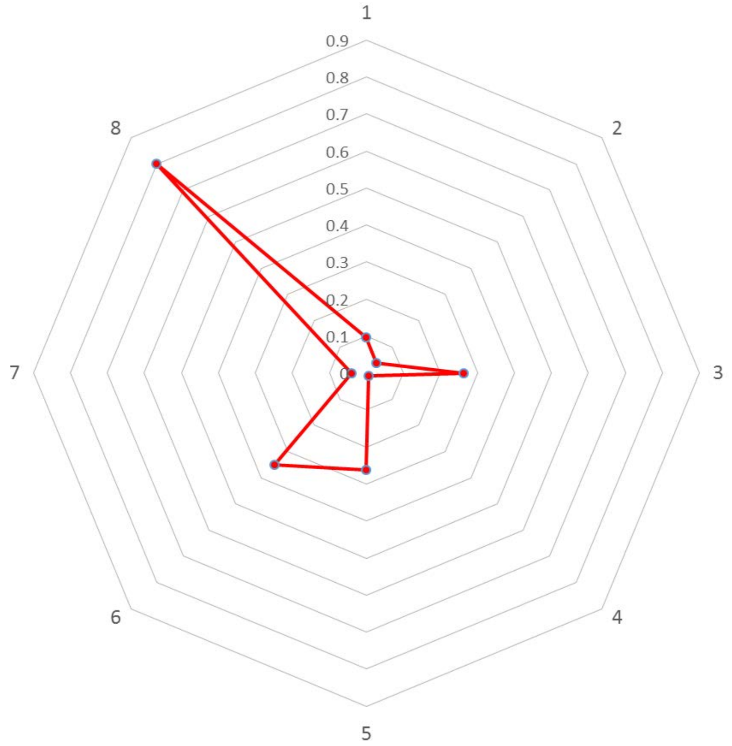
Based on case-study analysis, the concept would have moderate level of Safe System alignment for vehicle-vehicle crashes.

Table 4.5: Example of X-KEMM-X analysis results for the rural T-intersection with safety platforms and reduced speed limit

Result	Vehicle-vehicle conflict	Pedestrian-vehicle conflict
No. of conflict points	8	12
Average Pr(FSI)*	0.23	0.42
Maximum Pr(FSI)	0.80	0.95
Percent conflict points with Pr(FSI) > 0.1	50%	67%

** Pr(FSI) is the probability of a severe injury given the assumed impact speeds, angles and crash configurations.*

Figure 4.28: X-KEMM-X results for vehicle-vehicle conflicts for the rural T-intersection with safety platforms and reduced speed limit in Table 4.5



Source: ARRB Group.

Overall, this solution would have moderate to high level of Safe System alignment when used on low-volume rural roads.

4.6.4 Practice Readiness

The design is currently in the conceptual stage and will need to undergo engineering risk assessment and further design refinements before it is ready for trial.

4.6.5 Knowledge Gaps and Concerns

The stakeholders raised some concerns during the workshops regarding the design concept:

- Risk of high-speed vehicles losing control on ramps.
- Risk of rear-end crashes due to the safety platforms and significant speed reduction.
- Effectiveness of such a low speed limit was questioned; what enforcement would be possible or likely?
- Risk of drivers driving on the opposite side of the road to avoid the safety platform.

4.6.6 Further Design Improvements

The following design improvements were suggested through stakeholder workshops with the intention of improving the level of Safe System alignment. These were directed to the case study design in Figure 4.27, but could be considered in all future designs:

- Provide safety platforms on the major road approaches to moderate speeds more effectively; alternatively, replace with a raised intersection.
- Provide additional warning signage.
- Provide a speed camera on the major road.
- Widen the centreline, or provide a median for extra warning and alertness.
- Provide rumble strips on the major road.
- Provide safety barriers to reduce run-off-road crashes.
- Provide frangible lighting posts to reduce run-off-road crash severity.
- Consider alternative concept of a raised rural intersection with reduced speed limits (used in the Netherlands).

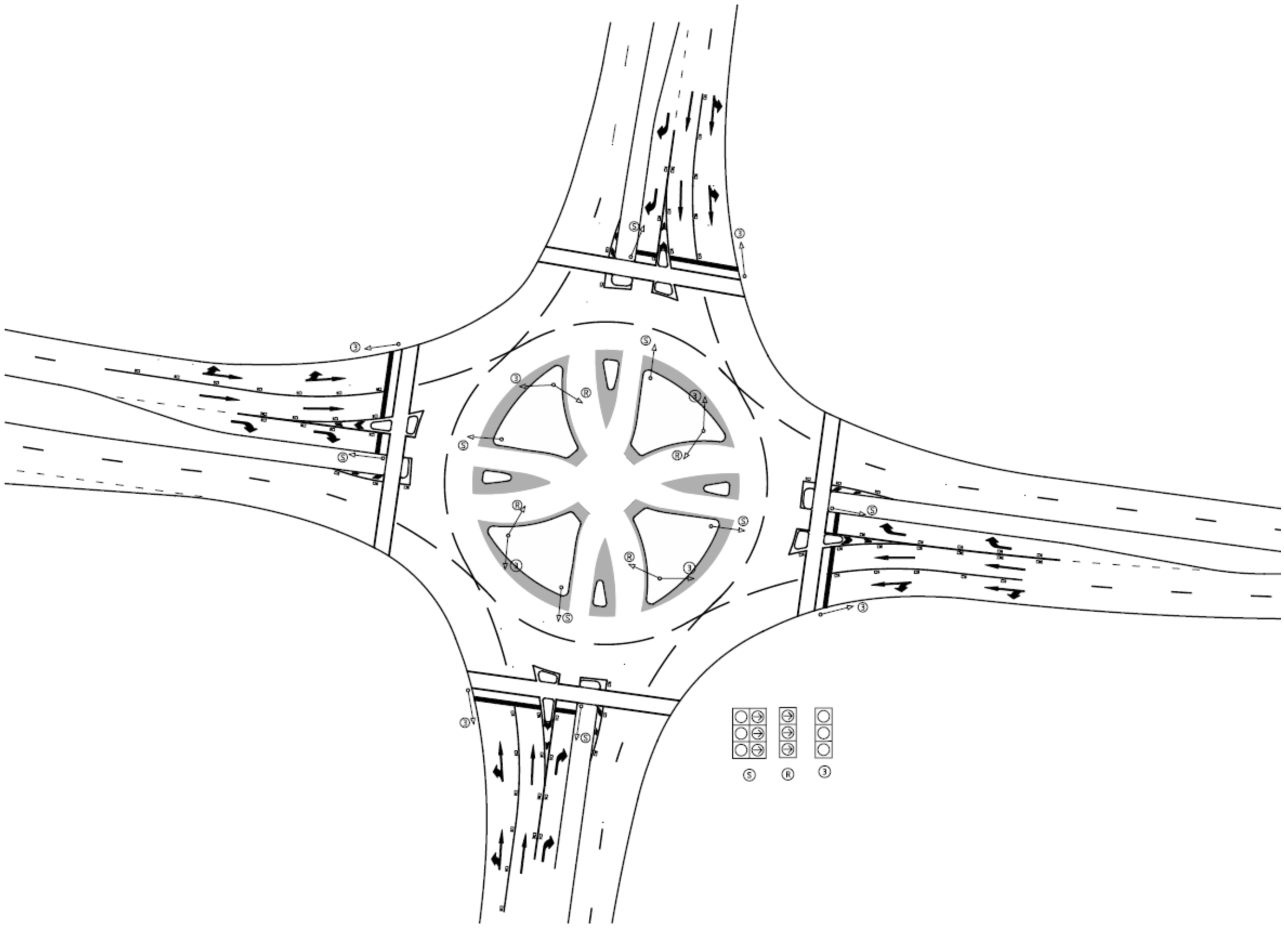
4.7 Cut-through Signalised Intersection

4.7.1 Description and Design Intent

Cut-through signalised intersection operates like conventional signalised intersection, but with the advantage of a roundabout-like deflection for through movements. All right-turn movements would be fully-controlled and executed via channels cut through the central island. Figure 4.29 shows the concept. This conceptual design offers many of the safety benefits of a conventional roundabout through reduced impact angles and speeds, but allows signalised operation. The overall footprint is expected to be smaller than a signalised roundabout (Section 4.2), because the right turn storage is accommodated conventionally at the approaches.

This concept is intended for large urban intersection sites where it might be fitted into a similar or enlarged footprint. The design was first proposed by Corben et al. (2010b) as a potentially viable Safe System alternative to a conventional signalised cross intersection. It is expected to be of value when turning traffic would be so high that a conventional or a signalised roundabout could not be used efficiently. This is more likely to occur in urban conditions.

Figure 4.29: Conceptual layout of a cut-through roundabout



Source: VicRoads (n.d.), based on Corben et al. (2010b) and 80 km/h operating speeds.

4.7.2 Application, Design Considerations and Costs

Cut-through signalised intersections are suited for application on high-speed major urban arterials other than motorways.

The horizontal deflections guide the drivers to reduce their speeds and potential impact angles. This would reduce the severity of adjacent-direction, opposing-turning and rear-end crashes. A driving simulator study by Stephens et al. (2017) showed that the design produced entry speeds of approximately 40 km/h for an approach speed of 70 km/h. This delivered three-quarters of the speed reduction of a conventional roundabout tested as the control in the same study. The study noted initial driver confusion due to the unfamiliar design, but this dissipated on repeated use of the intersection.

The concept is more complex to design and construct for large sites than either conventional signalised or roundabout intersections. Additional signal pedestals may be required in the central island.

The design of the cut-through paths should consider long heavy vehicles and their swept path. If adequate road reserve would make this feasible, this concept could be retrofitted at a high cost. This is mainly due to the required full reconstruction of kerbing and drainage, relocation of existing signals, services in the roadside, and large new pavement areas. A new 'greenfield' construction would be comparable with a large roundabout, i.e. high-cost.

4.7.3 Safe System Alignment

At present, there is no CRF for this design concept as it is yet to be trialled and evaluated. Given the entry speeds (approximately 40 km/h) and impact angles less favourable than a comparably-sized roundabout, the Safe System alignment would be expected to be somewhat lower. Two techniques were used in the following sections to estimate the level of Safe System alignment for the concept.

Safe System assessment

Figure 4.29 design concept was assessed using SSAF assuming an 80 km/h speed environment, 50 km/h entry speeds (as suggested by Corben et al. 2010b), and high traffic volumes. The SSAF assessment incorporated relevant minor improvements suggested by the study stakeholders.

The average SSAF score produced by the stakeholder groups during the workshops was 188 out of 448, i.e. moderately aligned, a good score under high-volume conditions. Run-off-road, intersection and motorcyclist crash types scored most heavily in this assessment. Pedestrians and cyclists scored poorly due to relatively high impact speeds. The practitioners noted the anticipated unfamiliarity of drivers to the concept, and potential for confusion leading to crashes approaching and within the intersection.

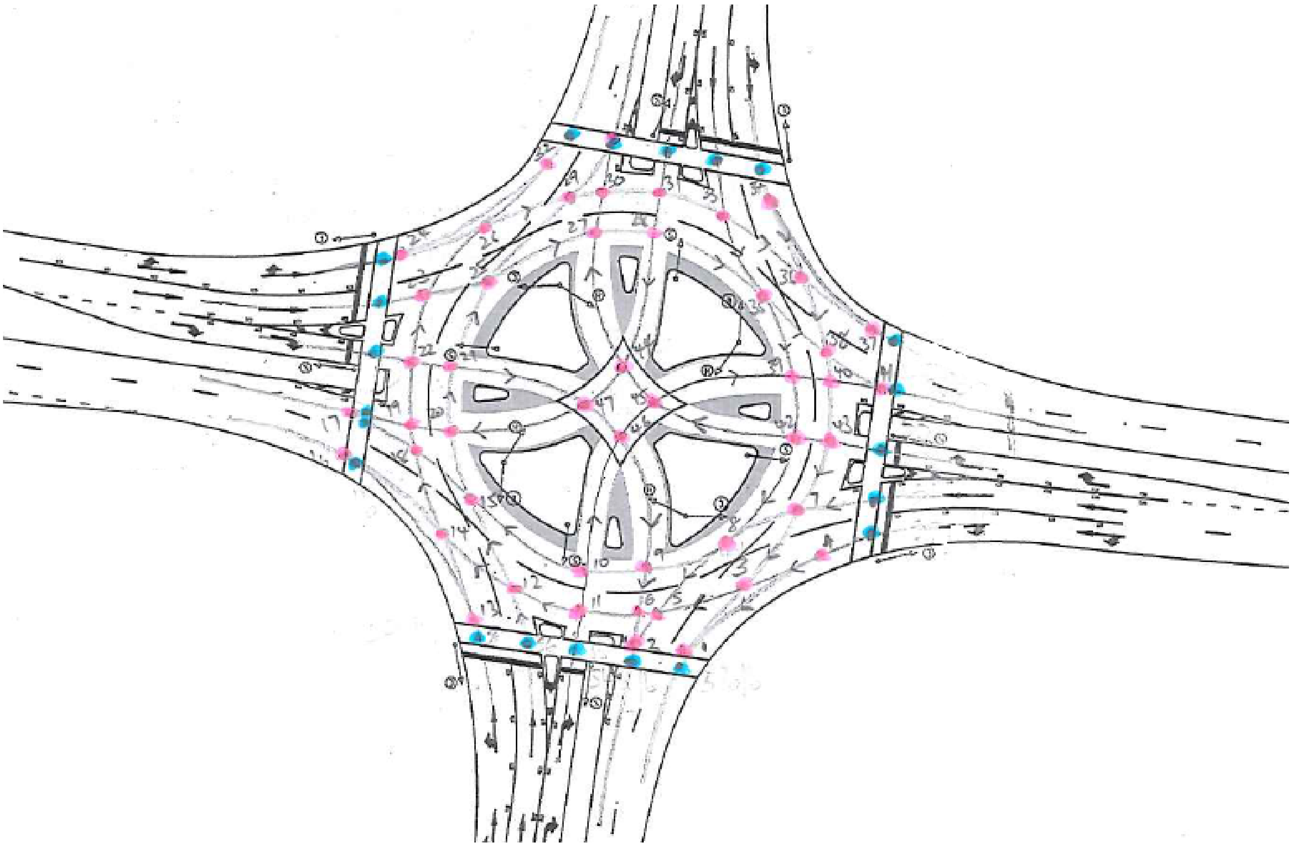
An equivalent conventional signalised intersection was evaluated by the authors and produced a score of 324. Thus, despite the noted drawbacks, the design concept was 42% more Safe System aligned than the comparable signalised arterial. This may be an early indicator of a CRF.

The SSAF assessment also generated several design improvements to achieve closer Safe System alignment, as listed in Section 4.7.6. The average 'after' score produced by stakeholders was 116 for the same operational conditions, i.e. borderline between highly and moderately aligned. This would be considered a good outcome for a high-volume intersection. This improvement in the score was achieved mainly through providing drivers with advanced warning signs and education on the operation of the cut-through design.

X-KEMM-X analysis

The cut-through design was further analysed using the X-KEMM-X method to evaluate the crash severity aspects of the design. The example used was that of a cut-through design, shown in Figure 4.30, in an assumed 80 km/h speed environment. For this analysis, entry speeds of 50 km/h were assumed.

Figure 4.30: A conceptual drawing of a cut-through design, showing major conflict points



Source: ARRB Group.

X-KEMM-X results are shown in Table 4.6. The main finding is that despite the smaller impact angles, the probability of a FSI outcome is still mostly above the 0.1 threshold, as shown in Figure 4.31. This was due to the 50 km/h entry speeds being too high for safe outcomes in adjacent direction collisions.

Due to the multi-lane design, there are many pedestrian-vehicle conflict points. The severity of these conflicts is also very high due to the relatively high entry speed. Similarly, cyclists and motorcyclists are also at risk of high severity outcomes. This prompted for several concept improvements discussed in Section 4.7.6.

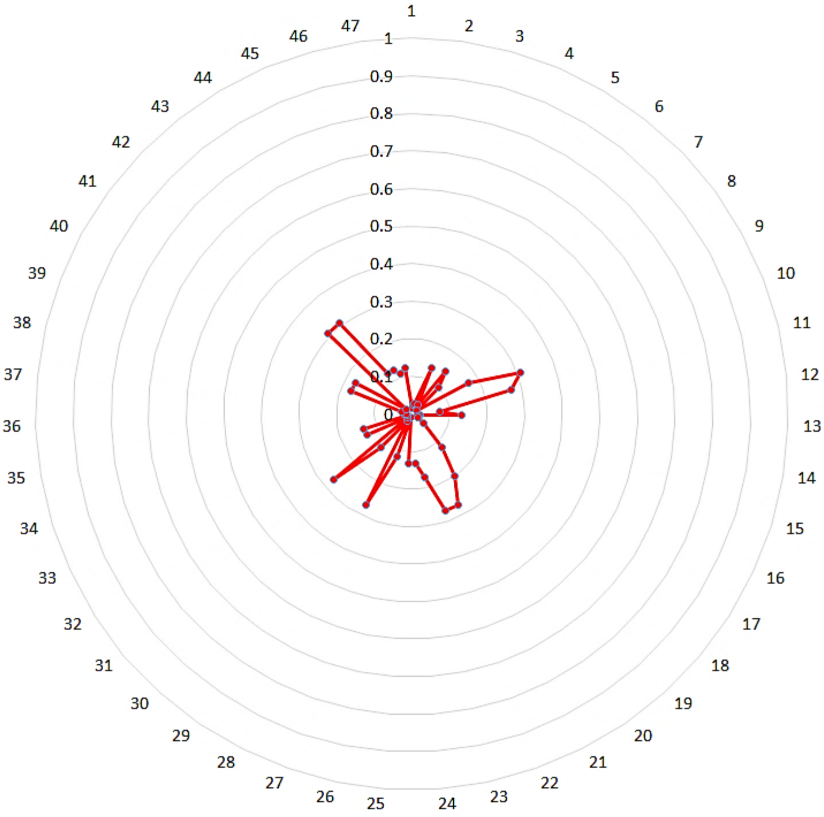
The case study design could be said to be moderately aligned for vehicle-vehicle crashes, and poorly aligned for pedestrians.

Table 4.6: Example of X-KEMM-X analysis results for the cut-through intersection in Figure 4.10

Result	Vehicle-vehicle conflict	Pedestrian-vehicle conflict
No. of conflict points	47	32
Average Pr(FSI)*	0.12	0.58
Maximum Pr(FSI)	0.31	1.00
Percent conflict points with Pr(FSI) > 0.1	60%	75%

** Pr(FSI) is the probability of a severe injury given the assumed impact speeds, angles and crash configurations.*

Figure 4.31: X-KEMM-X results for vehicle-vehicle conflicts for the cut-through intersection in Figure 4.10



Source: ARRB Group.

4.7.4 Practice Readiness

The cut-through design in Figure 4.29 underwent VicRoads risk assessments and driver simulator testing. At the time of writing no trials were scheduled.

4.7.5 Knowledge Gaps and Concerns

The following questions and concerns were raised through stakeholder workshops based on the case study design in Figure 4.29, but could be considered in all future designs:

- There is no possibility of a safe or efficient U-turn, can this be facilitated?
- What would be community acceptance of this unfamiliar concept?
- This concept would require educating drivers and other road users.

4.7.6 Further Design Improvements

The following design improvements were suggested through stakeholder workshops with the intention of improving the level of Safe System alignment. These were directed to the case study design in Figure 4.29, but could be considered in all future designs:

- Further tighten through vehicle deflections to reduce entry speeds to below 40 km/h and smaller angles.
- Cyclist facilities, i.e. hold boxes or off-road cycle lanes.
- Central island area needs to be well lit and delineated.
- Advanced warning signs, especially when the treatment is in trial.

- Make all signals hardware impact absorbent.
- Safety platforms could be introduced to support lower speeds on approaches and to provide raised crossings for pedestrians.

Other suggestions were also provided, which were outside the design intent, but could be considered:

- This concept could be explored for a smaller site, e.g. a three-leg intersection (less complex cut-through needed).
- A hybrid concept could be explored employing turbo-roundabout design techniques.

4.8 Urban Priority-controlled Raised Intersection

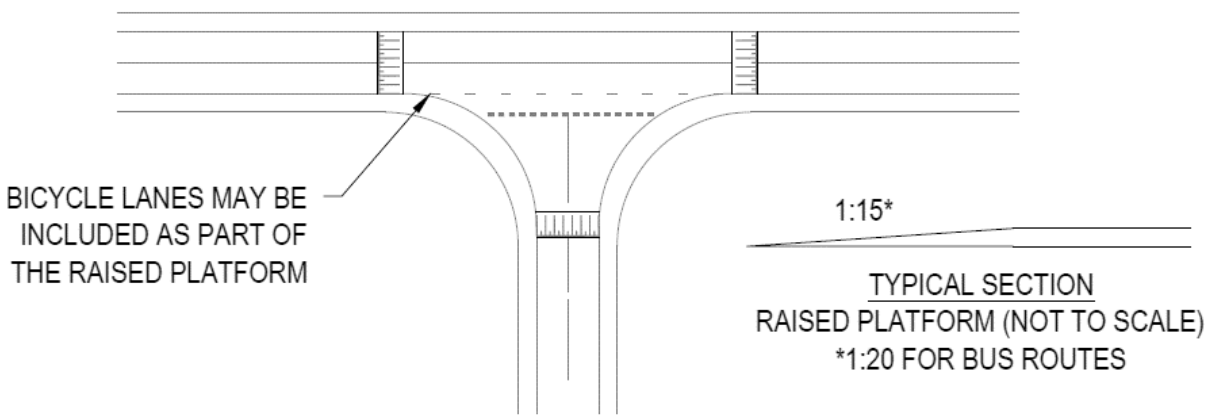
4.8.1 Description and Design Intent

Raised intersections are generally designed with conventional layout, but include approach ramps to elevate the intersection by 75–100 mm. The intent of the ramps is to provide vertical deflection for moderating intersection entry speeds. The lower speeds should reduce both severity and likelihood of collisions within the intersection. The intent is for this concept to be developed and trialled on high-volume mixed-arterial roads.

Raised intersections have a long history of use on local roads as a traffic calming device, to improve intersection awareness when sight distance is limited, to improve walkability in shared zones, and to define a boundary of a local zone (Austroads 2016d). At various locations throughout Europe, raised intersection platforms have been installed on local rural or urban roads with the aim to reduce the speed to 50 km/h or less. More recently, Austroads (2016c) reviewed the international and local applications of raised intersections on arterial roads.

Figure 4.32 shows a design concept based on an existing location in Adelaide. It aims to reduce operating speeds from 50 km/h to less than 40 km/h to facilitate the safe movement of pedestrians.

Figure 4.32: Concept functional design of a raised intersection



Source: ARRB Group.

4.8.2 Application, Design Considerations and Costs

Intersection platforms may be raised to sidewalk level, and bollards may be installed to define the edge of the roadway (Institute of Transportation Engineers 2017). Although this is the recommended practice, it should be noted that bollards themselves might be a safety issue, and installation should be carefully considered for each situation. The pedestrian access at raised intersections is a point of interest as well. Federal Highway Administration (2001) recommends installing detectable warnings e.g. flashing lights, to highlight the transition between the sidewalk and the street. To enhance access for the mobility impaired, it also recommends using a smooth surface, such as coloured asphalt, rather than bricks. Tactile ground indicators are often used in Australia.

Austroads (2016d) advises that the typical height of a flat-top road hump or raised pavement should be 75–100 mm with a total length of 2–6 m. These assumptions are not directly applicable in case of raised intersections. The size of the raised area would be extended. Thus, turning movements for long vehicles may be combined with pavement height difference. This could affect stability of large heavy vehicles and should be checked during detailed design. Refinements to pavement height and ramp position may be required. Victorian advice for high heavy vehicle traffic routes and/or principle freight routes is that platform heights should be designed to 75 mm with a less aggressive gradient of 1:25, and consideration given to raising intersections to provide access to heavy trailers with 100 mm ground clearance such as low-loaders. Such mild designs may offer limited speed reduction.

When compared to a conventional intersection, the cost of raising the entire intersection is likely to be a moderate-cost solution due to potential relocation of underground services (e.g. rising of the pit lids).

4.8.3 Safe System Alignment

Fortujin, Carton and Feddes (2005) evaluated Dutch examples finding that providing speed platforms at already signalised urban intersections reduced casualty crashes by 35%. This effect was achieved by adding plateaus in combination with other measures like speed cameras and signage.

The UK Mixed Priority Routes project evaluations included safety and traffic management benefits, however, it needs to be noted that raised intersection platforms were just one of the many treatments that were implemented at the sites. The results of the four projects where intersection platforms were included in safety platforms averaged a 42% casualty crashes reduction (sourced from Gordon 2008a, b and c).

Reekmans, Nuyts & Cuyvers (2004) summarised the road safety effects of some Dutch and Australian studies. They concluded that the installation of intersection platforms reduced the number of accidents by between 20% and 60% and the number of casualties by between 25% and 80%.

The most relevant evaluation comes from Makwasha and Turner (2017) who evaluated 10 raised priority-controlled intersection sites in Australia showing a casualty crash reduction factor of 55% (statistically significant at $p = 0.100$).

Safe System assessment

A Safe System assessment was undertaken for the unsignalised raised intersection based on Figure 4.32. Stakeholder and practitioner workshops provided an opportunity to assess and seek improvement ideas on this design concept. The assessment assumptions included moderate traffic volumes and 60 km/h approach speeds, with high volumes of pedestrians and cyclists. It was assumed that the design could reduce intersection entry speeds to 40 km/h.

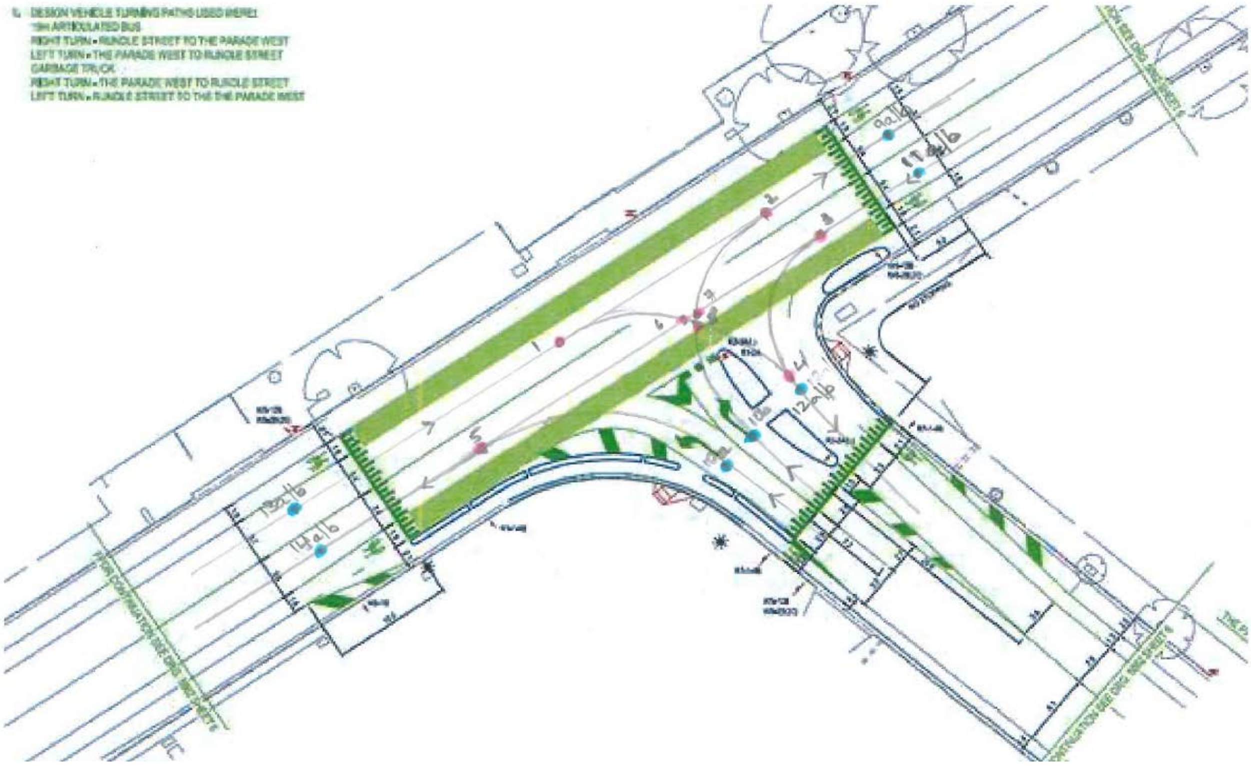
The average SSAF score produced by the participants was 198 out of 448, i.e. moderately aligned with Safe System. In this case study, pedestrians, cyclists and motorcyclist scores showed moderate to poor alignment. This was due to the large volumes, and due to impact speeds above the Safe System threshold of 20 km/h. Vehicle-vehicle risks were very low, i.e. highly aligned with Safe System. An equivalent unsignalised T-intersection was evaluated by the authors producing a score of 288. Despite the existing limitations to vulnerable road users, the case study design is 31% more Safe System aligned than its non-raised counterpart.

A number of design improvements were generated from the Safe System Assessment to achieve closer Safe System alignment for vulnerable road users. The average ‘after’ score by the stakeholders was 133 out of 448 (still moderate). Improvements were mainly achieved through reducing the speed limit and installing pedestrian and cyclist safety provisions.

X-KEMM-X analysis

The unsignalised raised intersection in Figure 4.32 underwent further analysis using the X-KEMM-X method to assess the crash severity aspects of the design. The same assumptions were used as in SSAF assessment. Figure 4.33 presents the identified conflict points.

Figure 4.33: An example of a raised T-intersection, showing major conflict points



Source: DPTI, email communication, Alex Druerden, September 2016.

The X-KEMM-X analysis results are shown in Table 4.7. The main finding is that, due to the presence of the raised intersection, vehicles approaching the intersection would naturally slow down. Hence, the possibility of FSI outcomes in vehicle-vehicle crashes were low, with half falling below the nominal FSI threshold of 0.1, as demonstrated in Figure 4.34.

However, despite the reduction in speeds through the intersection, the pedestrian-vehicle conflict points show high risk of FSI outcomes for pedestrians due to the impact speeds being still above their FSI threshold.

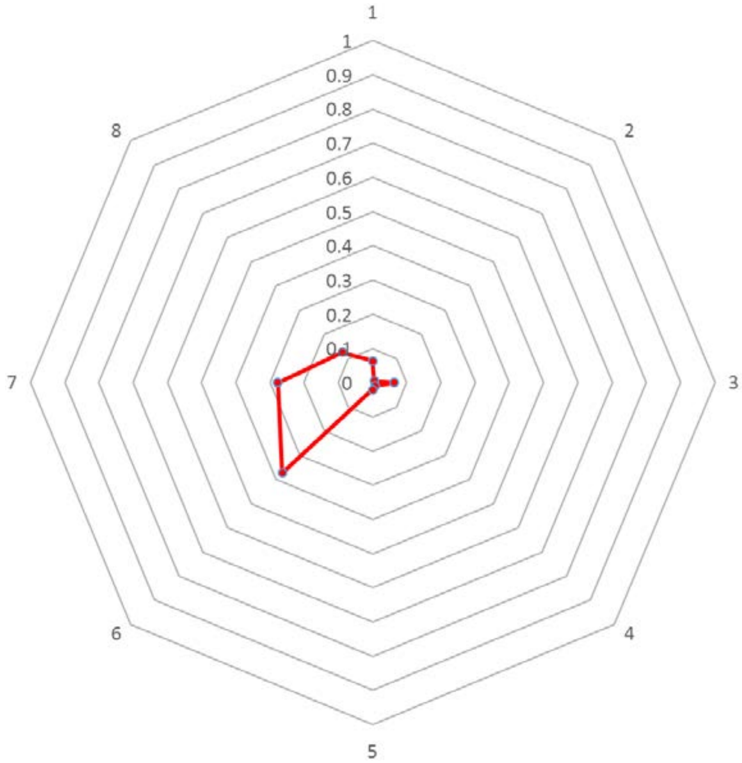
Overall, X-KEMM-X confirmed that through raising the entire intersection, the case study design was highly aligned with Safe System objectives for vehicle occupants, but only moderately for pedestrians. This finding prompted several concept improvements discussed in Section 4.8.6.

Table 4.7: Example of X-KEMM-X analysis results for the raised T-intersection in Figure 4.33

Result	Vehicle-vehicle conflict	Pedestrian-vehicle conflict
No. of conflict points	8	12
Average Pr(FSI)*	0.12	0.35
Maximum Pr(FSI)	0.37	0.56
Percent conflict points with Pr(FSI) > 0.1	37.5%	100%

** Pr(FSI) is the probability of a severe injury given the assumed impact speeds, angles and crash configurations.*

Figure 4.34: X-KEMM-X results for vehicle-vehicle conflicts for raised T-intersection in Figure 4.33



Source: ARRB Group.

4.8.4 Practice Readiness

Raised platforms at intersections are commonly used in the Netherlands and throughout Europe. Many examples exist on local roads in Australia. Trial installations on arterial roads were being prepared in Victoria at the time of writing. Figure 4.35 shows the design used as a case study, i.e. Figure 4.33. Figure 4.36 shows a Dutch example. There are numerous other examples of this treatment, e.g. along Lennox St, Richmond, Victoria.

Figure 4.35: Rundle St/The Parade West, Adelaide, SA

Source: Google Maps (2016), 'South Australia', map data, Google, California, USA.

Figure 4.36: An example of a raised intersection from the Netherlands

Source: Corben et al. (2010a).

4.8.5 Knowledge Gaps and Concerns

The review of available evidence and stakeholder inputs highlighted some knowledge gaps and concerns which need to be addressed through evaluations of recent and future trials:

- Emergency services – disturbance due to ramps.
- Can correct drainage be maintained?

4.8.6 Further Design Improvements

The following design improvements were suggested through stakeholder workshops with intention to improve the level of Safe System alignment. These were directed to the case study design in Figure 4.35, but could be considered in all future raised intersection designs:

- Consider priority pedestrian facilities – zebra, pedestrian operated signals.
- Speed limit reduction, e.g. 40 km/h, with steeper ramps to reduce speeds to 20 km/h.
- Ramp designs of 1 in 12 (as used in the Adelaide case study).
- Improved skid resistance on approaches.
- Narrow the lanes for appearance of low-speed environment.
- Improve bicycle facilities i.e. provide separation from traffic.
- Consider installation with signals (see Section 4.1.6).
- When platforms and raised areas exceed 100 mm in height, warning signs could be considered on arterial roads displaying the height.

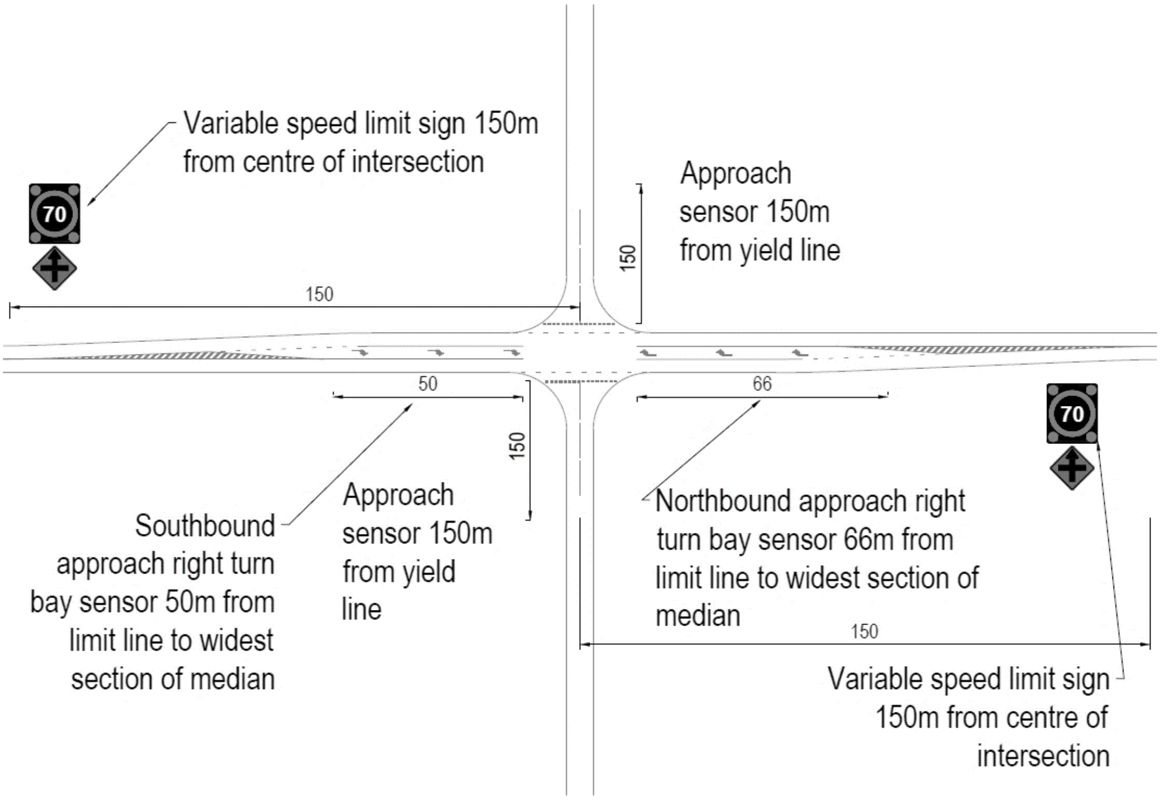
4.9 Rural Priority-controlled Intersection with Vehicle Activated Speed Limit

4.9.1 Description and Design Intent

This design concept introduces installation of a variable, vehicle-activated reduced speed limits on the major road approaches to a priority-controlled intersection. This ITS solution is intended to reduce approach and entering speeds of the major road traffic, and thus, reduce likelihood and severity of intersection crashes. It also alerts approaching road users to a potential conflict. The concept is also likely to extend major road traffic headways. Lower speed and longer headways make it easier for side road vehicles to access the major road when traffic flow is high – more of the available gaps meed drivers' gap selection criteria. A schematic example of this treatment is shown in Figure 4.37.

The lower speed limit is triggered by presence of vehicles approaching from the minor road approaches, or presence of turning vehicles in the main road. In some applications, lower speed limit can be simply triggered by high traffic volumes.

Figure 4.37: Concept functional layout of a rural intersection with vehicle activated speed limit



Source: ARRB Group.

The proposed design intent is to be a low-moderate cost retrofit for rural priority-controlled intersections. Also, the concept could be used to improve safety at intersection sites where meeting high design speed standards is not possible due to terrain (e.g. increased crash risk due to lack of sight distance). The concept can be used with cross, T and staggered-T intersections.

4.9.2 Application, Design Considerations and Costs

An ideal application of this concept would be for isolated rural intersections where the high-speed major road has a high traffic volume, and the minor road has a moderate to high traffic volume.

Speed limit reduction is delivered by a variable speed limit sign triggered by presence or volume of vehicles on the minor road approaches, in right-turn lanes, in median breaks, etc. Inductive loops are typically cut into the pavement at critical locations some distance back from the minor road give way/stop line. Loops can also be installed in right-turn lanes, slip lanes and median breaks, depending on the design of the intersection. Departure loops are also installed at minor road stop lines or in departures to acknowledge the vehicles clearing the intersection and ending the variable speed limit. For roads with thin or unstable pavements, vehicle detection can be achieved through use of infrared or radar detectors installed on poles.

The operation of the variable speed limit signs is managed by a signal controller, typically located in a small cabinet at the back of one of the speed limit signs. Mobile communications or cable conduits are used to connect loops, signs and the controller. Power supply is needed to operate this ITS system. Figure 4.38 shows the New Zealand trial site.

Figure 4.38: Example of New Zealand application of vehicle-activated intersection speed limits

Source: Mackie et al. (2014).

The cost of implementing this concept is considered low to moderate, as no major civil works should be required to install the system. The design should use the existing intersection footprint and is not expected to require major service relocations. Depending on the type of inductive loops used, it can be embedded into the existing asphalt pavement.

4.9.3 Safe System Alignment

A study was conducted by Mackie et al. (2017) on ten high-risk intersections in New Zealand where the speed limits were reduced from 100 km/h to 70 km/h, except for one site, where it was reduced to 60 km/h. In the two to three years post installation, there was an 79% reduction in fatal and serious injury crash frequency, and a total of 51% reduction in the overall crash occurrence rate (all severities).

From the same study, Mackie et al. (2016) also reported mean speed reductions of 15 km/h, from the average baseline of 88 km/h to an average of 73 km/h. The speed reduction benefits were monitored and maintained two to three years after implementation.

Sevefelt and Wessel (2012) reported the performance of six sites in Sweden with different original speed limits (50–90 km/h). There was an average speed reduction of 7.5 km/h when the lower speed limits were active. Some sites showed no reduction while others showed reductions up to 17 km/h.

Safe System assessment

To better understand the Safe System value of vehicle-activated speed limits at rural intersections, the concept was evaluated using the SSAF. The evaluation was carried out during stakeholder workshops by multidisciplinary groups. The average score for the concept was 184 out of 448, with assumptions of moderate traffic flows and entry speeds moderated to 70 km/h by the treatment. This suggests poor to moderate Safe System alignment. Intersection, head-on and run-off-road crash types were the key residual FSI risks. Pedestrian and cyclist volumes and scores were negligible in the case study. Despite the significant speed reduction, it remained in the high-severity range for most crash types.

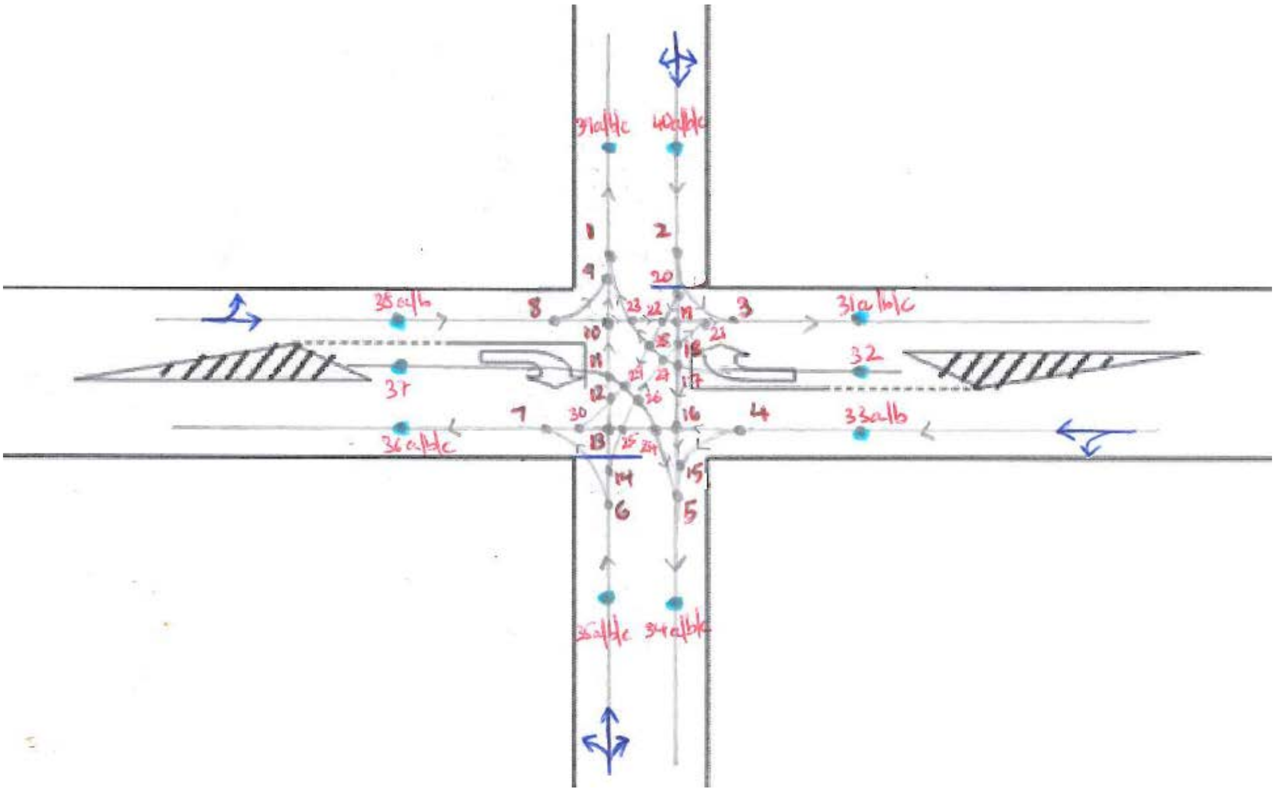
An equivalent rural cross-intersection with 100 km/h speed limit was evaluated by the authors, producing a score of 192. Thus, the estimated FSI risk reduction was only 4%.

The Safe System assessment generated design improvement ideas to achieve closer Safe System alignment for the higher at-risk crash types. These are listed in Section 4.9.6. The average 'after' score given by the stakeholders was 98 out of 448. This was mainly due to proposed increase in use of warning signs, rumble strips and further speed limit reductions.

X-KEMM-X analysis

Further analysis of the crash severity aspects of the case study were undertaken using the X-KEMM-X method. The example used was that shown in Figure 4.39, a rural cross intersection with 70 km/h speed limit.

Figure 4.39: Example of a rural cross-intersection, showing multiple conflict points



Source: ARRB Group.

The X-KEMM-X analysis results are shown in Table 4.8 and Figure 4.40. The main assumption is that, due to the reduced speed limit and advanced warnings, drivers would be able to reduce their speed resulting in lower impact speeds. The average probability of a FSI outcome in vehicle-vehicle collisions was 0.42, which is considered a moderate to poor level of Safe System alignment for that group. It is noted that several cross-intersection movements still registered very high probabilities of FSI outcome.

Table 4.8 shows that the chance of a FSI outcome for pedestrian-vehicle crashes are very high due to the high-speed environment, i.e. poorly aligned with Safe System. However, given the intended rural use of the design concept, there may be no pedestrians to be impacted.

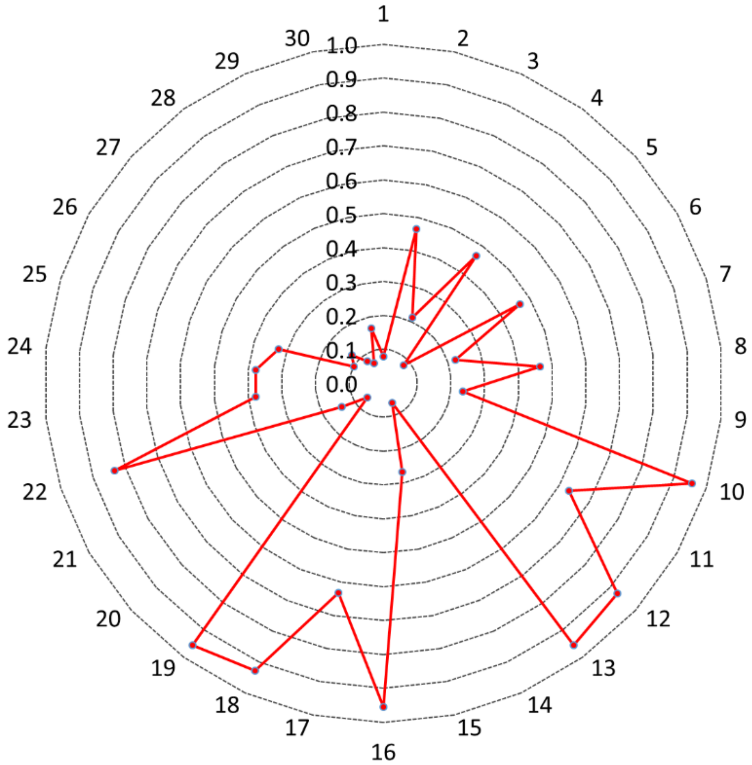
Table 4.8: Example of X-KEMM-X analysis results for the vehicle activated speed limit rural intersection in Figure 4.39

Result	Vehicle-vehicle conflict	Pedestrian-vehicle conflict
No. of conflict points	30	24
Average Pr(FSI)*	0.42	0.43
Maximum Pr(FSI)	0.96	0.99
Percent conflict points with Pr(FSI) > 0.1	76.7%	66.7%

** Pr(FSI) is the probability of a severe injury given the assumed impact speeds, angles and crash configurations.*

Overall, X-KEMM-X confirms that the reduced speed limit at the rural cross-intersection reduced the severity of conflicts for vehicle occupants, but not for vulnerable road users.

Figure 4.40: X-KEMM-X results for vehicle-vehicle conflicts for the rural cross intersection in Figure 4.39



Source: ARRB Group.

Both the SSAF and the X-KEMM-X analysis indicated more modest safety benefits than those indicated by Mackie et al. (2017). There may be several reasons for this. The trial sites were all high-risk locations, and this could have been due to regression-to-mean, i.e. the initial poor safety performance of the selected sites was due to a statistical spike, not due to underlying causes. In such a case, part of the observed safety benefit would be due to the spike passing, and part due to the treatment. Another possibility could be that the driver awareness improvement was greater than estimated in the SSAF assessment and it contributed more strongly to reduced crash likelihood (not accounted for by X-KEMM-X v0.5). Other systemic safety treatments or changes in the area might have also contributed to the safety benefit (e.g. greater enforcement, weather patterns, changes in economic activity).

Also, the two methods used may require further refinement to recognise the specific safety mechanisms of this treatment, e.g. awareness of the intersection, and thus the reduction in the likelihood of collisions.

4.9.4 Practice Readiness

The design concept was trialled in six intersection locations in Sweden reporting measurable speed reductions (average of 7.5 km/h), although no robust safety evaluation was ever published (Sevefelt & Wessel 2012). Mackie et al. (2016, 2017) reported on the deployment of ten trial sites in New Zealand, which provided a practical example of application under Australasian conditions (Figure 4.38). VicRoads and the Department of Planning, Transport and Infrastructure South Australia (DPTI) were finalising their own designs and trials at three rural sites at the time of writing.

4.9.5 Knowledge Gaps and Concerns

The review of available evidence and stakeholder inputs highlighted some knowledge gaps which need to be addressed through evaluations of recent and future trials:

- What is the reliability of the technology (% time operating as intended)?
- Operation in event of power failure.
- Potential for vandalism.

The preliminary Swedish review of variable speed limits reported a very high reliability of the system (99.8%), which was further improved post-implementation (Lind 2009).

4.9.6 Further Design Improvements

The following design improvements were suggested through stakeholder workshops with intention to improve the level of Safe System alignment. These were directed to the case study design in Figure 4.37, but could be considered in all future raised intersection designs:

- Addition of rumble strips on approaches.
- Provide a speed camera.
- Lower speed limit to 60 km/h.
- Apply speed humps/cushions on minor approaches.

4.10 Further Design Innovation

Previous sections identified specific knowledge gaps and development needs relating to specific Safe System intersection design concepts. These can be summarised as follows:

- Safe outcomes for pedestrians, cyclists and motorcyclists remain a challenge even for intersection design concepts with high Safe System alignment for vehicle occupants. This disparity is caused by a much lower biomechanical tolerance of vulnerable road users.
- More holistic transport approaches are needed to generate Safe System solutions meeting the needs of these user groups. These solutions may include exclusion/regulation of vehicle access to some parts of the road network, permanently or at selected times. Separation of vulnerable road users from vehicular traffic should be considered where appropriate. Other solutions may involve flexible priority arrangements, e.g. handing movement priority to cyclists and pedestrians on selected principal routes or at some crossings. Development of Movement and Place philosophy may assist in defining opportunities for such solutions (Austroads 2016e).
- Improving Safe System outcomes of two-wheelers at roundabouts should be a focus of a dedicated design innovation project.
- Better understanding of Safe System value of signalised roundabouts is needed. Available research is promising, but more dedicated evaluation of road safety effectiveness is needed.
- Refinements to safety platform design guidance is needed, especially in high-speed environments (60–80 km/h and > 80 km/h approach speeds). Heavy vehicle dynamics should be considered.
- Several requests were received for development of more low-cost Safe System design concepts for rural intersections.
- Operational impacts of many design concepts presented in this study were unknown (e.g. delay, capacity, queueing, travel time, reliability). Practitioners wishing to trial these designs should include operational assessment. Similarly, appraisal of asset maintenance impacts should be carried out.

- Innovative lighting solutions should be explored to eliminate the need for roadside poles and power supply to highlight presence of isolated rural intersections (e.g. smart road solutions).
- Impact-absorbing traffic signal, power and lighting poles need to be considered to address the consequences of primary and secondary loss-of-control crashes at intersections.

General observations and feedback was gathered through the 15 practitioner workshops delivered via Austroads project SS2061 *Safe System Infrastructure Workshops.* These inputs may assist practitioners in trialling the innovative Safe System solutions presented in the previous sections.

- Innovation culture in road and transport agencies is developing. Practitioners demonstrate demand for solutions to emerging challenges, e.g. Safe System, urban growth, autonomous vehicles, road access. Greater understanding and training in innovation management techniques would assist road agencies in Safe System implementation. Jurewicz (2017) proposes an innovation pathway for development of innovative infrastructure solutions to meet such new challenges.
- Better insights are needed into understanding road user needs, experience and values to guide the development of Safe System intersection solutions acceptable to the community. The development of multiple road use cases is a valuable technique to capture these needs. Such insight would have a positive impact on the implementation of all Safe System solutions, including speed management.
- Many innovative solutions were still emerging and some were yet to be trialled. With all innovative solutions, there is a need to clearly define objectives, assess risks of unintended outcomes, monitor performance, evaluate performance, and implement design refinements. This innovation process should be documented in trial evaluation frameworks prepared for each new solution.

Research recommendations arising from the study, which have a broader application for the road safety engineering practice, are as follows:

- The first module of the X-KEMM-X research method was developed under this study, version 0.5. As noted in Section 2.2, the method estimates a probability of an FSI outcome should a crash occur. This method already showed usefulness in Safe System intersection design analysis. The method has future potential for the estimation of FSI crash reduction factors for specific intersection treatments.
- Further method modules should be developed to deal with estimation of crash likelihood at each conflict point under different levels of traffic exposure. Cyclist and motorcyclist capabilities also should be investigated. The effect of mass disparity in collisions with heavy vehicles can be added as a sensitivity testing feature.
- Consideration may be given by Austroads and/or road agencies to the development of such a tool for practitioners. The tool would complement the qualitative SSAF method, which is most useful at the concept design stage.
- Revised intersection impact speed thresholds based on US research were proposed in Austroads (2015). This study demonstrated the need to continue refinement of this research in the Australian and New Zealand context to answer questions such as ‘what are the effects of intersection approach operating speeds on crash likelihood and severity (not impact speeds or delta-V)’, or ‘what are the FSI-critical impact speeds for cyclists and motorcyclists?’

5. Summary and Discussion

Intersection crashes account for approximately 30% of severe injuries in Australia and New Zealand. While research has been able to quantify the magnitude of the intersection problem, there is a lack of understanding surrounding the poor Safe System performance of traditional intersection designs. Current Austroads guides do not address this and there is little other practical guidance available to road agencies on how to modify intersection designs to minimise the occurrence of death and severe injury.

In response to these gaps, Austroads commissioned ARRB to seek initiatives to improve the design of intersections so that they would be better aligned with the Safe System objective of minimising death and serious injury.

The study involved a review of recent research and data relating to the Safe System performance of intersections to better understand who, where, how is severely injured at intersections. The main conclusions from this investigation, presented in Section 2, were:

- The top intersection types contributing to the FSI crash problem in New Zealand and Victoria were
  - urban priority-controlled intersections due to high crash rate, but also high number of crashes
  - urban signalised intersections due to high number of crashes, but also a relatively high crash rate
  - rural priority-controlled intersections due to the highest crash rate, but a lower number of crashes.
- The intersection type closest to the Safe System vision was the urban roundabout, followed by the rural roundabout.
- Three-leg intersections were safer than four- or multi-leg intersections due to fewer conflict points and reduced complexity.
- The main traffic movements of concern, according to the leading FSI crash types, applicable to both investigated jurisdictions, were
  - adjacent direction movements
  - opposing-turning
  - pedestrians crossing or stepping out
  - off-path movements, i.e. loss-of-control.
- Among the vulnerable road users, the following urban scenarios presented the greatest concern for Safe System intersection design (based on Victorian data)
  - pedestrians at priority-controlled and signalised intersections
  - cyclists and motorcyclists at priority-controlled intersections and at roundabouts (a high proportion but not a high number).

These learnings were extended by further, targeted analysis of US and Australian crash reconstruction research to develop a new research method for the analysis of severe injury probability when crashes occur at intersections. The method, called X-KEMM-X v0.5, focussed on impact speeds and angles, and different crash types (e.g. side, frontal, rear, pedestrian) at each conflict point. Thus, minimum, average and maximum severe injury probabilities can be estimated for any given intersection design.

A useful practitioner tool was produced using the X-KEMM-X method, viz. a chart showing the changes in severe injury probability as a function of impact speeds and angles (Figure 2.10). This tool would be useful in intersection design decisions, e.g. to support speed management and more forgiving layouts.

The X-KEMM-X method was useful in demonstrating the relative alignment of selected conventional intersection design concepts with Safe System objective of minimising fatal and serious injury in vehicle-vehicle and vehicle-pedestrian conflicts (Section 2.3). In general, priority-controlled and signalised intersections with through entry speeds of 50 km/h and above may be considered very poorly aligned with the Safe System objective.

Roundabouts were shown to be highly aligned with the Safe System for vehicle-vehicle conflicts (except of cyclists and motorcyclists), but poorly aligned for vehicle-pedestrian conflicts.

X-KEMM-X v0.5 may be developed in the future to account for conflict likelihood and exposure. This would provide a useful Safe System assessment tool for detailed intersection design by practitioners.

Further review of local and international literature and road agency trials identified innovative intersection designs which sought to address the key severe injury risk factors, and to achieve greater Safe System alignment. These solutions were analysed using the available research information and X-KEMM-X results. This showed that roundabouts and their derivatives (e.g. signalised roundabout, flower roundabout) had the greatest potential to deliver Safe System outcomes. The factors supporting Safe System performance included:

- reduction in the number of conflict points, e.g. via the number of legs or geometry
  Regulation offers similar potential (e.g. turn bans, movement consolidation).
- simplification of road user decision making and clear expectations, e.g. higher levels of traffic movement control, lower complexity
- reduction in intersection entry speeds via geometry, layout and/or speed management
- reduction in impact angles via geometry.

The review of the literature and the findings of the data analysis led to the development of the following Safe System intersection design principles, presented in Section 3. For all road users:

1. minimise conflict points
2. remove or simplify road user decisions
3. minimise impact angles
4. minimise entry and impact speeds.

Designer-level guidance was then proposed, based on these principles combined with the logic of Safe System Assessment Framework (Austroads 2016d). The resulting guidance is presented in Table 3.1.

Nine innovative solutions were chosen for further concept development. These concept designs were analysed using SSAF and X-KEMM-X techniques to assess and improve their levels of Safe System alignment. The results using the two methods generally converged. Substantial practitioner consultation was undertaken to convey the Safe System design principles used in the design concepts and to seek practitioner-driven concept improvements. Table 5.1 summarises the results detailed in Sections 4.1 to Section 4.9.

Stakeholders sought a further discussion on the difference between Safe System alignment and severe casualty crash reduction factor (CRF). It was observed that some reviewed solutions had reasonably high CRFs, yet their Safe System alignment levels in SSAF and X-KEMM-X were moderate or poor. The reason for this is that CRF is a measure of relative reduction in risk from a known baseline, i.e. the ‘before’ scenario.

A change from a very poorly aligned baseline (e.g. SSAF score over 400) to one which is borderline moderate/poor (e.g. ~224) can be sometimes aligned with CRFs in the 40–60% range. Similarly, treatments improving Safe System alignment from moderate/poor to high[9] (e.g. to SSAF score < 112) can yield similar CRFs from the research literature. In short, CRFs are a relative measure dependent on the baseline, while Safe System alignment is an absolute measure of alignment with the vision's objectives.

Thus, many concepts only moderately aligned with Safe System objectives can still act as supporting Safe System solutions, hopefully with a view to a future upgrade to a highly aligned solution. Practitioners should view these solutions in this context.

The nine innovative design concepts form a starting point for practitioners' trials and refinement. In preparation for trials, these innovative intersection designs will require:

- further design development (e.g. site-specific)
- engineering risk assessments
- traffic flow and operational risk assessments (e.g. for heavy vehicle, motorcyclist and cyclist impacts)
- development of evaluation frameworks ahead of trials (e.g. acceptance criteria, evaluation methods)
- trial planning and resourcing.

It is intended that some versions of the nine proposed concepts will be successfully evaluated. They may then become widely used to improve the Safe System performance of intersections, and may inform future revisions of the Austroads guides.

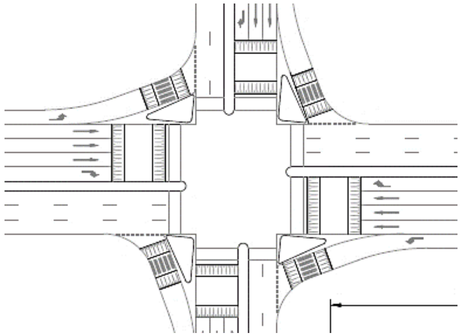
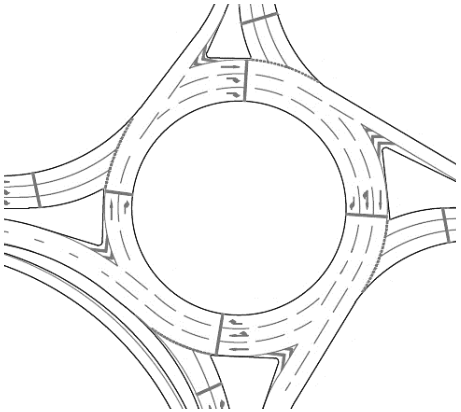
The Safe System performance for vehicle-pedestrian conflicts was generally poorer than for vehicle-vehicle conflicts. This was always due to intersection entry speeds being 40 km/h or 50 km/h, i.e. above the estimated biomechanical FSI threshold for adult pedestrians (20 km/h, Davis 2001). The same finding applied for cyclists and motorcyclists, although the impact speed threshold evidence was not precise for these two groups.

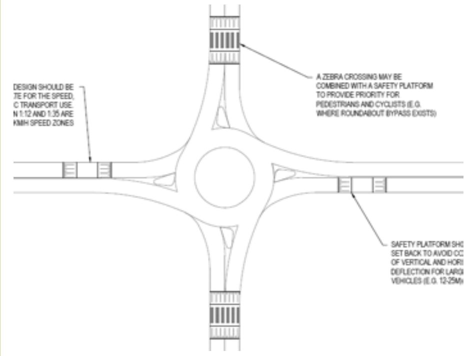
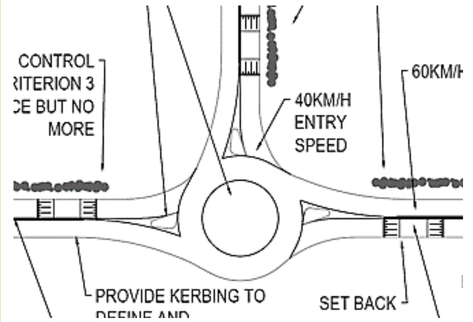
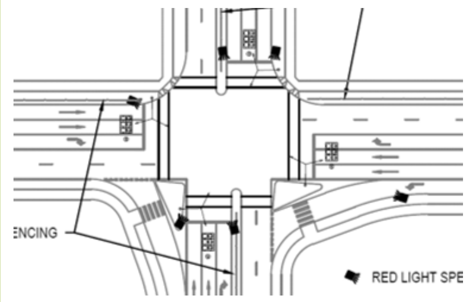
These findings lead to the conclusion that speed management and intersection design are unlikely to be the only mechanisms required for achieving Safe System outcomes for all road user groups. Autonomous vehicle technologies, C-ITS and appropriate network control/management are likely to provide more significant contributions in these areas with time.

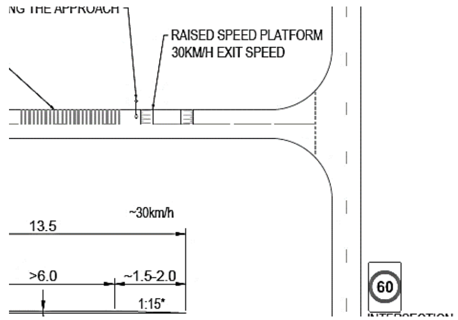
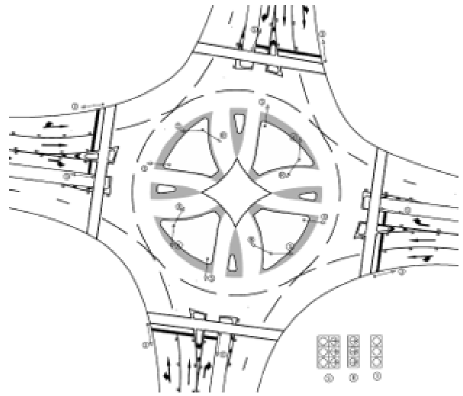
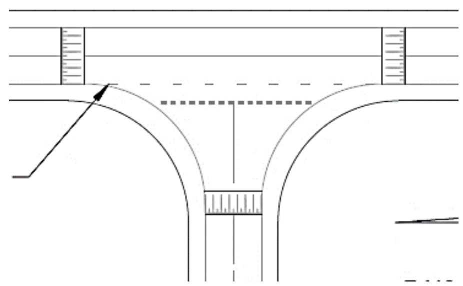
Further, broader transport planning initiatives, such as Movement and Place, offer more strategic contributions towards Safe System. In many cases the community may accept much lower speed limits to facilitate safe and efficient non-vehicular traffic (10–30 km/h) in a vibrant urban environment. Reassignment of road space and priority to non-vehicular transport modes is also possible, thus practically eradicating possibility of conflict. Road user separation and management may need to be considered more comprehensively (e.g. separate movement networks, over/underpasses, tunnels, shared and vehicle exclusion zones). Austroads (2016b) provides an outline of this approach.

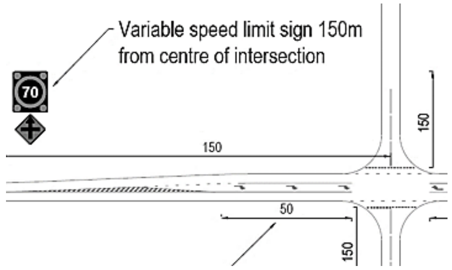
9 This would refer to SSAF or X-KEMM-X risk scores out the possible maximum. Poor alignment means that around 50% or more of the maximum risk score is retained. Moderate alignment means that about 25% of the FSI risk is retained. High alignment means that ≤ 12.5% of risk is retained. These are broad markers of Safe System alignment used by SSAF and X-KEMM-X.

Table 5.1: Summary of Safe System design concepts analysed in this study

Concept name	Applicability	Safe System alignment		Crash reduction factor	Cost (retrofit/new)	Image
		Vehicle-vehicle	Vehicle-pedestrian			
Signalised intersection with safety platforms (Section 4.1)	Urban Retrofit, greenfield Emerging solution, under trial	Poor to moderate	Poor to moderate	30% estimated casualty, retrofit to signals 50–60% casualty, replace priority-controlled (estimate)	Low to moderate	
Signalised roundabout (Section 4.2)	Urban, outer-urban Retrofit (large sites), greenfield Established traffic solution	Moderate to high	Poor	11% all-crashes, retrofit to roundabout 65% casualty, replace priority-controlled (estimate)	Moderate to high	

Concept name	Applicability	Safe System alignment		Crash reduction factor	Cost (retrofit/new)	Image
		Vehicle-vehicle	Vehicle-pedestrian			
Compact roundabout with safety platforms (Section 4.3)	Urban, outer-urban Retrofit, greenfield Emerging solution already in use	High	Moderate	55% casualty, replace priority-controlled (estimate)	Low to moderate	
Compact roundabout with safety platforms (Section 4.4)	Rural Retrofit, greenfield Conceptual solution, not yet trialled	High	Not available	70% casualty, replace priority-controlled (estimate)	Low to moderate	
Signalised intersection retrofit combination treatment (Section 4.5)	Urban, outer-urban Retrofit, greenfield Already in use	Poor	Poor	50% casualty and FSI, retrofit to signals (estimate)	Moderate	

Concept name	Applicability	Safe System alignment		Crash reduction factor	Cost (retrofit/new)	Image
		Vehicle-vehicle	Vehicle-pedestrian			
Priority-controlled rural intersection with safety platforms and reduced speed limits (Section 4.6)	Rural Retrofit Conceptual solution, not yet trialled	Moderate to high	Not available	Not available	Low	
Cut-through signalised intersection (Section 4.7)	Urban, outer-urban Greenfield Conceptual solution, not yet trialled	Moderate to high	Poor	Not available	High	
Priority-controlled raised intersection (Section 4.8)	Urban Retrofit, greenfield Emerging solution already in use	High	Poor to moderate	55% casualty, retrofit to priority-controlled	Moderate	

Concept name	Applicability	Safe System alignment		Crash reduction factor	Cost (retrofit/new)	Image
		Vehicle-vehicle	Vehicle-pedestrian			
Priority-controlled intersection with vehicle-activated speed limits (Section 4.9).	Rural Retrofit Emerging solution already in use	Poor to moderate	Not available	51% all crashes, 79% FSI crashes, retrofit to priority-controlled	Low to moderate	

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Appendix A Safe System Assessment Framework (Summary)

The Safe System Assessment Framework (SSAF), documented in Austroads (2016b), is a practitioner assessment tool for measuring how well a given design or concept aligns with the Safe System objective of minimising severe injury. It can be used to highlight areas of residual severe injury risk, and to assist in identifying design improvements to achieve the Safe System objective.

This framework has been adopted by several state road agencies to assess the alignment of projects with Safe System objectives, and has been found to particularly useful in identifying key safety risks, including at concept design stage.

Safe System assessment typically involves:

- identifying the objectives for the assessment (Appendix A.1)
- deciding on the scale and depth of the assessment (Appendix A.2)
- setting the context, including identifying the function of the road, relevant speed environment, main road user types, and likely vehicle composition (Appendix A.3)
- applying the 'Safe System Matrix' where major crash types are assessed in relation to key sources of risk: exposure (traffic and vulnerable road user volumes), crash likelihood and severity (Appendix A.4).

A case study illustrating the application of the SSAF may be found in the *Safe System Assessment Framework* report (Austroads 2016b). The example provided in this Appendix is for illustration purposes only.

A.1 Assessment Objectives

The first step is to identify and document the objective of the Safe System assessment. The framework can be used for different objectives, for instance:

- identifying whether a project or solution will produce a Safe System outcome
- identifying the level of Safe System alignment
- identifying and documenting Safe System-relevant issues that mean the project will not be aligned (i.e. severe injury risks)
- suggesting solutions that would move the project closer towards, or in full alignment with Safe System objectives
- developing and comparing alternative project options.

A.2 Scale and Depth of Assessment

The desired depth of assessment needs to be identified, for instance:

- at high level at the planning stage (key issues only, broad level of alignment, areas for improvement)
- in more detail for individual project components (quantitative level of Safe System alignment, identify specific problems and solutions).

Where a high degree of precision is required, the subjective assessment proposed in the framework can be replaced by more detailed quantitative information. For example, information could be added using the Australian National Risk Assessment Model (ANRAM) or the Extended Kinetic Energy Management Model (X-KEMM-X). Having this objective in mind will help to focus the assessment on the overall objectives.

A.3 Setting the Context

The prompts in Table A 1 provide guidance on considerations when setting the assessment context.

Table A 1: Template for setting the project context

Prompts
What is the reason for the project? Is there a specific crash type risk? Is it addressing specific issues such as poor speed limit compliance, road access, congestion, future traffic growth, freight movement, amenity concerns from the community, maintenance/asset renewal, etc?
What is the function of the road? Consider location, roadside land use, area type, speed limit, intersection type, presence of parking, public transport services and vehicle flows. What traffic features exist nearby (e.g. upstream and downstream)? What alternative routes exist?
What is the speed environment? What is the current speed limit? Has it changed recently? Is it similar to other roads of this type? How does it compare to Safe System speeds? What is the acceptability of lowering the speed limit at this location?
What road users are present? Consider the presence of elderly, schoolchildren and cyclists. Also, note what facilities are available to vulnerable road users (e.g. signalised crossings, bicycle lanes, school zone speed limits, etc.).
What is the vehicle composition? Consider the presence of heavy vehicles (and what type), motorcyclists and other vehicles using the roadway.

Source: Austroads (2016b).

A.4 Applying the 'Safe System Matrix'

A.4.1 Safe Roads and Roadsides, Safe Speeds

The main part of the Safe System assessment framework is the application of the Safe System matrix focussed on the contribution of road infrastructure design and speeds to severe injury risk. The purpose of the matrix is to assess different major crash types that have been identified from research as the predominant contributors to fatal and serious crash outcomes. These are run-off-road, head-on, intersection, other (typically rear-end and side-swipe), pedestrian, cyclists and motorcyclist crashes. Different elements of the matrix, along with examples of road attributes associated with risk generators, are shown in Table A 2.

As part of the assessment, a score is allocated to each cell of the matrix based on available information. This is typically based on subjective assessment by teams of road safety experts. Scores of between zero and 4 are provided at each cell. A score of zero indicates a full alignment with the Safe System vision for that component of risk of a given crash type. The higher the score, the further the project is from a Safe System condition – a score of 4 would be for the most unfavourable safety condition for the given context. Scores should be allocated considering the factors of interest shown in Table A 2 and the scoring guidance provided in Table A 3.

X-KEMM-X, detailed in the next Appendix, can be used to assess the probability of severe outcomes under the Severity heading. This provides a more analytical and theory-based input than expert judgement.

If quantification of severe injury risks is needed on a larger scale (e.g. road network, a route), then Australian National Risk Assessment Model (ANRAM v1) can be used in lieu of SSAF. This approach allows calculation of corridor and program benefit-cost ratios.

Table A 2: Safe System assessment framework for infrastructure projects

	Run-off-road	Head-on	Intersection	Other	Pedestrian	Cyclist	Motorcyclist
Exposure	AADT; length of road segment	AADT; length of road segment	AADT for each approach; intersection size	AADT; length of road segment	AADT; pedestrian numbers; crossing width; length of road segment	AADT; cyclist numbers; pedestrians	AADT; motorcycle numbers; length of road segment
Likelihood	Speed; geometry; shoulders; barriers; hazard offset; guidance and delineation	Geometry; separation; guidance and delineation; speed	Type of control; speed; design, visibility; conflict points	Speed; sight distance; number of lanes; surface friction	Design of facilities; separation; number of conflicting directions; speed	Design of facilities; separation; speed	Design of facilities; separation; speed
Severity	Speed; roadside features and design (e.g. flexible barriers)	Speed	Impact angles; speed	Speed	Speed	Speed	Speed

Note: When undertaking SSAF assessment for intersections, all legs and access points should be included. The length of each approach (leg) should be determined by features that influence the safety performance of the intersection (e.g. start of turning lane, parking limit, sight distance, geometric elements, etc.).

Source: Adapted from Austroads (2016d).

In addition to the score, comments are provided relating to each of the cells. This helps to record the rationale for the score, and to identify the specific issues of concern. This is very helpful in resolving the key residual risk factors for each project.

Once a score is provided in each cell for the exposure, likelihood and severity rows, the product of each column is calculated and entered in the final row, labelled ‘product’. The purpose of this multiplicative approach is that if a score of zero has been given for any component of a crash type (i.e. exposure, likelihood or severity), that crash type receives a total of zero and is eliminated from the score (as it has reached a Safe System condition). The maximum score for each crash type column is 64.

Table A 3: Safe System matrix scoring system

Road user exposure	Crash likelihood	Crash severity
0 = there is no exposure to a certain crash type. This might mean there is no side flow or intersecting roads, no cyclists, no pedestrians, or motorcyclists.	0 = there is only minimal chance that a given crash type can occur for an individual road user given the infrastructure in place. Only extreme behaviour or substantial vehicle failure could lead to a crash. This may mean, for example, that two traffic streams do not cross at grade, or that pedestrians do not cross the road.	0 = should a crash occur, there is only minimal chance that it will result in a fatality or serious injury to the relevant road user involved. This might mean that kinetic energies transferred during the crash are low enough not to cause a fatal or serious injury (FSI), or that excessive kinetic energies are effectively redirected/dissipated before being transferred to the road user. Users may refer to Safe System-critical impact speeds for different crash types, while considering impact angles, and types of roadside hazards/barriers present.
1 = volumes of vehicles that may be involved in a particular crash type are particularly low, and therefore exposure is low. For run-of-road, head-on, intersection and 'other' crash types, AADT is < 1 000 per day. For cyclist, pedestrian and motorcycle crash types, volumes are < 10 units per day.	1 = it is highly unlikely that a given crash type will occur.	1 = should a crash occur, it is highly unlikely that it will result in a fatality or serious injury to any road user involved. Kinetic energies must be fairly low during a crash, or the majority is effectively dissipated before reaching the road user.
2 = volumes of vehicles that may be involved in a particular crash type are moderate, and therefore exposure is moderate. For run-of-road, head-on, intersection and 'other' crash types, AADT is between 1 000 and 5 000 per day. For cyclist, pedestrian and motorcycle crash types, volumes are 10–50 units per day.	2 = it is unlikely that a given crash type will occur.	2 = should a crash occur, it is unlikely that it will result in a fatality or serious injury to any road user involved. Kinetic energies are moderate, and much of the time they are effectively dissipated before reaching the road user.
3 = volumes of vehicles that may be involved in a particular crash type are high, and therefore exposure is high. For run-of-road, head-on, intersection and 'other' crash types, AADT is between 5 000 and 10 000 per day. For cyclist, pedestrian and motorcycle crash types, volumes are 50–100 units per day.	3 = it is likely that a given crash type will occur.	3 = should a crash occur, it is likely that it will result in a fatality or serious injury to any road user involved. Kinetic energies are moderate, but are not effectively dissipated and therefore may or may not result in an FSI.
4 = volumes of vehicles that may be involved in a particular crash type are very high, or the road is very long, and therefore exposure is very high. For run-of-road, head-on, intersection and 'other' crash types, AADT is > 10 000 per day. For cyclist, pedestrian and motorcycle crash types, volumes are > 100 units per day.	4 = the likelihood of individual road user errors leading to a crash is high given the infrastructure in place (e.g. high approach speed to a sharp curve, priority movement control, filtering right turn across several opposing lanes, high speed).	4 = should a crash occur, it is highly likely that it will result in a fatality or serious injury to any road user involved. Kinetic energies are high enough to cause an FSI crash, and it is unlikely that the forces will be dissipated before reaching the road user.

Source: Austroads (2016b).

Table A 4 shows an example assessment to illustrate the approach (note the example in this Appendix is for illustration purposes only).

As an approximation, a design with the crash type score of less than 16 can be considered highly aligned with Safe System for that crash type (e.g. run-off-road or head-on scores in Table A 4). A design can be considered moderately aligned between 16 and 32, and poorly aligned above 32. The SSAF is a subjective tool and scores are indicative of Safe System alignment.

Table A 4: An example of a Safe System Assessment

	Run-off-road	Head-on	Intersection	Other	Pedestrian	Cyclist	Motorcyclist
Exposure	4	4	4	4	4	1	4
Likelihood	1	1	3	3	3	4	3
Severity	2	2	3	1	4	4	4
Product	8/64	8/64	36/64	12/64	48/64	16/64	48/64
Total SSAF score				176/448			

The sum of the scores for each crash type is then added to calculate the 'Total SSAF Score'. This score is out of a possible 448; it represents the Safe Speeds and Safe Roads and Roadsides pillars' contribution to Safe System for the project. The closer the total score is to zero, the more the project in question is aligned with the Safe System objective. Attention to minimising individual crash type scores is still needed.

As a rule-of-thumb, total SSAF scores of less than 112 can be considered highly aligned with Safe System, 112 to 224 moderately aligned, and above 224 poorly aligned. Consistency of Safe System alignment across all crash types needs to be considered. For example, a project can be qualified well-aligned with Safe System for passenger and heavy vehicles, but poorly aligned for vulnerable road users.

As noted previously, SSAF scores are indicative of Safe System alignment. SSAF scores should not be compared between different locations, or used for site prioritisation, as the values are influenced by site conditions beyond practitioners' control (e.g. AADT, speed environment). Scores can be compared for alternative design options for the same project to develop and select the option which is most Safe System-aligned.

A.4.2 Other Safe System Pillars

Along with the infrastructure- and speed-related assessment, broader issues are also assessed as part of this process. The Safe System approach demands that each pillar of the system must work together to help produce Safe System outcomes. The system comprises safe roads, safe speed, safe vehicles, safe road users and safe post-crash care. Although safe roads and speeds are typically included in safety reviews for infrastructure projects, the other elements are seldom considered.

In many circumstances, these other pillars will have a strong bearing on safety outcomes, and it is often the case that designers will have some ability to influence these to produce safer travel outcomes. This synergy is important to account for as it may reduce capital costs and improve overall project effectiveness.

For these reasons, the remaining pillars need to be assessed when reviewing projects. Table A 5 provides some prompts for additional issues considered during the assessment.

Table A 5: Additional Safe System components for consideration in infrastructure projects

Pillar	Prompts
Safe road users	Are road users likely to be alert and compliant? Are there factors that might influence this? What are the expected compliance and enforcement levels (alcohol/drugs, speed, road rules, and driving hours)? What is the likelihood of driver fatigue? Can enforcement of these issues be conducted safety? Are there special road and abutting land uses, e.g. entertainment precincts, elderly, children, on-road activities, or a recreational motorcyclist use? Are there environmental distraction factors (e.g. commerce, tourism), or known risk-taking behaviours?
Safe vehicles	What level of alignment is there with the ideal of safe vehicles? Are there factors that might attract large numbers of potentially unsafe vehicles (e.g. farm machinery)? Is the percentage of heavy vehicles too high for the proposed/existing road design? Do recreational motorcyclists use this route? Are there enforcement resources in the area to detect non-roadworthy, overloaded or unregistered vehicles and thus remove them from the network? Can enforcement of these issues be conducted safety? Has vehicle breakdown been catered for?
Post-crash care	Are there issues that might influence safe and efficient post-crash care in the event of a severe injury (e.g. congestion, access-stopping space)? Do emergency and medical services operate as efficiently and rapidly as possible? Are other road users and emergency response teams protected during a crash event? Are drivers provided the correct information to address travelling speeds on the approach and adjacent to the incident? Is there reliable information available via radio, VMS etc.? Is there provision for e-safety (i.e. safety systems based on modern information and communication technologies, C-ITS)?

Source: Adapted from Austroads (2016d).

Appendix B X-KEMM-X Method Development

B.1 Background

While the research findings reported in Section 2.1 quantified the magnitude of the intersection FSI problem, and some major risk factors, there has been a lack of deeper understanding surrounding Safe System performance of intersection designs.

Most existing intersection designs permit vehicles to travel along conflicting paths at speeds higher than the impact speeds regarded as thresholds of severe injury (Austroads 2015). Most standard layouts permit collision angles that do not optimise the protection of occupants offered by modern vehicles.

B.2 Estimating Probability of an Intersection FSI Crash Outcome

Review of crash reconstruction research suggests that estimated impact speed is generally a limited predictor of crash severity, with the exception of pedestrian and cyclist crashes. This is due to many additional factors controlling crash severity such as speed of the other vehicle, or relative masses of the two vehicles. It has been well established since the 1970s that a vehicle's delta-V 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 crashes involving roll-overs and impacts with roadside hazards (Joksch 1993, Shelby 2011, Rosen, Stigson & Sander 2011, Schmitt et al. 2014, Struble 2013). For this reason, off-path crashes were not the focus for development in X-KEMM-X, at this time.

There has been significant empirical research on the effect of delta-V on severity of two-vehicle crashes based on crash reconstruction databases held in the USA (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; they did not differentiate between crash configurations, e.g. head-on, side impact or rear-end. Applicability of these relationships to the three crash types was tested by this study's authors and did not return results which correlated well with other research. Sobhani et al. (2011) and Sobhani, Young and Sarvi (2013) provided further proof-of-concept models based on available Victorian in-depth severe crash data, showing that such models can be developed for different crash configurations.

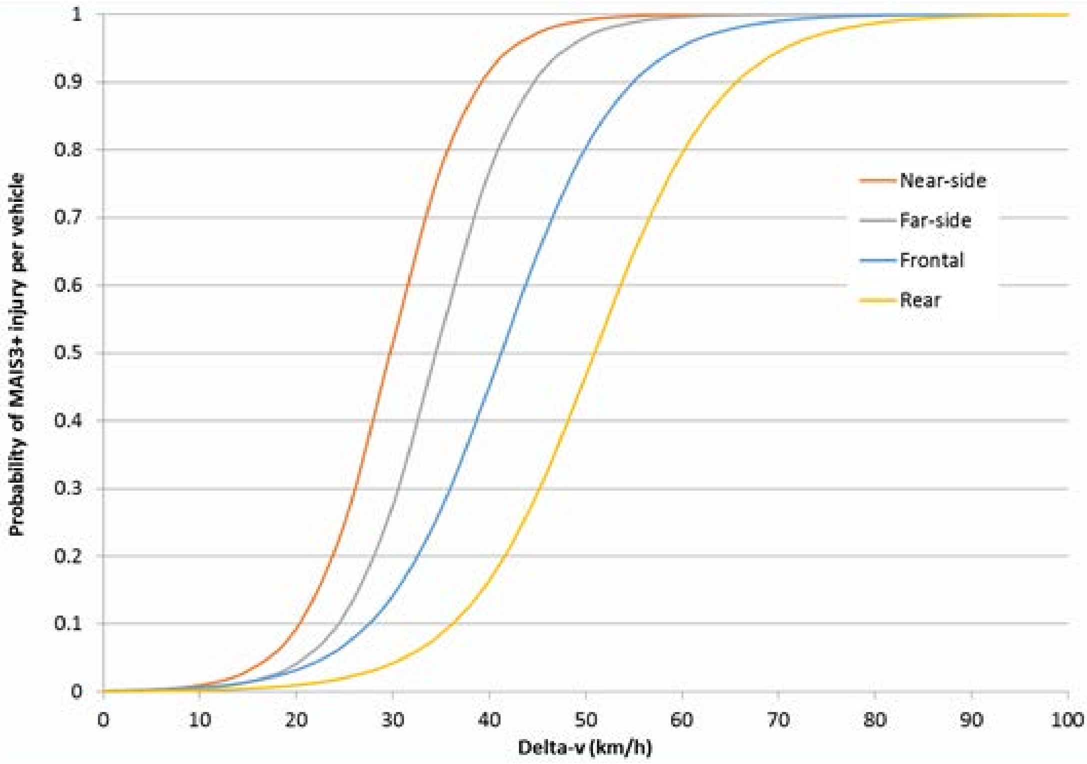
Later research by Bahouth et al. (2014) provided a much more robust set of delta-V severity relationships for head-on, near-side (i.e. driver side), far-side (i.e. passenger side) and rear-end crashes. These studies used a large sample of crashes of different severities drawn from the NASS/CDS database in the USA (over 100 000 crashes). The baseline collision severity used in the study was a non-injury tow-away incident. Crashes in the database are weighted so that sampling represents real-life crash severity distribution. The study used binary logistic regression to develop relationships between the probability of MAIS3+ injury[10] for any vehicle occupant in a given crash configuration and a range of factors such as delta-V, seatbelt wearing and age of the occupants.

Figure B 1 shows the resulting relationships between probability that a crash event will result in an MAIS3+ injury and the vehicle delta-V. These curves represent the risk to front-seat vehicle occupants only. The Bahouth et al. (2014) models assumed seatbelt use and the occupant age between 16 to 55 years old, where these were significant model parameters.

10 MAIS3 is considered the serious injury threshold with 8–10% chance of death; MAIS6 injury carries a 100% chance of death.

The curves are aligned in a logical order and reflect the effect of impacts on different parts of a vehicle. For a given delta-V value, the near-side is the most severe crash. In this crash configuration, the impact occurs on the driver side and the amount of protection offered by the vehicle is minimal. The far-side is next, showing the double benefit of the crush zone to the left of the driver (more likely to be empty). Next is the head-on impact, with the crush zone benefit of the engine compartment, but some likelihood of steering injuring the driver. The least severe crash configuration is the rear end, with the large and typically empty crush space behind the driver.

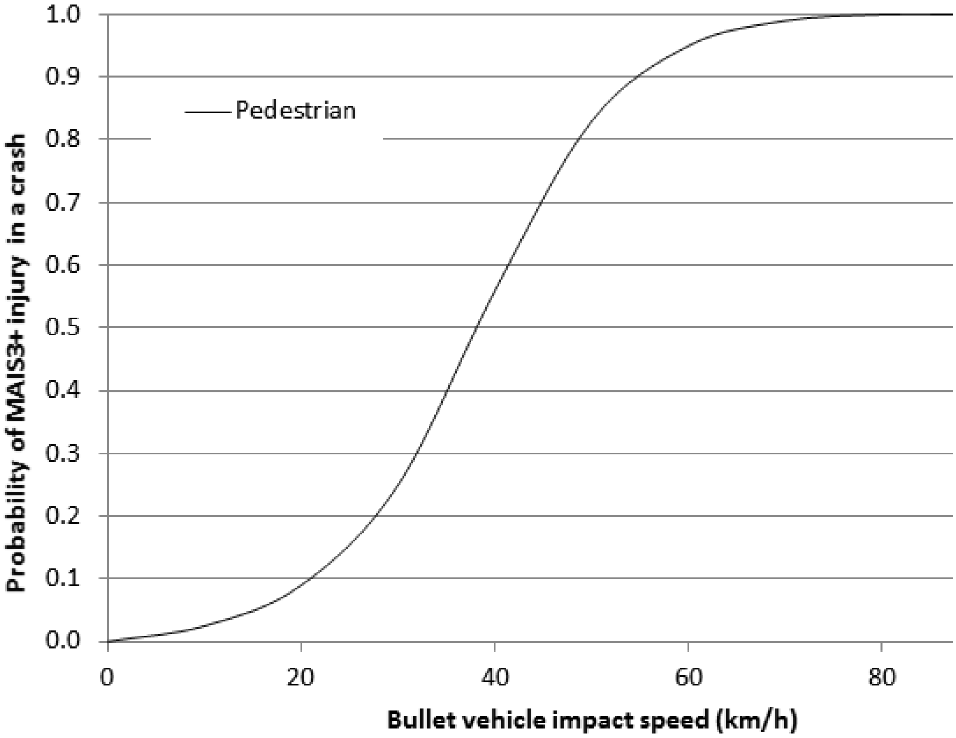
Figure B 1: Probability of severe injury of occupants vs. delta-V of a vehicle during a crash



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

Pedestrian probabilities of MAIS3+ injury (serious injury or death) are determined only by the bullet vehicle speed. The values have been sourced from Davis (2001) due to its quality of research method and the FSI probability output. Figure B 2 shows the relationship.

Figure B 2: Probability of severe injury for pedestrians vs. bullet vehicle speed



Source: Based on Davis (2001).

B.3 Impact Speeds and Crash Angles

The key difficulty in directly applying delta-V to Safe System infrastructure discussion is its relationship to design speeds. It is useful to resolve this and represent delta-V in terms of impact speeds, which can be conceptually aligned with design speed and speed limits more easily.

To address this, a useful analysis of back-calculation was performed by Tolouei, Maher and Titheridge (2011). Using Newtonian mechanics of momentum conservation, the authors showed that delta-V has the relationship with vehicle impact speeds and the angle between their paths as shown by Equation A1.

$$\Delta V = \frac{\sqrt{V_1^2 + V_2^2 - 2V_1V_2\cos\emptyset}}{2} \qquad \text{A1}$$

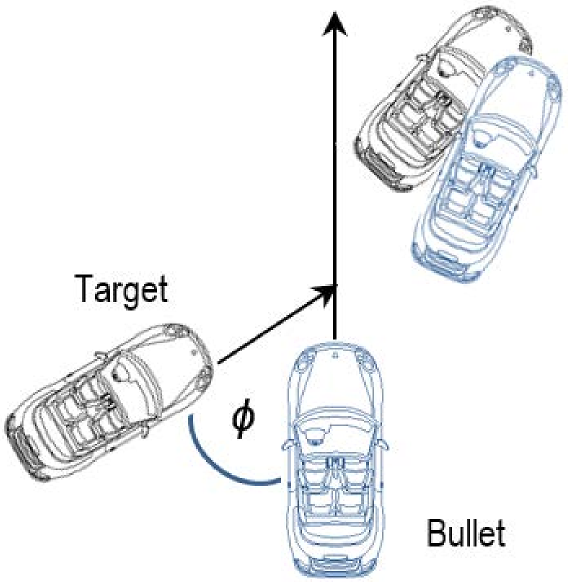
where

ΔV	=	delta-V, vehicle change in speed due to the crash
V_1 and V_2	=	impact speeds of 'bullet' and 'target' vehicles respectively
$\emptyset$	=	the angle between the axis of travel of both vehicles

Equation A1 is illustrated in Figure B 3. It is assumed in Equation A1 that the mass of the two vehicles is identical and the collision is inelastic (no rebound, a more conservative scenario). In such a case, ΔV has the same magnitude for both vehicle 1 and 2.

Tolouei, Maher and Titheridge (2011) provide more complex equations for situations outside these assumptions, e.g. unequal mass. Equation A1 indicates that the smaller the angle between the directions of the two vehicles, the lower the delta-V, and thus, the lower is the severity of a potential crash. Given a set of two known impact speeds and equal vehicle masses, the lowest delta-V, and the lowest crash severity, would be for a rear-end crash where the velocities are in the same direction.

Figure B 3: Layout of conflicting vehicles in Equation A1



B.4 Method for Assessing Intersection Designs

The following X-KEMM-X process was developed to quantitatively determine the probability of FSIs in crashes for a given intersection design:

Step 1: Draw a conflict point diagram for the intersection. This diagram shows all the crossings of conflicting traffic movements, including pedestrians.

Step 2: Measure conflict angles and indicate the assumed impact speed of the two vehicles involved in each conflict point. Impact speeds were based on approach speeds given by speed limits, or as determined by any speed management solutions which were part of the design.

Step 3: Compute delta-V for each vehicle involved in the conflict using Equation A1.

Step 4: Estimate the probability of an FSI outcome in a crash for each vehicle at each conflict point using the graphs presented in Figure B 1 and Figure B 2. To estimate this probability, it was necessary to decide about the impact location (i.e. near side, far side, front or rear) for each vehicle involved in the crash, i.e. which probability relationship to apply. The assumption was to always consider the worst-case scenario; therefore, for any angle crash the bullet vehicle (i.e. the hitting vehicle) will impact the target vehicle (i.e. the other vehicle) from the side rather than the front or rear. This is because, for an angle crash, there is a possibility that the target vehicle is impacted from the front/rear or side, and the side impact configuration is more severe than the front or rear impact (Figure B 1). For head-on and rear-end crashes, the assumption was that the target vehicle is impacted from the front and rear respectively, since the possibility of side impact for these types of crashes was very low. For all these crash types (i.e. angle, head-on and rear-end crash types), the bullet vehicle is assumed to be impacted in the front.

Step 5: After estimating the probability of each vehicle's occupants sustaining an FSI outcome, the overall FSI probability for the crash event is estimated using the union of these two probabilities as shown in Equation A2.

$$Pr(FSI) = Pr(FSI_{v1} \cup FSI_{v2}) = Pr(FSI_{v1}) + Pr(FSI_{v2}) - Pr(FSI_{v1}) \times Pr(FSI_{v2}) \quad \text{A2}$$

where

$Pr(FSI)$ = probability that the crash produces an FSI outcome[11]

$Pr(FSI_{v1})$ = probability that the bullet vehicle produces at least one FSI outcome

$Pr(FSI_{v2})$ = probability that the target vehicle produces at least one FSI outcome

B.5 Assumptions and Limitations

Calculating the probability of an FSI crash outcome requires some assumptions to be made to obtain a quantitative calculation output. The direction of the vehicle, mass of the vehicle, impact angles and speeds all need to be determined which may all be quite different in real life for each situation.

Another important assumption is that both vehicles were of equal mass, which is not usually the case due to the diverse makes and contents of vehicles on the road. However, making this assumption helped to establish a reliable relative comparison among different intersection designs. Further research could involve modelling mass ratios based on actual crash data. Other procedural assumptions in X-KEMM-X included:

- Lane change crashes within the intersection/roundabout were not modelled (low angle).
- Near-side crash model by Bahouth et al. (2014) is more severe than far-side due to lower probability of a passenger being present. In this study, assumption was made that a passenger is always present, hence all far-side crashes are modelled as near-side. This is a more conservative approach, which may be revised in the future.
- Any left turning lanes turn into the closest lane.
- Any right turning lanes also exit into the closest lane.
- If there are multiple turning lanes, then the exit lanes are adjacent to one another.
- All legal movements that can be made are developed in the model.
- No illegal turn movements are made.
- If one lane allows multiple movements, i.e. right turn or straight from the same lane, a rear-end crash is included (this is due to the change in speed and movement).
- Turning speeds were 30 km/h for right turn and left turn.
- Impact speeds may be lower if driver reaction and braking took place before impact – no such action was assumed due to lack of information about distribution of speed dissipation in collisions.

These assumptions were made to reduce confusion and provide a consistent conflict diagram across all intersection designs. In real crashes, there would be multiple additional possible conflicts due to rear-ends and lane changing; however, including these would make this analysis almost impossible to undertake. Also, these crash types are far less severe by their nature as shown in Figure B 1.

11 It is assumed that the probability that at least one person sustains an FSI in the bullet vehicle is independent of the probability that at least one person sustains an FSI in the target vehicle.

The intent of developing X-KEMM-X under this study was to focus on the effect of impact speeds and angles at approximated collision points to assist in the assessment of geometric intersection designs. Future research is required to add conflict probability estimation at each conflict point. This could estimate probability of critical road user error in response to traffic control and other location factors. Also, the element of exposure of road users to each conflict point needs to be considered. Only then will X-KEMM-X fully assess all fundamental aspects of vehicle-vehicle FSI risk.

Off-path crashes need to be considered once more reliable speed-severity relationships are proposed for roadside hazards in different crash configurations.

Cyclist crashes need to be considered once a more reliable relationship for speed-severity outcome is known for the key vehicle-cyclist crash configurations. Similar limitations exist for motorcyclists.

In the meantime, X-KEMM-X provides a useful comparative method for assessment of alternative geometric intersection designs.

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